Alpine Copper II – Alpenkupfer II – Rame delle Alpi II – Cuivre des Alpes II

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New Results and Perspectives on
Prehistoric Copper Production

Editors:
Rouven Turck, Thomas Stöllner, Gert Goldenberg

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Cover Image

Mine Bauernzeche near Schwaz (photo: Daniel Brandner); excavation of sluice box 5 at the Troiboden, Mitterberg (photo: Peter Thomas); Val Faller, Plaz, furnace 2 (photo: Mirco Brunner); background: Bottom surface of a massive slag fragment (rim) with negative (ascending) bubbles and a step (photo: Leandra Reitmaier-Naef)

Frontispiece

The beneficiation dumps at the Kelchalm (Kitzbühel) during the workshop's excursion on 25th of September 2016 (photo: Gert Goldenberg, University of Innsbruck)

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Editing

Dr. Petra Eisenach, Deutsches Bergbau-Museum Bochum

Univ.-Prof. Dr. Thomas Stöllner, Ruhr-University Bochum/ Deutsches Bergbau-Museum Bochum

Dr. Rouven Turck, University of Zürich, Institute of Archaeology, Department Prehistoric Archaeology

Assoz.-Prof. Dr. Gert Goldenberg, University of Innsbruck

Typesetting, Layout, Cover Design

Dipl.-Ing. Angelika Wiebe-Friedrich, Straßenhaus

Dr. Petra Eisenach, Deutsches Bergbau-Museum Bochum

Univ.-Prof. Dr. Thomas Stöllner, Ruhr-University Bochum/ Deutsches Bergbau-Museum Bochum

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Preface

From 2014 to 2018 the trinational research project "Prehistoric copper production in the Eastern and Central Alps – technical, social and economic dynamics in space and time" was carried out by project partners of the University of Innsbruck, department of Archaeologies (A), the German Mining Museum Bochum/University of Bochum, department of Archaeological Sciences (D), the Curt-Engelhorn-Zentrum Archäometrie in Mannheim (D), the University of Zürich, department of Archaeology (CH) and the Archäologischer Dienst Graubünden (CH). The joint project (D-A-CH-project) was financed by the Austrian Science Fund FWF, the Deutsche Forschungsgemeinschaft DFG and the Swiss National Science Foundation SNF in the framework of a Lead Agency procedure.

The essential aims of the project were to investigate and/or to provide:

- a reconstruction of workflows associated with copper production ("chaîne opératoire")
- procurement strategies with regard to different raw materials (fahlore, chalcopyrite)
- a mineralogical and geochemical characterisation of raw materials
- the transfer of knowledge by exporting or applying established technologies
- the dating of mining activities (beginning – duration – end)
- an econometric assessment of metal output in small, medium and large production units (single mines/smelting sites – mining districts – supra-regional networks)
- the positioning of Alpine copper on the Central European metal market during Bronze Age and Early Iron Age (provenance studies on metal artefacts)

The Eastern and Central Alpine copper economy played a major role in the metal supply of Central Europe during the Bronze Age and Early Iron Age. In that period, the Alpine economy changed considerably as mining and metal production transformed large parts of the landscape from remote even uncolonized areas into early industrialized regions. Three of the most important copper producers were selected for this joint research project: (1) the Schwaz/Brixlegg district in North Tyrol, Austria, (2) the Mitterberg district in Salzburg, Austria and (3) the Oberhalbstein district in Grisons, Switzerland. In all of these mining districts Bronze Age to Early Iron Age relics of copper ore mining and/or metallurgy are widespread and the archaeological investigation of a considerable number of sites is highly advanced. The state of research represents an excellent base for a supra-regional study dealing with the dynamics of prehistoric large-scale metal production in the three key-areas and beyond.

The fahlore mining district of Schwaz/Brixlegg played an important role during the Later Copper Age "Neolithic" and the Early Bronze Age, when "fahlore-copper" became an essential raw material for the Central European copper respectively bronze market. From the late Early Bronze Age on and especially during the Middle Bronze Age, the Mitterberg district dominated the copper supply. An estimated 20,000 tons of copper were produced in this region, mainly from chalcopyrite ore ("Eastern Alpine copper"). The Mitterberg area can be considered as a starting point for technological and economical innovations in copper production ("Mitterberg-process") and the associated occupation of the Eastern and Central Alps by specialized communities. Fahlore mining and metallurgy in the Schwaz/Brixlegg district reached a second prime during the Late Bronze Age and Early Iron Age. In the Oberhalbstein and in the Trentino chalcopyrite ores were exploited from the earlier Late Bronze Age to the Early Iron Age. Due to a different geological genesis, a geochemically distinguishable type of copper is to be expected compared with the "Eastern Alpine copper" and the "fahlore-copper".

Based on specialized (mining-)archaeological investigations, highly precise chronological data using dendrochronology, geochemical analyses and econometric evaluations, the joint project aimed to carry out a comparative and diachronic study of these three important prehistoric copper mining districts. The aim was to reconstruct and to better understand the development and significance of the districts, their economic dynamics and the manifold interrelations within the network of alpine metal producers. First results of this fruitful cooperation are published in this volume, together with contributions from other international authors working in the field of "prehistoric alpine copper".

This volume therefore marks a next step of reconsidering the state of research. A last similar step was made already 25 years ago. In 1995 the University of Innsbruck (Gert Goldenberg) together with the German Mining Museum in Bochum (Gerd Weisgerber) and the Ufficio Beni Archeologici in Trento (Gianni Ciurletti) organized the first international workshop „Alpenkupfer – Rame delle Alpi". This meeting was focused on prehistoric copper production in the Eastern and Southern Alps. The proceedings were published in 2004 in „Der Anschnitt, Beiheft 17" (mainly in german language). In the meantime the knowledge in this field of research had considerably increased and numerous research groups had achieved new and partly spectacular results from different regions in the Alps.

In 2015 a repitition of the 1995 workshop was projected in order to rediscuss the aspects of Bronze Age and Early Iron Age copper production in the Alps. A welcome occasion was offered by the trinational D-A-CH-project mentioned above.

The international workshop “Alpine Copper II” was held from 21st to 25th September 2016 in Innsbruck and was organized by a multinational committee of experienced investigators in order to include and to motivate researchers from all over the Alps (Gert Goldenberg, Austria/Thomas Stöllner, Germany/Rouven Turck, Switzerland/Elena Silvestri, Italy and Vanessa Py-Saragaglia, France). The organization on site was taken over by the team of the Research Center HiMAT (History of Mining Activities in the Tyrol and adjacent areas – Impact on environment and human societies). The aim of the 2016 workshop was to present and to discuss the updated state of the art concerning the prehistoric copper production in the Alps and to stimulate further fruitful synergies by developing and intensifying the international collaborations. During the workshop a thematic focus had been placed on the topics of the above mentioned D-A-CH-project.

During three days participants from seven countries (Austria, Germany, Switzerland, Italy, France, Norway and England) presented and discussed 30 papers and 8 posters dealing with the main topics Mining Archaeology, Archaeometallurgy, Ethnoarchaeology, Experimental Archaeology, GIS and Data Management. The discussion about new discoveries and findings completed the indoor part of the workshop. Two days of field excursions to Bronze Age and Early Iron Age mining and smelting sites in North Tyrol concluded the event.

The volume comprises 23 contributions issued from Alpine research environments between Lower Austria to the East, and the departments of Isère and Savoy to the West. There is a focus on the Eastern and Central Alps: Most papers emanate from the international “Alpine Copper” D-A-CH project, partly with data from the aforegoing project of the SFB HiMAT (“The History of Mining Activities in the Tyrol and adjacent areas”).

A wide methodological range is addressed in the papers: After a keynote by Thomas Stöllner highlighting essential elements of mining-archaeological research in the resource-scapes of the Eastern Alps, Thomas Koch Waldner and Susanne Klemm offer new assessments and updated information for two important mining districts of the Austrian Alps, i.e. famous Kitzbühel region in North Tyrol and the Lower Austria region respectively. Fundamental orientations on data setup and management in mining archaeological projects are given by Gerald Hiebel at al.

Mines and ores of various regions are the topics of the following section. Bernard Moulin et al. discuss the fascinating Early Bronze Age mining evidence in the Grandes Rousses massif in the French Alps, one of the few western disctricts with ongoing research. The Montafon in West Austria has been a focus of historical and prehistoric mining research for many years, as Rudolf Klopfer et al. discuss in their paper. Their research provide first sound indication for later Iron Age mining in the Montafon, while Bronze Age mining activity is still absent. New results of mining archaeological surveys in North Tyrol are introduced by Caroline Grutsch et al. This research made a new field of rather small scale prehistoric copper mining accessible. Evidence of fahlore mining in the Lower Inn Valley during Late Bronze Age and Early Iron Age is presented by Markus Staudt et al., while the mineralogical and chemical analysis of copper ore deposits of the Eastern Alps by Peter Tropper et al. provides a general overview of economically used ores during prehistory.

Ore beneficiation processes form an important part of the metallurgical “chaîne opératoire”. Spectacular are Thomas Stöllner’s excavation results from the “Sulzbach-Moos”-bog in the well-known Mitterberg mining district, along with Simon Timberlake’s experimental approaches to the treatment of chalcopyrite ores as evidenced at the Troiboden site of the Mitterberg.

The next step in the ore treatment is smelting that for long decades was one of the focusses of archaeological and archaeometallurgical research. Recent excavation work in the Oberhalbstein district yielded a broad variety of archaeometallurgical structures, relating to various steps of the copper producing sequence, as shown by Rouven Turck in an overview article. The massive slag finds of the reduction process offer ground for a new typological and morphological approach to slags, as Leandra Reitmaier-Naef shows in her contribution. Monika Oberhänsli et al. present comprehensive dendrochronological data for the newly investigated mining district of the Oberhalbstein in Switzerland, framing ore exploitation and processing there to the Late Bronze Age and Early Iron Age.

The Trentino ore processing evidence is reviewed by Elena Silvestri et al., the remarkable features and findings of recent excavations at Rotholz in North Tyrol by again Markus Staudt and colleagues. A second paper by Peter Tropper et al. focuses on slag-tempered ceramics of the same region, as a further element of the operational sequence (recycling of slag).

Production quantification, yet another aspect of copper production, is addressed by Erica Hanning using archaeological and geophysical methods on slagheaps. It is shown that the ancient slag heaps underwent massive transformation (erosion, reusage, vegetation) that considerably reduces the amount of slag represented at such sites and in our archaeological heritage. Many of these sites should have been even completely lost according to the amount of copper once produced at the Mitterberg. Roland Haubner et al. discuss various elements of the production sequence at Prigglitz-Gasteil in the Lower Austria district.

Finally, metal provenance and metal exchange are topics investigated by Caroline Grutsch et al. using finished objects and copper signatures from Early Bronze

The participants of the "Alpine Copper II" international workshop in Innsbruck in 2016, photo: Research Center HiMAT, University of Innsbruck, M. Staudt.

Age to Early Iron Age. New quantitative calculation of the combination of fahlore and chalcopyrite copper allows important insight to the amount of fahlore copper used in relation to chalcopyrite copper especially as deliberate alloy at the end of the Bronze Age and the beginning of the Iron Age. Chalcopyrite still was the main ore used.

Joachim Lutz et al. focus on raw material evidence, their interest lies with plano-convex ingots of the Salzburg region and spatial distribution patterns. As with the finished objects it turns out that the abundant amount was made of Mitterberg and Kitzbühel copper variations while a smaller amount resembles import of fahlore-copper likely from the Schwaz-Brixlegg mining district. It is remarkable that already the oldest ingots resemble an exclusive origin of the Mitterberg district. Bronze Age ingots from Styria and Upper Austria are classified by Daniel Modl in order to understand their production and distribution. His attempt is also to debate the phenomenon on a larger scale in order to establish a method in dealing with these find category. Last but not least, Stephan Möslein and Ernst Pernicka take up the task to re-contextualize the analytical data of the large 20th century Bronze Age metal analyses from the SSN ("Salzburg-Southern Bavaria-North Tyrol") project. All the analytical and archaeological data of this large scale analytical project are presented for the first time with an extensive catalogue.

From the beginning it was planned to publish the workshop proceedings again in the series „Der Anschnitt, Beihefte", as a second volume with the title "Alpine Copper II". More than a half of the contributions in this volume is related to the D-A-CH-project and thus provide a representative overview of the research activities in the frame of this joint project. The editorial work for the publication has been taken over in Zürich and Bochum, the layout and printing was performed in Bochum in cooperation with the printing house Marie Leidorf and Bert Wiegel. We especially thank several persons who made this volume possible. In a 1st step Rouven Turck by advice of Philippe Della Casa coordinated the reviewing process in Zurich. We are especially thankful to the numerous reviewers that took up the heavy task of bringing the papers into good scientific and formal shape and particularly for their indespensable advices and comments. This made the presented volume a real peer-reviewed one. Thomas Stöllner undertook the 2nd step of the editing process in Bochum and coordinated the proof-reading process with the authors. The layouting and pre-print-process was accompanied by Petra Eisenach, Bochum, and Angelika Wiebe-Friedrich, Straßenhaus, with whom we formed a tight cooperative atmosphere during finalization process of the volume. This is gratefully regarded and acknowledged. Elena Silvestri, Italy, and Vanessa Py-Saragaglia, France, are thankfully regarded for their contribution at the conference.

Zurich, Bochum and Innsbruck joined to bring the important ecomomic and social aspects of Alpine copper exploitation to a new scientific synthesis. The term resource-scape now helps to culturally and socially integrate this fascinating evidence to a better understanding of those specialized Alpine communities in the Bronze Age and the Early Iron Age. We therefore hope that the current volume will find an interested and benevolent audience.

Rouven Turck, Thomas Stöllner, Gert Goldenberg

Mining landscapes

Lower Inn-valley: The mining district of Schwaz-Brixlegg, with a view to the entrance of the Zillertal-valley, photo: M. Dehling

Der Anschnitt, Beih. 42, S. 13 – 30, 2019

Thomas Stöllner

Enmeshment within resource-scapes – Eastern Alpine copper production of the Bronze and Early Iron Age

ABSTRACT: *The Eastern and Southern Alpine mining regions are conceptualized here as a culturally tightly connected resource-scapes. It was a large region in which a constant flow of ideas and humans lead to the expansion and distribution of the technical knowledge of copper production since the Middle Bronze Age to many ore-deposit-regions. These technical and economic strategies allowed the colonization of Alpine valleys first but also the continuous economic stability and at least a survival within Alpine landscapes. It is shown that the enmeshment of processes and communities led to similar worlds of experiences that allowed different dwellers a necessary exchange and adoption of technical concepts. But this not always went hand in hand with a tighter adoption of cultural habits since the growing of population, the larger demand in copper as well as the different traffic conditions led to different cultural compounds in various regions since the Late Bronze Age.*

KEYWORDS: BRONZE AGE COPPER PRODUCTION, RESOURCE-SCAPES, ENMESHMENT, EASTERN ALPS

Introduction

There is hardly any Bronze Age mining landscape that has been so long and intensively investigated as the Eastern Alpine prehistoric mining districts (Fig. 1). Since the first half of the 19th century, famous sites such as the Mitterberg, the Lower Inn Valley district or the salt mining centers in Hallstatt and Dürrnberg were stimulating us with multifaceted insights into these prehistoric communities (recently various contributions in Stöllner & Oeggl, 2015). These communities acted as producers of a copper-compound, in which copper from various deposits of different chemical composition and quality was produced, consumed and exchanged even far beyond the regional networks. Since the beginning of the late Bronze Age (13th and 12th century BCE), there was a deliberate “blending” of copper-sorts from various deposit zones. Today we know, that copper from the fahlore districts in the Lower Inn Valley was mixed with that from chalcopyrite deposits. This mainly was reasoned in the elevated demand of copper during the Late Bronze Age, but also in the general expectation of a standardised black copper that allowed production of a large series of objects (Sperber, 2004; E. Pernicka, J. Lutz in: Stöllner & Oeggl, 2015, pp.107-111 Fig. 2). This can be shown by investigating the trace-element level of such a copper that was alloyed with tin. Tin and typical fahlore-trace elements such as silver and antimony stand in correlation to each other. The higher the amount of fahlore-components, the smaller the tin-level is (discussion: Stöllner et al., 2016). Since fahlores effects similar material properties as tin, this difference would speak for an interpretation that fahlore could have been used as a substitute for tin that had been delivered from far-distant regions. When exceeding the fahlore-content this would have led to a more silvery greyish surface colour, while tin would have resulted in more shiny golden surfaces. If comparing the hardness of fahlore-copper to tin-bronzes there is not much difference up to levels of 6 to 8%. Therefore, it is likely that tin was replaced by a certain amount of fahlore-copper if tin got sparse. Such an observation makes apparent that societies of the later 2nd millennium BCE kept detailed empirical knowledge that allowed them to produce metal products in relation to their metal properties and their proposed utility. Such required a raw material production that exploited geologically homogeneous ore deposits and practiced technical concepts that could be reproduced in a reliable way in order to meet a wide-ranging metal demand. Studies of the chemical compositions of copper and bronze objects allow the conclusion of a wide-ranging distribution of alpine copper within North-, Central and Central-East-Europe (e.g. Pernicka et al.,

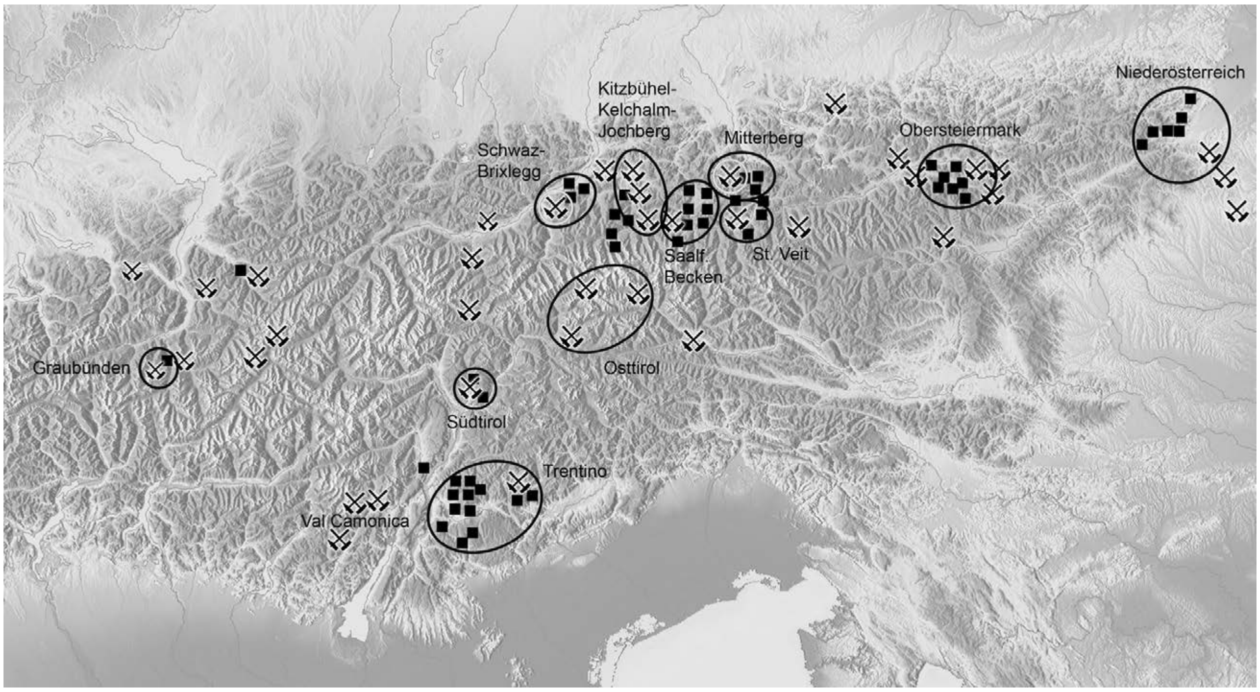

Fig. 1: The Alpine Copper mining districts after Stöllner, 2009, p. 40, Fig. 1.

2016, Fig. 3). During the 18th/17th and the 13th/12th century BCE black-copper produced from the large copper deposits at the Mitterberg-area (Salzburg Alpes) played an eminent role in supplying large areas, while Lower Inn Valley fahlores were of great importance before and during the later phases when they again contributed to the Alpine copper compound during the Late Bronze Age. But if one could get the impression that the production of black-copper would have been developed and directed along a clear technical and economic vision just from the beginning of the early 2nd millennium BCE, this idea only can be discussed with some restraint. Manifold processes of adoption and transformation that seemingly have been dynamic over time, especially in respect of societal, economic and technological processes (e.g. Bartelheim, 2007; Stöllner, 2010), determined the alpine copper-production.

What cannot be discussed in detail here is the question of far-distance-exchange practices in which the Alpine communities certainly were involved and in which copper as a product might have played an important role. There is no doubt that foreign contacts also had altered visions and perspectives and thus far-distant goods and ideas entered the Alpine landscapes: Late Bronze Age Mediterranean glass and Baltic amber were certainly examples, particularly for the transfer into the Alpes. Bellintani (2014, pp.124-125) recently has argued for ports of trade (such as at Salurn/Salorno), in which copper from South-Tyrol and Eastern Trentino was exchanged with prestigious goods such as glass and amber. Such objects likely were only by-products of the exchange as daily subsistence goods perhaps were more important. Such nodules might be assumed for all the large central valleys such as the Inn, Rhine, Adige/Etsch or Salzach and Enns Valley (such as hill-top settlements there).

Temporal, spatial and technical developments

There should be some comments about the temporal development of the eastern and southern alpine copper production before I shall discuss the enmeshment aspects within the mining districts. It has to be emphasized that copper production in the Alps always was determined by regimes of demand from the outside that were active in a supra-regional perspective. This is true already with the first usage of copper within the Münchshofen culture north of the Alps at the end of the 5th millennium when societies practiced the usage of small copper objects for the first time, obviously by supply basically from South-East Europe but also from the Lower Inn Valley (Krause, 2003; Höppner et al., 2005). Indications of metallurgy from the late Vasi a Bocca Quadrata culture (VBQ) are as early as those from the regions north of the Alps (Pearce, 2015). But it is not always clear if copper was exploited from ore-deposits nearby. Most of the provenance data even from sites near or inside the large Alpine valleys (e.g. the Adige, the Salzach and the Inn Valley: Höppner et al. 2005; H. Moesta in Lippert, 1992; U. Tecchiati in Stöllner & Oeggl, 2015, pp. 83-88) cannot be unambiguously traced back to regional deposits. The clearest example comes from the copper-objects of the 4th mill. Mondsee-group in Upper

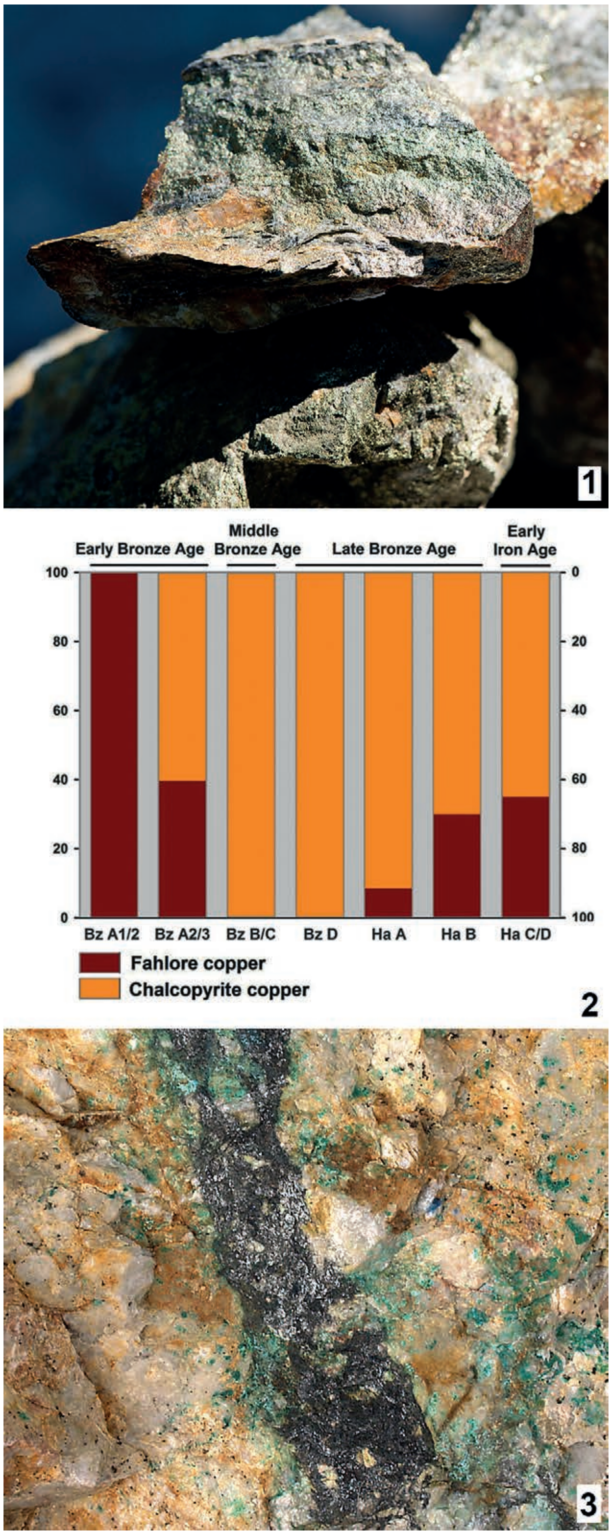

Fig. 2: Chalcopyrite from Mitterberg (1), fahlore in dolomite of the Late Bronze Age to Early Modern Age mine Mauk F, Radfeld, Tyrol (3); copper ore basis of northern alpine to southern bavarian copper and bronze findings (after Lutz & Pernicka, 2013) (2). (photo: DBM, M. Schicht, K. Stange, AVttention, Marienheide).

Austria and Salzburg, whose copper supply always was assumed to be from the Eastern Alpine copper deposits. Most of the provenance data show a clear correlation with Serbian copper ore deposits (E. Pernicka, C. Frank, in: Stöllner & Oeggl, 2015, pp.77-82).

It seems that the largest portion of copper was supplied to Western Austria and South-Germany also around the mid of the 4th mill. BCE from South-Eastern European supply networks. However, this does not mean that there were no attempts within the Alpine valleys. There is the proof of an establishment of younger to late Neolithic settlements alongside larger Alpine valleys that followed seasonal hunter- and gatherer usage strategies particularly in regard to high altitudes, where moving was easier than in Alpine valleys. Lithic resources such as rock crystal, radiolarite or silex became widely distributed within such hunting networks, including also prestigious pieces such as silex daggers, long blades and an axe made of rock crystal (e.g. W. Leitner, M. Brandl and T. Bachnetzer in: Stöllner & Oeggl, 2015, pp.59-69).

What is important in regard to the later development of the copper mining districts is the presumption that hunters and perhaps also herders were important mediators for the development of Alpine landscapes as resource-scapes within the 2nd millennium BCE. However, there were important changes at the main Alpine valleys during this time. Living grounds were continuously occupied since pastures, mineral deposits and cleared acres on terraces became anchors for stable living concepts[1].

In such a perspective, copper exploitation was decisive factor for a successful "colonization" of Alpine landscapes and this is especially visible when regarding these developments at the copper bearing landscape between the Salzach and the Inn Valley (Th. Stöllner; U. Töchterle in Stöllner & Oeggl, 2015, pp.117-124; pp.129-134). The Salzburg valleys of the Pinzgau and Pongau, the landscapes around the Glemm Valley as well as the valleys of the Kitzbühel river stream including the Brixen Valley were settled seemingly together with the advance of copper mining at the greywacke-zone. On the other hand, the Lower Inn Valley in the North Tyrol was settled at an earlier stage from the north. In such an already used landscape the fahlore exploitation led more to an intensification of settlement patterns around Schwaz and Brixlegg (Töchterle, 2015; U. Töchterle in: Stöllner & Oeggl, 2015, Fig. 2).

Such developments began earlier at the Lower Inn Valley, which was more easily accessible than the inner part of the Salzach Valley where the obvious barrier of the Pass Lueg hindered an easy access from the northern Alpine forelands. This barrier was successfully resolved from the 19th to the 18th century BCE when new settling groups founded small hilltop sites along the Salzach stream in rapid succession and began copper exploitation in their surrounding (Fig. 6). That seemingly expeditious process led first to a colonization of the Pongau-part of the Salzach Valley but not much later included also the upstream part of the Pinzgau (in general Stöllner, 2009).

For a long time the Mitterberg/Pongau mining region stayed to be an important producing area for copper before new districts became active around the end of the 14th

Fig. 3: Copper of the Late Early Bronze Age deposit 1 from Obereching near Laufen, Salzburg Austria, consisting of 154 rib ingots (photo: DBM, M. Schicht).

century BCE. We can list the areas around the Kitzbühel Alps (Kitzbühel/Kelchalm: Koch Waldner, 2013; Th. Koch Waldner and M. Klaunzer in: Stöllner & Oeggl, 2015, pp.165-173) and the Upper Styrian districts around the Palten Valley and Eisenerz (S. Klemm in: Stöllner & Oeggl, 2015, pp.195-200) (Fig. 1). All these new districts were based on profitable ore deposits of the Greywacke zone that could be exploited by a similar technical and economic concept (Fig. 8.1). The expansion of copper exploitation certainly was linked to the increased demand in copper during the later phases of the Bronze Age, but definitely led also to a dissemination of all the techniques already established at the upper Salzach Valley and around the Mitterberg. This is remarkable especially in comparison to a later phase of dissemination during the Urnfield period from the 12th century onwards. When recognizing those later examples there were many more adoptions and technical changes that were not known during the older radiation phase. A detailed view shows that our knowledge about those younger districts is restricted, though we only have detailed knowledge from some of them, because parts of the production chain are not known or even not studied. This is true for the eastern Trentino field where smelting is sufficiently studied while the mining is not, or even not known so far (Cierny, 2008; E. Silvestri et al. In: Stöllner & Oeggl, 2015, pp.201-208).

But it is even difficult to compare the technology if the ore-basis is different from the chalcopyrite-based deposits. This is especially remarkable for the fahlore-district between Schwaz and Brixlegg where we can deduce similar structures in organizing the landscape and the prediction process (e.g. at the Mauken Valley district: Goldenberg in: Stöllner & Oeggl, 2015, pp.151-163; G. Goldenberg et al., 2012; 2013) but where operation processes are different in detail because of different ores and host rocks (dolomites) (Fig, 8.2). Recent field-work at the region Oberhalbstein revealed new insights into the Late Bronze to Early Iron Age mining district and its technical solution especially in smelting technique that obviously was inspired by the older chalcopyrite smelting technology of the Mitterberg-process but was variegated (e.g. L. Naef in Stöllner & Oeggl, 2015, pp.215-219). Ethnographic examples show that archaeological sources can be treacherous and even misleading and only allow superficial observations about the manifold social and technical practices of traditional "copper-making" (as recently N. Anfinset reported for Nepalese copper making: Anfinset, 2000; 2011).

The youngest evidence of what we may call an Eastern Alpine production model can be dated to the Early Iron Age and even the developed phases of the Iron Age. It is interesting that during this time small-scaled districts were still in operation, such as the Eastern Tyrol Virgen Valley (concluding Stadler, 1992; for the smelting sites: Eibner & Presslinger, 1991, p.428, Fig. 1). Even though we have no secure dating from smelting sites there is evidence from metallurgical debris found in a Hallstatt period layer at the hill-top-settlement of Burg near Obermauer. These debris indicate a relation to copper-production during that time (Stadler, 1992, esp. p.553).

There is also evidence from the Mitterberg Eastern lodes. This has connection to the Hallstatt period graveyard at the Pestfriedhof near Bischofshofen where an iron pick was even found, whose metallurgical investigation ascertained a relation to mining work at ore-lodes, likely those at the Mitterberg (Stöllner & Schwab, 2009). In this line of evidence, we can also put slags that have been found at the Steinbühel hilltop settlement near Uttendorf at the upper Pinzgau region, near by the mining areas of the Kitzbühl-Jochberg and the Viehhofen mining districts. Some grave-goods of heavy copper and bronze tools from the graveyard indicate a possible connection. The best examples are known from the mining districts at Schwaz-Brixlegg from which dendrochronological dating from charcoal pieces related to fire-setting process allow the interpretation of operation periods till the end of the 8th century BCE (Fig. 8.2, K. Nicolussi, T. Pichler in: Stöllner, Oeggl, 2015, esp. pp.242-245). The same is indicated by ^{14}C-datings from slag-sites in the Oberhalbstein (recently L. Naef in: Stöllner & Oeggl, 2015, pp.215-219). The discussion about Early Iron Age metals provides another level of evidence, as they can be securely linked to a provenance from Eastern Alpine deposits (J. Lutz, R. Schwab in: Stöllner & Oeggl, 2015, pp.113-116). Copper-production obviously

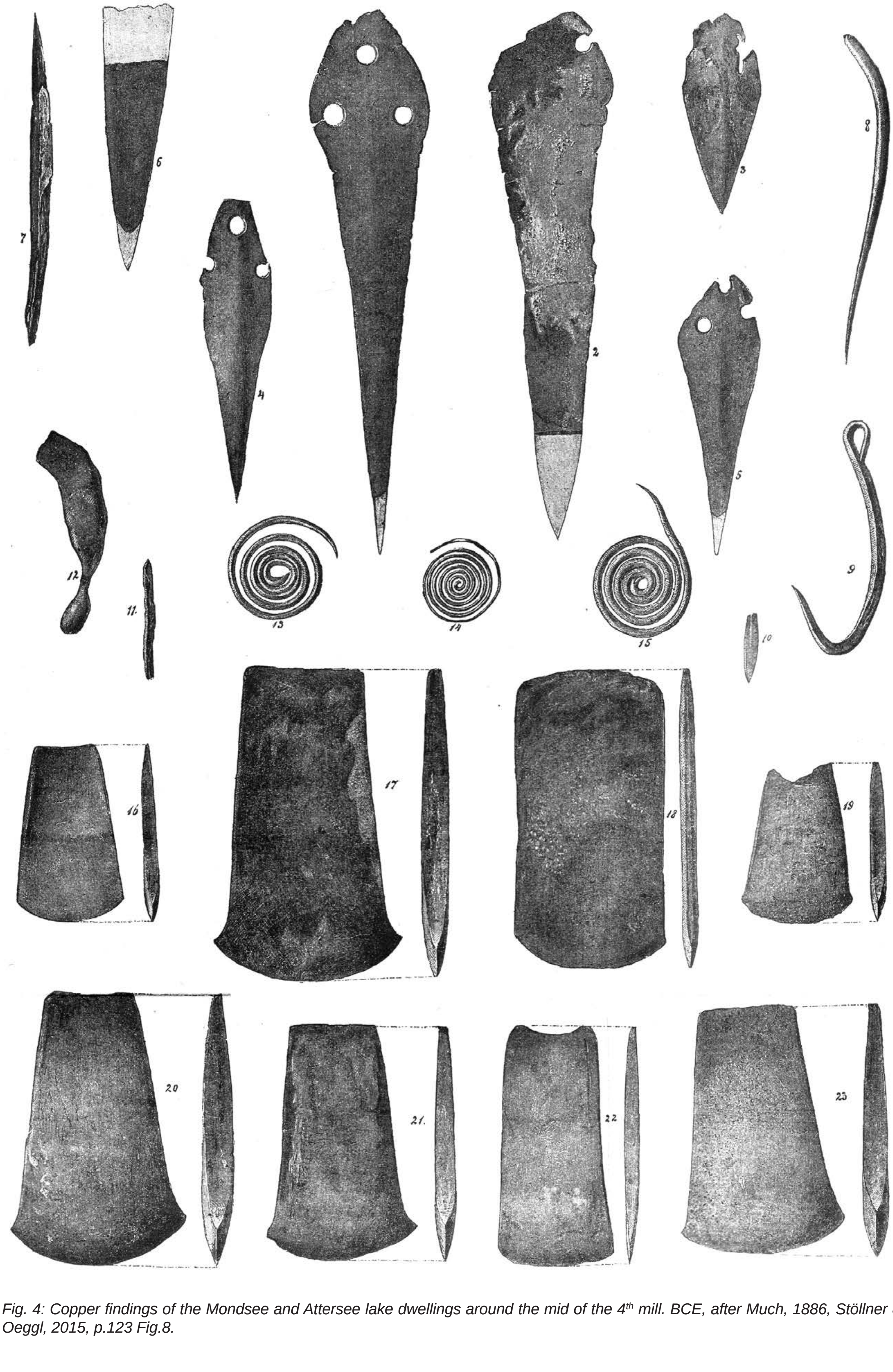

Fig. 4: Copper findings of the Mondsee and Attersee lake dwellings around the mid of the 4th mill. BCE, after Much, 1886, Stöllner & Oeggl, 2015, p.123 Fig.8.

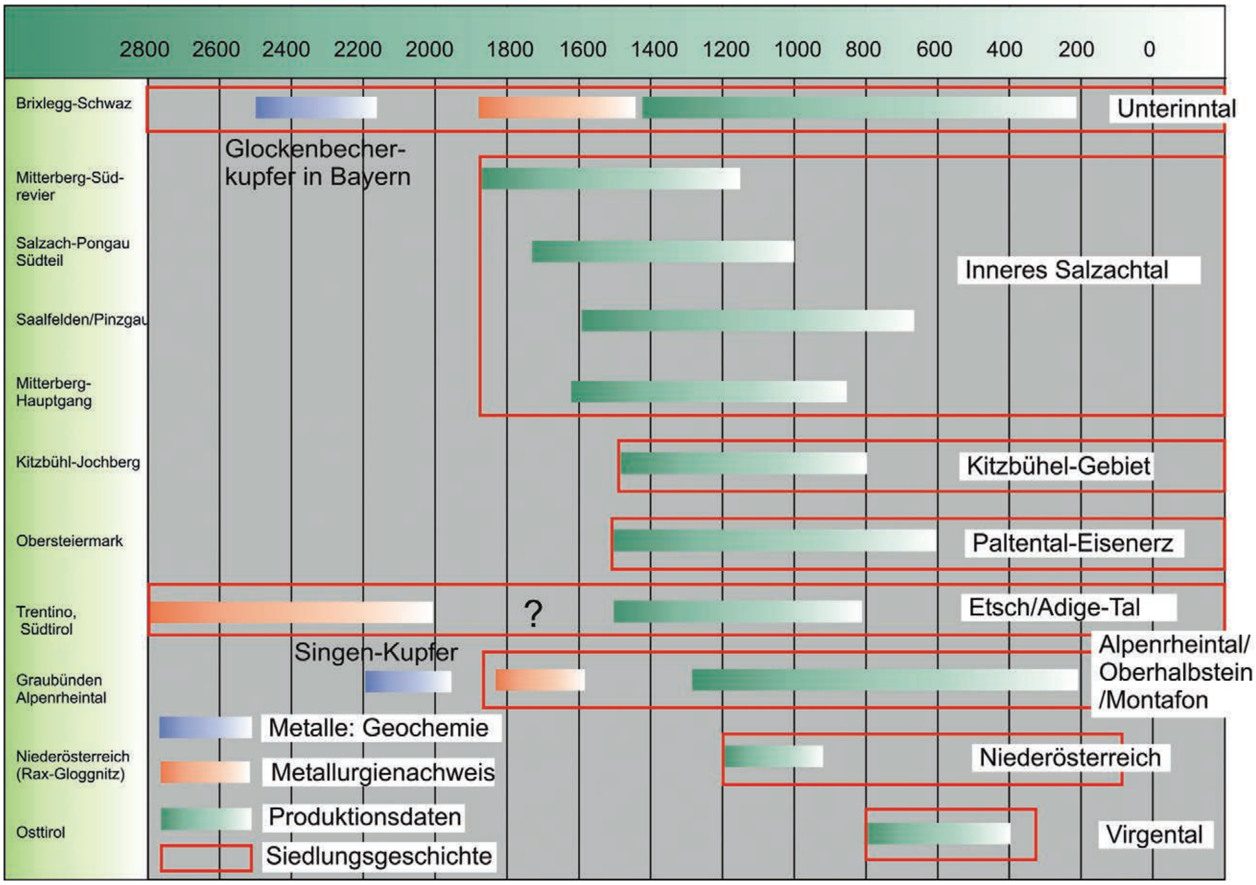

Fig. 5: The temporal development of the Eastern and Southern Alpine Copper ore districts based on chronological data from production sites, on the settlement of the copper ore districts of various valley systems and on different other indications such as the geochemical prove of the exploitation of an ore district or the prove of regional copper metallurgy, after Stöllner, 2010.

has taken a back seat step by step since the beginning of the Early Iron Age when various other activities started to take over the role as the most important economic activity, such as salt mining, the intensified high Alpine pastoralism and the stepwise increase in Alpine farming as well as cross-alpine trading and transport activities.

Comments on the economic and social structure of the copper mining districts

Various results on the Eastern Alpine copper mining districts did also reveal remarkable further insights. Those areas responsible for supply and logistics of the mining districts were situated along the main valleys and particularly on middle range terraces in favorable climatic position. This is different from the mining areas themselves where only campground and mining houses are known (e.g. Krause, 2009; Stöllner, 2011, pp.50-51). It also may seem that supply have been organized from the main-valleys to the Alpine mining hinterland, for instance in organizing the transports of already pre-worked pig meat parts (Stopp et al., 2010, pp.215-219; Goldenberg et al., 2012, pp.102-104). It should be further investigated if there was a connection with Hallstatt and its pork-meat production (Pucher et al., 2013). The slaughtering pattern of a Late Bronze Age copper producing site in Lower Austria indicates some connection between pig husbandry, copper and salt production (Trebsche & Pucher, 2013).

What is not clarified is the role that alpine pastoralism had in all the mining landscapes. There are features from the Kelchalm that indicate the enclosure of dairy cattle and their grazing in the surrounding of the mines. But what cannot be proven yet is a regular complementary pastoral landscape usage in the surrounding of the mines (e.g. also the recent discussion by Viehweider, 2017, pp.166-167).

To get an idea of the economic importance of copper production one simply can imagine the long lasting operation periods in various mining districts. More than 20,000 tons of black copper had been produced between the 17th and the 9th century BCE of which the largest portion was done from the 16th to the 13th century BCE (Zschocke & Preuschen, 1932; Stöllner et al., 2011, pp.115-128; Pernicka et al., 2016, pp.25-28). It would be not fallacious to assume a dominating role of the Mitterberg production especially from the 16th to the 13th century that supplied parts of Europe (see Pernicka et al., 2016).

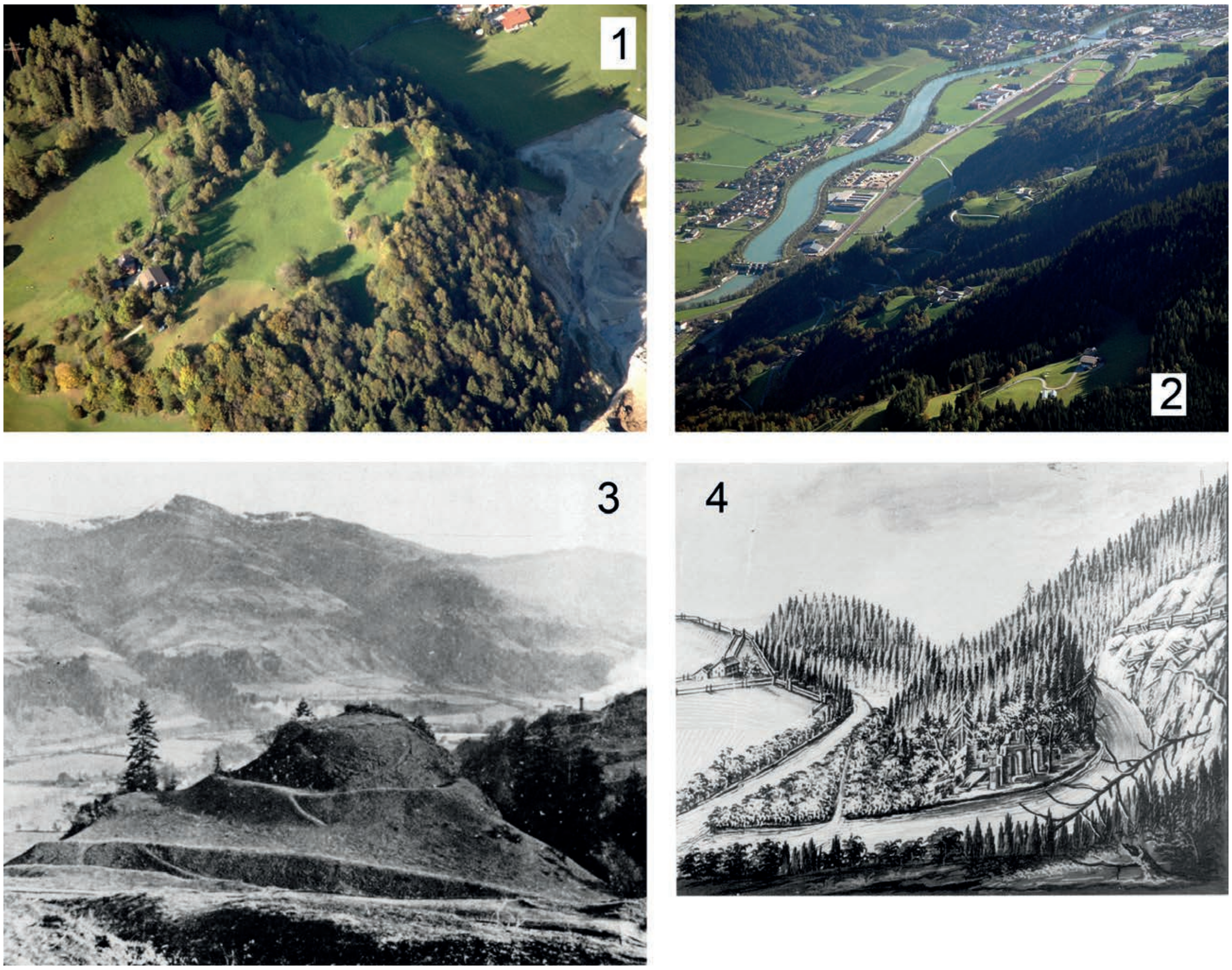

Fig. 6: Typical settlement grounds for the younger Early Bronze Age at the Salzach Valley, 1 Klinglberg near St. Veit, 2 Höchbauer-farmstead at the Einödberg, 3 Götschenberg near Bischofshofen, historical view around 1910, 4 Sinnhubschlößl at the confluent of Salzach-river and Fritzbach-torrent, historical view from North during the time of the entrepreneur Christoph Perner, 16th century AD (1-2, DBM/RUB, Th. Stöllner, 3 after G. Kyrle, 1918, 4 after E. Feldinger and F. Moosleitner, Archive Salzburg Archaeology, Salzburg Museum).

How these supplying networks were organized and how elites of the Alpine forelands were connected to these networks needs more investigation and discussion. What can be supposed is some kind of cooperation in the frame of copper and supply-goods exchange. This for instance can be seen by the already mentioned settlement of Prigglitz Gasteil in Lower Austria (Trebsche et al., 2013; P. Trebsche, in: Stöllner & Oeggl, 2015, pp.209-214; Trebsche & Pucher, 2013) that had presumably tight relations to the salt mine at Hallstatt. Salt certainly was a trade equivalency to transport pig-parts and copper to Hallstatt not only to rework the meat but also to use copper as a work-tool metal. There must have been many cooperations of that kind, which we understand step-by-step nowadays. Although the eastern Alpine mining organization seems well organized, it might have been precarious with respect to daily supply. This is apparent when looking to written sources about supply of Early Modern Times districts such as the Lower Inn Valley and Kitzbühel which always were dependent on outside food supply (e.g. Feichter-Haid, 2013). What had been gained from production had to be invested by the mining communities partly or even fully for food and other daily goods. This became certainly precarious if there was a crop failure that endangered the community and also the mining operation. One has to respect such circumstances when one looks for signs of societal welfare especially during the earlier phases of Alpine colonization and copper production: Within the mining communities a considerable accumulation of wealth cannot be observed (for instance by grave-goods or foreign objects, this already: Shennan, 1995). This might have slightly changed during the Late Bronze Age (13th and 12th century BCE) when larger graveyards such as in Northern Tyrol but also in other valleys (Kitzbühl, Salzach Valley) indicate a broader societal wellbeing. But it would be dangerous to put all the 13th to 11th century grave-equipment (Bz D to Ha A) in a sociological connection with mining operations (e.g. Sperber, 1992; 1999). Burial-customs and the dispersal of rank-indicating grave-goods (e.g. swords) are different between the North-Tyrol urnfields and the copper-districts. The accumulation of swords as grave-furniture is especially

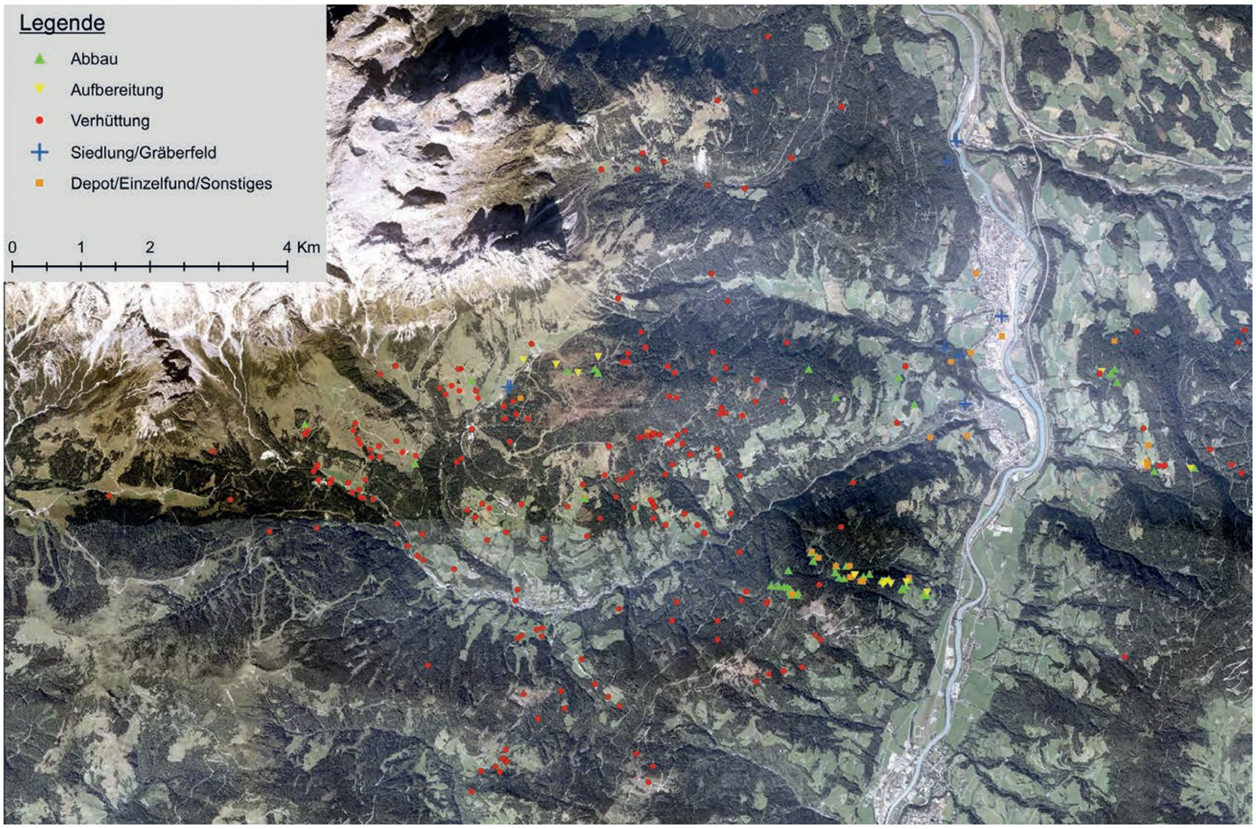

Fig. 7: Example of an alpine large district of the Bronze and Early Iron Age, general map of the archaeological sites at the Mitterberg-district on the basis of all prospections carried out between 2002 and 2016 (map/graphics: DBM/RUB, A. Hornschuch, Th. Stöllner, P. Thomas).

conspicuous and indicates a broader numbered group of sword-bearers and differently structured elite-groups. Such indicates a higher importance of lineage-based societal structure which also would mirror something very typical of a cooperatively organized society as we see in the Alps in general but specifically also in mining districts. Similar patterns had been emphasized for the social structure of the Iron Age salt mining societies of Hallstatt and Hallein (Hodson, 1990; Stöllner, 1998). There, burial customs prove a broader dispersal of wealth and social responsibilities expressed in standardized equipment within various social groups. These harnessments not only display accumulation of riches but also an ostentatious distinction of social status within these groups, sometimes with references to foreign or local identities and origin. This observation reveals a polymorphic social reality and even rivalry and concurrence between single groups.

Enmeshment – theoretical aspects

If we consider the circumstances of living within copper-producing communities, it easily turns out that all of them were confronted by similar challenges. This already was true when these communities first came to remote Alpine valleys at the beginning of the 2nd millennium BCE. Specific practices and activities were linked with provision of subsistence goods, with settling strategies and with difficult traffic conditions. But, it is obvious that experiences were shared in an alpine environment and therefore personal life-worlds were comparable in a specific way. We assume that working environments were variegated and thus produced also moments of identity within specific groups, such as miners and smelters that shared also common and complex cooperation and communication. This is an interesting and ideal arguing ground for archaeology to ask for processes of identity, since they reveal elements of enmeshment of societies with similar technical and economic practices over larger distances. Enmeshment is therefore used as a theoretical approach that follows networks of interwovenness of communities and their daily practices – from living and working to ritual and social spheres.

Understanding the complexity of these relationship and to what extent certain procedures must have been guided by tacit knowledge (Polanyi, 1958) (and hence how it is habitualized and embodied) will help us better understand the character of the contact between these communities and thus approach the social dimension of the above indicated similarities (Ingold, 2000; Von Rüden, 2016). I thus separate it from the concept of human and things entanglement theory in a way it recently was discussed by Hodder (2012; 2016)[2].

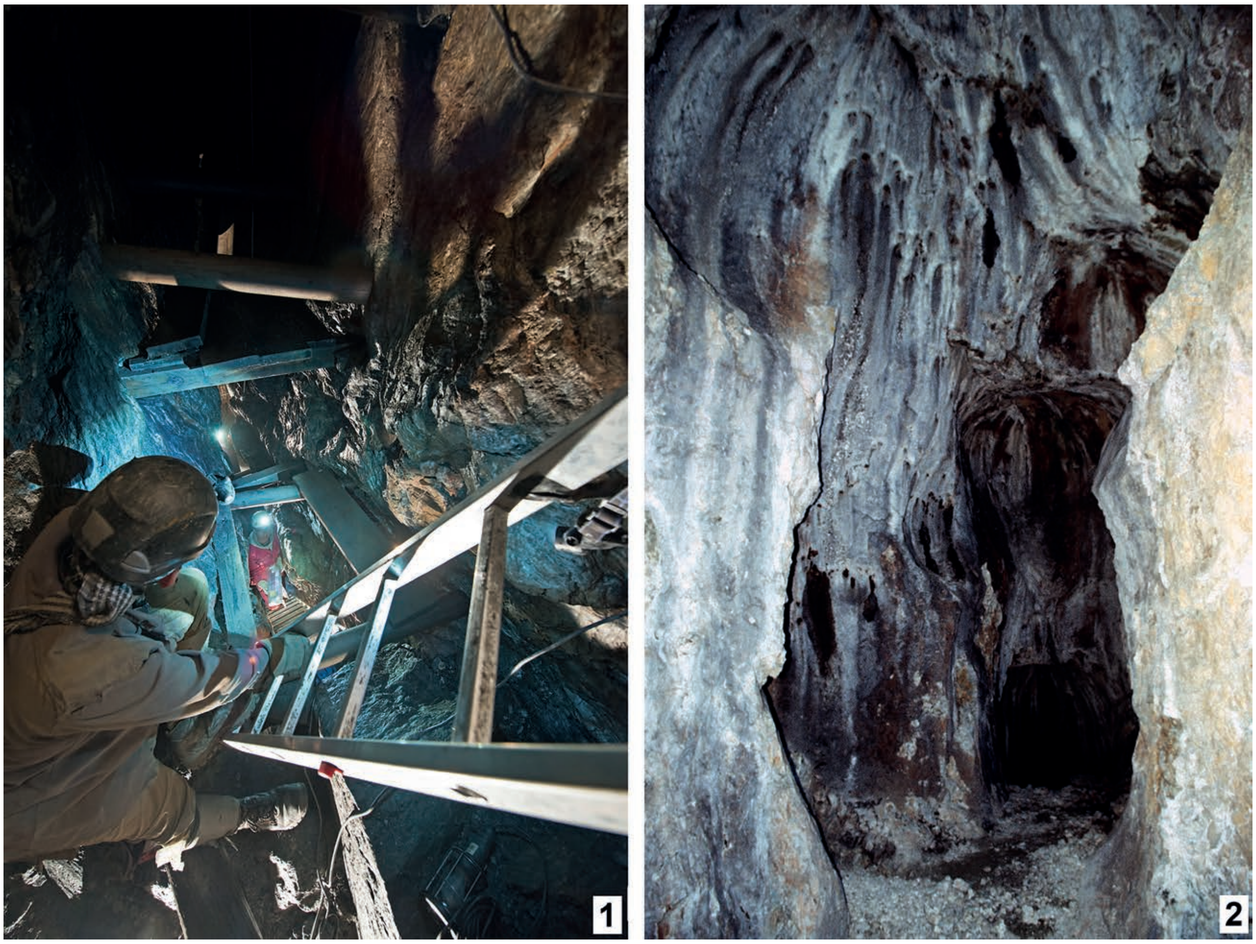

Fig. 8: Prehistoric mine at a chalcopyrite deposit of the type Mitterberg, Arthurstollen, KG Einöden, BH St. Johann (1); surface-near, fire-setted mine at a dolomite based fahlore deposit of the typ Schwaz-Brixlegg, Moosschrofen KG Radfeld, BH Kufstein, (2), (photo: DBM, Klaus Stange, AVttention, G. Weisgerber).

But one who expects that alpine regions of Bronze Age copper production would be manifested by similar material culture may be mistaken. Cultural binding is often linked with single alpine valleys between the early 2nd and the middle of the 1st millennium BCE and it is rather the traffic condition that seems responsible for relations of all kind. Inn, Salzach and Enns drain towards the east and this certainly suggests the strong connection to the Straubing culture of Southern Bavaria, Upper Austria and Salzburg (e.g. Möslein, 1997) (Fig. 3). A similar effect is true for the Upper Rhine Valley and its tributaries farther in the west, for which a tight connection to the South-Western Germany and East Switzerland Early to Middle Bronze Age can be described (e.g. Krause, 2003). Western Alpine Elements of a late Arbon culture became intermingled and also contributed farther in the east elements of an independent Alpine cultural group that were reshaped by the early Urnfield culture since the 13th and 12th century BCE. Such a dynamic is also visible further in the south in Southern Tyrol and Trentino where the Laugen-Melaun societies can be characterized as those who adopted the technics of the "Mitterberg" copper producing process (Marzatico et al., 2010; E. Silvestri et al., in: Stöllner & Oeggl, 2015, pp.225-232). It is interesting to see that Laugen-Melaun communities have produced a very specific ceramic decoration that certainly evoked feelings of affiliation, especially when regarding the Laugen-Melaun jug as a special item of domestic and public ritual practice. On the other hand, Laugen-Melaun communities opened themselves to the influences of the Riegsee-horizon during the 13th century BCE when they were in interregional exchange contacts by help of the copper they produced (in general Gleirscher, 1992)[3].

In the centuries before, these communities had an orientation frame that was focused on the southern primary settlement areas in Upper Italy, an area where many dwellers most likely came from during the late Early and the Middle Bronze Age.

We therefore have to consider three factors of endowing materialized identity. These are the small scaled regional and local life- and labour-environments (copper production, forms of agro-pastoral lives and economy), the interregional exchange processes that were important to enable food supply of alpine communities from the northern and southern alpine forelands by which the copper products were traded. And finally, there are the

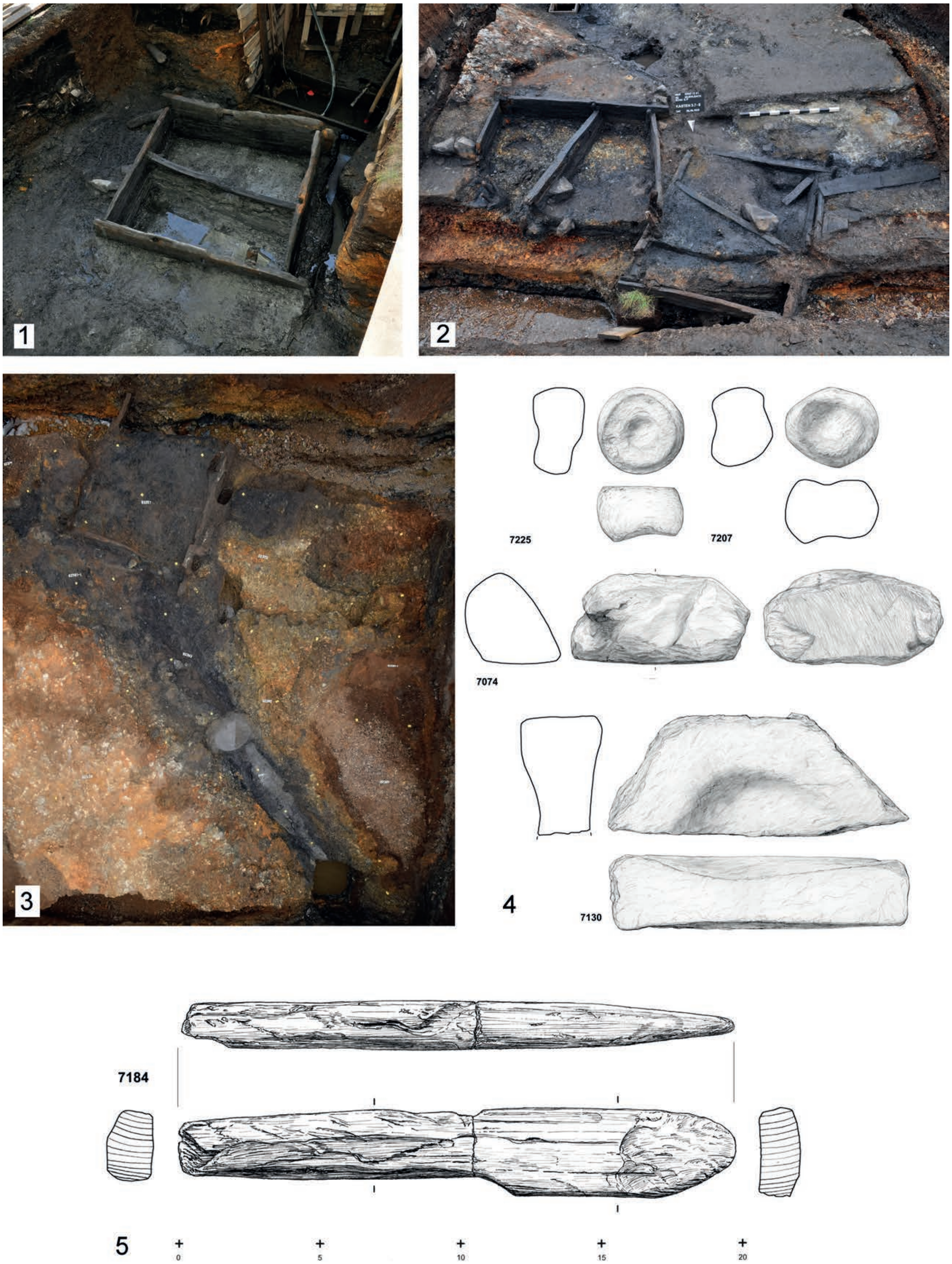

Fig. 9: Troiboden-Sulzbachmoos, excavation DBM/RUB, beneficiation boxes and tools of the Middle to Late Bronze Age at the Mitterberg, Nr 2/2009 (1), Nr 3, 7/2013 (2), Nr 8 plus channel and crushing site from 2014 (3); (4); wooden knife of box 2 (drawing/photos: DBM/RUB, A. Kuczminski, J. Schröder, T. Stöllner).

transversal relations over inner-alpine valleys and heights that led to a distribution and adoption of economic and technical processes, for instance of the copper ore mining or the copper ore smelting. It is therefore possible to consider various levels of identity alongside with further habitualized practices beyond the labour environments. Why, one can ask, is this important for our question about the copper production? Communication and cooperation between different communities were doubtlessly essential preconditions to successfully manage all the difficulties in an Alpine environment. Such cooperation was easier enabled if the relation was natural and confidential to the counterpart (by similar habits, customs, or materialized signs that can be reconstructed by archaeology easier than language).

It is likely that transalpine exchange was the moving factor of a development that helped a sustainable establishment of the copper exploitation strategies from the 14th century BCE in many alpine valleys.

This helped the technical and economic practices, which were basically first established in a successful way at the Mitterberg, to be distributed to a large area between the Grisons (Oberhalbstein) in the west, Trentino in the south and lower Austria/Viennese forest in the east (for the temporal argument: Stöllner, 2009).

That process along the eastern and the southern Alps is in fact a development of European dimension, because the rise of an important area of production was one decisive factor in the late Bronze Age's flush. Alpine copper got distributed since the middle of the 2nd millennium from southern Scandinavia, to central and southern Germany, to Bohemia and the middle Danube zone and northern part of the Carpathian basin (e.g. Krause, 2003; Lutz & Pernicka 2013; E. Pernicka & J. Lutz, in: Stöllner & Oeggl, 2015; Pernicka et al., 2016). In later periods much was also delivered to Upper Italy and part of the Mediterranean Sea (e.g. Jung et al., 2011).

Worlds of experiences between technics and landscape

In order to reconstruct "worlds" of experiences of alpine copper producers, it has to be emphasized, that there were different scapes of experiences that included economically driven exchange networks as well as the enmeshment of daily life practices. At the same moment there were different forms of knowledge transfer and the growth of knowledge to be considered for the different spheres of production, but also further related aspects of usage and consumption of the raw material copper.

The knowledge practiced in copper ore mining and exploiting ore deposits (especially in deep mining), in ore dressing and further beneficiation as well as in copper smelting, is complex. Many processes were practiced in a habitual way; it was embodied knowledge that was transferred via "silent" learning processes over generations. Such most likely included plenty of manually and serially operated work steps such as the hammer and pick-work below ground, the passing and pulling work in hauling loads, crushing and washing work in dressing the ores (Fig. 9), or even driving the bellows and controlling the heat at the smelting furnace (Fig. 10). So-called "tacit" knowledge (e.g. Polanyi, 1958) went hand in hand with externalized forms of knowledge. Ores had to be recognized and discussed with others while preparing different steps of mining and processing. Empirical aspects of touching and recognizing of mineral compositions necessarily had to be shared with others when deciding either upon different ways of further processing (crushing, washing) or dumping. The fabrication of tools for mining, hauling or beneficiation had to be coordinated and agreed upon metal- and wood working groups.

The same is true for charging the furnaces that followed rules of know-how developed over centuries, even more if different components of the charge had been carried to the smelting plant (rich ores, beneficiated concentrates, additional charges). The ways of knowledge transfer were therefore tightly related with the modes of different techniques that were practiced by specialized people and thus transferred by them. The way of transfer is easier to understand if these practices can be archaeologically and experimentally reconstructed and explained in detail according to the theoretical approaches of P. Bourdieu, M. de Certeau and T. Ingold (Bourdieu, 1977; De Certeau, 1988; Ingold, 2000). Bodily practices whose importance were already described by M. Mauss (Mauss, 1934) may have played an important role, if tools were used within the narrowness of a copper mine, or during the washing processes at the washing boxes of the wet beneficiation as well as during the smelting processes at the furnaces. Processes had to be coordinated hand in hand often without detailed explanation to reach a successful (semi) finished product (e.g. C.v. Rüden in Stöllner et al., 2016).

But there are other practical examples of those daily enmeshed practices: Besides technical practice within copper production there are also examples of specifically related daily culture practice. The usage of crushed copper slag pieces as temper for cooking had been reported as typical for the copper mining regions between the Lower Inn Valley and Salzach Valley, even in areas that were not directly located at the copper mining areas. Examples of such pots chronologically range between the late Early Bronze Age and the Late Bronze Age.

Despite a possible thermal effect of this slag temper (for instance in accumulating heat), this temper seems a peculiarity of regions in which a long-lasting "copper economy" could be established stepwise since the Early Bronze Age (e.g. Töchterle, 2015; Stöllner et al., 2016).

Further aspects can be considered for usage of similar tools within this core-region, including tools for winning, hauling as well as smelting (installations such as roasting beds and shaft-furnaces, tuyères/bellows) (Fig. 10) but also instruments for wet beneficiation of

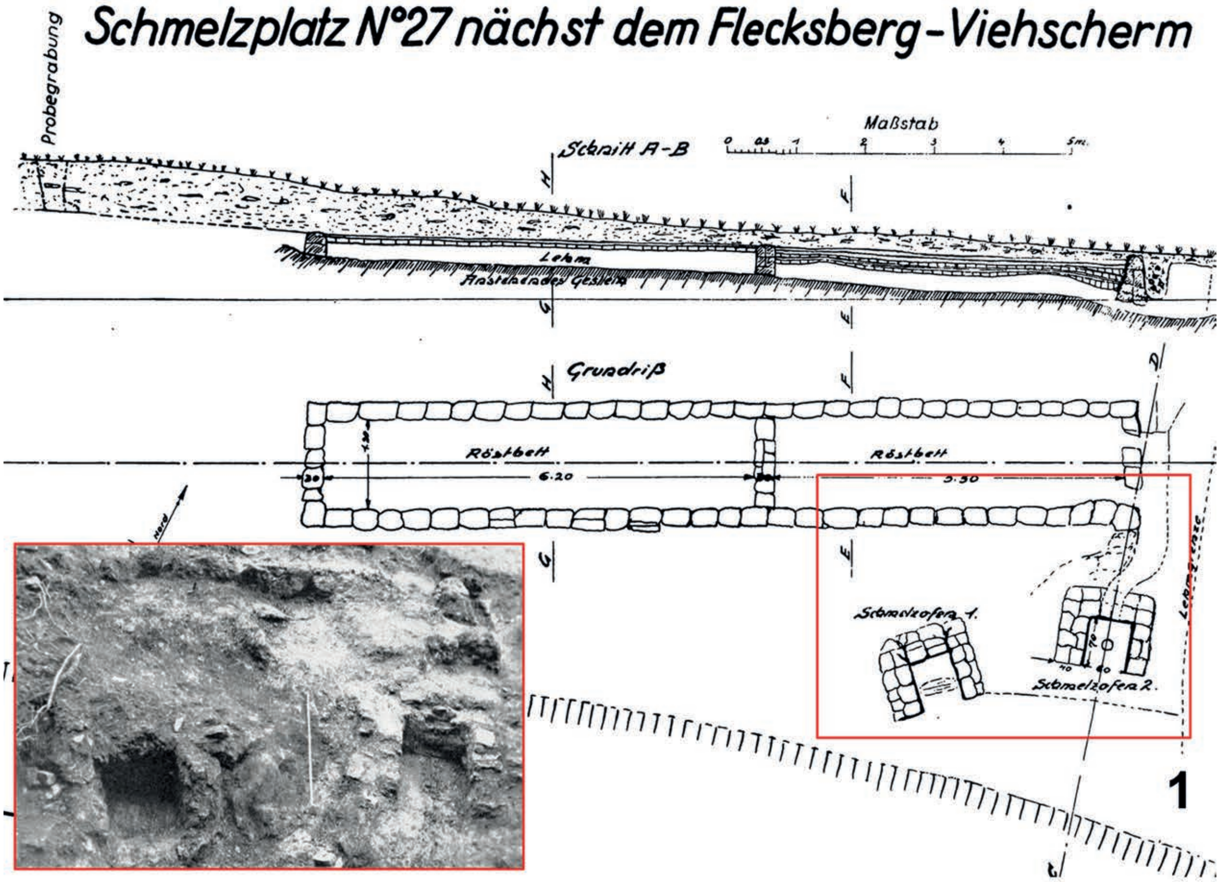

Fig. 10: Typical Eastern Alpine smelting sites from the Mitterberg; a roasting bed is situated above both shaft-furnaces built up in dry masonry while the slag was dumped down the slope beneath (after Zschocke & Preuschen, 1932, Taf. 3 und 5) (1); shaft-furnaces of the older part of the Late Bronze Age from Jochberg at the copper district "Wurzhöhe" within the Kitzbühl mining region, excavation University of Innsbruck (photo: DBM, G. Weisgerber) (2).

chatty ores (e.g. stone tools, wooden spatulas, wooden beneficiation boxes, Fig. 9).

A particularly tight relation can be observed for the districts of Kitzbühel and the older Mitterberg district, although there were smaller differences in technical solutions. One has assumed the knowledge transfer from the Mitterberg area along the river streams Salzach, Saalach and Kitzbühel stream and via mountain passages (the Dienten saddle and the pass Thurn) (discussion see e.g. Th. Koch Waldner & M. Klaunzer in: Stöllner & Oeggl, 2015, pp.165-173; Stöllner et al., 2016).

There is another important aspect to be considered. There could have been a certain amount of societal resilience and persistence especially in regard to technical and economical procedures once they were successfully established. It is astonishing that the prehistoric copper production of the Eastern and Southern Alps lasted over a very long time span, approximately between the 19th/18th century BCE and the middle of the 1st mill. BCE. These processes were not only economically successful and thus practiced over long time, they also held on to the already established technical principles, though some innovations altered them over that long time span. An older research tradition would have described such with a term like "abidance" that in some cases also included a vision to some kind of backwardness, which is simply a narrative construct (for younger periods see the commends of Bätzing, 2015, pp.85-86). But one also could make an effort in using the term "path dependency" by which C. Douglass North has described the consequences of economic paths and directions when it was successfully decided upon (with all the infrastructural and societal adoptions and investments included) (North, 2005). One therefore could argue that opening the copper exploitation around 2000 BCE also produced a certain narrowing in related innovation processes and economic developments.

At the end

All aspects discussed point to a vivid exchange within an Eastern and a Southern Alpine economic and social network. This network was regulated by the mobility of specialists and by various other types/examples of economic cooperation between different groups such as pastoralists, agrarian communities, trading specialists in the frame of good exchanges (subsistence goods versus salt versus metals). Such a development should have led to the introduction of different forms of highly specialized knowledge compounds that included some of the dwelling communities but may have excluded others at the same time. Such aspects also can be observed when looking at the distribution of symbols of an "object language" (Fig. 11) that helped a materialized communication between groups. Since the late Middle Bronze Age this interaction can be described by means of special burial rites or even some artefact groups that are especially known from these mining communities (e.g. helmets of Pass Lueg Type: Lippert, 2011; axes type Gmunden/Freudenberg: Stöllner et al., 2016, Fig. 19). Such artefact-type distributions are mirrors of those cooperation-compounds over a longer time span and provide access to regional identities that could evolve between the 14th and the 6th century BCE. But especially in the Early Iron Age we see cultural variation between the Northern Tyrol Inn Valley, the Kitzbühel region and the inner-alpine Salzach Valley on the one hand, and the Upper Austrian Salzkammergut on the other, as well the more southern Alpine areas in Southern Tyrol and the Trentino.

All these communities living in hazardous landscapes had to manage similar challenges in the frame of copper production and all the accompanying activities. This certainly influenced these communities' world-view. One could assume that they were forced to cooperate, but this is not self-evident at any case. If different communities lived in a valley system in a more precarious environment, this would also produce more concurrency and even hostility between them in order to supply one's own community and the safe-keeping of one's own existence. Thinking along such a line would have certainly supported the development of hostile activities such as combat, or at least habits of showing ostentatious prestige as a mean social distinction and practice. It might have helped to secure one's own group a better starting position in order to handle the precarious alpine life-worlds or to secure communal prosperity (for instance the practice of social signaling described for the high-lands of New-Guinea: Roscoe, 2009). Ritual practice and the involvement of numinous powers would be another. Practices of such kinds are easier to describe anthropologically than to evidence them by materialized practice. We may take the impressive guard weapons, the helmets of the Pass Lueg type (e.g. recently Lippert, 2011; hoard from the Piller Sattel: Egg & Tomedi, 2002). They certainly could be explained as part of a social signaling concept that inspired not only a feeling of perhaps "diffuse" common identity, but also were a prestigious item worn in meetings of all kinds (feastings, rituals, combats or negotiations). What kind of elite they were bound to is nonetheless not clear, in contrast to the rich graves we know from the Northern Alpine forelands (e.g. graves of the Hart a.d.Alz group). All of these were found in ritual contexts (hoards, river-findings)[4].

Materialized signs as such were certainly social signs that also played a role in a culture of remembering, such as frequently used "cult places" like the Alpine "burnt offering sites" also do (recently Steiner, 2010). This trend especially might have got stronger in the younger periods of copper production during the Later Bronze Age. If one considers the increasing frequency of findings of interregional character as well as symbols of social status (such as swords, helmets, metal-rich and heavy female costume gear), one could either argue for higher social control and surveillance or for a higher need in "social signaling" to mark territories of influence (in order to control

Fig. 11: Notched wooden sticks from the MBA-Troiboden beneficiation site (1) and the LBA beneficiation site of the Kelchalm (2) (photos: RUB, H.-J. Lauffer; DBM: M. Schicht).

exchange and the supply of goods). Perhaps the typical Laugen-Melaun jugs could be understood the same way for the late Bronze Age (see recently on the distribution: Gleirscher, 2015)[5].

Especially when considering that during the later 2nd half of the 2nd and the beginning of the 1st millennium BCE higher population rates and social complexity are generally presumed for many parts of the Alps. It is striking how different archaeological groups were developed especially during this time (such as in Hallstatt, in the Inner-Alpine Valleys or in the Tyrolean and Trentino Valleys, the Laugen-Melaun group for instance, see note 3). It seems these were the two side of the coins of the mining and economic as well as social networks related. On the one hand there was an ongoing expansion of similar economic strategies during the later Bronze Age (between the 14th and the 8th century BCE) that went hand in hand with the radiation and adoption of technical practices, while on the other hand an increasing development of regional identities in various alpine valleys can be observed at the same time.

Notes

1 The question if during the 2nd mill. herding and pastures was interrelated with mining is not clear to be answered yet; arguments already been discussed in relation to the east Alpine mining districts by Kienlin & Stöllner, 2009; for the cheese-production also: Jochem-Zimmermann, 2015; some relation to the salt-mining of Hallstatt can be discussed by high-pasture-usage during the late Bronze Age at the Dachstein plateau: Mandl, 2015; Kowarik, 2015. Milk and cheese production is evidenced at Grisons during the Hallstatt-period but yet not in the mining district of the Oberhalbstein: see Reitmaier, 2016.

2 Enmeshment of embodied practices of communities had been discussed also in the article of Stöllner et al. 2016; critics on Hodder's concept: Pollock et al., 2014.

3 Further recent literature on Laugen Melaun and its central Alpine distribution: Steiner, 2007, esp. 208-222; Marzatico, 2012, 177-204; Gleirscher, 2015.

4 Spatial concepts recently were discussed in a convincing investigation on the Alpine Rhine Valley by Ballmer, 2015, pp.71-89.

5 It had long be noted if the long-lasting ceramic traditions would not present also identity processes (such as the Raetian groups: already Gleirscher, 1992) that led to cultural harmonization in respect of tribal and supra-tribal identities. It certainly needs more discussion how daily practices of the sort mentioned here had contributed to such processes in the copper producing regions.

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Author

Thomas Stöllner – Research Departement and Institute, Deutsches Bergbau-Museum Bochum/Department of Archaeological Studies, University of Bochum

Correspondence and material requests should be addressed to: thomas.stoellner@bergbaumuseum.de

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Thomas Koch Waldner

Bronze Age copper production in Kitzbühel, Tyrol

ABSTRACT: *In the Kitzbühel mining district there are several rich chalcopyrite deposits, which have been used for mining since the 2nd millennium BC. From Pongau via Pinzgau, miners and with them the "Eastern Alpine copper technology" reached the Tyrolean Leukental during the Middle Bronze Age. The quality and frequency of the deposits led to the development of one of the most important alpine copper production centres of the late Bronze Age in this region. Thanks to the numerous finds, the working chain of prehistoric mining and metallurgy can be reconstructed. In the course of mining activities in the 19th century several prehistoric underground mines were discovered, which still contained numerous finds. Today, these sites are no longer accessible, which is why underground mining can only be reconstructed on the basis of finds, descriptions of findings and supra regional comparisons. The second and third link in the production chain ("chaîne opératoire") can be thoroughly investigated and reconstructed in detail thanks to the vast ore-processing heaps in the Kelchalm district near Aurach and more than 50 smelting sites between Kitzbühel and Jochberg. The way of working, the tools and the facilities show clear parallels to the mining regions to the east near Viehhofen and the Mitterberg area in Salzburg. On the basis of the current dating results, the geological-mineralogical situation and the geographical location of the Kitzbühel mining region, it can be assumed that the "Eastern Alpine copper technology" was transferred from here to the west in the Lower Inn Valley. The significant development was that chalcopyrite-oriented technologies were adapted to fahlore deposits, ushering in a new era of prehistoric copper mining.*

KEYWORDS: MINING, ORE-PROCESSING, SMELTING, COPPER, SLAG, CHALCOPYRITE, DEPOSITS.

Due to numerous Bronze Age traces of mining and metallurgy, the southern Leuken Valley from the Pass Thurn over Jochberg and Aurach to Kitzbühel is one of the most important prehistoric mining landscapes of the Alps. The abundance of sites with archaeological evidence of mining shows that this area was a supra regionally important production area for copper more than three thousand years ago. Essentially, this central mining area has significantly influenced the technological and economic development of Central Europe, the Alpine landscape and the society of the Bronze Age.

History of research

Favored by the historical and modern mining industry, which came upon many traces of prehistoric mining in various Austrian regions, these relics began to be documented relatively early. This resulted in the fact that already in the beginning of prehistoric research in Austria in the 19th century, there was a considerably strong awareness of the importance of mining archaeological monuments. Owing to the extraordinary findings and reports, the academic focus was put on the salt mines of Hallstatt and Dürrnberg as well as the copper mining areas of the Mitterberg region near Mühlbach/Bischofshofen and in the Kitzbühel region.

Matthäus Much, a pioneer of mining research, was the first prehistorian to collect and document the findings of prehistoric mining in the Kitzbühel area in the 19th century (Much, 1879; 1893; 1902). However, the systematic exploration began in the 1930s and was performed by the archaeologist Richard Pittioni and the mining engineer Ernst Preuschen. Their investigations of the ore-processing heaps of the Kelchalm district near Aurach between the 1930s and the 1950s proved particularly decisive. The findings and results from the excavation campaigns were presented in three extensive reports (Preuschen & Pittioni, 1937; 1954; Pittioni, 1947), which led to the fact that the heaps in the Kelchalm area are among the best explored Bronze Age mining relics of the Alps. Following these investigations, Pittioni and Preuschen put their main emphasis on the legacy of prehistoric copper smelting. Throughout the 1970s, they localized and investigated around 40 prehistoric smelting sites by means of prospecting and collecting information from the local population (Preuschen & Pittioni, 1955; Pittioni, 1968).

After Pittioni had retired, it was only in the 1990s that individual prospections and excavations were re-initiated and further smelting sites were localized. In the years 1993 and 1995 smelting facilities – a two-phase roasting bed and four shaft furnaces – were documented for the first time in the area of the Wurzhöhe west of Jochberg (Goldenberg, 2004).

Lastly, the Austrian Academy of Sciences facilitated several years of systematic research on prehistoric mining in the Kitzbühel region under the direction of the author. The funded project was located at the University of Innsbruck and was integrated into the research center "HiMAT". It included targeted prospecting and excavation campaigns as well as reassessment of preceding research findings and results (Koch Waldner & Goldenberg, 2012; Koch Waldner, 2013a; Koch Waldner, 2017).

Expansion of the eastern alpine copper technology taking into account types of mineral deposits

The mining region of Kitzbühel is largely characterized by deposits that are dominated by chalcopyrite located in slate as wall rock. Two conditions correlate with those of the mining regions east of Kitzbühel: the geological conditions, as well as the type of deposit in which chalcopyrite occurs predominantly in quartz, but also in iron carbonate and slate. In addition, there are rich fahlore deposits, which in several cases show similar geological conditions to those in the Lower Inn Valley[1].

From the late Early Bronze Age (17th century BC) to the emerging Late Bronze Age (13th century BC), only chalcopyrite was used as copper ore in the Eastern Alps and beyond (Pernicka & Lutz, 2015), where mainly the previously described type of deposits was exploited. From this type of chalcopyrite-oriented mining industry, a supra regional techno-complex, the so-called eastern alpine copper technology, developed in the area of the western Greywacke zone. According to current research, the techno-complex initially spread along the entire Greywacke zone, from Tyrol/Salzburg to Lower Austria and eventually beyond to South Tyrol, Trentino and Graubünden (Stöllner, 2009; 2015). In the course of the late Bronze Age (13th–8th century BC), fahlore was extracted and smelted, whereby the chalcopyrite technologies were adapted to the fahlore deposits.

Over the Kitzbühel Alps, the miners and their technologies eventually reached the Inn Valley, as well as the east alpine Kristallin and finally the Swiss Alps. To the east, the mining and metallurgical industry crossed the Eisenerz Alps to the east end of the Alps in Lower Austria. Following the deposits to the south, the knowledge about copper production from sulphidic ores spread over East and South Tyrol up to the southern edge of the Alps in today's Trentino.

In accordance with this expansion model, the miners and metallurgical workers reached the Kitzbühel region across the Pinzgau during the Middle Bronze Age. In the southern Leukental and the adjoining valleys, they encountered a large number of chalcopyrite deposits. This turned the region into one of the most important Bronze Age copper producers in Central Europe.

The chalcopyrite dominated deposits at Jochberg and Aurach belong to the copper-iron ore district of the Glemmtal-Unit and are essentially comparable to the deposits at the Bronze Age mining area of Viehhofen. To the north and west of Aurach the boundary of this deposit area extends to the "Hochhörndler Schuppenzone". Along the Brixen Valley, at the altitude of Kitzbühel, there is the fahlore/chalcopyrite ore region of the Wildseeloder-Unit (Heinisch et al., 2015). It was probably in this region that Bronze Age prospectors, for the first time, encountered a type of chalcopyrite that was strongly mixed with fahlore and with different geological conditions.

Besides shale, the copper deposits in this area are often connected to limestone breccia and dolomite. Due to the different geology and mineralization of the districts in the Wildseeloder-Unit and the Hochhörndler Schuppenzone, the historic Kitzbühel mining district was divided into three zones – a northern, a central and a southern one (Pošepný, 1880). The majority of the prehistoric mining traces can be found in the southern zone or the Glemmtal-Unit near Jochberg and Aurach. In addition to numerous smelting sites, especially at Jochberg, the ore-processing heaps as well as the subterranean Bronze Age mining in the Kelchalm district belong to this zone. It is important to emphasize that up until today, the research of this area only offers evidence for the use of chalcopyrite.

Further evidence of Bronze Age ore mining and copper smelting are found in the middle zone, which includes the area of the Wildseeloder-Unit and the Hochhörndler-Schuppen Zone. Prehistoric mining traces were found in the form of underground mining sites in the Schattberg district, as well as through evidence of ore-processing on the Götschen in the Brixen Valley and smelting sites near Kitzbühel and Aurach.

Given that the Kitzbühel mining region features both the chalcopyrite used in the Middle and Late Bronze Age as well as the fahlore used in the course of the Late Bronze and Early Iron Age, this region plays a special role considering the spread of prehistoric copper mining. The prospectors of the Bronze Age probably recognized quite soon that the area west of Kitzbühel – the Lower Inn Valley – shows a decrease in the share of the much

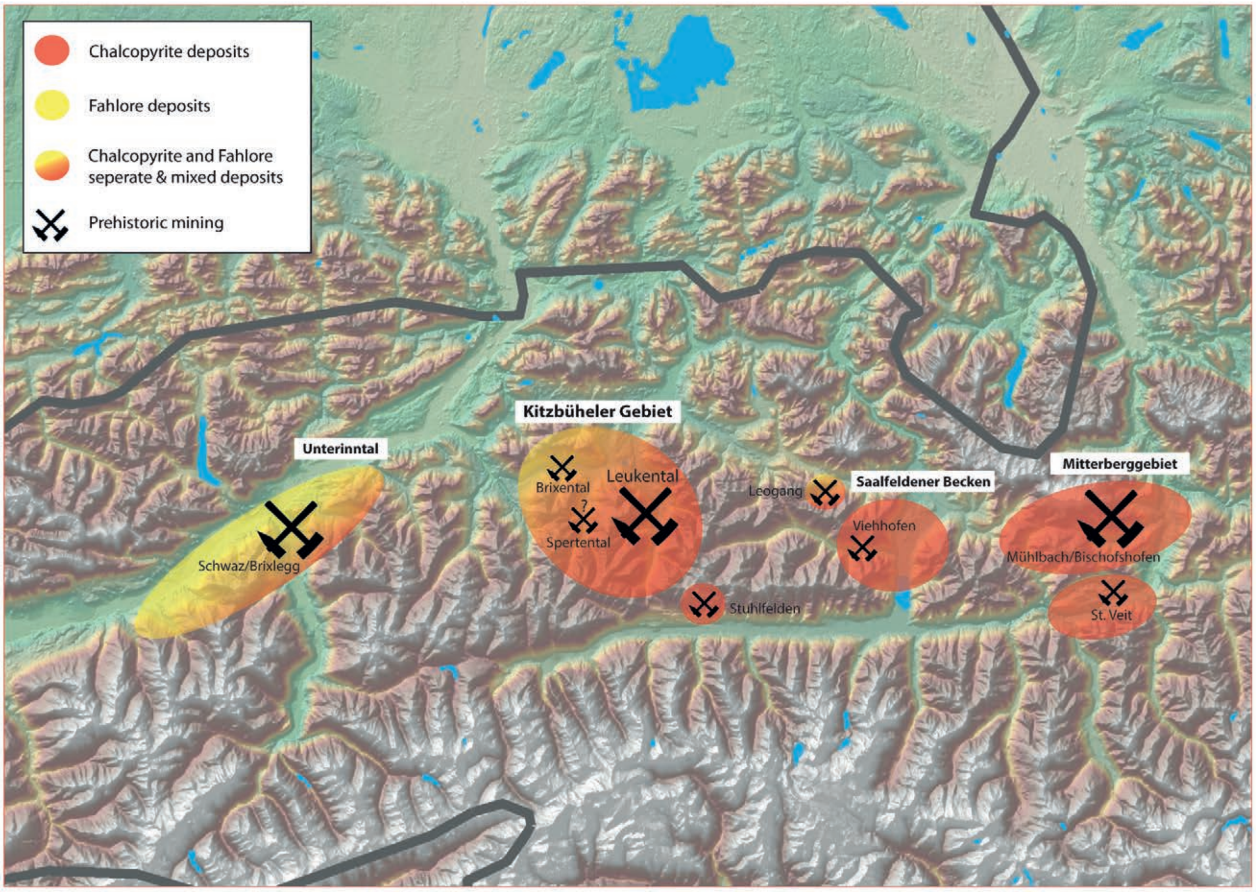

Fig. 1: Prehistoric copper mining regions in the western Greywacke zone (according to Koch Waldner 2017).

sought-after chalcopyrite. However, the considerable abundance of copper ore does not break off in the west, since chalcopyrite is replaced by fahlore. Given the chronological and geographic location of the Kitzbühel mining region – between the older chalcopyrite districts of Salzburg and the younger fahlore districts in the Tyrolean Lower Inn Valley – it seems probable that the miners and metallurgical workers of the eastern alpine copper technology – after an experimental phase with fahlore – started to explore fahlore deposits in the areas bordering on the west (Koch Waldner, 2017).

Traces of the prehistoric mining and metallurgy in the Kitzbühel region

The largest concentration of mining archaeological sites can be found in the southern Leuken Valley in the municipalities of Jochberg, Aurach and Kitzbühel. One must keep in mind, however, that the prospections of the 20th century exclusively focused on this part of the region. The mining relics that are situated outside the valley demonstrate that the prehistoric mining industry must have stretched beyond Leuken Valley. Up until today, however, these areas were not the focus of scientific research. These include the prehistoric ore-processing heaps on the Götschen in the Brixen Valley (Neuninger et al., 1970) as well as alleged Bronze Age mining traces on the Brunnalpe in the Sperten Valley.

This region was given particular attention due to the processing heaps in the Kelchalm district, wich are some of the most impressive surface relics of prehistoric mining in the Alpine region.

Thanks to the localization of numerous smelting sites by Pittioni as well as ambitious locals such as the former Jochberg village chronologist Georg Jöchl, the region was defined as a large-scale mining landscape. After further prospecting in the past years by employees of the Research Center HiMAT of the University of Innsbruck 52 smelting sites are known now.

Prehistoric traces as deposit indicator for historical mining industry

Prehistoric mining traces served as historical indicators for mining deposits. This has often led to an overprinting of Bronze Age pings and heaps through historical mining and processing activities. As a consequence, depressions and heaps of the Bronze Age could be clearly identified

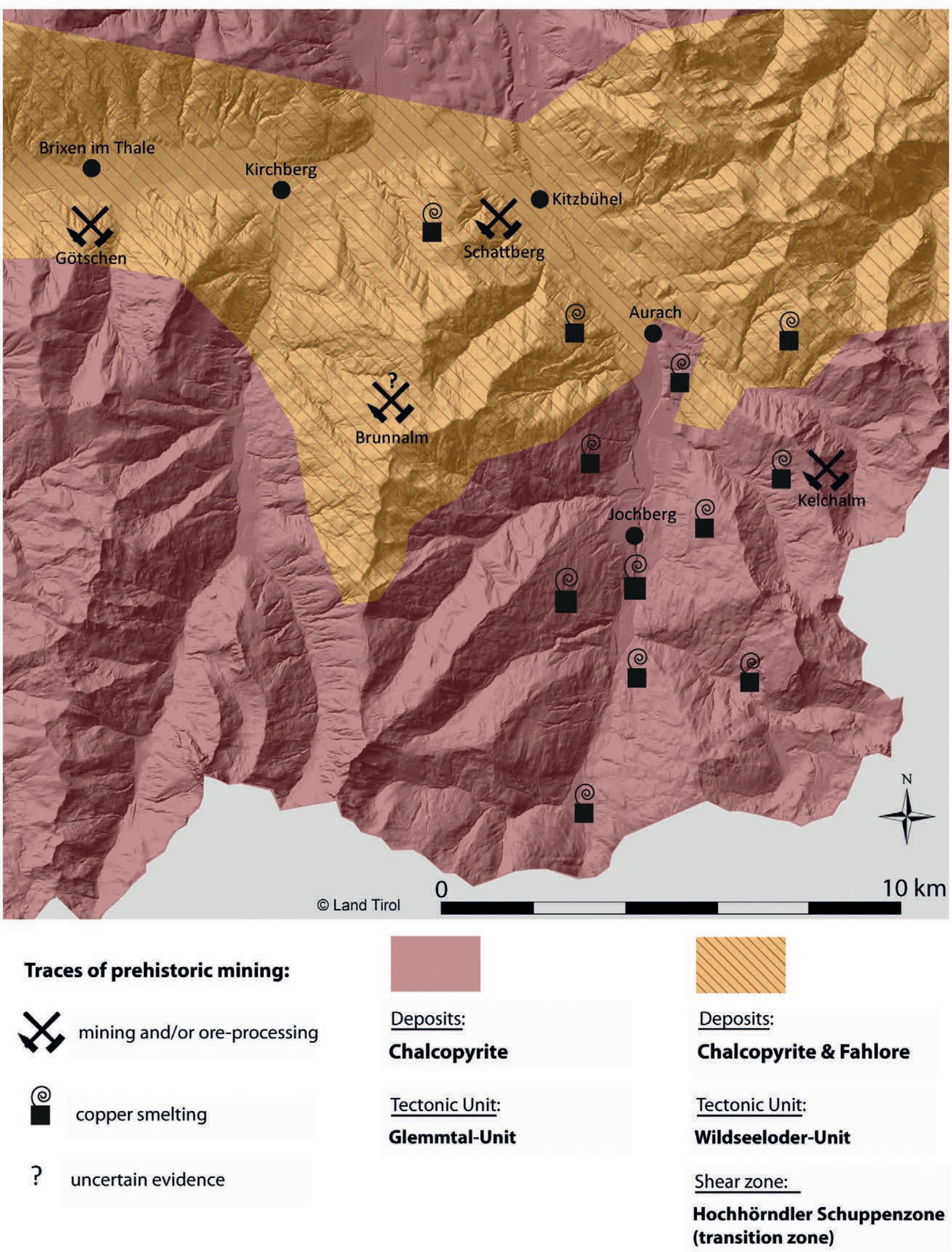

Fig. 2: Geological conditions and traces of prehistoric mining in the region of Kitzbühel.

solely in a few mining districts. Particularly noteworthy is the fact that the deposit of the Kelchalm district was rediscovered in the 18th century due to prehistoric heaps and depressions. The k.k. deposit researcher Franz Pošepný reported:

„Durch die 1751 gemachte Entdeckung des Erzvorkommens auf der Wildalpe, ist man auf die am Gebirgsrücken zwischen dem Aurach- und Wiesenegger-Thale befindlichen Pingen und Halden aufmerksam gemacht worden, was 1769 zur Begründung des Kelchalpner, gegenwärtig productivsten Kupferbergbaues des Kitzbühler Districtes führte.“ (Pošepný, 1880).

“The 1751 discovery of ore deposits on the Wildalpe to draw attention to the depressions and heaps on the mountain range between the Aurach and Wiesenegger valley, which in 1769 led to the establishment of a mine at Kelchalpe, the most productive copper mine in the Kitzbühel district”.

Smelting sites as indirect indicators for ore mining

The distribution of smelting sites from the Sinnwell district near Kitzbühel in the north up to the valley end at the Pass Thurn in the south serves as indication that Bronze Age miners prospected the entire Kitzbühel region. This also suggests that they made use of most of the exploitable copper deposits they could discover. Already Pittioni was convinced that the smelting sites to the west of Jochberg were supplied with the ores of the Wurzhöhe (Pittioni, 1976). Considering the spatial proximity of the smelting sites to the copper deposits, it seems evident that during the Bronze Age also those ore deposits were used, in the surroundings of which no traces of prehistoric mining have been found yet.

Mining

In the course of dismantling activities of historic and modern mining, researches documented prehistoric mining sites – labelled as “ Heidengruben “ or “ Alte Gruben “. The designation “Heidengrube” (“pagan pit”) suggests that historical miners were assuming a prehistoric time-framing for these mining relics. Detailed reports by prehistorians and depositors on these sites have only been available since the middle of the 19th century. It can be assumed that miners had already encountered the remnants of the prehistoric mining in earlier times. One should keep in mind, however, that such discoveries were not systematically recorded in the late Middle Ages and Early Modern Times. Furthermore, no relevant research has been carried out on mine reports and maps from this period.

Since the rock stability of the Wildschönau slate is relatively low and artificial cavities can thus not withstand the mountain pressure for very long, the portals and galleries collapsed after the abandonment of the historical or modern mining. Today, there are no more accessible underground sites, so the reports of Matthäus Much, Alexander Schernthanner and Franz Pošepný are important sources of information for prehistoric underground mining.

The low stability of the host rock suggests that the Bronze Age galleries had to be reinforced much more than in other prehistoric mining regions in the western Greywacke zone. Interestingly, Matthäus Much compared the severely broken old mines in the Kelchalm district with the “Heidengebirge” of the salt mines of Hallstatt and Dürrnberg and described the situation as a *„wirre Masse von Trümmergestein, Schlamm und Holzstücken“ “tangled mass of debris, mud and wood pieces”* (Much, 1879).

Even Pošepný, who traveled to the mines of the Habsburgian Monarchy in Siebenbürgen, Bohemia and the Alps, emphasized that the study of the Kitzbühel mining industry was made considerably more difficult by the brittleness of the rock as well as by the necessary dense timbering of the galleries (Pošepný, 1880). The great dimension of this fact results from the compilation of the gallery system in the Schattberg- and Sinnwell district to the west of Kitzbühel. In 1805 out of a total of 25.506 kilometers, 58% had been collapsed, 35% were timbered, and only 7% of the galleries were located in solid rock without timbering.

Findings of Underground Mining

The only traces of prehistoric underground mining that were investigated and described by scientists so far were found in the Schattberg and Kelchalm district in the middle of the 19th century. In 1843, a prehistoric mining site was discovered in the Schattberg, southwest of Kitzbühel. It included fresh-looking timbers, wedges of oak, a wooden shovel, a “leather apron” as well as stone tools for ore-processing, which Much compared with those found at the Mitterberg district (Much, 1879). In the course of the following years, further prehistoric mining sites were discovered near these pits.

In the Kelchalm district, “old mines” filled with water were discovered above the Danieli gallery, which experienced a water eruption in 1855 (Much, 1879; 1902; Pošepný, 1880). These pits included a variety of prehistoric finds, including burnt tapers, a bronze needle and even a wooden box construction (Much, 1879; Pošepný, 1880; Schernthanner, 1893). The keeper Anton Duxneuner had seen the box, which was made from spruce boards, and reported the following:

„Es standen drei Säulen in einer Reihe, und zwischen je zweien davon eine viereckige Holzkiste, über der eine Stange lag. Nebst offenbaren Trogfragmenten fanden sich auch aus Haselstauden angefertigte Siebe, so dass man die Existenz einer Siebsetz-Vorrichtung annehmen zu müssen glaubte, wobei die in die Kisten eingesenkten Siebe auf der oben befindlichen Schwungstange aufgehängt gewesen sein mögen.“ (Pošepný, 1880).

Fig. 3: Mating heads for gland pelts from the ore-processing heap 32 of the Kelchalm district - without scale (according to Preuschen & Pittioni, 1937 and Pittioni, 1947, compilation according to Koch Waldner, 2017).

"There were three pillars in a row, and a square wooden box, covered with a pole, was situated between two of the pillars. In addition to the trough fragments, sieves made of hazelnut shrubs were discovered, so that the existence of a sieve device was assumed, whereas the sieves indented into the boxes would have to be suspended from the swing-rod above."

Whether the findings were actually an ore-processing facility, however, cannot be fully confirmed. If the miner's interpretation were actually correct, this facility as well as the stone tools from the Schattberg would represent the only evidence for underground ore-processing of the Bronze Age copper mining in chalcopyrite deposits.

Another miner came across a further unique find in the old mines of the Kelchalm district. It was a broken wooden stick, which at certain intervals had notches and "*enigmatic*" symbols, which the finder interpreted as a probable mining measurement device. As nobody seemed to be interested in this unique discovery, he threw it away, so that today his interpretation cannot be confirmed anymore (Schernthanner, 1893).

On the surface, too, several finds were discovered that served for mining activities underground. Among the material collected during the excavations of Preuschen and Pittioni at the ore-processing heaps, there are leftovers of timber shafts for socketed tools (Fig. 3). The comparison with the shafts for bronze picks from the Mitterberg region demonstrates that the finds of the Kelchalm are of the same type (Koch Waldner, 2017; Thomas, 2018). This underlines the fact that in both mining regions the same miner's tools and comparable mining technologies were used.

Recent research was successful in finding several mining maps of the 19th century Kelchalm district that depict the find spots. Due to the importance of accurate surveying in underground mining, the visual map material provides a precise representation of the network. This enabled the calculation of the depth mining of the old cavity. The pit-plans were adapted to a geo-referenced orthofoto and a terrain laser scan. The distance between the entrance of the Danieli gallery and the site were determined by a vertical map drawing. Finally, the lowest point of the prehistoric mining site, which is situated in a depth of about 160 m, was calculated. The considerable depths point to an equally highly developed underground structure as that in the Pongau, where the deepest prehistoric copper mining in Europe – in the Arthur gallery near Bischofshofen – lies with a depth of more than 200 m (Thomas, 2018).

Processing

Traces of ore-processing were found in the Kelchalm district and on the Götschen near Brixen im Thale, since here the ore-processing heaps are only partially covered by plants and thus clearly visible. Whereas at the Götschen only prospections were carried out, Preuschen and Pittioni were able to gain important insights into prehistoric ore beneficiation technologies through their excavations on the heaps of the Kelchalm district. They are located in the flat slope of the Freibergsattel south of the Laubkogel on approximately 1760 m a.s.l. "Kelchalm" in the narrow sense refers to the area west of this saddle region. The area east of the ridge is called Bachalm. Given that in historical time, the deposit was approached from the Kelchalm, the entire mining quarter was named after it. During the archaeological excavations and prospections of Pittioni and Preuschen, it was possible to differentiate more than 50 heaps (Preuschen & Pittioni, 1937). The many finds and results from the "Scheidehalde 32" are connected with ore beneficiation (picking, sorting ...) – the separation of ore from dead rock. They show the process of prehistoric ore-processing ("chaîne opératoire") in an impressive manner. The latest excavation results emphasize that, at the beginning of prehistoric use, an existing forest stock was cleared in the ridge region (Klaunzer et al., 2010). The clearing of the trees, on the one hand, served to expose the rock, on the other hand the wood could then be used as construction material and fuel. Subsequently, work areas were set up.

The entire ore beneficiation process can be reconstructed on the basis of the finds from the "Scheidehalde 32". The extracted ore, partly still intergrown with dead rock, was first subjected to coarse comminution by the

Fig. 4: Aerial view of the Kelch- and Bachalm (© Land Tirol) with floor plan of the Kelchalm disctrict (after Pošepný 1880). The prehistoric heaps can be seen on both sides of the ridge. In the mine plan, the mined ore bodies are shown in grey and the prehistoric mining pit is marked red (according to Koch Waldner, 2017).

use of stone tools such as "Scheidhämmer" (cobbing hammer) and anvils. Then the ore was sorted out. The dead rock, often larger pieces, was thrown to the heap. This first working step is demonstrated by up to 10 cm chunks of dead rock in the processing heap. In case the ore was heavily grown together with the host rock, grinding stones, which were pulled over large stone blocks, were used for finer processing. With the aid of these ore mills, the ore-bearing rock was reduced to a uniform grain size. Subsequently, in a wet-mechanical working step, the pounded and finely ground material was separated in water due to the different specific gravity of the ore and the dead rock. This process is comparable to gold washing, in which the heavy, rich material accumulates under the lighter, dead material by constant swirling, securing and pivoting. The copper-rich concentrate obtained during the washing was finally separated by means of wooden knife-like tools.

Such knife-shaped instruments of wood, as later described by Georg Agricola (Agricola, 1556), were also found in the ore-processing heap of the Kelchalm (Preuschen & Pittioni, 1937).

Further findings related to the wet-mechanical beneficiation are the ponds that were documented on the Kelchalm, two wooden troughs (Fig. 6) and several wooden channels and ground channels (Preuschen & Pittioni, 1954). Wooden channels were used to transport clean water to the wet processing plants. Afterwards, the dirty water was derived with simple ground channels. The troughs measured about 175 x 80 cm at the time of their discovery. Similar to the box construction for the wet processing of ore from the Troiboden near Mühlbach (Stöllner et al., 2012; Stöllner, this volume), the troughs include a transversely running wooden rod. This indicates that the troughs were used for a similar wet processing technique as the boxes in the Mitterberg Region. A box construction made of boards in the area of "Scheidehalde 32" was interpreted as waste pit by Preuschen and Pittioni. According to today's research, it seems more obvious that this construction also represented a wet

Fig. 5: Prehistoric heaps on the Bachalm in the Kelchalm district (photo: T. Koch Waldner).

Fig. 6: Trough for the wet processing of ore from "Scheidehalde 32" in the Kelchalm district (photo: A. Blaickner).

processing facility (Koch Waldner & Klaunzer, 2015). In addition to the well-preserved wooden artifacts, such as posts, wedges, roof shingles, cooking utensils, and tally sticks ("Kerbhölzer"), which may indicate an early counting system, many ceramic fragments, animal bones and some bronze finds were discovered (Klaunzer, 2008).

One particular foundation stands out (No. 61 according to E. Preuschen and R. Pittioni) and is interpreted as a substructure for a building (Preuschen & Pittioni, 1954). This finding as well as the mentioned shingles and a wooden whisk (Pittioni, 1947) for butter production are the most important indications for a settlement in this mining area.

Smelting

The extracted ore was roasted on cobbled roasting beds and smelted in shaft furnaces. Since Pittioni mainly carried out prospecting in the municipality of Jochberg, the area is known for its prehistoric smelting sites. The frequent occurrence of these sites in and around Jochberg is not due to spatial organizational structures of the prehistoric mining system, but can be traced back to intensive archaeological prospections and the attention of the inhabitants in this area. A similar density of smelting sites could therefore

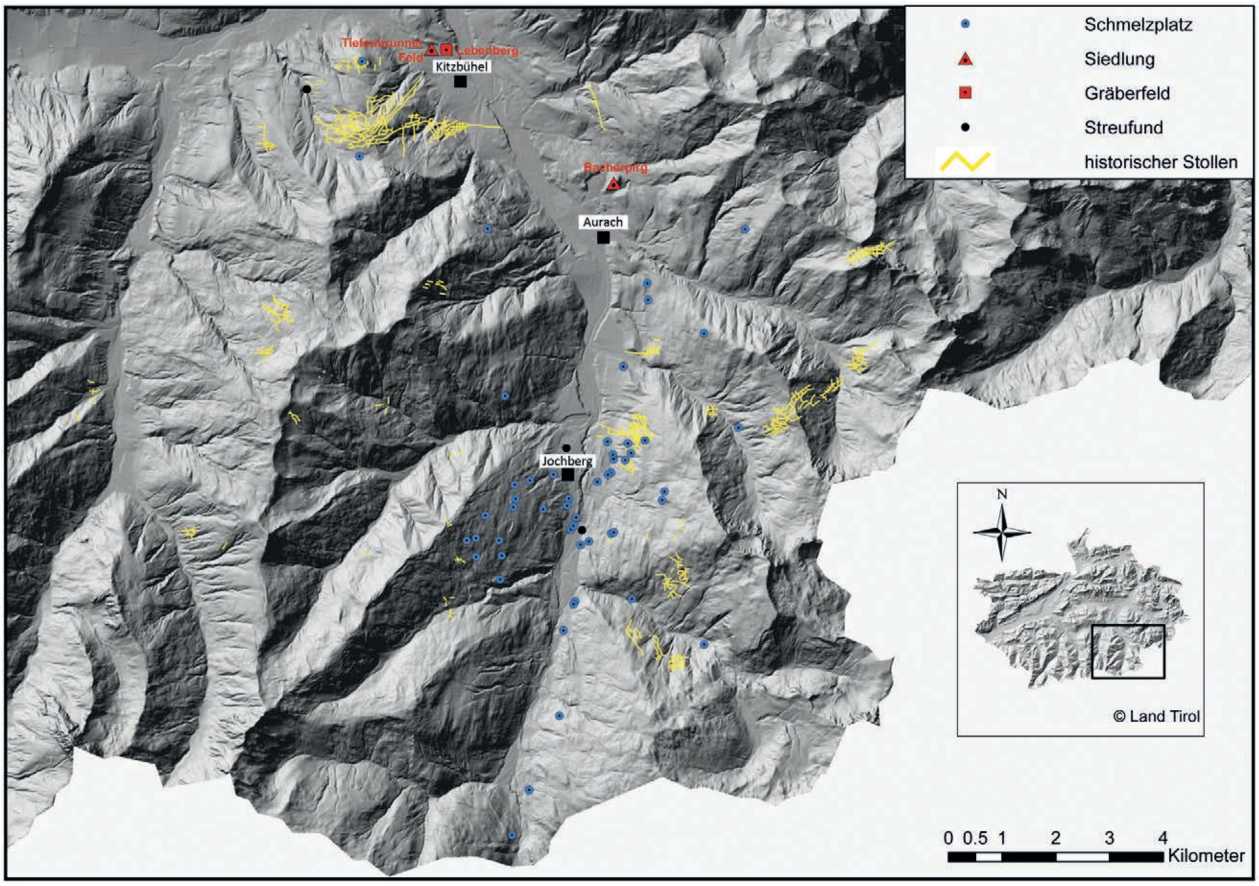

Fig. 7: Distribution of prehistoric smelting sites (according to Koch Waldner, 2017, produced by R. Skomorowski & T. Koch Waldner).

also be assumed for the municipalities of Kitzbühel and Aurach. In addition, it has to be taken into account that numerous construction measures, particularly in Kitzbühel, could be responsible for the destruction of many of the sites since the Middle Ages. This is also why their actual distribution cannot entirely be reproduced. Recent research has attempted to locate the sites mentioned by Pittioni. During research, several previously unknown smelting sites were discovered. A new coding was used to obtain a structured reference character. The smelting sites (SP) are provided with an additional abbreviation for the found area (for example, WH for Wurzhöhe, SK for Schützenkogel).

Smelting facilities

Pittioni carried out several excavations on slag sites from the 1950s to the 1970s. However, no well-preserved furnace structures could be discovered and documented. Prehistoric furnaces and roasting beds were first excavated and published at the WH/SP 1 (Hechenberg) site in the 1990s in the area of the Wurzhöhe (Goldenberg, 2004). Promising surface findings (slag and furnace fracture) as well as the results of a magnetic field measurement at this smelting place (1305 m a.s.l.) resulted in two excavation campaigns. Four smelting furnaces, including a double furnace and a two-phase roasting bed, were documented.

In the summer of 2012 another smelting facility was excavated and documented on the smelting site WH/SP 5 (Koch Waldner et al., 2013b; Koch Waldner, 2017). The site (1115 meters above sea level) was first mentioned by Pittioni in 1968 as SP 27. The remains of furnaces and a roasting bed were located along a terrain edge by means of surface finds, core drillings and magnetic field measurements. A double furnace and a part of the accompanying roasting bed were uncovered.

The roasting bed was made up of a pavement of flat stone slabs in a clay layer and larger boundary stones. The double furnace (Fig. 8) was located downhill, 1.20 m away from the roasting bed edge. The furnace walls were placed in a terrain edge, the interior was 50 cm wide and about 80-100 cm long. On the back of the furnaces were two pits filled with slag cakes and two further pits filled with stones. They probably served to reinforce the walls.

Of the hitherto investigated smelting sites, this is the only one where exclusively slag cakes (fragments), but no plate slag or slag-sand are present. These technological differences could be explained by the age of this site. On the basis of ^{14}C-data the WH/SP 5 site can be dated into the 15th century BC and thus representing the oldest explored smelting site in the region.

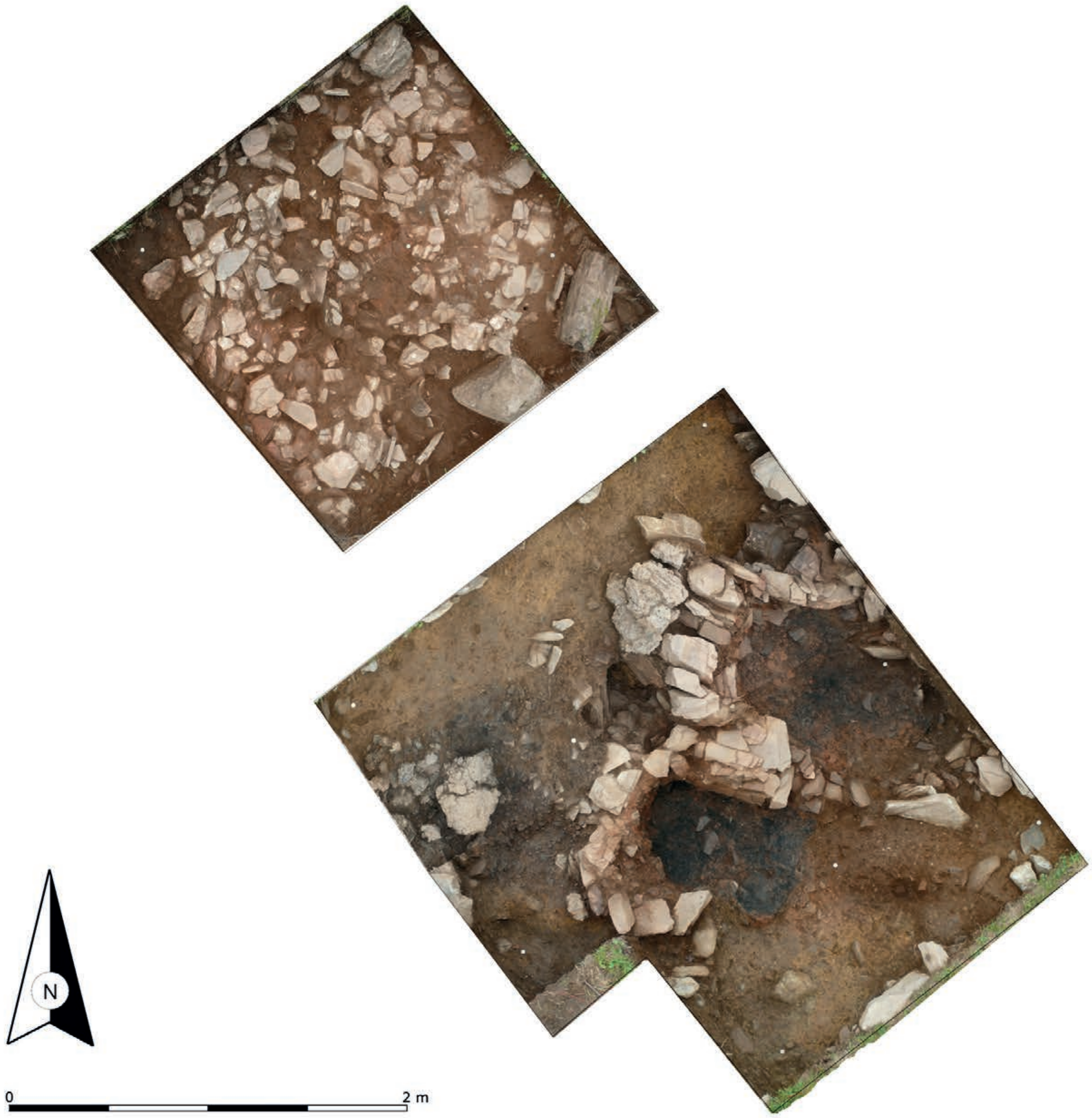

Fig. 8: Roasting bed and the double furnace with slag deposits behind of the furnace on the smelting site WH/SP 5 – photogrammetric plan (after Koch Waldner, 2017, plan: R. Skomorowski & T. Koch Waldner).

After Preuschen and Pittioni carried out initial archaeological excavations in the Kelchalm district's smelting site LK/SP 1 in 1932 (SP 1 according to E. Preuschen and R. Pittioni), the local population continued to work on the site in the 1970s. However, the results were not published. Only after intensive research both the photographic and the graphic documentation of these excavations, were finally found in 2013 (Koch Waldner, 2017). During the second, unpublished excavation, furnaces were uncovered, so that altogether at three sites smelting facilities were excavated.

By means of geomagnetic measurements, it was possible to locate further furnace records at the Wurzhöhe, which should be further investigated in the future.

Slag processing

The slag processing is based on a similar technology as the ore-processing. After a smelting process, copper was still bound in the slag. Consequently, the slag was crushed and ground on anvil stones. On the Wagstättalm (WH/SP 4) as well as on other smelting sites with slag sand, several stone tools could be found for such a preparation, including bucking plates (Fig. 11) and hammer stones (Fig. 12) (Koch Waldner et al., 2012b; Koch Waldner, 2017). The crushed and finely ground material was separated by means of a wet mechanical processing. A water source (spring, runlet, swamp etc.) in the vicinity of Bronze Age smelting sites is therefore

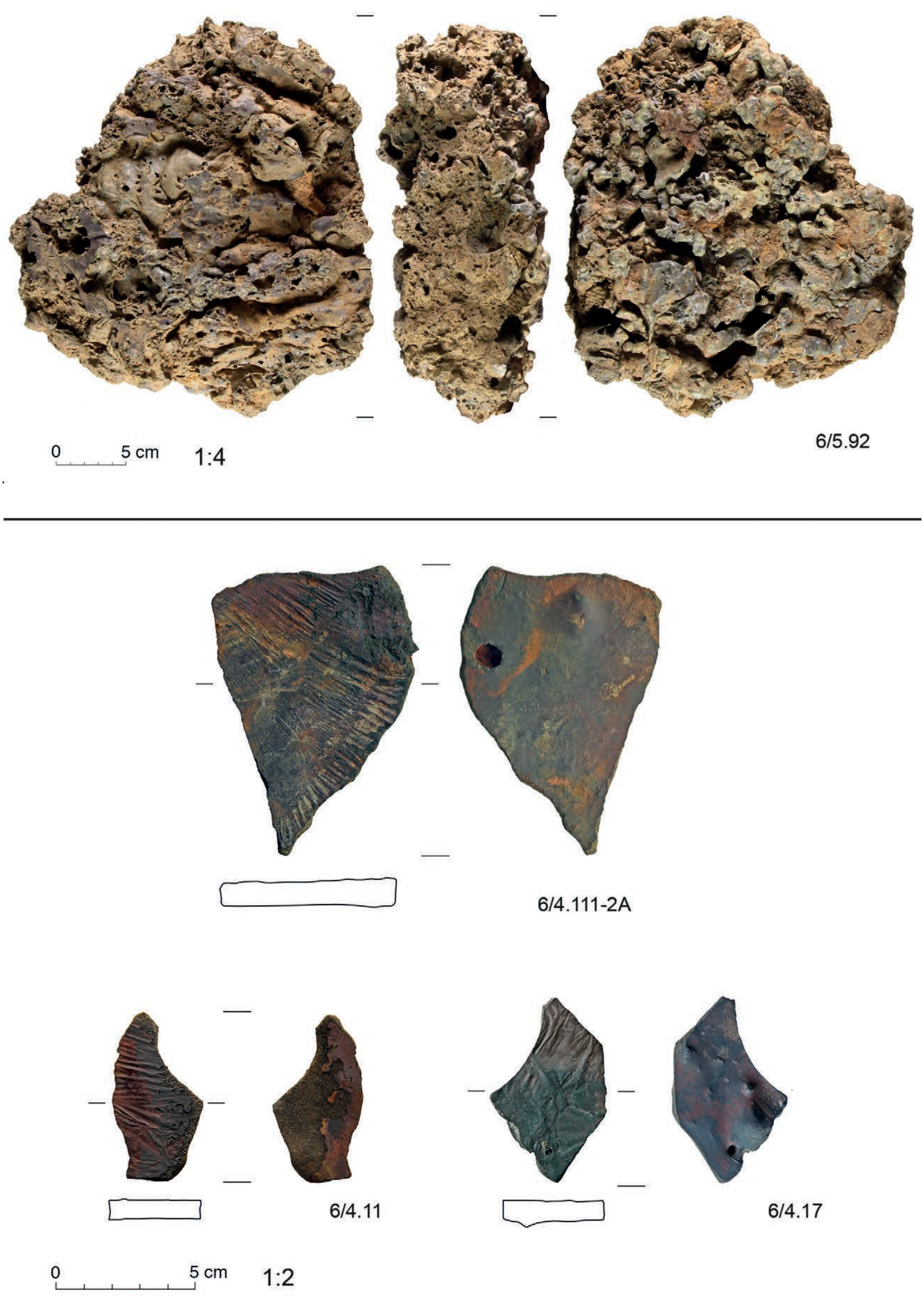

Fig. 9: Slag cake from the smelting site WH/SP 5 and plate slag from the smelting site WH/SP 4 (after Koch Waldner 2017; photos: A. Blaickner & T. Koch Waldner).

an indicative characteristic. The slag sand was finally removed and dumped as a waste product onto the heap. On the smelting site WH/SP 4 (1274 m a.s.l.), remnants of such a washing facility could be documented for the wet mechanical processing of slag (Fig. 10) (Koch Waldner et al., 2012b; Koch Waldner, 2017). These are two parallel, gutter-like channels, which were put in the ground and had wooden boardings on the sides. A plank was found in one of the washing troughs, which originally reinforced one side of the washing plant. The two channels were entirely filled with slag sand. The sand was mixed with waste from woodworking, twigs and spruce or pine needles, which points to the occurrence of woodwork directly at the smelting site. The slag sand heap is located downhill, in close proximity to the washing facility.

Ore-processing at the smelting site

During the prospecting of the past years, quartz pieces with ore residues were found at several smelting sites. At the Wurzhöhe, some cases demonstrate a particularly high proportion of the ore-containing material on the surface of prehistoric slag heap or in the vicinity of the smelting facilities. During a smaller trial excavation in the area of the slag deposit of the smelting site WH/SP 2, researchers detected particularly many quartz pieces with chalcopyrite residues as well as crushed quartz sand deposited directly in the slag sand (Koch Waldner, 2017). A bucking plate with quartz sand was also found at the bottom of a washing plant for slag sand at the smelting site WH/SP 4. At this point, it should be noted that quartz was apparently used as an additive in the smelting process. Since in addition to pure sand also larger quartz pieces with ore residue were found, it can be assumed that at least in some cases ore – at least partly – was processed directly at the smelting site.

This circumstance could be due to the exploitation of smaller deposits near the surface. The ore must have been smelted in close proximity, given that mining, beneficiation and smelting did not need to be spatially separated.

Different spatial organisation of the chaîne opératoire at large and small ore deposits

While numerous smelting sites are located close to the small deposits at the Wurzhöhe near Jochberg, processing heaps have not been found there yet. Bearing this in mind it is striking that only one smelting site was discovered in close proximity to the large deposit and the extensive prehistoric ore-processing heaps in the Kelchalm district near Aurach. This particular situation suggests that the single activities of the chaîne opératoire – mining, processing and smelting – were separated at large deposits with great depth while there was no need for a spatial separation of mining and smelting works at small deposits close to the surface. One reason of the different organization was certainly the high consumption of wood especially as fuel for the smelting works and for the stabilization of the underground mines. As mentioned before, because of the very brittle host rock the mines in the region of Kitzbühel had to be timbered much tighter than in most of the other historic mining regions in the former Austro-Hungarian

Fig. 10: Remains of a washing plant for the wet processing of slag sand at the smelting site WH/SP 4 (photo: T. Koch Waldner).

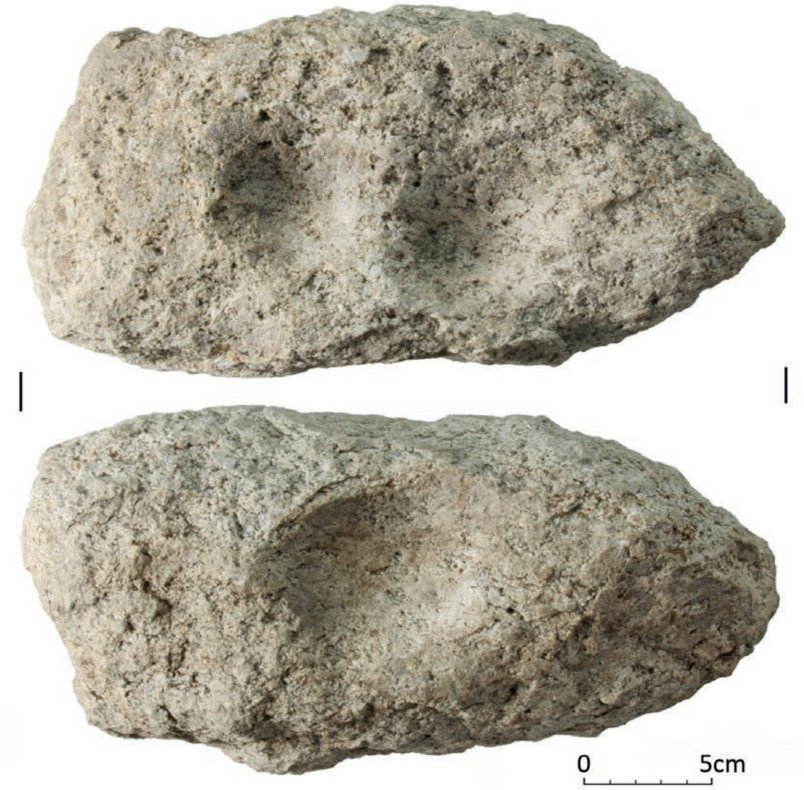

Fig. 11 & 12: Bucking plate and hammer stone from the smelting site WH/SP 4 on the Wagstättalm (after Koch Waldner 2017; photos: A. Blaickner & T. Koch Waldner).

Empire. Therefore it has to be considered that the consumption of wood just for the underground mining work was also very high in prehistoric times.

Small scale mining works did not over-exploit the scarce resources like the extensive mining works at the large deposit in the Kelchalm district. According to this model, also the absence of large mining traces at the Wurzhöhe could be explained.

Dating

In order to determine the duration of prehistoric mining in the Kitzbühel area, a total of nine smelting sites were dated by scientific methods in the framework of the author's research project since 2011 (Koch Waldner, 2017). Previously, Gert Goldenberg already published radiocarbon dates from the smelting site WH/SP 1 (Goldenberg, 2004) as well as dendrochronological dating of several woods from the dumps of the Kelchalm district (Pichler et al., 2009). Due to the dating results, one can suggest an initial phase of the mining industry in the middle Bronze Age or the 15th century BC. The mining industry was on its height in the early phase of the Late Bronze Age. Several smelting sites near Jochberg and the excavation sites in the Kelchalm district date to the first half of the 13th century BC.

This dating approach is confirmed by palynological investigations in bogs as well as the archaeological findings from the southern Leuken Valley and the excavation results of the Bronze Age burial ground "Lebenberg" in Kitzbühel. The partially excavated cemetery dates from the early (Bz D1) to the middle Urnfield period (Ha B1) or from the outgoing 14th to the late 11th century BC (Scheiber, 2011).

In summary, it can be argued that the majority of archaeological finds are from the Late Bronze Age and belong to the Urnfield culture. The oldest known finds, however, date in the transition period of the Early to the Middle Bronze Age. From later periods only a small number of finds is known, primarily from the early Iron Age. The absolute dating of archaeological sites connected to prehistoric mining also reflect a similar picture of the temporal development for the mining and metallurgical industry. This points to a link between the mining traces and those findings which are not directly attributable to the mining industry. The results from pollen analyses confirm the theory that the onset or the increase of archaeological finds is associated with Middle and Late Bronze Age mining. The first occurrence of grain pollen (Viehweider, 2015) during the 14th/13th century BC indicates the intensification of agricultural activities and suggests that the southern Leuken Valley was populated all year round for the first time by those people who were engaged in the mining industry.

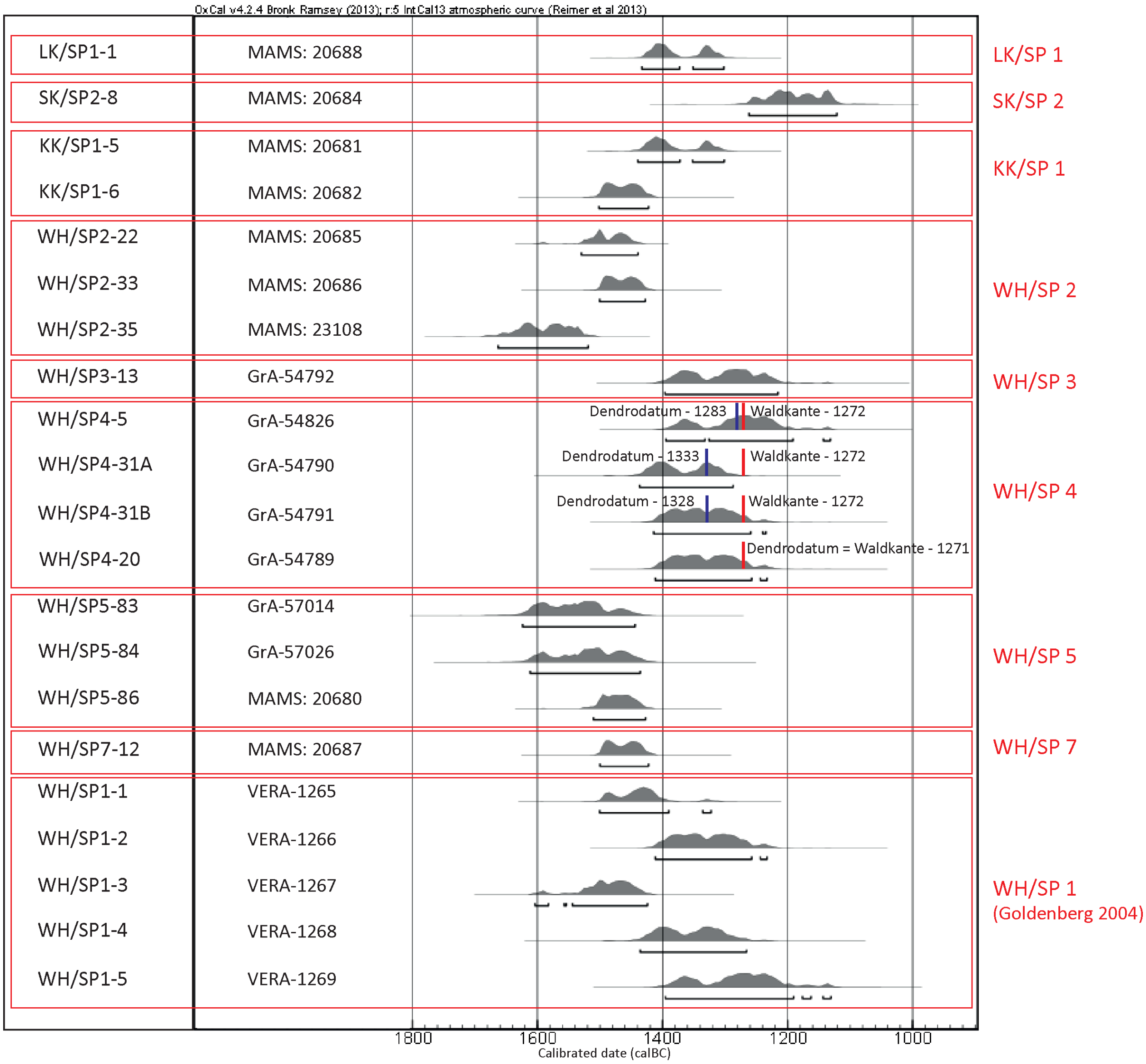

Fig. 13: Multiplot of ^{14}C-samples from different smelting sites near Jochberg and Aruach, as well as the dendrochronological data from the site WH/SP 4 (after Koch Waldner, 2017).

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Author

Thomas Koch Waldner – University of Innsbruck and Deutsches Bergbau-Museum Bochum

Correspondence and material requests should be addressed to: Thomas.Koch-Waldner@bergbaumuseum.de

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Susanne Klemm

Prehistoric copper production in Lower Austria – A new assessment

ABSTRACT: *The prehistoric copper mining area of Lower Austria is situated at the eastern edge of the Austrian Alps. This region of south-eastern Lower Austria is known for the medieval and modern mining of iron and copper ore. The copper ore deposits belong to three geological units: the Greywacke Zone, the base of the Northern Limestone Alps (or Northern Calcareous Alps) of the eastern alpine Mesozoic and the crystalline nappes of the Austroalpine Unit of the Central Alps. Of further interest for the study of prehistoric copper production are the ore deposits in the area of the orthoriebeckite gneiss belonging to the Greywacke Zone west of Gloggnitz. Ten prehistoric mining districts can be distinguished based on the structure of the landscape. Nine of these are situated north of the River Schwarza and its tributaries. Only one mining district is known south of the River Schwarza, although several copper ore deposits have been recorded there.*

Research on prehistoric copper production in Lower Austria started in the early 1930s by the speleologist Franz Mühlhofer and was continued in the 1950s with the recording and the archaeological investigation of sites of prehistoric copper smelting by the archaeologist and ethnologist Franz Hampl and the geologist Robert J. Mayrhofer. Since then up to 50 archaeological sites related to prehistoric copper production have become known. Only a few of these smelting sites can be dated to the Late Bronze Age. The remains of furnaces and roasting hearths were described by Hampl at the Prein sites, their construction details differing from smelting sites in Switzerland, the Tyrol, Salzburg and Styria. In the 1970s another type of furnace was found in the mining district of Kulm-Hafning, south-east of all the other mining districts. More recently, a number of sites with mining pits and other findings have been discovered which now widen the base for future research.

KEYWORDS: COPPER PRODUCTION, MINING, SMELTING, PREHISTORY, LOWER AUSTRIA

Introduction

The prehistoric copper mining area of Lower Austria is situated in the south-east of Lower Austria at the eastern edge of the Austrian Alps. Archaeological research started in the early 1930s, when the speleologist Franz Mühlhofer discovered mining pits of unknown date. Research was continued in the early 1950s with the recording and investigation of prehistoric copper smelting sites by the archaeologist and ethnologist Franz Hampl and the geologist Robert J. Mayrhofer from Lower Austria. Since then up to 50 archaeological sites related to prehistoric copper production have become known.

The majority of the archaeological sites, mainly slag sites and slag dumps from copper smelting sites, were discovered in the course of road construction works in the woodlands. Mining sites and sites of ore beneficiation are still a rarity, although new mining sites of unknown date have been recorded. The results of the archaeological investigations carried out by Franz Hampl, Helga Kerchler and others as well as the chronological framework of prehistoric copper production and its potential for future research in Lower Austria will be discussed. A physiographical division of the archaeological sites into 10 prehistoric mining districts is presented based on their distribution, setting in the landscape and the location of the known copper ore deposits. This study aims to identify the potential for future research on prehistoric copper mining and smelting in Lower Austria.

The landscape

This Eastern Alpine mining area of Lower Austria is situated in the areas south and east of the mountain ranges of Rax, Schneeberg, Hohe Wand, Semmering and Wechsel and reaches east as far as the lower mountain range called

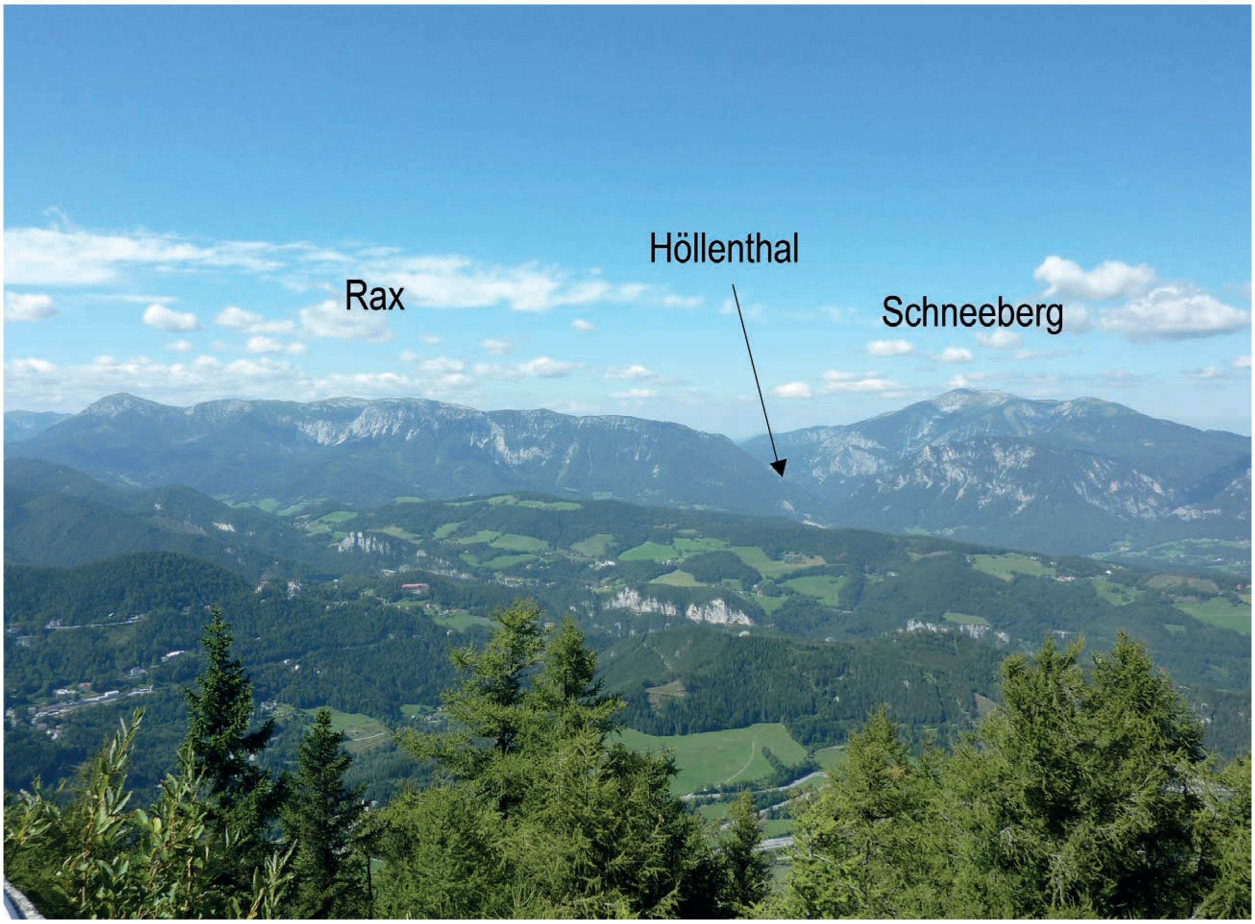

Fig. 1: The north-western prehistoric copper mining area at the foot of the Rax and Schneeberg mountain range. Photo taken from Pinkenkogel/Semmering from the south-west (photo: S. Klemm).

Bucklige Welt (Figs. 1, 2). The highest mountains, Rax (Heukuppe 2007 m a.s.l.), Schneeberg (Klosterwappen 2078 m a.s.l.) and Hohe Wand (Große Kanzel 1052 m a.s.l.) confine the prehistoric mining area to the north, while the Semmering/Wechsel region with Sonnwendstein (1523 m a.s.l.) and Hochwechsel (1743 m a.s.l.) at the border of Lower Austria to Styria confine the area to the west. The most important passages to cross these mountains to the western regions in Styria are Preiner Gscheid, south of Rax (1070 m a.s.l.), the Semmering Pass (984 m a.s.l.), and the Feistritz Sattel (1290 m a.s.l.). The archaeological sites of the mining districts 1-9 were discovered in areas at about 500-1030 m a.s.l. at the foot of these mountains or in the lower mountain range with heights from 450-1100 m a.s.l.

West of the Semmering/Wechsel region is the lower mountain range of Bucklige Welt, reaching a height of almost 1400 m a.s.l. in the west and 1000 m a.s.l. in the east, with mining district 10 in its northern part. The archaeological sites in this mining district are situated at 490-570 m a.s.l.

The rivers Schwarza, Preiner-Bach, Haidbach/Heidbach and Auebach drain the mountain region in the north, the rivers Feistritz and Pitten in the south.

In the north-east of these mountain ranges, the countryside opens out to a much lower, open and flat area, the most southern part of the Wiener Becken. At its north-western edge the hills of the Fischauer Vorberge separate a broad valley, called Neue Welt, at the foot of the Hohe Wand mountain, from the plain of the Wiener Becken.

The copper ore deposits

The copper ore deposits in Lower Austria are rather small in comparison with those of other prehistoric mining areas in the Eastern Alps (Fig. 2). Our knowledge of these ore deposits derives from the remains of medieval and modern mining, frequently from iron ore mines, from historical sources about these historical mines and from local findings of minerals (Hackenberg, 2003).[1] It is presumed that medieval and modern mines destroyed or were superimposed upon prehistoric mines, with the most recent mines having closed only as recently as the early 20th century.

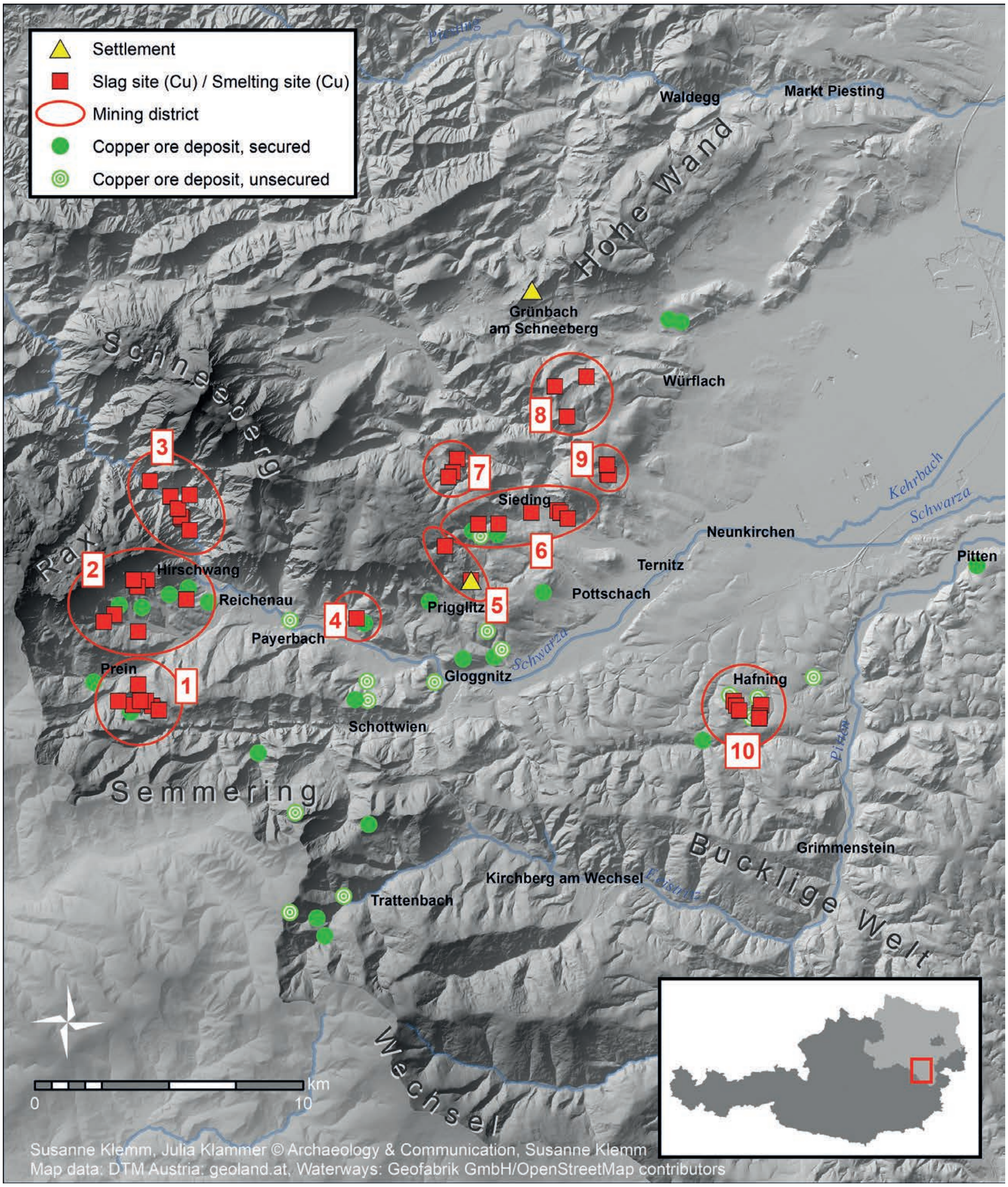

Fig. 2: Distribution of copper ore deposits and prehistoric copper mining districts in Lower Austria (graphics: S. Klemm, J. Klammer; © Susanne Klemm). 1 Prein-Breitenstein. – 2 Kleinau-Großau-. – 3 Kaiserbrunn-Höllental. – 4 Payerbach-Grillenberg. – 5 Prigglitz-Gasteil. – 6 Sieding. – 7 Gadenweith. – 8 Schrattenbach-Stixenstein. – 9 Flatz. – 10 Hafning-Kulm.

The copper ore deposits belong to three geological units: the Greywacke Zone, the base of the Northern Limestone Alps (or Northern Calcareous Alps) of the eastern alpine Mesozoic and the crystalline nappes of the Austroalpine Unit of the Central Alps. These units are situated in various geological positions. Most of the recorded sites of prehistoric copper production were found in the Greywacke Zone and at the base of the Northern Limestone Alps, where iron ore and chalcopyrite were mined. So far, only one group of sites is known from the crystalline nappes of the Austroalpine Unit. Also of interest for the study of prehistoric copper production are the ore deposits in the area of the orthoriebeckite gneiss belonging to the Greywacke Zone west of Gloggnitz (Heinrich, 2006).

The copper ore deposits of the Greywacke Zone – copper sulphides, mainly chalcopyrite but also fahlore, rarely native copper – are part of the siderite deposits, the copper ore being associated with quartz veins. Contents of arsenic and antimony are characteristic for chalcopyrite deposits in the eastern Greywacke Zone (Hampl & Mayrhofer, 1958, pp.46-51). Most prehistoric mining districts are situated in this geological zone, namely the mining districts 1-9 in the region of Rax and Schneeberg reaching as far as Hohe Wand (see Figs. 1, 2).

South of the River Schwarza and west of Gloggnitz, in the area of the Eichberg-Kreuzberg mountain range, there are copper ore deposits within the orthoriebeckite gneiss belonging to the Greywacke Zone. Archaeological finds and other findings indicate a mining area west of Gloggnitz (Hackenberg, 2003, pp.53-54, no. 69).

In the western part of Bucklige Welt, south of Neunkirchen, mining district 10 is situated in the area of Hafning and Kulm where copper ore deposits (chalcopyrite) in the crystalline nappes of the Austroalpine Unit are known. West of this area, in the region of the Semmering/Wechsel mountain range, also in the crystalline nappes of the Austroalpine Unit, further copper ore deposits were recorded as well as copper ore mining from the 16^{th}-20^{th} cent. AD, with its largest mine at Trattenbach (Hackenberg, 2003, pp.66-68, nos. 95, 97, 99, 100; Inventory of Abandoned Mine Sites in Austria, GBA Vienna/Austria). No prehistoric mining sites are yet known in this area.

The prehistoric copper mining districts

History of archaeological research

Meanwhile, around 50 archaeological sites directly connected with prehistoric mining and the smelting of copper ore are recorded in the region. No site or mining district yet represents all the features that cover the whole *chaîne opératoire* or metallurgical chain, such as mining, ore processing, roasting and smelting of the copper ore, the alloying with tin and the production of bronze artefacts. It is only at the large site of Gasteil-Sandriegel (Prigglitz I/Cu)[2] in the mining district of Prigglitz-Gasteil (district 5) that several of these steps have been identified (Trebsche, 2013; Trebsche & Pucher, 2013; Haubner, et al., 2015; Haubner, Strobl & Trebsche, 2017). As this is the case, our knowledge of early copper production is derived mainly from slag sites and slag dumps rather than from complete smelting sites as will be shown later.[3] So far no mining sites have yet been successfully investigated (see Fig. 2).

Excavation at the prehistoric settlement Grünbach 'Am Gelände', west of the Hohe Wand mountain, by Mühlhofer (1952, p.82) in 1935-1937 produced the first information about prehistoric copper production in Lower Austria in the form of copper ingots, a variety of copper slags, amongst the latter also thin plate slag, stone hammers, and grinding stones with single rilling. The mining pits at Rothengrub-Zweierwald and Netting, on the northern slope of the Kienberg, discovered by Mühlhofer (1930; Inventory of Abandoned Mine Sites in Austria, GBA Vienna, ÖK 75/1003) are still undated; copper ore deposits are known from Rothengrub-Zweierswald.

In 1951 the archaeologist and ethnologist Franz Hampl, Museum of Lower Austria, now called MAMUZ Schloss Asparn/Zaya, was notified by the school teacher Johann Danzer about the find of a bronze knife dating to the Urnfield Period as well as some copper slags in Prein (mining district 2) that had already been found in 1938. Hampl then started intensive interdisciplinary research on prehistoric copper and medieval iron production in the area in cooperation with the geologist Robert J. Mayrhofer, combining archaeology and geology with geophysics, archaeobotany, archaeozoology as well as spectral analyses of ore and copper matte (Hampl, 1953; 1976; Mayrhofer, 1953; Hampl & Mayrhofer, 1958; 1963; Mayrhofer & Hampl, 1958; Hampl & Fritsch, 1959).

Fieldwork in Prein, south of the Rax mountain range (mining district 1), from 1951-1953 by Hampl and Mayrhofer was followed by an investigation of the Stixenstein-Siebentannen I/Cu site (mining district 8), where Ernst Preuschen, the well-known mining engineer, who discovered most of the prehistoric mining areas in the Eastern Alps, had found some prehistoric copper slag in 1949 (Hampl & Mayrhofer, 1963, p.77). Since 1954 further fieldwork has been done on the southern foot of the Rax mountain in Kleinau, Großau, Thonberg/Hirschwang (mining district 2) and east of Kaiserbrunn (mining district 3). From 1955 to 1959 their research concentrated on the site of Prigglitz-Gasteil (mining district 5), while more investigations were done in 1959 at the Grillenberg in Payerbach (mining district 4). Also in 1959, another small excavation to the north-east of the Hohe Wand mountain took place where thin plate slag and some post-medieval pottery were found (Hampl & Mayrhofer 1963, p.77, tab. 1).

Research on the prehistoric copper mining area in Lower Austria came to a standstill with the early death of Mayrhofer in 1959. In the 1970s Michael Puhr, Neunkirchen, started investigations in mining district 10, Hafning-Kulm, which were continued by Helga Kerchler from the University of Vienna (Puhr, 1972; Kerchler, 1976). Kerchler also continued research by recording sites in the mining districts 3, 6, 7 and 10, these being Höllental-Kaiserbrunn, Sieding, Gadenweith and Hafning-Kulm respectively (Kerchler, 1976). Wolfgang Haider-Berky, Neunkirchen, recorded some slag sites in Sieding, Gadenweith, Schrattenbach-Stixenstein and Flatz (mining districts 6-9) as well as some potential mining sites (Haider, 1975a; 1975b; 1977; Haider-Berky, 2013).

The most recent and important investigations were carried out by Peter Trebsche, Danube University Krems, at the huge settlement and mining site of Gasteil-Sandriegel in the mining district Prigglitz-Gasteil in 2010-2014 (Trebsche, 2013; 2015; Trebsche & Pucher, 2013).

The mining districts of Lower Austria

The mining district Prein-Breitenstein

South of the Prein river, eight sites of copper smelting were recorded in Prein-Breitenstein (mining district 1). The sites were discovered at 680-820 m a.s.l. All of these sites, just like the sites of Kleinau-Großau (mining district 2), were found on slopes and in proximity to streams, as it is typical with most sites of this type in the Eastern Alps (Klemm, 2003).

Characteristic findings such as metallurgical slag, furnace stones, charcoals, fragments of technical and settlement pottery as well as animal bones with green patina were found in the layers of the slag dumps from the sites Prein I/Cu, Prein II/Cu, Prein V/Cu and Prein VII/Cu in mining district 1, Prein-Breitenstein (Hampl, 1953; Hampl & Mayrhofer, 1963).

At one site – Prein III/Cu – extensive excavations were carried out in 1952 and 1953 (Hampl, 1953; Hampl and Mayrhofer, 1963). Several features were discovered and interpreted as installations for the smelting of copper ore such as round, oval, and trapezoid stone settings and small rectangular or square stone structures as well as two slag dumps. Unfortunately, the 1950s' records of the excavation do not give clear and detailed information about these features, which were interpreted as the remains of roasting hearths and furnaces. Three single furnaces were described. From the excavation results of copper smelting sites in other regions of the Eastern Alps in Styria, Salzburg or the Tyrol, we know only of rectangular roasting hearths and shaft furnaces in a typical setting (e.g. Zschocke & Preuschen, 1932, pp.76-79, tab. III-VIII; Presslinger & Eibner, 1993, pp.28-31; Klemm, 2010; 2015; Goldenberg, et al., 2011, pp.74-76). Recent excavations in the Oberhalbstein Valley in eastern Switzerland uncovered the same type of rectangular roasting hearths and two shaft furnaces (Della Casa, Naef & Turck, 2015; see also Turck, in this volume). For his experimental reconstruction of the Bronze Age copper smelting furnaces, Hampl (1976) used the medieval bloomery furnaces as prototypes, thus suggesting that the shafts of the Bronze Age copper smelting furnaces were also free-standing and not built into the slope as archaeological evidence from all Bronze Age copper smelting furnaces in the Eastern Alps showed. As the published report by Hampl and Mayrhofer (1963) as well as the original excavation report[4] suggest that the site was not completely excavated, any evidence of twin furnaces might not have been recorded. Prein III/Cu is a complex multi-phase site and the short excavation campaigns as well as the excavation methods in the 1950s might have been insufficient to recognise and interpret the evidence as expected nowadays. No radiocarbon dates are available for this large and complex site. The site can be dated to the Late Bronze Age (Ha B) on the basis of late Urnfield pottery and a bronze pin, a type in use from the younger Urnfield Period (Ha B) to the early Hallstatt Period (Ha C); no typical Hallstatt C pottery has been found so far.

The only radiocarbon date from this mining district derives from site Prein II/Cu and dates the site to the 10th cent. BC (995 BC-925 BC, calibrated 2σ 95.4%) (Trebsche, 2015, p.44, tab. 2). All settlement pottery found at the Prein sites belongs to the Urnfield Period, mainly to its later phase.

The geologist Robert Mayrhofer (Mayrhofer, 1953; Hampl & Mayrhofer, 1963, p.54) recorded a recent pit for limonite on the western slope of the Fuchsgraben at 900 m a.s.l., and it is doubtful that prehistoric miners would have reached the necessary depth to reach the copper veins. Results of a geoelectrical survey near the sites Prein VII/Cu and Prein III/Cu were interpreted as a mining site; unfortunately, this could not be proved by excavation (Hampl & Fritsch, 1959; Hampl & Mayrhofer, 1963, p.92, fig. 10).

West of the Prein sites, in the Hollersbachgraben, an undated mining site is known. Mayrhofer (Hampl & Mayrhofer, 1963, pp.55-56) mentioned that copper ore from the Hollersbachgraben could have been smelted at the Prein sites. Though macroscopic description and spectral analyses of copper ore samples suggest that copper ore from the ore deposits north of Prein at the southern foot of the Rax mountain range (mining district 2) was used for copper production in Prein (Mayrhofer, 1953, pp.91-95). Further investigations are mandatory because of the distance between the ore deposits in mining district 2 and the smelting sites in mining district 1; water and wood for fuel for roasting and smelting were available in Prein as well as in the region of the Kleinau-Großau sites.

The mining district Kleinau-Großau

The prehistoric sites of the mining district Kleinau-Großau (no. 2) are situated at the southern foot of the Rax mountain range where copper ore was mined within the intensive mining of iron ore in the medieval and modern periods. This modern mining district stretched from Schwarzkogel, Schendlegg/Schendleck, Knappenberg, Kleinau, Hirschwang as far as Trautenberg and Thonhof. Copper ore was still mined in the early 20th cent. AD at Schendlegg. The ore deposits belong to the Greywacke Zone, the base of the Northern Limestone Alps also known as the Northern Calcareous Alps (Hackenberg, 2003, pp.32-37; Heinrich, 2006, p.287, tab. 18). The sites in the mining district Kleinau-Großau are situated at about 840-1030 m a.s.l.; copper slag was found at six sites and a copper ingot was discovered at another site.

Two of the seven sites demonstrate that natural erosion and massive deposits of rock waste as well as medieval and modern mining destroyed or covered older traces of mining, ore beneficiation and smelting. Prehistoric pottery, two animal teeth and three pieces of thin plate slag, a copper droplet, and some copper ore (Hirschwang I/Cu; Haubner, et al., 2015, p.31, figs. 2 and 3) were found 1.62 m below the surface on the site of a badly destroyed medieval iron smelting site and were enclosed in layers of fine quartz as known from ore beneficiation sites (Hampl & Mayrhofer, 1963, p.76). At the second site in Großau a copper ingot was discovered 1-1.8 m below the surface while a pit was being dug for a fishpond in 1967.[5]

Heavy erosion in the area of the Schwarzkogel was also proven by the unsuccessful search for smelting furnaces and roasting hearths at the Großau I/Cu site (Hampl & Mayrhofer, 1963, pp.53-54).

The mining district Höllental-Kaiserbrunn

In the narrow valley of Höllental between the Rax and Schneeberg mountains, north of the Kleinau-Großau mining district, eight sites with prehistoric copper slags were discovered in mining district 3, Höllental-Kaiserbrunn (Kerchler, 1976, p.96; Cech & Walach, 1995). These sites cannot be more exactly dated. The seven sites near the River Schwarza at about 510-530 m a.s.l. were badly destroyed by road works. A small excavation at one site only revealed smaller slag deposits (Kerchler, 1976, p.96). A geophysical survey in 1994 proved atypical anomalies that cannot be successfully interpreted without excavation (Cech & Walach, 1995). The site in the Krummbachgraben is situated at about 560 m a.s.l.

The mining district Payerbach-Grillenberg

Further east, copper ore was mined in the large iron ore mine at Grillenberg (Hackenberg, 2003, pp.25-29, no. 9). A small slag dump was excavated in 1959 at a prehistoric site in mining district 4, Payerbach-Grillenberg. Typical copper slags, though only a few thin plate slags, were found in the slag deposit of 0.2-0.25 m thickness. The search for roasting hearths and furnaces was unsuccessful (Hampl and Mayrhofer, 1963, pp.75-76).

The mining district Prigglitz-Gasteil

The first excavations by Hampl (Hampl & Mayrhofer 1963, pp.56-74) in the mining district Prigglitz-Gasteil (no. 5), north-east of Payerbach, were followed by new research by Trebsche (2013) from 2010-2014. The excavations at the complex site of Prigglitz-Gasteil I/Cu (also called Gasteil-Sandriegel) by Trebsche[6] confirmed and immensely broadened our knowledge of this large and exceptional mining centre. A vast settlement with an extensive production of bone tools, metal working and metallurgical activities of the Late Bronze Age was recorded (Trebsche, 2013; Trebsche & Pucher, 2013). The settlement layers of several phases of the later Urnfield Period, dating to a period from 1063-961 BC to 957-857 BC (phase calibration 68.2 %), describe activities that cover at least one century (Trebsche, 2015, p.53). Metal objects confirm these radiocarbon dating results. The settlement terraces were superimposed by debris from mining and ore beneficiation. Below these layers of the Urnfield settlement deposits, several meters thick remains of ore beneficiation demonstrate that copper ore mining at this mining district has a long tradition. Only when Trebsche and his team fully present their excavation results, will a full assessment of this mining centre be provided.

Mining pits are known but not yet dated. Copper and iron ore deposits are mapped in the Prigglitz area (Hackenberg 2003, p.30). North of the site at Gasteil-Sandriegel, slag sand, a Bronze Age socketed axehead as well as a Neolithic copper axehead were found (Hampl & Mayrhofer, 1963, pp.54-56; Hottwagner, 2000; Lang, 2000).

The mining districts Sieding and Gadenweith

Slag sites were recorded in the 1970s in the mining districts of Sieding (no. 6) and Gadenweith (no. 7): six sites in Sieding, three more sites at Gadenweith, all of them quite possibly of prehistoric date (Kerchler, 1976, pp.92-95; Haider, 1977, p.352; Haider-Berky, 2013, p.113[7]). There has been no archaeological investigation. The Sieding sites were situated at about 440-560 m a.s.l. while the Gadenweith sites were found at 650-770 m a.s.l.

Hampl (Hampl & Mayrhofer, 1963, pp.54-56, 81-82) had already recorded some mining pits of unknown date. Ore deposits at Florianikogel (Bürg/Vöstenhof) and an iron ore mine from the beginning of the 20th century in the Ambachgraben, also called Saubachgraben, are also known (Hackenberg, 2003, pp.23-24, no. 2 and 4; Inventory of Abandoned Mine Sites in Austria, GBA Vienna/Austria, ÖK 50/105).

The mining districts Schrattenbach-Stixenstein and Flatz

The slag site Stixenstein-Siebentannen I/Cu in the mining district of Schrattenbach-Stixenstein (no. 8) was discovered by Ernst Preuschen in 1948 and archaeologically investigated in 1953 (Hampl & Mayrhofer, 1963, pp.77-78). Wolfgang Haider-Berky (2013) recorded mining pits at the Hochberg near Gutenmann and two more slag sites in this district as well as another three slag sites in mining district no. 9 in Flatz. Leopold Neff (1985/86, p.242) recorded another slag site in mining district no. 8. The sites are situated at 600-760 m a.s.l. and are quite possibly prehistoric.

The mining district Hafning-Kulm

In 1969-1971 Puhr (1972) discovered six sites south of the town of Neunkirchen, in the mining district of Hafning-Kulm (no. 10); they were situated at 490-570 m a.s.l. Three of these were partly excavated in cooperation with Hampl (1976, tab. 1). The copper ore deposits are part of the

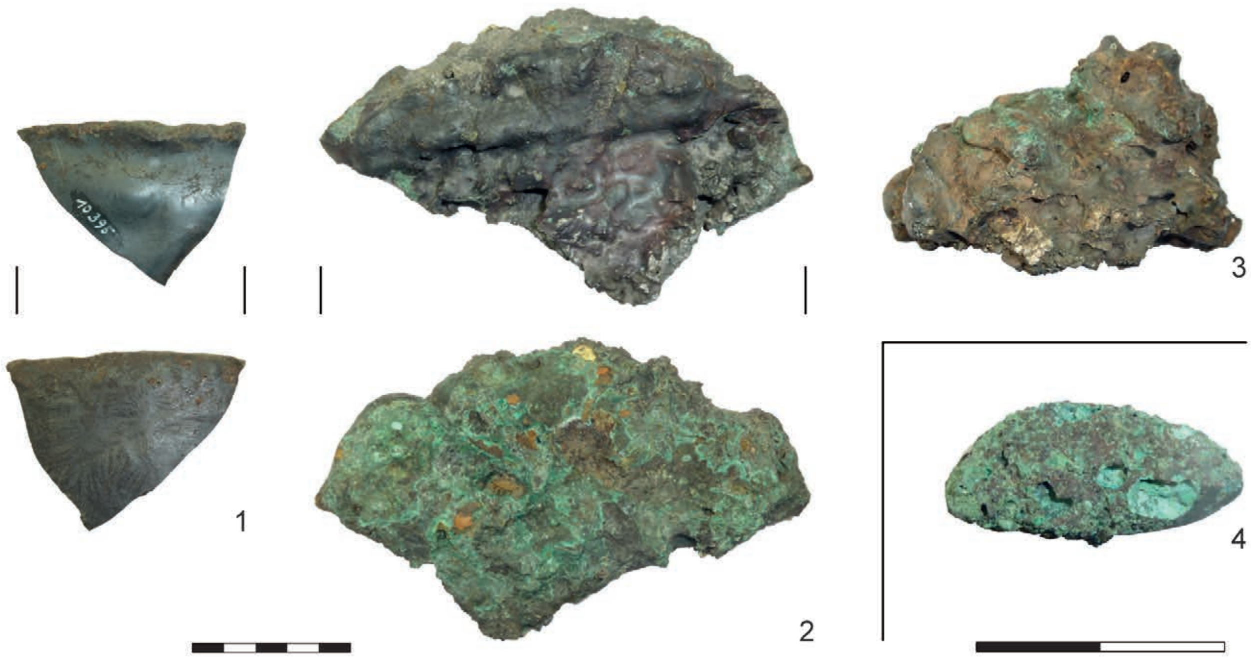

Fig. 3: Typical slag types from prehistoric copper production in Lower Austria (Photos: S. Klemm). 1 – thin plate slag, Hirschwang I/Cu, 2 – fragment of slag cake with rim, Prein VII/Cu, 3 – coarse slag, Payerbach I/Cu, 4 – copper droplet, Hirschwang I/Cu (Landessammlungen Niederösterreich).

crystalline nappes of the Austroalpine Unit unlike all the sites in the mining districts 1-9.

At the sites Hafning I/Cu, Hafning II/Cu and Kulm I/Cu, reoccurring features – small pits with a diameter of 0.15-0.17 and 0.29-0.35 m with canals at their sides – were recorded. While at the site Hafning I/Cu two pits with the same depth and size were found beside each other; a larger and one smaller pit were found at the site Hafning II/Cu. At the site Kulm I/Cu a feature with only one pit was excavated. It was argued that these features were remains of smelting furnaces. If so, no comparable features have been found elsewhere in the region so far. Roasting hearths, typical structures on Bronze Age copper smelting sites in the Eastern Alps, were absent. Both coarse as well as thin plate slag were found, although there were no tuyère fragments (Puhr, 1972).

During excavations in 1973, Kerchler (1976, pp.89-91) ascertained that the sites Hafning III/Cu and IV/Cu were, in fact, part of one large, multi-phase copper smelting site. Its slag dump seemed to have slipped off on the steep slope. At the working platform a small pit, 0.27-0.30 m in diameter and 0.13 m in depth, reddened at the base, was revealed; its function remains unclear. At another large smelting site, Weibnitz I/Cu, a characteristic slag dump, with vegetation absent, 11 m in length and 4.5 m in width with a slag deposit of 0.20-0.30 m thickness was investigated (Kerchler, 1976, pp.91-92).

Prehistoric pottery from the Late Bronze Age, the Urnfield period, besides the typical slags already mentioned, was found at all sites in this mining district. Settlement pottery at Hafning II/Cu dates this site to the latest phase of the Urnfield Period (Ha B3) (Puhr, 1972, p.197, fig. 8)[8]. The described remaining structures, pits with one or two canals, are reminiscent of features found at the medieval copper smelting sites in the Harz region, Germany (Asmus, 2012, pp.124-142, fig. 6.10). There are no historical documents on copper mining and smelting in the area of the mining district of Hafning-Kulm. Only future research will be able to reveal more evidence on the technology as well as the chronology and the dating of the described features.

Potential mining districts

Further indications of prehistoric mining are mining pits discovered in the 1930s, the 1970s and later in areas where no historical information on mining exists.

Mining pits of unknown date were discovered by Mühlhofer (1930; see also Mühlhofer & Pittioni, 1934) in the Hohe Wand region at Rothengrub and on the northern slope of the Kienberg, near Netting, in the early 1930s. Haider-Berky (2013, pp.106-108, fig. 11, 14, 15) mentioned more mining pits of unknown date at Pfenningbach-Grünbacher Sattel and at Sonnleiten-Neusiedl am Walde. These sites are situated to the north of mining district 8; no smelting sites were recorded in their vicinity.

Other mining pits of unknown date were identified near Gloggnitz; prehistoric mining activities are suggested (Hackenberg, 2003; Haider-Berky, 2013). Just north of Gloggnitz, and east and south of mining district 5, Prigglitz-Gasteil, there are mining pits of unknown date at Kohlberg near Pottschach and at Weißjacklberg. Copper ores such as chalcopyrite and fahlore deposits are known (Haider, 1975a; 1975b; Hackenberg, 2003, pp.29-30, no. 12, 13; 32, no. 16-18; Haider-Berky, 2013, pp.107-108, fig. 11-17). These copper ores were also mined in the Stuppachgraben on the north-eastern side of the Silbersberg from the 17th-20th cent. AD (Hackenberg, 2003, pp.30-32, no. 15).

West of Gloggnitz between the rivers Schwarza and Auebach, mining pits of unknown date were found in an area where copper ore deposits within the orthoriebeckite gneiss belonging to the Greywacke Zone are known. A hoard of seven small copper ingots of unknown date was discovered at a distance of only 50 m from these mining pits (Lang, 2001; Hackenberg, 2003, p.54, no. 70, fig. 65)[9]. In this area copper mining from the 16th-20th cent. AD is known at Gloggnitz, Pettenbach and Eichberg, though mainly magnesite was mined there (Hackenberg, 2003, pp.53-55, no. 69-71).

Archaeometallurgical analyses

Coarse copper slag, thin plate slag as well as some thick plate slag and copper droplets were found at slag dumps and smelting sites (Fig. 3). The samples taken at the excavations such as Prein, Payerbach, Hirschwang or other sites are typical for Bronze Age copper smelting sites in the Eastern Alps; chalcopyrite was used for smelting (Mayrhofer, 1953; e.g., Kraus, et al., 2015). Recent archaeometallurgical analyses of copper slags and a copper droplet from the Lower Austrian sites confirm that ore containing chalcopyrite was used for copper production at these smelting sites (Hackenberg, 2003; Haubner, et al. 2015, pp.28-32, figs. 2-4; Haubner, Strobl & Klemm, 2017). Large pieces of quartz are regularly found in the coarse slag while the thin plate slag is macroscopically more homogenous.

On the other hand, thin plate slags with maximal contents of about 0.5 wt.% tin were found during the excavation of the settlement at Prigglitz-Sandriegel. Additionally, corroded bronze droplets from this settlement contained tin; a content of 9 wt.% and 35 wt.% was measured. The thin plate slags and the bronze droplets from the settlement can be related to the production of bronze (Haubner, et al. 2015, p.32, fig. 1, fig. 2, g-l, fig. 3, f-h; Haubner, Strobl & Trebsche, 2017).

Further archaeological evidence: settlements, single findings, hoards

Hampl & Mayrhofer (1963, pp.82-85, fig. 24a-e) suggested in their study on prehistoric copper and medieval iron mining that the process of settlement formation in this mountainous region of south-eastern Lower Austria is firmly connected with the search for minerals, especially copper ore. Hampl interpreted single findings of polished stone hammers and axeheads as well as bronze axeheads as tools used for ore prospection since the Late Neolithic. Also, Late Neolithic findings from settlements and new findings of copper axeheads of the Altheim type and other single findings of bronze tools discovered in woodlands since the publication of Hampl and Mayrhofer (1963, pp.82-85, fig. 24a-e) underline this theory (e.g., Daim & Ruttkay, 1981; Neff, 1985/86; Haider, 1990; Klemm 1992, vol. 1, pp.274-276; Lauermann, 1998; Hottwagner, 2000; Lang, 2000).

The importance of large settlements as regards the organisation of mining and smelting of copper ore as well as the production of bronze in Late Bronze Age (Ha B) settlements is indisputable. The findings at the mining settlement at Gasteil-Sandriegel confirms this. Moreover, archaeological evidence, such as moulds for the casting of bronze objects and thin plate slags, presumably from the production of bronze, is known from other large Late Bronze Age/Early Iron Age settlements in the region, for example 'Am Gelände' near Grünbach, Kienberg, and Malleiten near Bad Fischau (Mühlhofer, 1952; Kaus, 1992; Klemm, 1992, vol. 1, p.265). The well-known hoard from Mahrersdorf, including a copper ingot and a pickaxe, and other findings of copper ingots in the region are further indications of mining and copper production in the region (Hampl, 1976, p.62; Lang, 2001; Haider-Berky, 2004, p.9; Lauermann & Rammer, 2013, pp.125, 128-133).

Conclusions

A division of 10 prehistoric copper mining districts in Lower Austria has been discussed based on the physiographical position of the archaeological evidence as well as the evidence of copper ore deposits. Evidence of undated mining pits situated near prehistoric settlements as well as archaeological findings close to copper ore deposits suggest further small mining districts in the region. So far, only the Late Bronze Age (Ha B) copper production can be assumed on the basis of copper smelting sites, slag dumps or singular slag findings and the large mining settlement at Gasteil-Sandriegel in the region.

At Gasteil-Sandriegel, the huge deposits of material from mining and ore beneficiation below the Late Bronze Age settlement layers suggest extensive mining over a long period. The actual research carried out by Trebsche and his team can be seen as the first major step to investigate this area of prehistoric copper production in the Eastern Alps since the research by Hampl & Mayrhofer in the 1950s.

A priority of future research should be the investigations of undated mining sites, for example, in one of the smaller mining districts or in one of the new potential mining districts. Future research should also aim at dating as many sites as possible with all available methods, especially as, so far, only Late Bronze Age sites have been identified. Also, new excavations of small smelting sites are necessary to achieve a clear picture of the construction of roasting hearths and smelting furnaces in this area of the Eastern Alps. New investigations in mining district 10, Hafning-Kulm, seem equally important, as the type of furnaces described is unusual for the Late Bronze Age.

Notes

1 An extensive bibliography and a comprehensive summary on the geological background, the copper ore deposits and the historic mining in the area: Hackenberg, 2003.

2 The site names follow the system of nomination by Franz Hampl.

3 For more information on the terminology of the type of sites see Klemm, 2003, pp.19-23, 28-36: Slag sites are sites with singular slags with no further evidence of a smelting site (for example, Hirschwang I/Cu). Those sites where slag dumps were identified but without further evidence of smelting (roasting hearths, furnaces) in close vicinity are referred to as slag dumps (for example, Prein II/Cu). Smelting sites are identified either by excavation or by geophysical survey showing the typical features of smelting sites (for example, Prein III/Cu).

4 MAMUZ, Schloss Asparn an der Zaya, archive, file Prein 1952 and Prein 1953. The author thanks Dr. Ernst Lauermann for the right of access to study the files.

5 MAMUZ, Schloss Asparn an der Zaya, archive, file Groß-Au.

6 Research project financed by the Austrian Science Fund FWF, P 30289.

7 The sites Thann 1-3 (Haider-Berky, 2013, p.113) are identical with the sites Sieding I/Cu–III/Cu listed by F. Hampl and H. Kerchler in Hampl, 1976, tab. 1 and Kerchler, 1976, p.95.

8 The pottery sherd shown in Puhr, 1972, fig. 8, was erroneously assigned to Hafning I/Cu in the publication (Inv.-No. 10196, Städtisches Museum Neunkirchen).

9 In Hackenberg, 2003, p.53 described as slag. See also Lang, 2001.

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Author

Susanne Klemm, Lammgasse 3/12, 1080 Vienna, Austria

Correspondence and material requests should be addressed to: susanne.klemm@gmx.at

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Gerald Hiebel, Gert Goldenberg, Caroline Grutsch, Klaus Hanke, Markus Staudt

A methodology to integrate information in prehistoric mining archaeology research

ABSTRACT: *In prehistoric mining archaeology research, different scientific areas are working together to solve fundamental research questions related to the production and use of metals in prehistoric times. They produce information according to the methodologies of their discipline and in the specific formats that best document their observations and research. These formats may be very different as the documentation of archaeological or geological prospection, archaeological excavations, surveying, mineralogical, geochemical and metallurgical analysis, experimental archaeology and ethnoarchaeology vary significantly even within one discipline. In this paper we want to present a methodology how to integrate information of the above mentioned disciplines in order to answer specific questions in prehistoric mining archaeology research. The methodology is based on building a conceptual model that is able to represent the information of the participating disciplines and to inform the archaeologist on observations, physical structures, geochemical ore/artefact signatures and interpretations related to prehistoric mining, ore processing and extractive metallurgy with all the employed technologies. The CIDOC CRM ontology is used as conceptual background to structure the data. After the main categories of the conceptual model have been defined they need to be specialised in a hierarchical thesaurus. The transformation and mapping of existing data to the conceptual model is realized with semantic web technologies. The integration of the information and the subsequent provision in adequate tools can help researchers of prehistoric mining archaeology significantly to answer their research questions.*

KEYWORDS: INFORMATION INTEGRATION, MINING ARCHAEOLOGY, SEMANTIC TECHNOLOGIES, CIDOC CRM, GEOINFORMATION

Introduction – Why is information integration necessary?

The need for information integration arises from the quest to solve the fundamental research questions related to prehistoric mining, ore processing and extractive metallurgy with all the employed technologies. As different scientific disciplines work on these questions the results they produce correspond to their practices and standards, which may be very different from each other. Looking at prospections, archaeological excavations, surveying, mineralogical, geochemical and metallurgical analysis, experimental archaeology and ethnoarchaeology it is obvious that they use different documentation methodologies. But they still want to answer specific research questions:

- Where are physical structures relevant for prehistoric mining/metallurgy?
- Which information do we have about physical things (structures/objects/samples) that are relevant for prehistoric mining/metallurgy research?
- To which technologies do these physical things relate?
- How are physical structures/objects/samples dated?
- What are the geochemical signatures of samples and from what objects or structures have they been taken?
- Which observations/archaeometric analysis/interpretations have been conducted on physical things?
- What can we learn from experimental Archaeology and Ethnoarchaeology about technology and the production process of objects/structures related to metallurgy?

The integration of information and its subsequent provision in adequate tools can certainly help researchers of prehistoric mining archaeology significantly to answer these questions.

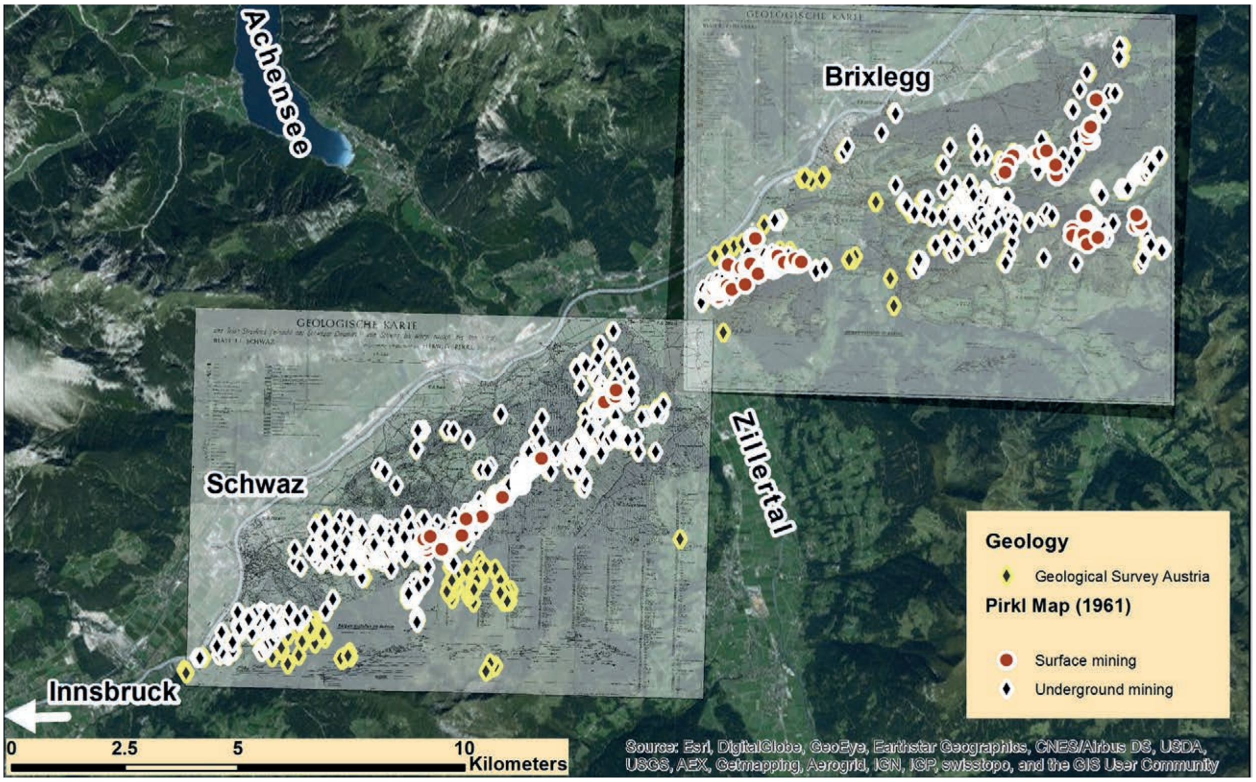

Fig. 1: Mining structures identified by Pirkl and the Geological Survey Austria (source: GBA, 2014).

The first step is to identify the information sources that hold the knowledge which is relevant to these questions.

What information sources hold relevant knowledge?

Scientific research is often organized in projects or specific structures. One of them related to prehistoric mining archaeology is the research centre RC HiMAT of the University of Innsbruck (The History of Mining Activities in the Tyrol and adjacent areas – impact on environment and human societies - www.uibk.ac.at/himat/) that investigates the mining history of the Eastern Alps from Prehistory to Modern Times. As examples for information sources available within the interdisciplinary work of the research centre we choose the area of Schwaz/Brixlegg in North Tyrol, Austria, where the localization, identification and interpretation of mining structures are targeted. Geological prospections are a fundamental information source about structures originating from mining activities. Herwig Pirkl (1961) investigated the Schwaz/Brixlegg mining area in a detail that has not been repeated since. The result was a publication describing the geologic and surface structures of the area. It contains three geological maps in the scale 1:10,000. Two of these maps have been digitized in the course of the works realized in the RC HiMAT. Structures identified by Pirkl as underground mining and surface mining have been registered together with their names and coordinates. In addition, information on mining structures provided by the Geological Survey Austria (GBA, 2014) has been integrated (Fig. 1).

Another source of information for the localization of mining structures is the digital high resolution elevation model (DEM) of the province of Tyrol. The Unit for Surveying and Geoinformation of the research centre examined the DEM for concave and convex surface structures that are in proximity of the structures identified by Pirkl (Fig. 2).

HiMAT's participation in the international research project "Prehistoric copper production in the eastern and central Alps – technical, social and economic dynamics in space and time" (financed by the Austrian Science Fund FWF, the German Research Foundation DFG and the Swiss National Science Foundation SNSF, 2015 - 2018) contributed significantly to the knowledge of archaeological sites related to prehistoric mining activities through archaeological prospections and excavations. In figure 3 these activities are illustrated together with find spots that have been extracted from archaeological literature. A detailed map of the area around a prehistoric mining structure called "Bauernzeche" shows the potential of integrating these sources together with a DEM vizualization (Fig.4). In the map we see the landscape relief and structures created through mining activities which were first observed by Pirkl and documented in geological maps. Decades later these structures were prospected

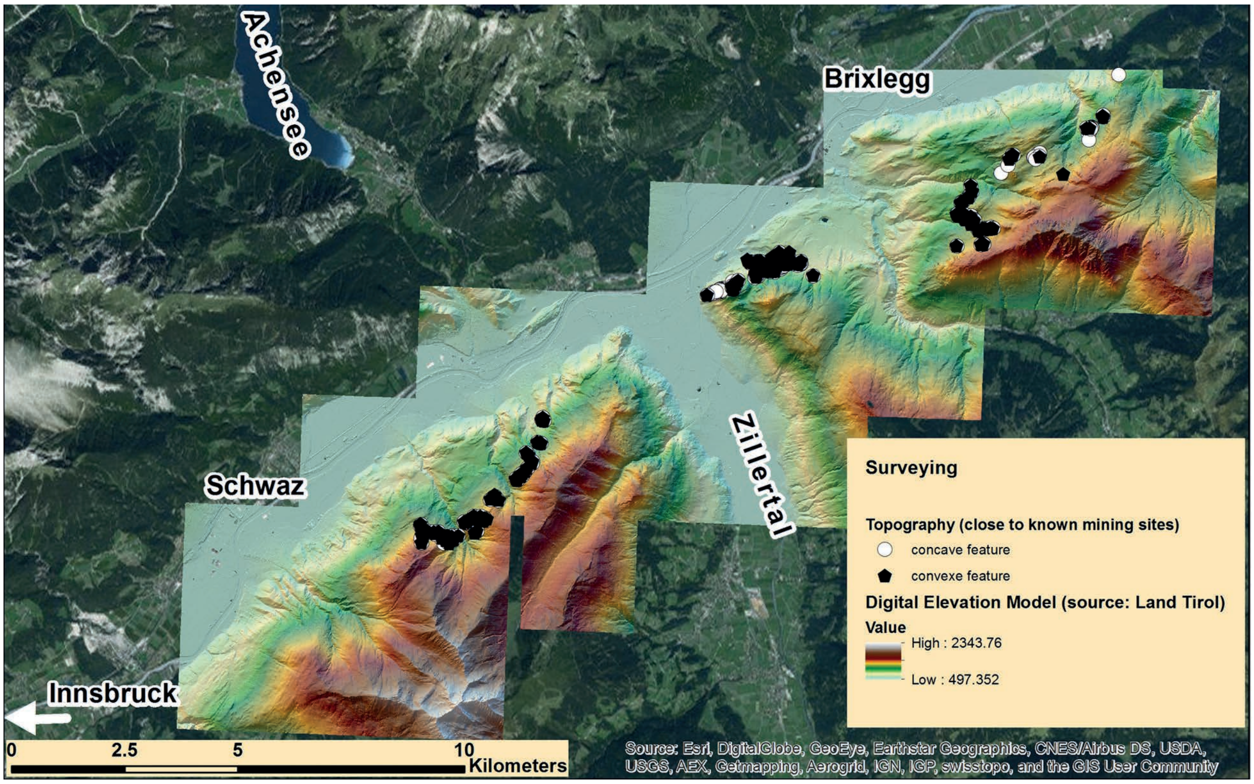

Fig 2: Surface structures identified in the high resolution elevation model of the province of Tyrol (source: Land Tirol 2009).

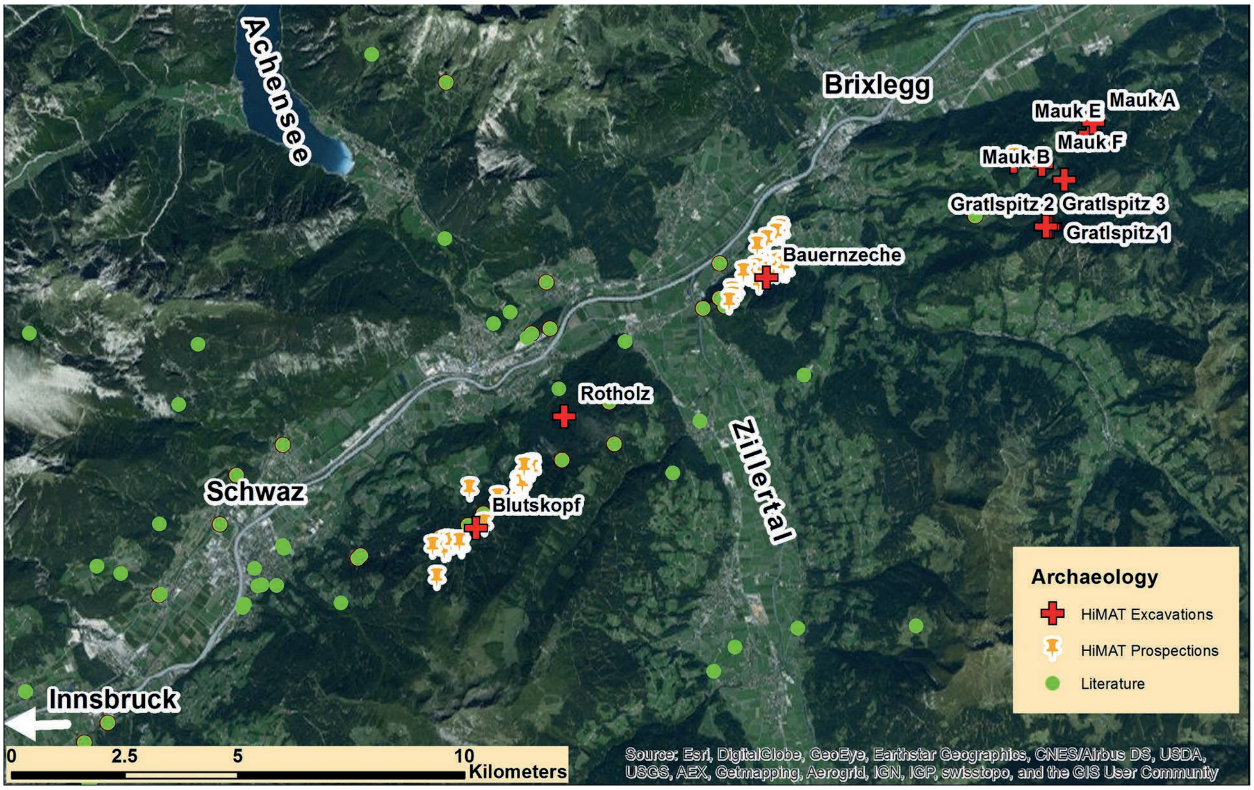

Fig. 3: RC HiMAT excavation and survey activities and archaeological sites extracted from archaeological literature (source: RC HiMAT, ESRI).

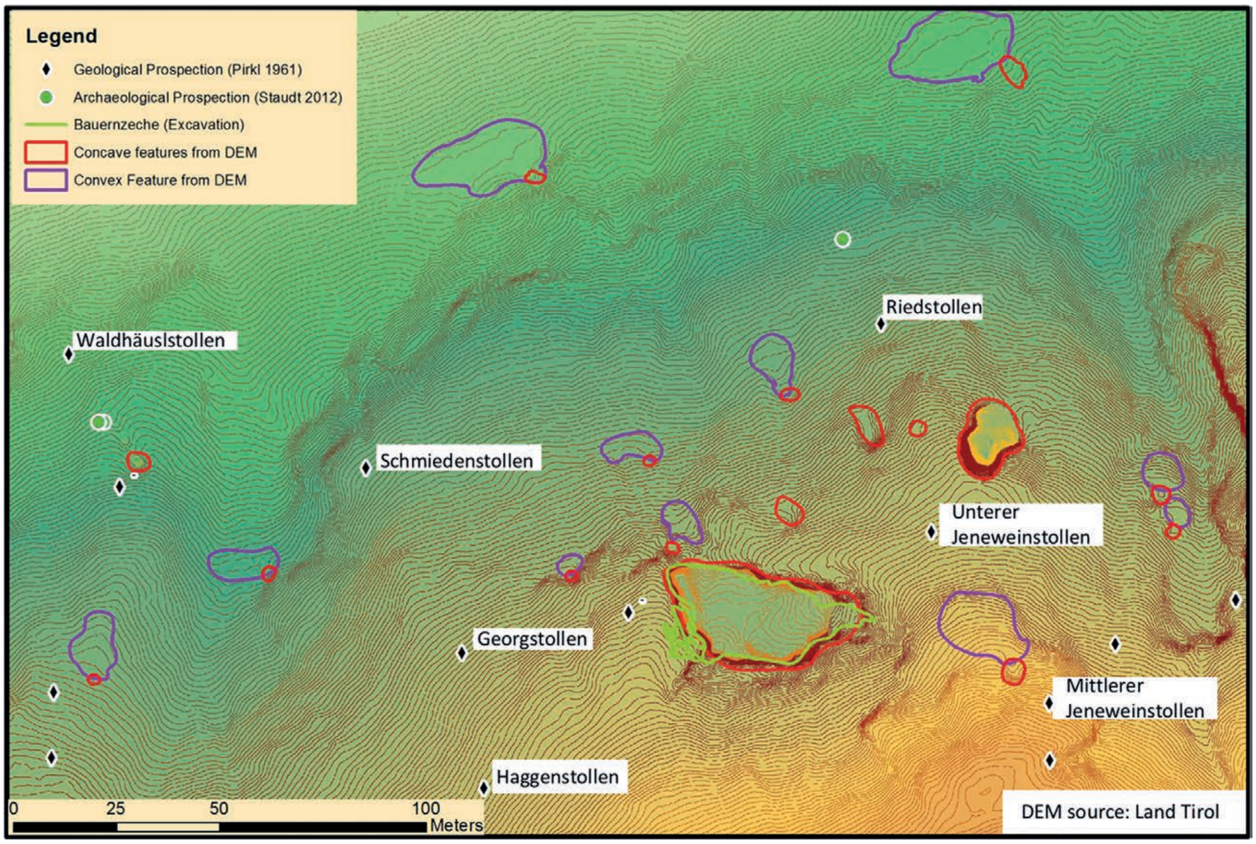

Fig. 4: Information sources that indicate physical structures related to mining activities.

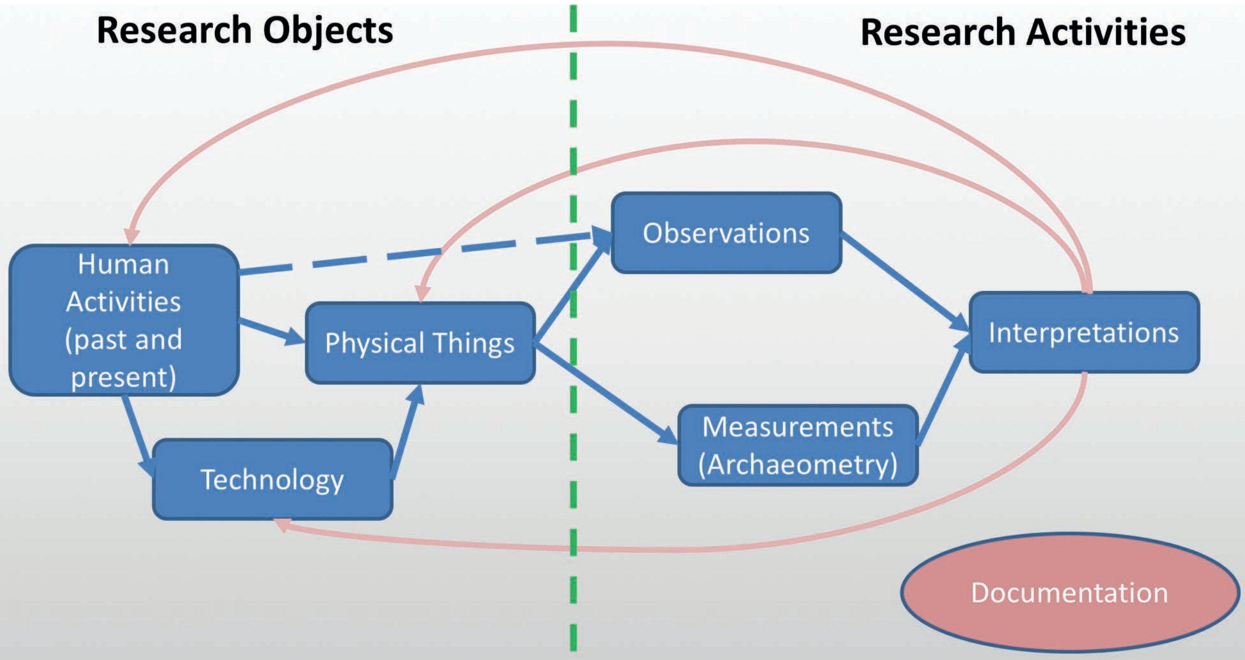

Fig. 5: Research objects and research activities in a network model.

again by RC HiMAT archaeologists and documented in field survey records. Then the high resolution digital elevation model was analysed and relevant physical structures in the vicinity of the observations made by Pirkl and the archaeologists were marked (Fig. 4). For the data sources displayed in figure 4 observations and analysis of these physical mining structures like pits, heaps, beneficiation and smelting sites are documented. The same physical structure may have been observed or analysed several times by different humans or different

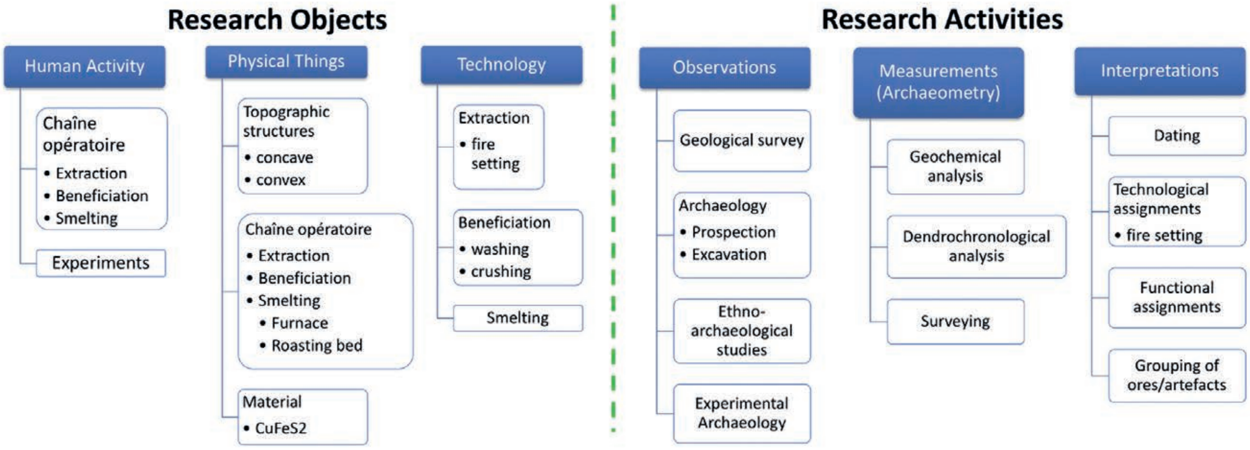

Fig. 6: Refinement of research objects and research activities in a thesaurus.

scientific methodologies. In addition to the observations there are interpretations of the physical structures as to their functionality and their dating based on observations and analysis. As shown in the illustration Geoinformation systems use layers to represent information. When used in archaeology physical structures, observations, analysis and interpretations are either mixed in one layer or there exist several layers for different information sources. On the represented area we find recent and historic observations of mining structures and there has been an excavation in the so called “Bauernzeche” where prehistoric mining activities using the fire setting technique have been verified. To integrate the information of observations, analysis and excavations together with the interpretations a network model is necessary that goes beyond the layer structure used in Geoinformation systems. This model should help archaeologists to make use of all the information available in one area and build a network that can be explored for further research.

Creating this network model the other information sources related to archaeometrical and archaeometallurgical analysis, experimental archaeology and ethnoarchaeology have to be taken into account.

How to integrate on a theoretical level? – The conceptual model

To integrate heterogeneous information sources a conceptual model that has the ability to represent the concepts coming from different domains and in particular from different methodologies and documentation practices is a necessity. The CIDOC CRM ontology (Le Boeuf et al., 2018) is an ISO standard in Cultural Heritage Documentation and an event centric data model that fulfills these requirements. Past mining activities and contemporary research activities (which are subclasses of events) are the essential nodes in the model that relate research objects with research activities as displayed in figure 5. The documentation of the research activities are the information sources shown in the previous chapter.

Extensions of the CIDOC CRM (2016) were used to model observations (CRMsci), interpretations (CRMinf), spatial information (CRMgeo) and digital provenance (CRMdig). The classes of the model had to be refined with a thesaurus (Fig. 6) in order to represent the detailed information of the available documentation and to answer research questions relevant for the domain. The integration of vocabularies originating from different sources is a serious challenge (Doerr, 2006). Within the DARIAH Infrastructure (www.dariah.eu) an approach was developed to integrate terms within a backbone thesaurus and thus create the ability to query upper levels without the need to reach consensus on lower level terms which is often an almost impossible task to accomplish (Dariah EU, 2016).

Figure 7 shows how to apply the model to the past human activity of ore extraction through fire setting. This mining activity with the specific technology created the physical structure of mine “Mauk E”. It was excavated and dendrochronological measurements have been conducted on wood samples, as well as a 3D documentation of the mine and the surrounding terrain took place. The interpretation from observations and measurements state that ore extraction took place between 720 to 707 BC and that the fire setting technology was used.

How to integrate on a practical level? – The implementation

The available information has to be converted in a structured format, either being a tabular format, a relational database or an XML structure. The terms used in the existing documentation have to be aligned to the thesaurus to obtain data that can be mapped to the classes of the ontology using the specialisations provided by the thesaurus. Karma (ISI, 2016), a tool of the semantic web community was used to map the information sources to

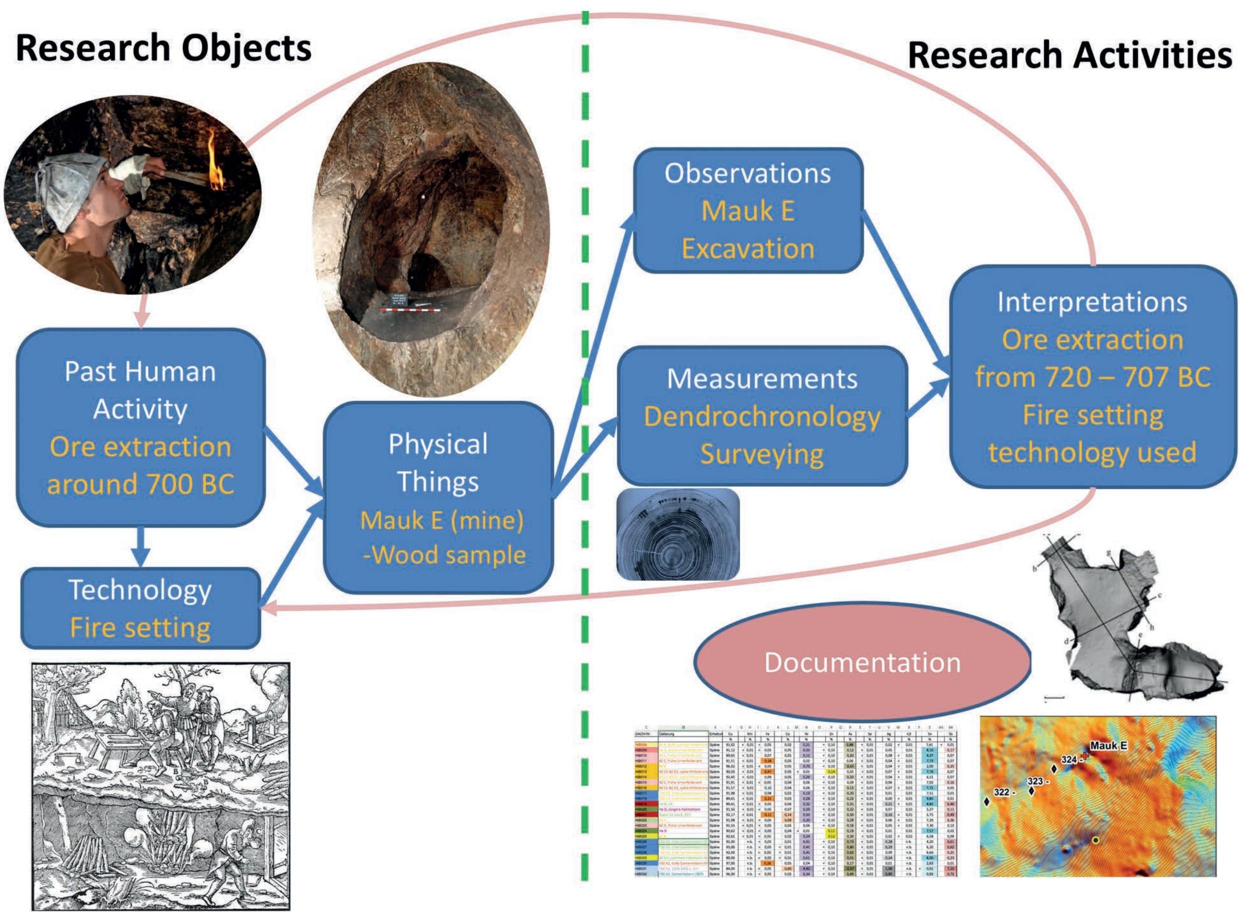

Fig. 7: Example of the modelling for the mine "Mauk E".

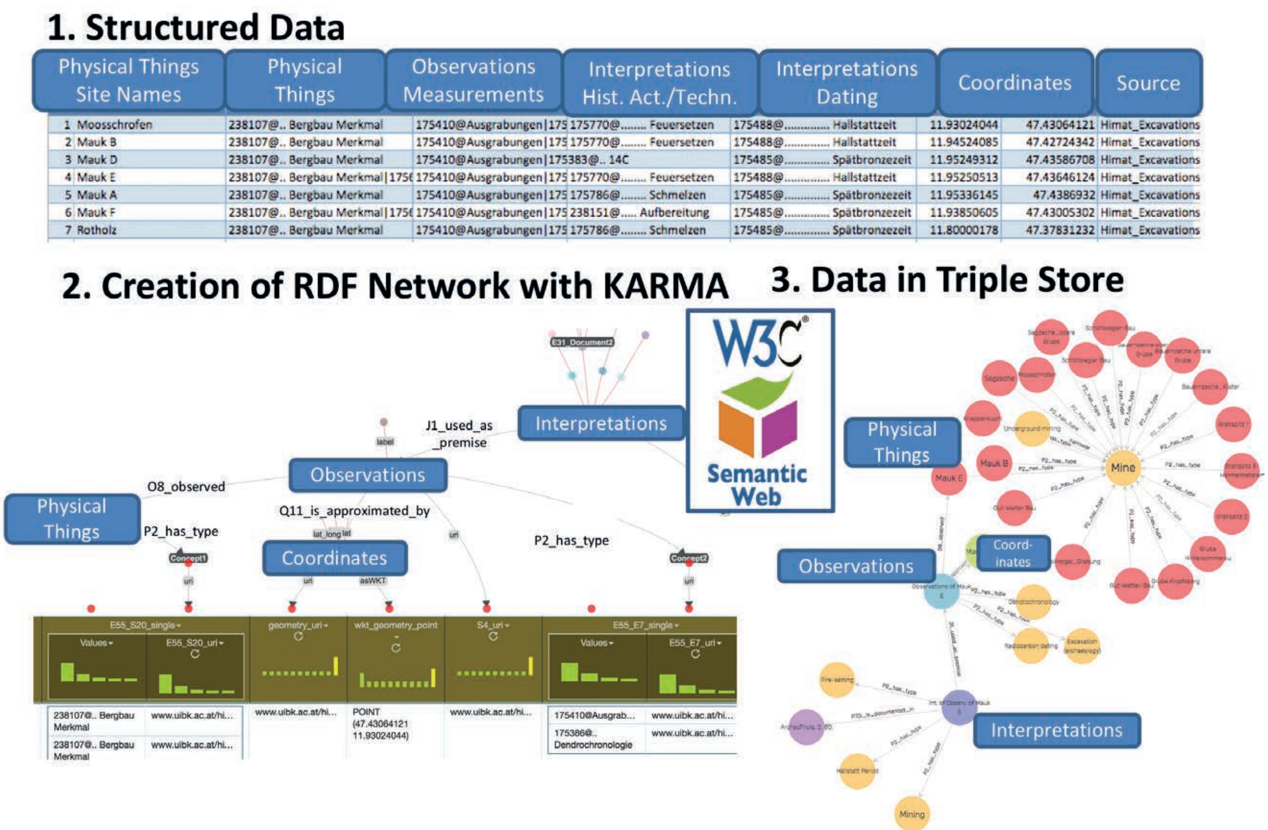

Fig. 8: Using Karma to map structured data to the formal definitions of the CIDOC CRM.

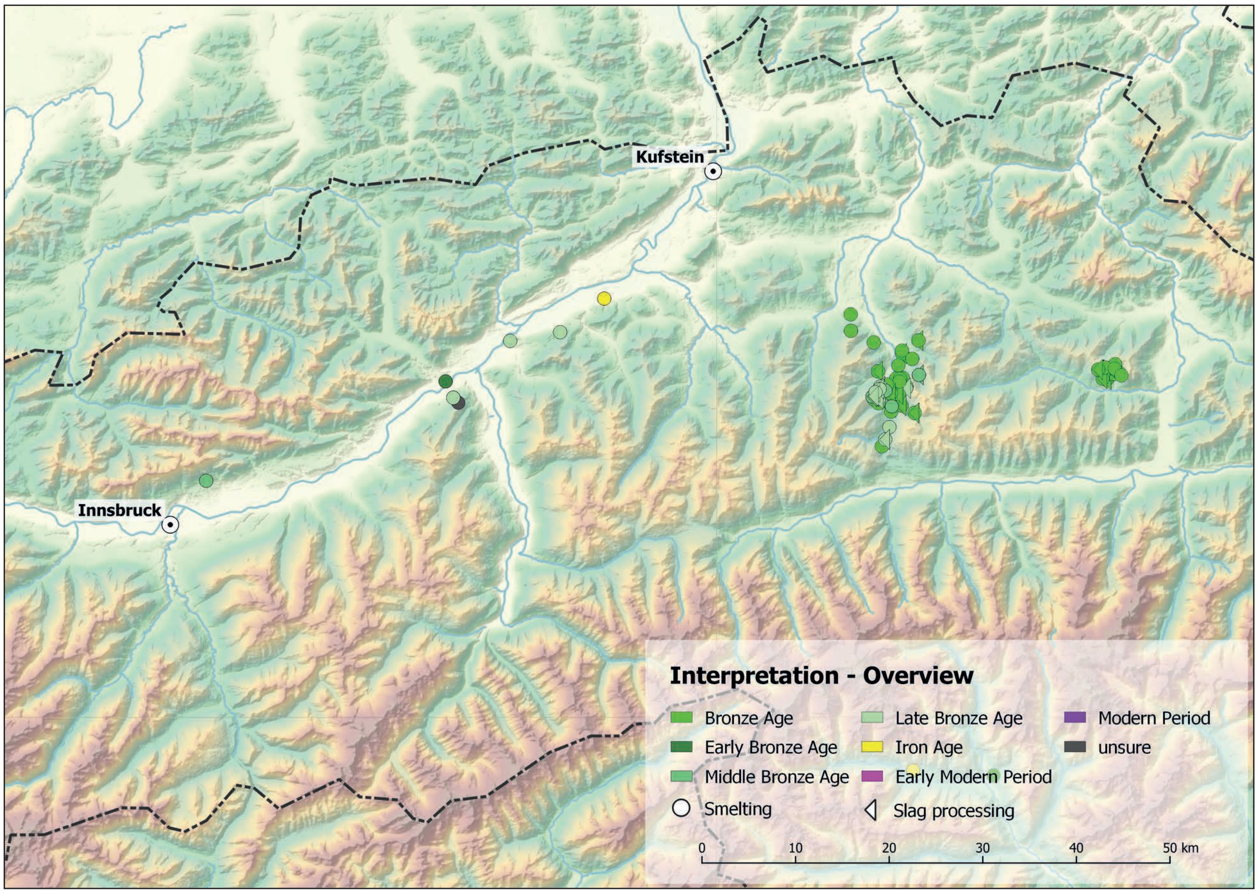

Fig. 9: Map of known archaeological sites in the eastern part of Northern Tyrol and Salzburg with interpretations of smelting and/or slag processing.

the data model. Figure 8 shows how the original data of the documentation, enriched with thesaurus terms is first structured in a tabular format. In a second step the tabular data is mapped to the formal definitions of the CIDOC CRM ontology with Karma. It can be exported in RDF (Resource Description Framework), a data format able to relate logical statements within a network (W3C, 2014). The thesaurus was created with the Karma tool as well and represented in SKOS (Simple Knowledge Organization System), a data model of the semantic web community for sharing and linking knowledge organization systems, such as thesauri, taxonomies, classification schemes and subject heading systems (W3C, 2009). The product is a knowledge graph representing the information of the structured data with the concepts of the CIDOC CRM and the terms of the thesaurus.

After mapping the different information sources and the thesaurus to the common data model the created RDF structure is ingested in a triple store, which is a database to store RDF data. In the triple store the linking of the resources (single information source elements like a specific underground mine or a concept like the Early Bronze Age) takes place performing the actual integration. Resources are either linked on a class level (because they belong to the same CIDOC CRM class, e.g. Observation), on the SKOS concept level (because the same thesaurus term was attributed to them, e.g. “Early Bronze Age”) or on an individual level (because they describe the same material structure object or observation, e.g. “Barbarastollen”). Linking on an individual level is also known as coreference or entity matching and may involve additional processes to assess the identity of individuals if no common identifier is available in the different data sources, which is often not the case.

Information provision

The integration of the information and the subsequent provision in adequate tools can help researchers of prehistoric mining archaeology significantly to answer their research questions.

The RDF network of the triple store can be queried using the SPARQL (W3C, 2013) query language. To show the potential of the integration one of the research questions concerning the location and dating of archaeological sites in the eastern part of Northern Tyrol with interpretations of smelting and/or slag processing is illustrated in a map (Fig. 9). Similar maps can be produced showing the physical structures or observations/measurements that lead to these interpretations. To create the map the results of the query were loaded into a Geoinformation system.

Conclusion and outlook

An approach to integrate information related to the field of prehistoric mining archaeology coming from various sources was developed through a common data model and using tools and specifications of the semantic web community to perform the actual integration. With a specific information provision example it was shown that the integration process works and that the triple store can be used to answer specific research questions.

In the current implementation several data sources from geology, surveying and archaeology in the area of Northern Tyrol are integrated. Further research will apply the methodology to sources from geochemical analysis of ore deposits and prehistoric metal artefacts, from ethnoarchaeology and experimental archaeology. The area of investigation will be enhanced to other alpine areas with prehistoric mining research specialized in copper mining. When the documentation of other research groups is targeted the usability of the methodology will be tested further.

Acknowledgements

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Authors

Gerald Hiebel – Unit for Surveying and Geoinformation, University of Innsbruck
Gert Goldenberg – Department of Archaeologies, University of Innsbruck
Caroline Grutsch – Department of Archaeologies, University of Innsbruck
Klaus Hanke – Unit for Surveying and Geoinformation, University of Innsbruck
Markus Staudt – Department of Archaeologies, University of Innsbruck

Correspondence and material requests should be addressed to: gerald.hiebel@uibk.ac.at

Prehistoric mines and their ores


The Mine „Bauernzeche“ of the mining district of Schwaz-Brixlegg, photo: P. Thomas

Der Anschnitt, Beih. 42, S. 67 – 86, 2019

Bernard Moulin, Eric Thirault, Joël Vital

Early Bronze Age copper extraction(s) in the Grandes Rousses Massif (Isère and Savoy departments, France)

ABSTRACT: *Field work between 2007 and 2012 led to the discovery and investigation of a large-scale Early Bronze Age mining field at the Grandes Rousses Massif (Dauphiné and Savoy parts). Mining archaeological and geological work resulted in a detailed description of the ore-geology that included a description of the structure and the composition of the mostly hydrothermal veins. Two major vein systems coexist: mesothermal sulfurised mineralisations of the "BPGC" type (= including sphalerite – i.e. blende in french – pyrite, galena, chalcopyrite), with supergene mineralisations (malachite, azurite, iron hydroxides) in the oxidation caps, and Alpine-type fissure mineralisations. Several small test-excavations allowed sampling of charcoal for radiocarbon dating and enabled also sampling for an ongoing palynological investigation. Already the old datings of the workings came as a surprise and ascertained the chronological span between the beginning of the 2nd millenium and the 17th century BCE. Fire-setting is attested as the main exploitation mode of the mining field. Fire-setting is used for test-excavations on the surface of the veins, and for digging the hard rocks (shafts, trenches, galleries). The article presents the current state of knowledge and concludes with the necessary further steps of investigation at this Bronze Age mining field.*

KEYWORDS: BRONZE AGE MINING, EARLY BRONZE AGE, ORE GEOLOGY, BPGC ORE TYPE, SULFURIZED MINERALISATION, FIRE-SETTING

Introduction

The survey, carried out in the Grandes Rousses Massif by a team directed by M.-C. Bailly-Maître with the aim of documenting ancient mines around the medieval site of Brandes, led to the discovery of the large-scale exploitation of copper ore at high altitude. Ad hoc trial trenches dug in the mine dumps, followed by radiocarbon measurements carried out on charcoals, provided an additional surprise: the dating to the Early Bronze Age (Bailly-Maître & Gonon, 2008). Subsequently, six campaigns of surface prospecting and palynological sampling took place between 2007 and 2012 with the aim of documenting the whole extraction field and of identifying remains related to ore processing (Moulin et al., 2012). In this article we briefly assess the geological and mineralogical setting of the site and the extraction features that were identified. The above-mentioned publications include a detailed presentation of the history of the research, of the workings that were identified and of the economic and social issues related to the Alpine area at the beginning of the Bronze Age.

The Grandes Rousses Massif, located in the heart of the internal French Western Alps (Fig. 1), forms a long north-south-trending ridge spanning over 17 km astride the departments of Savoy and Isère (Fig. 2). This high massif dominates the Bourg d'Oisans plain and the Romanche valley in the south, the Arves valley in the north and the Eau d'Olle valley in the west. The summit of the range culminates at 3,464 m at Pic de l'Étendard, which is ice-covered and clearly separates the two slopes.

The areas exploited during the Bronze Age are located between 2,410 and 2,650 m on a large apron planed by glaciers which reaches down to the Croix de Fer pass in the north (Savoy department) and between 2,200 and 2,700 m on the central bench terrace in the west (Isère department) sloping northwards from the Dôme des Petites Rousses up to the Couard pass. It is no exaggeration to say that the climatic conditions prevailing during the periods of ancient exploitation were mountainous: high snowfall and even freeze-up depending on the altitude, rugged slopes and rock faces, etc. Nonetheless it is possible to reach the exploited sectors in many places from the south, the west and the north.

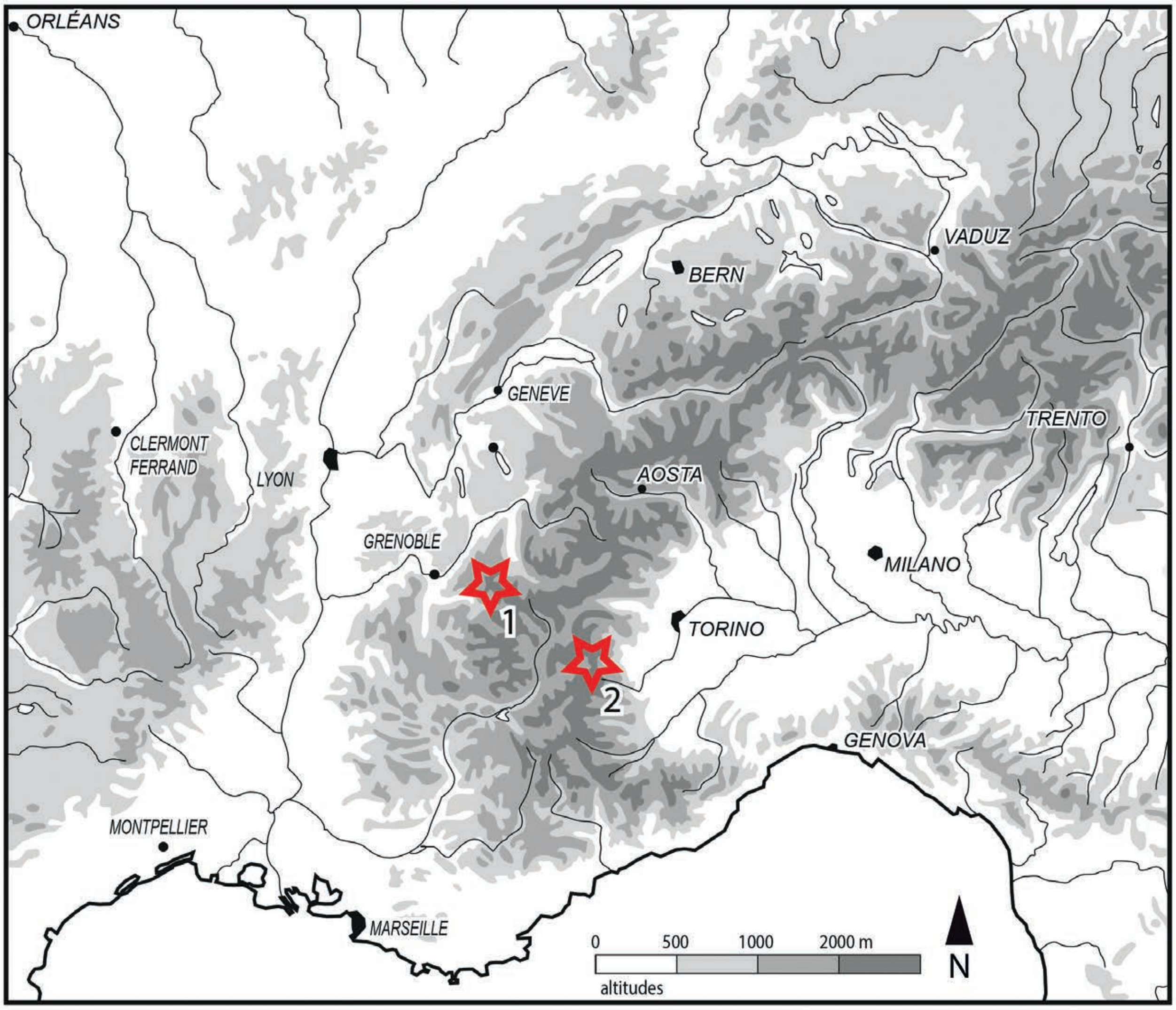

Fig. 1: Location of the Grandes Rousses Massif (1) and the sector of Saint-Véran/Molines (2) where the mines exploited during the Early Bronze Age were identified.

However, it is impossible to ensure efficient control of all these accesses.

Geological setting and mineralogical composition of the veins

Prior to any technological study of the mining activity, it is important to define the type of working, which, by definition, was completely or partially destroyed. It was therefore necessary in the field to characterise the remaining vein structures, to define the nature and the distribution of the ores and to characterise the gangues. This programme was carried out by one of the authors (BM). Each point of mineralization has been sampled (sulphides, supergene mineralisations, gangue, minerals of alpine-type fissures) during the survey. Characterisation of minerals of each point was made with stereomicroscope for the mean minerals (chalcopyrite, pyrite, galena, sphalerite, tetrahedrite, malachite, azurite) by optical and physical characters: hardness, colour, streak, cleavage, etc. (Fischesser, 1977).

The local geological setting

The Grandes Rousses Massif belongs to the external crystalline Western Alps. This massif hosts magmatic and crystallophyllian formations (granites, gneiss, micaschistes, etc.) predating the Carboniferous. The formations of the crystalline basement and the pinched synclinal fold of Le Houiller des Grandes Rousses are disconformably overlaid by a not very thick Triassic sedimentary cover (Barbier et al., 1976; Bartéfy et al., 1972; 1977; 2000). In the surroundings of the massif the Jurassic sedimentary cover is heavily expanded (half-graben of Ferrand in the east and half-graben of Bourg-d'Oisans

Fig. 2: View from above of the central sector of the Prehistoric workings in the Isère department (Plan des Cavales and La Jasse). Photograph taken in August 2008 in a south-western direction. In the background the Romanche valley.

– Ornon – Col du Sabot in the west; Fig. 3). In structural terms two aspects can be highlighted: the significance of large north-south-trending longitudinal faults which transformed the pre-Triassic peneplain into a series of impressing terraces from the east to the west and the presence of up warding of the centre of the massif along its north-south axis, culminating at the height of Pic de l'Étendard (3,464 m).

Structural geology and vein systems

The relationship between brittle tectonics and vein mineralisation is an established fact and mining geologists became interested very early in rock fracturing processes because these are privileged access ways for mineralised fluids. The faults in the strike-slip and shatter zones, and first and foremost the tension cracks, which are open faults, are likely to be mineralised and thus will form the veins. The configuration of the vein fields therefore is strongly dependent on the history of local and regional tectonics.

Quite a large number of compass measurements (725 values) were taken as regards the direction and dip of the vein planes of the Grandes Rousses Massif. All the direction measurements were transferred onto a rose diagram with radial sections of 10° (Fig. 4a). As a result, almost all the measurements are grouped together in the NW and SE quadrant of the diagram revealing three preferential directions which are the following: N 160°E – N 170°E, N 110°E - N 120°E and N 140°E – N 150°E and significant difference of the direction between the western vein field (Fig. 4b) and the northern vein field (Fig. 4c). With regard to the proper characteristics of the veins, a fairly large array can be observed ranging from straight and regular veins with parallel sides, between several decimetres and several metres thick (Col de Montfroid, Croix de Picheu, Plan des Cavales, Balme Rousse), and veins presenting a series of swells and pinchouts or digitations, with veins presenting "horsetail" structures. The fillings (gangues and sulfurised mineralisations) affect both the associated tension cracks and the main fractures.

Two major vein systems coexist (Fig. 3): hydrothermal sulfurised mineralisations of the "BPGC" type (= including sphalerite – i.e. blende in french – pyrite, galena, chalcopyrite) and Alpine-type fissure mineralisations.

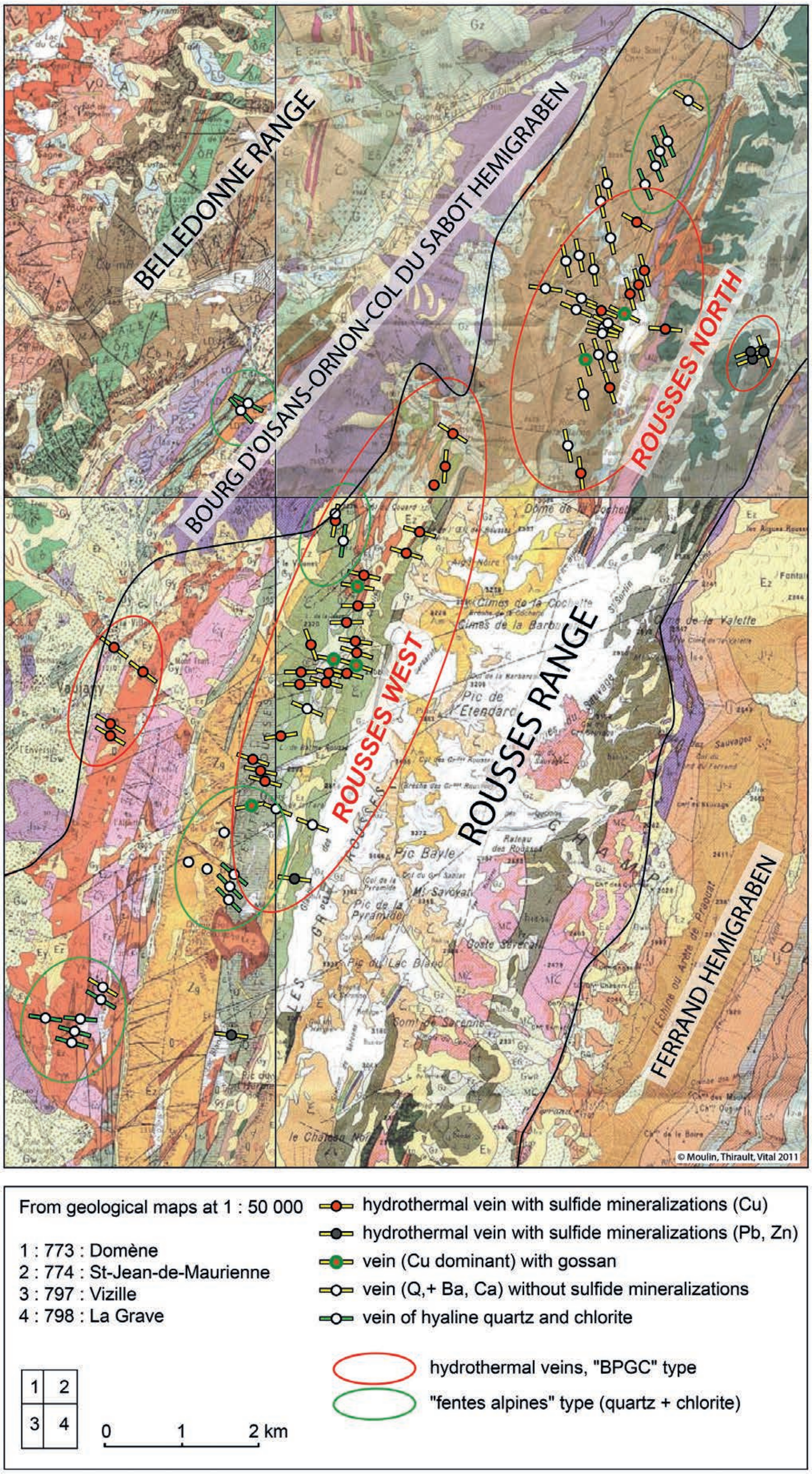

Fig. 3: Location and specification of the veins and main mineralogical and metalliferous indicators identified in the Grandes Rousses Massif during the survey (map base: assembling of the 1:50,000 scale geological maps after Barbier et al., 1976; Bartéfy et al., 1972; 1977; 2000).

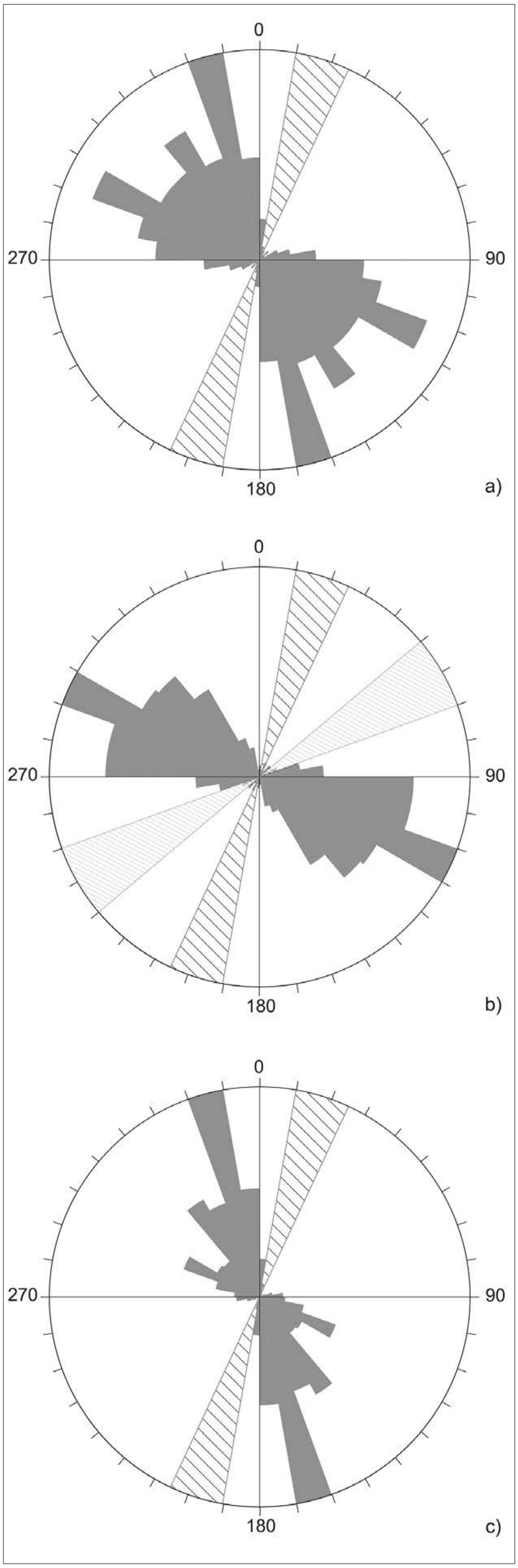

Fig. 4: Grandes Rousses Massif, rose diagrams of the directions of the vein planes; compass measurements presented from 10° to 10°; a) total of the measurements carried out in the massif (725 measurements, grey-shaded plot) and the direction of the large longitudinal accidents (10°-25°E); b) total of the measurements carried out in the Western Grandes Rousses, from the Dôme des Rousses to the Col du Sabot (301 measurements, grey-shaded plot) and direction of the longitudinal (10°-25°E) and transversal accidents (50°-70°E); c) total of the measurements carried out in the Northern Grandes Rousses, from the Aiguille de Laisse to the Rochers de la Curiaz (424 measurements, grey-shaded plot) and direction of the major longitudinal accidents (10°-25°E).

The "BPGC" type veins

The vein systems that formed at medium temperatures of the "BPGC" [= Blende (=sphalerite), Pyrite, Galena, Chalcopyrite] type of the Grandes Rousses Massif include the following sulphides, in order of frequency: chalcopyrite, tetrahedrite, pyrite, galena and sphalerite, within a gangue formed by milky quartz, barite and calcite. This vein system can be subdivided geographically into two large vein fields: the Western Grandes Rousses vein field (municipalities of Vaujany, Oz and Huez; Isère department) and the Northern Grandes Rousses vein field (municipality of Saint-Sorlin-d'Arves; Savoy department).

The vein field of the Western Grandes Rousses (area of Isère department) stretches from the Source des Demoiselles in the north to the Lac du Milieu in the south (Fig. 3). The veins cut the basement and sometimes intersect the Triassic dolomite cover in the northern part. The predominating direction (N 110°E to N 120°E), in the centre of a cluster of values comprised between 90°E and 150°E (Fig. 4b), is slightly orthogonal to the main direction of the main tectonic accidents of the massif (N 10°E to N 25°E). The directions of the veins formed by sulfurized mineralisations range between N 90°E and N 130°E, with a maximum of values comprised between N 120°E and N 130°E (Fig. 5a) corresponding to the "WNW-ESE transversal fractures" described by J.-C. Vathaire (Vathaire, 1965). The gangue is formed by quartz and barite; in some cases calcite is abundant and then forms the heart of the vein (Plan des Cavales 4). The gangue of the veins becomes enriched with barite in the eastern and south-western part of the vein field and even farther south of the surveyed sectors (Lac Blanc mine) and beyond (Brandes). The sulfurized mineralisations are unevenly distributed along the entire length of each vein but they present clusters such as "pockets", monomineral or plurimineral clusters in the centre of the vein or near the walls. As regards the mineral associations, chalcopyrite predominates while the presence of tetrahedrite and pyrite is more secondary, corresponding to mesothermal veins of the "(B)P(G)C type with predominating copper and subordinated Pb-Zn" (Routhier, 1963). Galena and sphalerite are indeed extremely rare in the central area (between La Fare and Cochette) and they

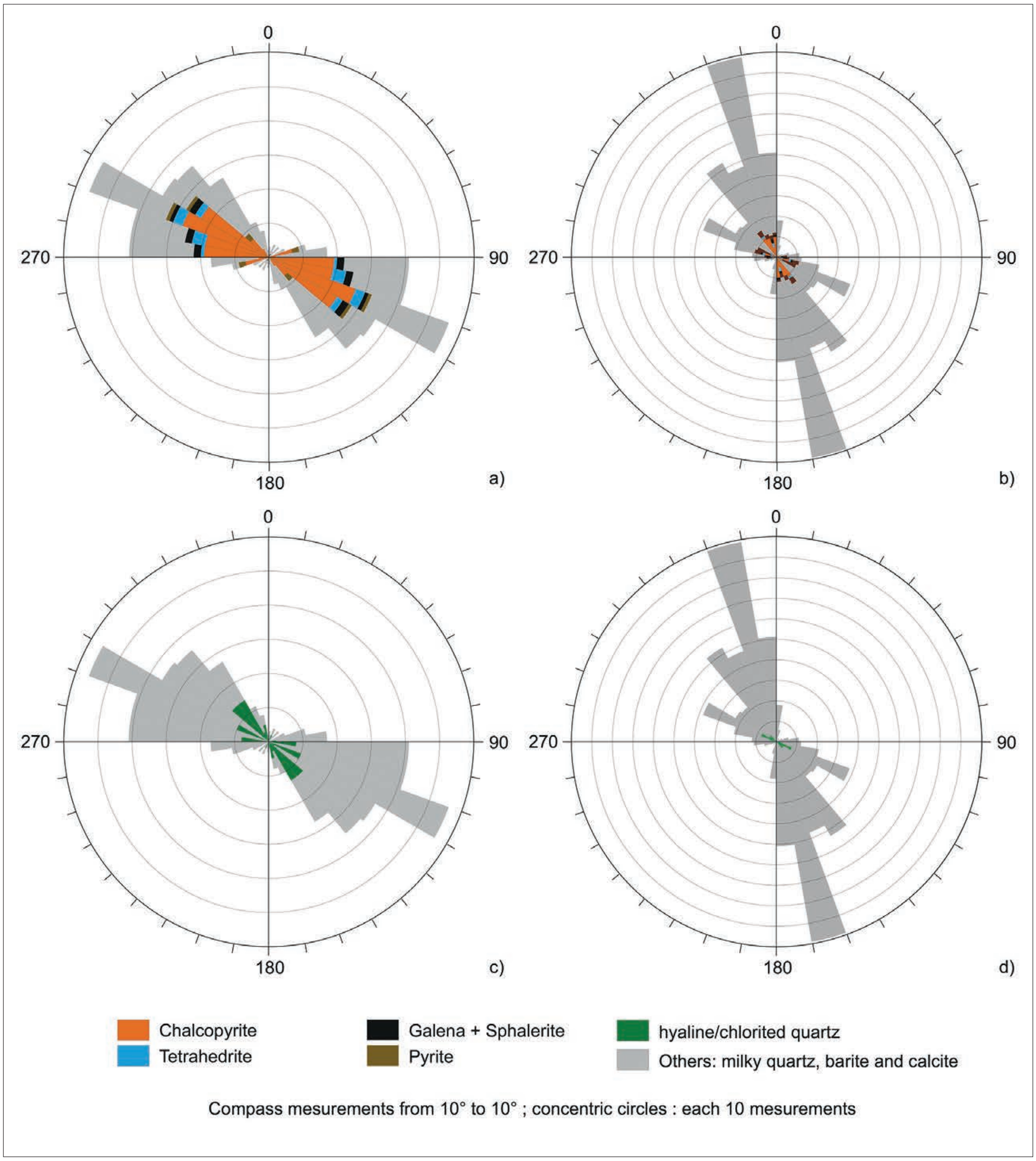

Figure 5: Grandes Rousses Massif, rose diagrams of the directions of the vein planes and the associated mineralisations; a) Western Grandes Rousses, sulfurised mineralisations of the "BPGC" type hydrothermal veins with milky quartz, barite and/or calcite gangue; b) Northern Grandes Rousses, sulfurised mineralisations of the "BPGC" type hydrothermal veins with milky quartz and calcite gangue; c) Western Grandes Rousses, Alpine-type fissure veins with hyaline quartz and chlorite; d) Northern Grandes Rousses, veins of the Alpine fissure-type with hyaline quartz and chlorite.

are predominating minerals only in the northern (source des Demoiselles) and southern areas (Lac du Milieu) of the vein field, then corresponding to the vein field of the "B(P)G(C) [= Blende, (Pyrite), Galena, (Chalcopyrite)] type including Zn-Pb-Ag with subordinated pyrite and chalcopyrite" (Routhier, 1963). In the southern part, farther up to Col du Lac Blanc (mining areas of several lakes: Lac Blanc, Lac de Brandes and Lac de l'Herpie), outside the prospected area, grey coppers and galena seem to be predominant, embedded in a barite gangue (Héricart de Thury, 1841; Vathaire, 1965).

The northern vein field of the Grandes Rousses (Fig. 3), located in the municipality of Saint-Sorlin-d'Arves (area of Savoy), extends from the western shores of the lakes (Lac Tournant, Lac Blanc de St-Sorlin and Lac Bramant) and continues northwards (Étendard mountain refuge, Rochers de la Curiaz). The largely predominant direction of the veins is N 160°-N 170°E, the two secondary directions being N 140°E - 150°E and N 110°E – N 120°E (Fig. 4c). Considering only the sulphide vein mineralisations, clearly less abundant than in the western vein field of the Grandes Rousses, a quite large bundle appears between N 140°E and N 180°E whereas a secondary group corresponds to N 100°E – N 120°E (Fig. 5b). Towards the west the veins are sterile; they become enriched with sulfurised mineralisations (chalcopyrite predominant, tetrahedrite, sometimes pyrite) on the western margins of Lac Tournant, Lac Blanc de St-Sorlin and especially Lac Bramant (veins of the "(B)P(G)C type with predominating copper and subordinated Pb Zn"). The evidence (Fig. 3) located east of the lakes is of a different kind: these are sulfurized veins with sphalerite and galena (galena predominating at Aiguille Rousse, sphalerite predominating in the mining areas of Rieu Blanc).

The veins formed in Alpine-type fissures

The vein system formed in Alpine-type fissures in the broader sense with a generally differing direction (Fig. 3), often including hyaline quartz, chlorite, oligist and more rarely siderite and albite. They are scattered in several distinct vein fields from the north (Rochers de la Curiaz) to the south (Lac Besson/Lac Noir; municipality of Oz). These veins, which are not discussed here, yielded massive chlorite and hyaline quartz, the latter being of potential interest for prehistoric people (Rostan & Thirault, 2016).

The mineralisations of the hydrothermal veins

The gangues

The gangues are formed, in order of frequency, of quartz, calcite and barite. Quartz is the main component of the sterile veins and the veins with sulfurized mineralisations. Generally, it has a milky aspect (Fig. 6g). The structure of the vein quartz can be massive or banded. Associations of quartz and barite and of quartz and calcite are frequent (Fig. 6h and 6i). Calcite occurs abundantly as a component of vein gangues, more particularly in the northern Grandes Rousses, as a filling of the veins with milky quartz walls. At the surface dissolution phenomena are frequent, mirroring the imprints of the original automorphous crystals. Distinct sections of the large mineralised veins such as Plan des Cavales 4 clearly had a median calcite filling that disappeared because of dissolution processes on the first few metres down from the surface. Barite occurs as various facies, from microcrystalline saccharide texture to the enlargement of large blades, including all the intermediate forms, either pure or associated with quartz (Fig. 6h).

The hypogene sulfurized mineralisations

The main sulphides and sulfosalts identified in the Grandes Rousses veins are the following in order of frequency: chalcopyrite, tetrahedrite, pyrite, sphalerite and galena (Moulin et al., 2012).

Chalcopyrite is an ubiquitous sulphide of the Grandes Rousses Massif. It is present in the form of pockets or monomineral clusters of varying sizes (Fig. 6a and 6i), sometimes reaching a weight of several hundred grams, in a milky quartz or barite, more rarely calcite gangue. It was identified in almost all the sulfurized veins (Fig. 3 and 5a-b).

Evidence of tetrahedrite was identified in 25 spots of the inventory (Fig. 3 and 5a-b), often associated with chalcopyrite and in distinct cases with galena (mining area of Lac du Milieu). Tetrahedrite appears as flecks or small masses included in quartz, barite or calcite veins, either in the bedrock or in the dolomitic bed. Small automorphous crystals (tetrahedrons) are sometimes present (Fig. 6b).

Pyrite occurs in veins with quartz and calcite or barite gangues, either isolated or associated with other sulphides in the "BPGC" veins as flecks or clusters. Pyrite also appears as diffuse impregnation in the enclosing rock. Given its unstable state, it frequently alters into limonite. Although pyrite is not an ore type exploited by prehistoric people, its importance as an associated ore in the "BPGC" veins in the primary sources is substantial because it can be considered as being the starting point of the chain of chemical reactions in the oxidation area producing ferric sulphate, a powerful oxidant (Routhier, 1963). These reactions will lead to copper ore enrichment in the area of cementation.

Sphalerite was only encountered in a few spots in the peripheral areas of the chalcopyrite vein fields (Fig. 3): in the north (Rieu Blanc mines as large monomineralic clusters of black sphalerite) and in the south (Lac du Milieu mine, brown sphalerite in association with galena). The polymetallic sulfurized veins rich in sphalerite of the Grandes Rousses Massif were probably exploited in protohistoric times for sulphides other than zinc sulphide the extraction of which is of a late date.

Galena was only identified in a very small number of find spots, at the periphery of chalcopyrite vein fields, included in barite more rarely quartz gangue, sometimes as monomineralic clusters (Fig. 6c) of several hundred grams (Lac du Milieu mine), or associated with sphalerite or tetrahedrite, pyrite and chalcopyrite (Demoiselles mine).

The main supergene mineralisations of the "BPGC" veins

The area of superficial alteration of the veins enables the formation of new minerals through oxidation and hydration on contact with atmospheric agents at the expense of primary sulphides. These are often strongly coloured and in ancient times they enabled the detection of underlying sulfurised veins. In particular cases, which are still difficult

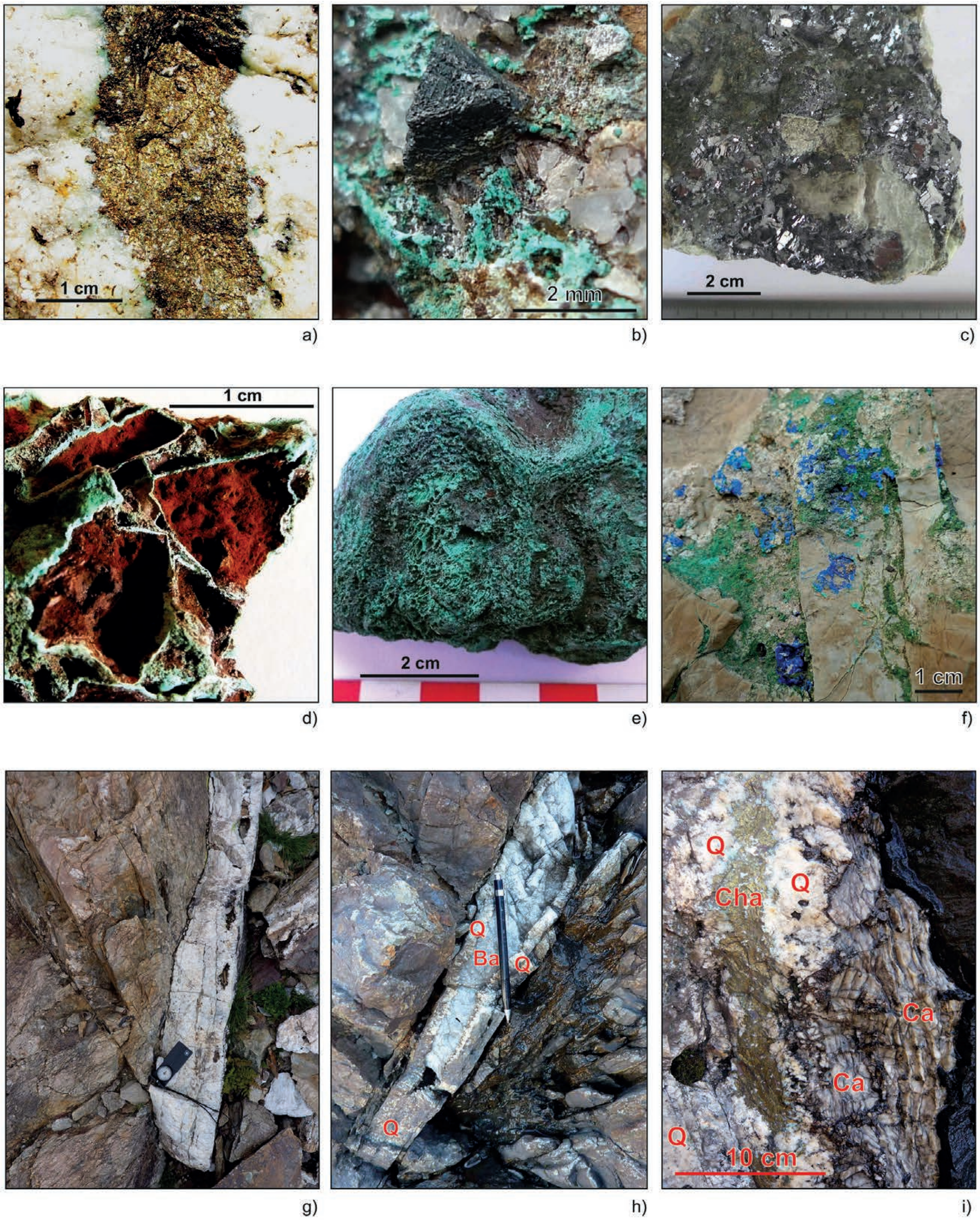

Figure 6: Grandes Rousses Massif, mineralisations and gangues of the hydrothermal veins; a) massive chalcopyrite embedded in milky quartz (Étendard); b) automorphous tetrahedrite (Demoiselles mine); c) massive galena (Lac du Milieu mine); d) box-work with a compartmented structure of brown limonite and malachite in perimorphosis (Cochette); e) massive concretioned malachite (Cochette); f) azurite and malachite on dolomite (Étendard Nord mountain refuge); g) massif and regular milky quartz vein (aiguille de Laisse); h) barite vein with milky quartz on the walls (La Fare); i) milky quartz vein (Q) with massive chalcopyrite (Cha) in the centre and calcite (Ca) on the walls (Étendard).

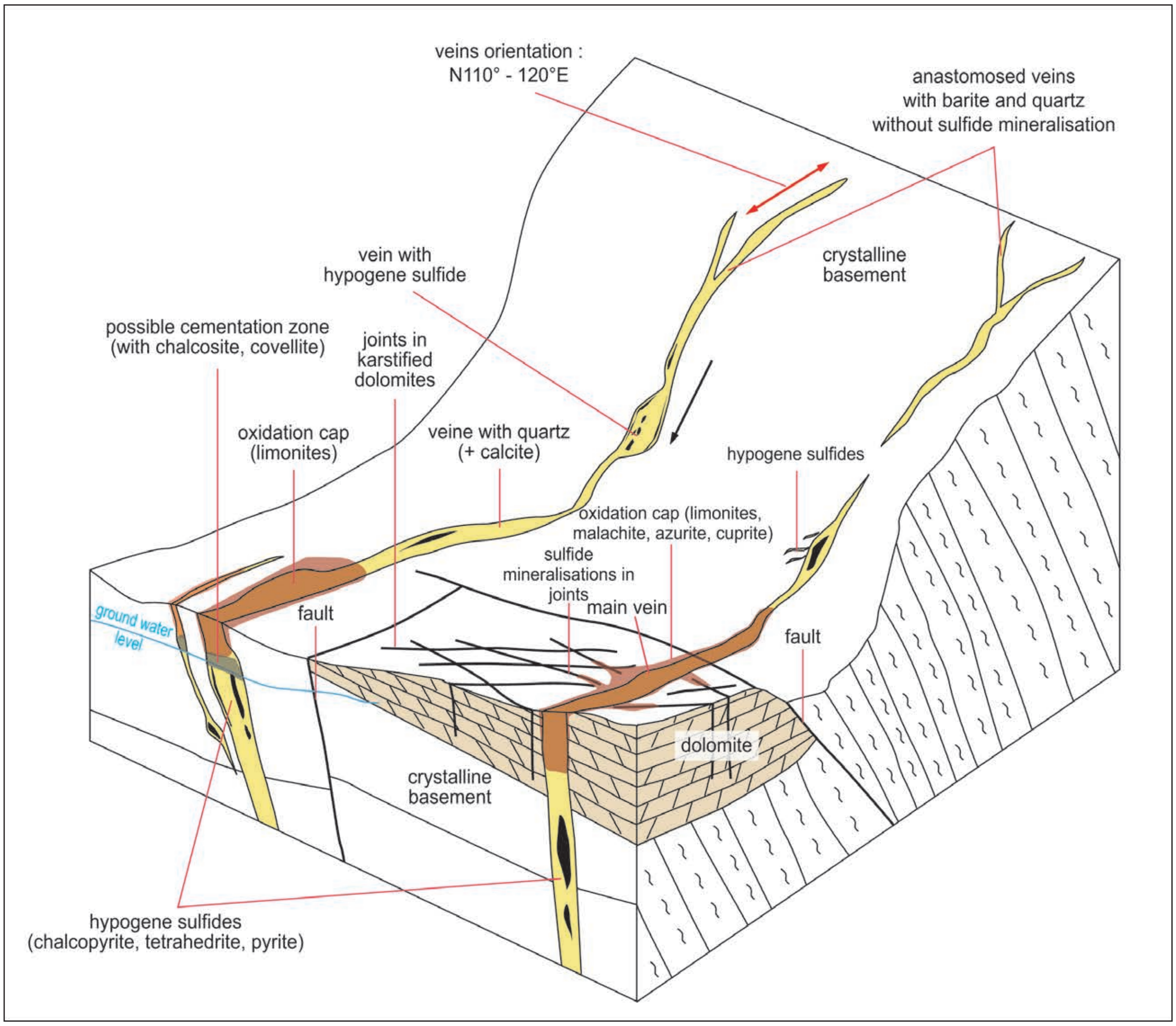

Fig. 7: Schematic block diagram showing the metallogenic context of the vein mineralisations and their alteration zones in the Western Grandes Rousses Massif.

to diagnose, phenomena of superficial enrichment may have created exploitable deposits (currently depleted) above distinct sulfurised veins.

Several types of limonites in the broader sense (iron hydroxides) were present in the oxidation caps. The earthy varieties are the most frequent; other more compact facies occur as box-work of primary sulphides, in the form of chalcopyrite, siderite and pyrite perimorphisms or pseudomorphisms (Fig. 6d).

Malachite is encountered frequently in the weathering zones of the sulfurised veins, more particularly when these latter cross the dolomitic cover or contain calcite in their gangue. Malachite occurs as green crustified clusters (Fig. 6e), as a coating (Fig. 6f) or as small needle-like or fibro-radiated crystals, also as perimorphism (Fig. 6d), often associated with the limonites of the oxidation caps. While malachite only appears as an accessory mineral in many spots, significant amounts of malachite were encountered in distinct sites (Cochette 9); the question whether it was extracted as copper ore remains open for the moment.

Azurite (Fig. 6f), which is more unstable than malachite, was more rarely identified than this latter. Generally, it is associated with the weathering zones of tetrahedrites, with antimony ochre. It occurs as small crystals or as a bright blue coating. Other weathering minerals of the oxidation and cementation zones were also mentioned (cuprite, chalcocite, covellite, tenorite, pyromorphite, cerussite; Vathaire, 1965).

Metallogeny of the oxidation zones of the veins

The oxidation caps correspond to the superficial part of the sites submitted to the oxidation of sulphides and their leaching (Fig. 7). In the contexts on which our study focused the development of these oxidised areas remains limited, about 2 to 3 m thick. The oxidation caps are characterised by the presence of often abundant

field reference	laboratory reference	object	result(BP)	deviance	calibration 68.2% probability	calibration 95.4% probability
Barbarate3	ARC-2430	fuelwood	3480	45	1879-1748	1914-1690
Barbarate3	ARC-2326	fuelwood	3395	70	1868-1608	1882-1527
Cochette4	ETH-31100	fuelwood	3480	55	1883-1744	1944-1666
Etendard1	ETH-31099	fuelwood	3515	55	1906-1756	2012-1692
PlandesCavales4	ETH-32540	fuelwood	3625	55	2119-1910	2193-1783
PlandesCavales4	ETH-34334	humidwood	3580	55	2025-1834	2126-1756
LacBramant	POZ-13993	vegetaldebris	3650	35	2121-1956	2137-1929

Fig. 8: Inventory of the radiocarbon dates available for the workings in the Grandes Rousses Massif. Calibration with OxCal software, version 4.1 (edition 2009). After Bailly-Maître & Gonon, 2008, completed.

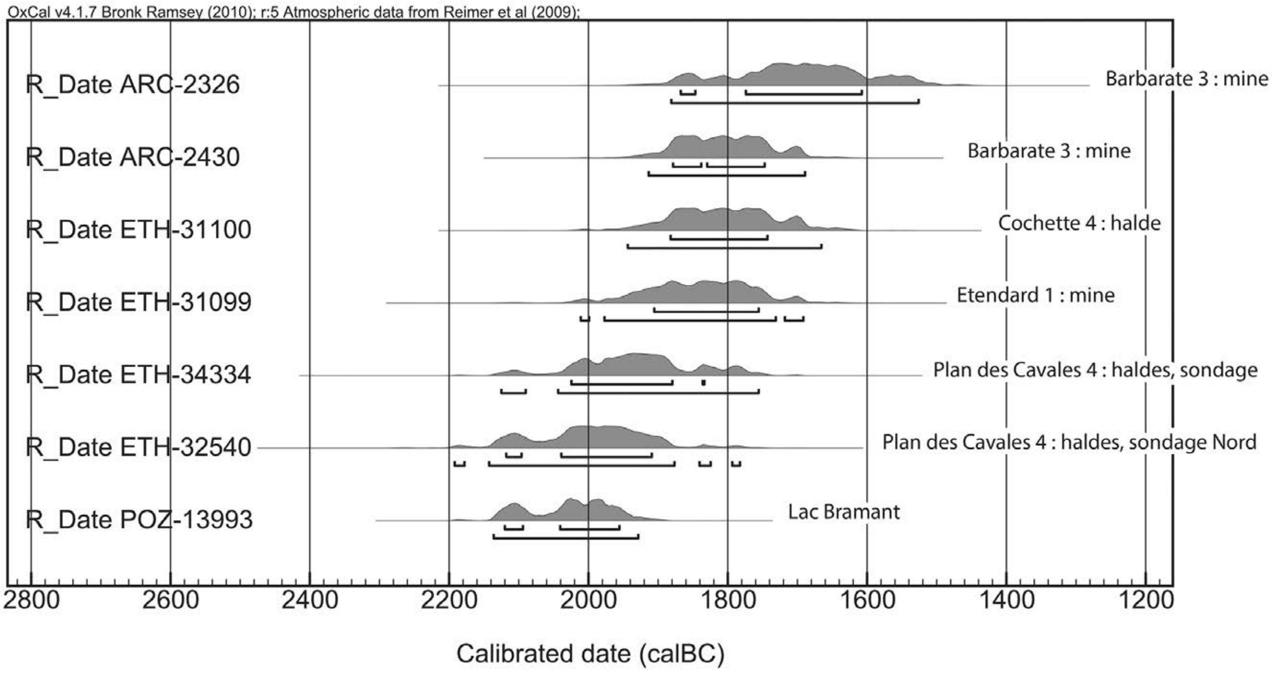

Fig. 9: Seriation of the radiocarbon dates for the workings in the Grandes Rousses Massif. Calibration with OxCal software, version 4.1 (edition 2009). The first line below the curve indicates the intervals at the 68.2% confidence level, the second at the 95.4% confidence level. For the data see figure 8.

limonites exhibiting various facies. When the sulphides were completely leached out, only the quartz skeleton remains, which then takes a spongy aspect. The oxidation caps present varying sizes at the surface of the inventoried vein deposits. As regards distinct sites with intense exploitation it is difficult to get a precise idea of the original size and quality of these superficial weathering zones as the initial aspect was strongly modified. This is also the case for the potential cementation zones that are precisely located below the oxidations caps in the zone of groundwater table fluctuation (Routhier, 1963). It should be noted, in this respect, that several galleries and trenches (Plan des Cavales 4, Lac Blanc de St-Sorlin 2, etc.) are currently flooded and thus lying in a favourable context for the formation of supergene sulphides (chalcocite, covellite) typical of the cementation zones, much richer in copper than chalcopyrite, a primary sulphide of the supergene deposit.

In addition to the hydrogeological context, whether linked to the presence of a groundwater table or not, other aspects should be taken into account: the supergene evolution of the veins depends on the presence or absence of pyrite associated with other sulphides on the one hand and on the nature of the enclosing rock and of the gangue on the other hand. The presence of pyrite favours the formation of sulfated solutions and, conversely, the presence of carbonated rocks inhibits the migration of distinct sulfated solutions. These then immediately react with copper sulphate to form copper carbonates (Routhier, 1963). This could be the case for distinct deposits of Cochette, close to the Triassic dolomite, where malachite occurs abundantly in the oxidation caps.

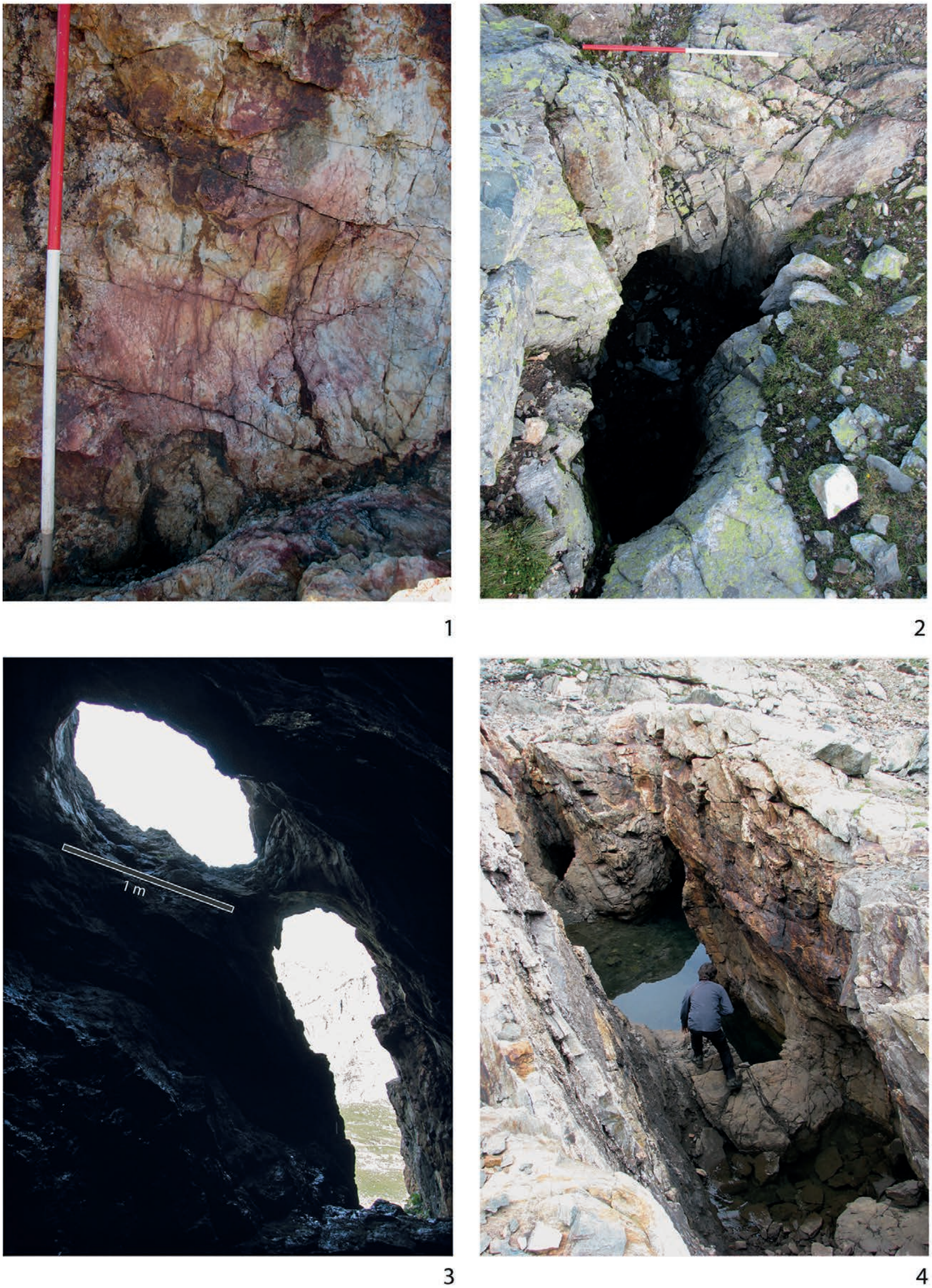

Fig. 10: Types of fire-settings. 1: working of a vein, notice the rubefaction of the quartz and its peel-like structure (Plan des Cavales); 2: vertical shaft on the vein (La Jasse 6); 3: gallery stemming from the connection of two workings, still marked by two accesses (Barbarate); 4: extraction trench produced by the coalescence of shafts and galleries (Plan des Cavales 4).

The dating of the workings

Two major extraction techniques are attested: galleries that were cut using explosives and metal tools and excavations of all sizes (ranging from the cupule to the gallery) achieved by thermic fracturing. The first are more or less precisely dated by written documents (Bailly-Maître, 2001) and are not very ancient, dated to one or two hundred years ago. The use of fire-setting is very common throughout all periods and is therefore not a precise dating criterion (Weisgerber & Willies, 2001; Ancel et al., 2012). At the end of the initial identification work six radiocarbon dates were made on charcoals stemming from the mine dumps, thanks to some test excavations realised under the responsibility of M.-C. Bailly-Maître (Bailly-Maître & Gonon, 2008; Figs. 8 and 9). The measurements range from the 21st to the 17th century BC, at the 68% confidence level. By analysing these dates in more detail, a succession can be identified: the two dates obtained for Plan des Cavales 4 can be attributed to the 21st and 20th century BC; clearly differing from the three dates stemming from Étendard 1, Cochette 4 and Barbarate 3, which can be assigned to the 19th and 18th century BC. An additional radiocarbon date obtained for the same gallery as the preceding one indicates an extension into the 17th century BC. Moreover, the drilling carried out in Lac Bramant, which yielded a copper and zinc pollution peak dated to the 21st-20th century BC, may indicate a working that was contemporaneous or slightly earlier in the Savoy area (Guyard et al., 2007).

We can only postulate that all the workings and fire-settings that could not be dated by radiocarbon analysis, also date to the Early Bronze Age. The heavy metals pollution peak in Lac Bramant provides an argument to support this hypothesis. The mining waste and the features located close to the workings (see below) were dated to the same period as they were presumed to be related to the extraction sites. We will present the "ancient" workings as a whole keeping in mind that only a few of these are precisely dated.

The use of fire in the workings: general organisation

In the field a distance of 4 km and the watershed crest separate the extraction sectors of the Dauphiné side of the Grandes Rousses Massif, oriented towards the west (municipalities of Huez, Oz and Vaujany), from those of the Savoy side, oriented towards the north-east (municipality of Saint-Sorlin-d'Arves). However, the typology of the extractions and the systematic use of fire-setting are similar and the radiocarbon dates make it possible to consider that these two areas form one mining district.

The mineralised veins outcrop at the surface, more particularly the supergene formations and the oxidation zones that are strongly coloured. It is therefore possible that the ancient miners looked for these indications in order to test the contents of the veins and then started their working. Four types of excavation carried out to search for copper ore could be identified (Fig. 10).

The fire-settings

We have registered 112 spots, a minimum number. Fire-setting aims at fracturing a vein by thermal shocks in various positions according to the slope and the structure of the vein: horizontally, vertically, following the vein axis, from the walls, etc. The setting of one or more fires makes it possible to break out a volume of quartz and ore that equals one cubic metre (Ancel & Marconnet, 2012). The result depends on the layout of the terrain: frequently these are cupules with very rounded shapes (forming a bathtub when developing horizontally) or a simple rounded notch. The erosion processes transform this initial stage to such an extent that it is sometimes impossible to determine whether these concavities were natural or made by humans. Most probably, these small fire-settings were tests aiming at evaluating the ore content of a vein identified at the surface. These tests are largely distributed across the mining field and they were encountered everywhere where workings were developed but also in areas without workings in which the ores are still visible today. These isolated tests are proof of a systematic survey of the mining area in prehistoric times.

The shafts and the trenches

Thirty shafts were identified. In this case, the vein was exploited through vertical digging, still using fire. This is a succession of thermal cupules, the processing of which is not easy to understand, but the result is clear: the excavation develops downwards following the mineralisation. We have inventoried 32 trenches. Invariably using fire-setting, the working followed the mineralised vein horizontally or obliquely. Nowadays the excavation is open, but it is difficult to determine, prior to any detailed study, whether the initial excavation was made in this way, for example by taking advantage of natural recesses identified for distinct veins through calcite dissolution (as is the case at Plan des Cavales 4), or whether these are galleries the roof of which had collapsed.

The galleries

Nineteen galleries were identified. These are fully underground workings that were carried out by following the mineralisations. One single cross-cut was identified at Cochette 7. All the other ancient galleries were workings. Some have direct access from the surface; others were carried out from a shaft. In many cases the galleries are

Fig. 11: Upper terrace of the Grandes Rousses, sector of Lac de La Fare (Isère): fire-settings and galleries for the extraction of copper ore. 1: no. 447, LF2, perched fire-setting on the right bank of a waterfall; 2: no. 448, LF2, two cupules stemming from fire-setting, currently flooded; 3: no. 454, LF1, refilled access to a gallery opened by fire-setting; 4: nos. 453 and 454, view of the three accesses of the gallery. The red and white stake measures 1 m in length.

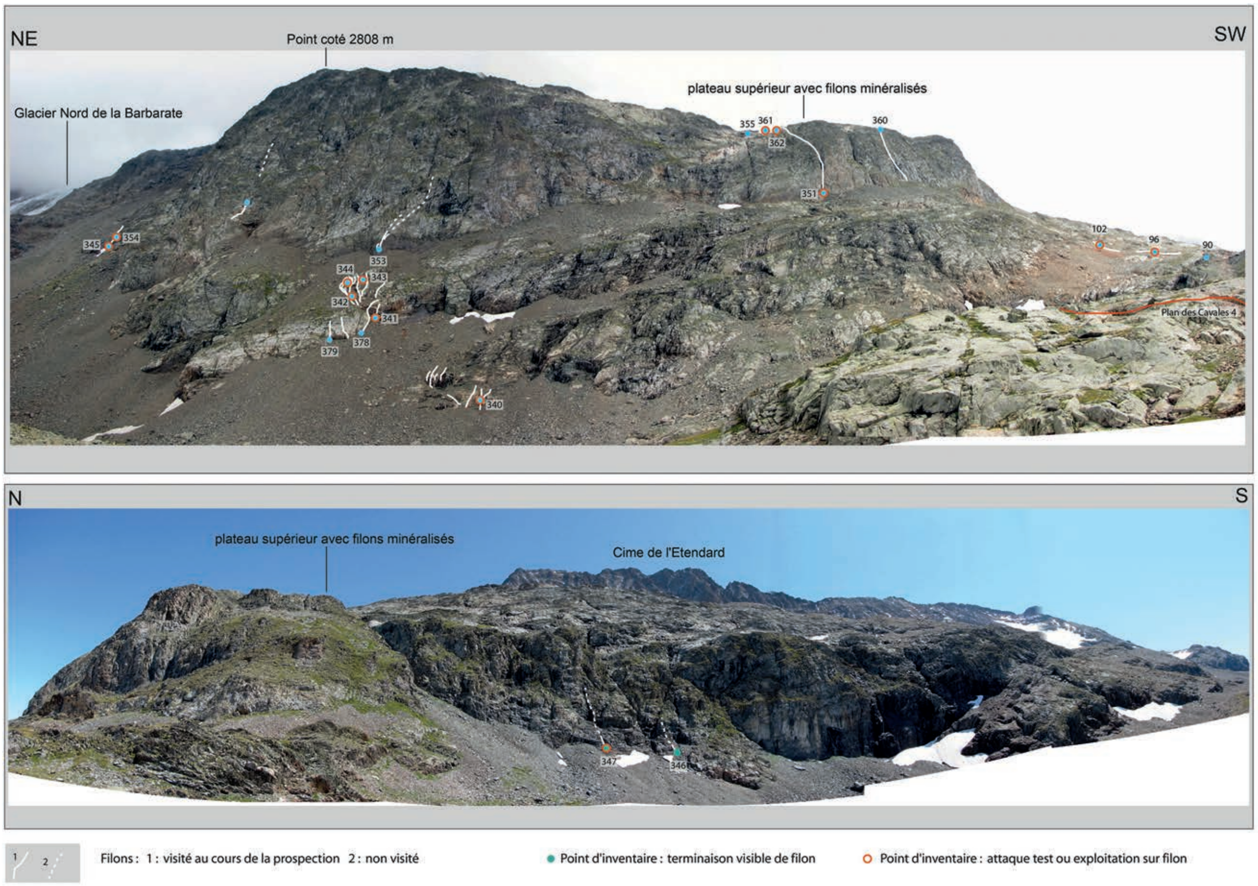

Fig. 12: Upper terrace of the Grandes Rousses, panoramic view to the eastern part of the Étendard sector (Isère department) with indication of the surveyed spots: "Étendard Nord" at the top, "Étendard Sud" at the bottom.

difficult, even impossible, to access because of collapses and obstructions. As a consequence, their real development is unknown and it remains impossible to define the size of the workings.

The trenches and associated galleries

It was possible to identify eleven diggings where open parts and subterranean parts are associated as regards the large workings.

Assessment

By adding a further 18 workings with unknown extraction techniques, 222 ancient extractions can be counted for the entire mining field of the Grandes Rousses Massif. The structure and the content of the mineralisations guided the workings of the miners. As this could be stated as early as the first discoveries, it is difficult to individualise an ancient mine because the diggings that are visible today result from the clustering of a more or less large number of fire-settings, carried out with varying sizes and modalities. Consequently, a detailed study of each digging is necessary in order to understand the project and its completion and to best define what corresponds to "one single" digging or "one single" working in the Grandes Rousses area.

In the current state of research the ancient extractions and their associated features are spatially distributed in two distinct groups. This partition also corresponds to different dispositions in the field, which warrant separate presentation.

The workings of the Dauphiné side

These workings develop along a length of 4 km on the upper terrace of the Grandes Rousses (alt.: 2,200-2,700 m), following mineralised veins on a strip that does not exceed 600 m in width (Fig. 11 and 12). The mining field is dense with peripheral extensions. It groups together all the working types described above. The fire-settings and all kinds of extractions (shafts, trenches, and galleries) are clustered in the same areas (Fig. 11). Within the exploited zone a distinct number of isolated fire tests can be identified, sometimes on veins other segments of which were subject to large workings (for example, Balme

Fig. 13: Plan des Cavales (Isère), altitude 2,500 m: two circular dry-stone features built at the edge of a cliff, immediately north-west of the extraction trench. Both features were erected on a ridge of unknown formation the visible surface of which is, however, rich in rubefied quartz fragments. The red and white stake measures 1 m. 1: overall view into a south-western direction (the Romanche valley is visible at top right); 2: detail of the southern circle (no. 62); 3: detail of the northern circle (no. 63).

Rousse 2 - BR2). This fact shows that all the mineralisations were identified and that the exploitations of veins presenting sufficient ore contents according to the criteria of that time were carried out systematically. According to the mineralogical observations, the boundaries of the mining field correspond more or less to the extent of the copper mineralisations. However, within the working area substantial mineralisations (according to our criteria) are still visible on the veins, whether in the workings or on the unexploited veins. In this way it is possible to measure

Fig. 14: Cochette sector (Isère), at an altitude of 2,330 – 2,340 m, small fire extractions were dug into the sedimentary cover (CO8). 1: no. 123, rock shelter (erratic block) with a semi-circular platform, clearly delimited in the northern part in close connection with the extractions; 2 and 3: no. 120, two adjacent fire-settings on the right bank of the torrent; 4: no. 124, extraction through a circular shaft of 1.5 m in diameter (in the background with stake), located on the right bank of the torrent (in the foreground). The red and white stake measures 1 m.

the mining value of this zone and the size of the workings and to intuitively evaluate the thresholds of the ore content that determined the mining.

The only exception to this statement is the eastern boundary of the extraction to the top. In this direction, the veins climb up the steep slope with large wall workings (Étendard and Barbarate sectors, altitudes 2,390 to 2,640 m; Fig. 12). Upwards, above the walls several isolated fire-settings on veins that are still highly mineralised today testify to their identification up to an altitude of approximately 2,700 m, but not farther. Is there a physical restriction (presence of *névés* or glaciers that masked the veins?) or a technical restriction (difficulty in bringing the wood for firing?) that forced the miners to give up any exploitation?

To conclude, it can be considered that the mineralisations of the Dauphiné side were entirely exploited if the technical and physical limitations and also the selection criteria of the Bronze Age miners are taken into account. We should keep in mind the possibly long duration of the workings and the possible resuming of ancient extractions. In any case, traces of workings carried out with explosives are almost inexistent in this mining field, apart from some tests in altitude (Étendard sector).

The largest workings group together all the extraction types. The most impressive are located on the terrace, at Plan des Cavales 4 and Balme Rousse 2, where the trenches and galleries follow each other on several hundreds of metres with probably large subterranean parts that are completely inaccessible without mechanical facilities. Smaller workings that also represent large excavations were carried out mainly at Plan des Cavales, La Jasse and Cochette, as well as at Barbarate and Étendard, through the digging of galleries into the walls. Some of these workings in addition yielded surface features the function and datation of which is not yet clearly established: areas in which the ore was crushed, stone circles, small retaining walls or heaps of stones removed from the field, canals (Fig. 13). These features are well distinguishable from the pastoralism features, wich are not numerous nearby the mines.

To get a complete picture, it should be noted that the extractions documented along the Cochette torrent (Cochette 8), at the northern boundary of the Dauphiné mining field, present a very different typology with small coalescing pits (Fig. 14). It will be important to determine whether these technical differences are linked to the site conditions (here the ore is embedded in carbonated sedimentary formations) or to temporal factors.

The workings of the Savoy side

On the Savoy side no ancient extraction was mentioned prior to our surveys. The geological mapping alone made it possible to advance the hypothesis that the copper mineralisations could be similar to those of the Dauphiné side and thus would have potentially interested the ancient miners.

After two survey campaigns (2009 and 2010) the boundaries of the copper mineralisations are well identified. It can be stated that the area delimited in this way was clearly prospected by the ancient miners because isolated fire-settings are attested across the entire mineralised area along a length of 3 km and up to an altitude of 2,650 m, and perhaps 2,700 m as regards two uncertain spots in the Lac de Tournant sector. However, in contrast to the Dauphiné side, only very few veins were mined. At La Curiaz 1 the vein was exploited in several points as attested by large thermic cupules but it is difficult to speak of a real working. On the other hand, four veins were subject to organised extraction:

- Above Lac Blanc de St-Sorlin (BS1), a succession of short galleries, shafts and thermic cupules with mine dump areas (Fig. 15).
- Above the preceding, a small working with a flooded gallery and mine dump (BS2).
- North of the Étendard mountain refuge, on the western decline of the crest, a small working (RE2) exceeded the stage of fire tests with a short removal and mine dumps. A stone feature built within the mine dump may be contemporaneous with the extractions.
- On the western shore of Lac Bramant, a working associates shafts and the beginning of a trench, with mine dumps (LB2: Fig. 15).

In addition, on the western shore of Lac Bramant isolated fire-settings were identified. The veins dip into the lake the current level of which currently exceeds its natural height, which makes it possible that additional extraction are flooded presently. In this lake a palaeoenvironmental drilling sample yielded a pollution peak of heavy metals interpreted by the authors as stemming from atmospheric pollution (Guyard et al., 2007). It is likely that this peak may be directly associated with the visible or flooded extractions if the drilling came through the thin deposits directly stemming from a working. In any case this is an important chronological marker to confirm that the Savoy side of the Grandes Rousses is indeed connected with the same mining complex as the Dauphiné side. As a conclusion, very large workings are not present on the Savoy side but the ancient miners prospected and tested the entire area and small extractions were made on well mineralised veins.

Concerns and prospects

Many aspects are still unknown. Here we mention five most important ones:

- The chronology of the workings is very unclear: the dates obtained make it possible to attribute distinct extractions, from the largest ones, to the Early Bronze Age. As regards the remainder, not a single dating element could be advanced. There is nothing to exclude the existence of workings dated to earlier or later periods.
- Although the surveyed area is already large, other sectors of the Grandes Rousses Massif (for example the eastern slope) remain completely unknown and it is possible that additional working areas are still to be discovered.
- Nothing is known about the processing of the ore after extraction; except for possible crushing areas next to the mine dumps there is no discovery related to ore roasting and to the production of the copper metal. The dating and the function of the sub-circular stone features identified near the large mines have to be documented.
- Knowing that there are opposed entities from a metallogenic and mineralogical perspective (hypogene mineralisations of the sulfurised veins / supergene oxidation mineralisations basement / carbonated cover, chalcopyrite veins / veins with grey copper ore) could it be possible to establish a chronology of the extraction and processing techniques according to these different types?

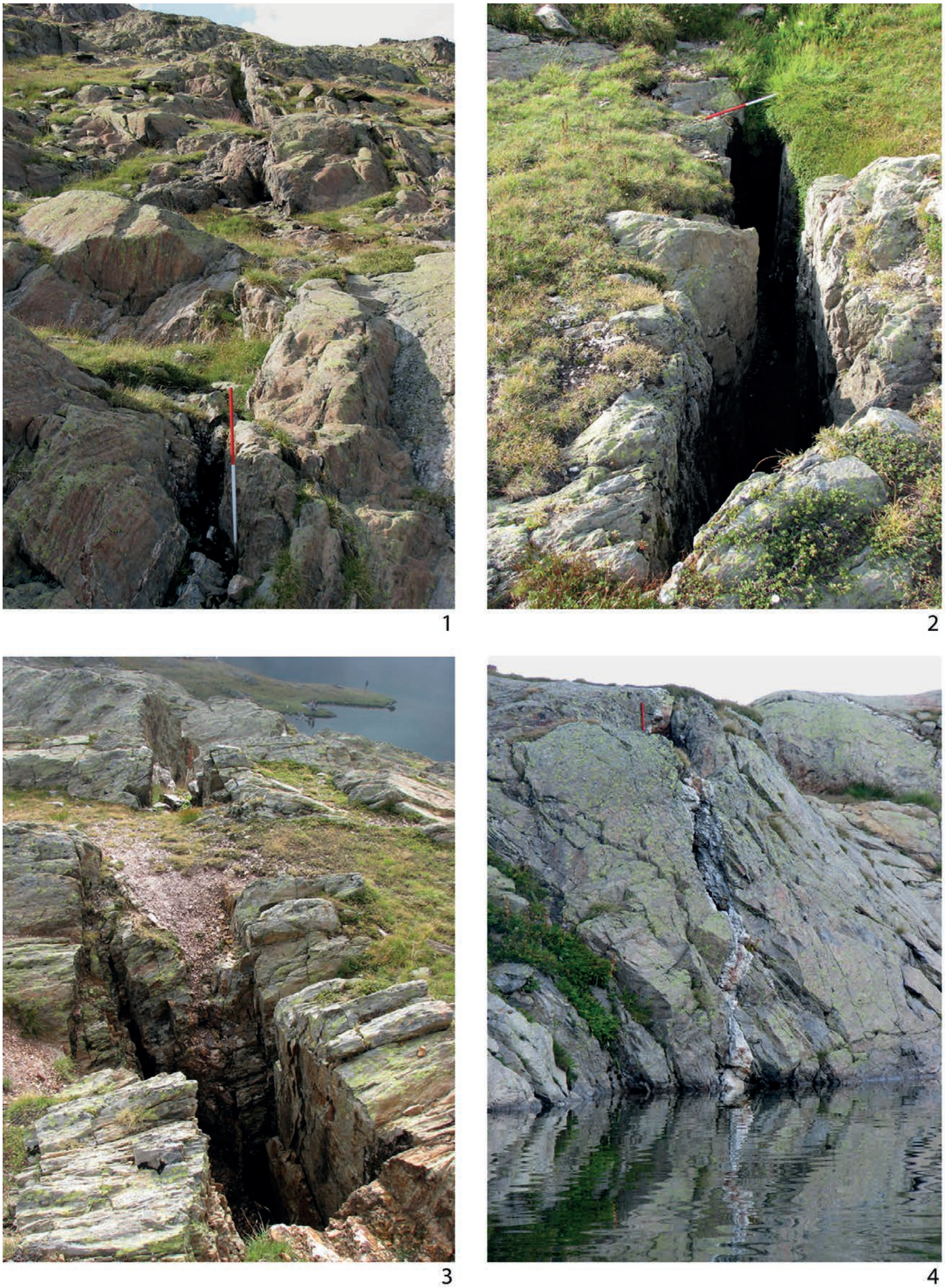

Fig. 15: Savoy sector, examples of copper ore mining. 1: no. 706, Lac Blanc de St-Sorlin, one part of the exploited BS1 vein, view to the north; 2: no. 709, BS1 working, filled trench; 3: no. 726-729, Lac Bramant, working LB2, overall view towards the south-east with the lake in the background; 4: Lac Bramant, fire tests at LB1 strung along a vein dipping into the lake, view to the north. The red and white stake measures 1 m.

- The social and cultural context of the workings remains enigmatic: no diagnostic vestigial remains, no settlement features have been identified so far.

The following achievements result from these survey operations:

- The inventory of the wet areas made it possible to launch several campaigns of palynological and paleoethnobotanical drilling (F. David) in the sectors located below the ancient workings. (1,800 - 2,100 m). Their potential is obvious as the dated sequences cover the last ten thousand years (ongoing study).
- The characterisation of the mineralisations exploited in the Grandes Rousses Massif on the basis of lead isotopic ratios is ongoing (F. Cattin). This would be a pre-conditional stage prior to any attempt to seek out connections between the exploited ores and the finished copper and bronze products.

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Authors

Bernard Moulin – Independent researcher, F 26400 Gigors-et-Lozeron
EricThirault – University Lumière Lyon 2 (France) & UMR 5133 “Archéorient”, CNRS
Joël Vital – CNRS, UMR “5140 “Archéologie des sociétés méditerranéennes” / Centre d’archéologie préhistorique du Rhône aux Alpes

Correspondence and material requests should be addressed to: eric.thirault@mom.fr

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Rudolf Klopfer, Astrid Stobbe, Rüdiger Krause

Prehistoric mining in a small medieval mining district in Montafon, Vorarlberg (Austria)

ABSTRACT: *Intensive settlement and mining activities during the Medieval period as well as the early Modern Age are evidenced in Montafon (Vorarlberg, Austria). A number of prehistoric settlements and numerous archaeological single findings confirm that these inner alpine environments were already settled and managed during the Bronze and Iron ages in varying intensity. New multidisciplinary investigations on mining activities (archaeology, vegetation history, geochemistry) have brought new indications for Iron Age mining. In the period between 250 and 50 BC, the anthropogenic indicators rise in the pollen diagram. A causal relationship of the landscape with a Late Iron Age mining phase seems likely in view of the synchronous rise of copper values (to over 1,400 ppm) in the mire and in a waste heap in the immediate vicinity, which dates back to the 4th/3rd century BC.*

KEYWORDS: MONTAFON, IRON AGE, MINING ACTIVITY, VEGETATION HISTORY, GEOCHEMISTRY

Introduction

The Montafon valley lies in the South of the Austrian federal state of Vorarlberg, on the borderline between the Western and Eastern Alps (Fig. 1). Located in this mountainous landscape is a small mining district with many traces of a long and varied history. The oldest known documented mention of mining in Montafon stems from 1319. The naming of eight iron melting furnaces in the Urbarium of Churraetia from 843/844 already confirms that mining for iron ores occurred during Carolingian times in the region of the Verwall mountains between Bludenz, the Klostertal and the Ill valley (Scheibenstock, 1996, pp.9-11; Neuhauser, 2012, pp.9-21).

The Montafon was Vorarlberg's most significant mining district for over centuries' time. Intensive mining activities during the Medieval period as well as the early Modern Age are evidenced in Montafon between St. Anton and St. Gallenkirch in numerous places with diverse traces of mining operations. These sites are located at mountain heights of up to 2,500 m a.s.l., such as the mining galleries and waste heaps on the Alpe Spora above St. Gallenkirch, or by the Rona Alpe (Alpguss) and the Fresch Alpe in the inner Silbertal. A few smelting places are known as well, for example, in Ganzenahl near the municipality of Tschagguns or Schmelzhof in the Silbertal (Krause, 2013).

The most abundant traces of mining activities are found on both sides of the Kristberg, as well as in the land parcels Knappagruaba and Worms on the Bartholomäberg. There varied evidence of mining was found: mostly large and small waste heaps (*Halden*) with waste rock and collapsed mining galleries. Particular mention should also be made of the impressively beautiful churches in Bartholomäberg, the mountain chapel on the Kristberg with their altars dedicated to miners, and the Romanic crucifix in Bartholomäberg, all of which underscore the status of medieval mining and the resulting prosperity (Krause, 2015, pp.85-88).

Various single findings from Montafon and a large complex of iron artefacts dated to the Iron Age from Bludenz-Unterstein (cf. Leitner, 1976) gave Elmar Vonbank reason to suspect that the iron ore occurrence in Montafon might have been exploited and used already during the Iron Age (Vonbank, 1966, p.86). Until now, though, no evidence for Iron Age mining has been detected, presumably owing to the fact that broad parts of the landscape are seriously marked by intensive mining industry. Through the closely interconnected disciplines of mining archaeology, archaeobotany and soil studies as well as heavy-mineral examinations, the first evidence for mining activities during the later Iron Age has been achieved. The question as to mining in earlier times as far back as the Bronze Age could not be clarified hitherto,

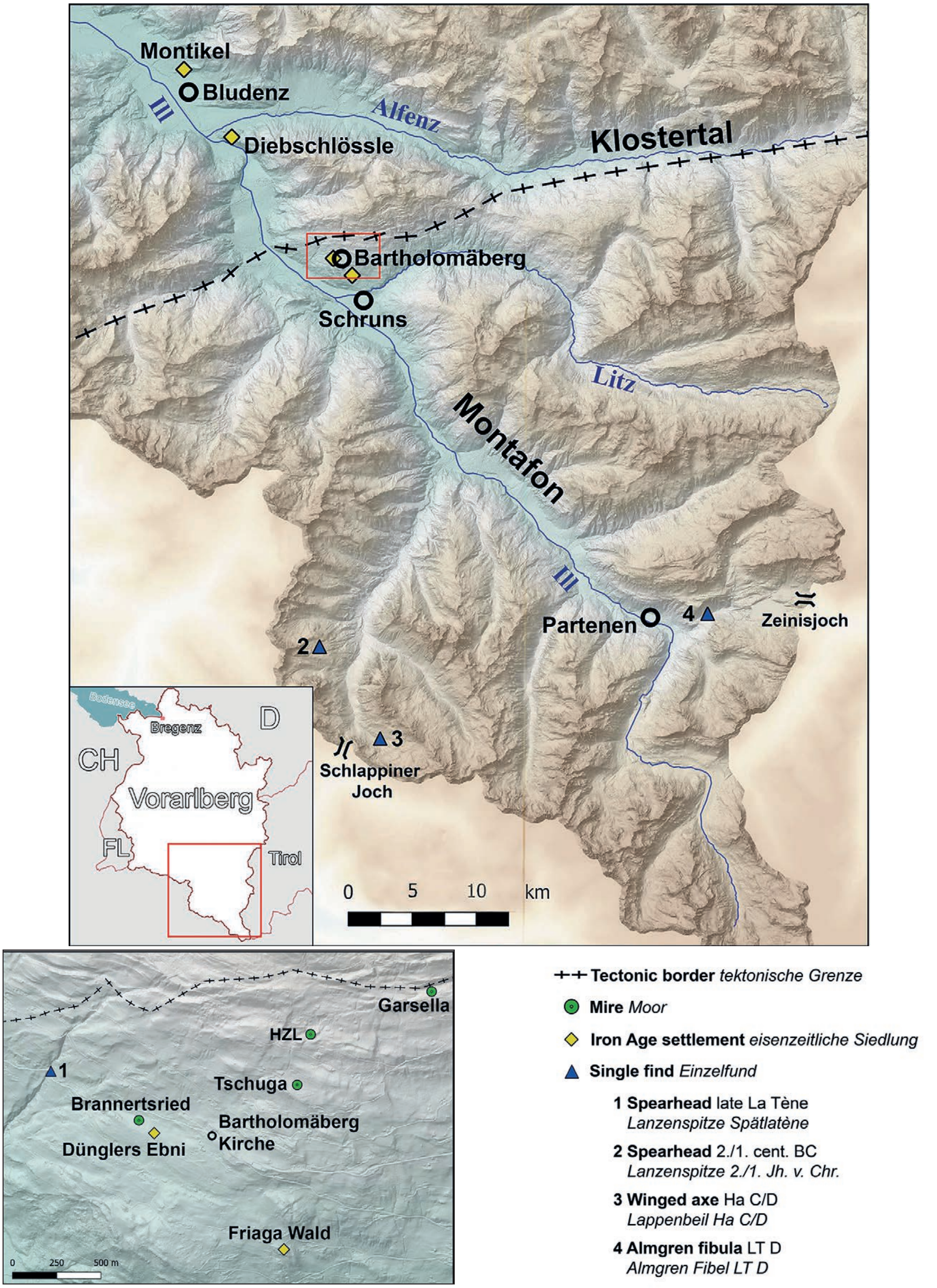


Fig. 1: Montafon is the southernmost valleyscape of Vorarlberg. The tectonic border between the Northern Limestone Alps and the Silvretta Crystalline Alps runs across the valley. Along this line are polymetallic deposits, which were probably exploited since the later Iron Age until recent times. One centre of this mining activity was the community of Bartholomäberg, located on the mountain of the same name (map: Montafonprojekt, map basis: Land Vorarlberg – data.vorarlberg.gv.at).

but this is being discussed based on numerous find complexes and radiocarbon ages.

Study area – Geographical setting of Montafon

Montafon is an almost 40-kilometre-long glaciated trough valley which is drained by the Ill River towards the Rhine River. The valley is enclosed within the alpine mountain ranges of the Verwall, Silvretta and Rätikon. Due to its inner alpine location, the climate of Montafon Valley is temperate with an intermediate position between sub-oceanic and sub-continental conditions. In Schruns, on the valley floor of the Montafon (689 m a.s.l.), the annual mean temperature is 7.4 °C and precipitation reaches 1,243 mm (Walter & Lieth, 1967; Werner, 2005). The present vegetation is dominated by sub-continental, interalpine spruce-fir forests with meadows and pastures in the subalpine region. The terraces in the southward-facing slopes of the Bartholomäberg have little woodland (mainly *Picea abies* (spruce) and *Abies alba* (fir)), while *Fagus sylvatica* (beech) is often admixed. On the valley floor at approximately 700 m a.s.l., grasslands as well as remnants of deciduous forest composed of *Fagus sylvatica* (beech), *Fraxinus excelsior* (ash), *Acer* (maple), *Tilia* (lime) and *Alnus* (alder) occur (Mayer, 1974; Waldegger, 2005). The actual pasture zone Allmein is situated at approximately 1,450 m a.s.l. The lower boundary (1,300-1,450 m a.s.l.) is characterized by remains of former mining activities, such as waste heaps, mining debris and pits. Today, this region is primarily used for meadows and pastures.

Geology and ore deposits of Montafon

The Montafon valley belongs almost entirely to the austroalpine nappe. The northern part is covered by the Northern Limestone Alps whereas the major part rank among the Silvretta. The ore deposits occur along this tectonic boundary (Fig. 1) of Mesozoic sediments and late Palaeozoic old crystalline (Heissel, et al., 1965). Aside from smaller deposits in the Silvretta mountains, four types of ore deposits are known from Montafon. First, disseminated copper ores in Permian ignimbrites, which also contain gold and molybdenum. Second, sedimentary baryte mineralisation associated with Permian volcanism, as well as, third, sedimentary copper mineralisation from the lower Triassic, which emerged through the processing of the disseminated copper ores (Angerer, et al., 1976, p.4; Tropper, et al., 2011, pp.27-29; Hofmann & Wolkersdorfer, 2013, pp.16-18).

Only the fourth type, young-alpidic silver-containing chalcopyrite-fahlore veins, achieved an economic significance in the past. The conditions of its formation must still be clarified precisely. Likely, in the course of the orogeny of the Alps, hydrothermal solutions along disturbances and surface borders formed ore veins, comprising chalcopyrite, silver-containing fahlore, pyrite, among others, sulfidic ores in association with mainly siderite, ankerite and quartz. The mineralisation is concentrated in the Phyllite-Gneiss-Zone, but also extends farther into the overlying sediment layers (among others, the Alpine Verrucano). In Montafon this zone of mineralisation (Fig. 1) reaches from Rellstal in the West to the Bartholomäberg as far as the ridge of the Kristberg in the East (Haditsch & Mostler, 1986, pp.282-288; Tropper, et al., 2011, pp.28-29). Thus, most of the mines were located within a 2 km wide belt southward of the tectonic border.

Archaeological sites and topography

The discoveries of single bronze and iron artefacts were already assessed as signs of human presence in prehistoric Montafon, even before the first settlement sites were revealed (Schwarz, 1949, pp.284; Vonbank, 1966, p.86). In addition to the bronze winged axe of the Hallstatt period, which was found on the Alp Vergalda (St. Gallenkirch), there are single Iron Age findings, including two Latène iron spearheads and a fibula of the type Almgrem 65c2 (Vonbank, 1966, pp.84-86; Krause, 2009b, pp.22; Demetz, 1999, p.223). One of the spearheads was found during construction of a service road to Fritzentobel (Bartholomäberg). The other two artefacts were discovered farther into the valley, each at the foot of a pass. On the Schafberg near Gargellen, close to the Schlappiner Joch leading into Prättigau in Graubünden, the aforementioned spearhead was retrieved during house construction. The remains of its wooden shaft could be dated to the 2nd/1st century BC. The late Latène fibula of the type Almgren 65c2 was found at the ascent of the Zeinisjoch, which leads to Tyrol.

The picture of settlement history in Montafon underwent a change in the 1990s. The first vegetation historical investigations indicated the presence of prehistoric settlement (Kostenzer, 1996), and were supported by later palynological studies (Oeggl, et al., 2005; Oeggl & Wahlmüller, 2009). The final evidence for human presence in prehistoric times was adduced by the discovery of a fortified settlement in Friaga Wald in 1999 (Krause, 2001, pp.43-47; Krause, 2009b, pp.28-34). Until now a total of five prehistoric settlement places are known in Montafon, whose beginnings lie in the later Early Bronze Age. With the exception of the site of Diebschlössle near Lorüns at the entrance to the Ill valley, all of the sites are located on the Bartholomäberg, which due to its favourable settlement parameters can be considered the nucleus of prehistoric settlement in Montafon. A settlement phase in the Iron Age could be confirmed for hitherto three places as well: Dünglers Ebni, Friaga Wald and Diebschlössle.

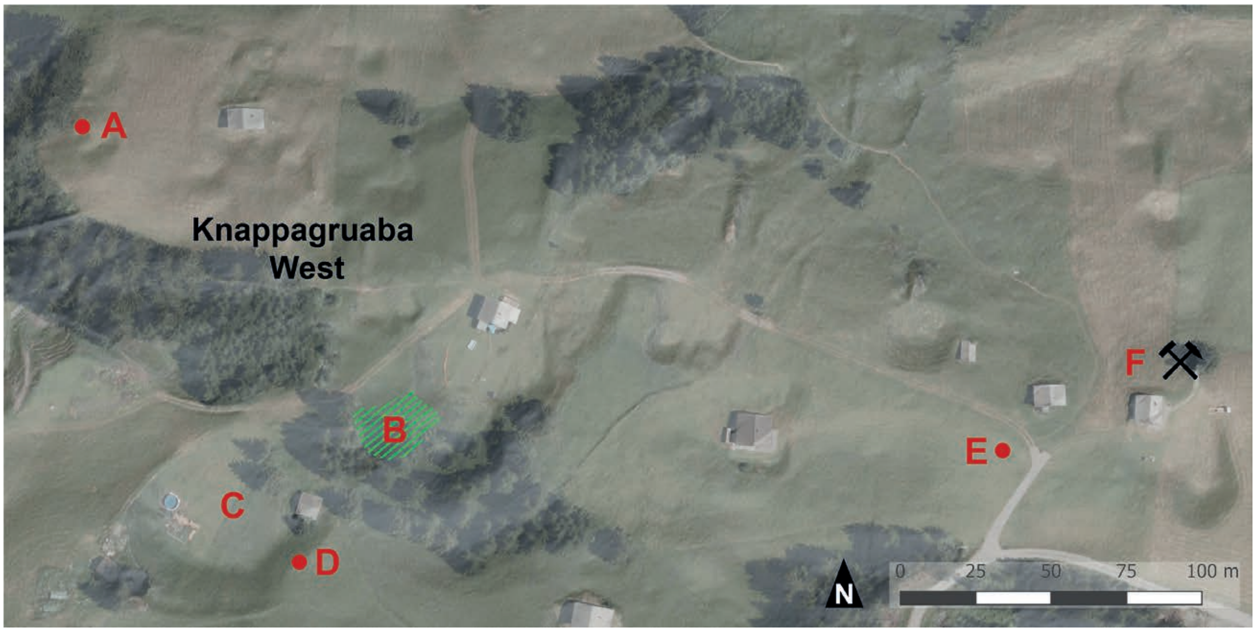


Fig. 2: Bartholomäberg, Knappagruaba. The field parcel Knappagruaba above Bartholomäberg. Numerous collapsed shaft openings and large-sized waste heaps are distinct in the underlaid elevation model. A Waste heap complex. B Mire 'Herbstzeitlose' (HZL). C Large waste heap. D Trial trenches from 2011 and 2012. E Settlement contexts. F Visitors mine 'St. Anna Stollen' (graphic: Montafonprojekt, data basis: Land Vorarlberg – data.vorarlberg.gv.at).

The Iron Age site of Dünglers Ebni is located on a flat surface on a mountain terrace southwest of the church in Bartholomäberg.[1] Dated house foundations and a large-sized stone pavement attest settlement there during the Hallstatt period. Indications of metallurgical processes are not present. All of the radiocarbon ages from the cultural layer fall into the Hallstatt plateau, and also the large quantity of local Illtal pottery cannot be localised more precisely within the Hallstatt period basing on the present state of research. The fragment of a handle of Taminser ceramic type, which was widespread in the Alpine Rhine valley, points to the later Hallstatt period.

The hillfort settlement in Friaga Wald is located in a topographically exposed place at a height of 940 m a.s.l., high above the Schruns basin. The stratigraphy of this site contains settlement phases of the Bronze and Iron Ages. Until now the Iron Age settlement has been dated to the transition from Hallstatt to Latène period. However, a renewed review of the findings did not confirm this date. Nonetheless, a completely restored vessel, belonging to the so-called Schneller ceramic type (Latène A-Latène C; Gurtner. 2004, p.106), two fragments of fibulae of the type Certosa VII (advanced Latène A; Teržan, 1976, pp.425-429), as well as the rim fragment of an early Latène Fritzen bowl[2], distributed in North Tyrol, attest a settlement in the Friaga Wald during the advanced early Latène period as well as in the middle and even into late Latène times. This is supported by a corresponding radiocarbon date to the 2nd/1st century BC.[3] Like at the site of Dünglers Ebni, no relics of metallurgical processing or production in Friaga Wald are known until now.

The inventory of Iron Age findings from Diebschlössle, located near Lorüns at the valley entrance (Wink, 2005, pp.47-49), together with early Latène Fritzener bowls and Schneller ceramic type (Krause, 2009b, Fig. 51, 1, 2, 6-8), corresponds with the spectrum of forms found in Friaga Wald. In addition, there are sherds of bowls with S-shaped profile, whose duration lasts until the middle Latène period. A few sherds derive from the Hallstatt time (Wink, 2005, pp.60-62).

The Montikel, the town hill of Bludenz, has three sites of findings: the Unterstein, Kleiner Exerzierplatz and the peak plateau. Between 1830 and 1935 more than 200 metal artefacts, mainly objects made of iron, were recovered at the foot of the hill. Most date to the later Latène period. The exact character of this particular site has not been clarified to this day; it might relate to findings originally from a place meant for burnt offerings and sacrifices, which eroded or slid downhill (Leitner, 1996, pp.36-41). Discovered on the Kleiner Exerzierplatz was a settlement layer with many disturbances within the later construction; the inventory consisted of Hallstatt to late Latène period findings (Leitner, 1996, pp.15-35).

New mining-archaeological investigations in Montafon

Since 2002 mining-archaeological investigations have been carried out in annual campaigns within the framework of the Montafon Project: first by the Free University in

Fig. 3: Bartholomäberg, Knappagruaba. Relicts of mining are comparably small-scaled in the western Knappagruaba, for which reason already at an early stage of work older find contexts were anticipated in this area. Near the forest (left in picture) the slope becomes very steep. At the transition of meadow to forest, trench 6 and 7 were laid out on a multiphased waste heap complex, in the late summer 2016 (photo: Montafonprojekt).

Berlin, and since 2006 by the Goethe University Frankfurt/Main, which brought forth a number of different find complexes dating from the high to the Late Middle Ages (Krause, 2009a; Krause, 2013). These undertakings also resulted in the discovery of different find complexes and in radiocarbon dating, which have enabled conclusions to be made about prehistoric activities that reach back into the Bronze Age. These could have been associated with a pasture economy as well as with mining activities. One focal point was investigations in the land parcels Knappagruaba (with the Herbstzeitlose mire) and Worms on the Bartholomäberg (Fig. 2).

Knappagruaba, north of the village centre of Bartholomäberg, lies at a height of ca. 1,330-1,350 m a.s.l. on a terrace with a slope to the South and within the traditional Maisäß zone. The lush meadows there are still used for pasturing today. The collapsed mining galleries with waste heaps in front are located in dense order and overgrown with grass. In the eastern part of the area are larger waste mounds and two accessible mines from the Middle Ages or the Early Modern Age. One has been restored as the sole mine open for visitors (Krause, 2015, pp.127). Located in the steeper western part of Knappagruaba are numerous waste heaps and structures, which indicate an older date in time (Fig. 3). Since 2015 systematic investigations have been conducted in this mountain landscape within the framework of an interdisciplinary project on mining archaeology, supported by the German Research Foundation.[4] Several preliminary investigations have formed the basis for the project. Initial indications of prehistoric activities in Knappagruaba were noted already during excavations in 2008 (Krause, 2009a, pp.530-531) and during archaeologically controlled dredging work in 2009: a pit containing prehistoric pottery.[5] Further indicators were gained through geomagnetic surveying carried out between 2009 and 2015. Systematic excavations in 2015 and 2016 yielded additional settlement find contexts, such as pit structures with a flat base, stone filled fire pits, and collapsed substructures built of stones. The pottery recovered in several places is clearly prehistoric. By means of charcoal samples the fire pits could be dated to the Middle Bronze Age (Tab. 2, samples 9, 10 and 12). Similar contexts of the same date already appeared in the settlement on Bodaweg. Through the analysis for heavy metals an association with metallurgy could be excluded. It seems that the pits are related to food production (Würfel, et al., 2010, pp.510-512). Furthermore, no indications of metallurgical activities were observed in the mining area in Knappagruaba.

Traces of mining confirming Iron Age mining on the Bartholomäberg were finally attested in Knappagrua-

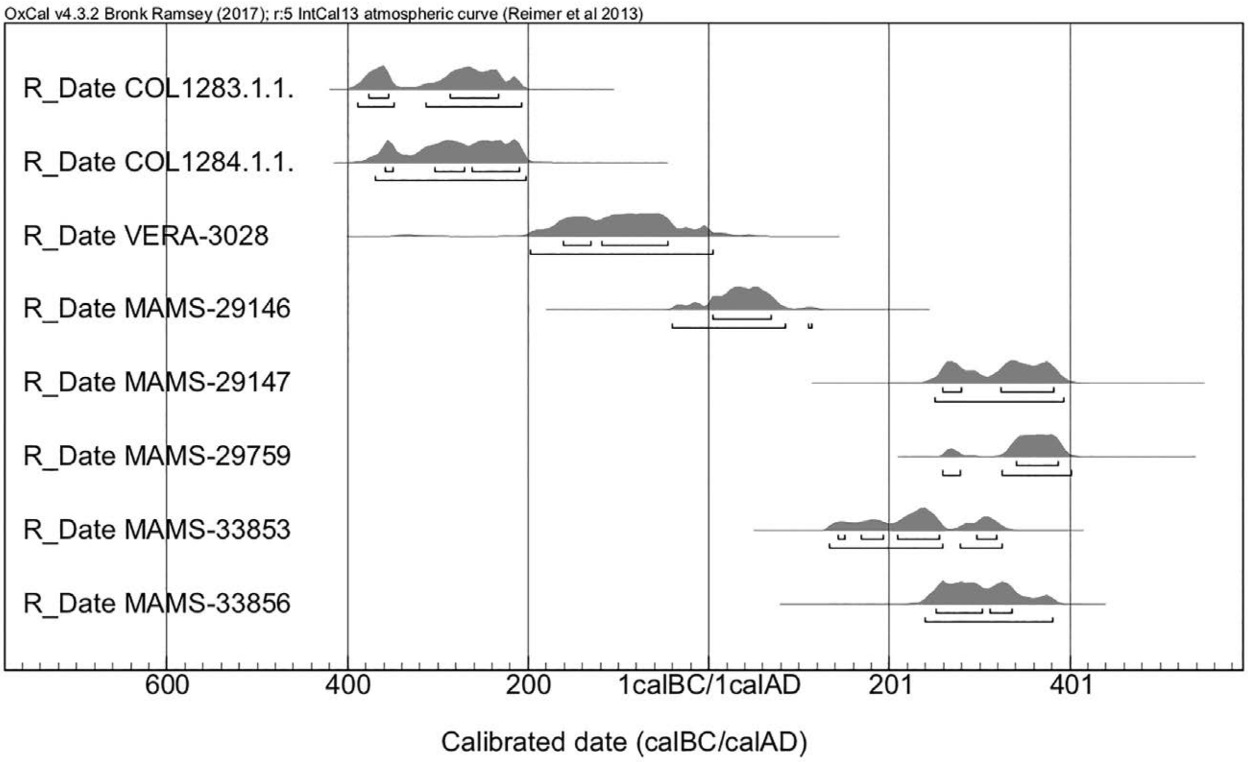


Fig. 4: Datings from Knappagruaba West as well as the Iron Age settlement layer in 'Friaga Wald'. Samples 1 and 2 derive from the large waste heap south of mire 'Herbstzeitlose' (HLZ) and attest the creation of the heap during the Iron Age. They overlap almost with the date for sample 3 from 'Friaga Wald'. Samples 4 to 8 are out of the High Medieval colluvium inside trenches 6 and 7 (graphic: Montafonprojekt).

Sample	Position	Laboratory number	14c-Age (BP)	1 Sigma	2 Sigma
1	Knappagruaba, great heap lowest fill	COL1283.1.1.	2245±24	cal BC 378 - 234	cal BC 389 - 208
2	Knappagruaba, great heap fossil soil below lowest fill	COL1284.1.1.	2219±24	cal BC 359 - 210	cal BC 370 - 203
3	Friaga Wald settlement, cultural layer	VERA-3028	2075±40	cal BC 161 - 46	cal BC 199 – AD 5
4	Knappagruaba, trench 6 infilling of mining shift	MAMS-29146	1963±27	cal AD 5 – 70	cal BC 41 – AD 115
5	Knappagruaba, trench 6 infilling of mining shift	MAMS-29147	1714±28	cal AD 260 – 383	cal AD 251 - 394
6	Knappagruaba, trench 6 feature 5 (colluvium)	MAMS-29759	1693±18	cal AD 341 – 387	cal AD 260 - 402
7	Knappagruaba, trench 7 feature 5 (colluvium)	MAMS-33853	1793±26	cal AD 145-319	cal AD 135-325
8	Knappagruaba, trench 6 feature 5 (colluvium)	MAMS-33856	1739±25	cal AD 253-336	cal AD 241-380

Tab. 1: Bartholomäberg, selected radiocarbon datings from the Knappagruaba and the Friaga Wald (table: Montafonprojekt).

ba-West, some 200 m away from the prehistoric settlement contexts. Numerous small-sized surface structures, small waste heaps and depressions from collapsed galleries are located there on the steep mountain slope. Two of the largest waste heaps in the area extend to the East and to the South. In the course of cutting a section through one of the waste heaps at least two fills of mining waste could be determined. Basing on radiocarbon ages, the upper, by far more massive fill consisting of phyllite-gneiss and mica slate could be dated to the Late Middle Ages; the lower deposit, by contrast, dates to the 4th/3rd century BC (Röpke, 2012b, p.274), thus to the Latène period (Fig. 4, Tab. 1).

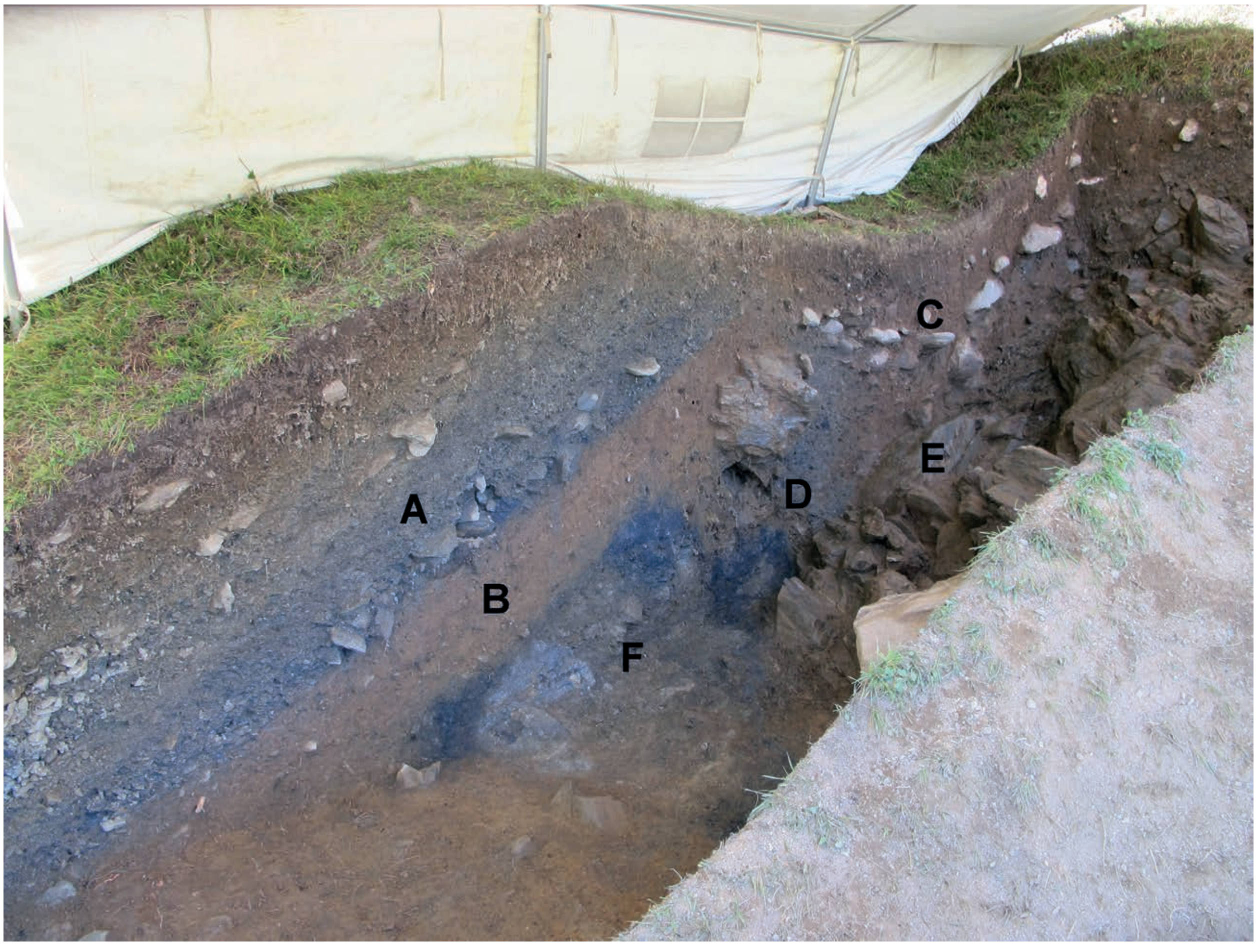


Fig. 5: Bartholomäberg, Knappagruaba, west profile of trench 6. A The layer of waste material dates from the 13th century AD. B The brown-reddish colluvium is from the High Medieval Period and contains older charcoals (Late Iron Age till 4th century AD). The backfilling C also contains charcoal from this age. Maybe the pitlike feature D belongs to another period of mining activity. The native rock E is decomposed in some parts F (photo: Montafonprojekt).

Further investigation on Late Iron Age mining was performed on a multi-phased, comparably small waste heap complex (Fig. 2, A), located on a steep slope with easy access to the ore veins (thin layer of organic litter). The complex contains traces of no less than two phases of mining activity (Fig. 5). The uppermost layer of waste material, mainly composed of mica slate, was piled up in the 13th century AD. It covered a reddish brown colluvium from the High Medieval Period. Five radiocarbon-dated charcoals are from the Late Iron Age to the late 4th century AD (Tab. 1, samples 4-6). Detectable under the colluvium are one or even more phases of mining activity (small heaps and pit features). Maybe this zone of Knappagruaba, not far from the Herbstzeitlose (HZL) mire, was part of the Iron Age mining area.

The question as to the presence of older mining activity that would possibly reach back to the Bronze Age still cannot be conclusively answered. In the course of various trial trenches and excavation in the mining zone on Bartholomäberg (Krause, 2009a; Würfel, et al., 2011, pp.127-134), several features were recovered that provided dates from the Bronze Age (Fig. 6, Tab. 2). They point to human presence and land-use practices at this elevation (1,300-1,450 m a.s.l.), which is far above the zone of the actual prehistoric settlements.

Palynological and geochemical investigations of a mire in the mining area of Knappagruaba

The environment of Knappagruaba has been completely altered by large and small mining waste dumps and numerous galleries; thus, tracing the location of possible prehistoric ore exploitation is difficult. One method of detection is provided by combining palynological analyses of pollen, microscopic and macroscopic charcoal, and geochemical parameters of peat cores from within the mining district. The opening of the landscape, the extraction of timber and fuelwood and the extension of settled

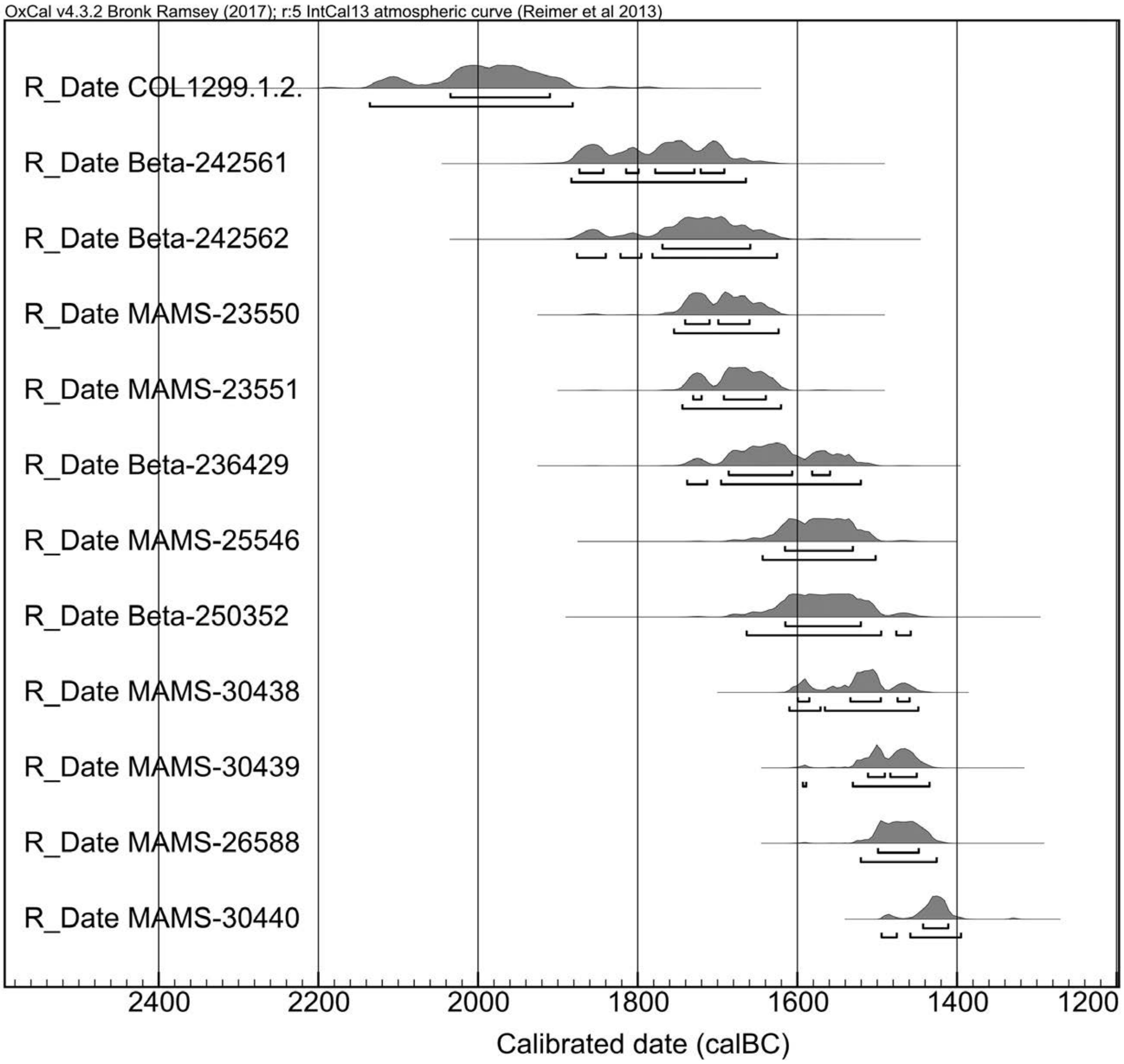


Fig. 6: Bronze Age datings from different find contexts within the mining zone of Bartholomäberg. In addition to well-defined settlement complexes (samples 9, 10 and 12 from fire pits), there are also finds without an exact context, like shallow pits or charcoal piles (samples 2 and 8) (graphic: Montafonprojekt).

areas are evident in pollen diagrams in the form of forest clearings and an increase of non-arboreal pollen (NAP). Fire activities are reflected in the abundance of micro- and macro-charcoals in the peat deposits. Furthermore, different methods applied in ore or metal processing caused the accumulation of heavy minerals, such as copper and lead during peat bog formation.

Ombrogenic bogs are not only excellent chronostratigraphic archives for pollen, but also for atmospheric depositions as by-products of metallurgical processes and procedures. The minerotrophic peats that are present in the Knappagruaba area are equally suitable for palynological studies, but their potential for geochemical analysis has been disputed, because influx and removal of elements by surface and groundwater can hardly be estimated. However, some investigations have re-evaluated the usefulness of mires for metal precipitation measurements (eg. Mighall, et al., 2009; Shotyk, et al., 2002; Breitenlechner, et al., 2010; Hansson, et al., 2015). The palynological and geochemical results presented here (section 6.1-3) can serve as an indicator for mining activities. Rather than reflecting the atmospheric pollution of minerotrophic peats with heavy minerals, they prove that higher concentrations are caused by contaminated slope water, which has long been circulating in Knappagruaba's mining galleries until today. In combination with pollen and charcoal analyses, evidence is presented for the effects of prehistoric mining in general and phases of increased mining activities in particular.

Sample	Position	Laboratory number	14c-Age (BP)	1 Sigma	2 Sigma
1	Roferweg Bergschmiede, underneath forge layer	COL 1299.1.2	3620±47	cal BC 2035 – 1911	cal BC 2136 - 1882
2	Knappagruaba Geländegraben, underneath old soil development	Beta-242561	3450±40	cal BC 1874 - 1692	cal BC 1884 - 1665
3	Knappagruaba Geländegraben, out of old soil development	Beta-242562	3420±40	cal BC 1770 - 1660	cal BC 1877 - 1626
4	Roferweg Bergschmiede, feature 102, shallow pit	MAMS-23550	3399±28	cal BC 1741 - 1661	cal BC 1755 - 1624
5	Roferweg Bergschmiede, feature 102, shallow pit	MAMS-23551	3383±27	cal BC 1731 - 1640	cal BC 1745 - 1621
6	Goritschang, within a sinkhole, close to mineshaft	Beta-236429	3340±40	cal BC 1687 - 1560	cal BC 1739 - 1521
7	Garsella West, drill core at a depth of 80 – 85 cm	MAMS-25546	3299±31	cal BC 1616 - 1531	cal BC 1644 - 1503
8	Knappagruaba Geländegraben, pit with fire debris	Beta-250352	3290±40	cal BC 1616 - 1521	cal BC 1664 - 1459
9	Knappagruaba trench 4, feature 14, fire pit	MAMS-30438	3247±24	cal BC 1600 - 1460	cal BC 1611 - 1449
10	Knappagruaba trench 4, feature 23, fire pit	MAMS-30439	3225±22	cal BC 1512 - 1451	cal BC 1594 - 1435
11	Knappagruaba trench 4, feature 10, concentration of charcoal	MAMS-26588	3206±25	cal BC 1500 - 1449	cal BC 1521 - 1426
12	Knappagruaba trench 4, feature 23, fire pit	MAMS-30440	3152±18	cal BC 1443 - 1412	cal BC 1495 - 1396

Tab. 2: Bartholomäberg, mining zone. Radiocarbon datings form the Bronze Age. (table: Montafonprojekt).

Fig. 7: Bartholomäberg, Knappagruaba. The small reed-covered mire 'Herbstzeitlose' (HZL). To the left and right are large mining waste heaps that probably date to the Late Middle Ages or early modern period (photo: Montafonprojekt).

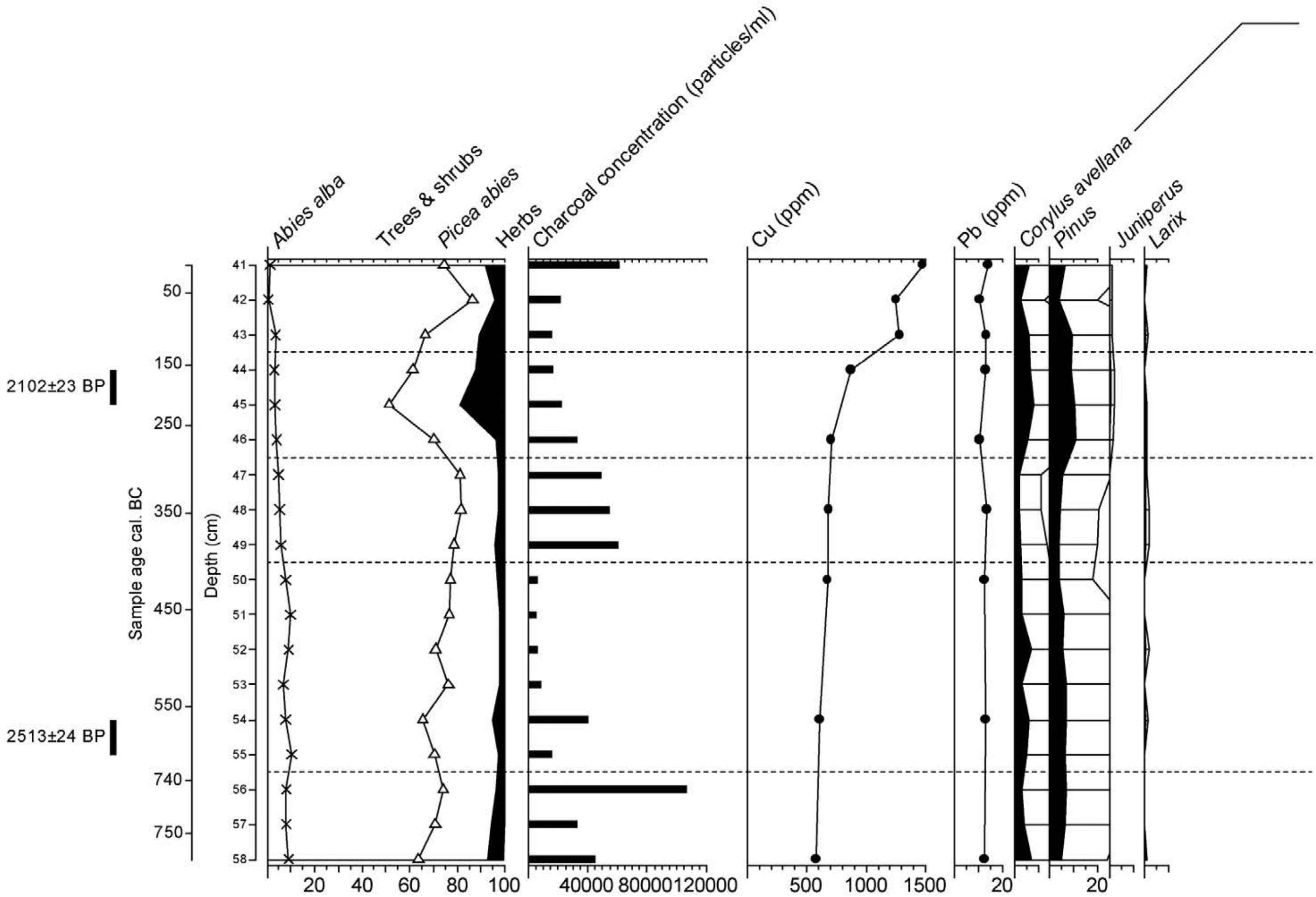


Fig. 8: Bartholomäberg, Knappagruaba. Pollen diagram of the mire 'Herbstzeitlose' (HZL) (graphic: Montafonprojekt).

The investigated mire at Bartholomäberg

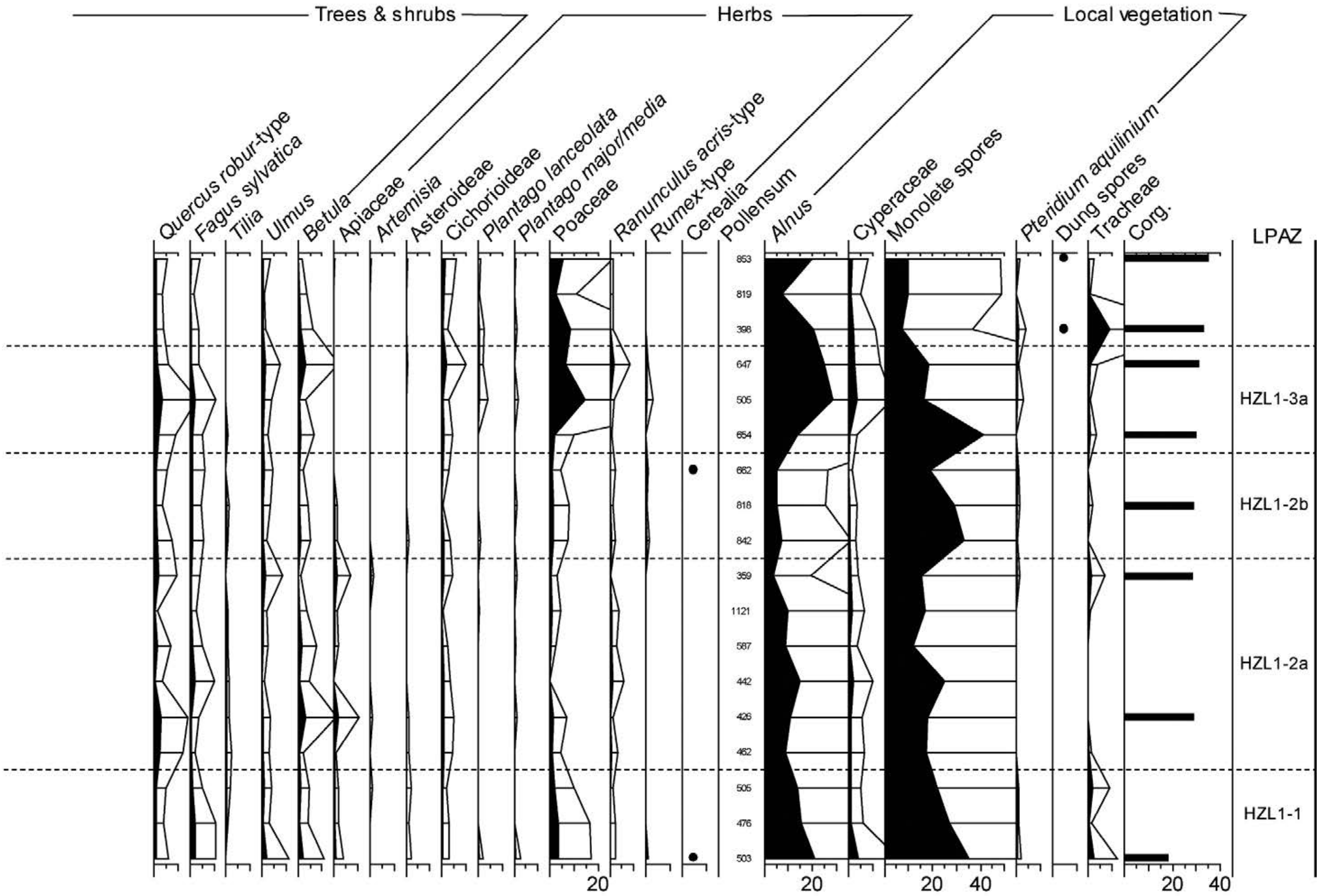
Today, the Knappagruaba mining area is largely deforested and used for grazing. Small forest patches that still exist consist of spruce (*Picea abies*) and fir (*Abies alba*), partly with beech (*Fagus sylvatica*). Wet depressions occasionally contain alders (*Alnus*). Above 1,400 m, spruce is accompanied by larch (*Larix*) and stone pine (*Pinus cembra)*. The small reed-covered mire Herbstzeitlose (HZL) is situated between mine dumps (Fig. 2, B, Fig. 7) at an altitude of 1,300 m a.s.l. and, thanks to its small size, especially suited for reconstructing the local vegetation.

With the help of an avalanche probe, two transect surveys were carried out to identify the thickest peats; subsequently, a core of 6 cm diameter and 109 cm length was retrieved with a gouge auger (coring 2) in the summer of 2015. Another core from the edge of the mire contains only 60 cm of peaty material (coring 1). The minerotrophic reed peats are underlain by sands. The PH value of all varies between 4.7 and 5.7. Samples were taken from the cores for further palynological and geochemical analysis.

Methods

The preparation of samples for palynological pollen analyses followed standardized methods of acetolysis and mounting of pollen grains in silicone oil (Moore, et al., 1991). For the calculation of pollen concentrations, *Lycopodium* tablets were added to each sample (after Stockmarr, 1971). Charred plant remains larger than 10 µm were counted and are shown as concentrations. Pollen grains were counted up to a regional pollen sum between 500 and 1,100, excluding local species like hydrophytes, hygrophytes or swamp forest species (alder).

The cores were sampled at intervals of 1 to 2 cm for geochemical analyses. Thanks to the key role of the elements copper and lead for the identification of prehistoric mining, only these two elements were measured. We decided against measuring scandium, a reference element used to normalize heavy mineral curves against their natural occurrence, due to the dominant role of aquatic rather than aeolian contamination in our area of study and the significantly higher metal values involved.



Continued from Fig. 8.

The samples were dried, homogenized and subsequently measured with the AAS (Atomic Absorption Spectrometer, model: Perkin-Elmer Pinnacle 900T).

AMS datings of peat samples were carried out at the Klaus-Tschira-Laboratory for Radiometric Dating Methods (Curt-Engelhorn-Centre Archaeometry, Heidelberg), and Beta Analytic (Miami, Florida). The results were calibrated with OxCal v4.2.4 (Bronk Ramsey and Lee, 2013); IntCal13 atmospheric curve (Reimer, et al., 2013). In this paper, only the analyses' results concerning the Iron Age are presented. Namely, peat growth stops at this point and does not continue until the Middle Ages; that part of the profile will be addressed in a future publication.

Results of analyses

The pollen diagram HZL 1 (Fig. 8, Tab. 3), can be divided into three zones (LPAZ). The beginning of pollen zone LPAZ HZL1-1 (800-600 cal. BC) is characterised by a dominance of spruce (*Picea*) (60%). Fir (*Abies*) reaches 10%. Hazel (*Corylus*), oak (*Quercus*), ash (*Fraxinus*), lime (*Tilia*), beech (*Fagus*) and elm (*Ulmus*) are constantly present. The NAP values lie between 4 and 7%. The appearance of *Rumex*, *Campanula*, Asteroideae and pollen grains of Cerealia, *Artemisia*, Chenopodiaceae and *Plantago lanceolata* suggests agropastoral activities in the wider surroundings of the mire. Alder (*Alnus*) used to grow on wet sites. Charcoal concentrations range between 3,300 and 10,600. Copper values range between 580 and 610 ppm, lead values between 12 and 13 ppm.

Pollen zone LPAZ HZL1-2 (600-300 cal. BC) contains two sub-zones. From 600 BC – Pollen zone LPAZ HZL1-2a – spruce dominates the pollen spectrum with up to 80%, while fir values decrease to below 5%. Minor NAP percentages and low charcoal concentrations point to a moderate degree of human impact in the vicinity of the mire. Copper has risen to 680 ppm, but lead values remain unchanged with 12-13 ppm. In pollen zone LPAZ HZL1-2b, charcoal concentrations increase significantly to 5,000-6,000. The values of Poaceae are slightly higher as well.

Pollen zone LPAZ HZL1-3 (250 BC-50 AD) can also be divided into two sub-zones. In Pollen zone LPAZ

LPAZ		Depth (cm)	Age cal. BC/AD	Charcoal concentration	Geochemistry (ppm)
HZL 1-1	Spruce/Fir Zone	58-55.5	800-600 BC	3300-10600	Cu 580-610 PB 12-13
HZL1-2a	Spruce Zone	55-49.5	600-350 BC	500-1500 (4000)	Cu 610-680 Pb 10-13
HZL 1-2b		49-46.5	350-250 BC	5000-6000	Cu 680-700 Pb 12-13
HZL 1-3a	Spruce/Pine/ NAP Zone	46-43.5	250-100 BC	1600-3300	Cu 700-870 Pb 10-13
HZL 1-3b		43-40.5	100 BC-50 AD	1500-6000	Cu 1250-1450 Pb 10-14

Tab. 3: Bartholomäberg, Knappagruaba. Pollen zones within the mire 'Herbstzeitlose' (HZL). (table: Montafonprojekt).

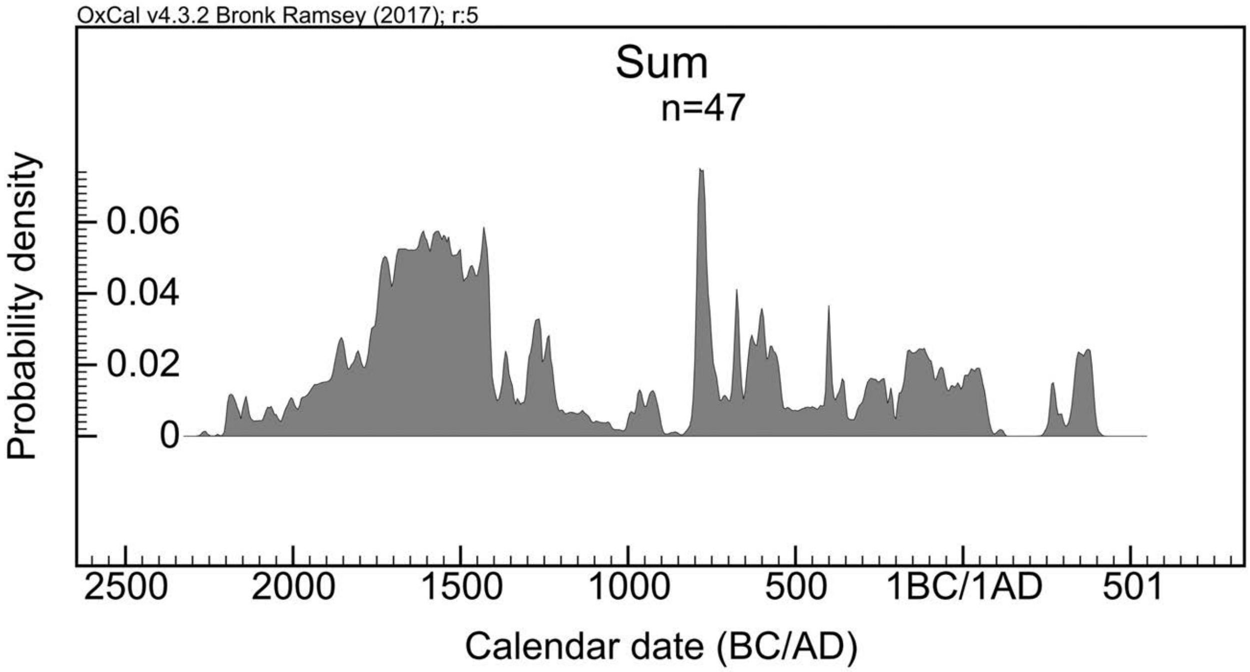


Fig. 9: Sum diagram of radiocarbon datings from Bartholomäberg, ranging from the Early Bronze Age to Late Antiquity. 25 datings are from settlement excavations, seven from mining situations, nine from finds without a closer context, and six datings from the mire profiles. They denote phases, that can be associated with episodes or developments in mining, for example, increased amounts of heavy minerals (graphic: Montafonprojekt).

HZL1-3a, spruce values drop to less than 50%. Fir values also decrease. Together with the rise of light-demanding hazels, pines and a closed curve of juniper (*Juniperus*), this documents an opening of the canopy. The curve of NAP rises to 19%, and Poaceae reaches a maximum of 15%. Other indicators of human and livestock presence (especially *Plantago lanceolata*) occur frequently. The alder, a wetland representative, shows increased values as well. Copper values have risen and now lie between 700 and 870 ppm; the values for lead are constant at 10-13 ppm. In pollen zone LPAZ HZL1-3b, the spruce curve rises again to over 80%. At the same time, abundant wooden vessels hint at the occurrence of spruce either on the mire or in its immediate environs. The NAP values have decreased, but their composition is mostly identical with the one of the zone below. Alder, however, decreases considerably. Charcoal concentrations lie between 1,500 and 6,000. Copper has risen to values of 1,250 to 1,450 ppm, while lead is steady at 10-14 ppm.

Iron Age activities in the mining district of Knappagruaba

The sub-alpine forest in Montafon had already been cleared to a large extent in the Early Bronze Age (Oeggl et al., 2005; Oeggl & Wahlmüller, 2009). This action has been well documented by settlement archaeology and

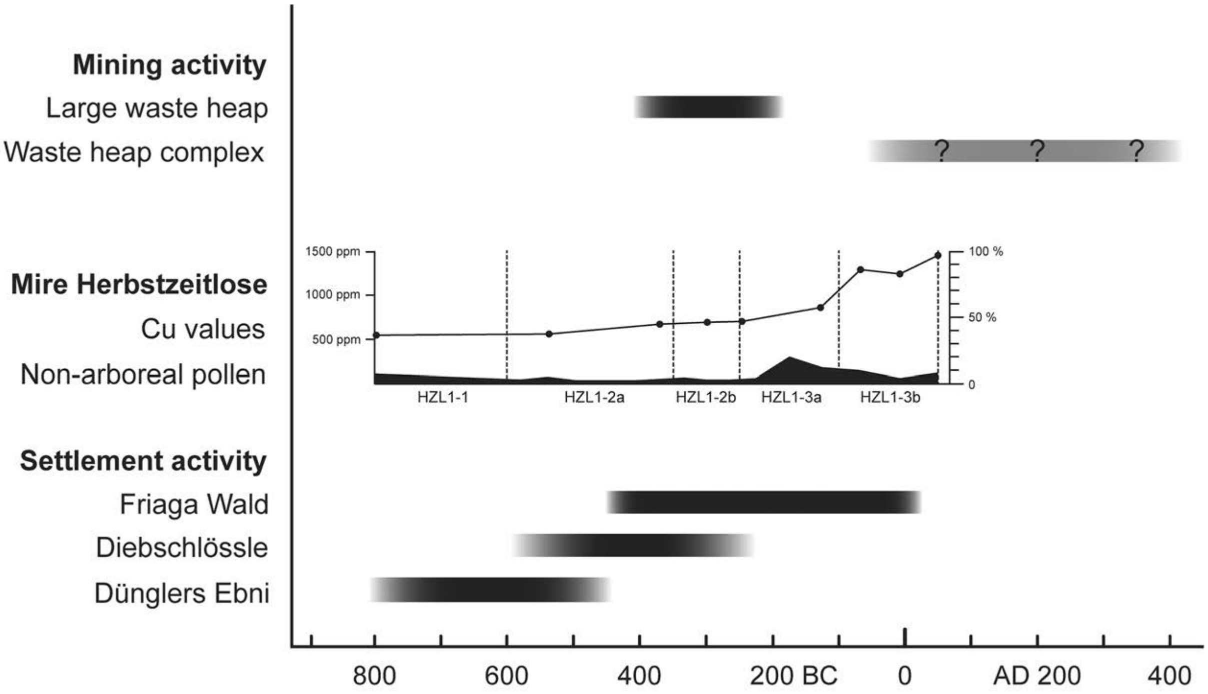


Fig. 10: Bartholomäberg. Settlement and mining activity compared to the geochemical and palynological results of the mire 'Herbstzeitlose' (HZL). The large waste heap is located in the immediate vicinity of the mire. As charcoal samples were dated, an old-wood effect cannot be ruled out. Radiocarbon dated samples out of a colluvium inside of the waste heap complex may be linked to mining activity. The rise of copper values and non-arboreal pollen is related to mining activity in the proximity of the mire at the same time as the settlement activity in the 'Friaga Wald' (graphic: Montafonprojekt).

data from the settlement zone on the Bartholomäberg. Human pressure on forests apparently increased during the Middle Bronze Age up to an elevation of about 2,000 m a.s.l (Wahlmüller, 2002). The high values of micro- and macro-charcoals in the pollen diagrams and the abundance of charcoals in the soils (Röpke, 2012a; 2012b) attest that fire played an important role in forest clearance. Spruce benefited from burning, while the more sensitive fir, a previously dominant component of sub-alpine forests, gradually disappeared in the course of the Bronze Age.

This development had already been completed when the Herbstzeitlose mire started to form at ca. 1000 BC in the central part, versus 900/800 BC at its margins. During this time, a spruce forest with low percentages of fir covered the Knappagruaba area. In the wider surroundings of the mire, land use practices were taking place, as indicated by findings of pollen of *Plantago lanceolata*, Chenopodiaceae and cereals. The settlement and grazing areas were probably located at some distance, because NAP and also coprophilous fungus spores are relatively few. The effects on the forests must therefore be rated as moderate. Data from the Tschuga mire confirm that human impact between 800 and 300 BC was distinctly less than during the Bronze Age (Schwarz & Oeggl, 2013). It seems that, unlike in the Bronze Age, land use was now largely restricted to areas below 1,200 m a.s.l. The high charcoal concentrations demonstrate, however, that burning was a part of land management practices, most likely in order to prevent bush encroachment and reforestation at a low grazing pressure. On the other hand, it could also have been the outcome of ore processing. This is suggested by the geochemical results from the respective peats. Particularly the copper values of 500-600 ppm are markedly high in relation to measurements from other mires. For instance, the Tschuga mire located approximately 100 m below, only reaches values of 50 ppm (Krause, 2015, p.103, Fig. 158). The latest measurements from the Garsella mire, ca. 100 m above, yielded copper values of merely 20 and 40 ppm. The peats from the centre of the Herbstzeitlose mire, which are about 200 years older, also reach copper values of ca. 230 ppm, thus indicating the lateral inflow of copper solutions already during the earliest phase. This may be interpreted as an effect of prospecting or initial processing which caused water contamination. Such practices intensified around 800 BC as revealed by the increased copper values. The influence on the surrounding vegetation was however spatially limited, for it is not reflected by any regional signal, apart from higher micro-charcoal concentrations. Nonetheless, they must have triggered erosion at Knappagruaba, since the peat profile from the centre contains minerogenic deposits from that period. This part of the sequence has copper values of merely 80-140 ppm, hence proving that copper is mainly bound to humic substances which is why the retention capacity of peats is decidedly higher (Würfel, et al., 2010).

Around 600 BC, anthropogenic influence was slightly reduced. The low NAP values and charcoal concentrations suggest that the vegetation around the mire was closed and land use in the wider area was minimal. Nonetheless, copper-bearing water was still seeping into the mire. This phase lasted until approximately 350 BC, when charcoal concentrations started to increase significantly without any obvious changes in NAP. These occur about 100 years later, with a distinct rise in NAP as well as heliophilous pioneer species like hazel, pine and juniper. The strong increase in Poaceae confirms the opening of the vegetation cover, which may also have been achieved by intentional burning. A similar development can be seen around 300 BC in the Tschuga mire, where crop production and pastoralism apparently intensified (Oeggl, et al., 2005; Schmidl, et al., 2005; Schwarz & Oeggl, 2013). For the Knappagruaba area, however, there is still no direct indication of agriculture or livestock raising. Coprophilous fungal spores only occur sporadically, and cereal pollen is completely absent. On the other hand, a local thinning and clearing of forests is clearly observable. A causal relationship with a Late Iron Age mining phase seems likely due to the synchronous rise of copper values (to over 1,400 ppm) and a waste heap in the immediate vicinity of the Herbstzeitlose mire, which dates back to the 4th/3rd century BC (Röpke, 2012b, p.274). As charcoal samples were dated, an old wood effect cannot be excluded.

Even the Tschuga mire, located 100 m above Knappagruaba, shows increased copper values in the Late Iron Age, although they amount to a maximum of only 100 ppm (Krause, 2015, p.103, Fig. 158). At that point, a hiatus is present in the diagram. The subsequent peats originate from the Middle Ages.

Discussion

Multidisciplinary investigations in Montafon have discovered prehistoric settlements and numerous single findings as far as the area of Bludenz, which confirm that these inner alpine environments were already settled and managed during the Bronze and Iron Ages in varying intensity (Fig. 9). Artefacts of the Iron Age attest the exchange and network with the Alpine Rhine valley as well as with neighbouring northern Tyrol. As described above (sections 2-5), new mining-archaeological investigations have achieved firm evidence for Iron Age mining on Bartholomäberg. Thereby, archaeological features and scientific data derive from a comparably small area in the mining district of Knappagruaba. There remains of outcropping hydrothermal ore veins are still visible in near-surface rock on the steep slopes, and mine drainage water flows out of the galleries and shaft openings even today. It can be assumed that there was an extensive occurrence of ores near the surface in prehistoric times. For example, when digging deep into the slope, ground water that is strongly contaminated with copper flows out. This content is confirmed by heavy metal analyses on peat profiles taken from the mire Herbstzeitlose (HZL), located in the midst of the waste heaps in this mining zone and in the sections of the Late Iron Age. It shows a strong rise in copper values, indicating mining activities. These find contexts were accompanied by distinct intrusions and changes in the vegetation. They also show an opening of the vegetation cover as the result of intensified land use in the surroundings. Subsequently accumulations of colluvia occurred in the mire (section 6.4).

The scientific data gained from geological, palynological and geochemical investigations were evaluated with specific reference to the different archaeological findings and contexts that were revealed. One waste heap of gangue represents the first mining archaeological context, which was covered by a large waste heap from the Late Middle Ages. It was discovered in the course of an excavation in 2012. It dates to the Late Iron Age and lies only a few metres down slope, below the Herbstzeitlose mire (Fig. 2). Thus, the data and find contexts could be set in immediate association with one another. Thereby the basic problem of the paucity of material from prehistoric mining became obvious: namely, traces of prehistoric mining are covered by extensive medieval and modern mining activities and can be recovered today only through specifically aimed prospection.

Nevertheless, the above-mentioned iron spearhead found in Fritzentobel in the settlement zone of Bartholomäberg might be indicative of Iron Age mining. Elmar Vonbank already interpreted the spot where the artefact was found in immediate proximity to the ocurrence of ore as an important indicator. The exposure of rock in the deep ravine (Tobel) would have enabled relatively easy access in terms of prospection and exploitation. However, archaeological evidence for mining has certainly been destroyed by erosion processes and subsequent mining in the area.

On the Bartholomäberg – and this applies to the entire inner Alpine settlement area in Montafon as well – until now neither in Bronze nor Iron Age settlements or in the mining zone have indications been found of metallurgical processes of preparing and smelting ores or the remains of copper or iron processing. This situation stands in strong contrast to the abundance of remains present in other mining districts, for example, in the Oberhalbstein in Graubünden or Mitterberg in Pongau, where there is a multiplicity of evidence for the chain of processing and production. An explanation for this difference might be that in Montafon in prehistoric times only the first beginnings of ore exploitation and its processing are present, and that possibly any further processing was not carried out at all in the ore and mining zone, but instead in another locality. The prepared and enriched ore had to be transported to these places. Two melting furnaces are known at least for the High and Late Middle Ages: the smelting furnace in Silbertal and in Tschagguns, which are located directly next to water courses. If we were to imply such a situation for prehistorical findings, then their preservation and discovery would be even more problematic and indeed coincidental.

These new results reinforce the suggestion that during the Late Iron Age small-scale mining for copper or iron was conducted in Montafon on the Bartholomäberg (Fig. 10). This has been affirmed consistently by radiocarbon datings for decisive mining contexts and the results of the vegetation history, soil studies and heavy-metal analyses. Moreover, this phase can be linked with archaeological settlement contexts on the Bartholomäberg. By continuing and intensifying mining archaeology investigations in this region, we have the opportunity to record in depth a comparably small mining district, in contrast to large mining districts in the Eastern Alps, and to use settlement contexts and data on the natural environment data in order to model its socioeconomic function.

Notes

1 This site was studied by Rudolf Klopfer for a master's thesis in 2014 at Goethe University in Frankfurt/Main. It is being prepared for publication.

2 The sherd bears a rare stamped decoration with a standing S (Lang, 1998, pp.170-173). Another sherd with comb-stamped decoration confirms relations to early Latène culture in Northern Tirol (Lang, 1998, p.173).

3 Concerned here is one charcoal sample from an Iron Age layer, trench 3, find complex 62 Vera-3028 2974 BP ±40 1σ 161-46 cal BC, 2σ 199 cal BC – 5 cal AD.

4 Since 2015 this project is supported by the German Research Foundation and titled: *Montanarchäologie im Montafon, Vorarlberg (*Österreich*) – Zur Archäologie und Geschichte eines Montanreviers in den Zentralalpen*.

5 Documentation was carried out by the *Archäologischer Dienst* company in Söll/Tirol, commissioned by the Austrian Federal Monuments Office. We express our gratitude for the provision of documentation and findings for scientific study.

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Authors

Rudolf Klopfer M.A. – Goethe-Universität Frankfurt, Institute of Archaeological Studies, Section III, Pre- and Protohistory
PD Dr. Astrid Stobbe – Goethe-Universität Frankfurt, Institute of Archaeological Studies, Section III, Pre- and Protohistory
Prof. Dr. Rüdiger Krause – Goethe-Universität Frankfurt, Institute of Archaeological Studies, Section III, Pre- and Protohistory

Correspondence and material requests should be addressed to: r.krause@em.uni-frankfurt.de; stobbe@em.uni-frankfurt.de; klopfer@em.uni-frankfurt.de

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Caroline O. Grutsch, Klaus-Peter Martinek, Peter Tropper, Joachim Lutz

Prospecting for copper – Mineralogical and first mining archaeological surveys in western North Tyrol, Austria

ABSTRACT: *The institutional mining archaeological research in Tyrol of the last years was focussed on the "big players" like Schwaz/Brixlegg and Kitzbühel areas. But beside these well-known major copper deposits there are more than 70 base metal mineralizations in Tyrol, west of the mining district of Schwaz/Brixlegg. In this area no systematic mining archaeological research was carried out until 2011, therefore the project "Prähistorische Kupferproduktion im Nordtiroler Oberland" was launched. The two main goals were the mineralogical and geochemical characterization of occurring copper ores and locating evidence for prehistoric mining in the target region. A selection of the most important results is presented here.*

Within this project more than 30 surveys in 27 different mining areas have been carried out and 21 copper ore occurrences were sampled and analysed. Three mining areas yielded indication for prehistoric or roman mining and are waiting for detailed examination. Furthermore many different historic mining traces from this area would also merit thorough documentation.

From a mineralogical point of view the results show, that even in a small area like western Tyrol a great diversity of copper ore parageneses can be found. Theoretically it would have been possible to produce the main prehistoric copper types from genuine ores.

KEYWORDS: WESTERN NORTH TYROL/AUSTRIA, PREHISTORIC MINING, MINING ARCHAEOLOGICAL SURVEYS, ORE SAMPLING, COPPER ORES, MINERALOGY, GEOCHEMISTRY

Premises and state of research

The institutional mining archaeological research in Tyrol of the last years, especially within the RC HiMAT[1], mainly focussed on well-known mining districts like Schwaz/Brixlegg, Mitterberg and Kitzbühel areas (Fig. 1), which have been of supra-regional importance already in the Bronze Age (e.g. Goldenberg et al., 2011, Goldenberg, 2015, Tomedi et al., 2013, e.g. Stöllner et al., 2016, Koch Waldner & Klaunzer, 2015). But beside these major copper deposits, more than 70 base metal mineralizations can be found in the (economic) geological and mineralogical literature for western North Tyrol (Gasser, 1913; Geognostisch-montanistischer Verein von Tirol und Vorarlberg, 1839-1842; Isser, 1888; Srbik, 1929; Klebelsberg, 1935, 1939; Mutschlechner, 1954, 1955, 1956, 1963, 1990, 1991; Matthiass, 1960, 1961; Vohryzka, 1968; Vavtar, 1986; Gstrein, 1990; Haditsch, 1995). These smaller mining areas and copper ore occurrences could have supplied local demand in prehistoric times as already proved elsewhere (e.g. in Styria, Presslinger & Eibner, 2004). Especially as there is some evidence for prehistoric copper production and processing from western North Tyrol. These include indication for smelting from the vicinity of Wenns/Pitztal (Tomedi, 2002), raw copper from the settlement Fließ-Silberplan (Nicolussi & Tomedi, 2008) and the hoard find from Moosbruckschrofen/Piller (Tomedi, 2002), a Bronze Age casting mould from Kiahbichl/Faggen (Sydow, 1998) and cast drops from Karrösten (Plank, 1973).

In addition to these indirect references there is also some unpublished direct evidence for prehistoric mining in the western part of Northern Tyrol. Bronze Age ceramic and miner's tools are known from Rotenstein/Serfaus and Knappenkuchl/Navis[2]. Moreover there is one published grooved hammer stone typical for prehistoric mining, which derives from Knappenkuchl/Navis (Steck, 2005).

But beside these few finds no systematic mining archaeological research in the western part of North Tyrol was carried out until the project "Prähistorische Kupferproduktion im Nordtiroler Oberland (Prehistoric copper production in western Tyrol)"[3] started. The project pursued the following goals:

1. the mineralogical and geochemical characterization of copper ores in order to enable comparison with investigations in other areas and prehistoric metal products

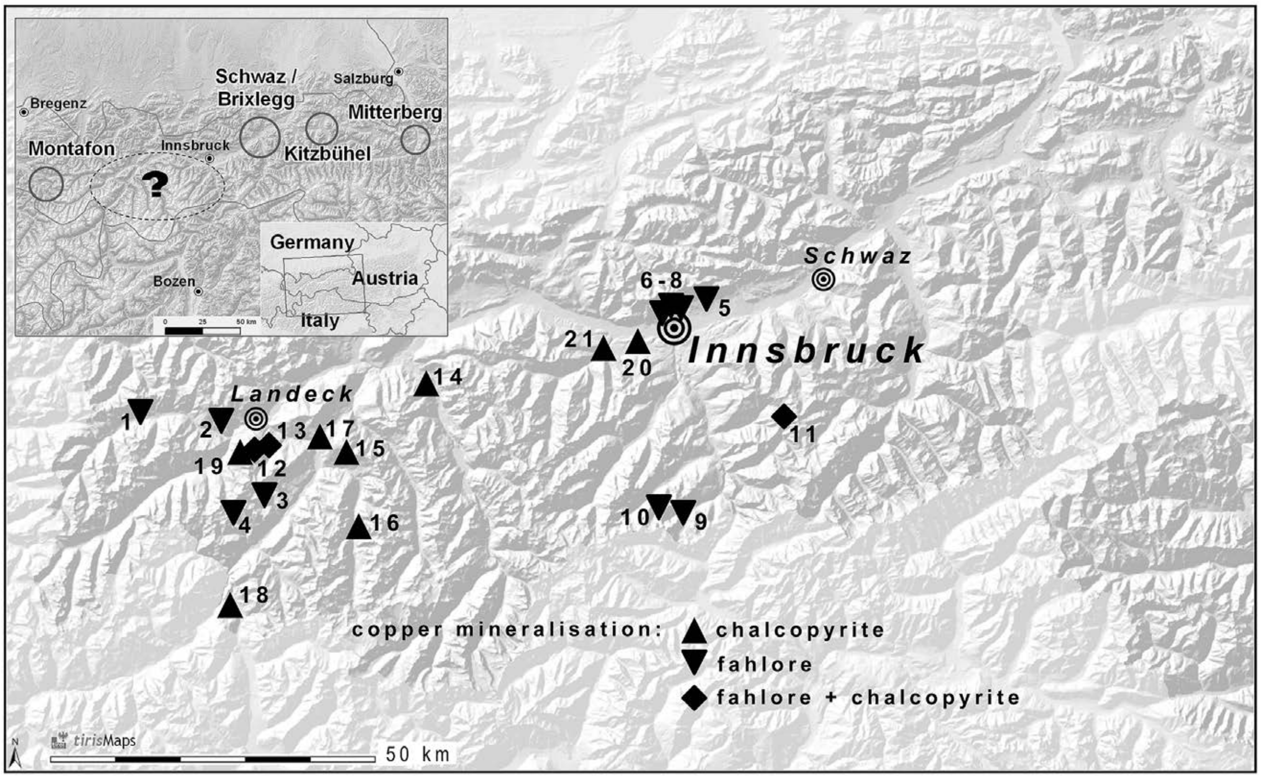

Fig. 1: Within the project "Prähistorische Kupferproduktion im Nordtiroler Oberland" surveyed and sampled copper mineralizations and mining sites. For corresponding site names see Table 1. Insert top left: mining archaeological research gap in the western part of North Tyrol in contrast to the key areas of the RC HiMAT (Salzburg: Mitterberg, Tyrol: Kitzbühel, Schwaz/Brixlegg, Vorarlberg: Montafon).

2. locating evidence for prehistoric mining in the target region
3. providing a basis for subsequent archaeological excavations

Due to the absence of mining archaeological investigations in this area, the project was based on the comprehensive economic geological, geological and mineralogical literature mentioned above.

Methods

At first, the economic geological, geological and mineralogical literature has been evaluated, including data about historic mining as well as geological and raw material maps. Selection criteria for a subsequent survey were:

1. occurrence of prehistoric relevant copper ores
2. accessibility in prehistoric times (outcrops)
3. known exploitation or indication for exploitation at any time (e. g. field names)
4. proximity of prehistoric metal (processing) finds
5. references from the public (any field observations)

In addition to maps and descriptions found in the literature, aerial photographs as wells as LiDAR scans were used to locate the mining areas in the field. Once located, the following work steps were carried out:

1. taking GPS points of the find spots, special structures and places of ore sampling
2. written and simple photographic documentation of mining traces and building relics
3. search for surface findings
4. ore sampling

If possible, ore samples were taken directly from the outcrop, otherwise from the mine heap. Polished sections mounted in epoxy and powder preparations were prepared and examined by means of ore microscopy, electron-probe microanalyses (EPMA), neutron activation analysis (NAA) and inductively coupled plasma mass spectrometry (ICP-MS).

Analytical methods

Electron-probe microanalysis (EPMA)

In total, 54 polished sections of selected ore samples were studied by ore microscopy (Leica DMLP) and 31 of these were further examined by EPMA. For standard

No.	site	coordinates (WGS84) latitude	longitude	mining traces	ore samples
1	Gand	47,146414	10,301975	mine galleries, breaches, heaps	E140
2	Flirscher Skihütte Flirsch	47,149260	10,443837	mine galleries, heaps	E141
3	Rotenstein Serfaus	47,049867	10,566795	mine galleries, shafts, breaches, heaps, blasting, timbering, ladders, stone tools	E004 E005
4	Masneralpe Serfaus	47,020278	10,490911	mine galleries, breaches, heaps, blasting, stone tools	E145 E146
5	Enzianhütte Rum	47,300700	11,430530	opencast, mine galleries, breaches, heaps, fire setting	E137
6	St. Helena Innsbruck-Hötting	47,283940	11,374030	mine breach and heap	E138
7	Knappenlöcher Innsbruck-Hötting	47,285410	11,371710	opencast, mine galleries, breaches, fire setting, kerf traces	E139
8	Höttinger Bild Innsbruck-Hötting	47,282529	11,369228	mine breach and heap	E026
9	Wildgrube Obernberg	47,011720	11,396140	opencast, mine galleries, shafts, breaches, heaps, fire setted galleries, kerf traces, traces of wedging down, blasting, wooden hoisting equipment and wooden tracks	E095 E159 E160
10	Gargglerin Gschnitztal	46,993317	11,337762	none	E158
11	Knappenkuchl Navis	47,152112	11,605062	mine galleries, breaches, heaps, fire setting, blasting, traces of wedging down, stone tools, forging tools	E006
12	Zirmegg Tobadill	47,112568	10,543418	mine breaches, heaps, crushing heap, building relics	E157
13	Knappenhäusl Landeck	47,117410	10,551420	mine or crushing heap with ceramic, bones and textile remains	E161
14	Haderlehen Sautens	47,197211	10,863742	mine galleries, heaps, blasting, wooden installations, leather shoe relics	E143 E144
15	Oberfalpetan Kaunerberg	47,080580	10,732620	mine gallery, heaps	E162
16	Tschingl Vergötschen	47,023670	10,750700	mine galleries, shafts, breaches, heaps, kerf traces, blasting, timbering, ladders, tracks, a tub, building relics	E154 E155
17	near Puschlin	47,100630	10,684080	mine gallery, kerf traces	E135
18	Großmutzkopf Nauders	46,867778	10,500278	mine galleries, breaches, heaps, timbering	E024 E151 E152 E153
19	Flathalpe Tobadill	47,104900	10,535960	mine galleries, heaps	E156
20	Knappenhof Axams	47,223230	11,275480	mine breaches, heaps	E149
21	Schwabenhof Sellrain	47,221800	11,225160	mine galleries, breaches, heaps	E148

Tab. 1: Surveyed and sampled mining areas. Sequential number corresponds to Fig. 1.

elemental analyses of fahlore-group minerals and sulfides the electron microprobe JEOL JXA 8100 SUPERPROBE with five WDS detectors and a Thermo Noran EDS system was used at the Institute of Mineralogy and Petrography of the University of Innsbruck. To cover the whole range of possible elements in the sulfides and sulfosalts, an analysis set-up with 21 elements (S, Cu, Fe, Zn, Hg, Mn, Mo, Cd, Ni, Pb, Co, Au, Ag, Ge, In, As, Sb, Bi, Se, Sn, Te) was developed. In a second step the best standard materials and peak/background counting times were determined. The obtained analytical conditions were 15 kV acceleration voltage and 10 nA beam current. The counting times were 50 s for the peak and 40 s for the background. The detection limits vary between 845 ppm for Pb and 119 ppm for S. Eleven peak overlap corrections were used to minimize interferences between various elements. Apart from galena (Pb standard), troilite (S standard) and cinnabar (Hg standard) all standards were pure metal standards.

NAA, ICP-MS analyses

The ore samples were chemically analysed by neutron activation analysis (NAA; for Fe, Co, Ni, Cu, As, Sb, Ag, Au, Se, Te, Zn, Sn) and inductively-coupled plasma mass spectrometry with a quadrupole ion filter (Thermo X-Series II QICP-MS; for Pb, Bi). The samples for NAA were irradiated together with appropriate neutron flux monitors and standard materials in the TRIGA reactor of the Institute for Nuclear Chemistry of the University of Mainz. Analysis of the activated ore samples (gamma-radiation) was carried out at the Curt-Engelhorn-Centre Archaeometry (CEZA) in Mannheim using Ge-detectors (methodology see Kuleff & Pernicka, 1995). As the detection limits for Ni are relatively high with NAA in fahlore samples, some Ni-values were additionally measured by X-ray fluorescence (XRF) with a portable Thermo Scientific Niton XL3t 980-HE spectrometer.

Fig. 2: Fragment of a hammer stone – surface find from the northernmost mine heap at Rotenstein/Serfaus. Probably one of the first indications for prehistoric copper mining in this area. Comparable finds are known from the Bronze Age and Iron Age mining areas in Schwaz/Brixlegg, Kitzbühel and Mitterberg for example.

Results

Archaeological results

By the above mentioned criteria 27 out of over 70 ore occurrences have been selected and more than 30 surveys were carried out during summer 2011. The surveys lasted one to two days per mining area. At 21 sites copper mineralizations were found and sampled (Fig. 1, Tab. 1). No comprehensive examination was intended, but a first evaluation of each sites potential for further investigations. As it is not possible to give detailed information about all surveys and sites in the present context, the most important information is summarized in table 1 (Tab. 1). These first insights are deepened in the following but only for selected sites.

The surveys – a synopsis

In the mining areas Rotenstein und Masneralpe (Tab. 1/Fig. 1, No. 3 and 4), both in the municipal territory of Serfaus, at an altitude of about 2,100 and 2,400 m a.s.l. respectively, several mineralized dolomite lenses are situated. In the area Masneralpe mine breaches and heaps were inspected, as well as three short mining galleries, of which one is flooded. Two anvil stones were photographed, but left in situ. The survey on the mine heaps and in the galleries of the much bigger Rotenstein (cf. ground plan and longitudinal section, Matthiass, 1960) yielded several anvil stones and the fragment of a hammer stone (Fig. 2). The former were again left in situ. The latter could possibly be one of the first evidence for prehistoric mining in this area, as such tools are so far only known from prehistoric mining contexts. Further evidence for a prehistoric mining phase, like Bronze Age ceramic and grooved hammer stones, is exhibited in the Berg- und Hüttenmuseum Brixlegg.

Another potentially pre-medieval mining area is Wildgrube/Obernberg (Tab. 1/Fig.1, No. 9). Five galleries with shafts and two opencast mines are still accessible. Different shallow fire-settings and fire-set galleries (Fig. 3), sometimes ripped with mallet and gad, were observed, as well as traces of wedging down comparable to Roman ones. Beside these remote or possibly Roman appearing mining traces, there are also kerf traces, wooden tracks and hauling installations, which most probably belong to a medieval/modern mining phase. For the fire-set galleries also a medieval/modern date is conceivable, as comparable finds in the Lower Inn Valley show (Staudt et al. in this volume). Only excavations could clarify if there are Roman or even older mining phases in this area.

Numerous wooden installations, like ladderways or a bent rail track and even an intact tub (*Spurnagelhunt*) were found in the three open galleries of Tschingl/Vergötschn (Tab. 1/Fig. 1, No. 16). No traces indicating a pre-medieval phase could be found during the one day lasting survey. Anyhow the medieval/modern installations would deserve documentation and protection.

The mining area on the Großmutzkopf near Nauders (Tab. 1/Fig. 1, No. 18) is spacious and reveals a number of different mining traces. Three rather short galleries can be accessed, one showing blasting holes, another being flooded after a few meters. In addition several collapsed adits whose arrangement – staggered one above the other – appears typical for modern time mining, are situated in a slope above the forest road. In a different area on the Großmutzkopf a quite large field of mining breaches was observed, which resembles the situations at Leogang, Blutskopf/Gallzein or even Mitterberg. This

Fig. 3: Fire-set gallery Wildgrube/Obernberg. If this gallery probably belongs to a Roman mining phase, which is slightly indicated by the shape of the fire-setting, could be proved by an excavation inside the gallery.

Fig. 4: Mining area Knappenkuchl/Navis. Top: portals and mine heap with the find spot (red circle) of the hammer stone (cf. Fig. 5). Bottom: Fire setting and position of the sondage (red oval).

area seems to be the most promising for examinations to clarify whether this mineralization was already mined in prehistoric times or not. Except for a grindstone no other surface finds were made. In addition to the mining traces two vitrified lime kilns were identified.

Glazed ceramic, wolly knitware and greenish colored animal bones were found on the mine or crushing heap at Knappenhäusl/Landeck (Tab. 1/Fig. 1, No. 13), but were all left in situ. Leather shoe fragments from one of the two accessible galleries at Haderlehen/Sautens (Tab.1/ Fig. 1, No. 14) were recovered. Marquita Volken (Shoe Museum Lausanne)[4] dated the objects into the second half of the 19th century. This would fit well with the last documented prospection activities at the end of the 19th century (Ladurner & Schulz, 1969). Neither Knappenhäusl/ Landeck nor Haderlehen/Sautens revealed indication for prehistoric mining during the short surveys.

Sondages

The surveys have been complemented by two small sondages, one in a fire-set pit located in the mining area Knappenlöcher/Innsbruck-Hötting (Grutsch & Martinek, 2016) and one in the mining area Knappenkuchl/Navis (Grutsch et al., 2014).

Knappenkuchl/Navis

(Tab. 1/Fig. 1, No. 11)

As already mentioned indications for prehistoric mining occur in the mining area Knappenkuchl/Navis. Mining activities took place in a dolomite lens (Fig. 4, top), which is situated at about 2,100 m a.s.l. in the Navistal. The belowground accessible area was mainly drifted by fire (Fig. 4, bottom). During the first survey 2011 G. Goldenberg found an eclogite hammer stone (Fig. 5). As the piece is not grooved and has only a few impact marks, it was not clear if it actually is a miner's tool. But the facts that it was found on the mine heap, that eclogite as well as amphibolite are the preferred raw materials for this kind of tools and especially that eclogite (and also amphibolite) cannot occur naturally in this valley[5] clearly argue for its use in a mining context. The already mentioned grooved hammer stone deriving from here, for which can't be any doubt about its use, is also made of eclogite or amphibolite respectively[6]. Comparable finds dating to the Bronze Age and Iron Age are known from many different prehistoric mining areas like Schwaz/

Fig. 5: The eclogite hammer stone from the mine heap Knappenkuchl/Navis, as one indicator for prehistoric copper mining in this area. Comparable finds are known from the Bronze Age and Iron Age mining areas within the Eastern Alps, but also other regions.

Brixlegg, Kitzbühel and Mitterberg, but also from others all over Europe.

Because of these indications the place was chosen to be examined by a small sondage belowground (red circle Fig. 4 bottom) in August 2013. The primary aim was the dating of the shallow fire setting. The departing galleries are blocked by collapsed rocks.

The sondage yielded modern findings, like matches and glazed ceramic, as well as an organic string and a bar-shaped piece of wood. The last 7 centimetres of sediment above the solid bottom consisted of moist, fine grained, dark grey material with particles of charcoal and red brown discolourations. In the excavated area, and maximum 50 cm above, blasting holes were observed, while above this level and on the roof none were detected. Some traces of wedging down exist at lower levels.

Mining activities from the 16th and 17th century are recorded in written documents (Srbik, 1929) but these sources could also refer to the currently not accessible working areas in the departing galleries. The finds and the situation in total are indicative for modern time mining activities, which were carried out by ripping the assumingly prehistoric fire-set mine, in order to evaluate its profitability. In the course of these activities the mine seems to have been cleaned down to the solid bottom (at least partly) and afterwards some blastings were carried out. In this context the bar-shaped wood could be a tamping bar, as its diameter fits well into the blasting holes, the organic string could be a match cord and the red brown discolourations would be weathering rests of iron tool swarfs. Nonetheless this is a hypothetic scenario. Though the previous surveys and the already mentioned finds displayed in the Berg- und Hüttenmuseum Brixlegg yield evidence for a prehistoric age of this mining area, no further evidence was found during the sondage.

Knappenlöcher/Innsbruck-Hötting

(Tab. 1/Fig. 1, No. 7)

The assumption that the mining area Innsbruck-Hötting[7] could have a prehistoric origin was already expressed by P. Gstrein (2008), who worked intensively on the geology and mining traces in this region (Gstrein & Heissl, 1989 a, b). To verify this assumption a fire-set pit[8] in the work zone Knappenlöcher/Innsbruck-Hötting was examined (Fig. 6, top). The pit is located at 880 m a.s.l., surrounded by the urnfield grave field Hötting in the south (at 600 m a.s.l., Wagner, 1943), the Bronze Age settlement Hötting-Allerheiligenhöfe in the south-west and Bronze Age ceramic finds in a cave in the north of the pit (at about 1,400 m a.s.l., Müller, 1999) and is therefore located in the middle of a prehistorically used landscape.

To gain datable material a 1.55 x 1.10 m trench was opened (Fig. 6, bottom). The sediments above the solid bottom were only 9 to 30 cm thick. In all layers modern material was documented. A charcoal sample from a depth of 18 cm brought the following date: MAMS 21367 (Curt-Engelhorn-Centre), 167 BP +/- 23; cal AD 1670-1944 with INTCAL 13, and cal AD 1665-1950 with SwissCal 1.0 – unfortunately a period for which no precise information can be gained. No indicators for prehistoric mining were found in the pit. Of course this does not mean that prehistoric mining can be excluded for the whole mining area.

Mineralogical and geochemical results

One of the central aims of the project was the mineralogical and geochemical characterization of the copper ores occurring in the examined mining areas, to enable comparison with prehistoric metal products and the copper ores of prehistoric mining areas. Therefore ore petrography, mineral chemistry and ore chemistry of the samples collected during the surveys will be discussed in the following.

Petrography of the ore samples

In the Permian Verrucano sediments fahlores are the predominant mineralization: at Gand (Tab. 1/Fig. 1, No. 1) tetrahedrite is the main ore mineral. Cinnabar HgS occurs dispersedly in altered zones of fahlore and moschellandsbergite Ag_2Hg_3 as µm-sized inclusions in unaltered fahlore. The ore occurrence near the Flirscher

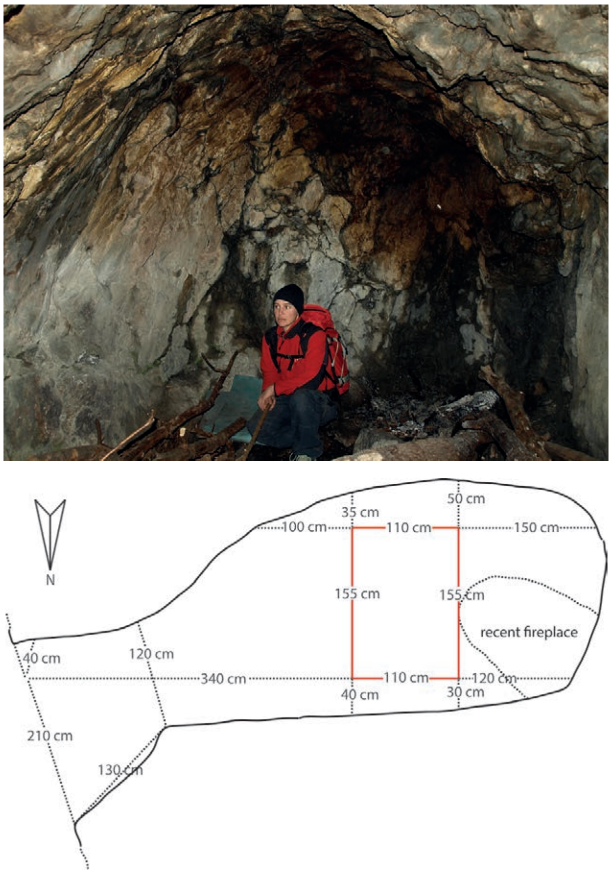

Fig. 6: Top: The fire-set pit in the Höttinger Graben (Knappenlöcher/ Innsbruck-Hötting). Bottom: The ground plan with the position of the sondage (red). No evidence for prehistoric copper mining was found.

Skihütte (Tab. 1/Fig. 1, No. 2) is composed of tennantite and cobalt/nickel-containing pyrite, gersdorffite NiAsS and siegenite $(Ni,Co)_3S_4$. Tetrahedrite from Rotenstein near Serfaus (Tab. 1/Fig. 1, No. 3; (1) in Fig. 7) is accompanied by chalcopyrite, pyrite, cobaltite CoAsS and siegenite. Gersdorffite and galena form µm-sized inclusions in fahlore. The ore from Masneralpe (Tab. 1/Fig. 1, No. 4) is composed of tetrahedrite, chalcopyrite and pyrite.

The mineralizations in the dolomite of the Brenner Mesozoic (Obernberg, Gschnitztal) and the North Tyrolean Calcareous Alps (Hötting, Enzianhütte) are characterized by fahlores associated with lead ores: the ore occurrence near Enzianhütte (Tab. 1/Fig. 1, No. 5) comprises tennantite, galena and geocronite $Pb_{14}(Sb,As)_6S_{23}$. At Hötting three localities have been sampled (Tab. 1/Fig. 1, No. 6, 7 and 8). Here, tennantite is accompanied by galena, enargite Cu_3AsS_4, seligmannite $PbCuAsS_3$ and jordanite $Pb_{14}(As,Sb)_6S_{23}$. In contrast tetrahedrite is the predominant copper ore at Obernberg (Tab. 1/Fig. 1, No. 9; (2) in Fig. 7). It is accompanied by bournonite $PbCuSbS_3$, galena and sphalerite. The ore from Gschnitztal (Tab. 1/ Fig. 1, No. 10) is composed of tetrahedrite with minor pyrite and chalcopyrite.

Fahlore mineralizations in association with chalcopyrite were found in the Tux Alps (Navis) and the Silvretta Crystalline Complex (Zirmegg, Knappenhäusl): at Navis (Tab. 1/Fig. 1, No. 11) chalcopyrite is accompanied by tetrahedrite-tennantite fahlores and pyrite. Gold was identified as µm-sized inclusion in fahlore. The ore from Zirmegg (Tab. 1/Fig. 1, No. 12) is composed of tetrahedrite, chalcopyrite and arsenopyrite FeAsS. At Knappenhäusl (Tab. 1/Fig. 1, No. 13; (3) in Fig. 7) tetrahedrite is accompanied by chalcopyrite and arsenopyrite. Bismuthinite Bi_2S_3 was identified as discrete bismuth mineral.

In the Ötztal Crystalline Complex a chalcopyrite-pyrite-mineralization is predominant: At Haderlehen (Tab. 1/ Fig. 1, No. 14) chalcopyrite is accompanied by pyrite, pyrrhotite and gersdorffite. The ore from Oberfalpetan (Tab. 1/ Fig. 1, No. 15) and near Puschlin (Tab. 1/Fig. 1, No. 17) is composed of chalcopyrite and pyrite. At Tschingl (Tab. 1/ Fig. 1, No. 16) the ore contains additional arsenopyrite and gersdorffite. The mineralization at Großmutzkopf (Tab. 1/ Fig. 1, No. 18; (4) in Fig. 7) is more complex and comprises in addition to chalcopyrite and pyrite, arsenopyrite, gersdorffite, galenite, tetrahedrite and Bi-Pb-sulfosalts. The chalcopyrite-pyrite mineralization at Flathalpe (Tab. 1/ Fig. 1, No. 19) contains cobaltite, at Axams (Tab. 1/Fig. 1, No. 20) galena, arsenopyrite and pyrrhotite and at Sellrain (Tab. 1/Fig. 1, No. 21) pyrrhotite.

Mineral chemistry

In this section a summary of the mineral chemistry of the most important sulfides is given.

Fahlore-group minerals: The general fahlore-group mineral formula is $^{IV}M(1)_6{}^{III}M(2)_6[^{III}X^{IV}Y_3]_4{}^{VI}Z$ (Johnson et al. 1988) with M(1)=Cu, Fe, Zn, Hg; M(2)=Cu, Ag; X=As, Sb, Bi; Y=S and Z=S, Se. Variations in the tetrahedrite (X_{Sb}), tennantite (X_{As}) and bismuth component (X_{Bi}) are as follows: the Sb- and As mole fractions are the major distinguishing features between fahlore-group minerals from the North Tyrolean Calcareous Alps (X_{As} = 0.88-0.99, Hötting, Enzianhütte), the Brenner Mesozoic (X_{As} = 0.05-0.09, Obernberg) and the Silvretta Crystalline Complex (X_{As} = 0.06-0.08, Knappenhäusl). Within the Permian Verrucano large variations in X_{As} occur and range between 0.26-0.36 (Gand) and 0.91-0.92 (Flirscher Skihütte). Accordingly, the Sb/As ratio of fahlore-group minerals from the North Tyrolean Calcareous Alps and Flirscher Skihütte is <1, and from Obernberg and the Silvretta Crystalline Complex 11-19. The samples from Knappenhäusl and Großmutzkopf show Bi concentrations which are between 0.9-1.2 wt%. In contrast Bi concentrations in all other samples are below 0.8 wt%. The tetrahedrite from Gand is mercury-rich (up to 20 wt% Hg) while at Obernberg and Großmutzkopf a silver-rich (up to 12 and 18 wt% Ag respectively) tetrahedrite occurs.

Chalcopyrite: Chalcopyrite compositions from all investigated locations show almost no deviations from the ideal stoichiometric compositions. The maximum concentration of an additional element is 0.17 wt% (Pb, Axams). Zn concentrations reach a maximum of 0.13 wt% (Masneralpe).

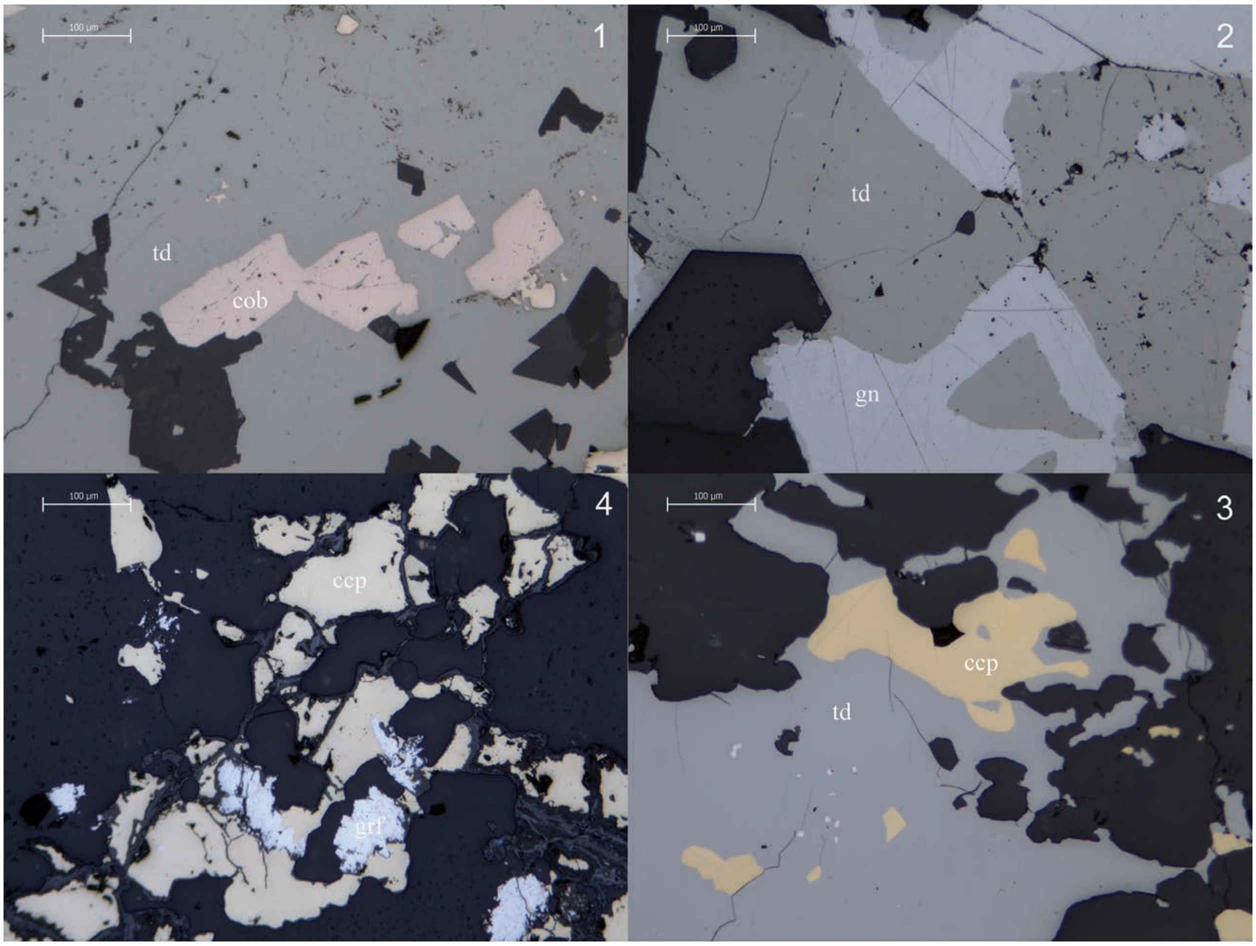

Fig. 7: Polished sections of ore samples. (1) Tetrahedrite (td) and cobaltite (cob), Rotenstein/Serfaus. (2) Tetrahedrite and galena (gn), Wildgrube/Obernberg. (3) Tetrahedrite and chalcopyrite (ccp), Knappenhäusl/Landeck. (4) Chalcopyrite and gersdorffite (grf), Großmutzkopf/Nauders.

Galena: Galena also shows almost no deviations from the stoichiometric composition. Ag concentrations of galena are in most cases near or below the detection limit, except for samples from Axams where they vary between 0.17 wt% and 0.24 wt%. Bi was always detected in galena. The mean concentration of Bi is 0.70 wt% and the highest concentration reaches 1.24 wt%. Galena from Axams for example shows 0.2 wt% Ag and 1.2 wt% Bi.

Pyrite: Besides the main elements Fe and S, pyrite only shows trace element concentrations at or below the detection limit except for Co which usually is below 0.3 wt% but ranges up to 9 wt% (Flirscher Skihütte). Arsenopyrite from Zirmegg contains some cobalt and nickel (up to 1 wt% in sum).

Ore chemistry

In order to provide a database for provenance studies of prehistoric copper and bronze artefacts, element concentrations in the ore samples have been determined by NAA and ICP-MS (Tab. 2).Typical impurities of prehistoric copper metal are arsenic As, antimony Sb, silver Ag, nickel Ni, lead Pb and bismuth Bi. The ore data plotted in the diagrams of Figure 8 were normalized to 100 % Cu to be comparable with each other and with artefact analyses.

It becomes apparent that at least four main groups of copper ores are present in the sampled area (Fig. 8). The square shaped data points represent ore samples with chalcopyrite as predominant copper mineral, while the triangular data points represent fahlore samples. Ore samples from Haderlehen, Sellrain, Axams, Oberfalpetan and Navis are low in impurities. Fahlore samples are generally high in As and/or Sb, some of the samples additionally show high amounts of Ag, Ni, Pb and/or Bi. An intermediate group is discernible, consisting of samples from Großmutzkopf, Flathalpe and Tschingl. In these samples the higher amount of impurities results from accompanying minerals of the arsenopyrite-gersdorffite-cobaltite series and occasionally galena and fahlore (Großmutzkopf).

The samples with predominant fahlore show a huge variation of element concentrations. While the variations of As, Sb, Ag and Bi are related to the fahlore mineral chemistry, elevated concentrations of Ni and Pb result from accompanying minerals.

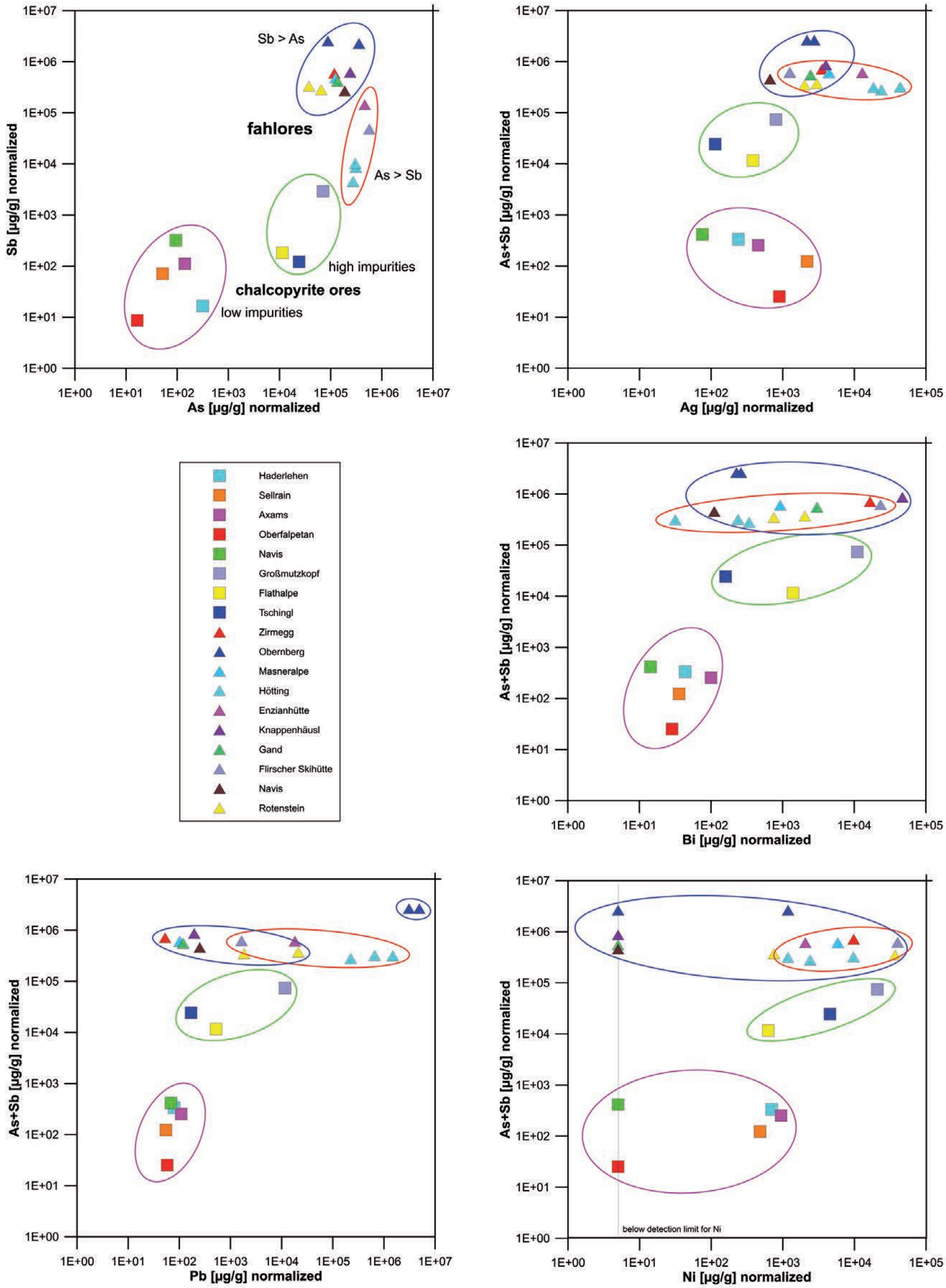

Fig. 8: Logarithmic plotting of normalized element concentrations selected from Table 2. Four copper ore types become apparent which are marked with circles.

Lab no.	Sample no.	Provenance	Cu %	Fe %	As µg/g	Sb µg/g	Co µg/g	Ni µg/g	Ag µg/g	Au µg/g	Zn µg/g	Sn µg/g	Se µg/g	Te µg/g	Pb µg/g	Bi µg/g
MA-121835	PP201E157	Zirmegg	13.3	7.1	15700	79000	73	1300	470	< 1	4500	< 1100	< 48	< 640	7.0	2210
MA-121836	PP202E159	Obernberg	5.8	< 1	20800	132000	< 31	*n.d.*	160	0.6	4500	< 1400	< 65	< 780	285000	15.2
MA-121837	PP203E156	Flathalpe	12.8	6.9	1460	23.3	47	80	49	0.032	73	< 360	12.8	< 23	67	179
MA-121838	PP204E155	Tschingl	7.9	5.7	1910	9.5	204	360	9	0.41	179	230	9.8	17	13.4	12.6
MA-121839	PP205E145	Masneralpe	15.4	3.2	19200	74000	330	900	680	< 1	10200	< 1000	< 72	< 690	15.7	143
MA-121840	PP206E139	Hötting Knappenlöcher	5.4	6.1	14800	245	170	130	1290	0.03	4400	< 720	< 2	< 50	12100	18.4
MA-121841	PP207E148	Sellrain	18.7	13.0	9.7	13.3	13.1	90	410	0.44	410	< 280	59	< 20	10.2	6.7
MA-121842	PP208E152	Großmutzkopf	6.6	5.6	4680	193	670	1380	53	0.61	91	< 420	8.7	< 31	770	730
MA-121843	PP209E143	Haderlehn	13.3	9.4	42	2.21	31	93	32	0.10	122	70	18.5	< 11	10.5	5.8
MA-121844	PP210E149	Axams	5.6	4.5	7.9	6.2	13.5	53	25.5	0.49	124	< 68	11.9	8	6.1	5.6
MA-121845	PP211E162	Oberfalpetan	9.8	8.1	1.62	0.85	29.3	< 96	88	0.057	288	60	20.8	< 10	5.7	2.8
MA-121846	PP212E138	Hötting St. Helena	3.1	0.9	9600	265	18.2	300	1360	0.28	2070	< 1200	< 10	70	20400	7.4
MA-121848	PP214E137	Enzianhütte	3.4	< 5	15800	4900	860	*70*	440	0.69	5300	< 4600	260	1100	620	n.d.
MA-121849	PP215E161	Knappenhäusl	8.5	6.7	20500	53000	46	*n.d.*	340	< 1	2990	< 7200	< 57	< 590	16.6	4000
MA-121850	PP216E140	Gand	4.7	3.7	6400	19400	13.5	*n.d.*	115	1.2	670	< 430	< 23	< 360	5.6	142
MA-121851	PP217E141	Flirscher Skihütte	1.7	0.3	9500	800	310	670	21	< 0.2	940	< 950	< 11	< 92	27.5	390
FG-011184	PP024E006	Navis	45	3.2	85000	121000	100	*n.d.*	300	0.60	27100	< 830	< 130	< 530	113	50
FG-011185	PP025E006	Navis	35	25.0	33	112	3.1	*n.d.*	26.5	0.042	129	< 210	19.5	6	24	5
FG-011186	PP026E095	Obernberg	11.0	< 2	9700	281000	< 11	*130*	240	< 3	63000	< 2000	< 170	< 1300	340000	25
FG-011187	PP027E004	Rotenstein	44	2.9	16600	146000	1000	*330*	1320	< 2	22600	< 1100	< 130	< 800	9300	900
FG-011188	PP028E005	Rotenstein	12.7	13.9	8300	36000	3800	4700	256	< 1	5100	< 740	< 65	< 560	235	96
FG-011190	PP030E026	Höttinger Bild	22.1	1.6	67000	2250	121	*260*	4100	< 0.5	13900	< 200	< 9	150	330000	7

Tab. 2: Element concentrations in ore samples from western North Tyrol as determined by neutron activation analysis (NAA, for the elements Cu, Fe, As, Sb, Co, Ni, Ag, Au, Zn, Sn, Se, Te) and inductively coupled mass spectrometry (ICP-MS, for Pb, Bi); n.d. = not detected; < = below detection limit. As the detection limits of Ni are relatively high with NAA in fahlores, some Ni values were additionally analysed by XRF. These values are italicized.

Conclusions

Current state of research is that during the Middle Bronze Age the copper production center at the Mitterberg/Austria has a monopoly position in the Eastern Alps and is additionally supplying other areas in Europe. At the latest from the 14th/13th century BC on the copper production at the Mitterberg is supplemented by production in Kitzbühel/Austria and Upper Styria/Austria. From the 13th/12th century BC on different other copper producers, for example the Trentino/Italy and the Lower Inn Valley/Austria appear and the Mitterberg but also Kitzbühel seem to face their decline. The reuse of fahlore copper from the 12th century BC on (cf. Grutsch et al., in this volume) is probably a reaction on a rising copper demand, which cannot be supplied sufficiently by the "big players" anymore (in general Stöllner et al., 2016).

In total it seems that during the Late Bronze Age and Early Iron Age a diversification of copper ore mining in the Eastern Alps and beyond takes place. This diversification also means a spread of know how. In this climate it is imaginable that also the smaller copper ore occurrences in western North Tyrol are prospected and mined. To get a first idea if this was the case or not, the above mentioned project has been undertaken. It has to be seen as a starting point to close the mining archaeological research gap in this region. The intention of the project was to survey mining areas in western North Tyrol with in prehistoric times usable copper ore occurrences to evaluate their potential having been mined in prehistoric times. For Knappenkuchl/Navis and Masneralpe-Rotenstein/Serfaus there is evidence that this was the case. The other areas did not yield evidence yet. This does not mean that prehistoric mining can be excluded there, especially as until now only one to two days lasting surveys have been carried out.

Beside a first evaluation of the mining archaeological potential of the sites, it was a central aim to provide basic information on the occurring copper ores. Therefore mineralogical and geochemical analyses have been carried out on the collected ore samples. It showed that 21 of the visited sites provide the in prehistoric times relevant copper ores chalcopyrite and/or fahlore, beside various oxidic copper minerals. The different occurrences can be distinguished by their trace elements. This distinction has its limits, as similar ore parageneses occur repeatedly in the Eastern Alps. Furthermore the conducted analyses show, that common prehistoric copper types (silver rich/ nickel poor fahlore copper, chalcopyrite copper with a certain amount of nickel and arsenic, trace element poor chalcopyrite copper, but also a lead rich fahlore copper) could have been produced in western North Tyrol.

As the mining areas in western North Tyrol would rather have been “small players”, it would be difficult to prove their produced copper in finished objects, as it would statistically be lost in the masses. Nonetheless it is worthwhile to study also smaller ore occurrences, like the ones in western North Tyrol, to gain a picture as complete as possible. In this sense further examination at least in the mining areas Knappenkuchl/Navis and Masneralpe-Rotenstein/Serfaus appears reasonable.

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Notes

1 Research Center “The History of Mining Activities in the Tyrol and Adjacent Areas – Impact on Environment & Human Societies”.

2 Objects displayed in the Tiroler Berg- und Hüttenmuseum Brixlegg.

3 Three project parts: one financed by the TWF - Tiroler Wissenschaftsfond (summer 2011) and two financed by the foundation D. Swarovski & Co (August 2013 and June/July 2014).

4 www.schoemuseum.ch

5 Kind information from Univ. Prof. em. Dr. G. Patzelt, Institute of Geography, High Altitude Mountain Research and Ao. Univ. Prof. Dr. Peter Tropper, Institute of Mineralogy and Petrography.

6 Eclogite and amphibolite are both tough, metamorphic rocks and are macroscopically not easy to distinguish.

7 In historic times not fahlore but galena was mined and used for silver extraction in Schwaz.

8 Only very few mines are still accessible. Most of them are either collapsed or closed, because they are part of the drinking water supply system of Innsbruck. Dr. P. Gstrein, who knows the area very well, kindly told us that there were other near-surface fire-settings which are now covered with concrete.

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Authors

Caroline O. Grutsch – Department of Archaeologies, University of Innsbruck
Klaus-Peter Martinek – München
Peter Tropper – Institute of Mineralogy and Petrography, University of Innsbruck
Joachim Lutz – Curt-Engelhorn-Zentrum Archäometrie gGmbh, Mannheim

Correspondence and material requests should be addressed to: caroline.grutsch@student.uibk.ac.at; talitha-cumi@gmx.at; kpmartinek@t-online.de

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Markus Staudt, Gert Goldenberg, Manuel Scherer-Windisch, Kurt Nicolussi, Thomas Pichler

Late Bronze Age/Early Iron Age fahlore mining in the Lower Inn Valley (North Tyrol, Austria)

ABSTRACT: *Within the framework of the international DACH-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, I-1670-G19, the DFG and SNF, 2015 - 2018) traces of Late Bronze Age to Early Iron Age mining activities were systematically prospected and investigated in the fahlore mining district Schwaz-Brixlegg, North-Tyrol, Austria. The aim was to reconstruct the production chain for copper from fahlore and to demonstrate the spatial and chronological development of the prehistoric mining activities in this district. Archaeological excavations were carried out at different places below and above ground comprising a series of fire-set mines, areas with surface depressions (german: "Pingenfelder") and one smelting site. Besides the uncovering, documentation and interpretation of prehistoric structures and findings it was essential to obtain organic materials like wood, charcoal and animal bones for radiocarbon dating and – in the ideal case – timber and/or charcoal for dendrochronological analyses. These investigations could be realised at different spots distributed alongside the mining district of Schwaz-Brixlegg. Parallel to the excavations relevant sectors of the mines were mapped, mine plans were drawn and 3D-models were generated. In addition to the archaeological fieldwork, ore samples from the mining district were systematically collected for mineralogical and geochemical analyses with the aim to characterise the mineral assemblages for subsequent provenience studies. This paper reports on the mining sites investigated within the DACH-project as well as on first results from archaeometric analyses.*

KEYWORDS: COPPER MINING, LATE BRONZE AGE, EARLY IRON AGE, FAHLORE, FIRE-SETTING, CHAÎNE OPÉRATOIRE, DENDROCHRONOLOGY

Introduction

Within the framework of the trinational DACH-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, I-1670-G19, the DFG and the SNF, 2015-2018) traces of Late Bronze Age to Early Iron Age mining activities were systematically prospected and investigated in the fahlore mining area Schwaz-Brixlegg, North-Tyrol, Austria. The main aim and goals were to reconstruct the production chain for copper from fahlore and to demonstrate the spatial and chronological development of the prehistoric mining activities in this district. Archaeological excavations were carried out at different places below and above ground comprising a series of fire-set mines, areas with surface depressions (german: "Pingenfelder") and one smelting site. Besides the uncovering, documentation and interpretation of prehistoric structures it was essential to obtain organic materials like wood, charcoal and animal bones for radiocarbon dating and – in the ideal case – timber and/or charcoal for dendrochronological analyses. These investigations could be realised at different spots distributed alongside the mining area of Schwaz-Brixlegg (Fig. 1). Parallel to the excavations relevant sectors of the mines were mapped, mine plans were drawn and 3D-models were generated (Staudt et al., 2017a; 2018a; 2018c). In addition to the archaeological fieldwork, ore samples from the mining districts were systematically collected for mineralogical and geochemical analyses with the aim to characterise the mineral assemblages for subsequent provenience studies. In the fillings and dumps of fire-set mines bigger fragments of charcoal are frequent and can be used for accurate age determinations. However, the prehistoric mines are often superimposed by younger activities showing traces of iron tools (hammer and pick) or black powder blasting. In such cases the Bronze Age and/or Early Iron Age layers are often not visible anymore or have been removed to an outside dump. This paper reports on the mining sites investigated

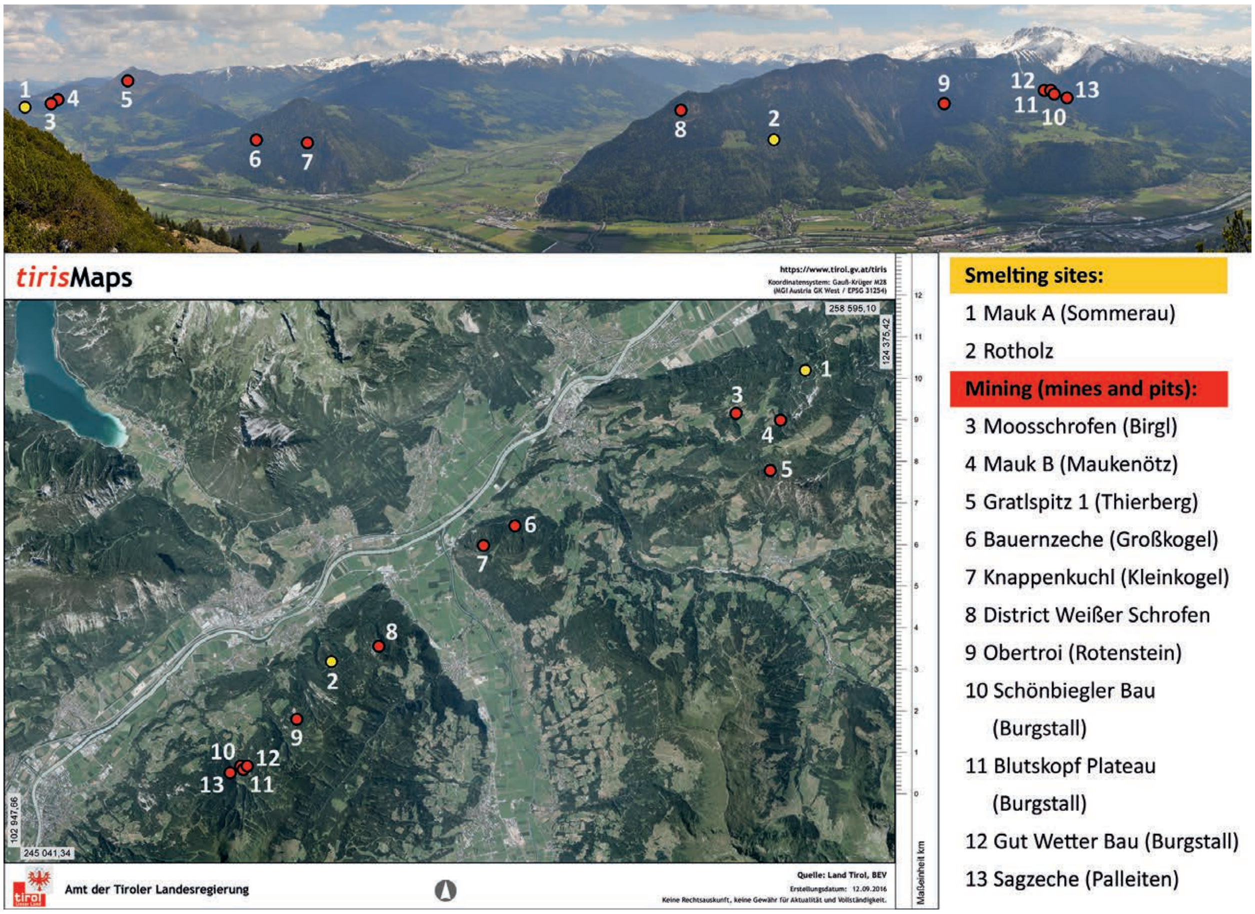

Fig. 1: The investigation spots of the DACH-project (2015-17) in the mining area Schwaz-Brixlegg (graphic: M. Staudt).

within the DACH-project as well as on first results from archaeometric analyses.

Evidence for prehistoric fahlore mining in the area of Schwaz-Brixlegg

The fahlore mining area of Schwaz-Brixlegg extends along the southern side of the central Lower Inn Valley and is well known for extensive mining in the late medieval/early modern period. In the fifteenth and sixteenth centuries AD cupriferous and argentiferous fahlores were extracted on a large scale in the so called "Schwazer Dolomit" (Wolfskron, 1897; 1898; 1899; Worms, 1904; Pirkl, 1961; Gstrein, 1978). The region became one of Europe's leading mining centres, as pictured in the "Schwazer Bergbuch" of the years 1554/56 (Bartels et al., 2006).

Joseph von Sperges (Sperges, 1765) and Joseph von Senger (Senger, 1806) considered that if there was any prehistoric or roman mining, these activities were concentrated only on iron ore. In the early 20th century Robert von Srbik assumed prehistoric copper mining activities in the mining area of Schwaz (Srbik, 1929). Because of Late Bronze Age finds in the vicinity of the mining district, Franz von Wieser (Wieser, 1904) and later Gerhard Kaltenhauser (Kaltenhauser, 1965) also supposed a connection with nearby mining activities.

A significant influence of North Tyrolean fahlore copper is proved for the Early Bronze Age (Krause, 2003; Möslein & Winghart, 2002; Martinek & Sydow, 2004; Höppner et al., 2005; Junk, 2003; Schubert, 2005; Krismer et al., 2013; Töchterle, 2015a). Corresponding early metallurgical activities could be documented along the Lower Inn Valley at hilltop settlements like Kiechlberg (Thaur; Töchterle, 2015b), Buchberg (Wiesing; Martinek & Sydow, 2004) and Mariahilfbergl (Brixlegg; Huijsmans and Krauß, 1998, 2015; Bartelheim et al., 2002) as well as in the cave site Tischofer Höhle (Kufstein; Mostler, 1969; Neuninger et al., 1970; Harb, 2002). Material analyses performed on Bronze Age metal artefacts (copper and bronze) show different geochemical characteristics. The results of these investigations are indicating the use of different copper ore occurrences in the east Alpine region and their time-dependent exploitation during the Bronze Age (Pernicka & Lutz, 2015). It could be demonstrated that after an early domination of "fahlore copper" in the Early Bronze Age this type of metal was replaced almost completely since the late Early Bronze Age and during the Middle Bronze Age by “chalcopyrite copper” (“east Alpine copper”) especially from the Mitterberg and Kitzbühel/Jochberg areas (Stöllner, 2015a, 2015b; Tomedi & Töchterle, 2012; Koch Waldner & Klaunzer, 2015). The fahlore copper reappears only in the Late Bronze Age and is then used in parallel and mixed with the east Alpine copper type (Pernicka & Lutz, 2015).

Since the 1980s archaeological field research and subsequent investigations have been dealing with this second prehistoric fahlore mining boom from the Late Bronze Age to the Early Iron Age (Egg, 1981; Gstrein, 1981; 1988a; 2013; Rieser & Schrattenthaler, 1998/99, 2004; Goldenberg & Rieser, 2004; Palme et al., 2002; Heiss & Oeggl, 2008; Schibler et al., 2011; Goldenberg et al., 2012; Goldenberg, 2013, Goldenberg, 2015; Pichler et al., 2013; Tomedi et al., 2013; Staudt & Tomedi, 2015; Goldenberg et al., 2019). Late Bronze Age copper ore smelting activities in the Lower Inn Valley are so far known from two smelting sites and can also be detected indirectly by analysing slag tempered ceramics from settlements as well as from cemeteries (Sölder, 1987/88, 2015; Zemmer-Plank, 1990; Huijsmanns & Krauß, 1998; Harb, 2002; Reider, 2003; Töchterle et al., 2013; Töchterle, 2015b; Krismer & Staudt, 2012; Krismer et al., 2013; Tomedi et al., 2013; Krismer et al., 2015; Staudt & Tomedi, 2015; Goldenberg et. al, 2019). A significant increase of burials in the region during the Late Bronze Age was attributed to the rise of fahlore mining and metallurgy by Lothar Sperber (Sperber, 2004). Excavations and archaeometrical investigations between 2007 and 2012 within the international special research project SFB HiMAT (supported by the Austrian Science Fund FWF, F3106-G02) could demonstrate a first big picture of the „chaîne opératoire“ in connection with the copper production in the Lower Inn Valley (Goldenberg et al., 2012; Schibler et al., 2011). For the first time it was possible to present dendrochronological data from different spots of the fahlore mining district (Nicolussi et al., 2009, 2015; Nicolussi & Pichler, 2013; Pichler et al., 2012, 2013).

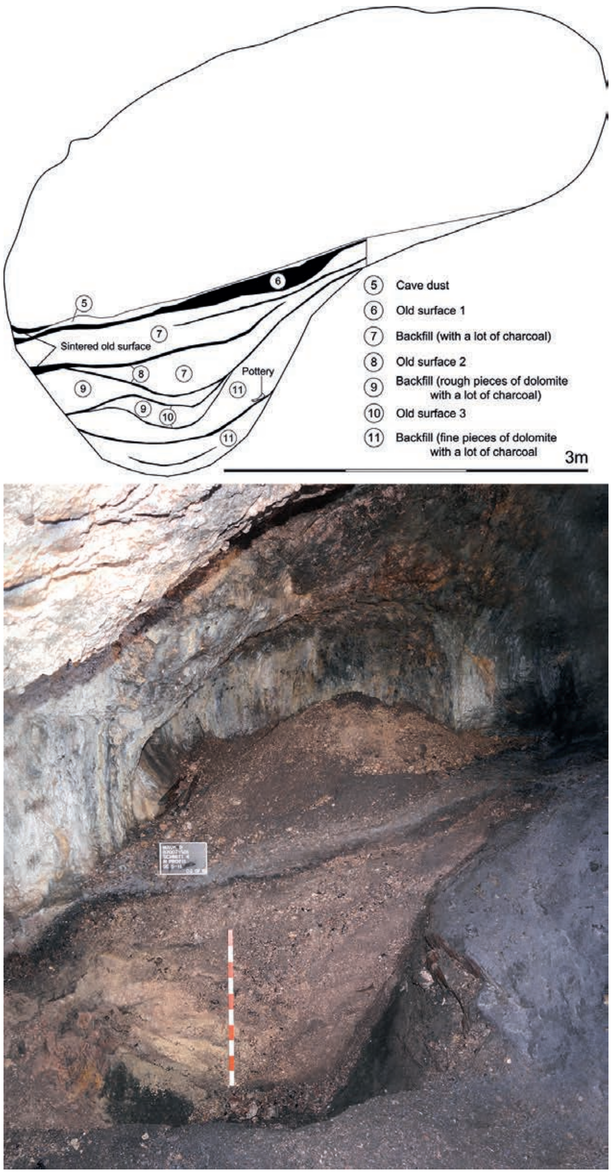

Fig. 2: Northern profile of section 4 in the mine Mauk B (graphic/ photo: M. Staudt).

Archaeological investigations underground in fire-set fahlore mines (2015 – 2017)

Mauk B (district Maukenötz/Sommerau, Brixlegg)

The small fire-set mine “Mauk B” is situated in a ravine in the upper part of the Mauken valley, just above the base of a small torrent (Staudt et al., 2017a). An upper and a lower mine entrance are visible. The exploitation of fahlore in the dolomitic host rock (Schwazer Dolomit) left behind characteristic traces of fire-setting in the form of cupola shaped cavities. The mine shows a horizontal extension of 17 m, a maximum height of 3 m and a width up to around 5 m. The floor of the front part of the mine is covered with an undated mudslide of reddish sandstone which came inside with floodwater. At the backmost area the original prehistoric surface (Fig. 2, layer 6) is apparent underneath a distinct layer of soft and fluffy “cave dust”, which is about 1 to 2 cm thick. Beside older sections (1 and 2) from previous investigations by Gert Goldenberg (Goldenberg & Rieser, 2004) two new sections (3 and 4) could be researched. In the first instance radiocarbon analyses from the older excavation showed quite unsatisfying dating (Late Bronze Age / Iron Age) caused by the problem of the “Hallstatt plateau” for the ^{14}C-calibration curve (OZB 360, 2691 ± 38 BP, cal. BC 919 - 809; OZB 361, 2507 ± 33 BP, cal. BC 788 - 511; OZB 362 U, 2491 ± 52 BP, cal. BC 787 - 425; OZB 363 U, 2262 ± 47 BP, cal. BC 395 - 203); VERA 1322,

Fig. 3: The eastern (left) and western (right) fire-set mines at the Moosschrofen (photos: M. Staudt and D. Brandner).

2440 ± 35 BP, cal. BC 754 - 407; all values: 2 σ, 95,4 %; Goldenberg & Rieser, 2004; Goldenberg, 2014).

In section 3 the mining layers are just a few decimetres (max. 40 cm) thick and only a few charcoal fragments could be collected. In section 4 the base of the mine could be reached in a depth of around 1.30 m. In the filling (consisting of finely broken dolomite) a few layers including ancient working horizons could be documented (Fig. 2). Partly sintered dolomite fragments inside these horizons could indicate longer breaks between the mining activities. Most of the recovered charcoal pieces come from section 4. In the fire-set backfill a hammer stone fragment and a piece of domestic pottery could be found. Two ^{14}C-analyses of charcoal fragments from section 4 date around the final phase of the Late Bronze Age and the beginning of the Early Iron Age (dendro-sample maub-51: MAMS 25907, 2689 ± 26 BP, cal. BC 897 - 805; dendro-sample maub-27: MAMS 25906, 2651 ± 26 BP, cal. BC 891 - 792; all values 2 σ, 95,4 %).

Altogether 81 charcoal pieces were selected for dendrochronological and dendrological analyses. With one exception all pieces originate from section 4. The assemblage is clearly dominated by spruce (*Picea abies,* n = 79 pieces), only two pieces could be identified as fir (*Abies alba*). The longest tree-ring series established for a single piece of charcoal from the mine Mauk B has 76 rings, however, the median of all tree-ring series analysed is just 29 rings. Most series could be clustered into several groups. One of these groups, based on tree-ring series of 23 charcoals and covering 108 years, dates to 812 - 705 BC referring to regional chronologies. One charcoal of this calendar-dated group has a waney edge proving the cutting of the tree shortly after the onset of the vegetation period in the year 705 BC. Due to a possible further waney edge identified on another charcoal, felling activities took also place in autumn/winter 705/704 BC. Another group of 12 crossdating tree-ring series resulting in a mean series of 74 rings is dated on the base of the two radiocarbon results mentioned above. The end year (last ring) of this mean series dates cal. BC 818 - 724 (95,4 %, median: 745 BC) due to wiggle matching calibration by using OxCal 4.3 and IntCal13 calibration curve (Bronk Ramsey et al. 2001, Reimer et al. 2013). The single charcoal from section 3 crossdates with a sample from section 4. Therefore similar calendar dates for these two sections can be assumed. The dated charcoals prove that exploitation in the mine Mauk B took place in the 8th century BC with the last record for the year 705 BC.

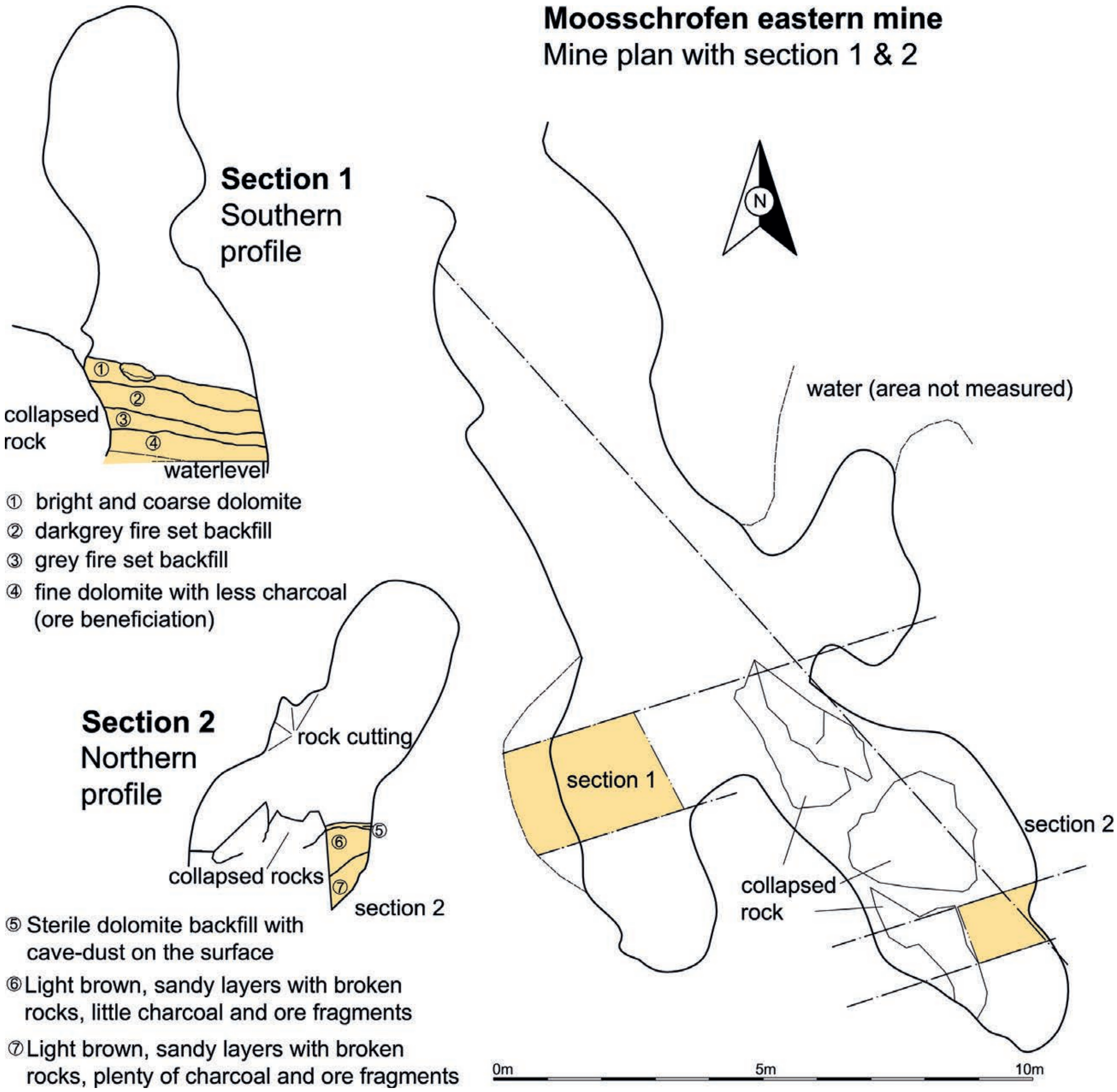

Fig. 4: The plan of the mine Moosschrofen (east) and cross sections of section 1 and 2 (graphic: M. Staudt).

Moosschrofen (district Zimmermoos, Brixlegg)

An ideal spot for mining archaeological investigations is located about 3 km east of Brixlegg. It is a 200 m long, 70 m wide and around 30 m high isolated rock called „Moosschrofen“, consisting of “Schwazer Dolomit”. A series of impressive dome-shaped cavities, representing the typical relicts of fire-setting, are visible from a distance in the vertical rock faces on the northwest side of the hill (Fig. 3). Even though some traces from younger work with hammer and pick as well as blast holes from black powder blasting are apparent, the main mining technique used on this site was fire-setting. In the 1990s Gert Goldenberg could prove a prehistoric exploitation of fahlore with radiocarbon analyses on charcoal samples (Goldenberg & Rieser, 2004). One sample from the eastern mining dump dates roughly into the Late Bronze Age/Early Iron Age (BETA 82923, 2700 ± 80 BP, cal. BC 1058 - 665, 2 σ, 95,4 %). Other charcoal pieces from the backfill inside the eastern mine are indicating a similar age (VERA 1324, 2710 ± 35 BP, cal. BC 918 - 806; VERA 1323, 2505 ± 35 BP, cal. BC 792 - 519; all values 2 σ, 95,4 %; Heiss & Oeggl, 2008).

Further charcoal samples could be taken within the DACH-project with the aim to generate more accurate dating by dendrochronological investigations (Staudt et al., 2017a). It was also scheduled to draw a mine plan as well as profiles to get a basis for the estimation of the amount of the exploited dolomite respectively ore.

Fig. 5: The northern profile of section 2 inside the eastern mine Moosschrofen (photo: M. Staudt).

The excavated fire-set dome situated in the eastern part of the Moosschrofen shows the biggest cubing with extensions up to 19 m and a maximum height of more than 8 m. In the back of the mine some big boulders of dolomite, which collapsed from the roof, are laying in and on the stowage (Fig. 4 and 5). It is not clear, if all these rocks came down during the mining activities or later on. In this mine two excavation trenches were traced out in the innermost parts (section 1: 12 m from the entrance and section 2: 17 m from the entrance, Fig. 4).

In section 1 four different layers could be distinguished and the floor level could not be reached because of up-coming water (at 1.80 m depth). Except for the topmost layer all other layers consist of finely crushed dolomite. In addition to a hammer stone fragment, some bigger pieces of charcoal could be picked up. The backfill-layers in this area are stratigraphic younger than the rock fall event.

In the small section 2 one of these big rocks lays on the surface of the topmost layer and is stratigraphically younger than the dump in this part of the mine. The layers in section 2 are much darker but as fine as in section 1 (Fig. 5). The sand-like material suggests that it could be the left over from ore processing work. Some fahlore fragments as well as pieces of charcoal could be collected for mineralogical/geochemical and dendrological/dendrochronological analyses.

Approximately 10 m eastwards of the excavation area some ceramic fragments from the Ha C period could be picked up "in situ" at a small fire-set cupola during former investigations by Goldenberg (Reider, 2003; Goldenberg, 2014; Goldenberg et al., 2019). This area belongs to the eastern mine Moosschrofen. More charcoal fragments originate from the dump underneath the big fire-set western cavern which is situated behind the modern cowshed. Due to erosion these samples were visible in a profile of the dump and it was possible to collect them without any excavation. Further a 3D-model of this tall mine (western mine) was rendered using photogrammetry (structure from motion = technique for estimating three-dimensional structures from two-dimensional image sequences).

Charcoals from both sections of the eastern part of the Moosschrofen mine have been analysed. The 57 selected pieces belong to the species spruce (n = 50) and fir (n = 7). All fir charcoals were collected in section 1. The length of the tree-ring series vary between 19 and 86 rings, the calculated median is 36.5. Crossdating of 37 charcoal series were successful and gives end years that range between 772 and 719 BC. However, most series end 742 BC or earlier, two end in the 730s BC and one ends with a possible waney edge in 718 BC. The three charcoals with the youngest end years originate from section 1, whereas the youngest end years from section 2 date into the 740s BC.

Gratlspitz (district Thierberg, Brixlegg)

The mountain Gratlspitz (1899 m a. s. l.) is situated between the tributary valleys Wildschönau and Alpbachtal and can be seen from a distance due to its exposed position. The Gratlspitz massif consists mainly of "Schwazer Dolomit" and fahlore mineralisations are frequent. The mining district is also known as "Thierberg" and fire-set mines can be recognised from the foot of the mountain up to the hilltop. This massif has been intensively exploited during the late medieval and modern times (Pirkl, 1961; Haditsch & Mostler, 1969; Mutschlechner, 1984; Gstrein, 1988a; Manninger, 2011). Near the hiking trail from the Holzalm to the summit some stone tools, pottery fragments and animal bones were found by Brigitte Rieser and Hanspeter Schrattenthaler (Schrattenthaler, 1994; Rieser & Schrattenthaler, 1998/99). Close to the summit a few pits and overgrown dumps can still be observed where prehistoric stone tools could be collected during field surveys done by the authors. All these findings prove prehistoric mining from the bottom to the top of the mountain.

Westwards of the Holzalm (a former miners hut, today a mountain guesthouse), along the northern foot

Fig. 6: A fire-set mine (red: Gratlspitz 1) at the north wall of the Gratlspitz (photos: M. Staudt and D. Brandner).

of the Gratlspitz massif, a series of mines showing clear marks from fire-setting are visible. Most of these prehistoric traces are overprinted by modern mining activities. The mine "Gratlspitz 1" is situated in the steep north face of the massif, where two side by side mining portals can be seen from a distance (Fig. 6). The mining entrance is accessible via a narrow path and with a gentle climb. From inside, this mine offers a good view to the Moosschrofen further down as well as of the Inn Valley. The mine is around 10 m deep and 9 m wide. During the excavation in the southern part of the innermost mine it was possible to reach the bottom of the mine which consists of hard dolomite rock (Staudt et al., 2017a). The backfill here is around 1.50 m thick and could be divided in four different working phases. The topmost layer derives from modern activities at a second window-like mine port (prospection only). Maybe this "window" was opened for better light conditions in the deeper part of the mine. Inside it is quite bright and working would have been possible without any artificial light (splints of wood, mining lamp). In the topmost layer of dolomite backfill some pottery fragments of early modern times, as well as a minor amount of prehistoric ceramic could be documented. It looks like the modern and prehistoric backfill has been mixed up. Beside the typical prehistoric fire-set traces, only a few tiny marks from iron-tools of more recent workings are visible on the wall.

Underneath this younger horizon two layers (3 and 4) consisting of fine dolomite sediment as well as bigger fragments of dolomite mixed with charcoal appeared. Most of the analysed charcoal, as well as some samples of fahlore, originate from these two older layers. At the western part of the section remains of a origin prehistoric layer including prehistoric pottery came to light. Additional to the archaeological excavations a 3D-Modell of the mine was created.

A first charcoal sample from this mine, collected by Gert Goldenberg, could be roughly dated into the Early

Fig. 7: A mainly fire-set mine (Gratlspitz 3) at the north wall of the Gratlspitz (photo: M. Scherer-Windisch).

Fig. 8: Fire-set walls and mine entrances inside the "crater" of the Bauernzeche with the investigated "upper mine" (above right) and "lower mine" (below; photos: M. Staudt).

Iron Age: VERA 1320, 2540 ± 45 BP, cal. BC 805 - 538, 2 σ, 95,4 %; Heiss & Oeggl, 2008). Another sample from the recent investigations dates into the last stage of the Late Bronze Age (MAMS 25905, 2669 ± 26 BP, cal. BC 895 - 798, 2 σ, 95,4 %).

The dendrochronological analysed charcoals consist of two groups, one already collected in the 1990s by Gert Goldenberg (n = 10) and the second one collected during the recent excavations (n = 13). Even though selected material was analysed, the number of tree-rings ranges between 16 and 50 (median: 20) and only two tree-ring series with more than 30 rings could be constructed. The species of all charcoals analysed is spruce. Six charcoal series were averaged into a mean series with 56 rings that dates 808 to 753 BC. The ^{14}C-date (see above) established on the base of few rings of one of the dendro-dated charcoals backbones this dating: the expected date of the last ring of the mean series is between cal. BC 847 and 750 (95,4%; median cal. BC 774) due to radiocarbon calibration by using OxCal 4.3.

To the west of the above mentioned mine "Gratlspitz 1", two other small fire-set mines "Gratlspitz 2" and "Gratlspitz 3" could be briefly investigated. In both cases the backfill material was rougher and no bigger charcoal fragments were apparent. In these two mines traces from blasting as well as from work with iron tools are visible. Therefore it can be supposed, that the prehistoric stowage has been removed either during the Late Bronze Age / Iron Age or in the course of modern prospection activities. In the mine Gratlspitz 3 (Fig. 7) an iron knife from the 15th/16th century AD could be discovered in an excavated fireplace.

Bauernzeche (district Großkogel, Reith im Alpbachtal)

The mining area Kogel, situated on the eastside of the Ziller Valley, can be separated into two units: the Großkogel (Reither Kogel) and the Kleinkogel (Hinterkogel). Casually

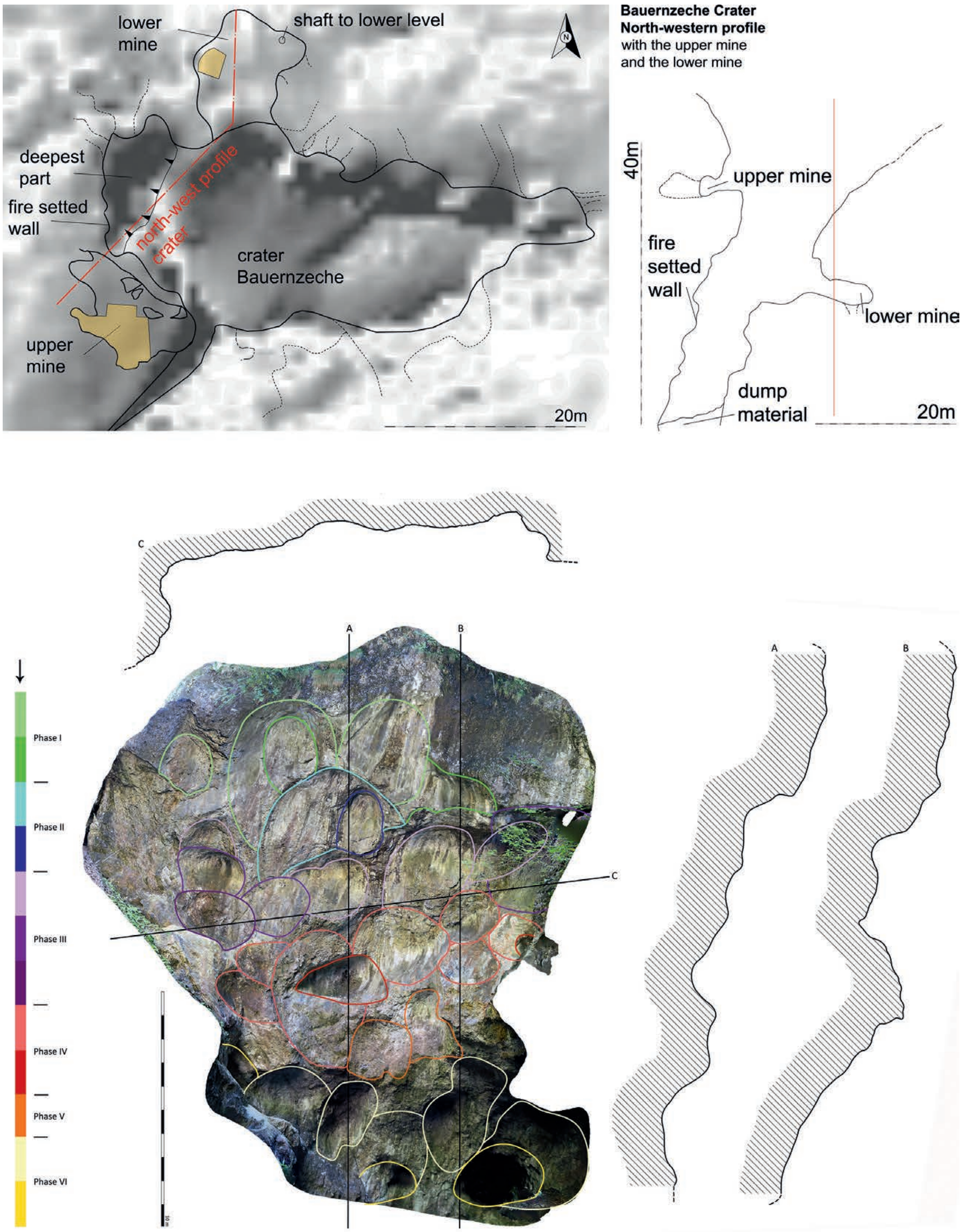

Fig. 9: The crater Bauernzeche with the position of the two excavated mines (top left) and the north-west profile of the crater (top right); 3D-model and profils of the wall underneath the excavated "upper mine" with different stages of fire-setting (bottom) (graphics: M. Staudt and M. Scherer-Windisch).

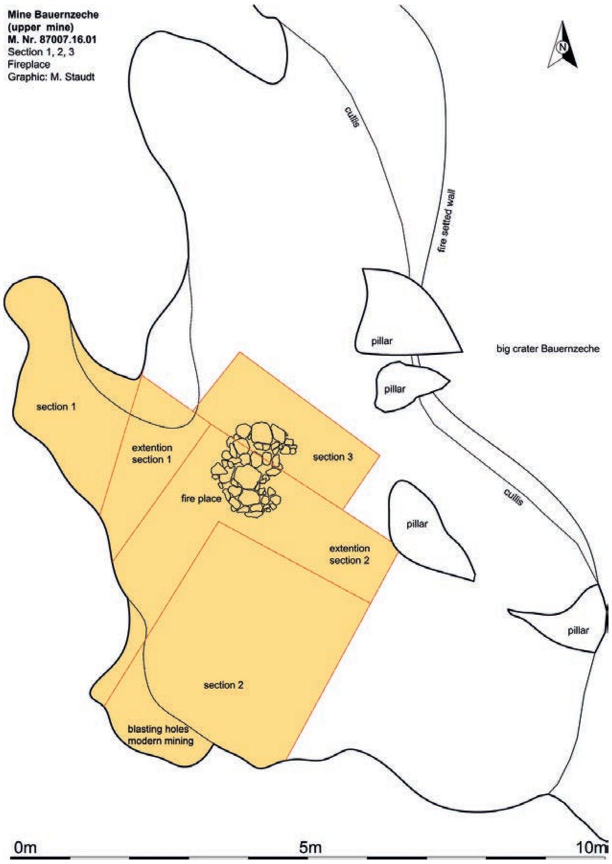

Fig. 10: Mine plan Bauernzeche "upper mine", with the fire place (graphic: M. Staudt).

the field name "Heidstein" is still in use (Mutschlechner, 1984) which can be translated to "stone of the heathens". The term "Heid…" or "Haid…" can be traced back to the descriptions of "old mining works" in the "Schwazer Bergbuch" of the 16th century AD (Bartels et al., 2006). In those days such surface-near and fire-set mines were generally interpreted as of pre-Christian age, originating from pagan or roman mining work. Along the northern slope of the Groß- and Kleinkogel Rieser and Schrattenthaler could prove prehistoric mining activities (Rieser & Schrattenthaler, 1998/99, 2002).

The so called "Bauernzeche" (Fig. 8) represents one of the most spectacular mining sites in the area of Schwaz-Brixlegg and shows very impressive fire-set walls, giving a nice picture of the enormous mining activities, which were carried out already in prehistoric times. This mining complex is situated at the northern hillside of the Großkogel which was exploited together with the Kleinkogel on a large scale in medieval and modern times (Isser von Gaudententhurn, 1888; Schmidegg, 1953; Pirkl, 1961; Gstrein, 1988a). The Bauernzeche is a big and deep hole with a cross-section dimension up to 50 m. The enormous size can be easily recognised on the LIDAR-based digital terrain model. On every wall traces of fire-setting as well as fire-set mining entrances are visible. It is not clear, if the whole complex is more a result of a huge collapsed mining system or of a large open cast mining. Most likely both aspects are to be considered. Beside the numerous and omnipresent relicts from prehistoric fire-setting, traces from medieval and modern day mining are also frequent. Within the frame of geological field surveys carried out by Herwig Pirkl, a "Bronze Age" fibula could be found (Gstrein, 2013) in the crater of the Bauernzeche (find not published).

On the western side of the crater a very impressive fire-set wall (higher than 30 m) is still well preserved. The wall shows an exceptional number of truncated fire-set cupolas which could be documented using photogrammetry (structure from motion, 3D-model, Fig. 9; Scherer-Windisch, 2017). By analysing the 3D-model and the system of overlapping of the fire-set cupolas it was possible to identify the progression of different stages of fire-setting, which shows a driving system from top to bottom. Some sintered backfill material, which is still visible on this wall, could be a sign for underground mining in origin.

Just above this fire-set wall, a small and typical prehistoric mine with some well-preserved pillars is located, the "Bauernzeche, upper mine" (Staudt et al., 2018c). This quite exposed mining spot (Fig. 8 and 11) is only accessible by climbing and was selected for detailed archaeological investigations. The steep and rocky track was secured with fixed ropes with the help of the Bergbau Aktiv Team (BAT) from Brixlegg. In front of the mine there is a narrow "balcony" left as a relic of the original mine. This shows clearly that in prehistoric times the mine was bigger and has meanwhile partly collapsed into the peripheral zone of the big crater of the Bauernzeche. The underground part of the mine is around 15 m long and 8 m wide/deep (Fig. 10). The maximum height of the mine is around 2.60 m (measured after excavation from top to ground). In the southwest corner traces of a few drilling holes are representing the remains of younger ore prospection activities. In the eastern part a former pillar was extracted. In the frame of previous investigations Goldenberg could collect small charcoal samples for two radiocarbon analyses (VERA 1608 and VERA 1609; Stöllner, 2009). These first dating attempts spread into the so called "Hallstatt plateau" of the calibration curve ("Iron Age") without a satisfying dating result.

Within the recent studies section 1 was set up in a tiny fire-set area in the western part (Fig. 10) of the mine. Underneath a 20 cm strong layer of natural collapsed dolomite (1) the typical "cave dust" (2) appeared. Below these fine strata, two layers of prehistoric backfill material, which could be separated by colour, became visible. Inside this material, a small amount of pottery, animal bones and hammer stone fragments were picked up. Together these two stowage layers (3a and 3b) are nearly 40 cm thick and overlay a cultural layer (4), which consists mainly of fine and homogeneous organic material, particularly charcoal with nearly no dolomite inside. This up to 15 cm thick stratum looks similar to what can normally be expected from an excavation at a settlement site and is very uncommon for an underground mining

Fig. 11: Bauernzeche “upper mine”, with some leftover pillars for static purposes (photos: M. Staudt).

site. The stratigraphically oldest backfill in the mine is left underneath the cultural layer and consists of a thin layer of small pieces of dolomite in section 1 (layer 5).

In section 2, which was excavated eastwards of section 1, the same sequence of layers became apparent but without the lowest backfill layer (5). The cultural layer (4) was deposited directly on the bottom of the mine. After opening the part between section 1 and 2 with an enlargement to the north a fire place, carefully set with flat dolomite stones, could be excavated at the bottom of the mine and inside the cultural layer. This impressive two-phase hearth construction was covered with tiny charcoal and thick ash layers (Fig. 12), proving a long-lasting use of the fire-place. Obviously this part of the mine was used as a miners lodge/shelter for quite a while in prehistoric time. Later in time the mining activities started again and the cultural layer as well as the fire place was covered with backfill material (3a and b).

Inside the described cultural layer a huge amount of pottery, greenish animal bones and stone tools as well as a few antler and bone tools were collected. In total 2274 pieces (33.25 kg) of pottery could be inventoried (Zetzmann, 2019). In the corpus of findings there are big fragments of domestic vessels as well as fine and occasionally also painted ceramics. Two pottery fragments show repair marks (holes, Fig. 13). Further two antler tools with production marks (cutting) and signs of use came to light as well as a tapered thin bone tool (bodkin). The different antler tools were probably used for crushing nuts or to loosen the rock slabs after fire-setting. A grooved stone hammer was picked up on the surface of the youngest prehistoric layer (3a). Further hammer stone fragments could be found in the backfill stowage (3a and 3b), in the cultural layer (4) and in between the fire place. A sharpening stone comes out of the cultural layer and a bigger stone with tiny dimples out of the top most backfill material. This stone is a sign for ore beneficiation inside the mine. In general it is approved that stone tools found at the prehistoric mining sites were rather used for ore processing than for mining. This is obvious in the mining area Schwaz-Brixlegg where most of the hammer stones found come from ore processing sites. In

Fig. 12: The two-phase fire place at the bottom of the Bauernzeche "upper mine", with the cultural layer and the overlapping backfill layers (photos: M. Staudt).

connection with fire-setting as the main driving technique, the use of hammer stones is usually not really necessary for the rock extraction (depending on the rock material; Gätzschmann, 1846; Py & Ancel, 2006). Inside the prehistoric mines fragments of stone tools are therefore only occasionally found. The unusual high amount of hammer stone fragments together with the backfill material inside the investigated sector of the mine Bauernzeche indicates ore beneficiation works inside the mine.

The pottery fragments from this mine often show a horizontal strip with finger impressions. These bellied vessels with different diameters are typical ceramic finds also in other fire-set mines in the area Schwaz-Brixlegg. In many cases they show a slightly inwards curved edge. This kind of shape and adornment is representative for the domestic pottery of the Early Iron Age (Ha C, 8th/7th century BC, Fig. 13). The ceramic finds give a good overview of the Early Hallstatt period. Settlements of this period are very rare in North Tyrol and therefore the corresponding pottery is difficult to find. The same kind of pottery is known from the dendrochronological dated mines Mauk E (707 BC, Klaunzer et al., 2010), Mauk B (705 BC, see above) and Moosschrofen (719 BC, Reider, 2003; Goldenberg, 2014). Comparable pieces could also be picked up in the "Heidenzechen" at the Eiblschrofen (Rieser & Schrattenthaler, 1998/99; Rieser & Schrattenthaler, 2004) and in front of the entrance of the "Ivanuslauf" (district Burgstall, Gstrein, 1981). The bigger vessels found inside the upper mine Bauernzeche were probably used for cooking and storing food. Also a representative and numerous selections of bowls were found inside the upper mine of the Bauernzeche. One of them shows painting marks inside the vessel. This finer kind of pottery represents the dinnerware of the prehistoric miners (Fig. 13).

From the excavation inside the "Bauernzeche, upper mine", three radiocarbon dates could be obtained from animal bones found in the youngest backfill (MAMS 28725, 2520 ± 20 BP, cal. BC 788 - 549, 2 σ, 95,4 %), the oldest backfill underneath the cultural layer (MAMS 28726, 2470 ± 20 BP, cal. BC 763 - 492, 2 σ, 95,4 %) and in between the two phases of the fire place (MAMS 28727, 2479 ± 20 BP, cal. BC 766 - 524, 2 σ, 95,4 %). Because of the "Hallstatt-plateau" of the calibration curve the ^{14}C-data again spread into the Iron Age and cannot be dated exactly. The dendrochronologically analysed charcoals (n = 14) from this mine resulted in relatively short tree-ring series from 16 to 39 values (median 23). Only few series could be clustered and no dendro dates could be established till now. The investigated assemblage is dominated by fir pieces, i. e. 12 out of 14 charcoals belong to this species, and the two other charcoals are spruce. It seems that some of the end years date into the 7th century BC, but due to the small annual rings there are no concrete dating approaches.

Inside the crater, opposite the massive fire-set wall and 15 m deeper than the "upper mine" it was possible to investigate another small fire-set mine, the "Bauernzeche, lower mine" (Fig. 9). The work was done in the upper level of this underground mine which is linked by a shaft to a deeper part. The surface of the prehistoric mining backfill was almost preserved and in the frame of a small excavation two prehistoric pottery fragments and some bigger pieces of charcoal could be picked up out of the 0.90 cm thick filling. Additionally to the archeological excavations a 3D-model was constructed of the lower mine Bauernzeche.

The investigated charcoals from the "lower mine" allowed the establishment of dendro-dates. Here also mainly fir (29 pieces out of 39) could be identified and the other analysed charcoals are again spruce. The length of the tree-ring series established for these 39 charcoals range from 17 to 66 (median: 27). Fir as well as spruce series could be crossdated and consequently averaged

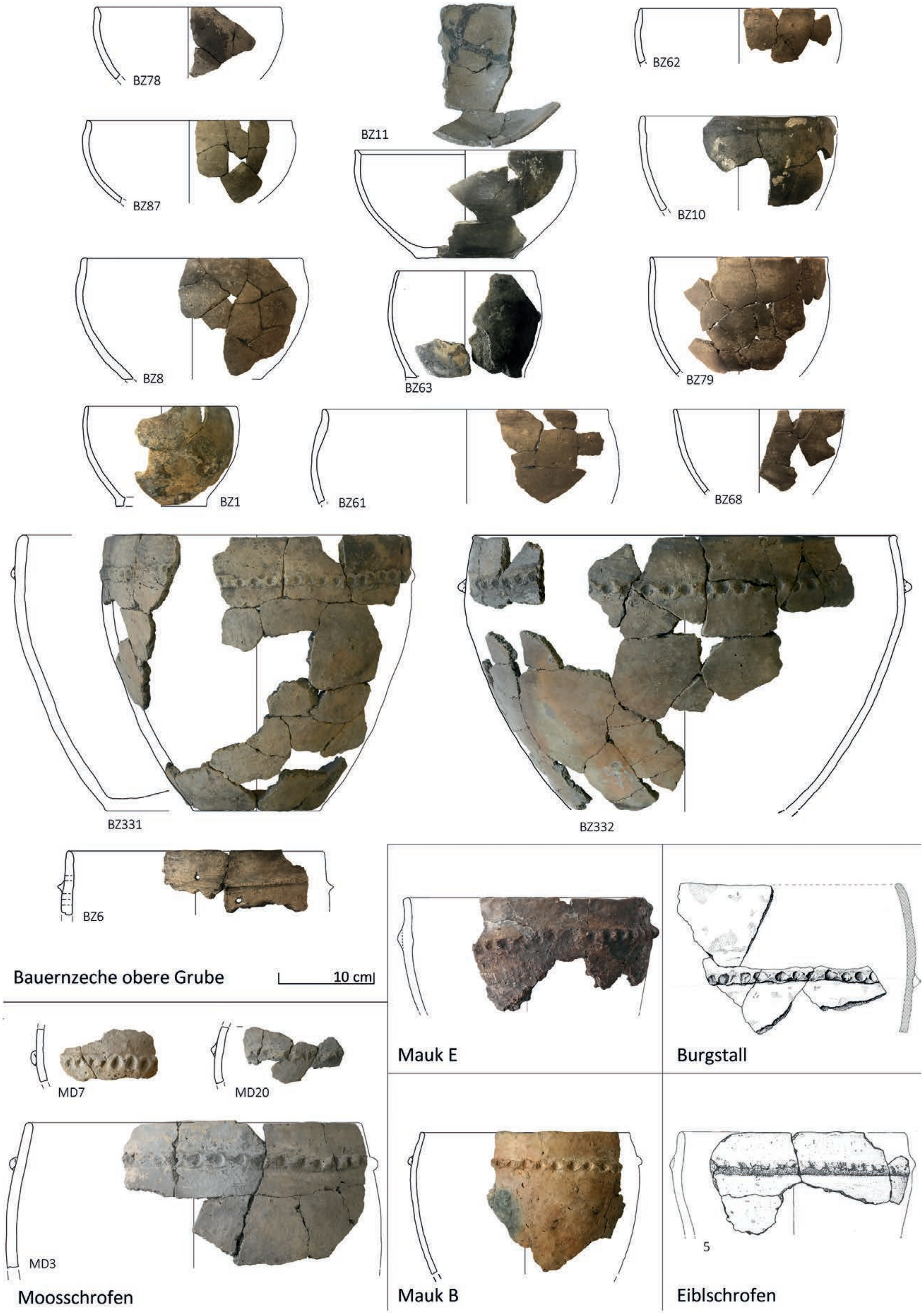

Fig. 13: Pottery from the Early Iron Age mines Bauernzeche, Moosschrofen, Mauk E, Ivanuslauf (Burgstall), Mauk B and Eiblschrofen (graphic: M. Staudt, B. Rieser and H. Schrattenthaler, P. Gstrein).

Fig. 14: The mine „Knappenkuchl" with the upper (top left) and lower (bottom left) levels, which are linked with a shaft/chimney (right; photos: M. Staudt).

to an 82 values long mean series, which dates 853 to 772 BC. Most series, i. e. 15 out of 21, have their last ring within the last decade of the mean series. Moreover, waney edges could be identified on few samples. A fir charcoal prove logging in autumn/winter 777/76 BC, a spruce as well as a fir charcoal document also such activities in summer 772 BC and an additional fir sample display only a possible waney edge which suggests cutting in summer 772, too.

Knappenkuchl (district Kleinkogel, Reith im Alpbachtal)

In mining history the Kleinkogel is as famous as the Großkogel (Isser von Gaudententhurn, 1888; Schmidegg, 1953; Pirkl, 1961; Gstrein, 1988a). Alongside traces of medieval and modern day mining, traces of fire-setting can be seen from the bottom up to the hilltop. The so called presumable prehistoric mining complex “Wilde Kirche” at the Kleinkogel shows a similar dimension as the “Bauernzeche” and also shows traces of fire-setting (Mutschlechner, 1984). This open cast mine was already illustrated in the Schwazer Bergbuch (Bartels et al., 2006). Underneath the “Wilde Kirche” and estwards of the modern Johannstollen (Pirkl, 1961; mine nr. 20) a Certosa-fibula could be picked up during a field survey (Huijsmans & Krauß, 2015). This artefact made of bronze dates into the Late Hallstatt/Early Latène period (Ha D2-Lt A).

The mine “Knappenkuchl” is located on the northside of the district Kleinkogel in a steep trench approximately 750 m westwards of the Bauernzeche (district Großkogel), around 170 m below the summit (1068 m a. s. l.). Obviously the western fire-set mining part has collapsed a long time ago. A younger mining system, exploited mainly by hammer and pick as well as by black powder blasting, with remains of wooden trails from a so called “Spurnagelhunt” (buggy) is evident directly underneath the prehistoric mine. Inside one of the adits, parts of a wooden ore trough could be collected by the authors.

In the prehistoric two-storied mine, little marks from younger mining actions are apparent. The mine consists of two levels, which are linked together with a fire-set chimney/shaft (Fig. 14). In the less voluminous upper level, the only small amount of dolomite filling left behind is less suitable for archaeological investigations (Staudt et al., 2018c). The lower level in contrast could be partly excavated with good results. In front (north) of the mine, on a small plateau, more buried fire-set entrances are partly visible. This plateau was probably created during modern mining activities and used as a base of a miners hut. Even though there are no visible structures left, most likely a part of the southern dolomite wall has been flattened for the same reason.

The lower level of the fire-set mine with a length of 25 m, a height of 3.70 m and a depth of more than 20 m shows different entrances on the north- and eastside (Fig. 15). Because of the sloping backfill, which

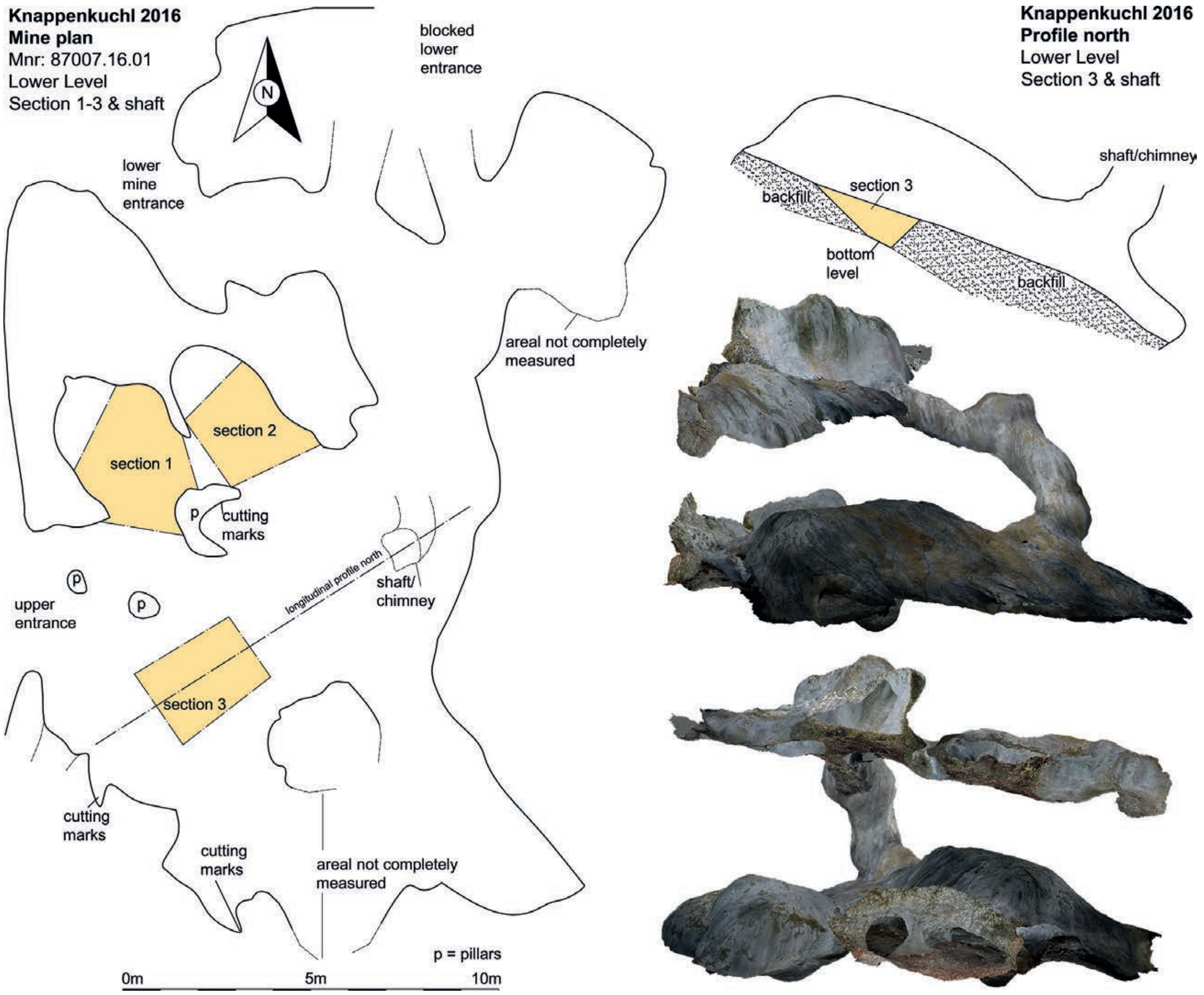

Fig. 15: Plan and longitudinal profile north of the lower level of the mine Knappenkuchl with the 3D-model (graphics: M. Staudt and D. Brandner).

covered the whole mine floor, it was only possible to measure the height in section 3 (see below). The areas on the east side could not completely be documented. There was too much backfill material and a shortage of investigation time, because of the arriving winter. At the peripheral zones in the western part some pillars are well preserved. In the southern part a collapsed zone and another blocked entrance or access to a further mining system is evident.

North and east of the highest entrance of the lower mining level, three sections could be traced out. Section 1 and 2 are situated between two fire-set cupolas and a pillar. In all sections the same sequence of prehistoric layers could be observed underneath grit dolomite pieces from younger mining periods. In this upper layer a fragment of a pipe bowl (17th/18th century AD) and some leather fragments, animal bones and remains of lighting sticks were picked up. In section 1 this stratum is up to 90 cm thick. The thickest prehistoric backfill material (1.10 m) was documented in section 3 (Fig. 15). In all the prehistoric layers charcoal pieces from fire-setting were collected for dendrochronological analyses. In section 2 and 3 prehistoric domestic pottery fragments were apparent and two fragments of hammer stones with mounting marks could be recovered. Where the fire-set cupola passes into the aeration chimney, some sintered dolomite debris is left on the wall. This may indicate, that the lower part of the mine was filled up once with stowage material, before this was removed later on for further mining activities or prospecting. Out of the chimney, a piece of sintered charcoal could be taken for radiocarbon analyses (MAMS 29941, 2966 ± 21, cal. BC 1261 - 1117, 2 σ, 95,4 %). One greenish bone fragment was picked up in the lower part of the top most prehistoric backfill material of section 3 for ^{14}C-analyses (MAMS 29940, 2908 ± 22, cal. BC 1193 - 1016, 2 σ, 95,4 %). A digital photogrammetric 3D-model (structure from motion) was created by Daniel Brandner out of the complete upper level, the linking chimney/shaft as well as the southern half of the lower level (Fig. 15).

Fig. 16: The southern prehistoric fire-set part of the mine Schönbiegler Bau with chimney (photos: M. Staudt).

Fig. 17: Northern profile of section 1 inside the southern part of the mine Schönbiegler Bau underneath the chimney (photo: M. Staudt).

Schönbiegler Bau (district Burgstall, Gallzein)

The mining district "Burgstall" lies to the south of Gallzein between the Bucherbach in the west and the Schlierbach in the east (Gstrein, 1986, 1990). Westwards of the Bucherbach, in the surroundings of the Kogelmoos, the famous legend of the "bull of Kogelmoos" was originated in 1409 (Gstrein, 1988b; Grundmann & Hanneberg, 1994). At the Blutskopf (district Burgstall) a lot of underground mines, pits and opencast mines are still visible. Within the frame of field surveys close to the hill top in front of the historic Ivanus mine, some fragments of prehistoric domestic pottery could be picked up by Peter Gstrein in the years 1963 and 1974 (Gstrein, 1978, 1981, 2015). This was the first documented pre-Christian ceramic find in the mining area Schwaz-Brixlegg. In the 1990s Rieser and Schrattenthaler could also prove prehistoric mining activities along the Blutskopf (Rieser & Schrattenthaler, 1998/99, 2002).

The mine "Schönbiegler Bau" is situated at the steep western hillside of the Blutskopf, above the Bucherbach. In the direct surroundings several small fire-set underground mines and opencasts with marks from fire-setting are visible. Again the coexistence of fire-setting techniques, cutting activities and blasting operations is apparent. In the 1990s Goldenberg could collect a tiny amount of charcoal samples from this mine which proved mining in the last stage of the Late Bronze Age (VERA-1319, 2680 ± 30 BP, cal. BC 897 - 802, 2 σ, 95,4 %; Heiss & Oeggl, 2008). In the frame of his dissertation Gstrein was able to draw a detailed plan of the whole underground mining system from late medieval to modern times (Gstrein, 1978).

The "Schönbiegler Bau" is devided into two west-east orientated mining systems (Staudt et al., 2018c). The southern part shows a big fire-set underground chamber with the extensions around 11 m x 7 m and a height of 7 m (Fig. 16). The whole floor is covered with dolomite backfill. In the east a younger dump, which comes from the adjacent modern mining area, is apparent. During the

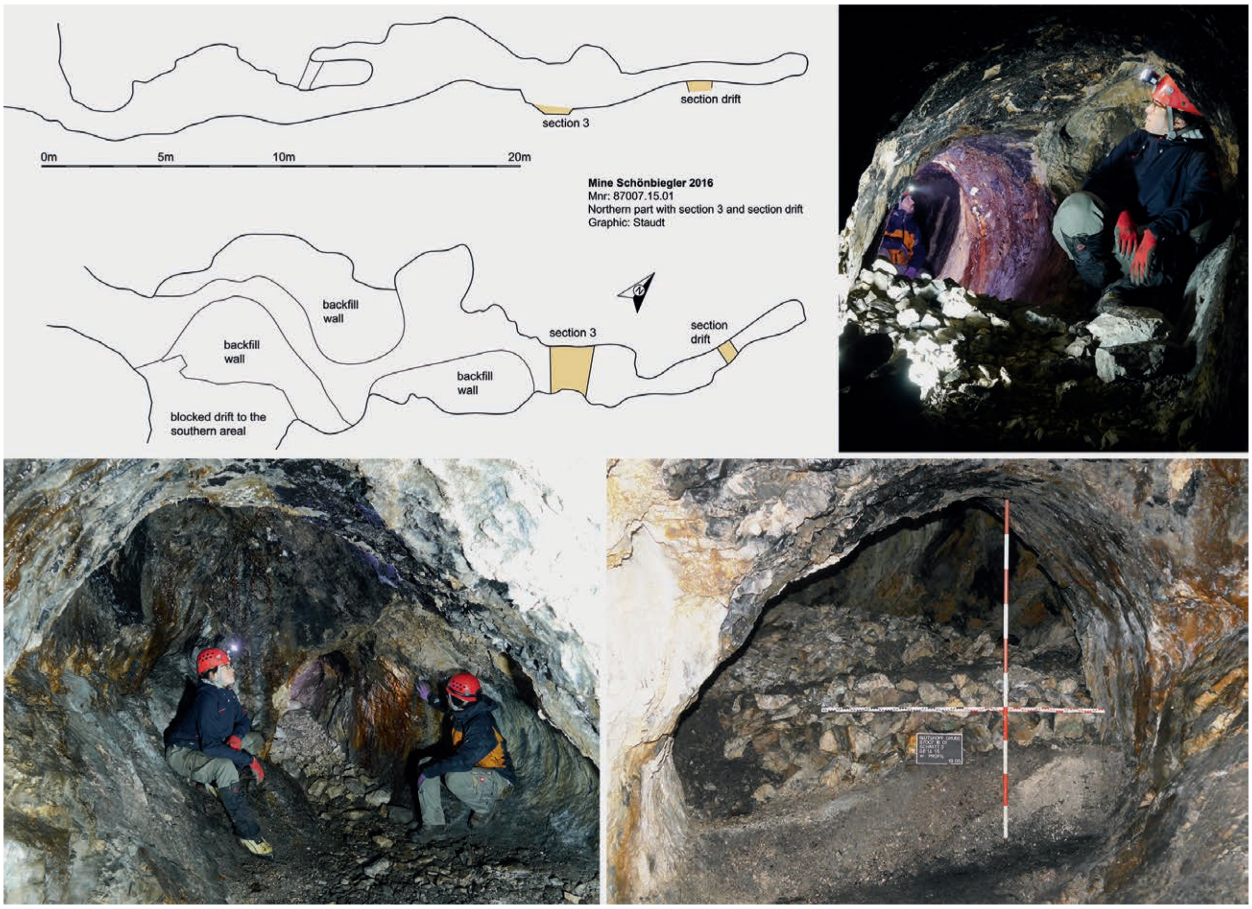

Fig. 18: Mine plan and "Seigerriss" (top left), western profile of section 3 (bottom right), the fire-set drift (top right) and the deepest prehistoric mining area (section 3, bottom left) inside the northern part of the mine Schönbiegler Bau (graphic/photos: M. Staudt).

excavation the ground level could not be reached and is assumed deeper. At the roof a small, 2.50 m long chimney up to the surface is visible. At the backside the modern mining gallery with a length of 45 m is adjoining. Section 1 was traced out in the southern fire-set mining system underneath the chimney (Fig. 17). The topmost layer included a few modern finds. Below, in a 10 cm to 50 cm thick dolomite deposit with finds from the 15th/16th century AD ceramic fragments of two miner lamps ("Schwazer Lampen") as well as fragments of domestic pottery came to light. Also here the prehistoric backfill material then becomes evident underneath the typical thin layer of "cave dust". This prehistoric dump could be distinguished into two layers, which include domestic pottery and a lot of bigger charcoal fragments. For technical and security reasons this excavation had to be stopped at 1.90 m depth and the ground level could not be reached. Radiocarbon analyses from charcoal samples out of this section show no exact dating (MAMS 29938, 2515 ± 20 BP, cal. BC 786 - 547, 2 σ, 95,4 %), due to the problem of the "Hallstatt-plateau" of the calibration curve.

The northern mining part was originally linked with the big chamber, but today the connection is collapsed. Entering this northern area is possible from the west through a collapsed open cast mine. In the northern part traces of fire-setting are visible up to the heading face, which is situated 35 m innermost in the east (Fig. 18). Although drifted by the fire-setting technique, the last 8 m look similar to medieval/modern drifts. Additional working traces from hammer and pick, as well as blasting holes, are discernible. A small excavation (section 3, Fig. 18) was realized inside the mine in front of this drift in a nice fire-set cupola 24 m southwards of the entrance. The fine structured backfill was up to 50 cm thick and could be separated in two layers of dolomite mixed with some charcoal fragments. The floor level shape is nearly flat. Radiocarbon analyses from section 3 show a more exact dating (MAMS 29939, 2639 ± 20, cal. BC 827 - 794, 2 σ, 95,4 %) than in the southern part of the mine.

Another section (section drift) was trenched out in the smaller drift in the nearly innermost fire-set part of the mine (Fig. 18). There the backfill on the floor was sintered and a few bigger charcoal fragments could be picked up for dendrochronological/radiocarbon analyses. No other datable artefacts could be collected during the excavations in the northern part of the mining system. The same shape of fire-set drift as in the deepest part of the investigated mine can also be observed in other mines in the area Schwaz-Brixlegg (Fig. 19). Inside a mine at the Kleinkogel (Reith i. A.) and another one at the district

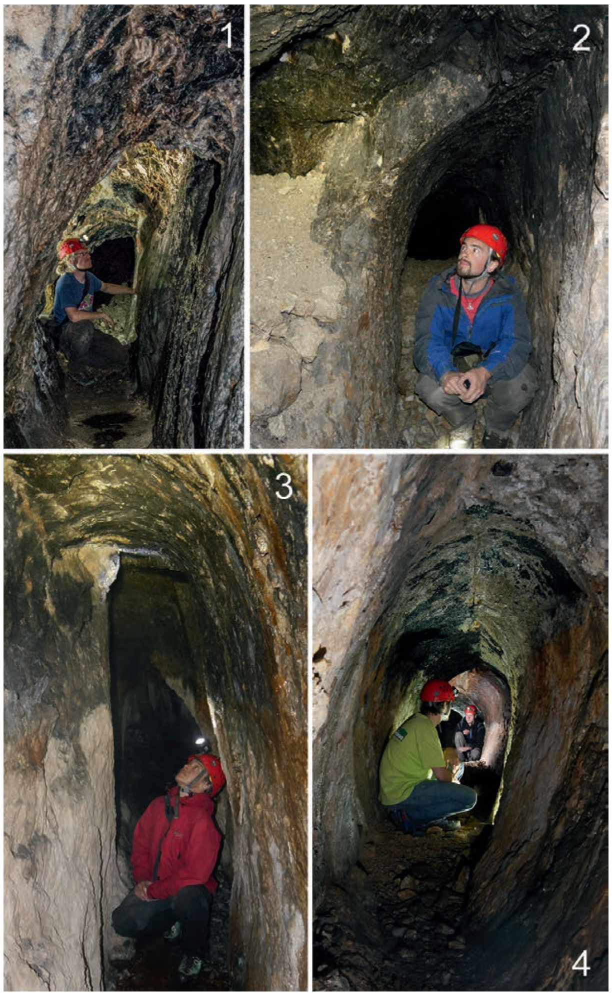

Fig. 19: Fire-set drifts from medieval/modern day mining activities: 1 - district Palleiten, 2 - district Weißer Schrofen, 3 - district Kleinkogel, 4 - district Hintersommerau (photos: M. Staudt and A. Schirmer).

Weißer Schrofen (Pirkl, 1961; mine nr. 502) the sequences of cutted drifts which merge to stratigraphic younger fire-set drifts show clearly medieval/modern activities. The illustrated pictures (Fig. 19, 1 and 4) of the fire set drifts Sagzeche (district Palleiten) and another one in the district Hintersommerau have not yet been dated. In the case of the "Schönbiegler Bau" it was possible to date this fire-set drift with radiocarbon analyses from a charcoal sample out of the sintered backfill. As it was expected, this deepest part of the northern mine was exploited in historic times and the fire-set drift dates into the 15th/16th century AD (MAMS 31599, 443 ± 30 BP, cal. AD 1415 - 1609, 2 σ, 95,4 %). A 3D-model (structure from motion) was rendered of this drift, as well as of the adjacent prehistoric fire-set copulas in the west.

The dendrochronologically analysed charcoals from the „Schönbiegler Bau" belong to two groups. Four samples were collected in the 1990s whereas 101 charcoals originate from the recent excavations. The material is dominated by spruce, only eight out of 105 charcoals have been identified as fir (*Abies alba*, 4 pieces) and larch (*Larix decidua*, 4 pieces). One of the larch pieces – together with three spruce pieces – belong to the group of late-medieval timber material that is not completely charred. Only short tree-ring series, i.e. 18 to 30 values long, could be established for these wood fragments. The length of the series of the other pieces vary between 9 and 61 rings (median: 20). In the end two mean series could be established on base of the prehistoric charcoals from this mine. The series of four charcoals could be cross-dated to a 59 years long mean series. Few rings of the innermost part of a charcoal were used for radiocarbon dating (MAMS 29939, see above) and the calibration dates the end year of the mean series to cal. BC 774 - 741 (95,4 %, median: 754 cal BC). A second mean series is based on 51 tree-ring series from charcoal of both sections 1 and 3. The mean series dates 768 to 703 BC (66 years), however, this calendar-dated series ends without a waney edge. For one of the tree-ring series included a prehistoric ^{14}C date is available (MAMS 29938, cal. BC 786 – 547, see above). The adjusted calibration of this ^{14}C result dates the last ring of the mean series to cal. BC 750 - 511 (95.4 %, median: cal. BC 601) which is in agreement with the dendro-date but highlights the limitation of radiocarbon dating in the Hallstatt period.

Gut Wetter Bau (district Burgstall, Gallzein)

The mine „Gut Wetter Bau" is situated near the surface and represents the uppermost part of the mining system called "Katzenstollen". The entrance is around 90 m to the south of the Ivanus mine on the top of the Gallzeiner Joch. Mining pits as well as traces of open cast mining characterise the surrounding landscape. The "Gut Wetter Bau" is accessible from the west through a sloping fire-set entrance. Inside traces of fire-setting are omnipresent (Fig. 20). On the eastside the mine is defined by a shear zone. The biggest dimension of the fire-set areal is around 15 m wide. The maximum height is up to 6 m. In the south the cavity is connected to a big mining system from the historic mining periods, which shows mining marks from hammer and pick, wedge pockets ("Keiltaschen") and blasting holes. This quite deep mine was documented by Gstrein in the 1970s (Gstrein, 1978).

During a prospection, one complete hammer stone and a fragment (with mounting marks) could be picked up on the backfill underneath the entrance, next to humous material slipped in from outside (Staudt et al., 2018c). Directly above these artefacts, some sintered dolomite with pieces of charcoal was left on the wall. The same kind of sintered material could be noticed on the opposite side at the big shear zone. It is assumed, that in prehistoric time backfill material covered the whole mine floor and was removed later on by subsequent mining activities. The radiocarbon sample from the sintered backfill dates into the Early Iron Age (MAMS 28724, 2528 ± 26 BP, cal. BC 788 - 579, 2 σ, 95,4 %). The fire-set part was documented

Fig. 20: The fire-set part of the mine "Gut Wetter Bau" (photos: M. Staudt).

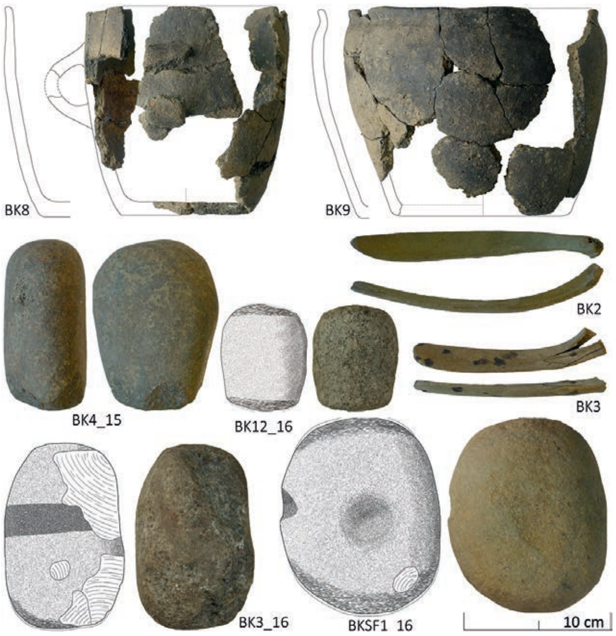

Fig. 21: Some Late Bronze Age findings from the Blutskopf plateau (stone tools, bone tools and pottery; graphic: M. Staudt and R. Lamprecht).

and a plan with cross-sections was established. So far, no archaeological excavation has been carried out, because there is not a lot of backfill left in the assumed prehistoric section.

Sagzeche (district Palleiten, Gallzein)

The Sagzeche is situated eastwards of Kogelmoos and next to the Bucherbach. This mine represents a medium-sized flat lying extraction area with around 200 m^2 and shows different Late Medieval/Early Modern Period driving techniques (Pirkl, 1961; Gstrein, 1978). At the roof of the mine some fire-set cupolas are still visible. Again a radiocarbon sample from sintered backfill was analysed and dates into the Late Bronze Age/Early Iron Age (MAMS 32531, 2613 ± 23 BP, cal. BC 816 – 780, 2 σ, 95,4 %). Also a trench with traces of fire-settings is apparent (Fig. 19, 1) but it looks more like the one at the Schönbiegler Bau (Fig. 18) which dates to the Late Medieval/Early Modern mining period.

Archaeological investigations above ground – mining pits "Pingenfelder" (2015 – 2017)

The Blutskopf plateau (district Burgstall, Gallzein)

Directly south-west to the entrance of the "Gut Wetter Bau" a few pits and traces from open cast mining are clearly visible (Fig. 22). This signs of mining can also be tracked alongside the hill top to the north east. In the frame of a field survey, domestic pottery fragments and artefacts for ore processing (hammer stone fragments and greenish animal rips with toolmarks), could be picked up in the year 2015 along a new forest track (Staudt, 2016; Staudt et al. 2017a). This track curls through the mining pits southeast of the open cast mines and passes the modern deflection station of a former ropeway for material transport (from the iron ore mines of the "Schwader Eisenstein" to the "Jenbacher Werke" on the bottom of the Inn Valley), where the foundation is still visible. After restoring the pottery finds, it appears that the pieces belong to two small pots of the Late Bronze Age (Fig. 21). One of them has a strap handle. Possibly the two vessels were originally stored next to each other and were only destroyed during the building of the forest track. Both pots are tempered with tiny slag fragments and prove the contact with nearby copper smelters (Staudt et al., 2017a).

Because of these prehistoric finds, which came out just underneath the forest floor, a small archaeological excavation was organized (Staudt et al., 2018c). Section 1 was situated on a small flat area between two pits and directly above the open cast mining area. Under the 10 cm to 20 cm thick forest humus, a mining/ore processing dump was visible. This max. 40 cm thick layer of broken dolomite (Fig. 22) contained a lot of prehistoric pottery, some fahlore, greenish animal bones and hammer stones as well as hammer stone fragments (Fig. 21). It was obvious,

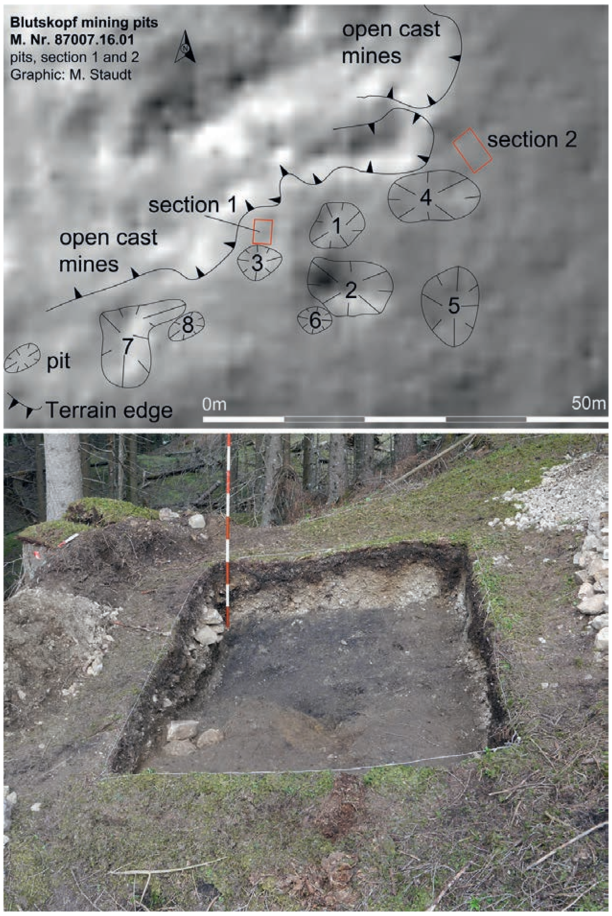

Fig. 22: The mining pits on top of the Blutskopf plateau (top). Section 1 with the prehistoric dump (bottom; photos: M. Staudt).

that the heap came from pit 1, which lies 4 m above on the east. In section 1 the dump was bordered with a "wall" of bigger dolomite stones to the southern pit (3) which is situated just next to the section. It is assumed that this construction was built to secure the mining activities in pit 3 and maybe the open cast mines too. This could indicate that mining was going on in pit 1 and 3 at the same time. A hammer stone with mounting marks was included in this construction. Underneath the dump a thin and dark cultural layer/working horizon, with finds and charcoal fragments, was visible on the natural ground.

By opening a small trench in section 1, it could be demonstrated, that the ore bearing dolomite at this place was originally covered by a very compressed glacial sediment. So the outcrop was not visible for the prehistoric miners. This indicates that the miners knew by experience and with a certain geological knowledge where to dig for the ore bearing dolomite.

Radiocarbon analysis was conducted on one animal rip which was used for ore processing and found in 2015 along the forest track. This find dates into the Late Bronze Age (MAMS 25911, 2743 ± 24 BP, cal. BC 968 - 826, 2 σ, 95,4 %). Two ^{14}C-analysed bones out of section 1, one from the dump and one from the working horizon, also date in the last stage of the Late Bronze Age (MAMS 28721, 2723 ± 19 BP, cal. BC 908 - 823, 2 σ, 95,4 %; MAMS 28722, 2709 ± 19 BP, cal. BC 900 - 815, 2 σ, 95,4 %). The greenish tinge of the bones is caused by the storage inside the cupriferous dump. By analysing such bones it was possible to identify the kind of ore contained in the dump (Rieder, 2014).

Section 2 was situated east of the boundary area of the mining pits. In this small investigation spot a lot of hammer stones and hammer stone fragments as well as pieces of fahlore with secondary minerals could be documented just 10 cm beneath the forest surface. These finds came out of a max. 10 cm thick cultural layer. In this horizon a small zone with reddish burned clay was visible at the western profile. This was probably a left over from a fire place without any stone edging. There was no evidence of mining activities in section 2. The large amount of hammer stones and hammer stone fragments as well as the pieces of ore suggest that this flat area was mainly used for the beneficiation of ore extracted from the nearby pits and open cast mines.

The pits on the plateau of the Blutskopf/Gallzeiner Joch are representing mining pits/shafts from the Late Bronze Age. At the neighbouring open cast mining area traces of fire-setting as well as collapsed fire-set mines are visible. The landscape was heavily remodelled presumably already in prehistoric times and the ore processing took place at the flat areas.

A hammer stone with mounting marks could be picked up at the eastern end of the Blutskopf plateau (Trebachwald). Remains of massive open cast mining occur in the direct surrounding of this find. It can be assumed that the local mining already started in prehistoric times and spreads over the whole Burgstall district (see also Rieser & Schrattenthaler, 1998/99, 2002).

Field surveys in Obertroi (district Rotenstein, Buch i. T.)

Within the frame of field surveys in the mining district Rotenstein to the south of Obertroi, a few prehistoric pottery fragments (some with slag temper), greenish animal bones and some hammer stones were picked up by the authors (Staudt et al., 2018c). These finds stretch along a north-south orientated mining pit field ("Pingenfeld"), which is situated north of the Geistgraben. The Schlierbach and Geistgraben separate the two mining districts Burgstall and Rotenstein. The pit field and the corresponding heaps look similar to the prehistoric ones from the top of the Gallzeiner Joch. The big pits are clearly visible in the digital elevation model and are presumably mostly from prehistoric times. Also some fire-set mines are visible, which are overprinted by younger mining activities (Hanneberg et al., 1997). Some of the large pits were filled up while building a forest road in the 1990s (Rieser & Schrattenthaler, 1998/99). Below and 200 m westwards of this pit field some dark cultural layers including animal bones and prehistoric pottery fragments came to light underneath a historic mining dump. Radiocarbon analyses were done on an animal bone and date into the Late Bronze Age (MAMS 33503, 2746 ± 24 BP, cal. BC 968 – 828, 2 σ, 95,4 %).

Mining pits and ore processing in the district Weißer Schrofen (Strass im Zillertal)

The mining district "Weißer Schrofen" is situated to the east of the "Raffl" farm and north of the Larchkopf on the west side of the Ziller Valley. It was an important mining area in historic times and – like the districts Burgstall and Rotenstein – part of the bigger district "Ringenwechsel" (Sperges, 1765; Isser-Gaudententhurn, 1893; Schmidegg, 1951; Pirkl, 1961; Arlt et al., 1999). Due to the low stability of the local dolomite in this area nearly all surface near mines and mining entrances from medieval and modern times are collapsed (Gstrein, 1978). However there are still a few signs of fire-setting activities left in the area north, west and south of the "Schrofenmarterl" (Perger, 1995; Rieser & Schrattenthaler, 1998/99; 2002). In 2007 Rieser and Schrattenthaler discovered a huge amount of slags on a small plateau underneath the Larchkopf and in the immediate vicinity of some mining pits. Because of the slag finds together with finds of prehistoric pottery they supposed a Bronze Age smelting site, even though the slags looked like medieval blacksmith slags (Rieser & Schrattenthaler, 2007). During field surveys conducted by the authors the slags could be clearly identified as the leftover of a blacksmith and not of a prehistoric copper smelting site.

Because of a number of illicit excavation trenches which were visible in this area and a few left over prehistoric pottery fragments in the rummaged soil, an emergency excavation with financial support from the BDA (Bundesdenkmalamt) could be organized in summer 2016 (Staudt et al., 2018a).

Section 1 was situated at the lower, flat western part of the plateau just above a steep wall and underneath/ northwest of the pit field (Fig. 23). In this section no structures became evident, but some artefacts from the 15th/16th century AD came to light including an iron mining pick, some stamped domestic pottery and a lot of stove tiles as well as some blacksmith slags. Therefore it was supposed that there was a former miners hut nearby on the north side of the plateau. The north-eastern part of the lower terrace consists partially of dump material and was filled up by hand, probably in the younger mining periods.

About 13 m to the east section 2 could be traced in one of the illegal excavation areas to verify the stratigraphy. Beneath the forest surface a 10 cm to 30 cm thick layer from the 15/16th century AD with stones from a hut foundation could be documented. By excavating these features a lot of slags were collected, which indicates the former position of the blacksmith hut. Directly underneath, an up to 1 m thick prehistoric cultural layer/dump appeared (Fig. 24). This homogenous layer consists mainly of organic material (waste) which is mixed with ore beneficiation sand/crushed dolomite. This layer furnished a big amount of greenish animal bones, domestic pottery (Fig. 25, Eß, 2018), hammer stones (Fig. 24) and hammer stone fragments as well as small pieces of fahlore. The most spectacular find of this section was a fragment (Fig. 24) of a socketed pick (type Mitterberg; Mayer, 1977). The distribution area of this kind of mining tool is around the Mitterberg district. These mining picks were mainly used in softer schist material (Stöllner & Schwab, 2009; Thomas, 2018; Koch Waldner, 2017). Most likely it was not the favourite tool within the solid Schwazer dolomite. The main driving technique in the fahlore area Schwaz-Brixlegg was fire-setting. So far only four pieces are known from the mining districts of North Tyrol (Goldenberg et al., 2019).

One isolated piece of plate slag out of the illicit excavation may indicate the direct contact of the miners with the smelters from the nearby Late Bronze Age smelting

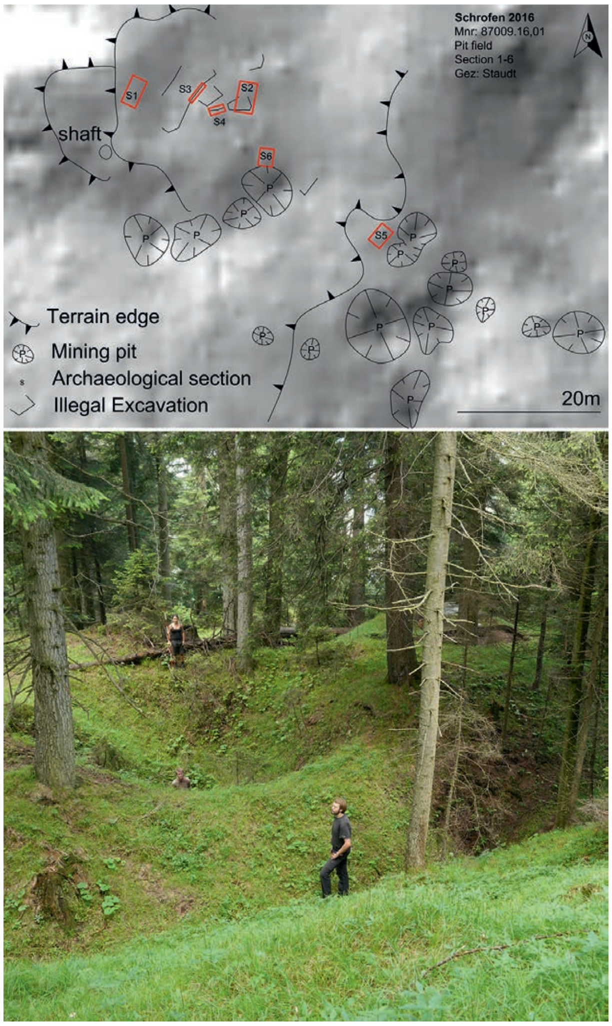

Fig. 23: Plan of the pit field Weißer Schrofen (top) and one of the biggest pits (bottom; graphic: M. Staudt).

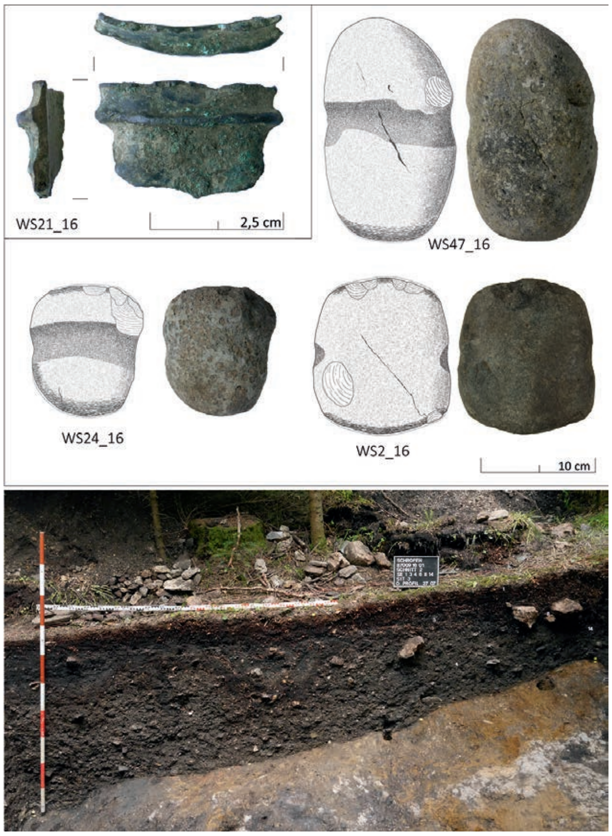

Fig. 24: Profile east of section 2 with the massive prehistoric layer (bottom left) which is rich in finds and miners tools (top, fragment of a bronze mining pick and hammer stones; graphics: M. Staudt and R. Lamprecht).

Fig. 25: Prehistoric pottery fragments (top) and the prehistoric layers which are sloping in the pit (bottom) in section 6 (photos: M. Staudt; graphics: M. Staudt and L. Eß).

site in Rotholz. The smelting site is situated around 1.2 km downwards to the west and is probably the place where the fahlore from the district "Weißer Schrofen" was smelted (Staudt et al., 2017b; Staudt et al., 2018b; see also article Staudt et al. for the smelting site Rotholz in this volume).

A few meters south-east of section 2 and directly north of a pit, section 6 was excavated. A flat layer with a height of 30 cm consisting of small pieces of dolomite with some iron fragments was deposited on an older humus, which has developed between the prehistoric and the modern mining phase. In the topmost prehistoric layer some ore beneficiation sand/crushed dolomite and a hammer stone/crushing stone deposit was apparent. Below, loose relocated soil and darker layers are falling down into the nearby mining pit (Fig. 25). That means that the growing layers slipped into the depression after the end of the prehistoric mining activities in this pit. Perhaps the side part of the pit was flattened with prehistoric material for a better worktop. This fact also shows, that the original cross section dimension of this pit was bigger than it is visible today. The pit was probably filled with soil material from the neighbouring pit. A classical mining dump was not visible and probably lies on the opposite side of the pit. It is not clear, if these pits are collapsed mining (hauling shaft) or ventilation shafts. Maybe they are just remains of open cast pits. It is conspicuous, that they are situated in a line. This could be a sign for a kind of "Duckelbau" as well. Therefore narrow shafts ("Duckeln") were sunk down to the deposit. Then the driving was continued circular along the shafts. The massive layers, dumps and the amount of prehistoric finds, suggest rather underground mining, than digging in open pits. Or maybe it is a mixture of both mining types. The prehistoric layers could be excavated to a depth of 1.40 m and contain hammer stones and hammer stone fragments, small pieces of fahlore, greenish animal bones and pottery fragments.

Section 5 was situated 16 m south east of section 6 on a clearly visible dump, directly west of the corresponding mining pit (Fig. 26). Underneath the forest humus, a 30 cm to 90 cm thick dolomite dump was apparent. In there, a few pieces of iron could be found. It was suggested, that this must be a heap of "modern" mining activities.

Below a more finely structured dump with hammer stone fragments came to light. This prehistoric heap is 1 m thick and lies on a 20 cm strong cultural layer, with some animal bones and domestic pottery fragments inside.

Fig. 26: Section 5 was traced out in a dump which belongs to a mining pit (top). Underneath the dump a prehistoric cultural layer is visible which is rich in finds (bottom; photos: M. Staudt).

Because of the aslope profiles of the section, only a very small area of this cultural layer could be investigated. The cultural layer consists of organic material mixed with fine ore beneficiation sand/crushed dolomite and looked similar to the prehistoric layer in sections 2 and 6. It looks like that around this pit field and on the plateau this prehistoric layer spreads in large scale and proves intensive prehistoric mining in the district Weißer Schrofen.

In total six animal bones were selected for radiocarbon analyses. The samples out of section 2 from the prehistoric layer show the following dates: MAMS 28731, 2720 ± 21 BP, cal. BC 906 - 819, 2 σ, 95,4 %; MAMS 28732, 2882 ± 20 BP, cal. BC 1125 - 996, 2 σ, 95,4 %. The ^{14}C-analyses from section 6 verify this prehistoric age: MAMS 28728, 2858 ± 20 PB, cal. BC 1110 - 940, 2 σ, 95,4 %; MAMS 28730, 2918 ± 21 BP, cal. BC 1207 - 1031, 2 σ, 95,4 %. One bone from the dump and one from the cultural layer out of section 5 also belong to the Late Bronze Age: MAMS 28729, 2778 ± 20 BP, cal. BC 996 - 848, 2 σ, 95,4 %; dump: MAMS 28733, 2794 ± 20 BP, cal. BC 975 - 912, 2 σ, 95,4 %.

The bone material from Schwaz-Brixlegg provides evidence for a remarkable change in the diet of mining communities in the Lower Inn Valley from the Late Bronze Age to the Iron Age, the transition from a pig to a cattle economy. The most important species (cattle, sheep/goat and pig) were delivered to the mining sites mostly as whole animals. In some cases, there is evidence for additional meat packages (especially ribs). According to the age and sex structures obtained from the 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 it can be observed also on other prehistoric mining sites in the Eastern Alps (Saliari et. al, in press).

Conclusions

Within the DACH-project continuous prehistoric fahlore mining from the Late Bronze Age to the Early Iron Age (12th - 8th century BC, Fig. 27) could be demonstrated for the mining area of Schwaz-Brixlegg. A series of underground mines as well as pit fields above ground were investigated. Fire-setting was the main extraction method in the hard dolomitic host rock. Charcoal as leftover from fire-setting is abundant in the dumps and backfills of the mines. This material proved to be very suitable for accurate dating by dendrochronological analysis. The ^{14}C-dating method was also applied, animal bones being the preferred material for dating with the aim to avoid old wood effects.

The radiocarbon analyses performed on animal bones and charcoal fragments from belowground date from the 9th/8th century BC up to the 7th - 5th century BC. Often the datings are inaccurate and dissatisfying due to the unfavourable course of the ^{14}C-calibration curve corresponding to the first half of the Iron Age (“Hallstatt plateau”). Only the analysed samples from the mine Knappenkuchl prove underground mining activities already in the 12th/11th century BC. Better results could be obtained by dendrochronological analysis. So far all the dendrochronological dated mines in the mining area Schwaz-Brixlegg date into the second half of the 8th century BC, which represent the final stage of the fahlore mining activities in general. It has to be taken into account that usually the younger backfill materials were left inside the mines when they were abandoned and that therefore it is difficult to date the beginnings of the mining work. A hint for the latest mining activities could be slag tempered ceramics from the grave 626 at the prehistoric cemetery in Kundl (Lang, 1998). By watching the original pictures of the excavation in the 1970s it becomes clear that some of the graves have been covered with flat anvil/grinding stones.

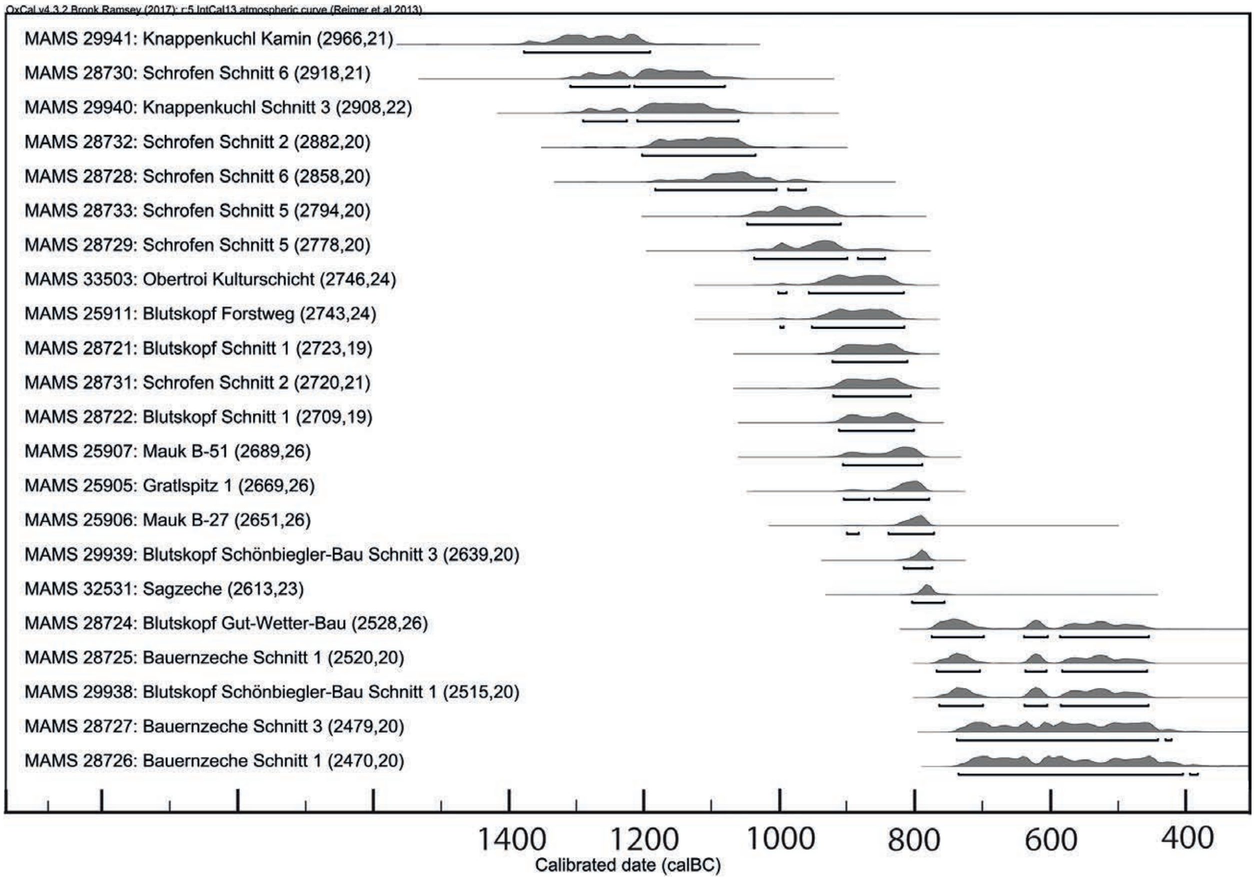

Fig. 27: Radiocarbon data from the investigated mining sites of the DACH-project 2015 – 2016 (graphics: OxCal v4.3.2.).

From the pit fields above ground only ^{14}C-dates are available for the moment. Though there is a clear tendency that these mining structures are older than the above mentioned mines. The Radiocarbon dates from the pit field “Weißer Schrofen” prove activities from the 12th to the 9th century BC. The dating results are overlapping with those from the nearby smelting site Rotholz (12th to 10th century BC). It can be assumed that both sites were active at the same time and that the ore from the “Weißer Schrofen” was smelted on the Rotholz smelting site. The pit field on the plateau of the “Blutskopf” dates on the basis of radiocarbon analyses into the 10th/9th century BC.

The present state of art suggests, that the second fahlore mining boom in the Lower Inn Valley lasted for about 500 years and ended in the Early Iron Age around 700 BC.

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Authors

Markus Staudt – Department of Archaeologies, University of Innsbruck
Gert Goldenberg – Department of Archaeologies, University of Innsbruck
Manuel Scherer-Windisch – Department of Archaeologies, University of Innsbruck
Kurt Nicolussi – Department of Geography, University of Innsbruck
Thomas Pichler – Department of Geography, University of Innsbruck

Correspondence and material requests should be addressed to: markus.staudt@uibk.ac.at

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Peter Tropper, Gert Goldenberg, Matthias Krismer, Daniel Bechter, Martin Steiner, Hans-Peter Viertler, Franz Vavtar

Mineral-chemical characterisation of chalcopyrites and fahlore-group minerals from selected Cu-ore deposits in the Eastern Alps

ABSTRACT: *In the interdisciplinary framework of the special research program (SFB) HiMAT "The History of Mining Activities in the Tyrol and Adjacent Areas: Impact on Environment and Human Societies" financed by the Austrian Science Fund 2007-2012), petrological and mineralogical investigations of ores from several copper mining sites in Tyrol (Schwaz-Brixlegg, Bachalm-Kelchalm-Röhrerbühel) and adjacent areas (Pfunderer Berg in South-Tyrol, Bartholomäberg-Silbertal in Vorarlberg, Mitterberg in Salzburg) have been carried out in the sub-project "Mineralogical-geochemical Characterization of Historic Mining Sites". The main goal of this sub-project was to summarize new and additional information on the mineralogical composition of the ores and on the chemical composition (major-, minor-, and trace elements) of the ore minerals, which were used as raw material for historic and prehistoric copper smelting. The results of this sub-project, which are summarised here provide a mineralogical and geochemical basis to develop i.) a better understanding of Bronze Age smelting in the Lower Inn Valley with respect to technological advances, and ii.) geochemical fingerprinting with respect to ore and artefact provenance and trade involving metallurgical artefacts in order to obtain a comprehensive overview of Bronze Age metallurgy in the Eastern Alps.*

KEYWORDS: CHALCOPYRITE, FAHLORE-GROUP MINERALS, RC HIMAT, GREYWACKE ZONE, EASTERN ALPS, SOUTHALPINE, KIECHLBERG

Introduction

Scientific background and state of research

The basis for a thorough archaeometric and archaeometallurgical investigation of historical mining districts is the comprehensive mineralogical/geological and archaeological study of all known ore deposits in the area (e.g. Bartelheim et al., 2002; Niederschlag et al., 2003; Nimis et al., 2012; Artioli et al., 2016). Data obtained through these studies can be used to perform provenance studies of the metals used for artefact production and thus trace prehistoric trade routes. For many decades, deciphering the provenance of metal artefacts from various prehistoric and historic periods has been essential for archaeologists, and has allowed gaining insight into cultural relations and trading routes as a function of space and time. A supraregional, large-scale geochemical survey of ore deposits and metal artefacts is crucial to track back metal artefacts to their ore sources (e.g. Junghans et al., 1960; Höppner et al., 2005; Nimis et al., 2012; Lutz & Pernicka, 2013; Pernicka & Lutz, 2015; Artioli et al., 2016). In combination with lead isotopes, the trace element compositions of artefacts have been used to discriminate between metals derived from different geological environments (e.g. Pernicka & Lutz, 2015; Artioli et al., 2016). In addition, mineralogical and mineral-chemical features characteristic for specific ore deposits will also be reflected in the resulting metal as shown from the Kiechlberg in the Lower Inn Valley by Krismer et al. (2012).

Geological overview

The Austroalpine basement of the Eastern Alps is typically polymetamorphic and records a sequence of four regional metamorphic events. It has been dated to the Late Devonian-Carboniferous, Permian, Cretaceous and Oligocene-Miocene, respectively (Hoinkes et al., 1999; Neubauer et al., 1999; Thöni, 1999; Oberhänsli et al., 2004; Schuster et al., 2001, 2004; Schmid et al., 2004; Cesare et al., 2010). The Late Devonian to Carboniferous imprint is related to the Variscan orogenic cycle (380-300 Ma), which resulted from the collision of the Gondwana and Laurussia continents and led to the formation of the Pangea supercontinent. In the Permian and Early

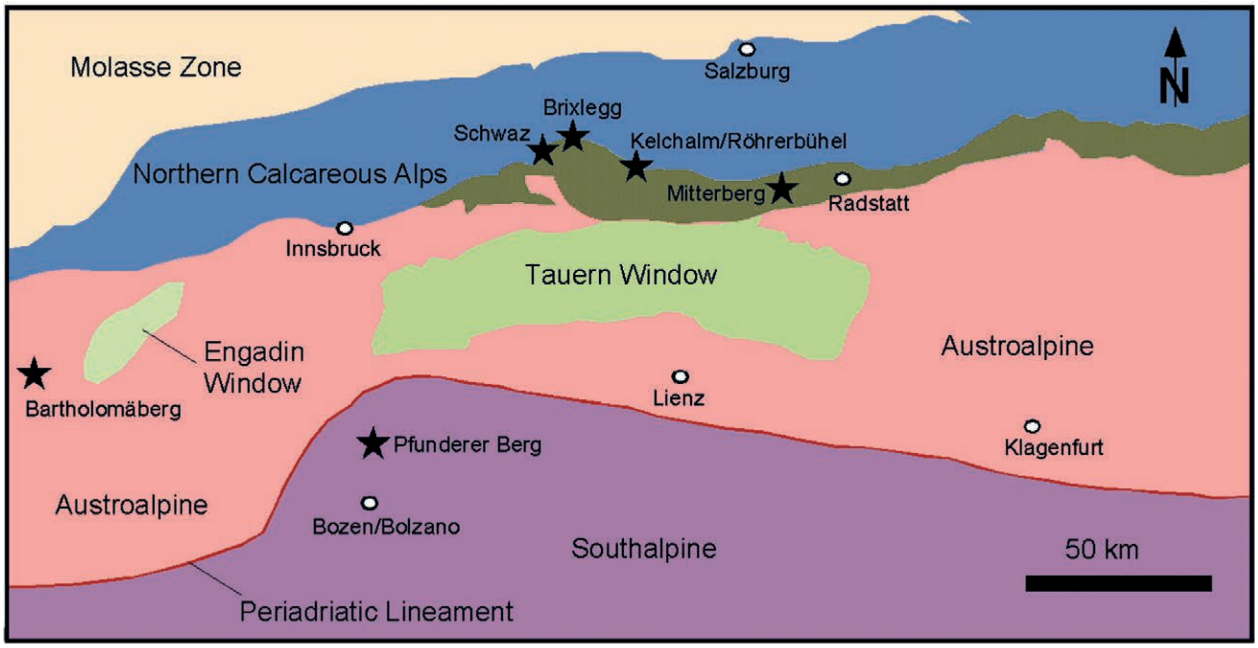

Fig. 1: Simplified tectonic overview of the Eastern Alps. Metallogenically the most important tectonic unit is the Greywacke Zone (dark greenish brown). Although this unit is part of the Austroalpine units it is shown separately in this Figure. It is bordered to the north by the sediments of the Northern Calcareous Alps (blue) and to the south by the Austroalpine (Innsbruck Quartzphyllite) and the Penninic Tauern Window (green). The Southalpine (purple) occurs to the south of the Periadriatic lineament (red line). The stars indicate the position of the ore deposits where Brixlegg also includes the Mauken ore deposits.

Triassic, large portions of the Austroalpine units were affected by lithospheric extension, due to the break-up of Pangea, and by related high-temperature/low-pressure metamorphism. The Eo-Alpine metamorphic event in the Cretaceous is related to intracontinental shortening within the northern spur of the Adriatic plate. Finally, in Oligocene to Miocene times, the continental collision between the Adriatic plate and the European plate after the closure of the Penninic oceans resulted in the Alpine orogeny and related metamorphism. The more southerly Southalpine units are separated from the Austroalpine units by the Periadriatic Lineament (Fig. 1). These units were not metamorphosed during the Alpine orogeny and consist of a Variscan metamorphic basement and a Permian-Mesozoic volcanic and sedimentary cover (Sassi & Spiess, 1993).

The Eastern Alps are known for their numerous fahlore- and chalcopyrite-rich copper deposits (Weber, 1997; Nimis et al., 2012; and references therein). The main mining districts are aligned along the west-east striking Northern Greywacke Zone (GWZ), which consists of Palaeozoic low-grade metamorphic schists with intercalated basic to acidic meta-vulcanites and marbles (Fig. 1). The west end of the GWZ is near the city of Schwaz in the Lower Inn Valley (Tyrol), where the largest fahlore-group mineral deposits of the Eastern Alps occur (Schwaz-Brixlegg mining district; Weber, 1997). East of Schwaz-Brixlegg, the mining districts of Röhrerbühel/Kitzbühel and Kelchalm/Jochberg contain extensive chalcopyrite deposits. At Röhrerbühel, fahlore-rich mineralizations are also known. Towards Salzburg, to the west of Bischofshofen, the Mitterberg mining district is found, which represents the largest copper (chalcopyrite) deposit of the whole Alps. Other significant copper ore districts include the chalcopyrite deposits from the Montafon (Bartholomäberg, Silbertal) in Vorarlberg, which occur in the Phyllitgneiss Zone as well as the Pfunderer Berg near Klausen in South Tyrol in the Southalpine domain. Due to their historical importance for metallurgy and metal trade in the Eastern Alps, prior to 2006 before the onset of the special research program HiMAT most geochemical, mineralogical and mining archaeological investigations so far have been focussed on the mining districts of Schwaz-Brixlegg and Mitterberg. In particular, only few mineral chemical data existed prior to this project for other important mining areas in Tyrol, Salzburg and adjacent areas, such as Vorarlberg (Montafon) and South Tyrol (cf. Brigo, 1971; Weber, 1997; Exel, 1998). In the meantime a wealth of data has been published especially with respect to the Italian ore deposits in the Southalpine domain (e.g. Nimis et al., 2012; Artioli et al., 2016).

In order to understand the beginning and the evolution of metallurgy in the Eastern Alps, a close collaboration between archaeologists, mineralogists/petrologists and geochemists is required to link the mineralogical and geochemical data of the ores from various, adjacent mining sites with the chemical data of metal artefacts from smelting and settlement sites. This is fundamental for further reconstructions concerning prehistoric mining and ancient metalworking activities. In this contribution, we present i.) a brief description of mineral assemblages, their chemical compositions and their textures in some of the most important copper deposits investigated in the course of a Ph.D thesis (Matthias Krismer, Schwaz-Brixlegg, Pfunderer Berg) as well as three Master's theses (Daniel Bechter, Bartholomäberg-Silbertal; Martin Steiner, Kelchalm-Röhrerbühel; Hans Peter Viertler, Mitterberg), and ii.) a compilation of the major and minor element compositions of the two most important ore minerals used in alpine prehistory, namely the fahlore-group minerals and chalcopyrite.

Analytical methods

Electron-probe microanalysis

Electronprobe microanalysis (EPMA) of fahlore-group minerals and chalcopyrites was carried out using a JEOL JXA 8100 SUPERPROBE electron microprobe, equipped with five WDS detectors and a Thermo Noran EDS system, at the Institute of Mineralogy and Petrography of the University of Innsbruck. To cover the whole range of possible elements, an analysis set-up with 21 elements (S, Cu, Fe, Zn, Hg, Mn, Mo, Cd, Ni, Pb, Co, Au, Ag, Ge, In, As, Sb, Bi, Se, Sn, Te) was developed. The obtained analytic conditions were 15 kV acceleration voltage and 10 nA beam current. The counting times were 50 s for the peak and 40 s for the background. The detection limits varied between 845 ppm for Pb and 119 ppm for S. All analytical standards were pure elements, excepting for Pb (galena standard), S (troilite standard) and Hg (cinnabar standard).

The chemical composition of fahlore-group minerals and chalcopyrite

The general composition of natural fahlore-group minerals can be described by the formula $M(1)_6M(2)_6[XY_3]_4Z$ (Johnson et al., 1988) where M(1) = Cu^{1+}, Fe^{2+}, Zn^{2+}, Mn^{2+}, Hg^{2+}, Cd^{2+}; M(2) = Cu^{1+}, Ag^{1+}; X = Sb^{3+}, As^{3+}, Bi^{3+}, Te^{4+}; Y and Z = S^{2-}, Se^{2-}. The complex structure can be described by corner-sharing M(1)-Y_4 tetrahedrons (Fig. 2). Six of these tetrahedrons form a ring structure and these rings form a three-dimensional structure with large cavities occupied by the semimetals. Fahlore-group minerals show complete solid solution between the Sb (tetrahedrite) and As (tennantite) end-members. Most natural fahlore-group mineral analyses show 13 S atoms per formula unit (a.p.f.u.), although the S content can decrease below 13 a.p.f.u. Ag frequently substitutes for Cu, with a maximum of 6 a.p.f.u. of Ag (end-member freibergite), but most natural fahlore-group minerals have Ag concentrations far below 6 a.p.f.u. Fe- and Zn-rich compositions are very common in nature.

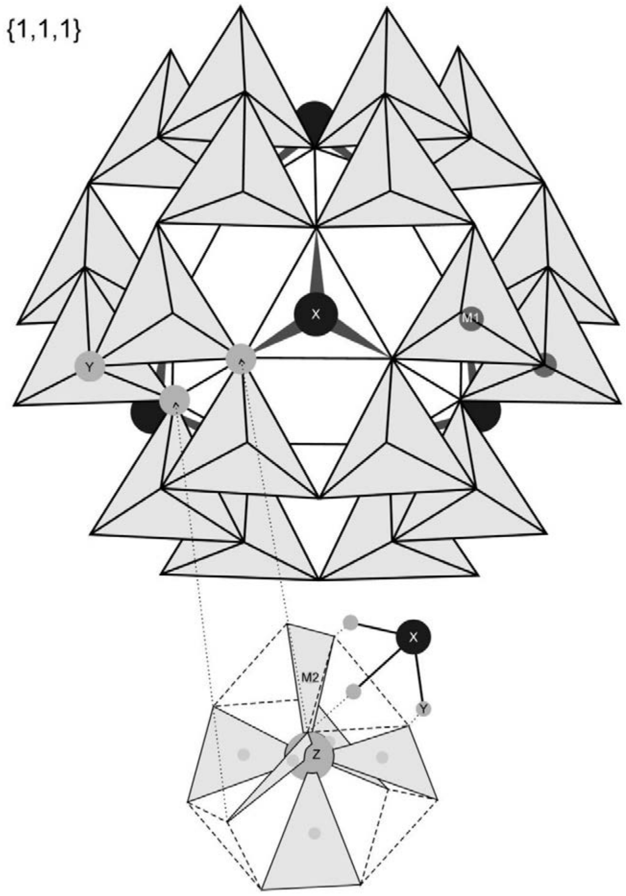

Fig. 2: Schematic illustration of the fahlore-group mineral structure according to Johnson et al. (1988). The chemical formula is ${}^{IV}M(1)_6{}^{III}M(2)_6[{}^{III}X\,{}^{IV}Y_3]_4{}^{VI}Z$. M(1) = Cu, Fe, Zn, Hg; M(2) = Cu, Ag; X = As, Sb, Bi; Y = S; Z = S, Se.

The nomenclature of fahlore-group minerals is based on the semimetal composition, the divalent metal composition and to the Cu/Ag ratio in the M(2) site. If Sb >(As + Bi + Te) the mineral is called tetrahedrite, if As >(Sb + Bi + Te) then the mineral is called tennantite. If Zn is the most frequent divalent metal atom, the fahlore-group mineral is denoted as "zincian". The same rule can be applied with other divalent cations (e.g. Fe, Cd, Hg). Any fahlore-group mineral solid solution containing Hg/ΣM^{2+} >50% (on the atomic basis) is called "schwazite" (Mozgova et al., 1980). The name refers to a fahlore-group mineral analysis from Schwaz by Weidenbusch (1849), which reported 56% Hg end-member component (corresponding to 15.57 wt.% Hg). However, later mineral chemical investigations (e.g. Arlt & Diamond, 1998) were not able to verify any fahlore-group minerals with "schwazite" composition neither in Schwaz nor in Brixlegg. The name freibergite, indicates a mineral with dominant Sb in the X site and dominant Ag in the M(2) site.

Chalcopyrite has an ideal chemical formula $CuFeS_2$, which corresponds to 34.63 wt.% Cu, 30.43 wt.% Fe and 34.94 wt.% S, and is generally characterized by limited chemical variations.

Results

Chalcopyrite

Kelchalm-Bachalm

These deposits occur in the Jochberg Unit of the GWZ. They are closely associated with the Ordovician basic volcanism, i.e., they are pre-Alpine, and are considered to be of hydrothermal syngenetic origin (e.g. Schulz, 1997).

Petrography: The gangue consists of quartz, ankerite and dolomite and the primary ore assemblage mostly consists of chalcopyrite and pyrite (Fig. 3a). The secondary mineral assemblage mostly consists of goethite, replacing pyrite and chalcopyrite, and, subordinately, of covelline, marcasite and azurite.

Mineral chemistry: Compared to the ideal stoichiometric composition of 25 at.% Cu, 25 at.% Fe and 50 at.% S, the analyzed chalcopyrites show only slight deviations in Cu (33.93 to 35.20 at.%), Fe (28.64 to 31.19 at.%) and S (33.36 to 36.13 at.%) as shown in Table 1a. This corresponds to a formula of $Cu_{0.94-0.97}Fe_{0.95-1.02}S_{1.96-2.02}$. Most other elemental concentrations are below 1 wt.% (maximum concentrations in wt.%: Pb 0.26, Cd 0.19, Mo 0.17, In 0.17, Zn 0.16, Bi 0.11, Se 0.10). Low-temperature chalcopyrites typically show a metal to S ratio close to 1, whereas high-temperature chalcopyrites show a metal to S ratio >1 (Merwin & Lombard, 1973). Chalcopyrites from these deposits show ratios of close to 1 and can therefore be considered of low-temperature origin (Steiner, 2011) .

Pfunderer Berg

The Cu-Pb-Zn-(Ag) deposit of the Pfunderer Berg is located near the Eisack Valley to the west of Klausen in the autonomous Italian province of Alto Adige-South Tyrol. The ore deposits are situated in the rocks of the Southalpine crystalline basement. The dominant basement lithology near Klausen is the Brixen quartz phyllite, which was affected by the Variscan metamorphism and later intruded by small Permian dioritic intrusions, which led to widespread contact metamorphism. These dioritic rocks have been called klausenites (Gisser, 1926). The Pfunderer Berg ore bodies are located either in the dioritic dikes, at the contact area between the intrusive rocks and the basement rocks, or in the contact metamorphic rocks, the hornfelses. The polymetallic Pfunderer Berg deposit formed due to hydrothermal processes related to the diorite intrusions (Brigo, 1971; Exel, 1998; Fuchs, 1988; Krismer et al., 2011b). The mining district is located to the south of the SAM (Southern limit of Alpine Metamorphism, Hoinkes et al., 1999). Therefore, the ores were not affected by Alpine metamorphism however the area south of the SAM experienced at least Alpine folding and faulting (Sassi & Spiess, 1993).

Petrography: The observed complex primary sulfide assemblage consists of galena + chalcopyrite + sphalerite + freibergite-tetrahedrite solid solutions ± polybasite ± acanthite ± electrum (Fig. 3b). The most common Ag-bearing phases are freibergite-tetrahedrite solid solutions, polybasite and acanthite and occur as few microns-large, pebble-shaped inclusions in galena. In one sample, previously unreported, intimately intergrown gustavite ($AgPbBi_3S_6$) and cosalite ($Pb_2Bi_2S_5$) were found. In this case sphalerite inclusions in chalcopyrite were interpreted as exsolutions from a higher-temperature Zn-bearing high-temperature ISS (intermediate Cu-Fe-S solid solution) phase. The occurrence of α-β transformation twin lamellae in chalcopyrite indicates high temperatures of formation >500°C, consistent with a strict genetic link with the Permian magmatic activity. Old mining records frequently mention high silver contents in the ores of this deposit and galena was considered to be the dominant silver carrier. It was recently shown that the presence of abundant Ag-rich mineral inclusions is responsible for the high Ag concentrations of bulk galena (Krismer et al., 2011b).

Mineral chemistry: The highest Zn concentration of matrix chalcopyrite is only 1.55 wt.%. Similar concentrations of around 1 wt.% were reported from experiments between 400°C and 500°C in the chalcopyrite stability field (Lusk & Calder, 2004) Significant detected trace elements in chalcopyrite are Pb, Sn, and Cd. In some cases, In concentrations of up to 0.11 wt.% were measured. EPMA spot analyses of matrix chalcopyrite grains yielded no Sn contents. Only some chalcopyrite inclusions in sphalerite show up to 4.5 wt.% Sn. The solubility of stannite in chalcopyrite is high, even if only the α-chalcopyrite solid solution or the Sn-bearing intermediate solid solution (ISS) above ~470°C is capable of elevated Sn concentrations (Moh, 1975). The trace elements Pb and Cd show no preferential behaviour for either the inclusions or the large chalcopyrite grains. The Pb content ranges from below the detection limit up to 0.30 wt.% and Cd is even lower, with concentrations ranging from below the detection limit up to 0.22 wt.%. Representative analyses are given in Table 1a.

Mitterberg

The Mitterberg mining district is situated ca. 50 km south of Salzburg, between Bischofshofen and Mühlbach at the Hochkönig. Geologically, the Cu-mining district Mitterberg - Mühlbach - Larzenbach is located in the Western Greywacke Zone. The dominant host-rocks are the Pinzgau Phyllites of the Jochberg Unit. These syngenetic Cu deposits (Early Paleozoic) were remobilized during the Cretaceous, which led to the formation of an economically important ore body occurring as a large epigenetic vein. These deposits represent the largest Cu resources of the Eastern Alps (Ebner & Weber, 1997).

Petrography: This deposit consists of hydrothermal veins showing the assemblage pyrite + chalcopyrite ± fahl-

	Pfunderer Berg			Kelchalm			Mitterberg		
As	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.04	0.03
S	35.79	35.60	34.78	35.06	35.85	35.35	34.05	35.38	33.36
Ag	0.02	0.01	0.02	n.d.	0.02	n.d.	n.d.	n.d.	n.d.
Cu	33.72	33.67	33.60	34.51	34.49	34.47	34.97	33.12	34.30
Ni	n.d.	0.04	n.d.	n.d.	n.d.	n.d.	n.d.	0.01	0.02
Ge	0.04	0.01	n.d.	n.d.	n.d.	0.03	0.14	n.d.	0.16
Pb	0.04	0.09	0.10	0.11	0.17	0.01	0.06	0.07	0.06
Sn	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.21	n.d.	0.14
Fe	30.21	29.90	30.30	30.72	30.63	30.53	30.77	30.71	31.19
Zn	0.43	0.10	0.23	0.06	0.09	0.05	0.03	0.05	0.03
Se	0.01	n.d.	0.04	0.08	n.d.	n.d.	0.01	0.01	0.05
Sb	n.d.	n.d.	0.04	0.02	n.d.	0.08	0.08	0.10	n.d.
In	0.01	0.08	0.10	0.12	0.08	0.05	0.08	0.04	0.09
Co	n.d.	0.02	n.d.	0.02	n.d.	n.d.	0.05	0.01	0.02
Te	n.d.	n.d.	n.d.	n.d.	n.d.	0.03	n.d.	n.d.	n.d.
Au	0.04	n.d.	0.06	0.14	n.d.	n.d.	n.d.	n.d.	n.d.
Cd	0.01	0.03	n.d.	0.07	n.d.	0.04	0.03	0.04	0.10
Bi	0.01	0.03	n.d.	0.02	0.04	0.04	n.d.	n.d.	0.08
Hg	0.01	0.06	0.03	n.d.	n.d.	0.03	n.d.	n.d.	n.d.
Mo	0.10	0.02	0.10	n.d.	0.08	n.d.	n.d.	0.01	n.d.
Mn	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
∑ wt%	100.43	99.68	99.39	100.93	101.44	100.72	100.48	99.59	99.62
As	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.001	0.001
S	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000
Ag	<0.001	<0.001	<0.001	n.d.	<0.001	n.d.	n.d.	n.d.	n.d.
Cu	0.950	0.952	0.973	0.992	0.969	0.982	1.035	0.943	1.036
Ni	n.d.	0.001	n.d.	n.d.	n.d.	n.d.	n.d.	<0.001	<0.001
Ge	<0.001	<0.001	n.d.	n.d.	n.d.	0.001	0.004	n.d.	0.004
Pb	<0.001	<0.001	0.001	0.001	0.001	<0.001	0.001	0.001	0.001
Sn	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.003	n.d.	0.002
Fe	0.968	0.962	0.999	1.000	0.979	0.989	1.036	0.995	1.072
Zn	0.012	0.001	0.006	0.002	0.003	0.001	0.001	0.001	0.001
Se	<0.001	n.d.	0.001	0.002	n.d.	n.d.	<0.001	<0.001	0.001
Sb	n.d.	n.d.	0.001	<0.001	n.d.	0.001	0.001	0.002	n.d.
In	<0.001	0.001	0.002	0.002	0.001	0.001	0.001	0.001	0.002
Co	n.d.	<0.001	n.d.	0.001	n.d.	n.d.	0.001	<0.001	0.001
Te	n.d.	n.d.	n.d.	n.d.	n.d.	<0.001	n.d.	n.d.	n.d.
Au	<0.001	n.d.	0.001	0.001	n.d.	n.d.	n.d.	n.d.	n.d.
Cd	<0.001	<0.001	n.d.	0.001	n.d.	0.001	<0.001	0.001	0.002
Bi	<0.001	<0.001	n.d.	<0.001	<0.001	<0.001	n.d.	n.d.	0.001
Hg	<0.001	<0.001	<0.001	n.d.	n.d.	<0.001	n.d.	n.d.	n.d.
Mo	0.001	<0.001	0.002	n.d.	0.001	n.d.	n.d.	0.001	n.d.
Mn	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
M:S	0.97	0.96	0.99	1.00	0.98	0.99	1.04	0.97	1.06

Chalcopyrite formulae calculated on the basis of 2 S. n.d.: not detected.

Tab. 1a: Representative electron-probe microanalyses of chalcopyrites

	Bartholomäberg			**Mauken**		
As	n.d.	0.18	0.02	n.d.	0.20	n.d.
S	35.24	35.39	35.44	34.57	34.24	36.13
Ag	n.d.	n.d.	0.01	n.d.	0.01	0.02
Cu	34.57	34.31	34.31	33.93	35.20	34.75
Ni	n.d.	0.61	n.d.	n.d.	n.d.	0.02
Ge	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Pb	n.d.	0.14	0.10	0.08	n.d.	0.11
Sn	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Fe	30.41	29.80	29.87	29.50	28.64	30.09
Zn	0.02	0.16	0.11	0.12	0.44	0.15
Se	0.04	0.01	n.d.	0.06	n.d.	0.01
Sb	0.04	0.03	0.03	n.d.	0.22	0.07
In	0.03	0.03	0.06	n.d.	0.02	n.d.
Co	n.d.	0.06	n.d.	n.d.	n.d.	n.d.
Te	n.d.	0.06	n.d.	n.d.	0.03	n.d.
Au	n.d.	n.d.	0.01	n.d.	n.d.	0.01
Cd	0.07	0.01	0.02	n.d.	n.d.	0.01
Bi	0.03	0.05	0.01	0.07	0.06	0.01
Hg	n.d.	n.d.	0.04	n.d.	n.d.	0.07
Mo	0.07	n.d.	0.17	n.d.	0.03	n.d.
Mn	n.d.	n.d.	n.d.	0.03	n.d.	0.02
∑ wt%	100.78	100.59	100.93	98.36	99.08	101.48
As	n.d.	0.004	<0.001	n.d.	0.005	n.d.
S	2.000	2.000	2.000	2.000	2.000	2.000
Ag	n.d.	n.d.	<0.001	n.d.	<0.001	<0.001
Cu	0.988	0.977	0.975	0.989	1.036	0.969
Ni	n.d.	0.019	n.d.	n.d.	n.d.	0.001
Ge	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Pb	n.d.	0.001	0.001	0.001	n.d.	0.001
Sn	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Fe	0.989	0.965	0.966	0.978	0.959	0.955
Zn	0.001	0.004	0.003	0.003	0.012	0.004
Se	0.001	<0.001	n.d.	0.001	n.d.	<0.001
Sb	0.001	0.001	<0.001	n.d.	0.003	0.001
In	<0.001	<0.001	0.001	n.d.	<0.001	n.d.
Co	n.d.	0.002	n.d.	n.d.	n.d.	n.d.
Te	n.d.	0.001	n.d.	n.d.	<0.001	n.d.
Au	n.d.	n.d.	<0.001	n.d.	n.d.	<0.001
Cd	0.001	<0.001	<0.001	n.d.	n.d.	<0.001
Bi	<0.001	<0.001	<0.001	0.001	0.001	n.d.
Hg	n.d.	n.d.	0.001	<0.001	<0.001	0.001
Mo	0.001	n.d.	0.002	n.d.	0.001	n.d.
Mn	n.d.	n.d.	n.d.	0.001	n.d.	0.001
M:S	0.99	0.98	0.97	0.99	1.00	0.97

Chalcopyrite formulae calculated on the basis of 2 S. n.d.: not detected.

Tab. 1b: Representative electron-probe microanalyses of chalcopyrites

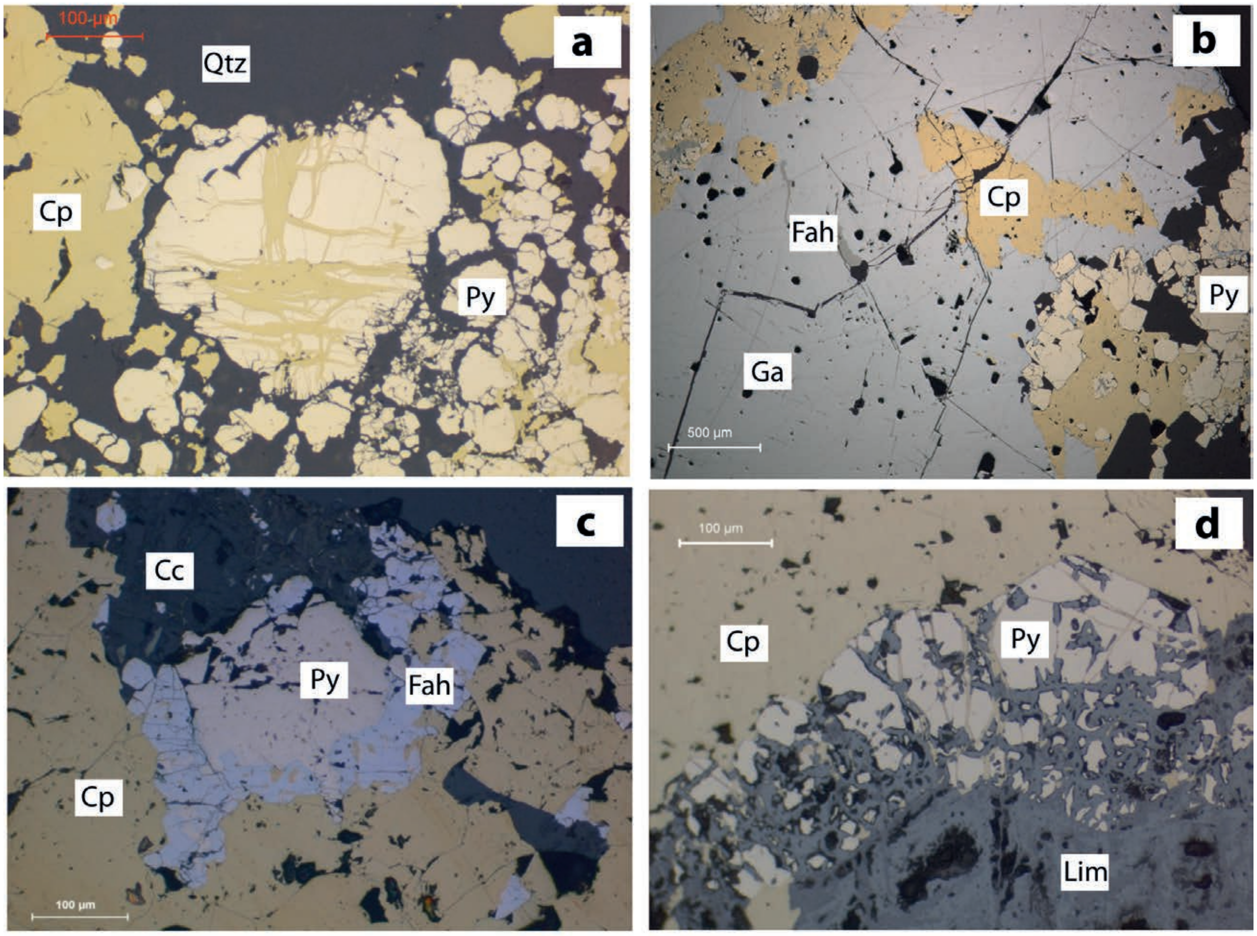

Fig. 3: Microphotograph of samples from chalcopyrite deposits. (a) Kelchalm-Bachalm; (b) Pfunderer Berg; (c) Mitterberg; (d) Bartholomäberg. The abbreviations are: Cp: chalcopyrite, Py: pyrite, Qtz: quartz, Ga: galena, Fah: fahlore-group minerals, Cc: calcite, Lim: limonite.

ore-group mineral ± gersdorffite ± sphalerite ± electrum ± corynite (Fig. 3c). The gangue consists of quartz, barite, Fe-rich carbonates (ankerite, siderite) and, rarely, wulfenite. Chalcopyrite replaces primary pyrite and gersdorffite. Chalcopyrite and pyrite were subsequently overgrown by fahlore-group minerals. Pyrite, gersdorffite, fahlore-group mineral and electrum show chemical zoning, indicating several stages of mineral growth during Eo-Alpine low-temperature remobilisation. Siderite-ankerite thermometry yielded low temperatures of formation of 190-330°C (Viertler, 2011).

Mineral chemistry: Most of the chalcopyrite analyses from Mitterberg show almost stoichiometric compositions. The mean concentrations of Cu, Fe and S are 24.40 at.%, 24.93 at.% and 50.16 at.%, respectively. In addition small amounts of As, Ni, Ge, Sn, Zn, Se were detected (Table 1a).

Bartholomäberg-Silbertal (Montafon)

The geological frame of the Montafon area is dominated by two major Austroalpine units, namely, the weakly metamorphic Northern Calcareous Alps in the northern part and the amphibolite-facies Silvretta Crystalline Complex with the Phyllitgneis Zone to the south (Oberhauser et al.,1998). The Phyllitgneis Zone is located between these major units and represents the lower metamorphic portion of the Silvretta Crystalline Complex. Regarding the genesis of the Bartholomäberg-Silbertal ore deposits Haditsch and Mostler (1986) considered it as an early possibly syndiagenetic (Permian) disseminated hydrothermal mineralization in sandstones (now quartzites) with subsequent Alpine hydrothermal remobilization. The ore deposits were exploited at two major mining sites, which are located above the village of Bartholomäberg and at the ridge above the village of Kristberg, respectively. The ore bodies occur mostly at the contact between the lower Triassic Alpine Buntsandstein (sandstones) of the Northern Calcareous Alps and the Phyllitgneis Zone. The ore bodies occur as lenses and, occasionally, as veins.

Petrography: The complex main ore paragenesis consists of chalcopyrite + fahlore-group minerals + gersdorffite + galena + sphalerite + pyrrhotite + pyrite + arsenopyrite ± corynite Ni(As,Sb)S ± alloclasite (Co,Fe)AsS (Fig. 3d). In minor concentrations acanthite Ag_2S, aikinite $PbBiCuS_3$, paraschachnerite Ag_2Hg_3 as well as native elements like bismuth and gold occur. The gangue is mainly composed of calcite, siderite, ankerite, barite and quartz. Azurite, malachite, covellite and limonite are the main representatives of secondary minerals. Whole-rock analysis of ore and slag samples yielded high Bi contents up to 1 wt.%, which distinguishes it from the other deposits investigated so far. Fluid inclusion studies support a relatively low-temperature origin of this deposit at ca. 250-300°C (Bechter, 2009).

Mineral chemistry: The chemical composition of chalcopyrite is close to ideal, with average contents of 50.31 at.% S, 24.62 at.% Cu and 24.77 at.% Fe (Table 1b). Except for Zn (0.05 at.% Zn), no minor elements were detected in substantial concentrations.

Fahlore-group minerals

Schwaz-Brixlegg (ore deposits in the Graywacke Zone)

The Northern Greywacke Zone consists of Ordovician to upper Carboniferous metasedimentary rocks, such as quartzphyllites, schists, marbles and basic to acidic metavolcanic rocks (Mostler, 1970). During the Variscan and Eo-Alpine orogenies, the rocks underwent greenschist-facies metamorphism and a strong tectonic overprint (Piber, 2005; Panwitz, 2006). The lithological sequence in the region of Schwaz and Brixlegg is characterized by quartzphyllites, called the Wildschönau schists and interpreted to represent a passive continental margin setting with turbidite deposits (Heinisch, 1988; Ebner & Weber, 1997; Panwitz, 2006). Pillow lavas, gabbroic rocks and metatuffites are intercalated within the Wildschönau schists. The gabbroic rocks yield Early- to Middle Ordovician ages (Panwitz, 2006). Furthermore, abundant are Devonian platform carbonates, the so-called Schwaz Dolomite. To the west of the city of Schwaz, the Kellerjochgneiss, also known as the Schwaz Augengneiss, occurs and represents a shallow granitic intrusion into the Wildschönau schists (Piber, 2005). The ore bodies of the Schwaz-Brixlegg region are mainly hosted in the Devonian Schwaz Dolomite, but they may also occur in the underlying Wildschönau Schists and as remobilizations in the overlying Northern Calcareous Alps (Goldenberg & Rieser, 2004). The ore genesis is still disputed. In earlier studies (Schulz, 1972; Gstrein, 1979), a syngenetic-sedimentary genesis was favoured. More recent studies (Frimmel & Papesch, 1990; Frimmel, 1991) suggested an epigenetic-hydrothermal origin. Arlt and Diamond (1998) carried out a detailed EPMA study of the fahlore-group minerals from the localities of Schwaz and Brixlegg. Their study provided the first comprehensive microprobe data for fahlore-group minerals from Schwaz and Brixlegg, but included only nine elements: Cu, Ag, Fe, Zn, Hg, Mn, Sb, As and S. The previously postulated geographic compositional trends, as well as the alleged occurrence of the mineral schwazite (one or more a.p.f.u. Hg in fahlore-group minerals), were refuted by their mineral chemical study. Recent comprehensive electron-probe microanalyses from Schwaz were obtained by Kharbish et al. (2007) and Krismer et al. (2011a).

Petrography: The ores of Schwaz consist of monomineralic fahlore-group mineral solid solutions (Fig. 4a). Strong compositional zoning is visible in the reflected light microscope, but more evident in BSE images. The zoning occurs along grain boundaries as well as along fractures or as irregular intergranular patterns. Late fahlore along grain boundaries and fractures appears darker in BSE images. In cases of irregularly zoned patterns within grains, the relative chronology of the different fahlore-group mineral generations is unclear since several possible miscibility gaps exist (Sack, 2017). In contrast to Schwaz, ores from Brixlegg show a more complex mineral assemblage (Fig. 4b). The main assemblage consists of large monomimeralic fahlore-group mineral grains that enclose small-scale mineral reaction domains. Similar to samples from Schwaz, the fahlore-group minerals show complex zoning patterns, nicely visible in BSE images. Three different mineral assemblages were observed in these reaction domains. Type 1 consists of enargite/luzonite-famatinite + sphalerite + pyrite + stibnite + chalcostibite. Type 2 consists of fahlore-group mineral (second generation) + enargite/luzonite-famatinite + sphalerite + pyrite + stibnite + chalcostibite. Type 3 is composed of fahlore-group mineral (second generation) + sphalerite + pyrite + stibnite + chalcostibite.

Mineral chemistry: The copper deposits of Schwaz-Brixlegg in the GWZ are characterized by more or less monomineralic fahlore-group minerals (Arlt and Diamond, 1998; Krismer et al., 2011a). The ore bodies occur as discordant veins, strata-bound bodies and breccias in the Devonian Dolomites (Schwaz Dolomite). Despite the similar age and conditions of formation, fahlore-group minerals from Schwaz and Brixlegg can be distinguished by their mineralogical and chemical compositions as shown below.

Mineral chemistry Schwaz: A total of 266 electron-probe microanalyses were made to characterize the compositional variations and zoning of fahlore-group minerals from Schwaz. The overall compositions are dominated by Cu, S, As and Sb, and include minor Fe, Zn, Hg and Ag (Tab. 2a). The mean overall mole fraction of the tetrahedrite component in fahlore-group minerals from Schwaz is 0.6 (Sb_{mean} = 18.15 wt.%) with a range between 0.4 and 0.9. The tennantite component ranges between 0.1 and 0.6 with a mean value of 0.4 (As_{mean} = 7.45 wt.%). All other possible elements substituting for Sb or As occur only as traces near or below the detection limit. Some spot analyses yielded Bi and In contents of up to 0.1 and 0.08 wt.% respectively. The Ag content is generally low and the molar fraction of the freibergite (Ag) component ranges between 0.004 and 0.020, with a mean value of 0.01 (Ag_{mean} = 0.51 wt.%). The most abundant divalent cations

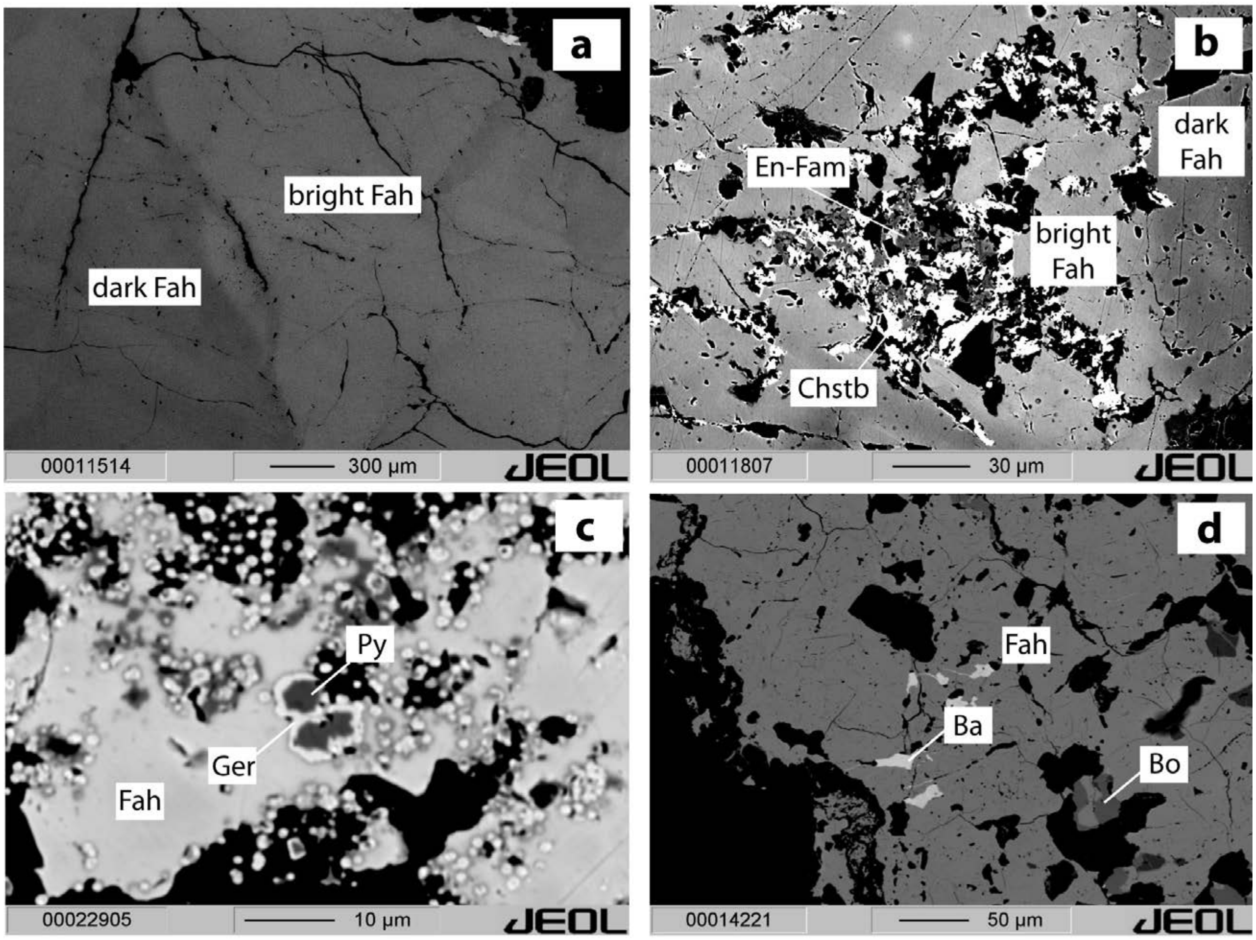

Fig. 4: Backscatter electron (BSE) images of samples from fahlore-group mineral ore deposits. (a) Schwaz; (b) Brixlegg; (c) Mauken; (d) Röhrerbühel. The abbreviations are: Fah: fahlore-group minerals, En-Fam: enargite-famatinite solid solutions, Chstb: chalcostibite, Py: pyrite, Ger: gersdorffite; Ba: balkanite; Bo: bornite.

are Fe and Zn, followed by Hg, with all other metals near or below the detection limit. Only some spot analyses revealed Sn and Cd contents near 0.5 wt.%. The mean molar fraction of the Fe component is 0.52 (Fe_{mean} = 3.09 wt.%), the mean Zn component is 0.37 (Zn_{mean} = 2.65 wt.%) and the mean Hg mole fraction is 0.09 (corresponding to 1.93 wt.% Hg). The BSE zoning of fahlore-group minerals is mainly a function of the As-Sb exchange, the higher the Sb concentration the brighter the patches appear in the image. The Hg and Ag concentrations show a correlation with the brightness. The Fe and Zn concentrations do not show a clear correlation with brightness and thus no correlation between divalent metals and semimetals can be observed. Representative fahlore-group mineral analyses from Schwaz are listed in Table 2a.

Mineral chemistry Brixlegg: The Sb and As contents in Brixlegg fahlore-group minerals are fairly similar to those at Schwaz (Table 2a). The Sb component has a mean mole fraction of 0.55 (Sb_{mean} = 16.69 wt.%) and ranges between 0.41 and 0.67. The As component has a mean mole fraction of 0.45 (As_{mean} = 8.50 wt.%) and ranges between 0.33 and 0.58. Bismuth, Indium and Germanium are occasionally above the detection limits, with up to 0.36 wt.% Bi. In is present in similar concentrations up to 0.19 wt.%. The Ge concentrations are lower, with maximum values of only 0.05 wt.%. The Ag contents are comparable to those at Schwaz and the mean molar fraction of the Ag component is 0.01 (Ag_{mean} = 0.39 wt.%). The most common divalent cations are, again, Zn and Fe, but the Hg concentration is distinctly lower compared to analyses from Schwaz. Noticeable are the high Zn contents (up to 7.61 wt.%), corresponding to a molar fraction of Zn component up to 0.92, representing nearly the Zn end-member. The mean molar fraction of the Zn component is 0.64 (Zn_{mean} = 4.96 wt.%) the mean Fe component is 0.31 (Fe_{mean} = 1.99 wt%) and the mean Hg component is 0.03 (corresponding to 0.74 wt.%). Representative fahlore-group mineral analyses from Schwaz are listed in Table 2a.

Brixlegg-Mauken (ore deposits in the Schwaz Triassic)

The Pb-Zn-fahlore-group mineral district of the "Anis-North Tyrolean Calcareous Alps" is an east-west striking ore belt extending north of the Inn Valley from the Mieminger Kette to the Innsbruck Nordkette (Schulz and Schroll, 1997). Thirty kilometres eastwards of the Innsbruck Nordkette, on the south side of the Inn Valley, the Schwaz Triassic (ST) contains similar ores in the same stratigraphic level (Schulz and Schroll, 1997). While the ores of the Mieminger Kette and of the Innsbruck Nordkette are mostly Pb-Zn dominated, with minor amounts of tennantite-rich fahlore-group minerals, the ores of the ST are dominated by tennantite-rich fahlore-group minerals and Pb-Zn phases represent only minor constituents. The copper deposits of the ST described in this study are situated south of the towns of Radfeld and Brixlegg. The landscape of this area is dominated by the Mauken Valley, which is a small N-S running tributary creek of the Inn Valley. In the following description, we will call this mining district "Mauken Area". The host rocks mainly consist of Anisian to Carnian/Norian limestones, dolomites, cellular dolomites and breccias of the Northern Calcareous Alps. In the Mauken Area, mining sites occur at Maukenötz, Silberberg and Geyer, which represent the easternmost part of the prehistoric and historic silver and copper mining area of Schwaz-Brixlegg.

Petrography: The mining districts in the Mauken Area are characterized by two ore types, which occur in two different geological units: 1.) the more common ore type consists of more or less monomineralic Fe-Zn-(Hg) tetrahedrite-tennantite and occurs in the Devonian Schwaz Dolomite which is part of the GWZ; 2.) the second ore type is hosted in the Anisian carbonates of the ST. The latter ore type shows a complex mineralogy, with tennantite-rich fahlore-group minerals (in part Ag-rich) as main copper mineral. The mineral assemblage consists of Fe-Zn tennantite + pyrite/bravoite + enargite/luzonite-famatinite ± chalcopyrite ± thiospinel ± gersdorffite-cobaltite-arsenopyrite ± galena ± sphalerite ± marcasite ± pearceite ± barite (Fig. 4c). The mineralogical and chemical composition of these ores is highly variable at a local scale (Table 2a).

Mineral chemistry: Table 2a presents selected analyses of fahlore-group minerals from the ST. The Sb and As mole fractions are the major distinguishing features between fahlore-group minerals from the GWZ and the ST. The Sb/As ratio in the GWZ is >1, whereas in the ST it is <<1. Fahlore-group minerals from the GWZ are richer in Zn, Hg and Ag and poorer in Bi compared to the ST. Analyses of GWZ samples show Bi concentrations, which are commonly above the detection limit, but in general <<0.5 wt.%. In contrast, Bi concentrations in samples from Silberberg-Geyer (ST) are below the detection limit, but some samples from Maukenötz (ST) contain Bi-rich tennantite containing >2 wt.% Bi. The Zn and Fe components of ST fahlore-group minerals show a bimodal distribution and wide scattering, ranging from near Fe end-members to near Zn end-members. Silver concentrations in both the GWZ and ST ores are generally low. Although the GWZ fahlore-group minerals are slightly richer in Ag, the mean concentration is only 0.21 wt.%, which is distinctly lower compared to the analyses of the GWZ fahlore-group mineral occurrences from the whole Schwaz and Brixlegg mining areas, as reported by Arlt and Diamond (1998) and Krismer et al. (2011a).

Röhrerbühel

The Cu ore deposit Röhrerbühel near Kitzbühel occurs in the western portion of the GWZ. The mining district is hosted in Early Paleozoic (Ordovician to Devonian) rocks, which consist of the Wildschönau Schists, basic metavolcanics, metatuffites and dolomites. Abundant Cu±Ag-bearing ore bodies occur within these Early Paleozoic metasediments containing the ore minerals chalcopyrite, pyrite, pyrrhotite and fahlore-group minerals. In the Devonian dolomites fahlore-group minerals and chalcopyrite occur. Well-known historical mining sites in the GWZ are Götschen (Brixen i. Thale), Brunnalm (Kirchberg), Röhrerbühel (Oberndorf), Sinnwell (Kitzbühel), Schattberg (Kitzbühel), Kelchalpe (Jochberg) and Kupferplatte (Jochberg). At some of these sites evidence for prehistoric mining has been documented (Mutschlechner, 1968; Goldenberg, 2004).

Petrography: Petrography revealed that the primary ore assemblage is chalcopyrite + Fe tetrahedrite + pyrite + bornite (Fig. 4d). As secondary minerals idaite, linneite, millerite, covelline, malachite, azurite, and rare Ag-bearing minerals namely pyrargyrite, an additional Ag-bearing sulfide and an amalgam-group mineral (eugenite) occur. Mineralogical investigations of the Cu deposit of Röhrerbühel also revealed the occurrence of the extremely rare Cu-Ag sulfide balkanite, $Cu_9Ag_5HgS_8$, (Steiner et al., 2010).

Mineral chemistry: Electron-probe microanalysis revealed that the fahlore-group minerals are compositionally highly variable and richer in Sb than As and thus belong to the tetrahedrite series (Table 2b). The tetrahedrite component (X_{Sb}) ranges between 0.60 and 0.90. The tennantite component (X_{As}) therefore ranges between 0.10 and 0.40, which corresponds to 2.13-7.62 wt.% As. The Fe-tetrahedrite component was calculated by the equation X_{Fe} = Fe/(Fe + Zn + Hg + Cd + Mo + Co + Sn + Pb + Ni) and ranges from 75 to 84%. The Zn-tetrahedrite component is definitely lower, ranging from 14 to 23%. All other possible elements (Te, Bi, In, Ge) substituting for Sb or As occur only as traces near or below the detection limit. The Ag content of Fe-tetrahedrite is as high as 1.54 wt.%; this corresponds to 0.24 a.p.f.u. Pb and Sn were detected only in trace concentrations. The Sn and Pb concentrations are very similar and their concentrations do not exceed 0.10-0.15 wt.%.

Pfunderer Berg

Analyses of fahlore inclusions in galena indicate compositions near the freibergite end-member. The Ag content of the inclusions is as high as 5.67 a.p.f.u. (30.3 wt.% Ag),

	Schwaz			Brixlegg			Mauken		
As	7.27	6.19	8.36	6.27	9.84	14.72	14.51	9.42	19.13
S	27.68	27.82	24.71	26.03	27.29	27.12	27.88	26.53	28.38
Ag	0.17	0.23	0.46	0.19	0.09	0.47	n.d.	0.20	n.d.
Cu	41.49	41.44	39.05	39.49	40.49	39.76	43.97	40.19	43.45
Ni	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Ge	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Pb	0.06	n.d.	0.07	0.05	n.d.	0.07	n.d.	0.26	0.14
Sn	0.06	0.05	0.04	0.08	n.d.	n.d.	n.d.	n.d.	n.d.
Fe	3.46	3.42	2.40	2.18	2.17	0.31	4.70	2.09	3.21
Zn	2.11	2.20	3.42	4.43	5.09	6.26	0.67	5.65	4.38
Se	n.d.	n.d.	0.03	0.07	0.02	0.03	n.d.	0.06	0.05
Sb	18.21	20.14	16.17	20.03	15.08	11.08	8.80	15.88	0.16
In	0.08	0.05	0.07	0.08	0.07	0.05	n.d.	n.d.	n.d.
Co	0.02	0.02	0.03	0.04	0.03	0.08	0.19	0.19	n.d.
Te	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Au	0.02	n.d.	0.11	0.01	n.d.	0.05	n.d.	n.d.	n.d.
Cd	0.05	0.02	0.08	0.16	n.d.	0.02	n.d.	0.08	0.10
Bi	0.11	0.02	0.16	0.05	0.19	0.17	n.d.	n.d.	2.01
Hg	0.12	0.15	3.72	0.35	0.45	0.41	n.d.	n.d.	0.09
Mo	0.04	0.01	0.05	0.06	0.06	n.d.	0.05	n.d.	0.13
Mn	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
∑ wt%	100.98	101.76	98.91	99.57	100.86	100.60	100.88	100.64	101.48
As	1.459	1.236	1.878	1.336	2.002	3.013	2.890	1.972	3.743
S	13.000	13.000	12.994	12.986	12.996	12.994	13.000	13.000	13.000
Ag	0.024	0.032	0.072	0.029	0.013	0.067	n.d.	0.029	n.d.
Cu	9.814	9.753	10.342	9.923	9.712	9.595	10.326	9.919	10.025
Ni	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Ge	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Pb	0.004	n.d.	0.006	0.004	n.d.	0.005	n.d.	0.020	0.010
Sn	0.008	0.006	0.006	0.011	n.d.	n.d.	n.d.	n.d.	n.d.
Fe	0.931	0.916	0.723	0.623	0.592	0.085	1.256	0.587	0.843
Zn	0.485	0.503	0.880	1.082	1.186	1.468	0.153	1.355	0.982
Se	n.d.	n.d.	0.006	0.014	0.004	0.006	n.d.	0.012	0.010
Sb	2.248	2.474	2.235	2.627	1.888	1.396	1.079	2.046	0.019
In	0.010	0.006	0.010	0.012	0.009	0.007	n.d.	n.d.	n.d.
Co	0.004	0.005	0.009	0.010	0.008	0.021	0.047	0.049	n.d.
Te	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Au	0.002	<0.001	0.009	<0.001	n.d.	0.004	n.d.	n.d.	n.d.
Cd	0.007	0.002	0.012	0.022	n.d.	0.003	n.d.	0.011	0.013
Bi	0.008	0.002	0.013	0.004	0.014	0.012	n.d.	n.d.	0.141
Hg	0.009	0.011	0.312	0.028	0.034	0.031	n.d.	n.d.	0.007
Mo	0.006	0.001	0.009	0.010	0.009	n.d.	0.008	n.d.	0.020
Mn	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Sb/As	1.541	2.002	1.190	1.966	0.943	0.463	0.373	1.038	0.005
∑Me	11.292	11.229	12.370	11.710	11.519	11.275	11.790	11.970	11.900
Fe+Zn	1.416	1.419	1.604	1.705	1.779	1.553	1.409	1.942	1.825
XAs	0.393	0.333	0.455	0.337	0.513	0.682	0.728	0.491	0.959
XSb	0.605	0.667	0.542	0.662	0.484	0.316	0.272	0.509	0.005
XBi	0.002	n.d.	0.003	0.001	0.004	0.003	n.d.	n.d.	0.036

Mineral formulae of all fahlore-group minerals were calculated on the basis of 13 S + Se. X_{Sb} = Sb/(Sb + As + Te + In + Bi + Ge); X_{As} = As/(Sb + As + Te + In + Bi + Ge); X_{Bi} = Bi/(Sb + As + Te + In + Bi + Ge); n.d.: not detected.

Tab. 2a: Representative electron-probe microanalyses of fahlore-group minerals

	Röhrerbühel			**Pfunderer Berg**		
As	7.62	4.43	2.42	0.69	1.84	0.44
S	25.38	25.19	24.79	23.94	24.72	24.84
Ag	0.31	0.97	0.37	10.50	7.27	3.12
Cu	39.78	38.32	39.09	30.08	32.34	36.38
Ni	n.d.	0.02	n.d.	n.d.	n.d.	0.01
Ge	n.d.	n.d.	n.d.	n.d.	n.d.	0.01
Pb	0.10	n.d.	n.d.	n.d.	0.15	0.12
Sn	n.d.	0.06	0.12	n.d.	n.d.	n.d.
Fe	5.99	6.33	5.72	3.48	1.18	3.17
Zn	1.36	1.70	2.04	3.58	7.43	4.18
Se	0.01	n.d.	0.04	n.d.	0.03	n.d.
Sb	18.34	23.17	25.28	27.91	26.32	28.58
In	0.10	0.07	0.10	0.08	0.10	0.07
Co	0.04	n.d.	0.03	n.d.	n.d.	n.d.
Te	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Au	0.06	0.02	0.06	0.03	n.d.	0.03
Cd	0.02	0.02	0.07	0.16	0.15	0.13
Bi	0.07	0.02	0.10	n.d.	0.05	0.03
Hg	0.07	0.04	0.05	0.03	n.d.	n.d.
Mo	0.08	0.03	0.03	0.13	0.03	0.01
Mn	n.d.	0.01	n.d.	n.d.	n.d.	n.d.
∑ wt%	99.32	100.41	100.30	100.60	101.61	101.13
As	1.667	0.977	0.542	0.160	0.413	0.099
S	12.998	13.000	12.992	13.000	12.993	13.000
Ag	0.046	0.148	0.058	1.692	1.134	0.484
Cu	10.261	9.961	10.318	8.227	8.561	9.590
Ni	n.d.	0.005	n.d.	n.d.	n.d.	0.003
Ge	n.d.	n.d.	n.d.	n.d.	0.001	0.003
Pb	0.008	n.d.	n.d.	n.d.	0.012	0.010
Sn	n.d.	0.008	0.017	n.d.	n.d.	n.d.
Fe	1.758	1.872	1.718	1.083	0.355	0.951
Zn	0.341	0.429	0.523	0.952	1.911	1.071
Se	0.002	n.d.	0.008	n.d.	0.007	n.d.
Sb	2.469	3.143	3.483	3.984	3.637	3.932
In	0.014	0.010	0.014	0.012	0.014	0.010
Co	0.012	n.d.	0.007	n.d.	n.d.	n.d.
Te	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Au	0.005	0.002	0.005	0.003	n.d.	0.002
Cd	0.003	0.004	0.010	0.024	0.022	0.020
Bi	0.005	0.002	0.008	n.d.	0.004	0.003
Hg	0.005	0.003	0.004	0.002	n.d.	n.d.
Mo	0.013	0.004	0.006	0.023	0.005	0.002
Mn	n.d.	0.003	n.d.	n.d.	n.d.	n.d.
Sb/As	1.481	3.217	6.426	24.927	8.803	39.881
∑Me	12.447	12.435	12.661	12.002	12.002	12.130
Fe+Zn	2.099	2.301	2.241	2.035	2.267	2.022
XAs	0.403	0.237	0.134	0.039	0.102	0.024
XSb	0.596	0.762	0.864	0.961	0.897	0.975
XBi	0.001	n.d.	0.002	n.d.	0.001	0.001

Mineral formulae of all fahlore-group minerals were calculated on the basis of 13 S + Se. X_{Sb} = Sb/(Sb + As + Te + In + Bi + Ge); X_{As} = As/(Sb + As + Te + In + Bi + Ge); X_{Bi} = Bi/(Sb + As + Te + In + Bi + Ge); n.d.: not detected.

Tab. 2b: Representative electron-probe microanalyses of fahlore-group minerals

	Bartholomäberg			Mitterberg		
As	3.05	1.74	5.66	4.01	17.86	11.42
S	24.77	25.25	25.33	25.22	30.14	27.70
Ag	0.74	0.53	0.44	0.01	0.05	0.13
Cu	37.25	37.47	37.57	36.22	41.45	40.03
Ni	0.01	n.d.	n.d.	2.12	0.02	0.01
Ge	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Pb	0.05	0.02	0.12	0.02	0.08	0.11
Sn	0.07	0.12	0.06	0..37	0.19	0.04
Fe	5.13	5.02	6.73	6.26	7.19	5.26
Zn	2.20	2.19	2.41	0.34	0.29	2.77
Se	0.02	n.d.	0.01	n.d.	n.d.	0.03
Sb	24.55	26.58	21.13	26.30	1.70	13.02
In	0.05	0.10	0.05	0.08	0.12	n.d.
Co	n.d.	0.03	0.01	0.06	0.01	0.01
Te	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Au	0.10	n.d.	0.03	n.d.	0.03	n.d.
Cd	0.10	n.d.	0.12	0.13	0.02	n.d.
Bi	0.84	0.87	0.65	0.54	0.05	0.05
Hg	0.41	0.25	0.18	0.36	0.15	0.32
Mo	0.02	0.06	0.07	n.d.	0.02	0.08
Mn	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
∑ wt%	99.35	100.24	100.66	101.35	99.38	100.98
As	0.684	0.383	1.241	0.663	3.291	2.289
S	13.000	13.000	13.000	13.000	13.000	12.995
Ag	0.115	0.081	0.067	0.002	0.006	0.018
Cu	9.847	9.716	9.712	9.404	9.005	9.459
Ni	0.003	n.d.	n.d.	0.596	0.004	0.003
Ge	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Pb	0.004	0.002	0.010	0.002	0.005	0.008
Sn	0.010	0.017	0.008	0.051	0.023	0.005
Fe	1.543	1.481	1.979	1.849	1.777	1.414
Zn	0.565	0.552	0.605	0.086	0.062	0.636
Se	0.004	n.d.	0.004	n.d.	n.d.	0.005
Sb	3.387	3.597	2.851	3.564	0.193	1.606
In	0.007	0.014	0.007	0.011	0.015	n.d.
Co	n.d.	0.008	0.003	0.017	0.003	0.001
Te	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Au	0.009	n.d.	0.003	n.d.	0.002	n.d.
Cd	0.015	n.d.	0.018	0.019	0.003	n.d.
Bi	0.068	0.069	0.051	0.043	0.003	0.004
Hg	0.034	0.021	0.015	0.030	0.010	0.024
Mo	0.004	0.010	0.012	n.d.	0.003	0.012
Mn	n.d.	n.d.	n.d.	n.d.	0.001	n.d.
Sb/As	4.953	9.402	2.297	5.376	0.059	0.702
∑Me	11.731	11.743	11.999	12.056	10.901	11.580
Fe+Zn	2.037	2.008	2.496	1.935	1.839	2.050
XAs	0.165	0.095	0.300	0.155	0.944	0.587
XSb	0.819	0.889	0.688	0.835	0.055	0.412
XBi	0.016	0.017	0.012	0.010	0.001	0.001

Mineral formulae of all fahlore-group minerals were calculated on the basis of 13 S + Se. X_{Sb} = Sb/(Sb + As + Te + In + Bi + Ge); X_{As} = As/(Sb + As + Te + In + Bi + Ge); X_{Bi} = Bi/(Sb + As + Te + In + Bi + Ge); n.d.: not detected.

Tab. 2c: Representative electron-probe microanalyses of fahlore-group minerals

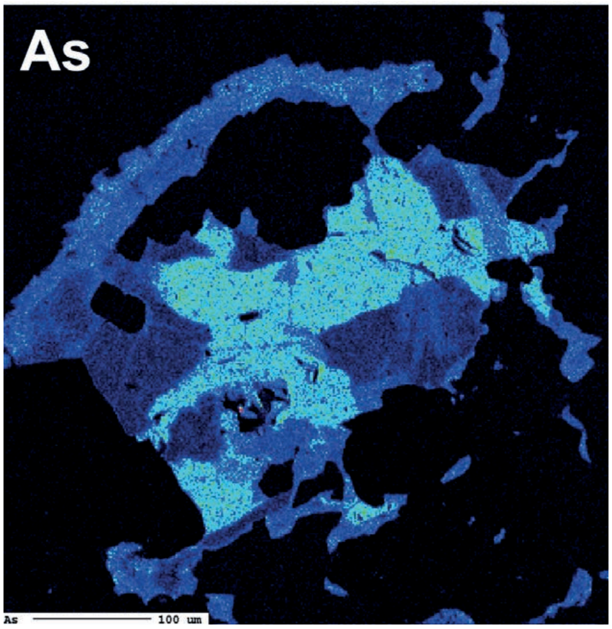

Fig. 5: Elemental distribution map of As of a complex zoned fahlore-group mineral from Bartholomäberg.

which corresponds to a freibergite mole fraction of 94.5%. The Ag concentrations show moderate variations, with a minimum freibergite mole fraction of 0.93% and a mean Ag concentration of 14.89 wt.%. Their chemical composition is in contrast to that of the large fahlore grains that are intergrown with chalcopyrite, sphalerite, pyrite and galena. The mean As concentration of the matrix fahlore is 0.96 wt.%, corresponding to 94.5% of the tetrahedrite end-member. The highest measured tetrahedrite mole fraction is 99.25%. Another notable chemical feature of the fahlore inclusions is their high Cd concentrations. Even if measured Cd concentrations <1 wt.% can be attributed at least in part to analytical interferences with Ag, the maximum measured value of 11.2 wt.% indicates uncommonly high Cd concentrations. Some analyses show Au concentrations up to 0.09 wt%. Chemical analyses of fahlore-group minerals are listed in Table 2b.

Bartholomäberg-Silbertal

The fahlore-group minerals show extensive As-Sb substitution on the X-site, between 0.029 a.p.f.u. As and 3.967 a.p.f.u. Sb (close to end-member tetrahedrite) and 2.602 a.p.f.u. As and 1.279 a.p.f.u. Sb (tennantite-tetrahedrite solid solution). The mean Fe and Zn contents are 1.532 and 0.508 a.p.f.u., respectively. In addition, minor amounts of In (average 0.012 a.p.f.u.), Bi (0.048 a.p.f.u.), Hg (0.024 a.p.f.u.) and Ag (0.070 a.p.f.u.) occur. Hg concentrations vary between 0.007 and 0.046 a.p.f.u. Hg and Ag concentrations vary between 0.049 and 0.111 a.p.f.u. Fahlore-group mineral analyses from the Kristbergsattel show on average 1.783 a.p.f.u. As and 2.108 a.p.f.u. Sb. The concentrations of Ag, In, Hg, Bi are similar to Bartholomäberg but Zn varies from 0.323 to 1.551 a.p.f.u. Zn (mean 0.561 a.p.f.u.). Representative analyses from Bartholomäberg are given in Table 2c.

Mitterberg

Elemental concentrations of the fahlore-group minerals show extensive As-Sb substitution on the X-site, with As in the range 0.663-3.298 a.p.f.u. and Sb in the range 0.193-3.673 a.p.f.u. Concentrations of Zn and Fe on the M(1)-site range from 0.017 a.p.f.u. to 0.382 a.p.f.u. and from 1.262 a.p.f.u. to 1.876 a.p.f.u., respectively (Table 2c). In addition small concentrations of Ni, Se, Bi, Hg and Sn could be detected.

Discussion

The complex geological evolution of the Alpine ore deposits

The Alpine-Balkan-Carpathian-Dinaride belt is one of the world's oldest mining areas and played a major role in the history of European civilization, from the prehistory up until the present day (Heinrich & Neubauer, 2002). This metallogenic and geodynamic province is part of the Alpine-Himalayan orogenic system, which is the result of the convergence between the African, Arabian and Indian plates and Eurasia, which took place mainly from the Cretaceous to the present. As a result of the complex Paleozoic as well as Mesozoic and Paleogene geodynamic history, with several oceanic basins and continental microplates involved, the metallogeny of the Alpine-Balkan-Carpathian-Dinaride belt region involved several phases of major ore formation and subsequent ore re-mobilisation. Due to the geodynamic evolution circulation of metamorphic fluids plays an important role in the genesis of the ore deposits of the Eastern Alps. Metamorphic mineral deposits are thought to have formed from hydrothermal solutions, which are expelled from geological bodies undergoing prograde metamorphism (Hanson, 1997). This may either be prograde, and then the fluids are predominantly the product of de-volatilization, or metamorphism may be retrograde, in which case the water involved can have various sources (marine, meteoric, etc.). Accordingly, specific deposits may have been formed by mixing of ascending devolatilization fluids with convecting meteoric waters. Tectonic control of these mineralizations is late-orogenic trans-tensional faulting, which exposed hot metamorphic rocks to fluid convection along brittle structures. All the ore deposits considered in this study record an early stage of mineral deposition during the Paleozoic, but many of them experienced extensive re-mobilisation under low temperatures mainly during the Eo-Alpine/Alpine orogeny (Neubauer

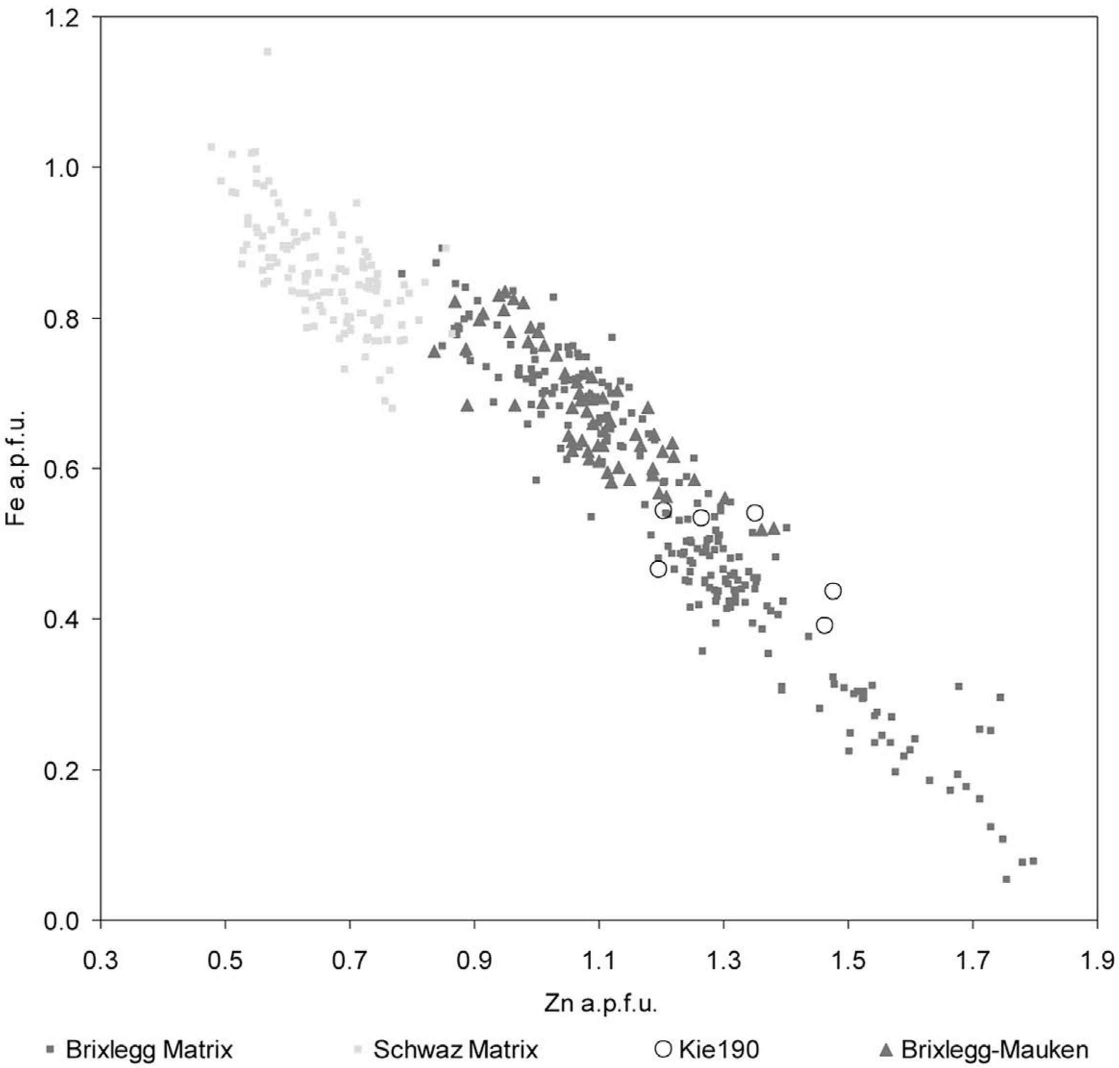

Fig. 6: Plot of Fe vs Zn of the fahlore-group minerals from Schwaz (light grey squares), Brixlegg (dark squares), Brixlegg-Mauken (dark grey triangles) and from an ore fragment in a slag fragment (Kie 190) from the Kiechlberg (open circles).

& Heinrich, 2003). This is evident in many ore textures showing complex chemical zoning patterns involving veining textures in fahlore-group minerals (Fig. 5, As zoning in fahlore-group minerals from Bartholomäberg) and the geothermometric estimates. Temperatures obtained by fluid inclusion microthermometry (Bechter, 2009) or siderite-ankerite geothermometry (Viertler, 2011) yielded temperatures ranging from <100°C up to 300°C some of the ore deposits investigated in this study. Among the ore deposits studied here, the only high-temperature ore deposit is the Pfunderer Berg ore deposit, which yields temperatures >500°C, consistent with its direct genetic link with the intrusion of small diorite bodies during the Permian (Krismer et al., 2011b). Keeping in mind the observations in Figure 5, the complex chemical zoning patterns of the main ore minerals has to be considered with caution when using mineral chemical data for ore provenance studies.

The prehistoric ore deposit – mining connection

The comparison between the ore mineral assemblage of prehistorically mined ore deposits in the Eastern- and Southern Alps clearly shows that here chalcopyrite and fahlore-group minerals were the most important phases used for the prehistoric copper production (Weisgerber & Goldenberg, 2004; Lutz & Pernicka, 2013; Pernicka & Lutz, 2015; Artioli et al., 2016). The beginning of Cu-metallurgy in the Eastern- and Southern Alps can be set into the Late Neolithic to Early Bronze Age. The earliest evidence of smelting and copper production in the Eastern Alps is known from the Mariahilfbergl near Brixlegg, which is located in the vicinity of the fahlore deposits of Brixlegg. Here the copper slags are associated with ceramics from the Münchshöfener culture, dating to the beginning of the Late Neolithic in southern Germany

(4500 - 4000 BC) (Bartelheim et al., 2002; Höppner et al., 2005). Early Bronze Age metallurgy has also been reported from the Buchberg near Wiesing in the Lower Inn Valley (Martinek, 1996; Martinek and Sydow, 2004). In the Middle- and Late Bronze Age abundant Cu metallurgy in the central Eastern and Southern Alps is known from the Mitterberg mining district (Salzburg, Austria) (Stöllner et al., 2004; 2006) from the Kelchalm/Jochberg/Kitzbühel mining district (North Tyrol, Austria) (Goldenberg, 2004) and from the Schwaz-Brixlegg mining district (North Tyrol, Austria) (Goldenberg & Rieser, 2004; Krismer et al., 2010; Goldenberg, 2015). In the Southalpine namely in the Trentino and Alto Adige/ South Tyrol regions, there is substantial evidence of Copper Age (e.g. Artioli et al., 2015) and Bronze Age (Metten, 2003; Cierny et al., 2004; Cierny, 2008; Addis et al., 2016, 2017) smelting activities. With regard to the temporal use of Cu-ores investigations of Lutz and Pernicka (2013) and Pernicka and Lutz (2015) show that at the beginning of the Early Bronze Age the fahlore copper of the Inn Valley dominates the region. In the Middle Bronze Age it is replaced by the east Alpine copper of the Mitterberg type. Fahlore copper reappears in the Late Bronze Age and is used parallel to east Alpine copper. In this period mixing of chalcopyrite and fahlore copper is also common.

In the Austroalpine Mitterberg and Kelchalm/Jochberg/Kitzbühel mining districts chalcopyrite is the predominant Cu carrier (Stöllner et al., 2004, 2006; Goldenberg, 2004). Concerning the Southalpine mining districts Pfunderer Berg (South-Tyrol) and various sites from the Trentino chalcopyrite is also the most dominant Cu carrier (Metten, 2003; Nimis et al., 2012; Artioli et al., 2016; Addis et al., 2017). Contrary the smelting sites from the North Tyrolean Lower Inn Valley provide evidence for the processing of fahlore-group minerals with dominantly tetrahedrite-tennantite composition (Krismer et al., 2012; Goldenberg, 2015). This resulted in elevated Zn concentrations, the presence of Ag (e.g. from fahlore-group minerals and/or balkanite in Röhrerbühel) and in some cases traces of Co and Ni (e.g. from Co-Ni bearing tetrahedrite-tennantite) in the smelting products. Different elemental distributions hance can be expected from the Southalpine smelting sites. The sphalerite- and galena-rich veins that accompany the chalcopyrite-rich vein at Pfunderer Berg were probably only of minor interest in prehistoric times, but the chalcopyrite-rich domains most likely were of considerable interest since Eneolithic times (Artioli et al., 2015). Since the chalcopyrite-rich domains contain sphalerite, galena, pyrite and Ag-bearing phases, this would produce slags and raw metals with elevated Zn, Fe, Pb and Ag contents during smelting, unless chalcopyrite was efficiently pre-concentrated before smelting. Due to the presence of Bi-phases elevated Bi concentrations in metallurgical products (especially in metal and sulfide phases) may also be expected. During smelting Fe and Zn would form silicates such as Zn-bearing fayalite, Zn-bearing clinopyroxene and Zn-bearing åkermanite/gehlenite and Ag and Pb would remain similar to Bi predominantly in the obtained metal or within distinct sulfide enclaves of the slags and the raw metal. Therefore the chemical major-, minor- and trace element contents of Southalpine metallurgical products will show a different geochemical signature and thus can be probably distinguished from the products of ores from the North Tyrolean and Salzburg sites in the Greywacke Zone (Artioli et al., 2016).

Linking smelting site and ore deposit - the example of the Kiechlberg

The Kiechlberg is a small hill at 1028 metres above sea level on the southern side of the Karwendel mountain range, a few kilometers northeast of Innsbruck. Superficial finds of artefacts and metallurgical slags led to first archaeological excavations, which started in 2007 in the frame of the SFB HiMAT (Töchterle, 2015). On the Kiechlberg, a huge amount of ceramic and flint artefacts as well as some metal objects made of copper and bronze were collected during the investigation of different prehistoric waste layers, indicating an occupation of the site from the Late Neolithic up to the Middle Bronze Age. Together with archaeological finds and almost in the upper layers of the studied stratigraphy, various slags and copper-rich semiproducts (unrefined antimony-rich raw copper) occur and prove primary copper metallurgy at the site during the Early Bronze Age. Unfortunately, no direct evidence of smelting facilities could be excavated at the Kiechlberg site. Many of the slag samples occur only as small fragments without any archaeological or macroscopic evidence whether they have been produced in a furnace, hearth or crucible or cooled in a separate receptacle (Hauptmann et al., 2003). It is suggested for this period that the charge was smelted with the aid of blowpipes and clay tuyeres within a crucible in a small hearth structure (shallow pit, Töchterle et al., 2013). The mineralogy of the excavated copper ore fragments (fahlore-group minerals with enargite-famatinite mineral reaction domains) as well as the chemical composition of slags and raw metal remains suggest that the smelted ore was primarily fahlore-group minerals mixed with enargite-famatinite, malachite, azurite and other secondary copper minerals (Cu-Zn-Sb-As oxides). The mineral assemblage as well as the chemical composition of the ore fragments from the Kiechlberg site match very well the ore mineralogy found in the mining district of Brixlegg/Radfeld including the Mauken area. Figure 6 shows the comparison of Fe/Zn ratios of EPMA spot analyses of fahlore-group minerals from an ore sample found at the Kiechlberg (Kie 190) and the Devonian dolomite-hosted fahlore-group minerals from Schwaz and Brixlegg. This diagram shows a very good agreement between the composition of the ore fragments from sample Kie 190 and the fahlore-group mineral compositions from Brixlegg (Krismer et al., 2011b). All these facts together suggest that the main sources of copper ores used for the copper production at the Kiechlberg site were the large fahlore-group mineral deposits of Brixlegg.

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Authors

Peter Tropper – Department of Mineralogy and Petrography, University of Innsbruck
Gert Goldenberg – Department of Archaeologies, University of Innsbruck
Matthias Krismer – Department of Mineralogy and Petrography, University of Innsbruck
Daniel Bechter – Department of Mineralogy and Petrography, University of Innsbruck
Martin Steiner – Department of Mineralogy and Petrography, University of Innsbruck
Hans-Peter Viertler – Department of Mineralogy and Petrography, University of Innsbruck
Franz Vavtar – Department of Mineralogy and Petrography, University of Innsbruck

Correspondence and material requests should be addressed to: Peter.Tropper@uibk.ac.at

Beneficiation:
Understanding a missing link?

Sulzbachmoos, Troiboden at the Mitterberg, excavation of upper features oft the sluice-box 5, photo: P. Thomas

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Thomas Stöllner

Between mining and smelting in the Bronze Age – Beneficiation processes in an Alpine copper producing district

Results of 2008 to 2017 excavations at the "Sulzbach-Moos"-bog at the Mitterberg (Salzburg, Austria)

ABSTRACT: *The second step of copper production, the copper ore beneficiation, is re-discussed on the basis of new field work that is carried out at the Troiboden at the Mitterberg between 2008 und 2017. The Sulzbach-Moos bog was a focus of research since the 1930s and helped E. Preuschen and later C. Eibner to develop a first operation model. The new research was able not only to uncover a lot of new installations but also to collect further detailed insights into work-processes that allow now a first reconstruction and an adoption of the older models. After the discovery of 15 wet beneficiation boxes it becomes clear that these installations were in the centre of the beneficiation processes that not only cleaned and concentrated the inter-grown chatty ores but also produced side products that might have been used as fluxing additives for the smelting (quartz, iron carbonates). Discussion is raised on the question which working steps were carried out within the boxes: Besides washing that separated and concentrated the ore compound, it is still unclear if the beneficiation specialists were able to separate the slightly heavier haematites and pyrites from the chalcopyrite ores.*

KEYWORDS: ORE BENEFICIATION, ORE WASHING, OPERATION PRACTICES, ORE MINERALOGY, DENDROCHRONOLOGY, WETLAND ARCHAEOLOGY

Introduction

It never has been doubted that ore beneficiation/ore dressing is one of the most important steps of metal production in order to prepare the ore for the subsequent smelting. Georgius Agricola already dedicated his 8th book for describing various techniques of his time (Agricola, 1556). Ore dressing is – especially when carried out without sophisticated machinery or chemistry – very demanding and time-consuming work, as not only traditional description but also experiments indicate. It is essential to separate the dead rock from the ores but even more, it is important to separate different mineral components to enable a better smelting procedure. It is most likely that already during the Bronze Age, smelting recipes were known and practically important to produce more standardized products such as matte and black copper. Therefore, the greatest concern is to understand the demands of the smelting plants on the one hand and the yield of the ore deposits on the other hand. These two parameters also have to be considered at the Mitterberg district, if this working step is to be fully understood. Although beneficiation processes were studied in the Eastern Alpine mining districts in some cases, it is astonishing that this step of work is still understood only on a superficial level. There was a rather short discussion on the basis of fieldwork carried out by R. Pittioni and E. Preuschen at the Scheideplatz 32 from the Kelchalm and some discussion by C. Eibner based on work he had done at the Sulzbach-Moos site at the Troiboden (e.g. Eibner, 1979). A Late Bronze Age beneficiation site recently investigated at the Schwarzenberg-Moos near Brixlegg has not been examined conclusively yet but envisages some possible answers, as the site was small and operated only during a short time (Goldenberg, 2015, p.156; Nicolussi, et al. 2015, pp.242-243).

Although the work of R. Pittioni and E. Preuschen was pioneering in many respects, the Kelchalm reports can be characterized rather as excavation reports (Preuschen & Preuschen, 1937; Pittioni & Preuschen, 1947; 1954; Koch Waldner & Klaunzer, 2015; Koch Waldner 2016). They are lacking a comprehensive reconstruction of the chaîne opératoire. This has to do with the fact that many installations were not yet fully understood and did not allow a conclusive interpretation. Even today there is a lot of debate about various features (Klaunzer, 2008;

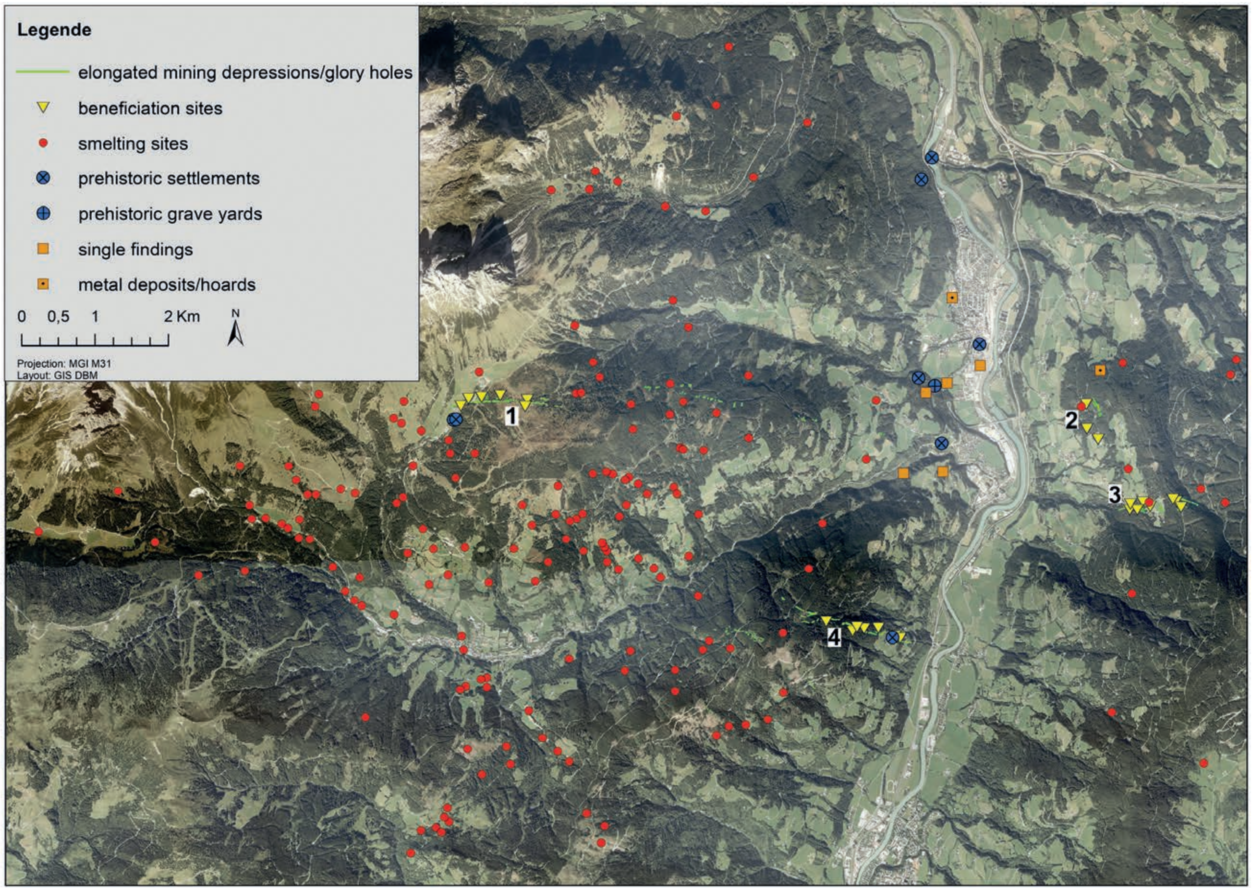

Fig. 1: The "Mitterberg" mining district (the mining field of Mühlbach-Bischofshofen) at the centre of the Salzach-Pongau region as displayed by mining lodes (and their surface depressions), beneficiation and smelting sites as well as settlements, single finds and graves; 1: Main Lode beneficiation sites; 2: beneficiation at the Buchberg Lode; 3: Winkelgang benficiation sites, 4 Brander Lode beneficiation sites; Deutsches Bergbau-Museum, Bochum, Ruhr-University Bochum, Mitterberg project; the four wet beneficiation areas are marked separately.

Koch Waldner, 2016, pp.216-228). The situation is even worse with the older Troiboden excavation that never was published conclusively but only in preliminary reports (Eibner-Persy & Eibner, 1970; Eibner, 1972; 1974). The consequence was that all the evidence was interpreted based on artefacts and their possible usage rather than on the basis of a detailed analysing of artefacts, features, sediments and mineralogy altogether. The only attempt was made by C. Eibner, who tried to develop a model (Eibner, 1979, pp.157-161) that considered and discussed ore separation, washing and copper ore concentration. Eibner's attempt had lacked larger insight to the structure of the site, a statistical evaluation and mineralogy of the beneficiation dumps as well as a decision regarding which of the possible wet mechanical techniques had been used at the end to concentrate fine grades. Principally he considered the usage of troughs (such as the piece found in 1867 from the underground mines, see below), and the usage of jigging as well as the usage of puddles (Agricola: "Planherd") possible. There was even much discussion about a copper concentrate ("Schlich"), which he found in a wooden water pipe at a stone dam (Eibner 1972, pp.8-10; 1974, pp.21-22). It was not possible to decide if this pipe intentionally had helped to produce such concentrates or if the concentrate had emerged incidentally within this pipe.

The Mitterberg as a research area: large scale production in the Bronze Age

It has long been known that the copper deposits in the Mitterberg region in the eastern Alps were mined on a large scale during the 2nd and the early 1st millennium BCE. It is actually the first mining region for copper that was investigated archaeologically (Much, 1878/1879). These first investigations were stimulated by observations of copper mining engineers such as J. Zötl and J. Pirchl (the older), who were the first to keep findings and notes (for the research history in detail see Thomas, 2018). Ground-breaking studies on the production processes were published by Kyrle (1918) and Klose (1918), and on the mining techniques and ore beneficiation by Zschocke and

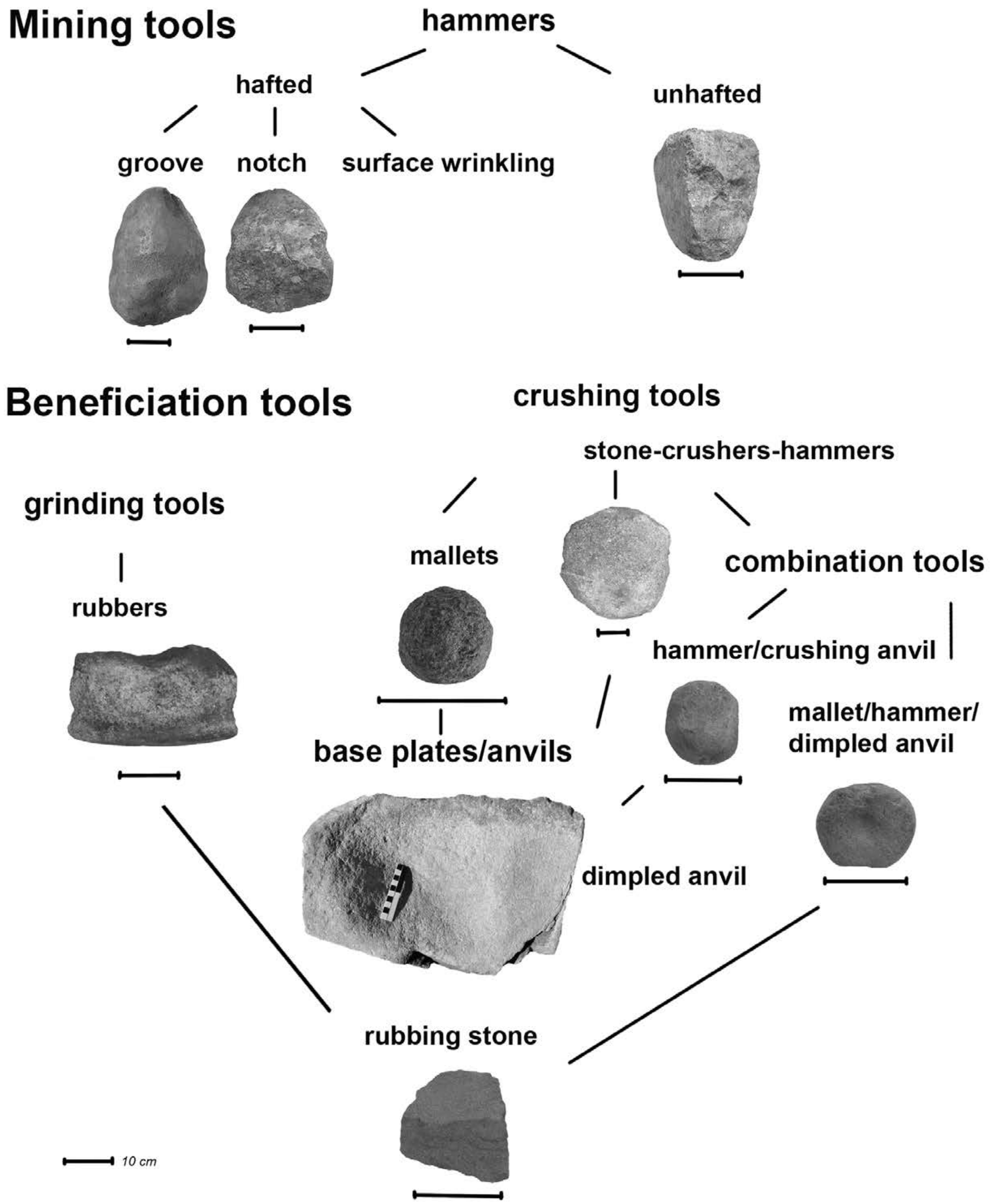

Fig. 2: Bronze Age stone tools at the Mitterberg district according to their usage in mining and beneficiation, modified after A. Maass, in: Stöllner et al., 2009, p.151 Fig. 50.

Preuschen (1932). They documented numerous mines and remains of extractive metallurgy, like furnaces and about 150 slag sites. The situation was exceptionally favourable for the study of ancient mining and smelting techniques, because the mine seems to have been abandoned after the Bronze Age and was only rediscovered in 1827. Mining resumed only in 1837 and ended in 1977. Thus, there was no medieval and later exploitation of the mine that would have destroyed more ancient traces.

After World War II archaeological research concentrated on ore beneficiation (Eibner-Persy & Eibner, 1970, Eibner, 1972, 1974), on smelting plants (e.g. Eibner, unpublished; Herdits, Löcker, 2004) and the search for settlements. These are preferentially located in the valleys, and the focus was on subsistence strategies (Lippert, 1992; Shennan, 1995) and the spatial organisations of the mining communities and their structures (Stöllner, 2003). New underground investigations (Stöllner et al.,

Fig. 3: Beneficiation dump 3 east of mine 3 at the Brander Lode district during documentation, when exposed by road construction in 2006 (photo: DBM/RUB, Th. Stöllner).

2004, Stöllner et al., 2009a) began first by a project of the Academy of Sciences in 2002 and were continued later with the HiMAT research cluster, which comprised interdisciplinary research on all aspects of mining in the eastern Alps (for Mitterberg e.g. Stöllner, 2011; Stöllner et al., 2011a; Stöllner et al., 2012a; 2012b; 2012c). During recent years work was continued by the D-A-CH-Project, in which framework also the work at Mitterberg was continued (Stöllner, 2015; Stöllner et al., 2016; Pernicka et al., 2016).

The question asked from the earlier work onwards was about the importance of the technique, presumably developed at the Mitterberg in a procedural combination, which has been called the Mitterberg process later on. Nowadays we have good arguments that chalcopyrite smelting, a sophisticated ore-dressing technique, and deep mining had been successfully established first in this region before they spread to other regions in the Eastern Alps (e.g. Stöllner, 2009)[1]. In addition, it became clear that the Mitterberg was one of the main producing regions during the middle and later 2nd millennium when it dominated the markets between the 17th and the 13th century BCE (Pernicka et al., 2016). Therefore, it is not only of regional importance to understand the technical and economic principles that were determinants for the beneficiation processes. As we will see, the Sulzbach-Moos bog has the advantage of providing access even to the oldest known ore-beneficiation in the Eastern Alps dating back to the beginning of the 14th century BCE. It therefore gives us an idea of the earliest concepts of wet beneficiation of ores so far known in the Alps and beyond.

The Mitterberg mining region and its beneficiation areas

As the Mitterberg mining regions consists of various mining districts it was clear from the beginning of the recent survey program that more beneficiation sites can be expected. During 2006 and 2016 several surveys had been undertaken in the Mitterberg mining region including particularly the Main Lode district, the Brander Lode area in the Southern district and the Buchberg Lode and Winkel Lode areas in the Eastern district (Fig. 1). Most of the evidence collected consists of typical working stones such as characteristic mallets and crushing plates, rubbers (especially those with a lateral denting) and grinding plates (Fig. 2). Another indication of working processes are typical beneficiation sediments (ore-containing crushing and washing debris) that were discovered at cut-offs of forest tracks as well as by opening through digging and by systematic drilling (Fig. 3, Scheidehalde Pinge 3: Stöllner et al., 2009, pp.129 Fig. 49). As the systematic survey near the Brander Lode mining depressions (Pingenzüge) had shown already in 2006, beneficiation took place nearly alongside the mines particularly by dry crushing and separation processes. Wet beneficiation certainly required constant water flows what reduced the possible locations, especially if the mines were localized at steep slopes and terrains. Wet beneficiation therefore can be evidenced more seldom, although one should never exclude deliberate water usage at any time and location if water was necessary and available. However,

Fig. 4: Aerial photography of the Troiboden plus the Sulzbach-bog in the front (photo: R. Pils, Bischofshofen).

there are four sites so far indicative of wet beneficiation processes: Besides the famous Sulzbach-Moos bog site at the Troiboden (Fig. 1.1), we are able to localize such places south of the Buchberg mining depression down the hill at a wet bog/field area (Fig. 1.2, survey 2008/2009). North of the Winkelgang mining depression we are able to locate a very large ore-dressing area whose water supply nowadays comes from a slope fracture up the hill and upwards from the mining (so called Scheidhalde 1, Fig. 1.3, survey 2016). A similarly large beneficiation area was surveyed in 2006 south and westwards of mining depression No. 3/4 at the Brander Lode district. A swampy bog area had been observed at a flat depressed area and delivered a large range of stone tools, thus indicating centralized wet beneficiation for the surrounding mines 3, 4 and probably also 5 at the summit of the Einödberg mountain (Stöllner et al., 2006, pp.129-131) (Fig. 1.4).

The Mitterberg as a research area: the Troiboden and its research history

First finds at the Troiboden were made at the beginning of the 20th century when the area had been used to cut turf for the heating of the mining houses at the Mitterberg. During this work some wooden poles had been discovered, later recognized as pile work ("Pfahlbau") (Zschocke & Preuschen, 1932, pp.109-111) (Fig. 4). The construction of a drainage ditch in 1928 („Rösche") led to the discovery of the Bronze Age ore beneficiation dump at the Sulzbach-Moos bog. Based on these first observations, some soundings have been carried out under direction of Ernst Preuschen. Those soundings led to a first differentiation of coarser and finer sediments ("Grobkorn" and "Feinkorn"), as well as the washing loss and finer grained losses ("Waschabgang"; "Feinkornabgang"). In the frame of those first investigations, F. Firbas described the palynological sequence for the first time. The Bronze Age dumps intercepted the bog development, but re-developed in the later Holocene in small pools between the single beneficiation dumps (F. Firbas in: Zschocke & Preuschen, 1932, pp.173-176; recently re-evaluated by Breitenlechner et al., 2014; E. Breitenlechner, K. Oeggl in: Stöllner et al., 2012, pp.4-6).

The first extensive archaeological investigations took place at the Troiboden from the late 1960s onwards when E. Preuschen, C. Eibner and A. Eibner-Persy started by support of the Bochum VFKK society a first real excavation. The excavators settled on a location near the drainage ditch for the first trenches in 1968/1969 which led to a first complete stratigraphical sequence of one of the debris dumps. Additionally a first wooden operation chest was discovered and documented (Eibner-Persy & Eibner,

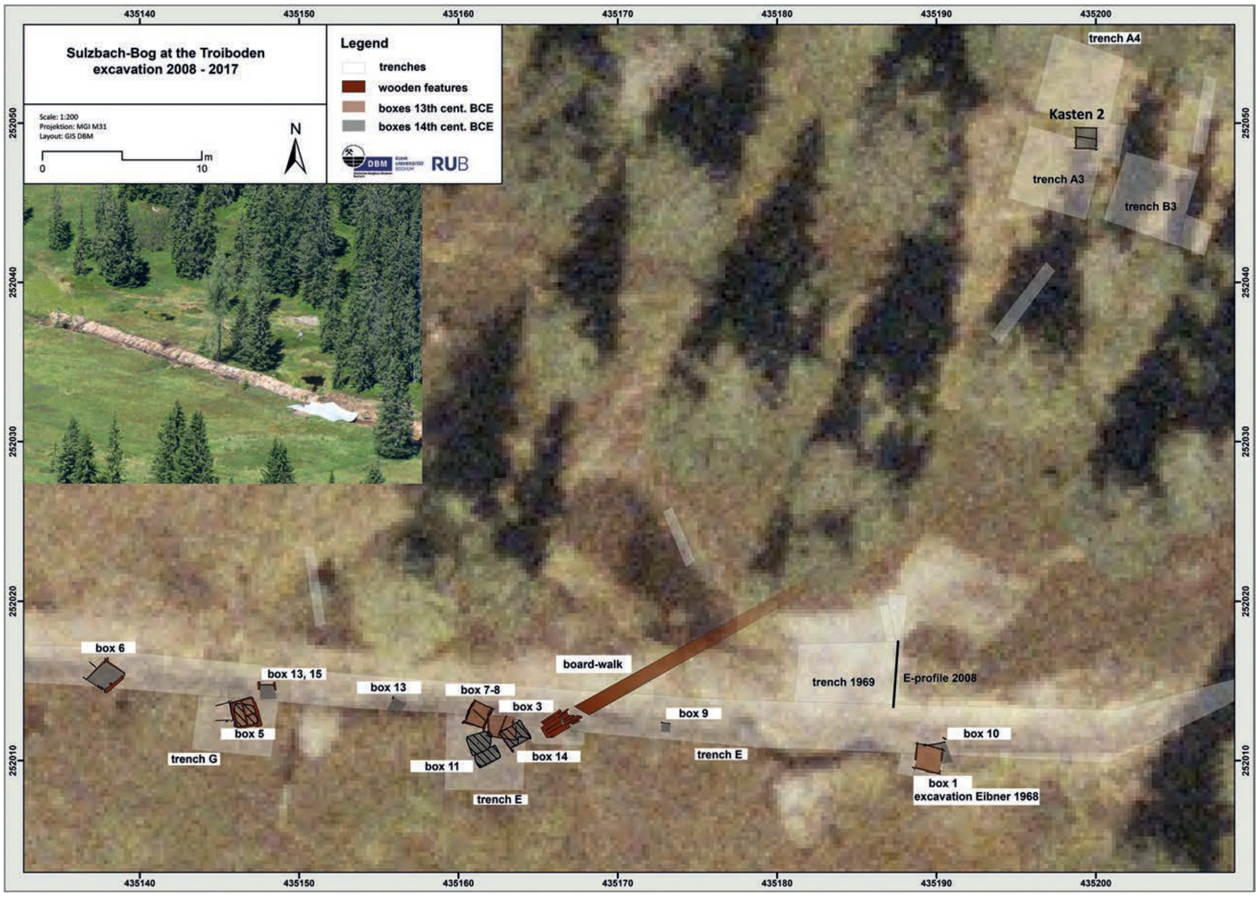

Fig. 5: Sulzbach bog excavation 2008-2017, overview of the excavation trenches and the boxes 1-15 (map/graphics: DBM/RUB, J. Schröder, Th. Stöllner).

1970). The later excavation of 1970-1972 concentrated at an area northwards, at a flat area that is intermediate of beneficiation tailings and the mining tailings that were dumped near the eastern part of the Main Lode mine in the north (Eibner, 1972; 1974). At the edge of the operation quadrants A3 and A4 a second wooden chest was discovered but not excavated. This feature finally led to the reopening of the Troiboden excavation 36 years later by the author and his team.

C. Eibner and E. Preuschen were able to deduce a first modus operandi for the beneficiation processes: They started on the basis of their differentiation of beneficiation waste (see above) and concluded that only chatty ores were processed at the Troiboden, while rich ores directly went – after having them crushed to nut-size – to the smelting plants (Eibner, 1979). Preuschen assumed the usage of jigs ("Stauchsetzsieben") to separate gangue and ore as he interpreted evidence from old mines inside the Danielistollen at the Kelchalm near Kitzbühel in this way (Preuschen & Pittioni, 1937, 3 p. note 3, 155). One of the most important conclusions concerned the question of wet beneficiation as C. Eibner assumed the production of a flour-fine ore concentrate that was finally concentrated by wet beneficiation techniques at the end. One of the arguing angles was the discovery of a fine ore concentrate ("Schlich") inside a hazelnut pipe (Eibner, 1972, p.7-8 Fig.) (Fig. 15.1). An analysis of the copper content showed a concentrate of 10.2% that is much elevated with regard to the chatty ores used from the mines (1-2% at the mining debris). But – and this should be remembered – this is rather little when concerning the copper content of pure chalcopyrite, which reaches up to a third of copper content. What Eibner could not explain those days was the usage of the wooden chest found in 1968 that he described rather unspecifically as "somehow related to wet mechanical beneficiation" and also interpreted the chest as a storage for fine ore concentrates (Eibner-Persy & Eibner, 1970, p.19). A modification in explanation can be seen later (Eibner, 1979, 160 "Sortieren und Klassieren in der Wasserströmung").

During the recent research, especially the ore-beneficiation site at the Troiboden produced a splendid excavation result based on the waterlogged preservation of the sediments there: During the first two years of work we concentrated on re-evaluating the old trenches of C. Eibner 2008/2009. The second wooden chest was investigated with the help of various methods; the team was able to collect arguments for the processes of washing and concentration carried out in those boxes. Within two seasons of work we also were able to date the usage of the box to 1377 and

1376 BCE (Stöllner et al., 2012; Nicolussi et al., 2015 pp. 239-240). Further work was started in 2011 alongside the older drainage system from 1928 that allowed a large-scale section through the whole beneficiation site: We were able to establish a profile of about 100 m length (Stöllner et al., 2012b; Stöllner, 2015) (Fig. 5). This excavation that has been carried out normally within 5 to 6 weeks during the summer since then (7 campaigns) has provided excellent insight into the beneficiation areas, including wet and dry beneficiation areas: Up to now about 15 wooden chests (sluice boxes), once used as tyes to concentrate the ore, have been discovered and partly excavated.

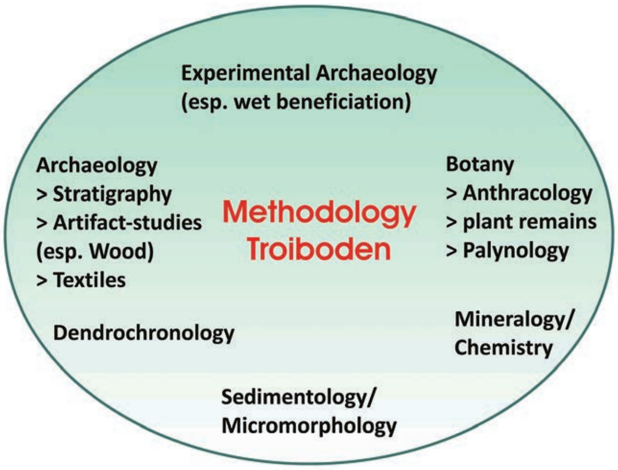

Fig. 6: Scheme of the methodological concept of interdisciplinary work of the Troiboden research (graphics: DBM/RUB, Th. Stöllner).

The modern excavation since 2008

Strategy of research

A first excavation in 2008 and 2009 led to first experiences about excavation-techniques, problems and water drainage at the excavation fields and the way to systematize sampling and describing protocols. This allowed a multidisciplinary approach that concurrently was carried out with the excavations (Fig. 6). Besides rather traditional approaches such as archaeological, archaeobotanical, dendrochronological or mineralogical methods we also included micromorphological and experimental studies[2]. A site like the Troiboden excavation requires a long lasting strategy as the stratigraphy most of the time exceeds 2 to 3 meters and the largeness of the site prevents an easy overview. So the decision was made in 2011 to start a long-term excavation alongside the old drainage gully from 1928 which already had destroyed part of the upper strata. This excavation ended up as profile trench of about 100 m. As the geophysical survey carried out 2008 and 2009 made perfectly clear, this trench (trench E) cuts through a large part of the whole beneficiation area, thus revealing a complete insight into stratigraphy and chronology of the dumping and beneficiation processes. Since the related mining area in the North, the eastern branch of the prehistoric Main Lode mine, is no longer accessible in its underground parts, this excavation also allows some conclusion on behalf of the dating of the mining activities there. A trackway discovered in 2014 in nearby trench F led in the direction of this mine thus indicating the ore delivery was from there (see Fig. 5).

It was a question from the beginning if the large beneficiation area at the Sulzbach-Moos bog served as a central area for the processing of chatty ores. A first survey of the surroundings of the western parts of the prehistoric mining area evidenced other but smaller beneficiation areas north- and westwards of the mining depressions. Until now there is no evidence of another site at which wet beneficiation was carried out, but this might not be the final conclusion as those sites are not sufficiently investigated (Fig. 7; Stöllner et al., 2012a, pp.36-37 fig. 5).

Excavation results

Reopening the excavation of 1970-1972

The reopening in 2008 and 2009 first intended to collect further wooden samples for dendrochronological dating but quickly extended the old excavation fields. At the Eibner trench from 1969 we documented and sampled the stratigraphy as we simply reopened the old trench, while the excavation between trenches A3/A4 and B3/4 led to excavation of the wooden chest No. 2 that had already been discovered in 1972 (Stöllner et al., 2012a) (Fig. 9.1). The excavation did stratigraphically distinguish the filling of the box for the first time and was able to understand the different processes of washing inside the box. It also turned out that the chest was reused in a second year by rearranging the complete installation somewhat higher in the ground. By re-excavating trench B3 in its eastern part we managed also to fully excavate a layer of split half-trunks that finally were identified as part of a wooden grating to stabilize the wet ground in front of a hearth westwards (Stöllner et al., 2012a, p.7 fig. 4).

„Rösche 1928“, the long profile stratigraphy, the layout of the site and its chronology

The team has been working from 2011 onwards at the 100 m profile (Fig. 5). At present we are able to understand the general chronology of about 70 meters of the general profile since the first overall documentation in 2011 only covered the uppermost part of the profile (Stöllner et al., 2012a, pp.37-38, Fig. 6). As the drainage system of the modern excavation uses the drainage gully of 1928 we deepened the ditch (trench E), step by step in the following years. By re-documenting and sampling the profile we have revealed a three-phase embankment of dumps generally in its central parts. The primary structure of

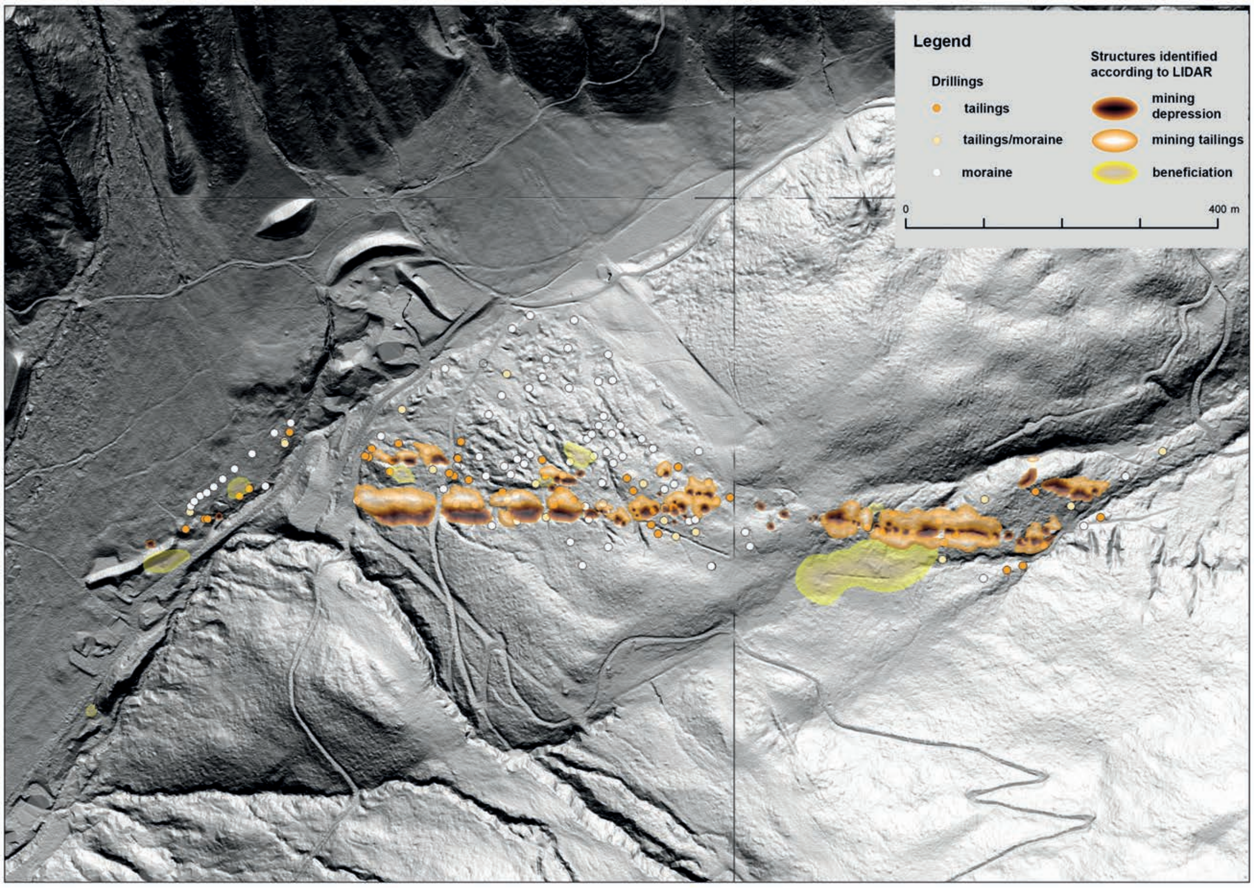

Fig 7: Mitterberg, Main Lode, the mining area according to mining structures and geological based soils, according to a drilling survey in 2009/2010 (map/graphics: DBM, A. Hornschuch).

Lab-No	Sample	C14 Alter	±	13C	Cal 2 sigma
VERA-4868	Without artefact number, lowest level	3045	35		calBC1420-1220
MAMS 14658	A-Troi-7273	3085	20	-23,0	calBC1416-1304
MAMS 14660	A-Troi-7292	3067	22	-23,4	calBC1408-1270
MAMS 14657	A-Troi-7285	2922	21	-21,6	calBC1248-1026
MAMS 14659	A-Troi-7284	2893	21	-23,9	calBC1189-1006

Tab. 1: ^{14}C-dates from the Troiboden, Sulzbach-bog excavations.

embankment is still preserved in most parts of the profile apart from the easternmost part where erosion and scouring transported sediments downhill and flattened the original tailings. The upper layers however showed the original embankments better, since dumps and their areas in between are preserved in their original structure. As the younger peat bog did grow up in pools in between this helped the original dumps to be preserved in their original shape. This allows some observations especially in the western parts where the area is flatter and better preserved. Dumps often alternate with pool areas in which wood chests and work areas of the wet beneficiation were discovered in some cases (the later trenches E and G). This picture indicated another conclusion: Dumps and work areas were resettled all the time and perhaps in the direction of the water supply that was easier to handle at the fringes of the dumping areas. This allows the conclusion that dumping areas were continuously expanded during the work processes. It can be assumed that this might have ended in a congestion of the area and therefore forced to reorganization of the dumping areas: The lower two levels are rather flattened and, as organic rich sediments indicate, stayed uncovered for some time before new material was dumped on them. Work processes were organized possibly in a centralized way if one regards some of the features at the earliest phase of the beneficiation site. At trench B3/A3/A4 and in the area of trench F a wooden grating and surface levelling as well as the installation of a board walk were made during the year 1378/77, possibly during one organized process.

During the years, a series of ^{14}C datings (Tab. 1, Fig. 8) and annual dendrochronological dates could be

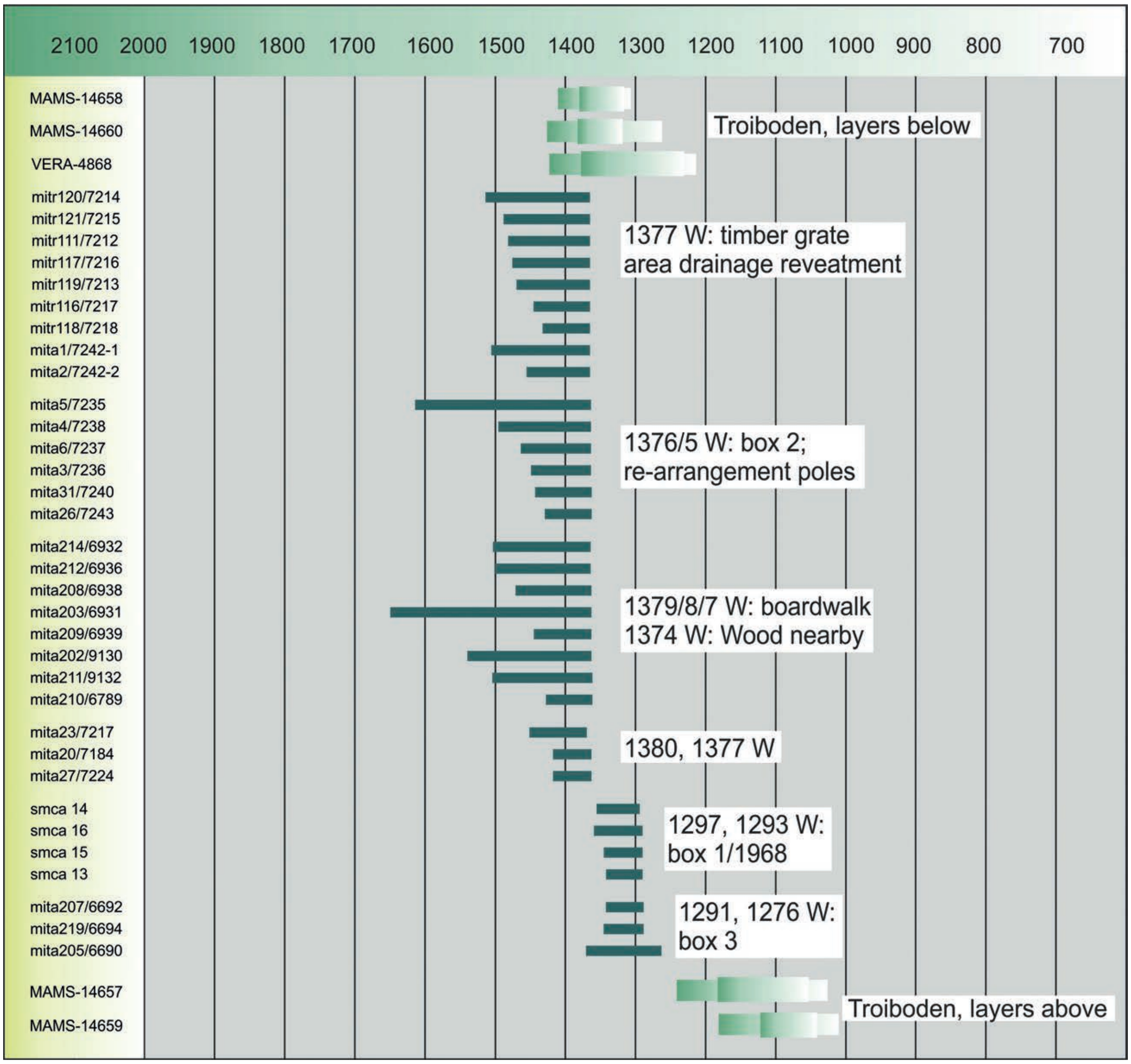

Fig. 8: ^{14}C-dating and dendro-dates from various features indicate a 200 to 250 years operation period; dendro dates after K. Nicolussi, T. Pichler, Univ. Innsbruck, data: Pichler et al., 2018 and Table 1 (graphics: DBM/RUB, Th. Stöllner).

collected that allow a first estimation concerning the operation period and possible centrally directed operations. According to the data series around 1380 and 1377 it is clear that large parts of the site at the eastern and also southern parts of the area had been managed during this time for the first time. If we take the stratigraphic position of box 2 and 3 there is also no doubt that they represent the rather stratigraphically upper end of the 2nd phase of embankment processes. Box No. 3 that can also be related with a tailing in which a Riegsee-knife was discovered which belongs to the 1st quarter of the 13th century (the operation is rather around 1276 than around 1291, as the chest was built by possible re-use of older planks) (Fig. 9.1). Two ^{14}C-datings have been taken from illumination spills the uppermost and stratigraphically youngest layers: As they delivered datable wood only in small quantities, no dendrochronologically dates are available yet. The ^{14}C-2σ range indicates a dating that is about 100 younger in average. Therefore, we can conclude a general operation of about 200 or perhaps 250 years of operation at the beneficiation at the moment.

„Rösche 1928“, trench F

In this trench a complete sequence had been investigated between 2012 and 2016 within five campaigns. Two operation levels could be discovered of which the first was conducted after the initial foundation in the years after 1377. There was a sequence of two wooden chests (No. 11, 14)/ boxes. No. 14 is seemingly the older one and was dug into the ground-laying turf (Fig. 9.1, Fig. 10). Some meters in the east another box (No. 9)

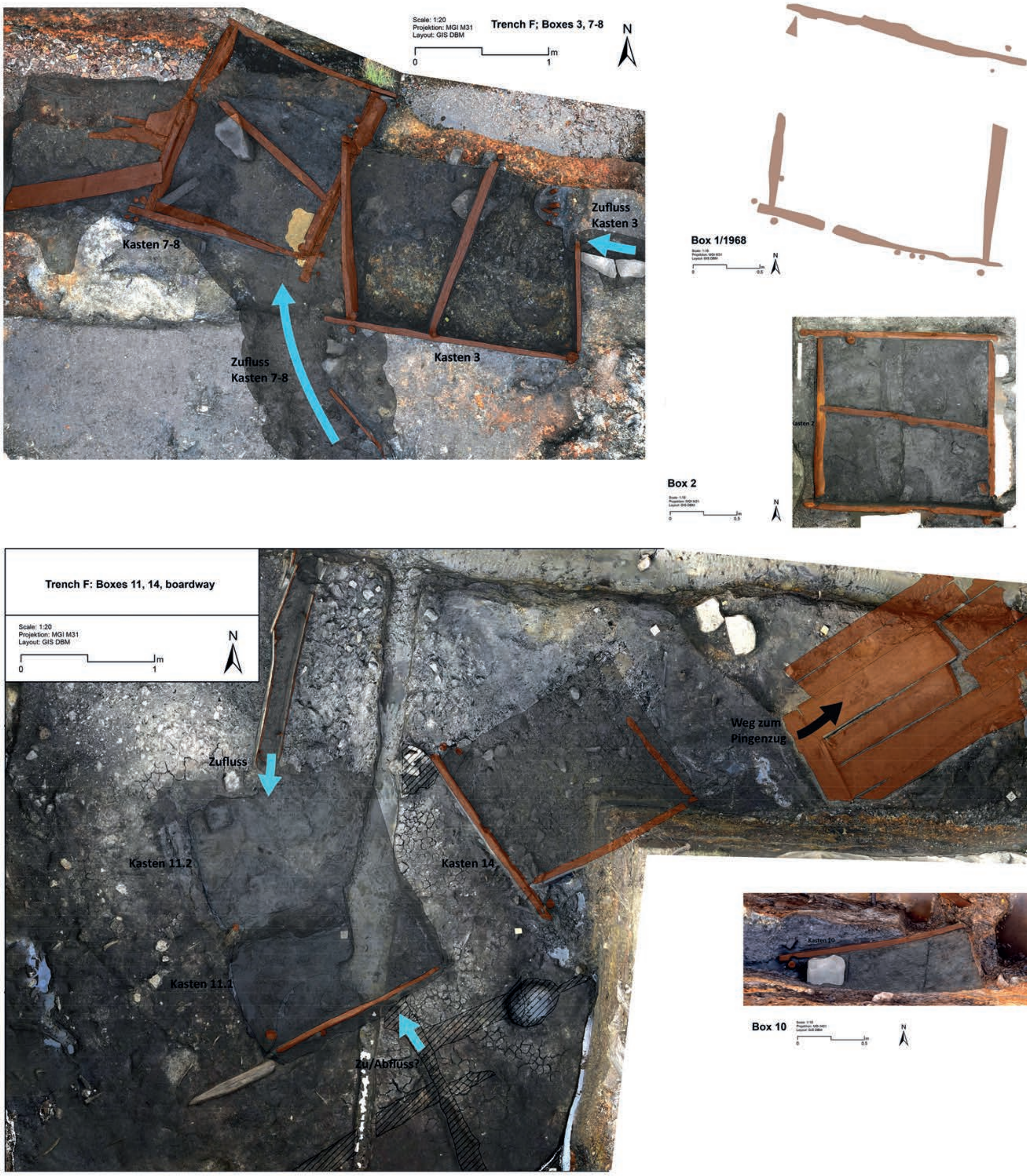

Fig. 9.1: Wet beneficiation boxes 1-3, 7-8, 10 from the eastern part of the Sulzbach-bog excavations (graphics/photo: DBM/RUB, J. Schröder).

that was discovered sidewards at the southern profile revealed a comparable stratigraphic position. West of box 14 another box (No. 11) was installed (Fig. 9.1). But different to box 14 this box was rebuilt several times and finally was used as a pool shaped wet beneficiation installation. As No. 11 was re-installed west of No. 14 we can interpret this rearrangement in relation to a levelled flour and a hearth that was built on top of box No. 14. The whole operation area was filled up by tailings over some time before a second operation level was installed decades later: A sequence of three boxes, No. 7-8 and 3, indicates that this area also was managed over some years (Fig. 9.1). The lowest box was rebuilt and repaired (box 7 and 8) while the re-arrangement of the area led to a complete reorganization of the water system. During the older phase water was drained into the box installation from the southeast. The youngest box got its water directly from the east and drained it to

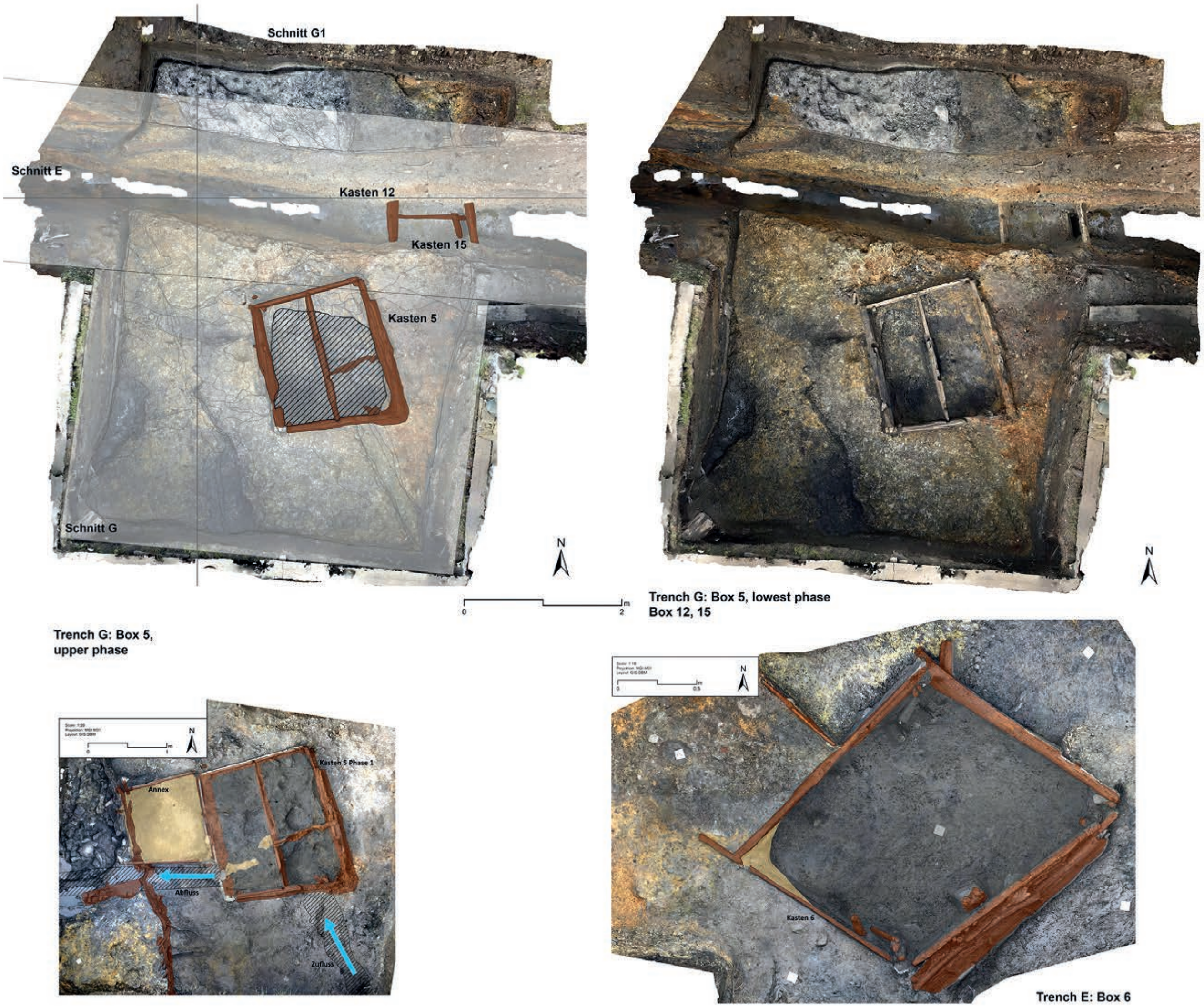

Fig. 9.2: Wet beneficiation boxes 5-6, 12, 15 from the western part of the Sulzbach-bog excavations (graphics/photos: DBM/RUB, J. Schröder).

the west. During its operation, ores and minerals were crushed and separated nearby at the summit of small dumps southwards (Fig. 11). After cessation of work, the area remained unchanged and got in-washed by sediments from its surrounding dumps that were piled up still during that period.

„Rösche 1928“, trench G

A similar sequence comparable to that in trench F was investigated at trench G; unfortunately, the excavation has not been finished yet. But what already has been found provides an insight into four operation periods between the early 14th and the 12th century BCE. Box 15, a wet beneficiation installation that was discovered on the top of the ground-laying turf, seemingly represents the oldest operation period. A second smaller box, No. 12, was found on top of an occupation and sedimentation layer over tailings that filled and levelled the older operation level (Fig. 9.2). This operation is not dated yet but it obviously represents one of the oldest installations of the second phase, of which box 5 possibly also belonged as one of the youngest. But, also this second operation phase was refilled with dumps on whose surface the third operation phase was arranged: This level has been investigated currently and consists basically of installations in relation to box 5 which also displayed at least two arrangement phases with changes of the water supply (Fig. 9.2). Beside washing and beneficiation activities box 5 provided also insight into the reuse of wooden planks, perhaps over some time, as well as reconstruction that led to the construction of a planked annex that was used as storage for washed mineral. This phase can be allotted to the latest phase of the second operation level, similar to the installations of chest 3, 7-8 at trench F.

Finally, we were also able to evidence a youngest phase that only consists of a water pool (feature 86142) north of the dumps that filled box 5 after its usage (Fig. 9.2). If this youngest operation can be connected with the period of activities before, or if those operations are part of the youngest work level at the site, is unclear yet and awaits further dating.

Fig. 10: Lowest operation layer with boxes 11, 14 and relating tailings on top of the ground laying peat bog (photo: DBM/RUB, J. Schröder).

Box 6 and Box 10 at trench E

This feature was investigated during the 2016 campaign when heavy rain and water flow flushed out parts of the wooden construction of box 6. According to stratigraphical observations chest 6 belongs to the same operation level as box 5 (Fig. 9.2). Both boxes seemingly also used the same water pool that stretches on several square meters between them. This box also was re-arranged in a second phase, but obviously more as a matter of repair than of reorganization. The sidelong planks have been doubled and elevated and a crotch was used to underpin the crossbeam. As the box had been pressed from west to east this repairing was necessary. If a cross-plank mounted outside the box in the west was used to construct a storage similar to box 5 remains unsure. The excavation has not reached the lowest level here, so it remains open, if older installations were forerunning box No. 6.

In general, there is now some evidence that installations for wet beneficiation were not scattered randomly over the area but concentrated at several areas. Therefore, it comes not as a surprise that even beneath box 1 (excavated by C. Eibner in 1968) another installation (box 10) was found (Fig. 9.1). According to its stratigraphic embedding box 10 should belong to the uppermost level of the 14th century/ Middle-Bronze Age activities and therefore would predate box 1 to the 2nd half or the end of the 14th century BCE.

The wet beneficiation and its features: an overview of 15 wooden tyes/sluice-boxes

Constructive elements and modifications

These aspects are important to discuss if there was a general principle in constructing the boxes in order to understand functional principles (Fig. 9.1-2/Table Fig. 12). From 15 boxes only 8 can be discussed in more detail as excavation and observation level are sufficient. Most of the boxes are made of planks, often split from larger trunks, sometimes also made of reused timber and half-split, smaller trees. The joints are made by notched mortices at two of the opposite planks near the outer rim. This principle was observed and described with the wood of box 2 (P. Thomas in: Stöllner et al., 2012a, pp.13-18). This principle is also known from other Middle to Bronze Age joints (e.g. the St. Moritz well revetment: Oberhänsli et al., 2017, pp.95-117; 150-154). This principle cannot be observed regularly (only at some planks of box 3 and 7/8, 9, 10), since most of the time planks simply were put together in a rectangular to quadrangle pit, in which case some planks have been lessened in width towards the outer rims (such as box 1, 5-6). In many cases cross beams are evidenced either by the beams themselves or

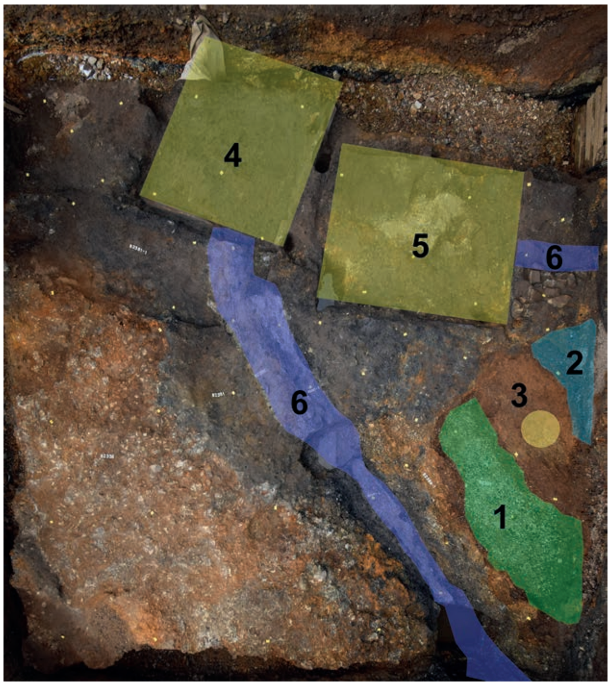

Fig. 11: Vertical photo plan with a crushing site in trench F south of boxes 3 and 7/8, east with coarser siderites (grade II) (1) and west with quartz mixed with siderites (grade III) (2) and the presumed location of a crusher when working and separating the grades (3); 4-5: boxes 3, 7/8, 6: water channels (photo/graphics; DBM/RUB, J. Schröder, Th. Stöllner).

by notches put in the middle of the planks (2-3, 5-6, 7-8, 12, 14). These notches have been morticed with chisels similar to the notches at the outer rims which often reached the centre of the plank (u-shaped: box 2, 3, 5, 6, 7, 8, 12, 14) from the upper rim while others are only mortices that were worked into the plank. This way of making is more seldom (box 2, 7). In some cases also wedges have been observed that held the crossbeams in a certain position (box 2: Stöllner et al., 2012a, Fig. 12; box 5). U-shaped notches and wedges evidence that crossbeams could be moved up and down, something that also became apparent when looking at the unfilled box 3 where the crossbeam was found in the lowest position, while normally the crossbeams are at the uppermost position since the box was filled with beneficiation sediments.

The question of the water regime inside the boxes is a more difficult problem to asses: It was not possible to gather enough information from all the boxes excavated, especially regarding the efflux. In some cases influx and efflux are evidenced by notches at the outer rims or inside the planks (2, 3, 5, 6, 7/8) and sometimes by channels (2, 3, 5, 7/8, 11) (Fig. 9.1-2). Even if the efflux is rather unclear (box 4, 6, 7/8, 14), there are probable locations according to the general layout of the box and its location with regard to surrounding features such as tailings. The common principle is to have a slightly diagonal crossbeam, over which water was drained to the efflux slightly diagonally as well. It seems that the basic principle was to drain the water out not directly from the box. There is one exception where the water was managed in a different way. Box 5 shows an influx from southeast or from southwest; the efflux has changed from northwest to southwest and obviously the influx was changed in the later operation phases. A second row of smaller crossbeams that were put on the main crossbeam obviously allowed a more flexible usage of the box (Fig. 9.2).

Many of the boxes also provided evidence for reconstructing a second phase (box 2, 5, 6, 7/8, 11), and in one case this reconstruction had to do with a repair due to heavy flooding.

Artefacts

None of the artefacts found in the boxes or in their surroundings have been found in "in situ" position, which prevents a clear functional linkage to the beneficiation processes in the boxes. The best examples are crushing mallets with dimples on the surfaces as well as dimpled anvils. Both types can be linked with crushing work that possibly was carried out nearby as features south of box 3 indicates where a crushing place was discovered. Artefacts of this kind have been discovered in or near boxes 2 (e.g. Stöllner et al., 2012a, p.22 Fig. 14) (Fig. 13), 5, 7 and 10. An interesting case are textile fragments that are often evidenced nearby the boxes, in many cases in or nearby the in- and efflux channels (1-3, 5, 7/8). One possible interpretation relates their usage with the water regulation and the necessary plugging up of their leakages[3]. Another group of tools also were possibly related to the work processes around the boxes: so-called wooden knives (Fig. 14.2-3.7184), a category of tools known best from the Kelchalm (Klaunzer, 2008; Koch Waldner, 2016) and from the Schwarzenberg bog near Brixlegg (Goldenberg, 2015, pp.156-157 Fig. 8). Since their cutting edges are rather blunt they might have been used to separate different mineral fractions during the wet separation processes inside the boxes. Experiments made in 2012 (see article Timberlake this volume) showed that these tools fit well to such a work. A spatula shaped "knife" 10375 (Fig. 14) was discovered plunged between the eastern plank and the pit thus indicating the usage during the operation of box 6. If tools that are shaped similar to scrapes with a clearly marked shoulder at the blade are used in a similar way is uncertain. Some of them might have been simply used to clean working faces, channels and drains.

Some observations about the filling and the surrounding of the boxes

Another aspect that could be used to understand beneficiation processes in and in the surroundings of the boxes are the filling of the boxes and the surroundings of the installations. Apart from the channels there are special

	water in- and efflux/ draining channels	cross-beam, move-able	recon-struction 2nd phase	fabrics found nearby	wooden spatula/ "knives"
1					
2					
3					
4					
5					
6					
7-8					
9					
10					
11					
12					
13					
14					
15					

Fig. 12: Characteristics of operation and construction as observed or not observed with boxes 1-15, dark grey: evidenced, light grey: unknown, red: not evidenced (graphics: DBM/RUB, Th. Stöllner).

features that are undoubtedly related to the processes inside the box.

- Planks that indicate the level of operation from outside have been discovered with box 7 and box 6 (Fig. 9.1, Fig. 15.4)
- Box 14 had been accessed directly by a boardwalk that proves the supply of chatty ores from the north-east (Fig. 9.1, Fig. 10), presumably from the Eastern branch of the Main Lode mine. Such ore was found in a pit situated half a meter southwards. The ores found there were rather large pieces of chatty ore intermingled with quartz. Perhaps these pieces were selected before being further crushed. This is the only storage pit that we know so far. Another storage had been found west of box 5 as part of its youngest operation level. The storage annex was built up of small planks and even the rather homogenous quartz rich sand was stored only in a quantity of about 0.3 to 0.4 cubic meters of sand.
- Most of the time gullies and drainage ditches were made without any revetment. But, there are exceptions: There is a wood-planked channel that likely drained box 11 in a higher operation level (feature 82454) (Fig. 15.5-6). At box 4, the influx channel had been framed with larger stones, while channels near box 7/8 and 5 had been framed locally by a plank/pole revetment.
- Nearly all the boxes had been constructed between tailings and during younger phases also above older dumps that had been levelled for that construction. Sometimes the boxes were refilled by beneficiation debris later, which prevents the understanding of their contemporary surrounding.

Despite such aspects, there is valuable information about the washing processes made by the excavation inside the boxes: Such information could be harvested from boxes 2, 5, 6, 7/8 and 11, while boxes 3 and 14 had been emptied and in the later cases refilled with debris. Some observations can be reported:

- Inside the boxes corner parts often showed accumulation of coarser mineral sands while pools and uneven finer silty sediments occurred rather at the central areas.
- Dark reduced or orange, corroded mineral sands often were fanned out at influxes (box 5, 6, 7/8) (Fig. 15.3). At box 6 such a fan-shaped sedimentation was correlated with fine, silty sediment at the opposite part of the box (Fig. 15.4).
- While fine grey washing silt never contained high mineral content this is opposite with middle fine to coarse mineral sand that sometimes contained even organic components (charcoal, organic wood); they alternate often with the layer-type mentioned above. This would set the development of those layers in an operational relationship. It can be assumed that the fine silty sedimentation was part of the coarser components that were separated manually (Fig. 15.1-15.2).
- In one example, such coarser sands were discovered at a pond alongside the crossbeam. While such an observation could not be repeated more than one time, it may be an undeliberate effect. However, till now the usage of the crossbeams is unclear insofar as accumulations were banked up on both sides of them. This would indicate a special usage either in ponding or directing the water as well as the water level.

Mineral compound and first micro-morphological observations

At the Troiboden one is able to distinguish coarser and finer sands and gravels with specific dominating components already by the naked eye. During all the research years, a systematic sampling and description program has macroscopically classified the sediments of the embankments during the excavations. Mineral components (e.g. quartz, iron-carbonates, ores) and their grain-size (1 mm to more than 1 cm) have been classified and counted in a semi-quantitative way. Although this strategy only provides a general insight to the layers, it allows a general access to the classification of coarser work processes such as crushing and hand-separation. Until now, more than 1000 layers have been investigated this way, but the systematic evaluation is still in progress. Since the coarse sieving program does not regard the silty and clay components, this investigation only will provide insight in layers in which gravel portions that are generally larger than the fine materials (GM-FM relation) (see for that Rashidian, 2016; Fig. 16). A first systematic and

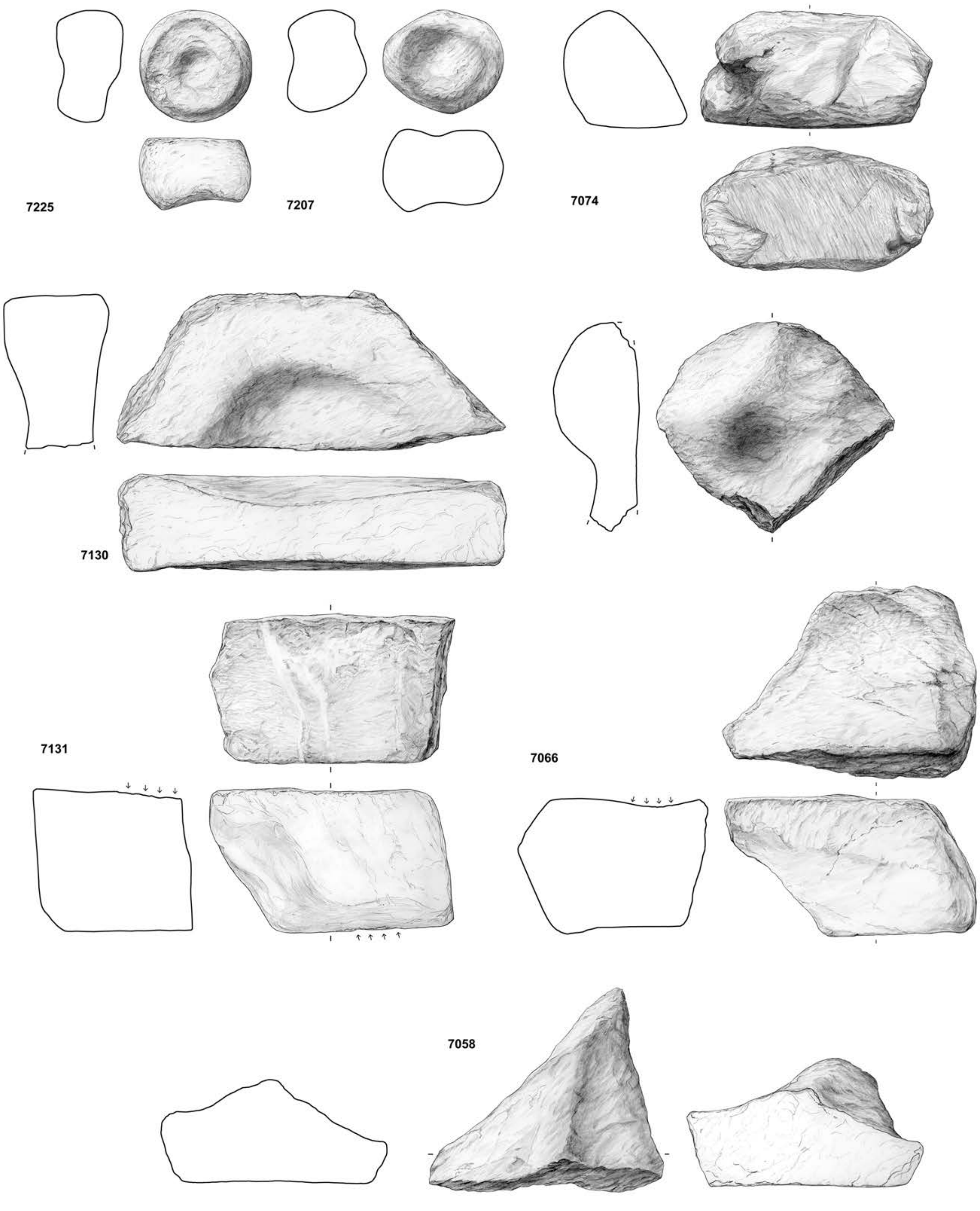

Fig. 13: Crushing and grinding stones found in or nearby box 2 in 2009, after Stöllner et al., 2012a, Fig. 14 (drawing: DBM/RUB, A. Kuczminski).

rather detailed investigation of all the layer components was made by E. Rashidian on the basis of five Kubiena boxes that contained 29 layers altogether. On the basis of this investigation Rashidian was able to establish five debris types ranging from very coarse to very fine (type I-V) (Rashidian, 2016, pp.15-17)[4]. This investigation made clear that all the sediments investigated were not accumulated naturally but had an anthropogenic origin. This provides an argument to interpret each of them as debris resulting from a deliberate process. But still, the

Fig. 14: Wooden tools from the Sulzbach-bog excavation, 1-3 after Eibner, 1972, p.7, Fig; 6516, 6676, 7184, 10375 after Stöllner et al., 2012a, p.23 Fig. 15 and unpublished (photos/drawings: RUB, A. Kuczminski, E. Neuber).

processes are rather difficult to understand in detail as the frequency of these patterns as well as steadiness of single attributes are not studied and compared sufficiently yet. Experimental and archaeological contextualization are further prerequisites that will be necessary for this heuristic process, especially when regarding the mostly not understood working processes in relation to the wet beneficiation.

As it regards the mineral components, the dominating rocks are basically sericite schists and sericite quartzite, quartz as well as dolomites as host rocks of the deposit. Portions of chatty ores consist frequently of carbonated ankerites, but only seldom of pyrites (FeS_2) and chalcopyrites ($CuFeS_2$). The recent investigations of Rashidian (2016, p.13) proved the rather low copper-content in all the 29 layers sampled which coincides with older investigations made by Stöllner et al. (2012a, pp.23-25). This indicates a very efficient separation from gangue and host rock. According to the new investigations of Rashidian the copper content does not exceed an average of 0.5%. The generally older estimations made by Zschocke & Preuschen (1932, pp.43-44) have to be corrected even to larger degree than estimated by Stöllner et al. (e.g. Stöllner et al., 2011, p.122). If we count with 1.16 ha of the beneficiation area that was dumped to an average height of 4 m (46400 m3) this would result in 13122 tons of debris, given a factor of 3.536 average of specific weight of all the basic mineral compounds[5]. The copper-loss of the chatty ores (approximately 1/3 of all the ores exploited) would result in 65 t, which is much lower than previously thought.

However, the processes themselves, especially those in the washing boxes, are more difficult to assess. The investigation of Stöllner et al. (2012a, pp.23-26) and of Rashidian (2016, pp.6-7, profile sections 7289-7290 and 7293-7295) showed undoubtedly that some of the debris layers even could exceed the above mentioned low copper contents. But, as Rashidian's investigation also evidenced, there is no systematic elevation inside the boxes in relation to beneficiation debris outside (e.g. sections 7289 to the others). Only at box 2 more elevated copper contents could be found reaching up to more than 5% copper (layer 82143 in box 2). There is also an interesting elevation with two silty-organic layers at box 4 (section 7289) where layer 82279-2 which probably was a washing residue near the wooden log of the box (there was presumably rather a small pond inside the box). This sediment exceeds considerably the copper amount of a washing silt found beneath everywhere in the pond. This brings to mind the influx accumulations of washing residues at boxes 5 and 6. On the other hand, pyrites and chalcopyrite have also been observed as finely dispersed portions in fine silty materials in box 2. Such greyish silty layers might have been accumulated during rather lentic water levels (D. Fritzsch, H. Thiemeyer in Stöllner et al., 2012a, pp.25-26). Given this fact one should not consider such chalcopyrite/pyrite accumulations as deliberate, rather as sediment residues of washing and concentrating processes of any possible kind.

In consideration of concentration processes there are other micromorphologic observations made in box 2. There, the residues have been stirred up and moved, either by the water stream or manually (Fig. 17.2). And it seems that the coarser sands have been sorted according to their specific weight (Fig. 17.1). It is likely that from such sandy and coarse-sandy accumulations the richer, ore containing parts have been already removed by manual collection. This makes it complicated to assess what originally was achieved by these processes.

Fig. 15: Features from beneficiation boxes (1-4) and revetments (5-6); 1: box 8, feature 82397-12, 2: box 8, feature 82396-0, 3: box 5, feature 86130, 4: box 6, feature 82878-880; 5: channel box 5, feature 86105; 6: channel box 7/8, feature: 822345 (photos: DBM/RUB, J. Schröder).

Results and interpretation: some ideas on the reconstruction of work processes

Ore and material transport

It can be considered a most probable fact that a large part of the rich ores ("Derberz"), basically the dominant chalcopyrite from massive veins, had been sorted in the mine and been transported directly to storages and smelting plants. According to the estimate of Zschocke & Preuschen (1932) a third of all the ore-body consisted of chatty ores and had been brought to the more time-consuming wet beneficiation. According to Bernhard (1965) the first mineralization stage was dominated by nickel-rich pyrite (FeS_2), the second by chalcopyrite ($CuFeS_2$), and the third by cobalt-rich copper ores, mainly in the eastern extensions from the Main Lode. Accessory minerals include Gersdorffite (NiAsS), Millerite (NiS), arsenopyrite (FeAsS), and fahlore, mainly of the tetrahedrite ($Cu_{12}Sb_4S_{13}$) type, which can also be arsenic, because tetrahedrite forms a solid solution with its arsenic-bearing tennantite ($Cu_{12}As_4S_{13}$). The gangue material mainly consists of quartz (SiO_2), dolomite ($CaMg(CO_3)_2$), siderite ($FeCO_3$), and ankerite ($Ca(Fe,Mg,Mn,)(CO_3)_2$). Regarding these mineral components it is clear that only gangue rich materials were

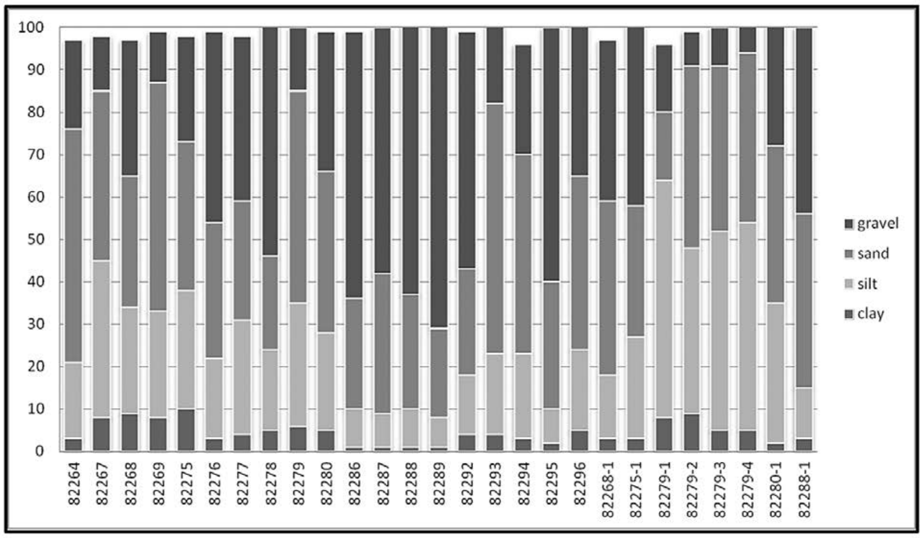

Fig. 16: Layers and their grade according to their weight of the sampled material; due to losses not always corrected to 100%, after Rashidian, 2016 (report).

worked at the Sulzbach-Moos bog site where especially the accessory minerals can be found.

It certainly has to be asked if the large Sulzbach-Moos site played a central role for all the western mining parts of the Main Lode and its side veins, or if it was only related to the Eastern part of the Main Lode mining, as the localization may indicate. Even if the site seems large it is rather small if one calculates the amount of chatty ore once brought up to the ground. According to the older calculations roughly only 5 to 10% of all the chatty ores would be present at the site. This would indicate other larger wet beneficiation sites elsewhere (see Fig. 7), most likely at the western slopes and on both banks of the Mühlbach stream[6]. It is therefore likely that the Sulzbach-Moos bog site was basically operated in relation to the mining of the Eastern part of the Main Lode mine. A boardwalk from BCE 1379-77 discovered in 2014/2015 even allows the reconstruction of the ore delivery via transport tracks from this mine to the site (Fig. 5, 9.1). The boardwalk came from the northeast and ended once at the wooden box 14. Such a boardwalk does indicate that certain areas of beneficiation had been selected in the swampy area at the beginning of the work in order to ensure an easy and regular supply of ore to the wet beneficiation. Further trackways that once might have connected the mining entrances with different areas on the site are therefore most likely. How the ore was carried is not known as we are lacking any indication of hauling vessels that could have been used to transport larger portions of selected chatty ores.

Crushing and grinding

Typical tools such as stone hammers and mallets, dimple stones, rubbers with fixation notches (Type Mitterberg) and grinding plates are the best evidence of this step of work. While grinding plates are found rather seldom and even dimpled anvils were found only in a fragmented stage there is a larger number of mallets and mallet-anvils (Fig. 13) as well as typical rubbers. It is likely that the anvil and grinding plates were more often reused and relocated during the work. According to a crushing place found in situ in the eastern part south of box 3 the work was carried out often on top of the basically dry dumps (Fig. 11). There, it could also be observed that the crusher was working most likely in the centre of two dumps, near which a coarser gravel of siderites and a finer coarse sand of hematite and quartz was separated. It is therefore likely that the grading fractions from gravel to coarser sands are basically the result of crushing work (Typ II-III, after Rashidian, 2016) while coarser rubble that often is mixed with limonitic degraded clay can be allocated to rubble separated from the ores when they were carried to the beneficiation plant.

The segregation of minerals by wet and dry working processes

There is no distinct correlation between the mechanical treatment and distinct minerals. This makes a clear identification and assignment of sediments to working processes so difficult. It rather seems that debris of type II to IV (even fine sand) correlates with all the accessory minerals like quartz, muscovite, microcline, clinochlore, hematite, magnetite and lepidocrocite that were segregated as debris (Fig 16, after Rashidian, 2016) (Tab. 2). Differences can only be seen within the mineral compounds of group 2 (very reduced content of iron oxides) and of group 5 (finer grading with calcite levels). This indicates that the basic separation from “copper containing minerals” did lead to a reduction in most of the accessory minerals by crushing and subsequent washing. If we look to the mineral groups 2 and 4 we could see opposite component structures at a similar grading size between II and IV. While iron oxide minerals are lacking in group 2 (which makes them lighter), they seem more frequent in group 4. Group 4 is therefore

Group	Mineral composition	Average mineral density (gm/cc)[7]	Features (grading type)
1	quartz, muscovite, microcline, clinochlore, hematite, lepidocrocite	19,65	82279 (other), 82280-1 (III), 82268 (III), 82286 (II), 82287 (II)
2	quartz, muscovite, microcline, clinochlore (little or no iron oxides)	10,69	82276 (III), 82264 (IV), 82279-2 (other), 82275 (other), 82275-1 (III), 82267 (IV).
3	quartz, muscovite, hematite, magnetite	15,68	82293 (IV), 82269 (IV), 82288 (II), 82268-1 (III), 82289 (II), 82296 (IV)
4	quartz, muscovite, microcline, clinochlore, hematite, lepidocrocite, magnetite	24,84	82292 (II), 82288-1 (II), 82294 (IV), 82295 (III), 82280 (III)
5a/5b	quartz, muscovite, microcline, clinochlore, hematite, calcite (5a: low calcite levels; 5b: higher calcite levels)	19,7	5a: 82277 (V), 82279-2 (other). 5b: 82279-1 (V), 82279-3 (other)

Tab. 2: Mineral composition of samples according to the Kubiena-sampling and its layers and the determination of the grading type after Rashidian (2016). Investigations by the laboratory of the DBM (D. Kirchner).

specifically heavier. Both groups represent therefore two sides of the coin, means the heavier and lighter parts of a beneficiation process during which iron minerals were reduced. Copper minerals with specific weights of about 4.1 were removed.

However we interpret the mineral composition at the moment, it is clear that further detailed investigation is necessary to develop a finer scheme of mineral content and of mineral portions at various layers and grading types. If we consider the different specific weights of minerals and their composition to generally comparable gradings, it is likely that most of the separations were done by wet mechanical separation (Fig. 21). This is apparent when regarding the fact that the lighter silicates and feldspars can be visually distinguished from the basically heavier brownish iron oxides. Both have been segregated from the chalcopyrites and pyrites during these working steps.

Washing procedures

The question still to be tackled is to understand the different working operations carried out in and around the washing boxes. Technical aspects like the water drainage system prove that the ore dressing specialists used water inside the boxes, most likely to wash and separate minerals at the influx stream. Crossbeams were kept adjustable or were converted to new and mostly higher positions, likely because beneficiation debris, mostly finer sand and silt (grading types IV and V) filled in the boxes constantly. Spatulas possibly were used to clean the boxes from time to time, especially in their upper working section (Fig. 14. 6672, 6516, 10375). If the cross-beams were rather used to step on them or put planks above them to work inside the boxes or if they had also another function to direct or even pond water streams inside the boxes, is unsure. Since the water was directed through the boxes in a slightly diagonal way – given the position of in – and effluxes - it is possible that this had the effect of a swirling of sands and finer gravel. This could indicate especially the swirling and concentrating of the finer grading IV by help of flat ponds (Fig. 15.1). Besides the boxes, ponds often displayed the latest stage of a washing installation such those that have been found on top of box 5, 7 or 11. If slightly depressed ponds have been observed (even inside the boxes) then laminar accumulations of fine gravel can also be observed (Fig. 15.2). It is likely that these accumulations are the debris of a separation on top of which a perhaps lighter product (such as calcite and silicates, group 5) was manually removed, while iron and other ore components stayed before they were further treated (Fig. 15.2). According to experiments, it is likely that an ideal separation of a chalcopyrite/pyrite concentrate was a grading of coarse sand around 1 and 2 mm (see Timberlake this volume). If a finer sand was milled and worked is uncertain. All the finer sediments seem rather accumulated as a result of washing coarser material but not an indication of a flotation (in general for the 19th cent.: Rittinger, 1867). Although experiments had proven the fact that small chalcopyrite flakes would swim on the water due to the surface tension, a possibility to easily concentrate and use such flakes is still unknown. Principally such a technique would require a separation between the heavier iron oxides (hematite, pyrite, magnetite, 5-5.2 gm/cc) and chalcopyrite (4.2 gm/cc). This can only be done by a flotation process that would lead to concentration of chalcopyrite in relation to other iron-sulfides and iron-oxides[8]. If existing, such a flotation would not have been carried out in the boxes so far excavated. If the stone dam that was excavated in Eibner's trench A3 had such a function is likewise unsure: The description (Eibner, 1972, p.8) shows that water that carried finer sediments including pyrites was drained through a pipe and led to the accumulation of grey to blue sediments north of the dam. But it simply could be also a dam that pooled water for the washing procedures carried out in the northeast at box 2.

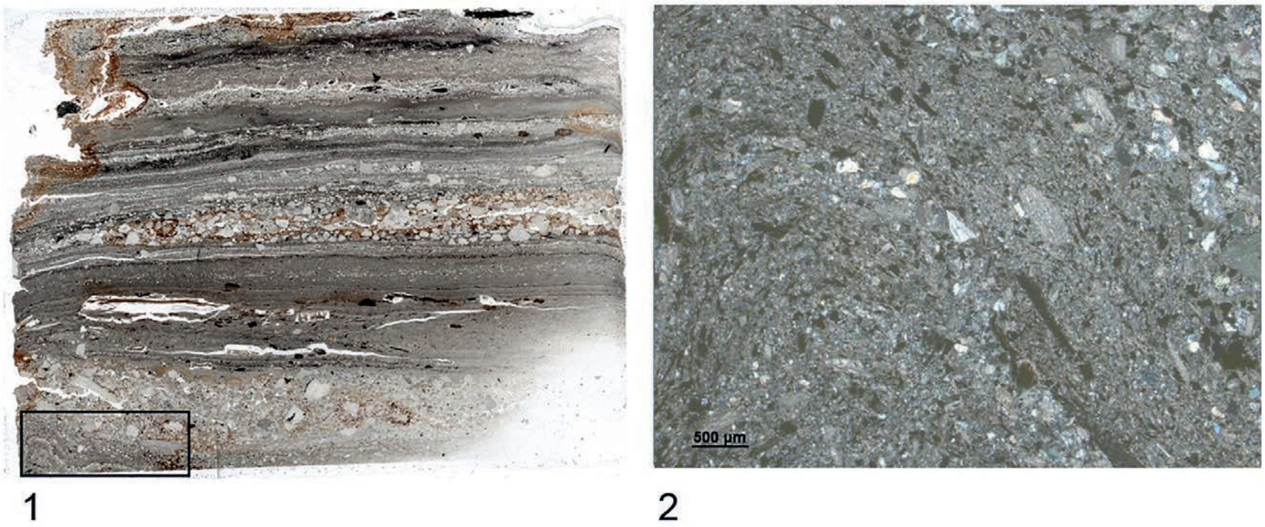

Fig. 17: Micromorphology of sediments of box 2, after D. Fritzsch and H. Thiemeyer in: Stöllner et al., 2012a, pp.25-26 Fig. 18 and report, 1: overview of the upper part, 2: Layer 16, with swirled sediments.

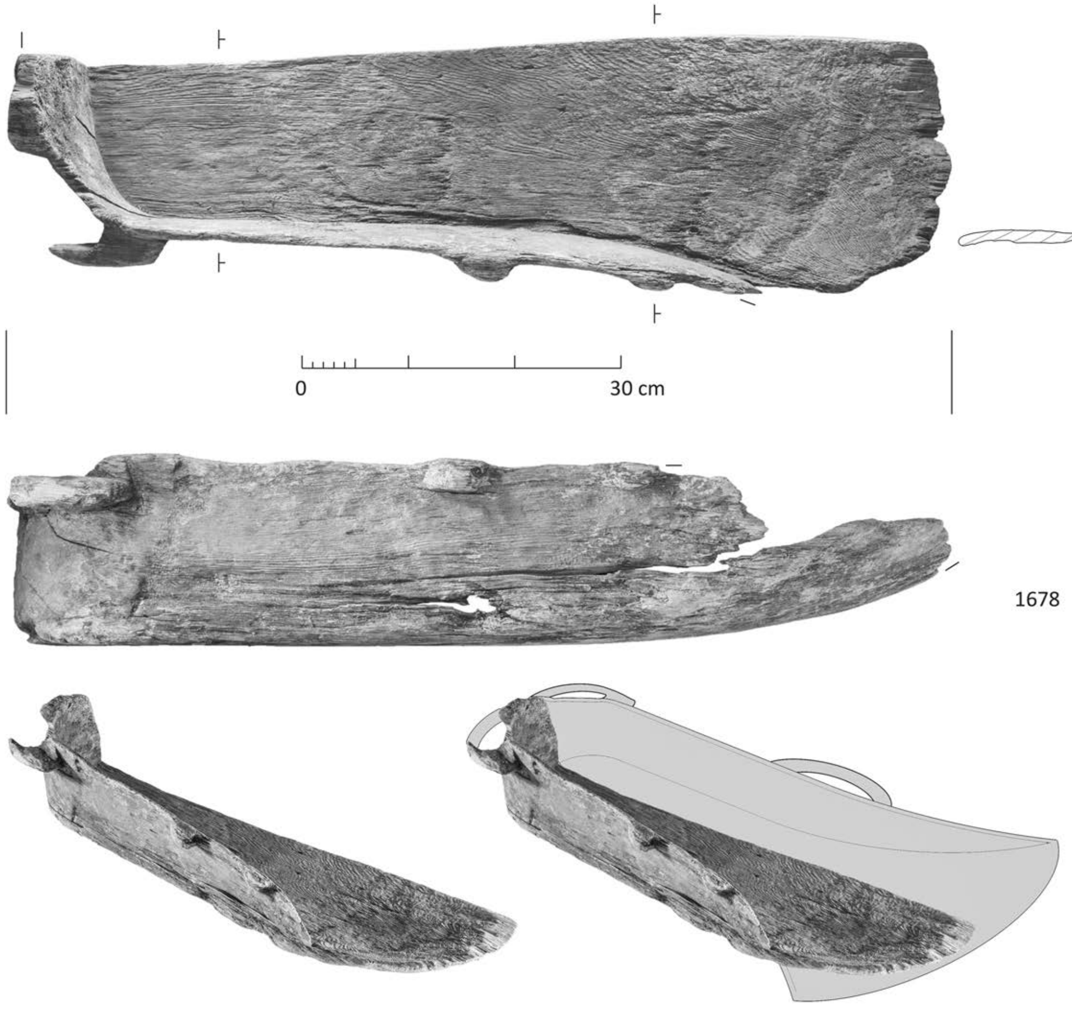

Fig. 18: Trough 1678 found in the open western mine cavern of 1867 after Thomas, 2018, p.357-358 Fig. 329-330.

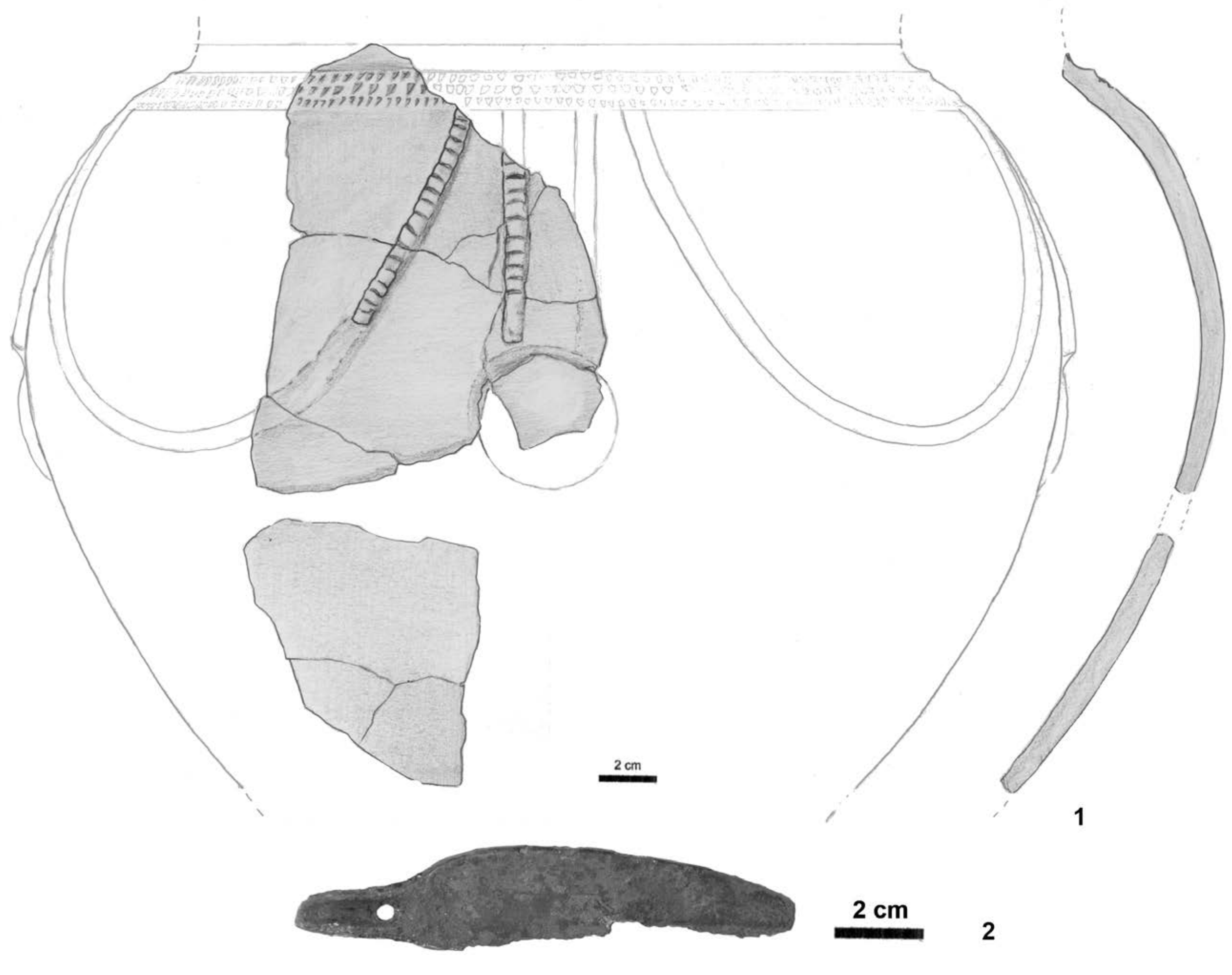

Fig 19: Troiboden, Sulzbach-bog, excavation 2013, large container with distinct decoration found nearby a hearth (1), Riegsee-knife (2), found nearby the boxes 3, 7-8 (drawing/photo: RUB, H.J. Lauffer).

A word should be added to the question of the usage of troughs to concentrate the sand grading and separate it from lighter fractions. According to other panning experiments (e.g. Modl, 2015; Timberlake this volume) it is clear that a trough can be used easily for such a purpose. At the Mitterberg there is one trough that would be a candidate for this. The piece was found in 1867 at the so-called open mine ("Offener Verhau") of the Bronze Age mines of the Mitterberg Main Lode. Despite several other troughs it is the only piece that was undoubtedly used for concentrating ores particularly because its form resembles later gold concentrating troughs from Romania ("Verespatak troughs: Eibner, 1979; Thomas, 2018, pp.357-359; Salzburg Museum Inv. No 1678) (Fig. 18). According to the lack of findings at beneficiation sites is may be doubted that such tools were originally used above the ground to a great deal. If our reconstruction applies to the ancient reality and working practice then we have to conclude that ore separation was done more effectively with help of the boxes than on a small scale with such troughs. These practices would more or less lead to the same result: While in troughs the water was swirled by moving the trough, it seems that in the boxes the water was "buddled" by spatulas and sticks. Perhaps the trough had its use for smaller quantities, for instance underground to test the mineral components of the ore body exploited. The ore body of the Mitterberg is more variegated as one would expect from a mono-mineral ore-body (Bernhard, 1965)[9]. But honestly at the moment we cannot exclude the possible usage of such troughs also at sites like the Sulzbach-Moos bog.

Work organization and social aspects

There is no doubt that complex work organization such as beneficiation work requires a larger working gang combining persons of different experience levels. This became already clear when analyzing the wooden construction work of box 2, which displayed the cooperation of an experienced carpenter with a rather unexperienced

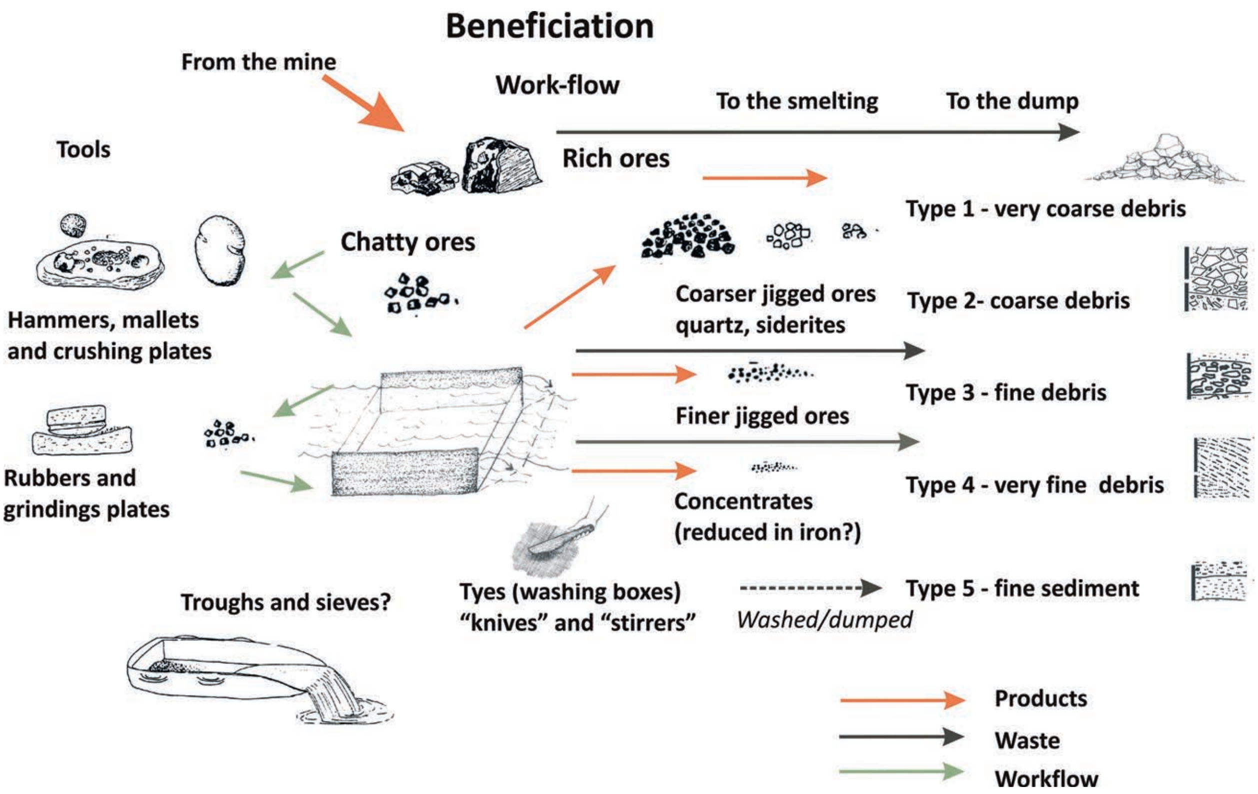

Fig. 20: Reconstruction of the beneficiation processes at the Mitterberg Main Lode area on basis of the features of the Sulzbach-Bog beneficiation site, graphics on the basis of Eibner 1979 and Rashidian 2016 (graphics: DBM/RUB, Th. Stöllner).

person (perhaps an apprentice: see P. Thomas in Stöllner et al., 2012a, pp.15-16). Also the experiments showed that working the boxes presumably needed only two persons, of which one was working in the box while the other was controlling the water flow (see Timberlake this volume). On the other hand, there might have been more persons involved in transport and dry separation work by crushing, separating and grinding. If our picture is correct this working operation also would have included carriers who brought material to the site, perhaps even special loads on which a decision had already been made about their workability and benefit. This would have required communication with working gangs more distant from the beneficiation sites at the entrances or even inside the mine.

Four carved yew wood sticks found at the Troiboden beneficiation site may be a hint to such communication systems. These sticks resemble similar notched sticks from the Kelchalm excavation in the 1930s (Fig. 11). Such notched wooden sticks might even go beyond an immediate practical use and indicate similarities in a rather abstract organizational principle (Pittioni & Preuschen, 1947, p.87, Taf. 15-16; also Wedell, 2011, pp.194-196). But despite their rather speculative interpretation as either a code system or as numbering sticks for accountancy, they are considered as evidence of a complex work organization. Besides work organization there are also indications of social life: Cooking and eating as a form of communal practice certainly was an important integrative practice. A cooking hearth was already discovered during the earlier excavation (Eibner, 1972, pp.9-11). Another one was discovered in 2015: A massive cushion stock was made of phyllite slabs that prevented moisture to the fire-place on top. The dispersal of ceramic and fine crushed calcined animal bones in the surrounding area indicate a likelihood of food preparation activities on site (e.g. by cooking stews with small sliced meat portions). Another finding that made this cooking hearth outstanding was the discovery of an even nicely decorated ceramic vessel in the surrounding area (even the above mentioned sticks were found in the surrounding area) (Fig. 19.1): The decoration of the vessel displayed notched decoration known from Inner-alpine household ceramics and a chip carving decoration in triangles as typical for the for-alpine vessels (e.g. the Riegsee-area: Koschick, 1981) of BZ C and D. This cultural connection is stressed also by the finding of a Riegsee-knife near an early 13th century BCE beneficiation installation of box 3, 7-8 (Fig. 19.2). The combination is conspicuous and might reflect a deliberate combination of styles. However, the vessel was not a typical cooking pot and household ware but might have been used for special commensal occasions. Commensality of this kind – even on a small scale - might have helped to withstand the difficulties during the daily-work processes.

Fig. 21: Reconstruction of the Middle to Late Bronze Age beneficiation work at the Sulzbachmoos (Troiboden) (drawing: DBM, Flemming Bau, Moesgård).

Conclusions and Summary

The second step of production, the ore-dressing, was always a matter of debate but never exhaustively studied in the Mitterberg area. First and famous investigations at the Troiboden not only revealed insights (concluding Eibner, 1979), but left many questions open, especially in respect to the product that has been taken from the ore beneficiation. Main goals initially were to date and to differentiate the ore-dressing residues according to the old results of E. Preuschen and C. Eibner (e.g. Eibner, 1979). During the recent research, especially the ore-beneficiation site at the Troiboden produced a splendid excavation result based on the waterlogged preservation of the sediments there. This provided an excellent insight into the beneficiation areas, including wet and dry beneficiation areas: Up to now about 15 wooden chests (sluice boxes), once used as puddles to concentrate the ore, have been discovered and partly excavated.

Despite such fascinating insights, much has to be resolved still. What was the way of processing the ores and the gangue exactly and how were the boxes used to separate and to concentrate in reality?

What can be concluded especially when looking to Agricolas book VIII is that the boxes can be characterized as a sort of “buddle” (German: Planherde), by which several washing and concentration processes were enabled. These buddles were in the centre of the beneficiation processes that were carried out after a first initial process of dry separation (grade I) by a constant workflow between washing, concentrating and crushing (grade II-II) and milling (grade IV) (Fig. 20-21). Even wet crushing would be an interesting alternative as many such tools have been discovered within and in the surroundings of the puddles. This is different from what Eibner (1979, pp.159-161) has assumed who set the wet beneficiation at the end of the châine opératoire. The biggest problem still is if other concentration processes like jigging or working with troughs were additionally practiced. There is no evidence yet basically, because most of the work that was possible in buddles (also according to Agricola) also would have been possible in our boxes (as it is also mentioned by Agricola as the older method before jigging sieves were invented).

Another problem are fine ore concentrates, because such products have never been found. Even the concentrate (10.2 % Cu, 0.12 % Ni, discussed by Eibner 1974, pp. 21-22) – although it does resemble the grading quality of a floated ore concentrate – may not have been produced deliberately. Although fine ore concentrates with copper contents up to possibly 35% copper (means rich chalcopyrite concentrates) can be assumed, such a concentrate never had been found. This makes it difficult to balance all our arguments. One even has to ask whether other by-products also were produced, being necessary for the smelting and the slagging process. Besides a separation of iron oxides and chalcopyrites (which perhaps was done by help of the washing boxes), other minerals might have been processed to be used as flux for the smelting process.

In the end, one could presume that a standardized beneficiation product should go to the smelting sites, perhaps on specific request, because the direct ore quality might have been different or the slagging process at the smelting site required a standardized charge. What is therefore needed is a more detailed analysing of the mineralogical features, as we still need more experiments to understand the work practice. To approach these questions is certainly difficult when only working with the residues and not with the beneficiation product itself. Therefore, it is also certainly necessary to know more about the products that once reached the smelting plants. Such sites have also to be studied carefully in respect of their ore and mineral debris.

Notes

1 But I want to emphasize that many of the techniques, commonly called the Mitterberg process, did not occur from the nowhere. There have been forerunners such as deep mining that we know earlier from the Western Alps at Saint Véran (Rostan & Rossi, 2002) or the question of shaft-furnace smelting, where we can find hearth-shaped installations in late 3rd millennium contexts of the Etsch-Valley (recently: Angelini et al. 2013).

2 Archaeology/stratigraphy/survey/data structure: A. Hornschuch, J. Schröder, M.A., B. Sikorski, M.A., Prof. Dr. Th. Stöllner (DBM, Ruhr-University), Artefact studies: B. Horst, B.A., E. Neuber, B.A. (Ruhr-University), Dr. K. Grömer (textiles, NHM Vienna), sedimentology/mineralogy/chemistry (Dipl.Min. D. Kirchner, Prof. Dr. M. Prange, A. Blömeke, B.A., DBM/Ruhr University), Archaeobotany (Dr. N. Boenke, Ruhr University), Palynology (Prof. Dr. K. Oeggl, Dr. E. Breitenlechner, Univ. Innsbruck), Dendrochronology (Prof. Dr. K. Nicolussi, Dr. Th. Pichler, Univ. Innsbruck), Micromorphology (Dr. D. Fritzsch, Univ. Frankfurt), Experimental Archaeology (Dr. S. Timberlake, Univ. Cambridge). Thanks go to all collaborators of the research during all those years, especially the students of the Ruhr-University who took part at the excavations. I gratefully remember team members like Robert Pils, Bischofshofen, Katherina Arnold, M.A:, Judith Smuda, M.A., Dipl. Geogr. Klaus Röttger (†), Anton Gontscharov, M.A., Linnéa Naumann, M.A., Hans-Jörg Lauffer, Nicolas Schimerl, B.A., Dr. Andrea Turner, Dr. Peter Thomas, M.A., Prof. Dr. K. Hanke, Dr. Kristof Kovacs, and Dipl.Ing. Gero Steffens. Finally, I would like to express my gratefulness in direction of the Radacher family, especially the landowners Christl and Peter Radacher, but also to Peter Radacher senior, and Heidi Radacher who always had enormous interest and gave support to our project. We are also grateful to the FWF within the HiMAT project and the DFG within the D-A-CH project for enabling the research by their financial contribution. I thank R. Campbell, Los Angeles, for editing the manuscript, and many thanks go to Dr. Peter Thomas, Bochum, and Dr. Simon Timberlake for discussion.

3 Moss and clay also might have been used for this work; moss has not been observed in such a clear relation to allow a clear archaeological prove.

4 Thanks to E. Rashidian, M.A., University of Frankfurt, and her dedication to that work. The sampling did intend to cover a large variation of different layer types, thus should provide a good first overview about possible layer types at the Troiboden in general.

5 Microcline 2.56 gm/cc; calcite 2.71 gm/cc; quartz 2.72 gm/cc; muscovite 2.76 gm/cc; ankerite 3.05 gm/cc; epidote 3.4 gm/cc; siderite 3.96 gm/cc; chalcopyrite 4.2 gm/cc; pyrite 5 gm/cc; hematite 5 gm/cc: Average: 3,536 gm/cc.

6 As smaller beneficiation sites are still preserved, it is likely that they had consisted once of larger tailings that are nowadays eroded at least in parts.

7 Microcline 2.56 gm/cc, clinochlore 2.65 gm/cc, calcite 2.71 gm/cc, quartz 2.72 gm/cc, muscovite 2.76 gm/cc, ankerite 3.05 gm/cc, siderite 3.96 gm/cc, lepidocrocite 3.96 gm/cc, chalcopyrite 4.2 gm/cc, pyrite 5 gm/cc, hematite 5 gm/cc, magnetite 5,2 gm/cc. The sum only shall provide a hint to understand general differences of specific weights of Rashidian's mineral groups 1 to 5.

8 It is unfortunate that the so-called Schlich, found by Eibner in his 1971 excavation was not analyzed according the whole chemical elements, so it is unsure what had been concentrated there besides copper and nickel and if this chemical composition also included other mineral components (such as an elevated iron content); Eibner, 1974, pp.21-22.

9 The Mitterberg-trough will be subject of another detailed investigation by P. Thomas, K. Nicolussi, Th. Pichler. N. Schimerl and Th. Stöllner.

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Author

Thomas Stöllner – Research Departement, Deutsches Bergbau-Museum Bochum/
Institute of Archaeological Studies, Ruhr-University Bochum

Correspondence and material requests should be addressed to: thomas.stoellner@bergbaumuseum.de

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Simon Timberlake

Some provisional results of experiments undertaken using a reconstructed sluice box: an attempt to try and reproduce the methods of washing and concentrating chalcopyrite at the Middle Bronze Age ore processing site of Troiboden, Mitterberg, Austria

ABSTRACT: *On-going experiments carried out by the author in 2012 and 2016 on the Mitterberg have attempted to reconstruct the use of the wooden sluice boxes found by the RUB/DBM team during excavations carried out on the Troiboden MBA processing site. A number of different hypotheses for their function and also means of operation have been tested, including as a simple washing box, as a buddle, as a tye, a simple form of jig used with sieves, and as a panning box. Several possibilities, some more probable than others, have been suggested, but no firm conclusions drawn. In addition, some useful general observations have been made, alongside recommendations for procedure in the case of future experiments*

KEYWORDS: ORE WASHING, CHALCOPYRITE, WATER FLOW, SLUICE BOX, BUDDLE, TYE, JIG SIEVE; PANNING, CONCENTRATE

Introduction

The archaeological context and interpretation of the wooden sluice boxes found at the ore processing site of the Troiboden is discussed elsewhere in this volume, and in the already published literature on this site (see Stöllner et al., 2012; Rashidian, 2016; see Stöllner 2019, this volume). However, the current series of experiments conducted during the DBM and RUB excavation campaigns of 2012 and 2016 were designed specifically to establish what exactly it was possible to achieve using just these boxes, a controllable water flow, and credible materials such as wooden spatulas and scoops (similar to those found at the Troiboden in 1972 and in 2009: See Stöllner et al. *ibid.* 21 + Abb.15 and Eibner, 1972, Abb. 7) and a range of coarsely-woven textiles and stick-mesh frames or sieves and containers. By no means all the latter types of objects have been identified from the Troiboden, yet some of these (or similar examples) have previously been reported from the mining area of Brixlegg at Radfeld, Mauk A (Goldenberg & Rieser 2004) from the Mitterberg and Kelchalm (Pittioni & Preuschen 1954) mining areas, and all of them would have been available to the Alpine cultures of the Middle Bronze Age and also the late Bronze Age at Kitzbühel and Radfeld. In this respect, given that a number of stated hypotheses were being tested, and that the procedures being attempted were to be repeated and also verified, the practice of these experiments conforms well with the procedural guidelines for the science of experimental archaeology first established by John Coles in 1973. Furthermore we should remember that such experiments can also be used to *predict* the sorts of archaeological traces formed by the processes investigated – a phenomenon which may prove useful during future archaeological work (Timberlake, 2015, pp.145-146). In fact the latter approach is a very valuable tool and an acceptable practice to follow when undertaking experimental mining archaeology.

The main hypothesis being tested here by experiment was that this box (and the other 8-9 similar-looking variants of these boxes) found embedded these now dendrochronological and radiocarbon-dated 14^{th}-13^{th} century BCE working floors of the processing site was being used to wash and concentrate (by means of gravity separation and water flow) the crushed chalcopyrite ore from the adjacent Main Lode mine. However, included within this were a series of other practical hypotheses which could be tested experimentally, none of which were necessarily mutually exclusive. First perhaps is that these boxes were primarily used just for 'washing' the ore.

Ore washing is a process first referred to (in technical detail) by Agricola in *De Re Metallica* (1556), and before that by Pliny (AD 77), whilst interpretations of processing features at Classical period mining sites such as Laurium in Greece as well as at Bronze Age mining sites (Timberlake, 2014, p.48) suggests that cleaning the ore is an important first stage of its preparation for the smelter, and in fact precedes the stage of concentration. In this respect it has been very interesting to note the importance attached to the washing (but not the gravity separation or concentration) of chalcopyrite within the 2015 film of the Nepalese tribal copper smelters *Tama Gaun* (see Anfinset in his lecture during the conference, see also: Anfinset, 2011). This appears to have been an indigenously – developed mining and smelting tradition, yet one which shares certain similarities perhaps with the sorts of processes which *could* have been taking place in the Eastern Alps during the prehistoric period (Goldenberg et al., 2012). There are inherent dangers in making these archaeo-ethnographic parallels, particularly in respect of theories concerning archaeological experiment, yet there is still a valid point to be made here I think. Washing the ore is a natural and spontaneously-developed stage of the ore preparation process which becomes visible once we are looking at furnace charges beyond the easy capability of hand-sorting and cleaning (i.e. above 5-8 kg in weight). For this purpose square or rectangular structures (made of either stone or wood) will be built, and the ore washed within a flow of water to remove both organics, clay, silt and sand and even the light particles of rock brought in from the mine and crushing floors. Apart from removing the fine waste material, this aids visibility in the subsequent selection and concentration process of the ore. On the Troiboden the pre-sorted and broken-up ore from the mine would have arrived in baskets, most likely mixed with clay, flakes of mica, charcoal and possibly wood. Of course the washing of the ore may well have been carried out twice; first on its arrival from the mine, and secondly following crushing of this to the grade size required for smelting. A set of experiments therefore were designed to test the effectiveness of this using the boxes.

Much thought also went into planning experiments to test the possible use of this box for the gravity separation of ore from the lighter gangue minerals, in effect the concentration of the chalcopyrite. Likewise this included attempts at separating the finely-crushed chalcopyrite from the pyrite and other heavy minerals.

The **first** hypothesis to be tested was the use of a controlled water flow into the box to try and separate out piles of mixed gangue and chalcopyrite composed of different ore grades and grain sizes. In effect this was using the box as a tye or strake – a process which is described and illustrated in Agricola (ibid., pp.306-308). Here it is shown as involving a series of interconnected boxes, usually set into a slope, in which the ore minerals and gangue become separated into layers as a result of a fast, turbulent or variable water flow. Whether this is comparable to the water flow regime achievable within a single box is an interesting question, as might be the separation of the mineral into vertical/ horizontal layers, and following that the effective recovery from the box of selected enriched fractions.

The **second** hypothesis was to test its possible use as a buddle. In this scenario the tank would be filled with water and the finely ground ore rapidly mixed into it and agitated, the water then perhaps being rotated, allowing the heavier minerals to settle out first at the base. Possible examples of these are described in Agricola (ibid., p.300), some off which just consisted of wood-lined boxes set into the ground. Yet others, including simple stone-lined boxes without any planks or openings have been recorded from the hand-dressing floors of a number of Medieval – Postmedieval metal mines (see Craddock 1995, p.166 Fig. 5.9).

A **third** hypothesis was that the box was used in combination with a sieve as a jig. Jigging is another technique used for ore separation and concentration, and is likewise described and first illustrated in Agricola (ibid., pp.310-11), thereafter becoming one of the principal ore-dressing techniques employed within Postmedieval mines (latterly as manual or automated jigging frames). In terms of primitive ore dressing, it is suggested that a container bottomed with a sieve and filled with finely crushed ore and gangue of similar grain size might be pushed down gently, but repeatedly, into a still water-filled tank in order so as to saltate the mineral grains and thus allow for gravity separation. This may occur within the container, or else may be divided between the container (which retains the lighter gangue fraction that can be discarded) and the heavier sulphide-rich fraction which passes through this and settles upon the floor of the tank. The crucial skills to master here are the techniques of saltation (such that the separation of minerals divide accurately between the gangue and the sulphides collecting in the tank), and the control of grain size. Without competence in both, the process as a whole becomes inefficient.

The **fourth** hypothesis was to examine the possible use of this box to assist in the panning (therefore the gravity separation) of chalcopyrite from the other sulphide and gangue minerals using a simple scoop, ladle or trough, perhaps even suspended from a rope hanging to a frame or tripod. Agricola does not mention this specifically as a concentration technique suitable for sulphide ores, yet there are examples of its use in gold recovery. In particular we find shallow wooden troughs with handles (*Sichertrog*) being used for the panning of gold out the rivers in Transylvania (Apuseni Mountains, Roumania). Although there is no evidence for the use of these pans

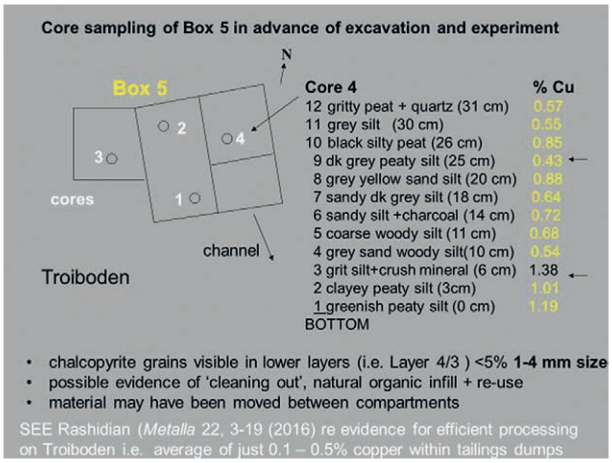

Fig. 1: Core sampling in 2016 of Box 5 in advance of excavation and experiment, with Core 4 copper values (diagram: S. Timberlake).

in water-filled sluice boxes, there are some examples described as having been used for panning *above* water-filled wooden tanks during the 19th century (Pošepny 1868). The use of similar troughs or pans during the Middle Bronze Age for gravity separation of chalcopyrite continues to be a possibility – and such a hypothesis is worthy of testing by experimentation. In fact there are a number of wooden artefacts from the Bronze Age mines of the Mitterberg, from Brixlegg (Mauk F) and Kelchalm some of which could have been used for the panning of sulphide ores.

The *modus operandi* of the tank itself also needs to be addressed. For example, do we know whether the tank required one or more people to operate it? Was it always water-filled? Was the cross-bar used for sitting on, or for leaning against? Might this bar also have helped deflect the water current, and for what purpose? What was the working depth of the tank i.e. were the sides dug into the sediment (as has been suggested), and if so was the tank then dug out in the middle? Finally, how quickly and easily could the tank have been emptied of water (assuming that it was important function to recover the waste or ore fraction from the tank with the minimum of disruption)? Answers to all or most of the above questions can be addressed by experiment, and following this a range of possible scenarios examined.

The analysis of a sediment core from Sluice Box 5 (September 2016) – crushed ore, grain size and copper concentration

Prior to the planning of the 2016 experiments an opportunity arose to core the *in situ* sediment fills present within the compartments of a recently excavated sluice box (Box 5) from the Troiboden. In September 2016 four cores were taken from three of the interconnected boxed compartments. These were examined sedimentologically, which included visual particle size analysis and mineral grain identification undertaken using a binocular microscope, and semi-quantitative elemental analysis (% Cu) with a Niton pXRF. The results for Core 4 from the sediment-filled compartment closest to the northern inflow channel to the box were compared with those from Core 3, an annexe to the box on its western side (see Fig. 1). In Core 4 grains of crushed vein mineral and rock appeared to be enhanced within the lower layers 3 and 4 at a depth of 21-26 cm, from a level just above what was presumed to be the original peat-cut floor of the box. Just under 5% of these grains were recognisable as the sulphides chalcopyrite or pyrite, with all of the visible ore grains being in the range of 1-4 mm. The slightly higher pXRF reading of 1.38% copper for layer 3 reflects the very small increase in the number of ore grains within this layer which remained upon the box floor after concentration – a value which probably accurately reflects the presence of c. 5% chalcopyrite within the sediment with a copper content of around 20-25%. The results for Core 3 on the other hand show a slightly different pattern. Here considerable numbers of grains of crushed vein rock consisting mostly of the gangue minerals quartz, ankerite and goethite (with slightly elevated copper values of between 0.57 and 0.82%) remained within layers 4-6 and 8 in the upper half of this infilled compartment, evidence perhaps for the use of these multi-compartment boxes for the dumping or storing of the already separated fractions of ore concentrate and waste. Whilst it is difficult to be certain of this as a true function of the box, the evidence obtained so far from this coring study has provided a useful database for this on-going programme of experimental work.

To some extent the results of the copper analyses of the sediments recovered from Box 5 supports the general conclusion of Rashidian (2016, pp.3-16) concerning the efficiency of the ore processing on Troiboden; i.e. that a high rate of recovery of chalcopyrite from the middling ores which exceeded 95% has resulted in a loss to the spoil (tailings) averaging just 0.1-0.5% of detectable copper. Not surprisingly some of this copper will have been lost to solution within the oxidising conditions of the tips, and in some cases we are may be finding this copper re-deposited (i.e. 'fixed') within the organic peat horizons underlying the tailings and the boxes themselves (N.B. Layer 1 within Cores 3 + 4 contained 1.08 and 1.19% Cu respectively).

In September 2016 some of the archaeological sections within the vicinity of Box 5 were likewise sampled for copper. Thus layer [82246] just outside of Box 5 was found to contain 0.68% Cu, the fill [86041] of the drainage channel on the south side of this box 0.91% Cu, the upper tailings debris sampled within the east profile of Trench G 0.54% Cu, the lower tailings debris within the same profile 1.26% Cu, and the tailings debris of the north profile of Trench E (Rösche) 0.01% Cu. These results were slightly higher than those obtained by Rashidian, yet were from samples taken in the field only using pXRF, so in actual fact these may well be comparable.

August 2012: The reproduction of Box 1 – its manufacture and installation within the riverbed site below the Athurhaus: the controlled waterflow ore-separation experiments

Box manufacture

The reproduction of Box 1 excavated on the Troiboden in 2008-2009 was undertaken in August 2012 by the prehistoric wood technologist Wolfgang Lobisser (Vienna Institute of Archaeological Science) to the dimensions of the original pieces recorded in Stöllner et al*.* 2012, Abb.11 (see Stöllner 2019, this volume). Consisting of four morticed plank uprights and a crossbar the facsimile was manufactured from the same wood species (*Picea abies*) using reproduced Middle Bronze Age bronze carpentry tools which included an adze, axe and gouges (Fig. 2).

Fig. 2: Construction of Box 1 facsimile in advance of experiments in August 2012 (photo: S. Timberlake).

Box installation

The four sides of the box were slotted together and this was then placed in a suitable position to the side and downslope of the active stream course within the stone-covered riverbed (Fig. 3) The box was dug into the dry gravel riverbed to about half its depth, and the original gravel and stones emptied out from the middle. Fine gravel was now collected and the base of the box re-filled to a height of 10-15cm from the base, and levelled. On top of this was added a layer of clay gathered from the stream bank to a depth of c. 26 cm from the base. This was again levelled and then 'puddled' to make a reasonably flat surface, then left overnight to dry. The depth of placed sediment within the experimental box thus corresponded to the approximate depth of sterile sediment found within the archaeological example.

A small reservoir with a clay lining was then constructed in front of the inflow to the box, and the box was

Fig. 3: 2012 river bed experimental ore-washing and processing site, Mitterberg (photo: S. Timberlake).

Fig. 4: Water-filled reconstructed box ready for experiments, showing lay-out of leat, diversionary channel and drain (photo: DBM).

Fig. 5: Rock slabs collected from river bed for use as mortar stones and anvils, along with crushed chalcopyrite. The stones show working faces/hollows from 6-8 hours of use (photo: S. Timberlake).

then tested to ensure that it was watertight and could maintain the same level of water fill. A small channel was then dug into the riverbed on a suitable gentle gradient up to the main course of the active stream. At this point, close to the junction with the stream, was built a small clay plug dam with a stone core. The centre of this dam would form part of an easy to break and repair sluice designed to control water flow along this inflow channel to the box. This set-up was tested and the box filled with water, the channel remaining slightly open in order to maintain a slow but steady and continuous flow of water into and across the box (Fig. 4).

Following the first buddling experiment (1A) the floor level of the box was raised up (using a mixture of fine river gravel and clay/silt) to the level of the bottom of the outflow hole at its rear, leaving a very slight slope towards this from the inflow. A plank was also placed across the top of the box at its rear for use as a seat. The outflow channel outside of the box (i.e. to its rear) was then deepened to ensure that a fairly rapid and constant flow of water spread across the inside floor of the box. This was for the purpose of using the box as a tye or strake to separate out piles of ore simply by controlling the flow of water.

Ore preparation

Approximately 50 kg of chalcopyrite ore associated with vein quartz and ankerite was mined using sledge hammers and picks from an exposed vein outcrop close to the Arthurhaus. In addition to this a number of boulders rich in chalcopyrite were collected from the floor of the

Mineral	Specific gravity (gm/cc)	Comments
microcline feldspar	2.56	gangue minerals
calcite	2.71	
quartz	2.72	
muscovite	2.76	
ankerite	3.05	
epidote	3.4	
siderite	3.96	
chalcopyrite	4.2	ore concentrate
pyrite	5	included
hematite	5	

Tab. 1: A table of specific gravities of minerals common to the Mitterberg ore veins.

Fig. 6: Using the box as a buddle with a facsimile wooden shovel. August 2012 (photo: DBM).

riverbed upstream of the experimental site. In total some 75 kg of ore was available.

Most of the ore crushing was attempted using just stone tools. These were selected from a range of water-worn rock slabs along the river bed and were collected for use as anvils or mortar stones. Naturally-indented boulders were chosen wherever possible for making mortar stones, and as the use of these progressed the development of deeper mortar hollows as a result of the continuous pounding and crushing of the ore was closely monitored and recorded (Fig. 5). Suitable cobbles for use as hand-held crushing stones were also gathered from the riverbed, and wherever possible these were chosen from harder rock types, such as quartzites, gabbros or ultrabasic rocks, the latter lithologies being quite rare but still present in small amounts within fluvial assemblage. The use of such mortar stones, stone anvils, and occasionally grind stones in this process is supported by the archaeological evidence from the Troiboden, although stones of exactly the same size, shape and composition were difficult to come by within walking distance of the experimental site.

In 2012 the ore crushing was carried out on the dry riverbed next to the experimental site by five or six RUB - Archaeological Institute students (see Fig. 3). All of this work was fully documented, and from the initial processing some 7 buckets consisting of several different grades of crushed ore and gangue were obtained permitting 11 separate washing experiments to be undertaken. The categories included hand-picked lumps which made up a *'high-grade' ore* (perhaps 60-80% pure chalcopyrite), a *'middle-grade' ore* (40-60% chalcopyrite) and a *'poor-grade' ore* (perhaps 20-40% chalcopyrite in quartz). The three grades were then crushed and 'milled' to approximately three different grain sizes within the following size ranges: *coarse* (<10 mm >5 mm), *medium* (<5 mm >3 mm) and *fine* (<3 mm). However, an extra finely-milled high-grade ore sample of < 2 mm was also prepared using a grindstone in an attempt to separate the pyrite from the chalcopyrite.

As a general rule, the sieves were only used as a guide in the business of grain size separation, so much of this work was carried out instead by eye and by guess-work, much as it probably would have been done during the Middle Bronze Age at the Troiboden site.

In brief, the following experiments were carried out using the reconstructed box in 2012, the results (data) of which are shown in Table 2 [N.B. unless otherwise stated the weight of each of the fractions was recorded when wet. They should not be regarded therefore as being composed of 'pure' sulphide or gangue but simply as 'enriched' samples]. Table 1 provides an indication of the specific gravities of some of the commonly occurring minerals within the Mitterberg ore veins, in particular at the Troiboden.

Using the box as a buddle (Experiment 1A)

The first experiment was undertaken to try and buddle a bucket sample of coarse poor-grade quatz-rich chalcopyrite within the waterfilled box. Using a facsimile of the wooden paddle found at the Troiboden (see Fig. 6), the water was stirred in a clockwise direction in order to agitate and suspend the grains for the purposes a gravity separation. This was not particularly successful, although a slightly richer chalcopyrite concentrate of 0.613 kg (out of 1.75 kg of sample) was removed from the floor of the box.

Using the box as a 'tye' to concentrate a poor-middling ore (Experiments 1C + 1D, 2, 4.1 + 4.3 and 5)

In these experiments small piles of crushed ore were placed directly in front of the inflow hole upon the raised floor of the box, and the controlled flow of water from this then used to separate out the coarse from the fine-crushed

Experi-ment	Hypothesis	Procedure	Ore	Chalcopyrite	Comments
1A	use of the box as a **buddle** for gravity separation	closed water-filled box agitated and allowed to settle	**1.72** kg 20-40% ch @ <10 mm	**0.613** kg sulphide	
1C	use of the box as a **tye or strake**	separation of a pile raked back and forth under continuous water from the inflow	**4** kg – same –	138 g (from 450 g)	method separated out fine-grained fraction (0.503 kg) from coarse (3.514 kg) = returned for re-milling
1D	– same –	washed the same but sieved (<3 mm) to improve gravity separa-tion	**7 kg** – same –		2.146 kg (>3mm) returned for re-milling – from finer grained 3 fractions incl sulphide separated from semi-circular spread
2	– same –	fine milling to try and improve the degree of separation	225 g 20-40% ch @ 4 mm	108 g	partial collection of gangue (98 g +)
4.1	the use of the box as a **tye** to test the separation + recovery of known composition	the washing of a fine-milled synthetically composed ore	250 g sulphide + 250 g ankerite + 100 g quartz	250 g	sulphide-rich concentration scooped up with spatula and squeeze to remove water (incl. 25% gangue)
4.3	– same –	The same – but put through a sieve to remove >3 mm fraction	100 g each of quartz, ankerite, crushed rock + sulphides	101 g sulphides (wet)	229 g gangue left in <3 mm fraction
6.1	use as **tye** with slow-water pulsed washing for better recovery?	first passed through 2 mm sieve	511 g of high grade fine-milled ore	293 g of sulphide	65 g of gangue (incomplete collection)
6.2	better recovery through finer milling + repeated washing?	2 mm sieved and washed x4 times	1.117 kg of high grade ore	833 g of sulphide -rich fraction	
4.2	**separation of the chalcopyrite from pyrite**	fine-milled high-grade ore pulse-washed + separated with a spatula	208 g of high grade ore	not recorded – but different samples taken for analysis	no visible gravity separa-tion was evident

Table 2: 2012 buddle and tye box experiments – using water flow to separate out ore and gangue and to concentrate chalcopyrite.

grains, and the heavier (sulphide) minerals from the lighter (gangue) minerals. The results from Experiments 1C and 1D suggest the re-deposition and partial separation of the mixture in the water flow, the finer grained material (consisting both of sulphides and gangue – but with an enrichment in chalcopyrite) reporting to the base and to the edges of the pile (Fig. 7). It was not really possible to recover a concentrate from this. However, after col-lecting the now-separated coarse (<10 mm >3 mm) and fine (<3 mm) fractions with a wooden spatula these were dried and re-milled down to a finer grain size (<3 mm). The sample was then re-washed and a better recovery of sulphides obtained. So, after a somewhat lengthy process it was possible to raise the chalcopyrite % from a poor to a middling-grade ore.

In Experiment 2 the same poor grade ore was milled to a standard size (<4 mm). The ore was washed in the same way, but this time the gangue and sulphide-rich

Fig. 7: Washed and partly separated chalcopyrite and gangue within the 'tye box' [Experiment 1d] (photo: S. Timberlake).

fractions were carefully separated, dried and weighed. Thus 225 g of a slightly richer middling grade chalcopyrite concentrate was obtained just in one step from 275 g of ore.

Experiment 5 involved the attempted separation of 1.6 kg of finely milled ore by means of a more skilful use of water flow through the repeated opening and closing of the inflow hole into the box using a fabric bung. This enabled a much better grain density separation under gentle water flow conditions. Another effect of this was the flotation of the finest chalcopyrite dust upon the water surface, much of which accumulated on the far side of the box to the rear of the wooden bar (Fig. 8). An attempt was made to collect this using the wooden spatulas, but it proved difficult to recover. Almost 50% of the processed and partly separated sample was recovered from the floor of the box. This was a good result showing that there was very little loss from the box, yet the improvement in grade from 'digging' the sediment out was probably little more than 20-30%.

A better result was obtained in Experiments 4.1 and 4.3 using finely-milled synthetically composed ores made up of 250 g of pure chalcopyrite, 250 g of ankerite, and 100 g of quartz (in the case of Experiment 4.1) and exactly 100 g portions each of quartz, ankerite, sulphide and rock (within Experiment 4.3). These minerals were separated out in the water flow, the sulphide fraction being collected more or less in its entirety in Experiment 4.1, but just as a 50% concentrate within Experiment 4.3. This seems to suggest that a complete separation is theoretically possible this way, but that it is practically difficult and time-consuming to achieve, and probably only effective when using just small amounts of carefully milled, simple, and moderately-rich ores.

Using the box as a 'tye' to concentrate a rich sulphide ore (Experiments 4.2 and 6)

Finely-milled high-grade ore was washed in a similar way, but then passed through a 2 mm sieve in order to try and eliminate the grain size from the gravity separation effect of washing. It was also hoped that a much cleaner and richer concentrate might be obtained if the mix was better prepared and already enriched by careful sorting. The first experiment (6.1) yielded a c. 60+% concentrate of chalcopyrite, which may in fact be the same as the ore treated. However, the second experiment (6.2) yielded a c. 75% concentrate, but only after four separate washes followed by collection.

The final experiment (Experiment 4.2) was designed to see if it was possible to separate chalcopyrite (specific gravity 4.2 gm/cc) from pyrite (SG 5 gm/cc) in its finely-milled form by means of skilfully controlled pulsed washings at the inflow to the box. Unfortunately very little visible separation could be seen, and given the number of attempts trying to do this it seemed unlikely that this procedure could ever have been successfully achieved. Nevertheless, samples from both the bottom and top layers were returned to the DBM for analysis.

Fig. 8: Flotation of fine chalcopyrite bubbles upon the water surface. August 2012 experiment (photo: S. Timberlake).

August 2016: Further experiments carried out using the reconstructed box – including ore preparation, ore-washing, gravity-separation, ore flotation, jigging and panning

These experiments were conducted by the author, and the RUB students Eva Neuber and Tim Teufel between the 4th and the 16th August at the same riverbed site.

Re-assembly and experiments with water flow and the sealing/ emptying of the box

The box was once again assembled and dug into the dry riverbed. The level of the river was considerably higher at this point, therefore there were difficulties in digging a leat to the box, and also in controlling the water flow. Because of this a much better sluice and also a system of release channels became necessary, and on several occasions during the experiments the box became inundated by water and silt after nights of heavy rain.

One of the experimental modifications made to the box following the leakage of water from its joints and base was the use of sphagnum moss as 'caulking material' to seal around the inside edges. This proved to be a very effective method of stopping water leaks, as well as a method of closing-down the water inflow and outflow to the tank. Indeed, moss was much preferable to clay or sand in this respect, and it would be worthwhile therefore to search for the use of this same material within the excavated box(es) upon the Troiboden. The necessity of digging high waterflow release channels around the box as well as other channels adjacent to the box sides to drain water away from the surrounding sediments when emptying the box raise important questions about the practical issues of using these, as it does about the actual environment in which these were used. Certainly as regards water flow rate and the maintenance of clear still-water conditions which may or may not be necessary for washing and separation the environments of the peat-covered plateau of the Troiboden and that of the experimental site are barely, if at all, comparable.

One final experiment to do with construction and use was carried out to try and solve the issue of how to rapidly and completely drain the box (and thus remove its contents) without completely dismantling it. An earlier attempt to do this by removing the back board proved problematic, for even the slightest sediment flow or movement made it difficult, if not impossible to replace. This was an unanticipated problem. Removal of the back board had been suggested as an operating feature, but experimentation now suggests this to be highly unlikely. Instead experiments have shown that the box, so long as the level of its working floor lies above the base of the drainage cut issuing from its outflow, can simply and effectively be emptied of water by digging a sump beneath the board into the drain (see Fig. 15). Once emptied of water the accumulated ore or gangue sediments may then be removed using a wooden shovel or series of large spatulas. The sump hole may then be blocked up again with clay or moss before re-filling with water

Ore preparation

Some 58 kg of ore remained for the experiments carried out in 2016. This consisted of 7.963 kg of high-grade (>60%) ore, 20.95 kg of medium-grade (40-60%) ore, and 29.152 kg of low-grade (<40%) ore).

Following the coring exercise carried out on Box 5 at the Troiboden site a simple experiment was devised with the goal of crushing a medium-grade ore using just stone hammers and a mortar stone to a size believed to have been the standard equivalent for wet processing during the Middle Bronze Age (i.e. around 4 mm). The necessity for skill in this task soon became apparent, such that by Experiment 3 just one person undertook the crushing and milling of an ore in preparation for its separation by jigging. This reduced any variability in assessing the efficiency of the process.

Interestingly the scale of loss from 'prehistoric' ore processing compares well with more modern methods, although the time required to process just a few kilograms of ore to the required size for concentration and for smelting provides us with a clue as to the labour-intensiveness of the ore preparation process carried out on the Troiboden. Even assuming a much-improved and more consistent work rate, 1.5-2 hours may have been required to reduce 5 kg of ore to a size suitable for processing. What it was also possible to show was the difficulty in reducing this to a standard size without the use of sieves or screens. Chalcopyrite and pyrite in particular are brittle, resulting in a much higher than expected report of material to the finer grain fractions (i.e. < 0.5 mm). Even so, the greater proportion of this ore (i.e. > 50%) remained within 1-4 mm fraction. Continued milling of the ore upon a grindstone (or mortar) produced a more consistent grain size (0.5-2 mm) suitable for separation, although not of course necessarily the size desirable for smelting.

Fig. 9: Using the water-filled box with a woven wattle frame and sacking for the washing of the crushed ore in August 2016 (photo: S. Timberlake).

Use of the box for washing ore

This simplest use of the box for was addressed by a couple of experiments involving the construction of a square frame made out of woven hazel (*Corylus* sp.) branches gathered from the banks of the river. The frame did not function a sieve, but rather as a rigid grate on which a loose fabric could be laid and upon which copper ore might be placed in order to rapidly wash within the water-filled box (Fig. 9). The experiments were carried out using several fabrics, including a synthetic fleece (mimicking a tightly woven fabric) and also hessian (as a coarsely woven fabric; see also Grömer et al., 2018). Freshly crushed but not size-graded ore was experimented with alongside ore intentionally mixed with clay, soil and vegetation, and charcoal – much as it might have arrived at the Troiboden washing floors from the Main Lode workings.

The most effective washing out of the lighter rock (mica schist particles) and clay was achieved by immersing (dipping and agitating) the frame into a fairly fast stream of water passing through the box, although this could also be achieved within the still water-filled box through more intensive agitation and the stirring of the spread-out ore upon the hessian bed. The use of smaller open-weave baskets for washing were also experimented with, and in some ways the use of these seem much more likely, and probably more efficient.

In conclusion it can be said that upwards of 20% of the dirt and lighter rock waste accompanying the ore (alongside the organics) could have been removed by washing this within boxes, or perhaps inside of baskets in a stream of flowing water. The advantages of using a box includes the control of water flow, the provision of a silt trap, and the possibility also of collecting and re-working the waste.

Washing and cleaning the ore was probably an essential pre-requisite to assessing its grade and grain size following crushing.

Further 'tye' box experiments to try and improve the gravity-separation of sulphides and capture chalcopyrite by flotation

A short series of experiments were undertaken to try and refine the 'tye' box water flow-assisted gravity separation of ore achieved in 2012. None of the samples used and recovered here were measured, as this was primarily an attempt to see whether the technique worked under the higher water flow conditions present.

In the second experiment the box was first emptied of water, and a shallow clay cone constructed upon the inside rising towards the intake, the highest point lying only a few centimetres short of the inflow. The surface of the clay was then moulded into riffles by means of semi-circular grooves. Crushed ore was added to the top of the cone, but the power of the water flow scoured much of the ore and the clay away, though a small concentration of chalcopyrite (sulphides) did remain within the highest riffle with some of the lighter gangue minerals below. Most of the ore was lost to the water current, which proved difficult to control, even with the use of fabric and moss 'bungs' to slow the rate of inflow (Fig. 10). Whatever remained upon the clay likewise proved difficult to collect.

Fig. 10: Tye box experiment in August 2016 using the clay cone and sphagnum moss as a 'bung' to control water inflow (photo: DBM).

It seems unlikely that a more complex use of the tye box for the gravity separation of sulphides would have been any more effective than the 'rough and ready' results achieved in 2012.

Experiments in ore concentration using the 'jigging method'

Jigging is a method of ore concentration based upon a very simple principle[1]. Basically this is a form of gravity separation of ore and gangue minerals which is assisted manually or mechanically through the vertical agitation of the grains inside of a sieve container suspended in water. The heavier metallic fraction (the ore) will also partition within the sieve itself, if the sieve is fine enough,

Crushing experi-ment	Ore grade %	Process	Weight before crush-ing (kg)	Weight after crush-ing (kg)	Loss (kg)	>4 mm (kg)	4-1 mm (kg)	1-0.5 mm (kg)	<0.5 mm (kg)	Time pe-riod (hrs)	Rationale
1	40-60	crushed	4.838	4.679	0.159	1.486	2.005	0.445	0.757	3.5	crush to c. 4 mm
2	40-60	crushed	5.236	5.019	0.217	0.590	2.419	0.882	1.192	2.21	same
3a	40-60	crushed	3.466	3.275	0.191						
3b	40-60	no further crushing		1.091							sieve into 3 equal portions
3c		crushed again	1.104				1.05			1	to try and improve upon yield for jigging
3d		milled upon grindstone	1.104					1.066		1.5	milling takes more time but gives more even grain size (0.5-2 mm)

Table 3: 2016 experiments – some data on ore preparation

Experi-ment	Sieve type	Procedure	Question/ hypothesis	Weight + of ore added (g)	Grade and size of ore	Duration and num-ber of motions	Weight remains sieve (g)	Weight con-centr (g)	% chalcop through sieve	Comments
Bucket 1.1	4 mm	sieve bucket in 19 cm water	possible? is even grain size better?	835 g	25% 1-4mm	1 minute (24x)	90 g		30% ?	insufficient separation
1.2	4 mm	same	increase speed?	835 g	25%	1 minute (69x)	5 g		25%?	insufficient separation
1.3	4 mm	same	speed + rota-tion?	835 g	25%	1 minute (75x)	<5 g		25%	motion is difficult
1.4	4 mm	same	shorter time?	835 g	25%	25 secs (7x)	205 g		40%+?	slower more effective
1.4.1	4 mm	same	ore spread over sieve?	835 g	25%	25 secs (7x)	85 g		50%	separation in bucket
1.5	2 mm	similar w hessian	use of fabric sieve?	835 g	25%	2 minute (135x)	745 g	90 g	75%?	enriched but low recovery
1.6	2 mm	same	slower	835 g	25%	2 minute (10x)	c. 800 g			separates out on sieve
1.7	2 mm	larger bucket 10 cm water	stretched fabric + water vibration?	835 g	25%	2 minute (10x)	c. 800 g			no clear sepa-ration
'Mini-jig' 2.0	4 mm	plastic bot-tle sieve base	use of a jig container	1091 g	25% >4 mm – 0.5 mm	4 minute	1060 g		low	coarser frac-tions retained in jig container
2.1	4 mm	same	fine fraction of 2.0 added	1091 g	25%	4 minute	370 g		c. 50%	quartz retain in container
2.2	4 mm	same	residue of 2.1 re-sieved	370 g	25%	4 minute	231 g		50%	all <5 mm ch separates
2.3	4 mm	same	with grain size control	370 g	25% <4 mm	15 secs	53 g		60%?	
Withy sieve 3.1	5 mm	'authentic' use in Box	attempt in flowing water	639 g	25%?	45 secs (10x)				separation is on size only
3.2	5 mm	same	placed whilst under water	639 g	25%?	30 secs (3x)			30-40%?	chalcop on bottom
3.3	5 mm	same	under water flow	639 g		30 secs			>50%	concentrate below sieve
3.4	5 mm	same	with control of water flow	639 g		30 secs				zoned concentrate
'**Mini-jig'** 3.5	4 mm	use still within box	quick vs slow submerganc	480 g	25% 1-4 mm	10 minutes	282g	192g	75%	25% chalcop remaining in jig
3.5.1	4 mm	same	residue of 3.5 re-sieved	282 g	25% 1-4 mm	3 secs			60%	just 15% of jig residue is ch
3.6	4 mm	same	re-sieve 3.5 add finer frac	600 g	0.5-4 mm	56 secs			75%	<30% of jig residue is ch
3.6.1	4 mm	same	re-sieve 3.6 enriched frac						75%	25% of jig residue is ch
3.6.2	4 mm	same	re-sieve 3.6 jig residue						40%	minimal enrichment
3.6.3	5 mm	same	re-sieve 3.6.2 jig res						40%	30% of jig residue is ch
3.7	2 mm	same	hessian over sieve	504 g	2-3 mm	48 secs			75%	45% jig residue is ch
Basket 3.8	1-2 mm	same	ore washed in water flow	600 g		6 minute			60%?	most washed out
3.9	1-2 mm	same	ore washed over hessian	600 g		1.2 minutes			60%	grain size separation
3.9.1	1-2 mm	same	repeat of 3.9 using finer gr	968	<2 mm	1.5 minute			50%	20% of jig residue is ch

Table 4: 2016 experiments using various different types of jigging sieves – within and outside of the reconstructed box.

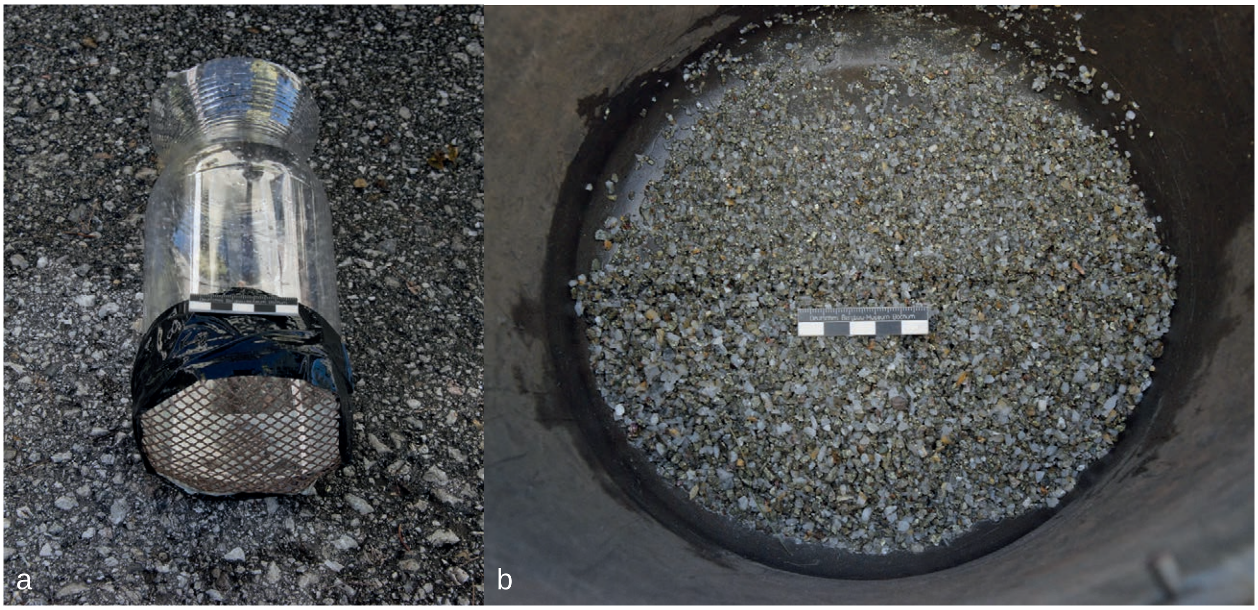

Fig. 11a + b: The 'mini-jig' sieve container used to test the principle of jig separation of the chalcopyrite (sulphide fraction) from the lighter quartz-rich gangue. Figure 11b shows this gangue fraction in the sieve with about 25% of the chalcopyrite remaining (photo: DBM).

with the lighter gangue minerals forming the layer on top. This can be skimmed off using a rake or spatula, and the concentrate beneath collected.

At least 26 experiments were conducted within the box, and on a smaller scale in buckets of water, using reduced-size improvised sieves and sieve containers to investigate the jigging method applied to the concentration of the Mitterberg ores. Given what was available at the time, or could easily be made on the spot (which included materials credible to the period), most of the sieves used by the experimenters were coarse meshed (4 mm). This allowed the passage of much of the crushed mineral, yet retained a relatively higher proportion of the lighter fraction(s) when used correctly. Most experiments therefore were simply limited to seeing whether the principle worked, and if so whether this held out promise for further investigation. As such, the collected data (Tab. 4) provides a good guide to its potential, but not to the efficiency of the process.

Almost all of the experiments showed jigging to be a relatively quick and effective method of separating out gangue and enhancing the percentage of ore minerals; the lighter material remaining in the sieve and the enriched ore deposited upon the floor of the box (or into a pan placed beneath the sieve ready for further processing). The experimental results were quite variable, though typically an average recoverable enrichment of between 20-30% (chalcopyrite/pyrite) could be achieved just through the skilled use of a jigging sieve, the best results being achieved using the flask-like 'mini-jig' (Fig. 11 a+b). Some success was also achieved using a woven withy (*Corylus* sp) sieve – equivalent perhaps to the use of a basket (Experiments 3.1-3.4; Fig. 12). The form of the former suggests what might have been used in association with these wash boxes; a wooden container possessing a perforated sieve-plate bottom upon which the ore may be concentrated and separated from the gangue. There are few contenders at present moment from these Alpine copper ore processing sites, one of them being the wooden 'Wasserkübel' described by Klose (1918) from the Mitterberg. However, this seems more likely to be domestic in purpose rather than proto-industrial.

The use of a pan to concentrate ore

The final series of experiments with the water-filled box involved the use of an improvised pan to try and enrich a low-medium grade chalcopyrite ore.

The particular technique of panning used was based upon the long-handled vanning shovel (traditionally used in Cornwall for assaying tin) and the light wooden Transylvanian gold pan from the Apuseni Mountains (Roumania). Such a wooden trough was described from Verespataker, Roumania where it was used above a water-filled box for the pan concentration of gold (Pošepny 1868). More relevant perhaps are the remains of another similar four-handled wooden trough found underground within the Western part of the St. Josefi Main Lode mine which was described by Klose (1918, Fig. 53; see also Thomas 2018, pp. 357-358) (Fig. 13). The function of this trough may have been to process chalcopyrite, as suggested by Modl (2015, 223) and it has been referred to as a *Sichertrog*. In the current experiment it was decided to test the hypothesis that this could have been used with the wash box to enrich a poor-quality ore to a sufficient degree to successfully smelt it.

It was found that a small hand shovel (Fig. 14) or a short metal pan with a handle and a 200 mm long x

Fig. 12: Experiment 3.1 or 3.2 in August 2016 Using an open weave withy sieve (Corylus or Salix) in an attempt to jig separate good ore from gangue within the water-filled tank (photo: DBM).

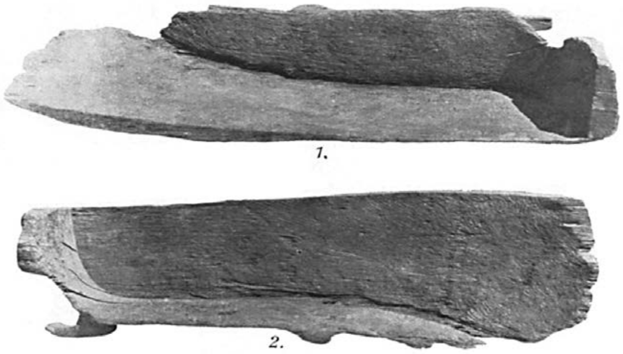

Fig. 13: The broken Bronze Age sichertrog found within a mine on the Mitterberg. Illustrated by O. Klose (1918), now in the Salzburg Museum.

Fig. 14: A reciprocating 'pan' separation of chalcopyrite from gangue within the water-filled box using just a flat-tipped hand shovel. Note the good retention of sulphide (photo: DBM).

150 mm deep opening at the front could be filled with between 0.5 to 1 kilogramme of ore (consisting of 25-40% chalcopyrite) and be panned to a concentrate of c. 95% chalcopyrite. This could be achieved by means of a gentle forward and backwards 'rolling' motion of the filled pan upon the surface of a slow-flowing current of water. Bit by bit this motion saltated the lighter rock and mineral grains across the lip of the pan onto the floor of the box. After several hours of practice using this technique it was possible to clean and enrich a kilogramme of ore in just 20-25 minutes. The use of the cross-bar for resting the pan against was ideal in this respect. Over the course of one afternoon some 4 kilogrammes of ore were processed this way – the product being the equivalent of a high-grade hand-picked ore.

Needless to say, we are making a big assumption in assuming that a 95% chalcopyrite concentrate was either a necessary or desirable ore grade to smelt with in these MBA Alpine furnaces, yet the point we should be making here is that this is a *viable* way in which a pure standardised product might be obtained.

Conclusions

What we know about the use of these boxes and the processing of the ore

1. It seems possible that Box 2 could have been operated by one person, with another in assistance to control the water inflow into the box, the leat, and the drain. The rate for washing/ore separation would probably have been one 'basket' at a time (i.e. probably not more than 5-10 kg per hour).
2. Most of the operations may have been carried out within still or slow-flowing water. It may have been desirable to control water flow where this was necessary for washing, though it was probably never designed for 'fast water' use. The environment of the Troiboden is very different from that of the experimental site.
3. We would expect to see these boxes associated with a feeder leat, a release or diversionary channel, a drain, and perhaps also a silt trap located at the front.

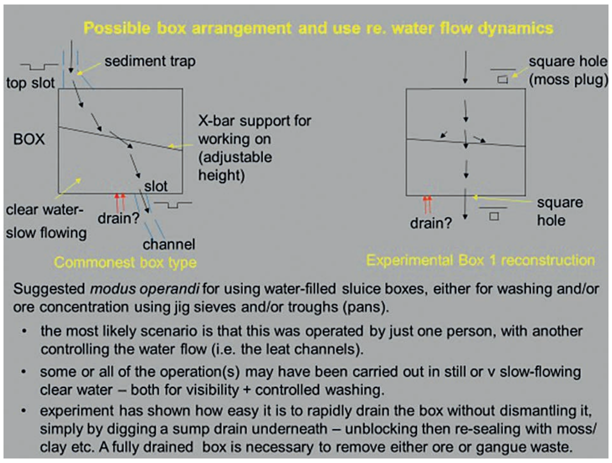

Fig. 15: A diagram showing the suggested modus operandi of the two different types of box (diagram: S. Timberlake).

4. It seems likely that the box was emptied of water by digging a sump beneath the drain, rather than by removing the back board. The drained sediments might then have been dug out.
5. It seems unlikely that these boxes were ever used as buddles.
6. I remain un-convinced that any of the boxes were designed for the *in situ* collection of ore concentrate from the sediments within their base. Experimentation suggests that the concentrated ore will have settled into lenses in between and surrounded by the gangue minerals from the washings – for which the subsequent draining and recovery would have been a difficult and time-consuming process. Traditionally tye boxes or strakes tend to be longer structures with sloping floors associated with faster flowing water.
7. Not all of the boxes found upon the Troiboden were used for the same thing. Box 2 constructed with holes both for inflowing and outflowing water is an oddity in this respect. More common are the boxes with slots (or no slots) in the top and some evidence for a diagonal water flow (Fig. 15). The wooden cross-bars may have been used for deflecting the current, but more likely were used for support.
8. Quite possibly all of the boxes could have been used for the washing of the mined and crushed ore. This may have been their main function. It has been shown that up to 20% of the accompanying clay, silt and light rock particles can be removed using just a gentle-moderate stream of water.
9. With a mortar or anvil stone the greater part of the ore can be crushed to a grain size of between 1-4 mm suitable for the purposes of gravity separation and concentration – the ideal being around 4 mm. This is supported by the sedimentological evidence from the Troiboden archaeological site.
10. Experiments have shown that it would have been possible to separate up to 60-70% of the sulphides (chalcopyrite and pyrite) from the gangue minerals (mica, rock, quartz, ankerite, feldspar etc.) through the skilled use of sieves within the water-filled boxes. However, it would not have been possible to separate pyrite from chalcopyrite.
11. Although partial flotation of the finely-milled chalcopyrite was observed within the tank, it probably would never have been possible to recover this.
12. Woven basket or container-like jigging sieves could have been used to enrich the poorer (20-40% chalcopyrite) ores. A 'moderate' enrichment could have been achieved using this method once the ability to make suitable sieves had been mastered.
13. Better control in achieving a standard grain size, an improved grade, recovery and a more efficient use of the ore could have been achieved by repeatedly re-processing and re-working the rejected material.
14. Waste mineral fractions (such as quartz) may have been collected for use as a flux.
15. The panning of the crushed ore using tight-weave baskets or wooden troughs may have been carried out to produce a high-grade chalcopyrite concentrate from. 'middling' ores.

Recommendations for future work

- The current experiments using jigging sieves and pans should be continued, but the equipment for these should be constructed in advance of this, be made out of credible materials, and be built to a suitable scale.
- The experimental site should move to the same environment and setting as the objects being studied (i.e. the Troiboden may be a better location)
- A proper means of sampling the products of these experiments is required (i.e. full chemical/mineralogical analysis of the processed ores and washed concentrates will be necessary rather than just calculated guesswork)
- It may be better to experiment with a 'more typical' box from the Troiboden (in concern of the construction of effluxes and influxes) and to use this facsimile within a series of repeat experiments
- Careful excavation/re-excavation of one or more of the smelting sites on the Mitterberg is required to properly understand the nature of the prepared ore charge and fluxes used. This way we might obtain a better idea of the grade of ore concentrate they were trying to achieve at the Troiboden.

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Lobisser the work was joined by Manuela Hirt, Benedikt Horst, Eileen Konzack, Roland Lavelle, Rashida Hussein Oglü, Lisa von Bömmel-Wegmann und Prof. Dr. Thomas Stöllner), whilst much of the work in 2016 was carried out by Eva Neuber assisted by Tim Teufel (who also provided me with the notebook data on the jigging experiments). The photographs are those of the RUB/DBM and myself.

Note

1 Simple hand-jigging techniques involving water-filled wooden tubs or boxes and sieves are described and illustrated in Georgius Agricola's *De Re Metallica* (1556, Book VIII, 310-311), and subsequently in most Postmedieval texts on the arts of mining and processing ores. In fact mechanical jigging was a standard method of ore concentration used in 19^{th}-20^{th} century industrial metal mining (see Earl 1968, 79), which continues in some parts of the world today.

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Author

Simon Timberlake – Institute of Archaeological Studies, Pre- and Protohistory, Ruhr-University Bochum

Correspondence and material requests should be addressed to: simon.timberlake@gmail.com

Smelting and its archaeometallurgical investigation

Excavation of smelting site Rotholz at the lower Inn-valley, photo: G. Goldenberg

Der Anschnitt, Beih. 42, S. 209 – 228, 2019

Rouven Turck

Organising smelting places. A keynote on Iron Age copper smelting in the Oberhalbstein (Canton of Grisons, Switzerland)

ABSTRACT: *Since 2013, systematic archaeological investigations in the Swiss valley of Oberhalbstein, Grisons, have been conducted in order to contextualise long-known traces of primary metallurgical activities. The present paper highlights some of the first archaeological features excavated, focussing in particular on copper smelting technology. The discussed features present strong evidence for an extensive copper metallurgy, and it is the aim of this paper to comprehensively introduce the local metallurgical operational sequence (chaîne opératoire). The features allow reconstructing separate processes as part of the metal age smelting technology. Even a small number of finds facilitates a preliminary integration of the material into the wider tradition of Alpine copper processing.*

KEYWORDS: GRISONS, OBERHALBSTEIN, PRIMARY COPPER PRODUCTION, COPPER SMELTING, ROASTING BED, FURNACE, IRON AGE

Introduction

The present paper discusses the most relevant archaeological features documented as part of the 2013 to 2016 excavations in the Oberhalbstein valley, Switzerland, conducted by the University of Zurich in collaboration with the Archaeological Service of Grisons/Graubünden (ADG) as part of a SNF-DACH project (SNF Projekt Nr. 100011E-153668). The aim of this paper is to present features which can be seen as archaeological evidence of the different stages of ore processing, roasting and smelting. The focus lies primarily on the site Gruba I due to the high quality of data recovered from the site. Additionally, the sites of Alp Natons and Val Faller, Plaz, with their relevant central features, including a roasting bed as well as smelting furnaces, will be discussed.

It is our goal to show evidence for the local processing of copper, and to add to the existing, diverse body of literature concerning Alpine copper technology (e.g. Eibner, 1982; Hanning et al., 2015; Reitmaier-Naef, 2018; Reitmaier-Naef, 2019).

Especially for Gruba I and Val Faller, Plaz, distinct patterns of organisation are discernible, relating to different stages of work. Detailed discussions regarding slags in the context of copper smelting can be found in Reitmaier-Naef`s (2019) contribution to this volume, while Oberhänsli et al. (2019) discuss the dendrochronological data[1].

Methodology and site selection

The selection of sites (Fig. 1) is a result of a systematic survey of the terrain. The applied field strategies (Della Casa et al., 2016) are based on those used in classical archaeological surveys, and focus on evidence such as slags and ores visible above ground as indicators for ore mineralizations and smelting sites.

Geophysics is used to pinpoint the exact location of slag heaps and to supplement the preparatory work process ahead of the excavations. Of great importance is also the relocalisation of known sites based on literature research, a catalogue of which had already been published (Schaer, 2003). Last but not least, cooperation with local associations, farmers and residents constitutes a cornerstone of our research and provides many leads regarding promising sites in the area based on oral history.

Alp Natons

The site Alp Natons has been known previously based on finds of slags. The excavation described here is situated exactly between the two sites Alp Natons I and II (JbAS 102, 2019, p.175), as described by Schaer (2003, No.51-52), at 1947 m above sea level. The site had been

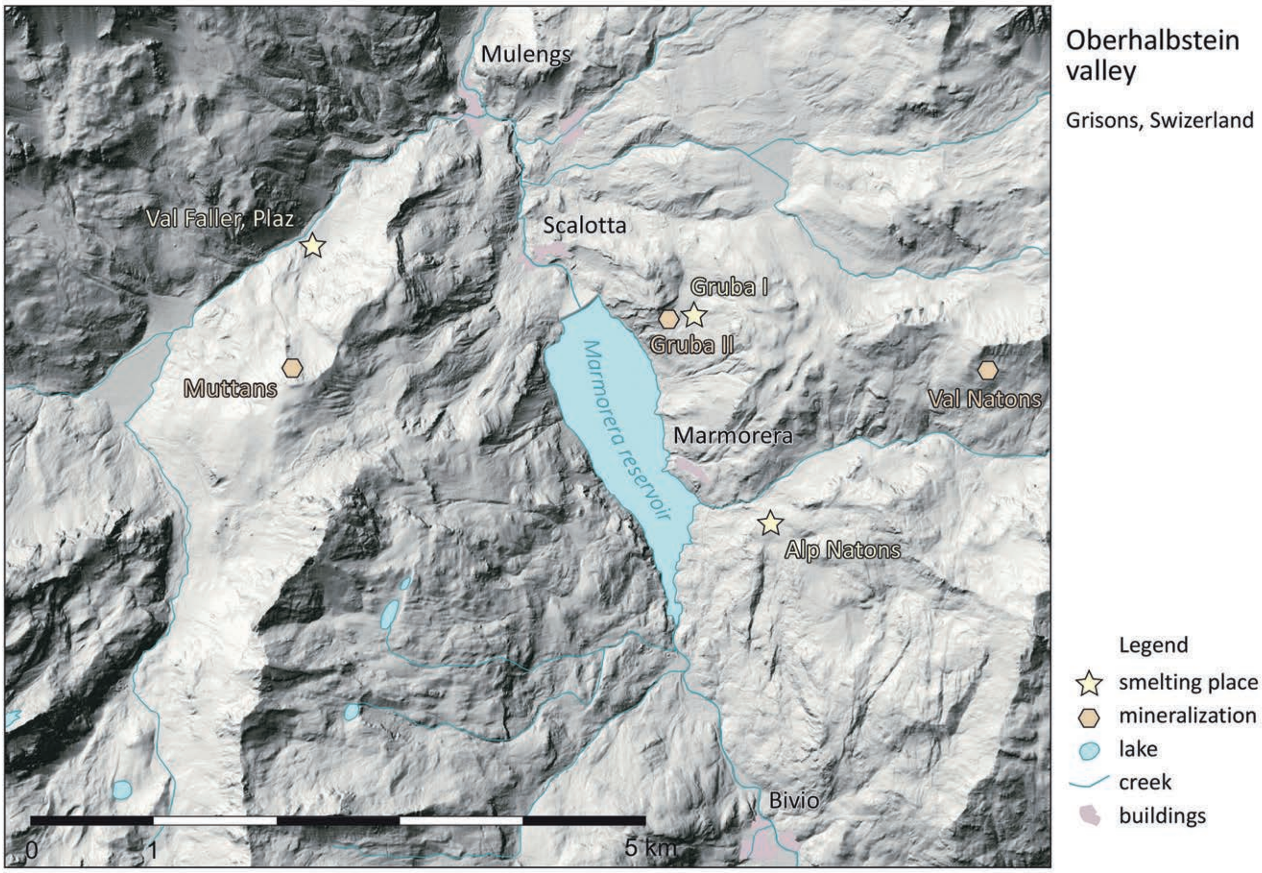

Fig. 1: Map of the Oberhalbstein, "upper valley", showing mineralization and smelting places mentioned in the text (graphic: Anja Buhlke, Rouven Turck/UZH).

identified during a systematic survey when remnants of a structure were discovered immediately underneath a public footpath.

Gruba I

The site Gruba I has been documented by Schaer (2003, No.37, there labelled "Ried südlich Gruba I"), and is one of the well-known sites mentioned many times before in abridged reports (e.g. Fasnacht, 2004). The site was selected for excavation because of possible remnants of a smelting furnace and a slag heap identified and visible above ground. It lies at 1850 m above sea level and has been described recently in JbAS 99 (2016, p.187).

Val Faller, Plaz

This smelting site had been previously exposed by road construction work resulting in the discovery of slags (Schaer, 2003, No.26). Due to this incident, an excavation and documentation of the site was in the interest of the ADG. A concrete localisation of suspected features was realised by geomagnetic survey beforehand (Della Casa et al., 2016 fig. 9). The site, lying at 1770 m above sea level, has been published in an abridged report (JbAS 100, 2017, p.219).

Research Summary

The Oberhalbstein valley runs from the metal age settlement of Motta Vallac in the north (Bradler, 2018), at an elevation of 1300 m above sea level, up to an elevation of 2500 m above sea level at Avagna (Reitmaier-Naef et al., 2015, pp.46-47).

Alleged prehistoric finds from smelting contexts are known for the Oberhalbstein since the 1950s and were discovered during building work around the Marmorera reservoir. They were first thought to be evidence of iron technology (Zindel, 1977). Only a mineralogical analysis of slags (Geiger, 1984; Geiger, 1988) finally pointed towards local copper smelting.

A few isolated radiocarbon dates vaguely suggested a prehistoric context for the smelting sites (Geiger, 1984). This interpretation was relevant in two ways: In the valley itself, the casting of metal artefacts is known from settlement contexts dating to the Bronze Age (Rageth, 1986; Fasnacht, 1991). Secondly, medieval smelting and smithing activity is also evidenced (Eschenlohr, 2012), which is why the systematic dating of sites is of great importance.

Schaer (2003) was the first to summarize all of the potentially prehistoric smelting sites, numbering to about 40. Due to the absence of systematic field work, the Oberhalbstein was soon listed as one of the Metal Age copper mining districts (Bartelheim, 2013, Fig. 2; Trebsche & Pucher, 2014, Abb. 1), but its scientific potential was usually estimated low because of the lack of research data (O`Brien, 2015, p.105).

The area under observation stretches from around Stierva, Tiragn (Naef, 2013) to the surroundings of Bivio near the peaks of the Julier Pass (JbAS 99, 2016, p.184). Additionally, slag heaps are known from the neighbouring valleys of Avers (Turck et al., 2017), Bergell (Wenk et al., 2019) and the Oberengadin (Schweizer, 1982).

Fewer slag heaps are known for the northern, lower valley stage with its Bronze Age settlements (Rageth, 1986; Bradler, 2018) as first defined by Schaer (2003), ranging from an elevation of 1300 m to 1700 m above sea level, than for the higher, southern valley stage ranging to an elevation between 1700 m and 2100 m above sea level.

The cultural and historical significance of the Oberhalbstein settlement area during the metal ages, including the important Septimer Pass leading to the Bergell valley, has been presented before, most recently by Turck et al. (2014, pp.250-252). Finds and features dating to the Iron Age deserve special attention in this context (Turck, 2015, pp.134-135).

Features evidencing the chaîne opératoire of copper smelting

In the following, excavated archaeological features that allow for a near complete reconstruction of the operational sequence of primary metallurgical activities in the Oberhalbstein valley will be discussed.

Mining

Prehistoric copper mining activity had not been proven until 2013. Initial leads (e.g. Brun, 1988, pp.63-65) were followed up during fieldwork, however, they shall not be discussed in depth here. Essentially, the previously documented sites of Vals (JbAS 98, 2015, pp.197-198), Cotschens, and Avagna (Reitmaier-Naef et al., in press) denote ore mineralizations that were exploited in prehistoric times. Non-destructive methods in geophysics gave promising preliminary results for metal age mining in Gruba II with the use of "Pingen", i.e. mining pits and galleries (Ullrich et al., 2019, pp.55).

For the three sites that shall be the focus of this paragraph, the following mineralizations already described by Dietrich (1972) are relevant (Fig. 1):

Fig. 2: Val Faller, Plaz, grinding stone and plate (photo: Anja Buhlke/UZH).

Following multiple notes (Dietrich 1972, p.39; Brun, 1988, p.62; Bernoulli et al., 2003, pp.102-103, Fig. 11) it was possible to establish a promising spatial relationship between smelting site Alp Natons and copper mineralization named Val Natons (Reitmaier-Naef, 2018, p.32).

In the case of Gruba I, it was possible to draw a possible connection to the site Gruba II (Reitmaier-Naef et al., 2015, p.45; JbAS 100, 2017, pp.218-219) at 200 m distance – a series of mining-related sinkholes. Whether the mineralization exhausted in modern times (Dietrich, 1972, 26-28; Brun, 1988, pp.56-61) was already exploited in prehistoric times, is impossible to say due to modern disturbances.

It would be logical for the site Val Faller, Plaz to be connected to a mineralization at Muttans (Dietrich, 1972, pp.34-38) – but this connection can so far not be proven. Comprehensive publications addressing the topic of prehistoric mining are currently in preparation.

Ore dressing and processing

So far, evidence related to the dressing of ore is scant in the Oberhalbstein valley. A few select stone objects (so-called „Gezähe") originating from an exploited pit at Cotschens hint at the crushing of ore in the immediate vicinity of the mine (Reitmaier-Naef et al., in press). To date, Val Faller, Plaz is the only smelting site where a grinding stone and a hammerstone could be recovered (Fig. 2).

Sluice boxes for ore washing as known from Troiboden, Mitterberg and Mauken in Austria (see Timberlake, 2019; Stöllner et al., 2012, Stöllner, 2019; Goldenberg et al., 2011a, pp.69-72), could not yet be archaeologically evidenced in the Oberhalbstein. Schaer's (2003, p.15) claims about a site named „Marmorera, gegenüber Natonsbach", which was poorly documented in the 1950s, could not be verified.

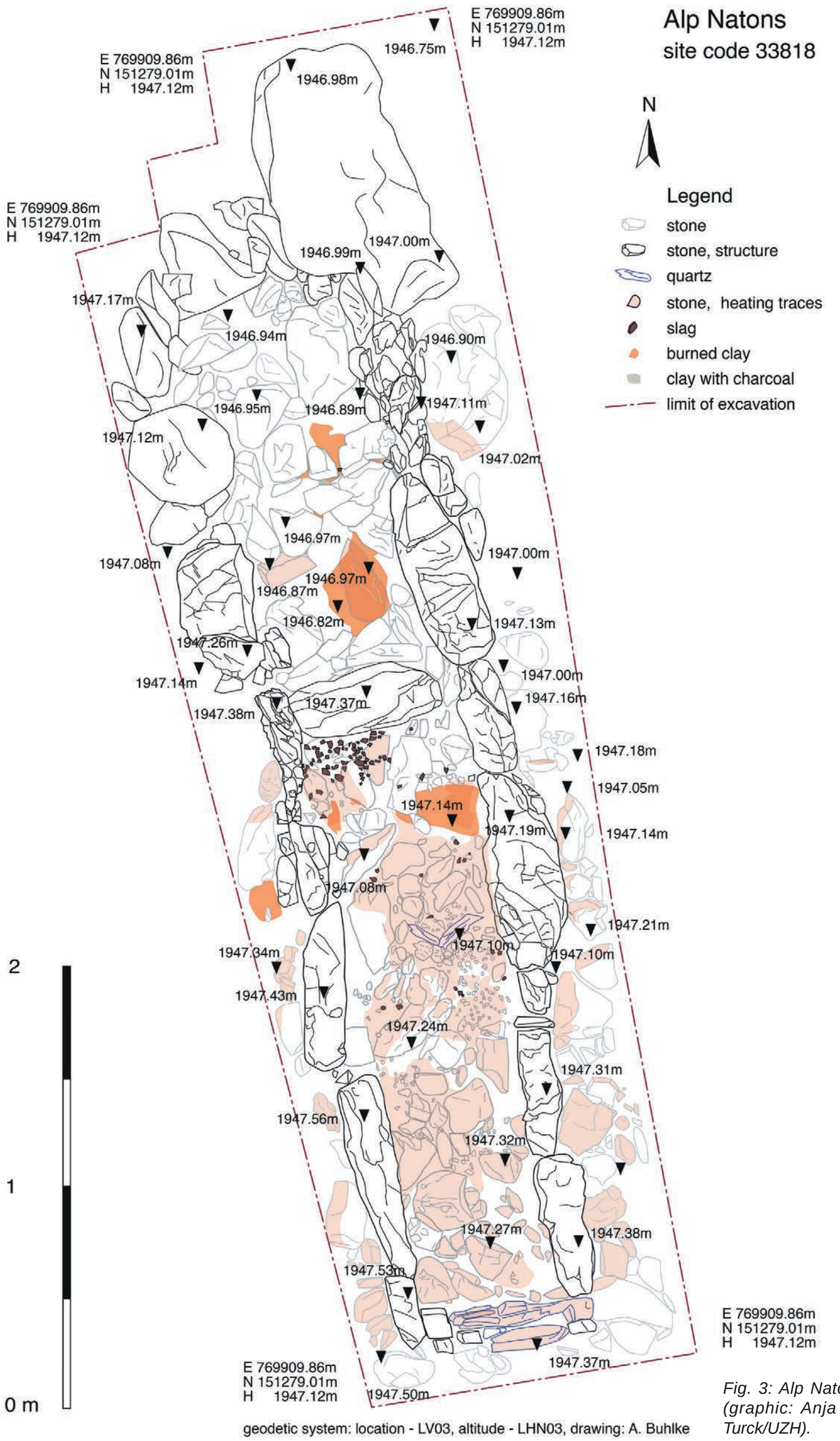

Fig. 3: Alp Natons, roasting bed (graphic: Anja Buhlke, Rouven Turck/UZH).

Roasting

At Alp Natons, as a result of the systematic survey in 2014, a roasting bed (Fig. 3) was first discovered, and then fully excavated in 2018. The feature is situated immediately below the ground surface. It measures 5.20 m in length while its internal dimensions are 70-80 cm. Its orientation runs almost along a North-South axis.

The large stones bordering the roasting bed demand special attention – they are up to 70 cm long and 30 cm thick, and many of them show reddish traces of heat.

A secondary addition to the stone bed is a large slab, which separates the feature into a northern and a southern part – 2 m and 3 m in size respectively. At first sight, the slab is reminiscent of a furnace's rear wall, like the one documented at Gruba I (JbAS 97, 2014, p.220).

On the inside, the structure contained many collapsed stones showing traces of heat in a secondary context. A multiple use of the structure is therefore evident. Slags, turned red by exposure to heat, lie in a dense cluster to the south of the stone slab. Parts of the lateral walls were smeared with clay, some of which is preserved *in situ* and also shows a reddish colour. Additionally, a clay lining could be identified. In terms of finds, charcoal, slags and burnt clay were recovered and samples taken for further testing.

Possible vestiges of another roasting bed, which had already been perturbed in prehistory, have been found at Gruba I, sector 55 (Fig. 4). A two-layered stone structure (upper Pos. 624 and lower Pos. 639) of a length of 2 m could be identified in the southeastern part of a 14 m^2 sondage. The lower layer shows intense traces of heat, while for the upper layer those traces are rather weak. Nevertheless does the upper layer show signs of tool use, making it likely that the stones were worked intentionally. More stones showing similar traces could be identified throughout the whole excavation area (e.g. Pos. 674).

A stone negative is located at a right angle towards the bounding stone (Pos. 649/650), indicating that a stone belonging to the construction was possibly removed.

The eastern and northeastern part of the stone structure is characterised by a large, charcoal-rich pit (Pos. 607), which damaged the original construction. In the northern part of the pit, right at the bottom, another stone negative (Pos. 647/648) could be identified. It is therefore possible that the pit impaired the roasting bed. If we interpret the second stone negative as evidence of the far end of the roasting bed, the structure would have measured at least 4 m in length – dimensions that roughly fit those found at Alp Natons. The two layers of the stone structure (Pos. 624 and 639) evidence the two-phase character of the construction.

For Val Faller, Plaz, the features are not as easily interpreted (Fig. 12): East and southeast of the smelting furnaces two ambiguous, rectangular stone structures (No. 1 and 2) could be identified. By dimension, these rectangular features find their counterpart in the structures discovered at Mauken and Jochberg in Austria (Goldenberg, 2004; Goldenberg et al., 2011a), but the absence of verifiable traces of heat on either stones or clay makes an unambiguous interpretation of the features impossible.

Smelting

The first smelting place presented here is Gruba I. Furnace 1 and its nearby slagheap were published in a preliminary report (Turck et al., 2014, pp.250-254; see also JbAS 97, 2014, p.220; JbAS 98, 2015, pp.196-197; JbAS 99, 2016, p.187). The features discussed below were excavated between 2013 and 2015 (Figs. 5-8).

The first prehistoric smelting furnace (Figs. 5-6) to be discovered in the Oberhalbstein was made up of two to three extant layers of stone, built up against a stone slab at right angles (Pos. 530). The front of the furnace had been destroyed immediately after its latest use. The front was surrounded by a stone structure with heat marks (Pos. 562). The furnace was dug into a pit (Pos. 539/547) measuring 50-60 cm in depth. A number of slag fragments, flakes of charcoal and some burnt stones were found inside and outside the furnace. The furnace bottom was covered with small stones (Pos. 601). A grey compound (some sort of "seal", Pos. 541) containing small flecks of charcoal and slag was worked into the left gap between the side and back walls, suggesting that it was used to repair the furnace. The rear wall of the furnace was dug vertically into the ground (Pos. 530) and intentionally fixed with wedges (Pos. 538). Three postholes located to the north (Pos. 528A and 528B, Fig. 5 and 7) and northwest (Pos. 577, Fig. 7) indicate a roof build over the work area.

The related slagheap (Pos. 563 and Pos. 614, Figs. 7-8) situated 2.5-3 m southwest of the furnace was partly surrounded by a layer of stones (Pos. 570).

Most tuyère fragments were found close to the southern part of the furnace (Fig. 8). Several fragments of burned clay associated with smelting activities in the furnace were located to the south and northwest of the furnace. Within this activity area, two pits of ca. 60 cm diameter each had been dug (Fig. 7; Pos. 616 and Pos. 621). The first pit was mostly filled with charcoal and some slags, while the second pit was lined with partly burned stones and clay. Lots of small quartz fragments could be documented therein.

The dense distribution of ceramic tuyère fragments directly south of the smelting furnace 1 at Gruba I is noticeable. We may be looking at a work site where damaged tuyères were kept or discarded to the right side of the furnace (Fig. 8).

Taking the whole context of the 2013-15 excavations at Gruba I into account, the density map (Fig. 9) permits the hypothesis that more smelting furnaces could be located in sector 56/8, and even more so in sectors 60 and 62. This predictive observation will need to be verified.

An overview over the numerous ceramic tuyère fragments can be found in Nüssli (2018), where a convincing tuyère reconstruction has also been advanced.

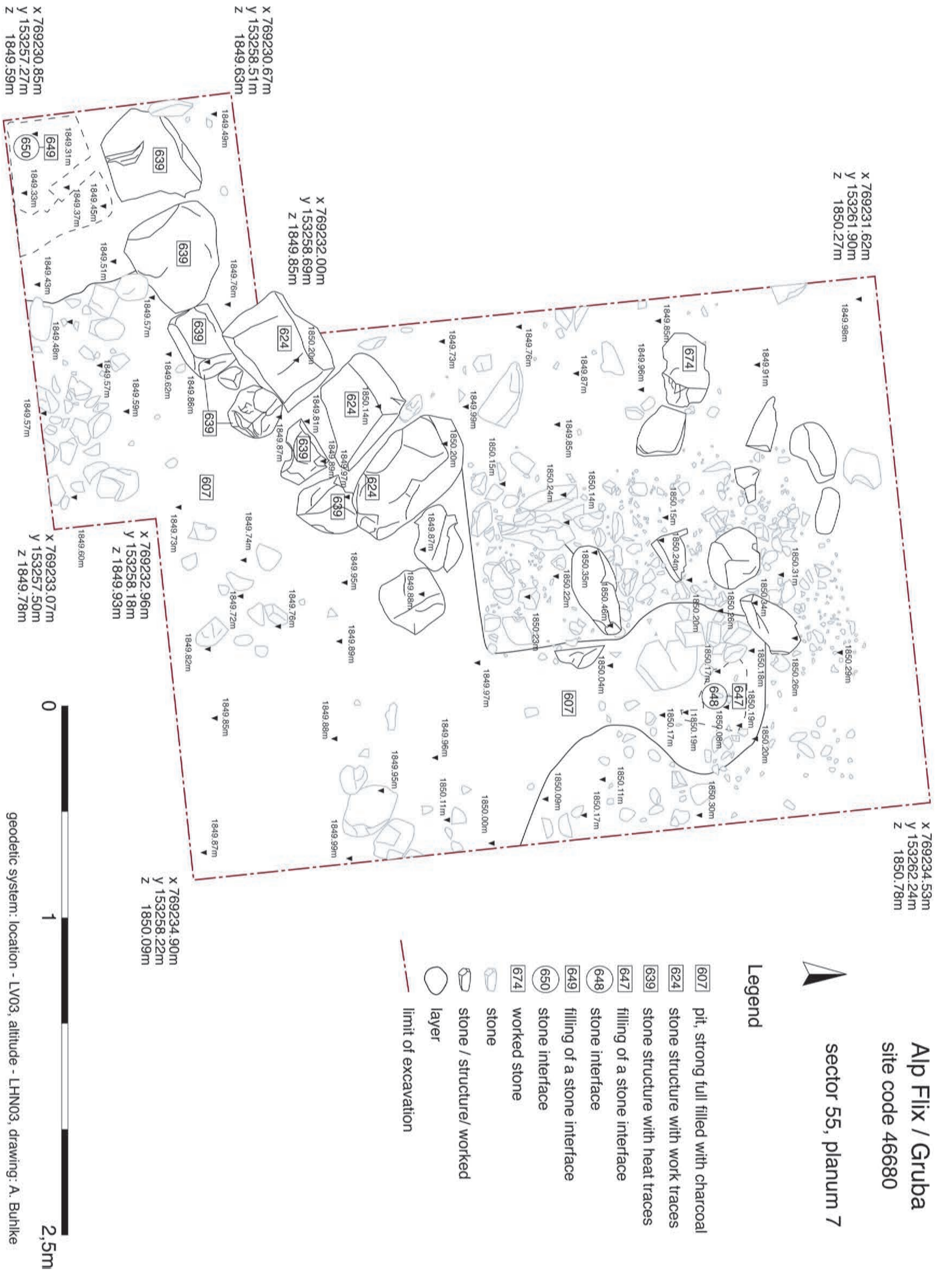

Fig. 4: Gruba I, roasting bed ? (graphic: Anja Buhlke, Rouven Turck/UZH).

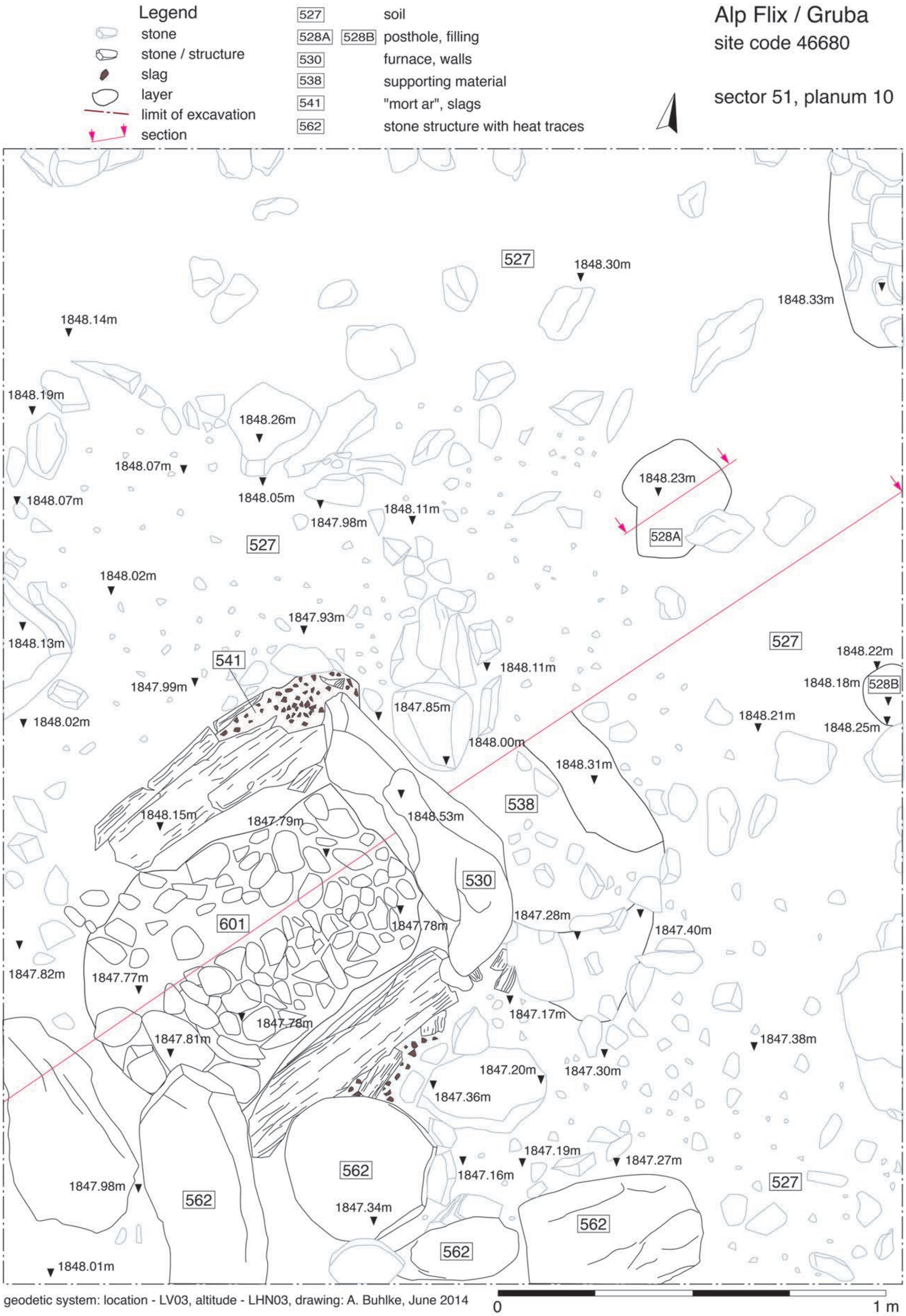

Fig. 5: Gruba I, furnace 1 (graphic: Anja Buhlke).

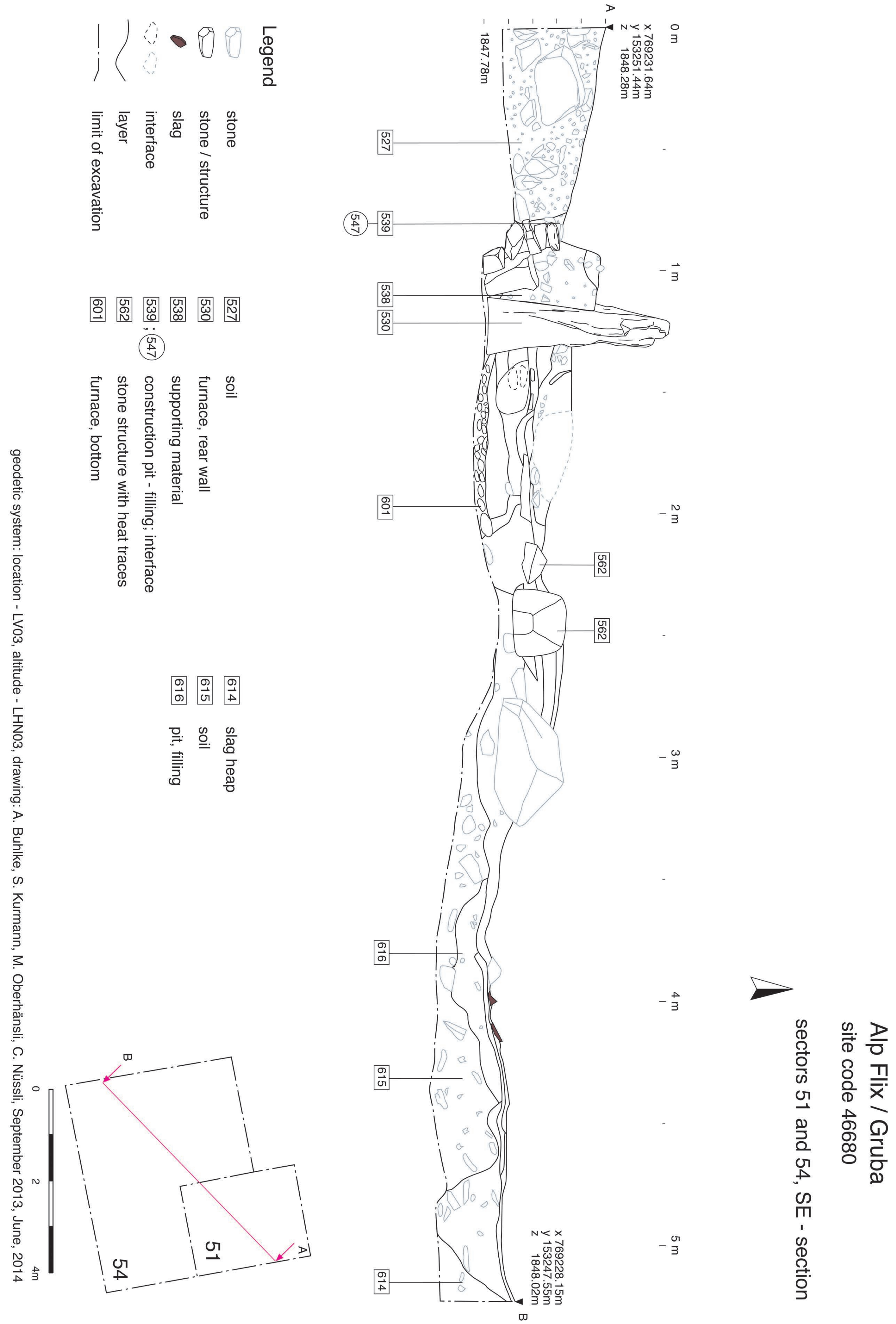

Fig. 6: Gruba I, SO-Profile, furnace 1 (graphic: Anja Buhlke, Simon Kurmann, Carlo Nüssli, Monika Oberhänsli/UZH).

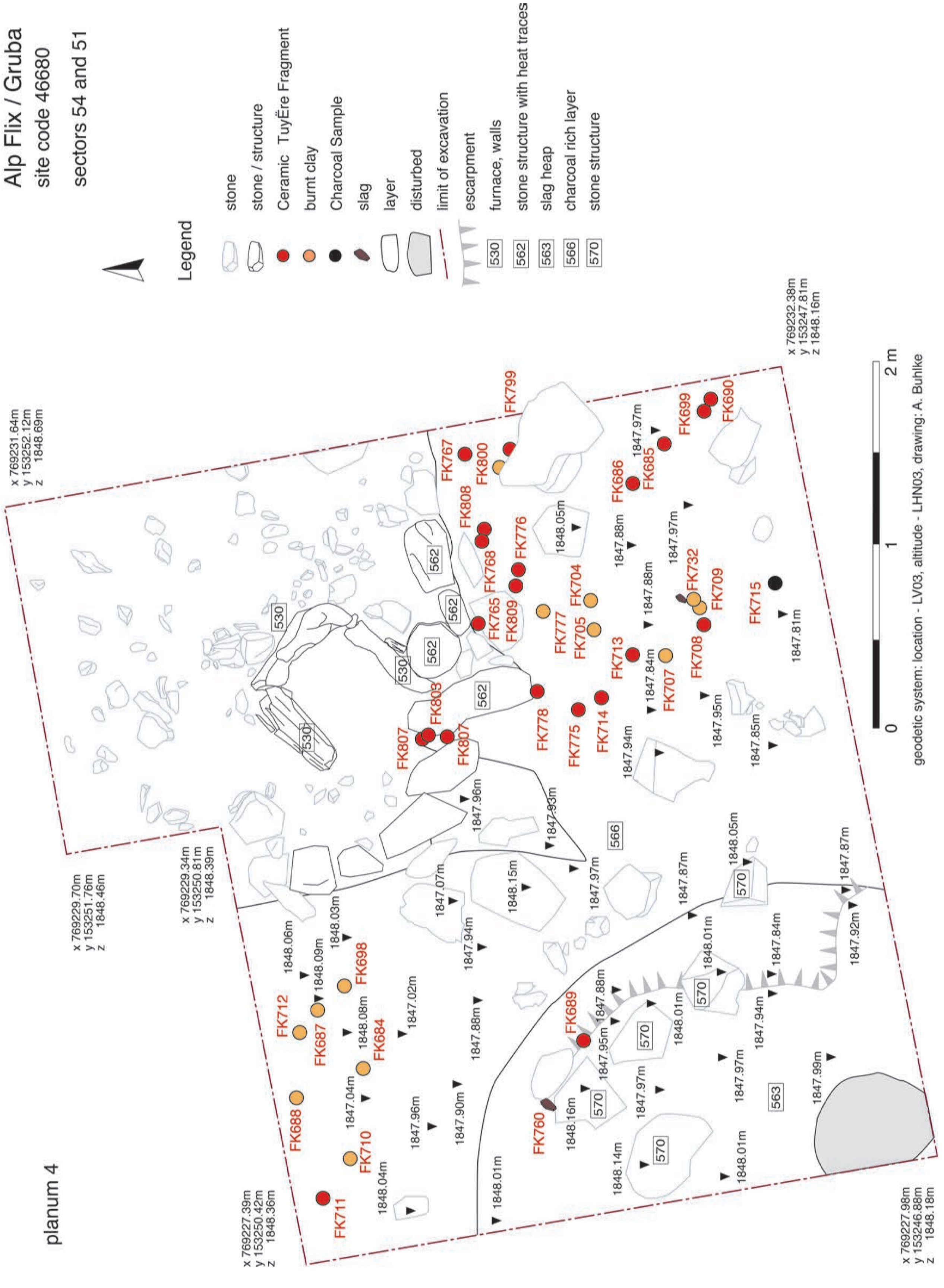

Fig. 7: Gruba I, furnace 1, slag heap 1, findings: tuyères (graphic: Anja Buhlke).

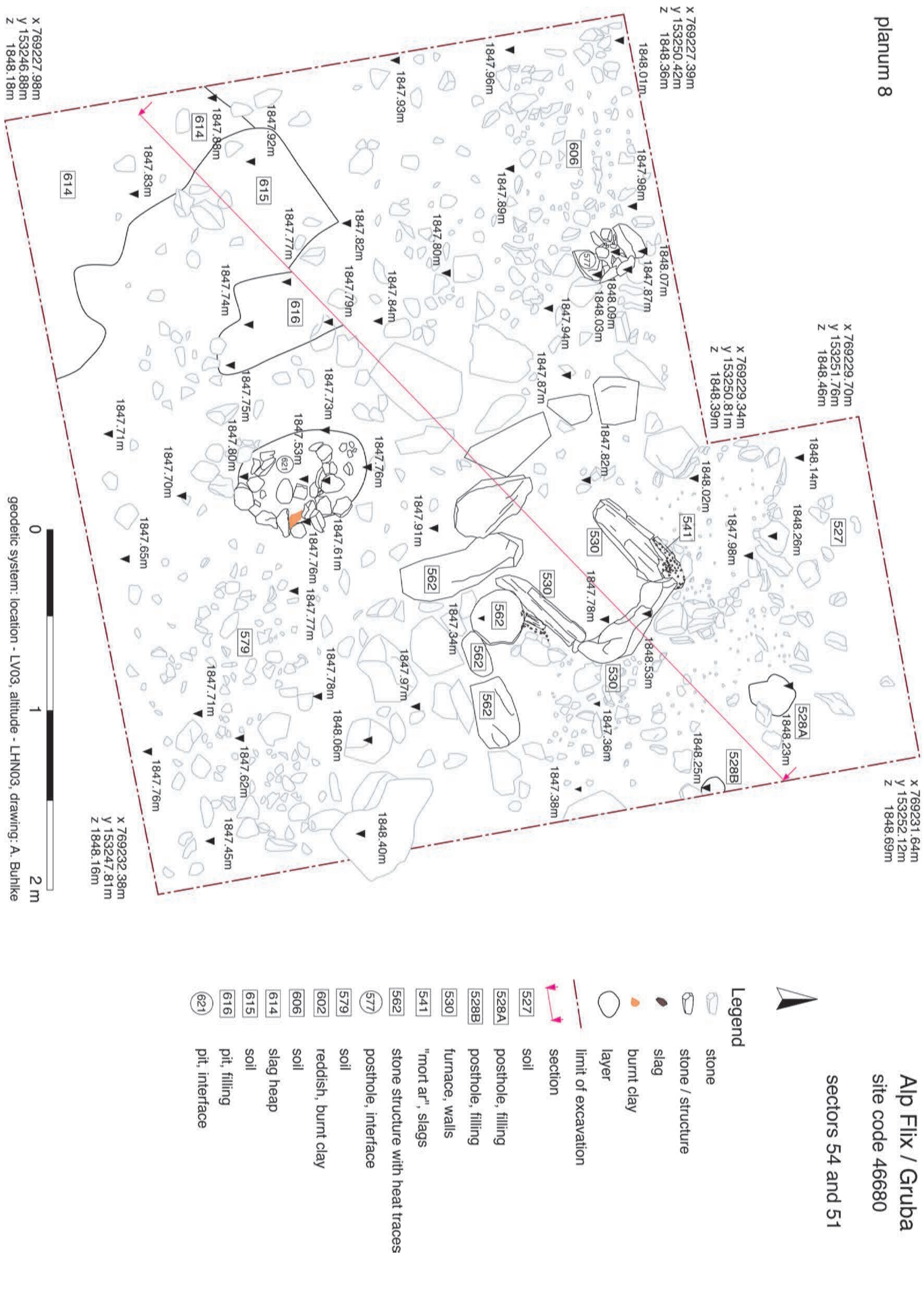

Fig. 8: Gruba I, post holes and pits (graphic: Anja Buhlke).

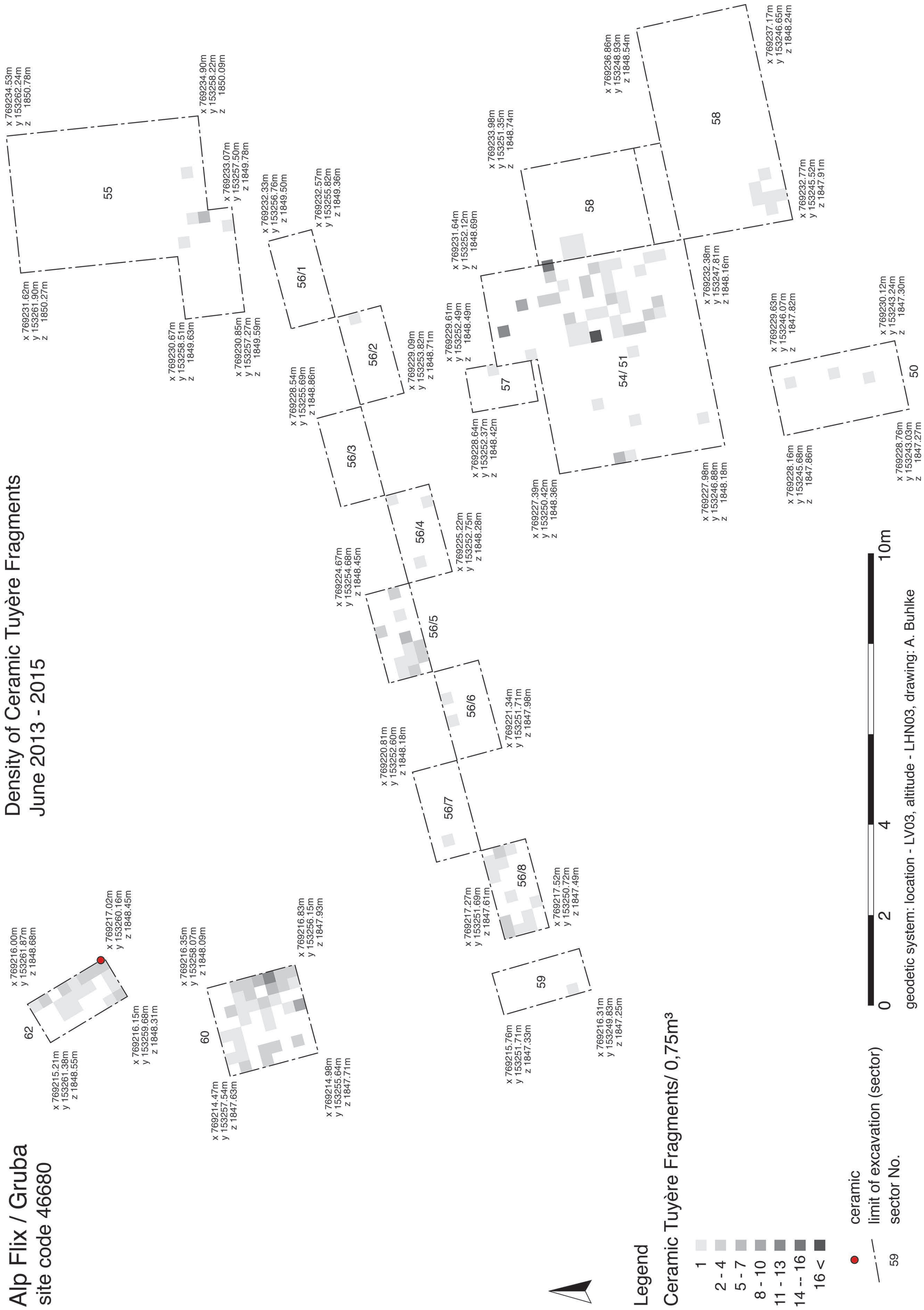

Fig. 9: Gruba I: tuyères, density map (graphic: Anja Buhlke, Carlo Nüssli, Rouven Turck/UZH).

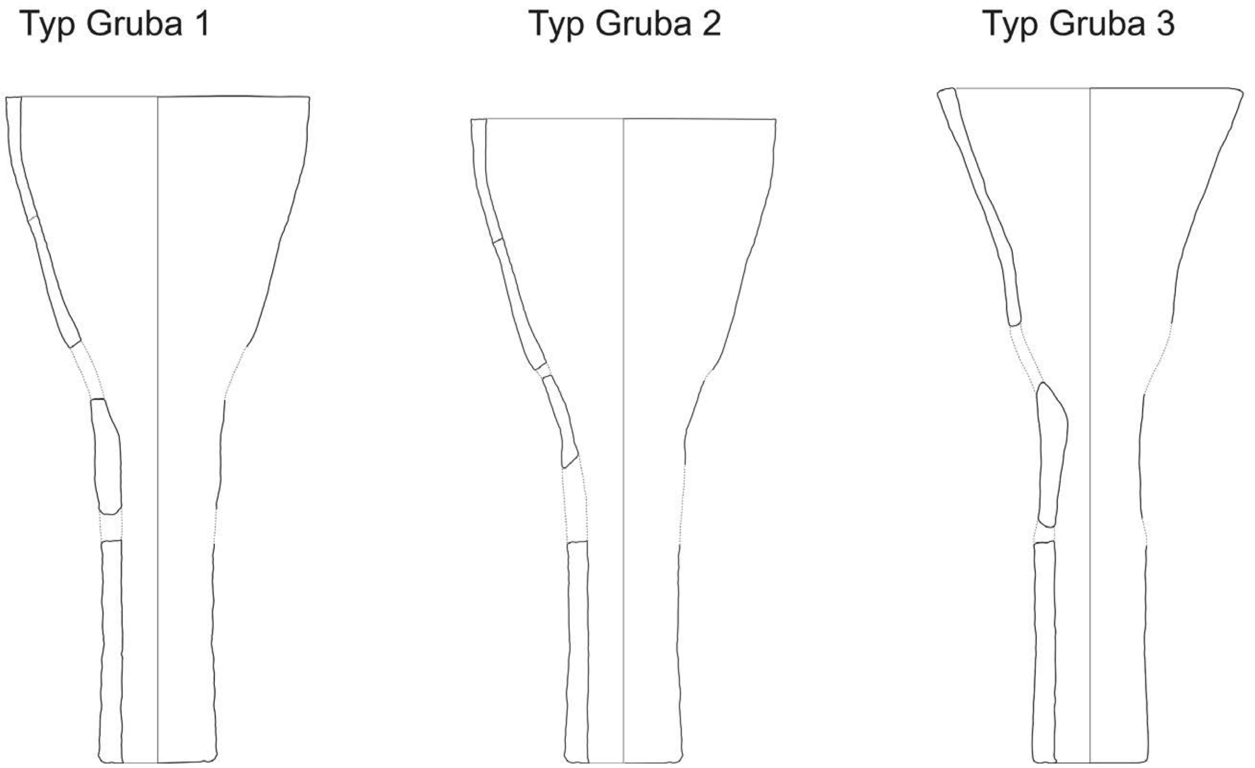

Fig. 10: Reconstruction of tuyères (graphic. Carlo Nüssli/UZH).

The ceramic tuyères with an inner diameter of 12-16 cm at their base and a length of up to 40 cm are in their basic shape (Fig. 10) reminiscent of those found in Mauken in Austria (Töchterle et al., 2013, Abb. 7), even though the burnt-in holes probably used to tie the bellows to the tuyère are missing. It has rightly been pointed out that Gruba I, with more than 500 documented tuyère fragments, from which at least 29 tuyères can be reconstructed, yielded an exceptionally large number of fragments compared to other sites of the Trentino, Mitterberg, Lower Inn Valley, etc. (Nüssli, 2018, pp.135-139). The pipe endings show traces of slagging (Fig. 11) and thus must have been inserted into the smelting furnace. Experiments regarding the tuyère's practical utilisation have not yet been conducted (cf. Goldenberg et al., 2011b; Hanning et al., 2015).

Two more smelting furnaces were uncovered at the site of Val Faller, Plaz (Fig. 12) (JbAS 100, 2017, p.219). Based on a geomagnetic survey (Della Casa et al., 2016), an area of 50 m² was excavated. The diameter of the documented slagheap measured more than 2.50 m. The thickness of the heap was determined by sectioning, revealing a thickness of at least 1.05 m. In the immediate vicinity of the slagheap lies a tripartite stonewall supporting the slope. Its eastern side is partially collapsed and consists of two to three layers of blocks of stone. The horseshoe-shaped furnace 1 (Fig. 13) was built into the supporting wall's northern side. Furnace 2 (Fig. 14) was instead integrated into the lower western flank of the wall structure. Furnace 1 is characterised by a kind of clay plaster covering its upper layer. The furnace's eastern side was insulated with a packing layer of slags. To the west and surrounding furnace 1, a work area was identified measuring 2.30 x 1.30 m. It is located atop the wall and runs towards the south with its central and western part boasting a layer of red and orange burnt clay.

Furnace 2, lying further to the west, resembles the shaft furnace found at Gruba I based on its stone rear wall and lateral walls attached at a right angle. Parallels to furnace 1 (Val Faller, Plaz) exist in the shape of the stone furnace floor. Both furnaces were in use at the same time.

Lying between the two furnaces and atop the north-western part of the wall, a grindstone measuring 0.5 x 0.45 cm (Fig. 2) was discovered. The wall, including both furnaces, runs from west to east at a length of ca. 4.0 m.

To the northeast of the described features, it was possible to partially excavate a pit measuring 1.0 m in diameter and 0.5 m in depth. The pit was essentially filled with charcoal and partly lined with stones and clay. It shows similarities to the pit discovered at Gruba I, sector 55 (Pos. 607) (compare with Fig. 4) and sector 54 (Pos. 621) (compare with Fig. 8).

Comparison of the smelting sites Gruba I and Val Faller, Plaz

Both sites have similarities and differences. For Gruba I, only one furnace could be clearly identified, while Val Faller, Plaz yielded two. Both these furnaces are integrated into the natural slope by means of a dry-stone wall, while the

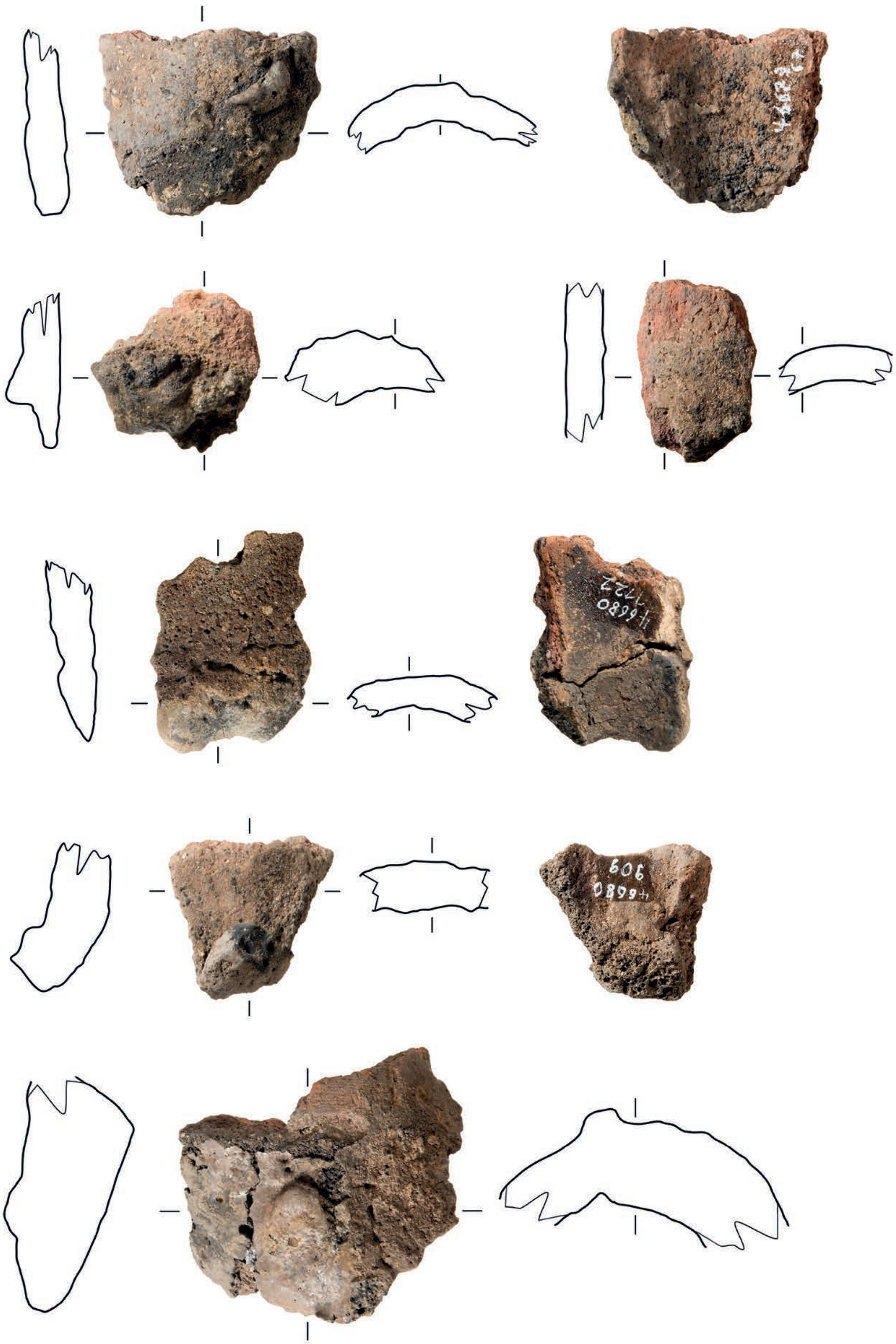

Fig. 11: Fragments of tuyères (graphic: Carlo Nüssli/UZH).

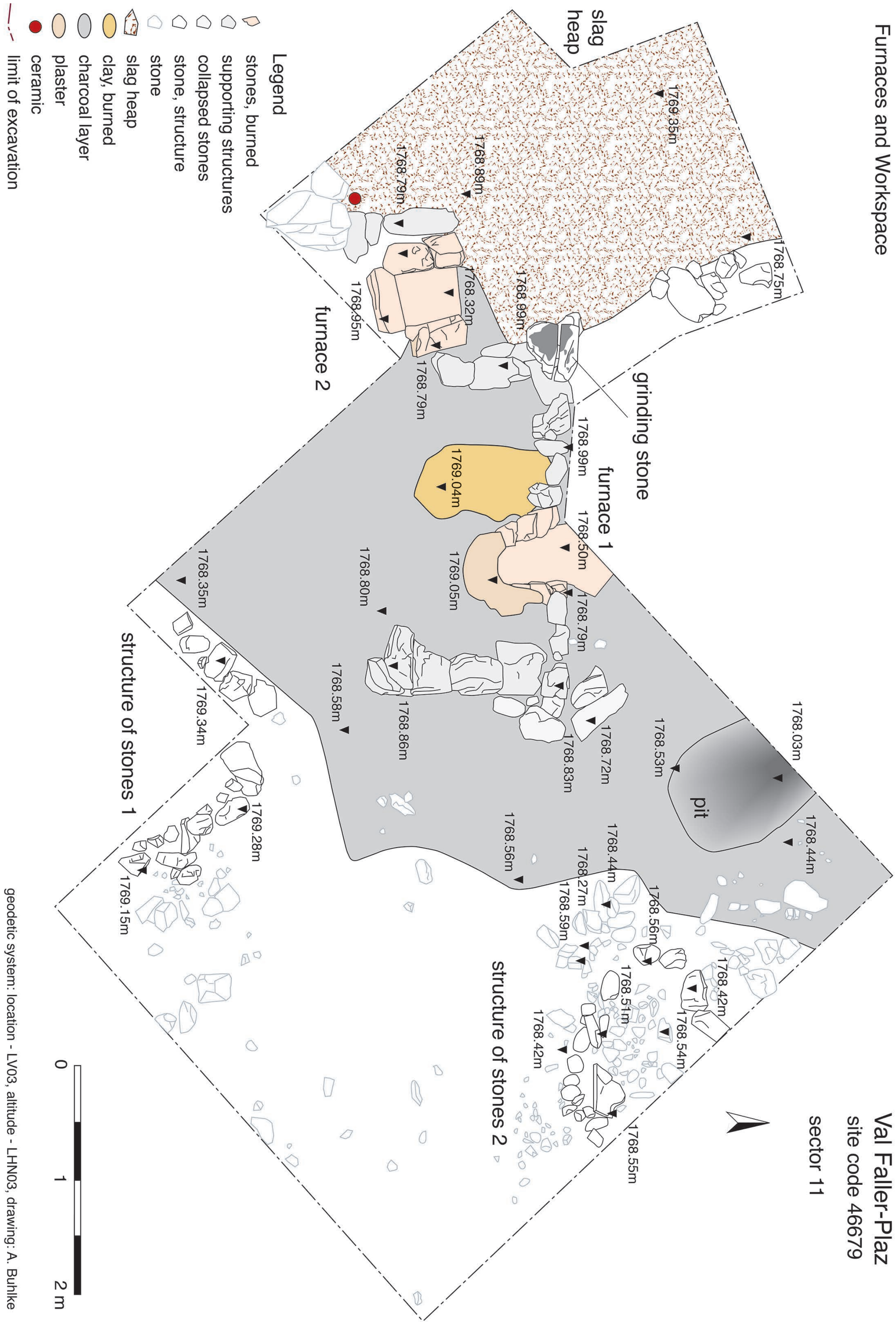

Fig. 12: Val Faller Plaz, furnaces 1 and 2 (graphic: Anja Buhlke/UZH).

Fig. 13: Val Faller, Plaz, furnace 1 (photo: Mirco Brunner/UZH).

Fig. 14: Val Faller, Plaz, furnace 2 (photo: Mirco Brunner/UZH).

furnace at Gruba I is freestanding and was constructed in a pit. For Gruba I we can assume a roofed structure covering the workspace near the furnace. For both sites, possible roasting beds can be presumed, but due to the ambiguity of the features they cannot be assigned without doubt.

The construction of pits seems to follow a systematic pattern – the pits from both sites, Val Faller as well as Gruba I (sector 55, Pos. 607), share similarities, as in each case they seem to have mainly contained charcoal, similar to pits for charcoal burning documented in medieval times (Klemm, 2010, pp.189-191; Fig. 2, pit type 2). Whether these are specific vestiges of the smelting process or charcoal burning pits, is yet to be discussed.

Pit 621 at Gruba I is much smaller and shallower, and it has been suggested that it was used to burn or crush quartz which can be used as a flux in the furnace. No similar features could be documented at Val Faller, Plaz. On both smelting sites, the slagheaps lie in the immediate vicinity of the furnaces at 2-3 m distance.

Comparison of the roasting beds and smelting furnaces

Despite the roasting bed at Alp Natons being smaller, a comparison with the bed of Flecksberg-Viehscherm published by Zschocke & Preuschen (1932, pp.76-79, Taf. III) is viable. These authors also documented a dividing block of stone or slab being integrated into the structure, resulting in approximately the same proportions. The description of layers of partially burnt clay and slags seem to follow a similar principle as described for roasting beds at Mauken (Mauk A, Goldenberg et al., 2011a, pp.74-76) or Jochberg (Goldenberg, 2004, pp.169-170). The dimension of the roasting bed of Alp Natons is much larger and its construction is more sturdy.

The three different smelting furnaces can be roughly divided into two groups: While a comparison between the furnace found at Gruba I and furnace 2 identified at Val Faller results in many similarities between the two, including nearly all aspects of their construction except the stone floor, the horseshoe-shaped furnace 1 at Val Faller, Plaz contrast sharply with the other two.

The following parallels to other smelting furnaces from the Eastern Alps can be drawn: Val Faller's furnace type 1 is, with regards to its size and shape, reminiscent of furnaces from the region of Kitzbühel (Koch Waldner & Klaunzer, 2015, Abb. 7), and to a lesser extent of the heavily fragmented furnaces discovered at Mauken (Mauk A, Goldenberg et al., 2011a). Smelting furnaces from the Eisenerzer Ramsau seem to have been constructed alike, despite being twin furnaces (Klemm, 2015).

A comparison to the furnaces in Trentino (Cierny, 2008) seems generally possible, even though the Oberhalbstein valley does not possess furnace batteries on such a massive choro- and chronological scale as is the case in Trentino. At Sant'Orsola Val (Silvestri et al., 2015, Abb. 7) furnaces were built into the slope integrating the use of a dry-stone wall, thus resembling the Val Faller type of furnace construction.

For the rectangular construction of furnaces with massive rear and lateral walls as witnessed for furnace 1 (Gruba I) and furnace 2 (Val Faller) there are no comparative examples from the Eastern Alps.

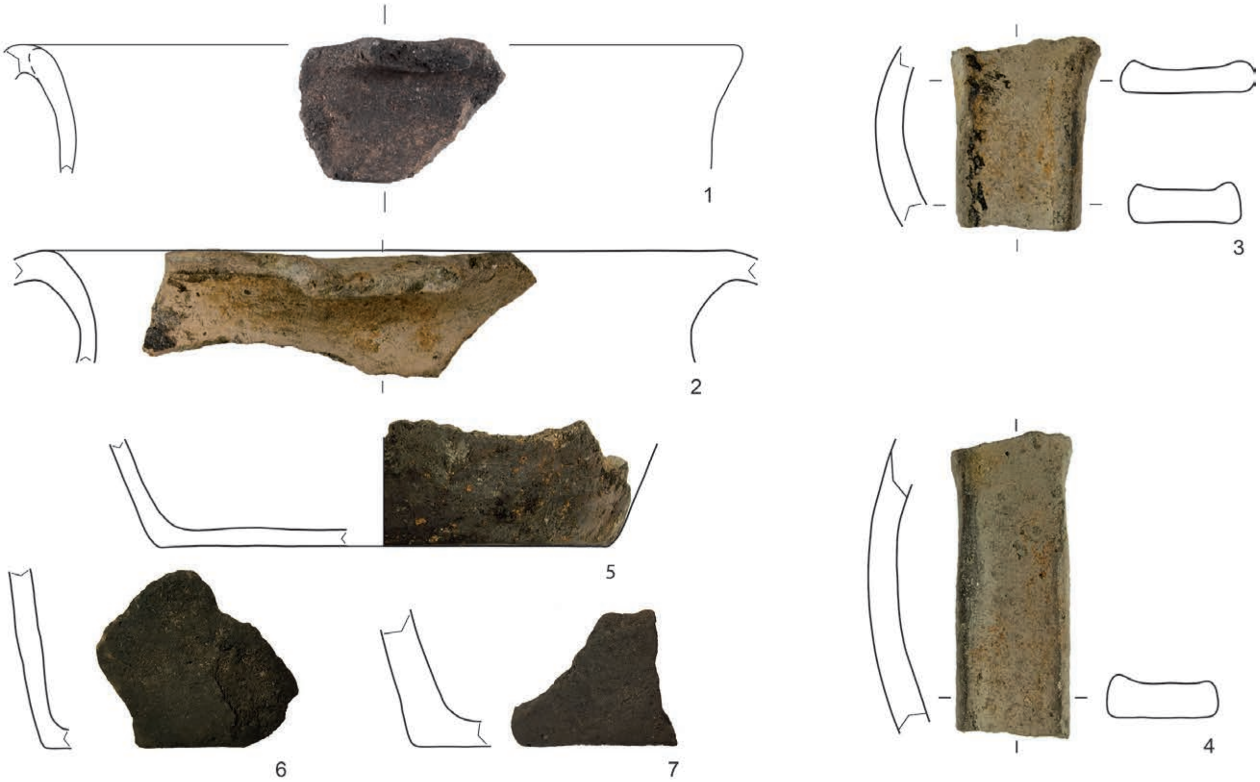

Fig. 15: Ceramics, Taminser pottery: 1. Gruba I; 2.-7. Val Faller, Plaz (photo/graphic: Michelle Bradler, Pierina Roffler/UZH).

Historico-cultural classification and relative chronology

The small numbers of domestic pottery from both excavated sites are the only diagnostic finds of all fieldwork campaigns. The two rim sherds found at Gruba I (Fig. 9; Fig. 15.1) and Val Faller, Plaz (Fig. 12; Fig. 15.2), where also two flat handles (Fig. 15.3-4) and three bases (Fig. 15.5-7) were discovered, can all be identified as pottery of the so-called "Taminser" style.

A few comparative finds from the northern Rhine valley shall be listed here exemplarily: Cazis, Cresta (Murbach-Wende, 2016, pp.162-165), the eponymous burial ground of Tamins (Schmid-Sikimic, 2002, pp.250-255), Chur, Markthallenplatz (Rageth, 1992, p.85), Wartau -Ochsenberg (Schmid-Sikimic, 2012, pp.112-114) and Montafon (A) (Klopfer, 2015, p.73). In the Oberhalbstein valley, Taminser pottery has been found at Savognin Padnal (Rageth, 2002, p.100) and Motta Vallac (Roffler, 2018, p.33). Another two fragments were found in smelting places (Schaer, 2003, Taf. 3, 90; Taf. 3, 96).

In relative dating, the pottery has been assigned to the 6th century BC, although the lack of closed finds is evident (Schmid-Sikimic, 2012, p.113; Murbach-Wende, 2016, p.162). Dating the material to the Early Iron Age matches up well with the sites' dendrochronological results (Oberhänsli et al. 2019).

Interpretation

Based on archaeological fieldwork, it was possible to evidence some of the essential processes of the operational sequence of the copper smelting metallurgy in the Oberhalbstein valley (Fig. 16).

While the evidence for ore dressing is scarce, ample evidence for the mining, roasting and smelting of ores – as part of an at least two-stage process – exists.

As can be shown exceptionally well for Gruba I and, to a lesser extent, for Val Faller, Plaz, the smelting processes took place in a highly organised work environment. The smelting furnaces were elaborately roofed over (Gruba I) or, possibly for the sake of insulation, integrated into the slope by means of walls. The slagheaps are located in throwing distance to the smelting furnaces.

The roasting bed from Alp Natons and the furnace of type 1 from Val Faller, Plaz can be compared to Bronze Age precursors in the Eastern Alps. A rectangular type of smelting furnace as identified at Gruba I (furnace 1) and Val Faller (type 2) seems to represent a type so far unique to the Oberhalbstein valley.

The two types of furnaces show, analogous to the three types of slags defined (Reitmaier-Naef, 2018; Reitmaier-Naef, 2019), evidence of a multi-phased copper smelting process.

Oberhalbstein “chaîne opératoire“, documented features, primary copper production				
copper mining	dressing / processing, mechanical	dressing / processing, washing	roasting	smelting
✔✔	(✔)	--	✔	✔✔

Fig. 16: Features: primary copper chaîne opératoire of the Oberhalbstein valley (graphic: Rouven Turck/UZH).

Elements of a settlement based on the processing of ore („Werkplatzsiedlung”, as e.g. in the Mauken valley: Goldenberg et al., 2011a, p.76) and social and economic conditions of miners and smelters (Stöllner, 2015) cannot be convincingly advanced, as we are missing the necessary specific finds and features: No evidence of subsistence economy, food supply or other activities addressing the daily life of Iron Age mountain inhabitants could be identified so far.

Conclusion and forecast

This paper introduces all archaeological features excavated to date within the SNF-DACH project in the Oberhalbstein valley that form part of the primary metallurgical processes. Except for missing evidence regarding wet processing, and only scarce information related to ore dressing, the operational sequence is deemed complete. A roasting bed and smelting furnaces were documented for the first time in the Swiss Alps.

The sites Gruba I, including a furnace and possibly a roasting bed, and Val Faller, Plaz with its two dissimilar furnaces, are of central importance. Different work steps in the process of copper smelting could be discerned in particular at Gruba I.

The two different types of furnaces documented at Val Faller, Plaz point towards a smelting process that was made up of at least two separate steps. Both discussed smelting sites date, based on relative as well as absolute datings, to the Early Iron Age-late Hallstatt period.

Note

1 The excavations have been published regularly since 2014 as abridged reports in the Jahrbuch Archäologie Schweiz: Jahrbuch Archäologie Schweiz 97, 2014, pp.220-221; 98, 2015, pp.194-200; 99, 2016, pp.184-187; 100, 2017, pp.218-219; 101, 2018, p.195, p.198, pp.263-264; 102, 2019, p.175, p.238. On behalf of the Zurich research team including Leandra Reitmaier-Neaf and Philippe Della Casa, we would like to thank our cooperation partners from the DACH team – especially Gert Goldenberg, Caroline Grutsch und Markus Staudt – for their initial support to the fieldwork. We would also like to thank our colleagues from the Archaeological Service of Grisons (ADG), with Thomas Reitmaier being named as their representative, for their long-standing support. We are also grateful for many useful leads by Jürg Rageth and Andrea Schaer.

Abbreviation

JbAS: Jahrbuch Archäologie Schweiz

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Author

Rouven Turck – Universität Zürich, Institut für Archäologie, Fachbereich Prähistorische Archäologie

Correspondence and material requests should be addressed to: turck@archaeologie.uzh.ch

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Leandra Reitmaier-Naef

Copper smelting slag from the Oberhalbstein (Canton of Grisons, Switzerland)

Methodological considerations on typology and morphology

ABSTRACT: *Mining archaeologists and archaeometallurgists have attempted to decipher the prehistoric multistage process of copper smelting from chalcopyrite for a number of decades. For this purpose, various examinations of archaeological remains, historical and ethnographical comparisons and archaeological experiments have been carried out. Apart from archaeological structures such as furnaces, very little if any of the original raw materials (copper ore) or final products (matte/raw copper) remain from which the process could be reconstructed. Only smelting slag is usually available in vast quantities. By conducting geochemical and mineralogical analyses of this by-product, information can be gained concerning the raw material, charge composition, process temperature, furnace atmosphere and even the resulting (intermediate) product. Despite these efforts, a number of questions remain unsolved, e.g. the much-debated association of different slag types with different process steps or reactors. From an archaeological point of view, this is due in part to the fact that slag samples are usually described and discussed in insufficient detail, if at all. They are often generally classified as one of only two tentatively defined types: "slag cakes" and "plate slags". This paper aims to demonstrate the additional value of a detailed archaeological evaluation of macroscopic characteristics of smelting slag using finds from the Oberhalbstein region (Canton of Grisons, Switzerland) as an example. The typology and morphology of smelting slag must be taken into account in addition to, and not instead of, further investigations, particularly of geochemical and mineralogical analyses.*[1]

KEYWORDS: COPPER SMELTING, PROCESS RECONSTRUCTION, SLAG TYPOLOGY, BRONZE AGE, IRON AGE, CENTRAL ALPS

Introduction

The Oberhalbstein region is located in the central Alpine Canton of Grisons (Switzerland) and has a north-south extension of 35 km. Connecting the Rhine and Albula Valleys with the Engadin Valley to the north across the Julier Pass and with the Bregaglia Valley to the south across the Septimer Pass, the Oberhalbstein Valley has been an important transalpine traffic route since prehistoric times. The first perennial settlements throughout the valley date back to the beginning of the 2nd millennium BC. Besides trade and Alpine farming, the exploitation of local copper ore deposits also formed part of the economy from no later than the Late Bronze Age onwards.

Although site distribution maps have therefore included the Oberhalbstein region in south-eastern Switzerland as a prehistoric copper production region for a number of years[2], no systematic archaeological investigation had until recently been carried out. For this reason, little was known about this prehistoric mining district, which stands in sharp contrast to the long tradition of research in the eastern and western Alps.[3]

The Department of Prehistoric Archaeology at the University of Zurich and the Archaeological Service of the Canton of Grisons have been carrying out extensive fieldwork in the Oberhalbstein in recent years as part of an international research project entitled "Prehistoric copper production in the eastern and central Alps - technical, social and economic dynamics in space and time".[4]

The current results clearly show the peripheral location of the copper production area under investigation – both from a geographical and a chronological point of view. While most of the (south)eastern and western Alpine mining districts flourished during different periods of the Bronze Age, the Oberhalbstein Valley did not reach its production peak until the Early Iron Age.[5]

This raises questions regarding the economic, technological and social significance of the Oberhalbstein

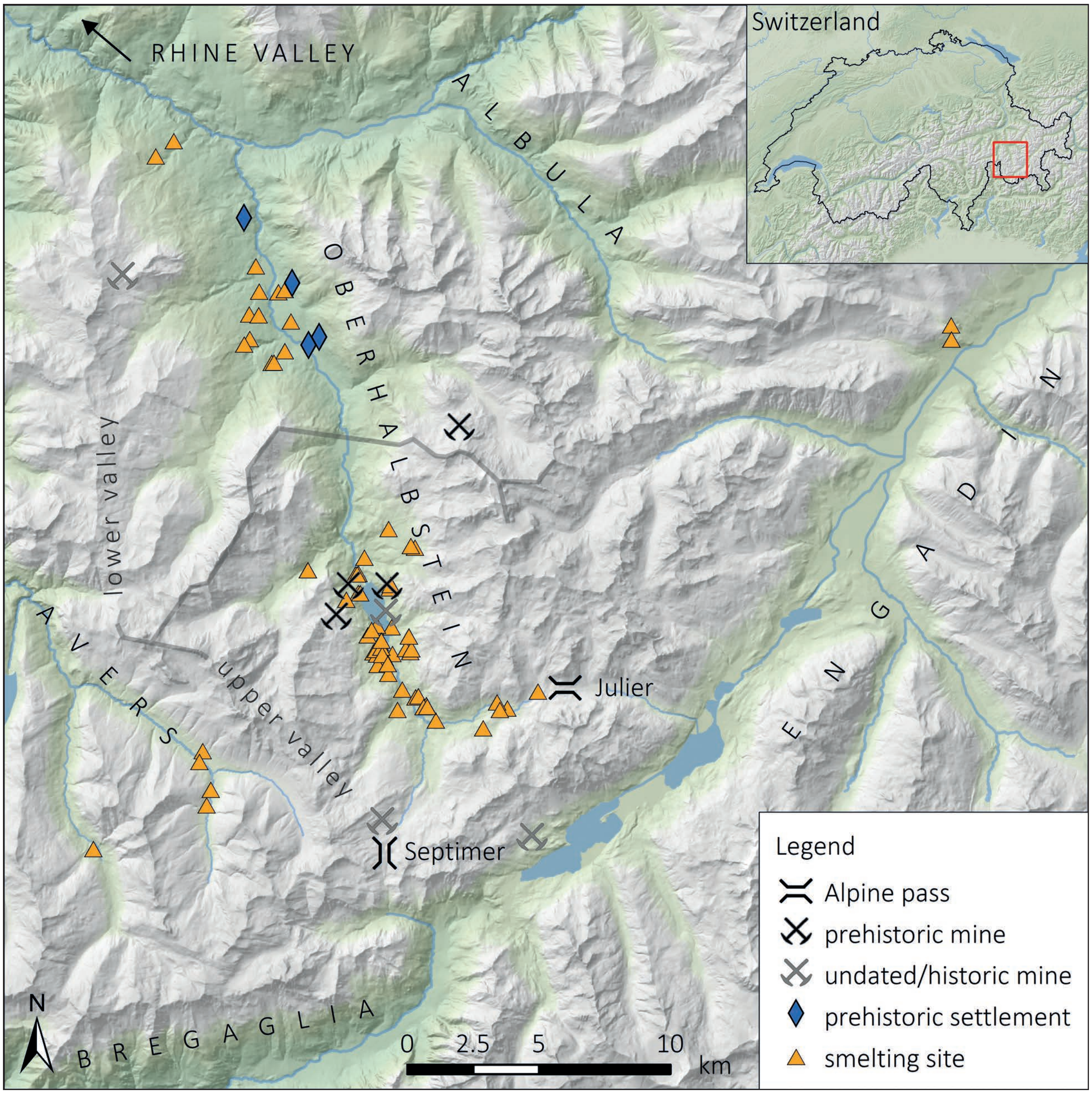

Fig. 1: Site distribution map of the study area (map: L. Reitmaier-Naef, University of Zurich; geodata: Federal Office of Topography and Canton of Grisons).

Valley in the context of prehistoric copper production and the associated processes in the Alpine region. Thanks, among other things, to the availability of an extensive material basis in the study area and a considerable body of (published) data from other regions, this paper focuses on the technological aspects of the smelting process.

The study area contains a significant number of mainly small dispersed sulphidic ore deposits with a rather low copper content. The majority are found in the ophiolithic serpentinite of the Platta nappe. Like the smelting and mining sites, mineralisation is divided along the same lines as the geography of the Oberhalbstein Valley. While the ores in the lower part of the valley show simple compositions of pyrite, chalcopyrite and magnetite, the mineralisation in the upper part of the valley is much more complex in that it includes varying percentages of pyrrhotite, chalcopyrite, magnetite, ilvaite, sphalerite, bornite and bravoite. [6]

In order to investigate and attempt to understand the production process ("chaîne opératoire") from start to finish or at least to an advanced stage, the mineralogical and geochemical evaluation of the ore mineralisation was studied as part of a subproject, which included surveying, sampling and analysing the majority of the known outcrops.[7]

As part of the ore prospection a series of old workings were documented, most of which were already known. Besides a number of medieval/modern sites, at least three prehistoric mining sites were identified and investigated.[8] A more detailed investigation of another set of promising mines of unknown date is still ongoing.

While our knowledge of prehistoric mining in the Oberhalbstein Valley has clearly been extended in recent years, the next step in the process, i.e. ore beneficiation, has not yet been sufficiently studied since no beneficiation site has been uncovered so far. It remains unclear whether this type of site never actually existed in the study region or whether the lack of evidence simply reflects the current state of research. Moreover, the complete absence of slag sand at smelting sites means that there is no evidence of the use of (wet)mechanical enrichment methods. It is therefore conceivable that a simple beneficiation process was carried out in the immediate vicinity of the individual mines and that this did not take place at specific sites. This assumption is reinforced by the most recent discovery of several stone tools in the vicinity of a prehistoric mine in Cotschens.[9]

The vast majority of mining-archaeological evidence points to smelting sites. Around 80 smelting sites and slag deposits dating from the Late Bronze and Early Iron Ages are known throughout the Oberhalbstein and the adjacent Avers and Engadin Valleys at altitudes of between 1100 and 2050 m a.s.l. Almost all of these sites were re-recorded or even newly discovered in the course of an extensive survey in 2014-2018.[10] Furthermore, excavations at selected sites around Lake Marmorera in the upper part of the valley extended our scarce knowledge of smelting structures in general.[11]

A number of prehistoric settlements near these mining archaeological sites regularly yield slag finds, thus creating a link to copper production activities. It is not yet clear which steps in the copper mining process, if any, took place at these sites, though a substantial number were subject to archaeological excavations in the 20th century.[12] Future investigations of the slag material and metal artefacts will hopefully shed further light on this matter.

Smelting slag – a key to deciphering the smelting process

All mining and smelting sites are characterised by a scarceness of or an imbalance in the archaeological finds. Apart from a very small number of potsherds and potential stone tools, the finds consist merely of fragments of tuyères, and large amounts of smelting slag and charcoal.

As a consequence, only two main groups of material besides the archaeological finds and structures are available for analysis, from which the reconstruction of the local smelting process can be attempted: copper ore[13] and smelting slag. Intermediate and finished products such as matte and copper have not yet been discovered at any of the smelting sites in the Oberhalbstein Valley. This paper will therefore focus mainly on the slag.

There are different ways of approaching this type of archaeological material. The most common approach involves mineralogical and geochemical analysis in order to decipher step by step the chemical reactions that take place in the process of turning ore into metal. While appropriate analyses have been carried out at the German Mining Museum in Bochum in collaboration with Prof. A. Hauptmann, they are not the subject of this paper.[14]

Since the results of such analyses are not always self-explanatory, complementary investigations such as historical or ethnological comparisons and archaeological experiments must be carried out in order to provide a more plausible interpretation of the data. In recent years, various studies have demonstrated the importance and considerable potential of such approaches.[15]

However, since no archaeological evidence in the form of smelting furnaces or roasting beds were known in the research area until recently, the data available was too limited to allow for scientific archaeological experiments.

With a view to overarching questions, economic and econometrical aspects are also of interest with regard to wide-ranging dynamics and processes.[16] However, this complex topic is still subject to theoretical and methodological debate. A significantly large database and extensive knowledge of the study region are required in order to deal with the numerous variables and to produce realistic results.

Therefore, a different approach has been taken for the present study, which focuses on the typology and morphology of slag, a popular archaeological method, which is often neglected or at least not sufficiently considered in this specific field of research.[17] This is all the more surprising given that typological methods represent a cornerstone of archaeological science.

In recent decades the precise mode of operation of Middle and Late Bronze Age smelting sites in the Alps has been subject to ongoing scientific debate. One of the key issues is the question as to whether different slag types (slag cakes and plate slags in particular) were the result of the same smelting processes. Slag tapping is yet another controversial issue.[18] However, the typology of slag almost always forms an inherent part of the line of argument without it actually being a subject of the discussion. An exception is a study by A. Schaer from the early 2000s, which was one of the main inspirations for the study presented here. Unless it was further processed into slag sand, slag is usually available in large quantities and therefore well suited for statistical evaluation at least from the Middle Bronze Age onwards. In contrast to most other archaeological finds, slag does not seem to have served any specific purpose upon completion of the smelting process. Above all, slag was a waste product, a side effect of the technological process. It can therefore be assumed that its outer form was a product of its function, not of an intentional shaping process. Therefore, it is not necessary to take socio-cultural factors into consideration when typologically evaluating this material. Typological changes over time and space thus most probably represent a modification of the framework conditions such as the nature and availability of the raw material. It must be borne in mind, however, that socio-cultural reasons may have had a bearing on certain technological choices. However, even if the classification of smelting slag can be understood as an attempt to build a functional typology, the resulting types should not automatically be seen as historical entities.[19]

Moreover, due to its material properties such as the fact that it was at least partially liquid, slag is a material that carries a lot of information concerning, for example, the process reactor, the solidification process and/or the deposition milieu. A detailed investigation of such morphological characteristics may help us answer any open questions concerning the smelting process, or at least give an indication as to how the data should be interpreted.

In the Oberhalbstein Valley specifically, slag is often the only source of information available with regard to a particular smelting site. Because comprehensive sampling and investigation of the material by mineralogical and geochemical means is not feasible, typological and morphological investigations seem to be an appropriate approach, so as not to neglect many of the smelting sites within the prehistoric mining area. Whilst the evaluation of all the slag material from our own fieldwork and from earlier surveys, test trenches and excavations would be useful, it would also be very time-consuming. The work therefore requires a clear sampling strategy. A two-stage evaluation process was therefore applied consisting of an initial rough typological quantification followed by a detailed morphological analysis and documentation of selected pieces of slag.

Typology – a different approach to the study of smelting slag

The question that inevitably comes to mind revolves around the definition and terminology of different slag types. What types exist and how can they be distinguished? The discussion is further complicated by the slightly inconsistent use and definition of slag types in the archaeological literature. In terms of Middle and Late Bronze Age chalcopyrite smelting, the discussion is mainly dominated by the trilogy of the porous, coarse so-called “slag cake” (Schlackenkuchen), the homogenous, thin and platy, so-called “plate slag” (Plattenschlacke) and the deformed “slag sand” (Schlackensand) consisting of crushed slag. Other terms such as “Blasenschlacke” or “Laufschlacke” are also sometimes used[20], which does not help matters, especially since there is often no explicit definition of the different types for the specific region concerned. An independent typology was developed for the Oberhalbstein slags by A. Schaer, who divided the material into seven types. These types can be at least partially correlated to the types mentioned above (Tab. 1).

The scarcity of typological descriptions for the slag often stands in contrast to a very detailed mineralogical or geochemical characterisation, which cannot be easily equated with macroscopic characteristics. Archaeometallurgical analyses can assist in answering questions concerning the raw material, the chemical reactions that took place during individual steps in the process, the (intermediate) product created, the process atmosphere and temperature, the cooling rate of the slag etc. However, they should not form the basis for an archaeological classification of the material since the sample usually represents only a small fraction of the total number – quite irrespective of the high variability between and within different fragments of slag. In order to avoid overvaluing random samples, the typology and sampling should, rather, be based on independent archaeological classification, which can and should subsequently be tested using the results of the scientific analyses.

It appears unreasonable to establish a fixed universal typology with a long list of criteria for each type, since certain distinctions must be made between the mining regions based on the differences between the raw materials on one hand and for chronological reasons on the other. However, based on the assumption that a high degree of standardisation existed in smelting technology from the Middle Bronze Age onwards[21], one would generally also expect to see a certain standardisation among waste products over the course of time and throughout different areas. A more detailed macroscopic description of the slag, particularly in connection with archaeometallurgical analyses, would undoubtedly increase the comparability of the sampling and research results. In addition, the publication of more and better-quality illustrations would be helpful.

Against this background, it appeared more reasonable to refer to the most widely used typology and terminology when examining the slag from the Oberhalbstein Valley rather than using the classification developed by Schaer[22]. Two notable exceptions applied:

Firstly, since there was no evidence of slag processing, the category of slag sand was not taken into consideration. The same applied to special types of slag such as drops, taps and slagged stones or furnace walls, since the sample number was too small to achieve a statistically significant result.

Secondly, because quite a considerable quantity of slag could not be assigned to either of the two commonly used types (slag cake or plate slag), the spectrum had to be extended by an additional type. In line with two recent works from the Trentino region[23] this intermediate type was called “massive slag[24]”. Although this type of slag is seemingly found in the southern and central Alps only, the possibility of its existence in other areas cannot be excluded.[25]

The polythetic classification used here therefore consisted of the following three types[26], which were defined on the basis of their fundamental shape, homogeneity, porosity, liquidity and thickness:

mining district	period	coarse, porous, heterogenous slag	platy, thick, slightly heterogenous slag	platy, thin, homogenous slag	crushed slag	reference
Mitterberg (A)	MBA	A (Schlackenkuchen)	-	C (Plattenschlacke)	-	Herdits 1997
	MBA	Schlackenkuchen	-	Plattenschlacke	Schlackensand*	Stöllner et al. 2011
Kitzbühel (A)	MBA	Schlackenkuchen	-	Plattenschlacke	Schlackensand	Krismer et al. 2012
	MBA	Schlackenkuchen	-	Plattenschlacke	Schlackensand	Koch Waldner/ Klaunzer 2015; Koch Waldner 2017
Eisenerzer Ramsau (A)	MBA	B (Blasenschlacke); A (Laufschlacke)**	A (Laufschlacke)**	C (Plattenschlacke) 3-10 mm thickness	Schlackensand*	Doonan 1996
	MBA	B (Blasenschlacke); A+B (Typen-kombination)**; A (Laufschlacke)**	A (Laufschlacke)**; A+B (Typen-kombination)**	C (Plattenschlacke) ≤ 5 mm thickness	Schlackensand*	Kraus 2014
Raxgebiet (A)	LBA	lumpy slag (cake or amorphous)**	rich slag (7-36 mm thickness)**	fine slag (3-7 mm)**	-	Larreina-Garcia et al. 2015
Trentino (I)	LBA	Schlackenkuchen, slag cake	massive Schlacke	Plattenschlacke, plate slag (3-8 mm)	Schlackensand, crushed slag	Silvestri et al. 2014; Silvestri et al. 2015a
	LBA	coarse slag (slag cake)	massive slag	flat slag (Plattenschlacke)	slag sand	Addis et al. 2017
	LBA	Schlackenkuchen	heterogene Plattenschlacke	homogene Plattenschlacke	Schlackensand	Metten 2003
Unterinntal (A)	LBA	Schlackenkuchen, (heterogene Schlacken)	-	Plattenschlacke	Schlackensand	Goldenberg 2013; Goldenberg 2014
	LBA/EIA	slag cake (typ II and III)	-	plate slag (typ I)	slag sand	Staudt (in press)
Oberhalb-stein (CH)	LBA/EIA	K	B1 (1.05-1.4 cm), B2 (1.4 cm <)	A1 (0.2-0.55 cm) A2 (0.6-1.0 cm)	-	Schaer 2003
	LBA/EIA	Schlackenkuchen, slag cake	massive Schlacke, massive slag (≥ 1.5 cm)	Plattenschlacke, plate slag (<1.5 cm)	Schlackensand*, slag sand*	Reitmaier-Naef 2018
various districts	MBA/LBA	Schlackenkuchen	-	Plattenschlacke	Schlackensand	Hanning et al. 2015
various districts	EBA-EIA	Schlackenklötze; stückige Laufschlacke**	stückige Laufschlacke**; plattige Laufschlacke**	plattige Laufschlacke?**	Sandschlacke	Eibner 1992

* missing in the archaeological record but mentioned in the cited publication
** classification uncertain

Tab. 1: Overview on the terminology used in recent papers/works for prehistoric copper smelting slags in the Alps.

Slag cake (SC): basic amorphous shape exhibiting bulges on top and flattened bottom surface; layered internal structure; high heterogeneity (numerous small to large inclusions of unmolten material fused together by a liquefied slag matrix); high porosity (interspersed with numerous small to large bubbles); high viscosity (only partially liquefied); low density; thickness irrelevant

Massive slag (MS): platy, disc-shaped basic form with a flat, usually partially blistered top surface and a flat to highly textured bottom surface (drops, bulges); internal structure not layered; medium heterogeneity (small to average number of small to medium inclusions of unmolten material in a mass of liquefied slag matrix); medium porosity (interspersed with a small to average number of small to large bubbles); low viscosity (predominantly liquefied); middle to high density; thickness ≥ 1.5 cm

Plate slag (PS): basic platy shape with flat to smooth top and bottom surfaces; internal structure not layered; low heterogeneity (few or no small inclusions of unmolten material in a liquefied slag matrix); low porosity

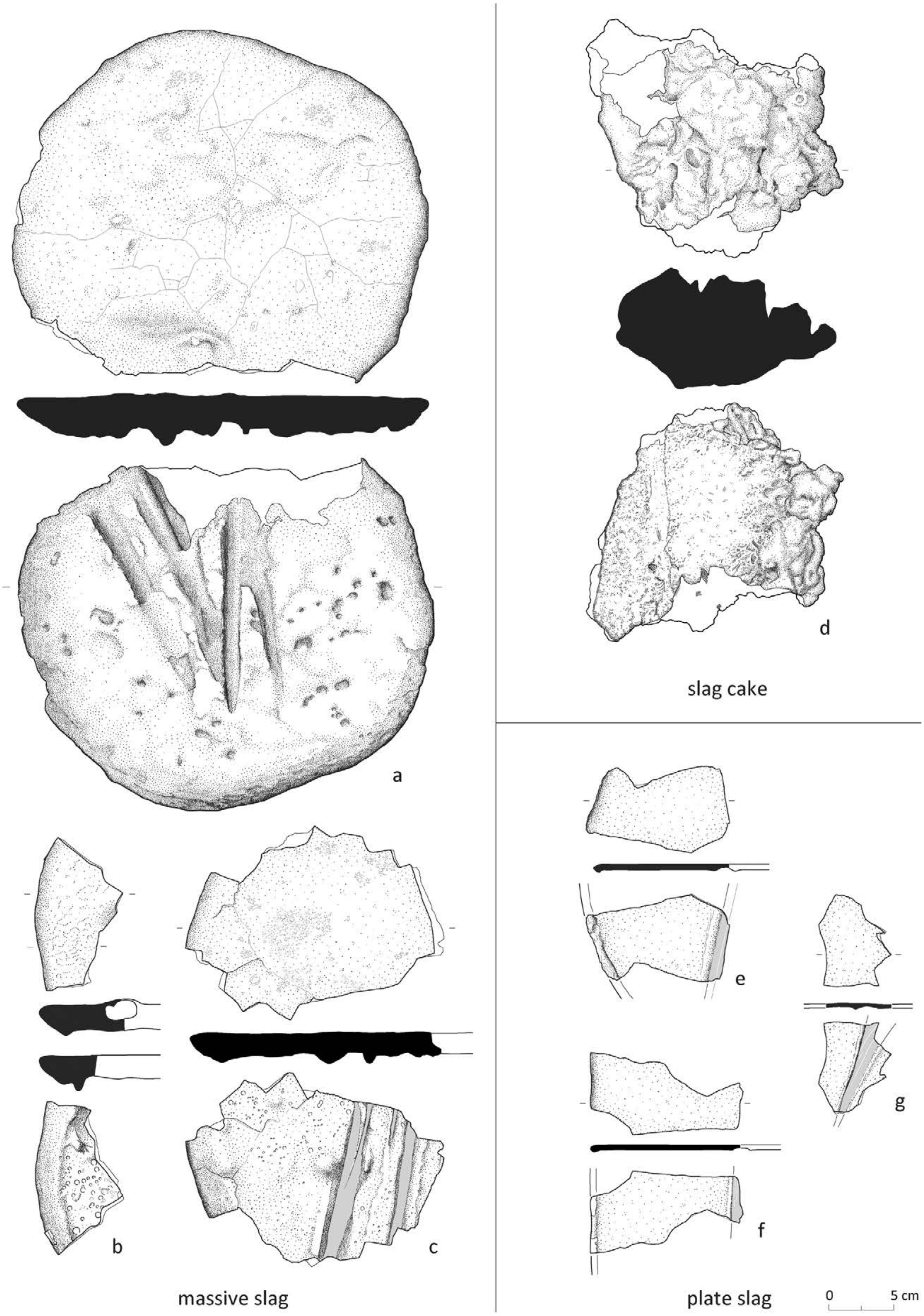

Fig. 2: Fragments of the three evaluated slag types with specific characteristics: rim (a-f), lip (b; e-f), tool imprint (a; c; e-g).

Fig. 3: The surface colour changes are due to strong corrosion (a-c) and surface reactions during the drying process on a metal lattice (f). (Ill./photo: Archaeological Service of the Canton of Grisons).

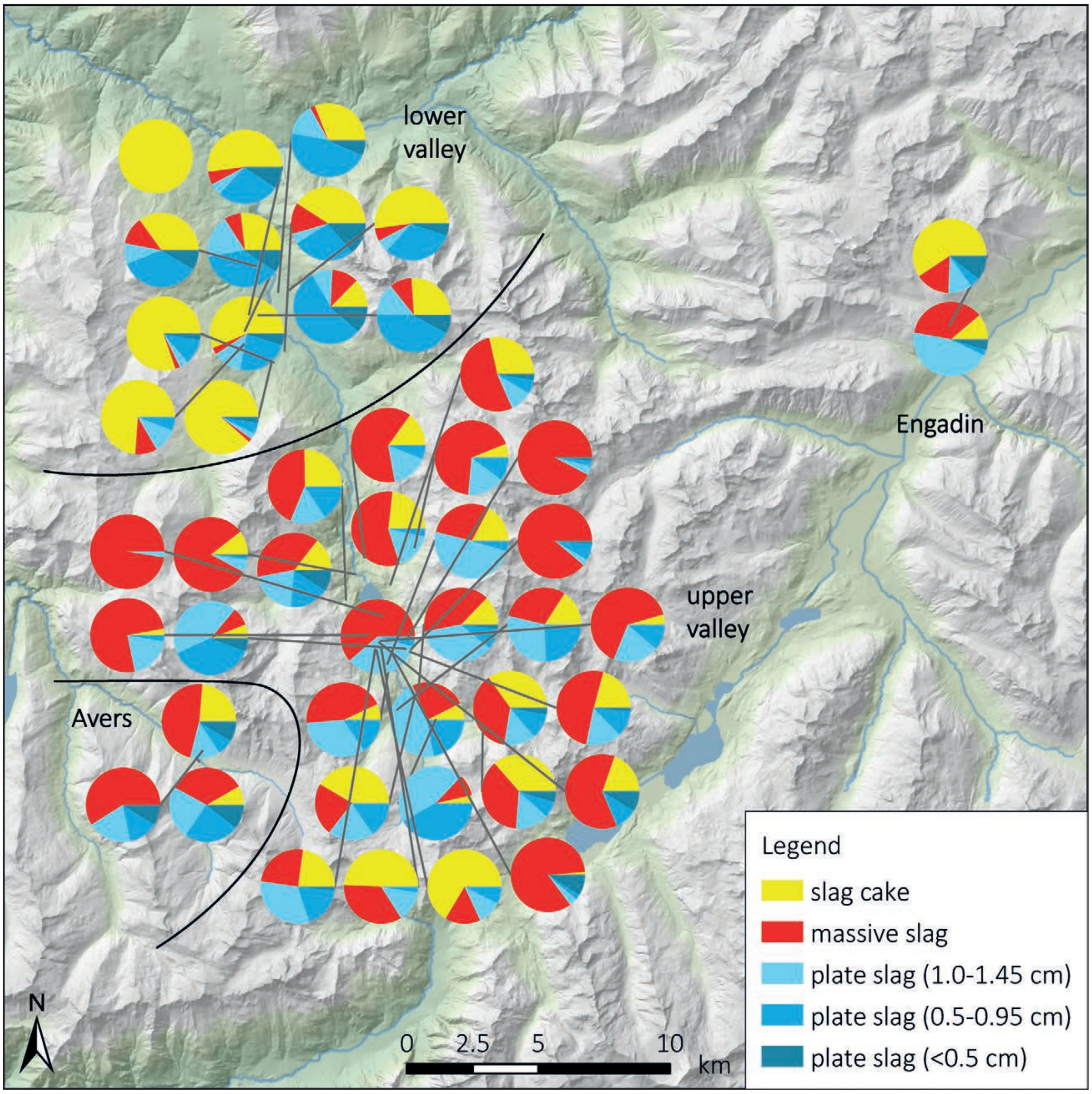

Fig. 4: Mapping of different proportions of slag types grouped by smelting site (map: Leandra Reitmaier-Naef, University of Zurich; geodata: Federal Office of Topography and Canton of Grisons).

(interspersed with few or no small bubbles); very low viscosity (completely liquefied); high density; thickness < 1.5 cm (subdivided into three subgroups 1.0-1.45 cm / 0.5-0.95 cm / 0.2-0.45 cm).

While in most cases the distinction between slag cakes and massive or plate slag posed no difficulty, the distinction between massive and plate slag was less evident. Clarification was required regarding the question as to whether there existed a clear boundary between two platy slag types or whether they merged seamlessly into one another. To simplify the data collection, particularly in the case of small slag fragments on one hand and to detect a potential threshold value on the other, these two types were distinguished by thickness: the maximum thickness of a plate slag was set at 1.45 cm with a subdivision into 0.5 cm steps (1.0-1.45 cm / 0.5-0.95 cm / 0-0.45 cm) in order to determine whether and in what way the differences related to the thickness of a plate slag. The information found in the literature suggests that there was no general rule (see Tab. 1).

In addition, further characteristics such as magnetism[27], fragmentation and secondary minerals were documented but not taken into account for the classification, as they are influenced by other factors such as the state of preservation and the supply of raw material at the site concerned.

So far, the dataset contains almost all earlier finds retrieved prior to 2012 and a large proportion of the slag collected during surveys since 2013. In addition, a large part of the sample derives from the partially excavated sites of Gruba I, Val Faller and Scalotta I.[28] Just under 12,000 slag fragments weighing a total of 421 kg were examined overall.

More than half (57.3%) of the investigated slag fragments were classified as plate slag, 27% as massive slag and only 15.6% as slag cake. This reflects a type-specific degree of fragmentation rather than the actual ratio between the different types. The picture changes towards a predominant proportion of massive slag (38.6%) followed by 35.9% slag cake and only 25.5% plate slag once the representation is based on weight.

Spatial distribution of slag types

At first glance the map with the results plotted by weight percentages and grouped by smelting site shows that the sites in the lower (northern) part of the valley tend to yield significantly more slag cakes than the sites in the upper (southern) part of the valley (Fig. 4). All sites show a small amount of massive slag: the largest share is represented either by slag cakes (8 sites)[29] or by plate slags (5 sites)[30].

Interestingly, the proportion of massive slag is smaller than the other two categories at each site. In fact, the actual presence of massive slag might be questioned in more than one case, since the evidence often consists of only a few individual fragments measuring 1.5 cm in thickness or slightly more. Therefore, they may just belong to the grey zone at the upper end of the plate slag scale.

The upper, southern part of the valley shows a completely different picture, with smelting sites containing significantly more massive slag and rather small proportions of slag cakes, rarely more than 25%. At 24 out of 34 sites, the massive slag, at up to 95.7%, represented the largest category by far.[31] In line with the northern part of the study region it is also clear that, with very few exceptions, all sites yielded a considerable quantity of plate slag, regardless of the ratio between slag cakes and massive slags. In seven cases, plate slag was even the largest category.[32] Only in three cases, all located south of Lake Marmorera, slag cakes were the largest category.[33]

A similar picture, dominated by massive slags and plate slags of 0.5-1.45 cm thickness, can be seen in the neighbouring Avers Valley. The samples from the two sites in the Engadin, on the other hand, clearly show different compositions – a result that can probably also be partially explained by the small sample quantity.[34]

Not included on the map are 19 sites, which yielded less than 20 slag fragments – including the prehistoric settlements of Motta Vallac and Davos Tignignas Sot I – and four samples with uncertain site allocations.

This brings us to an important aspect of discussion: the critical assessment of sources. The results presented may have been distorted by various factors including selective sampling. The majority of slags were collected throughout the 20th century under different circumstances and with varying intentions. The situation was certainly better in relation to the newly discovered sites where slag finds were sampled systematically. Nevertheless, the chronological and spatial distribution remains an unknown and potentially complicating factor. Even systematic sampling of a slag heap does not necessarily lead to a representative result because smelting sites are only rarely fully examined.[35]

Despite these objections, the results of the typological examination of the smelting slag from the Oberhalbstein Valley appear to be consistent and correspond with the study undertaken by Schaer[36]. It does seem likely that the reason for the apparent differences in the slag type combinations between the two areas of the Oberhalbstein Valley lies either with the raw material source[37] (same process, different raw material) or the smelting process (e.g. different production phases). The former seemed a plausible explanation a few years ago, since the Late Bronze Age smelting sites appeared to concentrate mainly in the lower part of the valley, while the Early Iron Age sites clustered primarily around Lake Marmorera in the upper part. New dendrochronological and radiocarbon analyses[38] have now shown, however, that copper was most probably produced both in the lower and in the upper part of the valley in both periods. It seems unlikely that different processing techniques were used simultaneously throughout the valley in both production phases. It is therefore highly likely that the differences in type composition were down to the raw materials, which, due to their differences in composition behave differently and therefore produce different slags or slag type proportions. This interpretation is confirmed by the results obtained from ore and slag analyses carried out in respect of both valley sections.[39]

Morphology – from big to small

In order to obtain more specific information on the smelting process(es), we must turn our attention to a more detailed study of the slags. The main goal of such a detailed examination of individual slag fragments is to identify and more precisely define the different slag types and to determine any relevant information with regard to the smelting process that has potentially been imprinted in a slag fragment's morphology. Furthermore, it is hoped that the information collected will make it easier in the future to macroscopically evaluate copper smelting slag in a more timely fashion.

So far, out of the sample presented, more than 2000 particularly significant specimens have been selected for further investigation. They have undergone the initial step of being recorded in a catalogue of characteristics and measurements as described above. All fragments that

site			fragments						weight (in g)						proportion by weight (in %)				
area	village	name	total	SC	MS	PS-A	PS-B	PS-C	total	SC	MS	PS-A	PS-B	PS-C	SC	MS	PS-A	PS-B	PS-C
OBERHALBSTEIN (LOWER VALLEY)	Cunter	Dafora	1035	120	18	169	603	125	15754	4886	337	2206	7291	1034	31,0	2,1	14,0	**46,3**	6,6
	Riom-Parsonz	Davos Tigignas	139	77	10	33	17	2	7438	5483	704	810	430	11	**73,7**	9,5	10,9	5,8	0,1
	Cunter	Glignia II	109	51	9	12	28	9	2631	1372	147	146	830	136	**52,1**	5,6	5,5	31,5	5,2
	Salouf	Gneida	236	84	15	18	86	33	2382	833	286	218	845	200	35,0	12,0	9,2	**35,5**	8,4
	Riom-Parsonz	Motta Mola	764	65	37	106	426	130	10402	2714	996	1467	4418	807	26,1	9,6	14,1	**42,5**	7,8
	Salouf	Motta Vallac	6	2	0	0	3	1	122	40	0	0	74	8	32,8	0,0	0,0	**60,7**	6,6
	Riom-Parsonz	N Riom	19	0	0	1	14	4	245	0	0	102	126	17	0,0	0,0	41,6	**51,4**	6,9
	Savognin	Oberhalb Savognin	31	1	2	4	18	6	285	36	33	26	158	32	12,6	11,6	9,1	**55,4**	11,2
	Savognin	Parseiras I	92	16	3	12	46	15	9289	7454	189	374	1027	245	**80,2**	2,0	4,0	11,1	2,6
	Savognin	Parseiras II	175	32	2	18	81	42	14505	12823	231	380	712	359	**88,4**	1,6	2,6	4,9	2,5
	Savognin	Son Martegn	516	94	25	30	219	148	9219	3768	1251	428	2507	1265	**40,9**	13,6	4,6	27,2	13,7
	Riom-Parsonz	Tigignas Sot I	4	2	0	0	1	1	28	5	0	0	6	17	17,9	0,0	0,0	21,4	**60,7**
	Riom-Parsonz	Tigignas Sot II	103	13	1	9	55	25	3570	958	260	677	1334	341	26,8	7,3	19,0	**37,4**	9,6
	Riom-Parsonz	Tigignas Sot III	140	15	6	29	78	12	5315	2996	160	680	1220	259	**56,4**	3,0	12,8	23,0	4,9
	Stierva	Tiragn	33	25	0	2	5	1	60370	60098	0	127	112	33	**99,5**	0,0	0,2	0,2	0,1
	Riom-Parsonz	Ual da Val	404	24	4	30	259	87	5914	3086	337	308	1630	553	**52,2**	5,7	5,2	27,6	9,4
OBERHALBSTEIN (UPPER VALLEY)	Sur	Alp Flix I	76	6	39	19	12	0	1964	121	1324	319	200	0	6,2	**67,4**	16,2	10,2	0,0
	Sur	Alp Flix II	128	33	41	37	17	0	2681	624	1519	448	90	0	23,3	**56,7**	16,7	3,4	0,0
	Sur	Alp Flix III	16	2	6	8	0	0	487	23	389	75	0	0	4,7	**79,9**	15,4	0,0	0,0
	Marmorera	Alp la Motta	182	14	98	56	13	1	3348	96	2516	642	86	8	2,9	**75,1**	19,2	2,6	0,2
	Marmorera	Alp Natons	81	4	33	18	14	12	6317	61	5777	245	155	79	1,0	**91,5**	3,9	2,5	1,3
	Marmorera	Bajols	12	0	5	3	2	2	224	0	134	49	19	22	0,0	**59,8**	21,9	8,5	9,8
	Bivio	Barscheinz II	14	0	0	6	8	0	110	0	0	57	53	0	0,0	0,0	**51,8**	48,2	0,0
	Bivio	Barscheinz III	23	3	3	10	7	0	297	22	71	139	65	0	7,4	23,9	**46,8**	21,9	0,0
	Bivio	Bötg da las Serps	30	1	2	13	14	0	362	13	34	164	151	0	3,6	9,4	**45,3**	41,7	0,0
	Bivio	Brüscheda I	228	68	59	40	33	28	4330	1513	1623	596	482	116	34,9	**37,5**	13,8	11,1	2,7
	Bivio	Brüscheda II	2	0	0	0	0	2	14	0	0	0	0	14	0,0	0,0	0,0	0,0	**100,0**
	Marmorera	Burgfelsen	111	5	74	13	16	3	6355	192	5353	421	341	48	3,0	**84,2**	6,6	5,4	0,8
	Bivio	Caschegna	84	14	31	12	22	5	2875	117	2281	163	295	19	4,1	**79,3**	5,7	10,3	0,7
	Bivio	Clavazöl	14	3	6	3	2	0	265	68	128	42	27	0	25,7	**48,3**	15,8	10,2	0,0
	Bivio	Clavè d'Mez I	5	2	1	2	0	0	1353	1269	41	43	0	0	**93,8**	3,0	3,2	0,0	0,0
	Marmorera	Clavè d'Mez II	197	44	35	72	41	5	3052	697	761	990	558	46	22,8	24,9	**32,4**	18,3	1,5
	Bivio	Clavè d'Mez III	29	4	1	9	15	0	205	48	9	65	83	0	23,4	4,4	31,7	**40,5**	0,0
	Marmorera	Clavè d'Mez IV	165	32	74	40	19	0	9857	4865	3417	1323	252	0	**49,4**	34,7	13,4	2,6	0,0
	Bivio	Cresta	4	1	0	1	2	0	89	19	0	36	34	0	21,3	0,0	**40,4**	38,2	0,0
	Bivio	Fuortga	214	5	110	20	11	68	5550	69	4660	199	124	498	1,2	**84,0**	3,6	2,2	9,0
	Sur	Furnatsch	459	67	180	149	58	5	17112	2575	10690	2738	1031	78	15,0	**62,5**	16,0	6,0	0,5
	Marmorera	Gruba I	1022	207	401	213	114	87	45243	12880	24035	4423	2756	1149	28,5	**53,1**	9,8	6,1	2,5
	Marmorera	Mot la Bova	31	3	1	14	10	3	265	16	21	114	99	15	6,0	7,9	**43,0**	37,4	5,7
	Marmorera	Pardeala	32	0	19	4	5	4	14930	0	14293	367	142	128	0,0	**95,7**	2,5	1,0	0,9
	Marmorera	Pareis I	811	69	332	233	161	16	26379	1180	16802	5202	2937	258	4,5	**63,7**	19,7	11,1	1,0
	Marmorera	Pareis II	28	7	13	0	5	3	442	87	273	0	44	38	19,7	**61,8**	0,0	10,0	8,6
	Marmorera	Pareis III	20	5	3	9	3	0	113	21	29	39	24	0	18,6	25,7	**34,5**	21,2	0,0
	Marmorera	Pareis IV	21	0	9	7	4	1	444	0	270	151	19	4	0,0	**60,8**	34,0	4,3	0,9
	Marmorera	Pareis V	10	3	3	0	4	0	497	330	50	0	117	0	**66,4**	10,1	0,0	23,5	0,0

site			fragments						weight (in g)						proportion by weight (in %)				
area	village	name	total	SC	MS	PS-A	PS-B	PS-C	total	SC	MS	PS-A	PS-B	PS-C	SC	MS	PS-A	PS-B	PS-C
OBERHALBSTEIN (UPPER VALLEY)	Bivio	Plaz I	137	31	22	51	32	1	1936	802	444	389	298	3	**41,4**	22,9	20,1	15,4	0,2
	Bivio	Plaz II	65	8	17	26	11	3	667	86	268	241	61	11	12,9	**40,2**	36,1	9,1	1,6
	Marmorera	Pra Miez	32	7	9	8	6	2	1143	286	494	177	178	8	25,0	**43,2**	15,5	15,6	0,7
	Bivio	Preda	26	4	8	12	2	0	410	71	118	203	18	0	17,3	28,8	**49,5**	4,4	0,0
	Bivio	Radons	22	4	5	8	5	0	214	34	65	63	52	0	15,9	**30,4**	29,4	24,3	0,0
	Marmorera	Scalotta I	2077	338	890	592	249	8	29925	2947	19819	5694	1387	78	9,8	**66,2**	19,0	4,6	0,3
	Marmorera	Scalotta II	227	26	160	21	10	10	11789	1235	9641	648	139	126	10,5	**81,8**	5,5	1,2	1,1
	Bivio	Sot al Crap	53	4	16	22	10	1	1052	73	467	347	162	3	6,9	**44,4**	33,0	15,4	0,3
	Sur	Spliatsch I	3	0	0	1	1	1	34	0	0	18	9	7	0,0	0,0	**52,9**	26,5	20,6
	Marmorera	Sül Cunfin I	29	4	8	9	7	1	894	187	455	139	101	12	20,9	**50,9**	15,5	11,3	1,3
	Marmorera	Sül Cunfin II	36	0	20	4	7	5	2975	0	2645	81	212	37	0,0	**88,9**	2,7	7,1	1,2
	Bivio	Sur Eva I	41	8	8	15	6	4	1240	452	464	180	88	56	36,5	**37,4**	14,5	7,1	4,5
	Bivio	Sur Eva II	1	0	0	0	0	1	12	0	0	0	0	12	0,0	0,0	0,0	0,0	**100,0**
	Bivio	Sur Gonda	6	1	2	2	1	0	310	95	61	128	26	0	30,6	19,7	**41,3**	8,4	0,0
	Bivio	Tges Alva I	8	0	7	1	0	0	292	0	258	34	0	0	0,0	*88,4*	11,6	0,0	0,0
	Bivio	Tges Alva II	19	2	7	10	0	0	591	65	380	146	0	0	11,0	*64,3*	24,7	0,0	0,0
	Mulegns	Val Faller Plaz	591	103	197	89	107	95	37277	5377	14401	7660	6392	3447	14,4	*38,6*	20,5	17,1	9,2
ENG.	Madulain	Alp Es-cha Dadour	20	2	1	2	3	12	2154	1280	324	225	97	228	**59,4**	15,0	10,4	4,5	10,6
	Madulain	Plaun Grand	119	16	11	27	22	43	8117	906	2925	3715	205	366	11,2	**36,0**	45,8	2,5	4,5
AVERS	Juppa	Skilift	192	14	42	25	34	77	9281	2191	4415	1215	649	811	**23,6**	47,6	13,1	7,0	8,7
	Juppa	Ober-Juppa I	115	3	27	26	31	28	2532	14	1484	486	326	222	0,6	**58,6**	19,2	12,9	8,8
	Juppa	Vorderbergalga I	19	2	10	2	3	2	920	79	695	82	57	7	8,6	**75,5**	8,9	6,2	0,8
	Juppa	Vorderbergalga II	28	1	3	5	12	7	314	26	106	74	75	33	8,3	**33,8**	23,6	23,9	10,5

Tab. 2: Number and type distribution of the investigated slags per smelting site, including sites with less than 20 slag fragments (not considered in the text). The most frequent type (by weight) per site is written in bold.

are either part of a rim, bear an imprint of a structure or object or contain other informative traces, deformations or inclusions, have been more closely examined. Of particular interest are pieces of a certain size that exhibit a combination of several characteristics, since they help identify relationships between specific traces.[40]

One good example of this is the question concerning the top and bottom of a slag. Plate slags, in particular, often exhibit two completely smooth and level surfaces, distinguished only by a characteristic lip whose origin remains unclear. Illustrations of plate slag (where illustrations are provided at all) clearly show a lack of agreement with regard to the correct orientation of such fragments, which originates from a lack of reflection rather than representing any particular opinion regarding functionality.[41] However, one possible answer lies in the morphology: many of the massive and plate slag fragments – but hardly any slag cakes – show imprints of elongated tools on one surface only (Figs. 2 and 3: slags a, c, e, f, g). We can safely assume that these traces mark the underside of the slag, since they were generated by lifting the slag off the molten metal, as a comparison with the ethnoarchaeologically documented and experimentally examined "Nepal Process" plausibly shows.[42] This assumption can be confirmed by comparing the bubble formation on both surfaces (Fig. 5). The bubbles on the side that bears the imprint are in negative, while those on the other side are in positive, which means that they denote the original orientation of the slag within the reactor. Interestingly, a few pieces of plate slag have both a lip and an imprint on the same side (Fig. 2 and 3: slag e, f, g). This clearly proves that the lip marks the underside of the plate slag. A similar observation can be made on several massive slag fragments, which occasionally also exhibit a more or less distinct step on the underside (Figs. 2 and 3: slag b). The obvious explanation for this morphological feature is that it marks the negative of an underlying metallic melt of a slightly smaller size. Similar, easily recognisable traces were identified, for example, on the bottom surfaces of early copper smelting slags from Shahr-I Sokhta or Nevali Çori.[43]

Apart from the discussion revolving around the top or bottom, the tool imprints themselves are also of

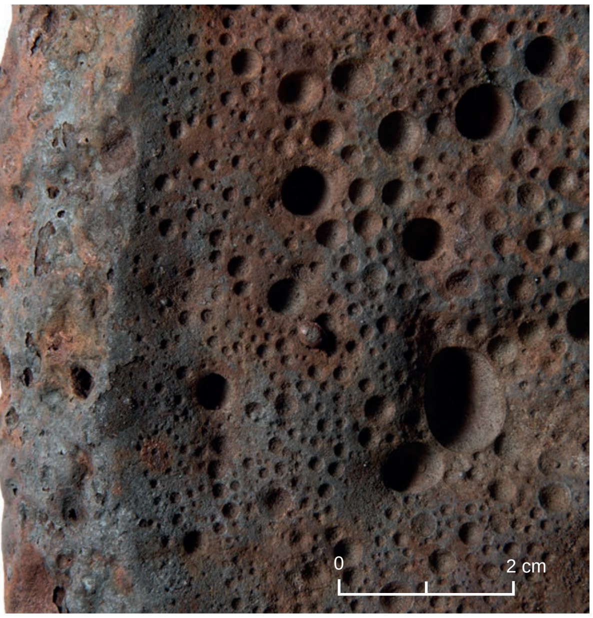

Fig. 5: Bottom surface of a massive slag fragment (rim) with negative (ascending) bubbles and a step (photo: Archaeological Service of the Canton of Grisons; L. Reitmaier-Naef).

Fig. 6: Bottom surface of a plate slag fragment with half of a tool imprint (r.) and an undulated surface showing the direction of the insertion (photo: Archaeological Service of the Canton of Grisons; L. Reitmaier-Naef).

interest: they vary in shape (straight to pointy), profile (flat to round) and width (0.5-2.5 cm). Most fragments show only a single imprint, others, however, bear two or more (Figs. 2 and 3: slags a, c) – usually in multiple directions. A handful of the larger massive slag fragments exhibit two or more imprints positioned like a branch fork, but due to the sharp intermediate angle and a lack of direct evidence for a connecting piece, they are probably just the result of two crossed tools or two stabs made by the same tool. Judging by a number of imprints with a distinguishable texture, it is, nevertheless, conceivable that the tool imprints originated from simple wooden sticks (Fig. 3: slag g). Drops and bulges alongside the imprints attest to the fact that the slag was only superficially solidified when it was lifted off the molten metal (Figs. 2 and 3: slags c, g). This argument is reinforced by the phenomenon of undulated surfaces sometimes accompanying imprints on plate slag fragments. The so-called “Milchhautrunzeln” are often labelled as flow structures and thus as evidence of tapping. On closer inspection, it becomes obvious that they are much more likely to have originated from lifting the slag when it was only superficially solidified. In contrast to the tapping scenario, this is also a more plausible explanation for the occasional occurrence of double-sided undulated surfaces (Fig. 6).

Furthermore, the fact that imprints almost exclusively occur on massive and plate slag provides an important clue in terms of reconstructing the smelting process. In contrast to the perforation seen on the slag cakes from the Mitterberg region[44], the few imprints documented are also located on the bottom surface of the slag but are only barely visible. Therefore, they most likely originated from some time after the smelting process, when the slag had already almost completely cooled down (in the furnace/reactor).

Apart from the impressions, the rim shapes also provide some information about the conditions that prevailed at the time of the slag formation (Fig. 7). While slag cakes always show a layered rim with (1b: 8%) or without (1a: 92%) a boundary, massive slag almost exclusively exhibits bevelled rims with (2b: 42.7%) or without (2a: 48.5%) a step on the underside. The angles of type 2 rims vary between 30° and 50° and their outer surfaces are frequently characterised by a rough, blistered texture which most probably represents the nature and shape of the reactor.[45] The transition between the bevelled rims of the massive slags and the lip-shaped rims of the second and third plate slag subgroup is taken up by the plate slag fragments of the first subgroup (1-1.45 cm) showing a wide range of rim shapes (2a: 17.8%; 2b: 42.2%; 3a: 24.4%; 3b: 11.1%; 3c: 4.4%). The other two subgroups only exhibit rims of the types 3b (32%) and 3c (68%).

This result provides additional classification criteria and further evidence to suggest that there is no sharp border between the two platy slag types, since the thickest plate slags share characteristics with both the thin plate slag and the massive slag categories. It remains unclear whether the two types defined represent different technological entities or only two subgroups of one and the same type. It seems possible, that the differentiation between the two is based mainly, if not solely, on differences in the material properties (esp. viscosity) and interrelated characteristics (e.g. the shape of the rims). The results of the type distribution clearly show that it is, nevertheless, legitimate or even central for a detailed understanding of

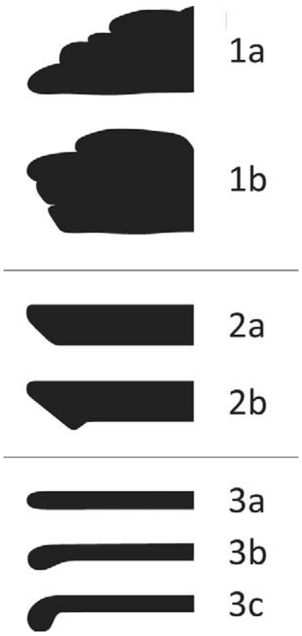

Fig. 7: Overview of the different rim shapes: 1a: layered rim; 1b: layered rim with boundary (angular); 2a: bevelled rim; 2b: bevelled rim with step on the underside; 3a: rim without specific characteristics; 3b: slightly thickened rim; 3c: rim with distinct lip (ill.: L. Reitmaier-Naef, University of Zurich).

the process applied to divide the plate-shaped slags into (at least) two types.

From the outside, this probably looks like a small increase in knowledge. Overall, however, findings as those described above lay an important foundation for future morphological evaluations and may eventually help answer further research questions. In order to paint a complete picture, a number of other attributes such as the diameter and colour of the slag should also be taken into account.

Conclusion

The typological and morphological evaluation of the smelting slag from the Oberhalbstein Valley has provided important indications for the reconstruction of the local Late Bronze and Early Iron Age smelting process. A significant difference in the slag spectrum between the lower and upper parts of the valley points to technological differences, more likely based on the raw material used rather than the period of production or the process, as shown by newly obtained absolute dates as well as geochemical and mineralogical analyses.

The morphological criteria of the different slag types have allowed us to make a series of interesting observations. Closer examination has yielded further confirmation of a profound difference between the coarse, viscous slag cakes and the platy, less viscous, less heterogenous massive and plate slags. The amorphous cakes most probably formed and cooled within the smelting furnace. They were not removed after the smelting process had been completed until a certain period of time had elapsed and therefore each presumably represents a single smelting process. This type of slag is thus quite probably associated with a first smelting step within the typical shaft furnace, which is known from almost all Bronze to Iron Age copper districts in the central, eastern and southern Alps.

The opposite is true for the other two types: the fact that they were lifted whilst only partially solidified, clearly evokes the image of an accessible reactor where slag plates were repeatedly removed during a dynamic smelting process. Since none of the investigated slag fragments showed any convincing evidence of tapping, this option has been excluded. The alternative scenarios of a second smelting step in an open, pit-shaped reactor proposed by Hanning et al.[46] seem to offer the best fit. For the Oberhalbstein, this interpretation can now also be linked to a concrete archaeological finding thanks to the most recent excavations: Previously unknown, hearth-shaped furnaces that strongly resemble structures in Nepal have been documented at two smelting sites – Gruba I and Val Faller.[47]

However, a conclusive overall picture of the prehistoric smelting process used in the Oberhalbstein region can only be obtained by bringing together the results of the macroscopic investigation, the existing archaeological findings and the archaeometallurgical analysis.[48] Furthermore, the individual steps of the overall development of the copper smelting process from the time and area of origin (MBA Mitterberg area) to the target region (EIA Oberhalbstein Valley) should be subjected to a more detailed examination in order to reach a better understanding of the intention and impact of technological adaption processes.[49]

Notes

1 In accordance with the principle that *“A typological study of finds would not be sufficient, and a scientific analysis of the material is necessary.”* Hauptmann, 2010, p.8.

2 E.g. Stöllner, 2009.

3 Summary of the state of research at the end of the HiMAT-project: Goldenberg et al., 2012.

4 Project funded by FWF, DFG and SNF; project partners: University of Innsbruck, Deutsches Bergbau-Museum Bochum and the Curt-Engelhorn-Zentrum für Archäometrie in Mannheim.

5 See Oberhänsli et al. in this volume.

6 Dietrich, 1972; Reitmaier-Naef, 2018.

7 Geochemistry: German Mining Museum Bochum, material science laboratory; mineralogy: cooperation with Klaus-Peter Martinek, Munich.

8 Marmorera, Vals; Marmorera, Cotschens; Tinizong-Rona, Avagna-Ochsenalp; see Reitmaier-Naef et al., 2015; Reitmaier-Naef et al., in prep.

9 Reitmaier-Naef et al., in prep.

10 Della Casa et al., 2015; Reitmaier-Naef, 2018.
11 See Turck in this volume.
12 Nauli, 1977; Wyss, 1981; Wyss, 1982; Rageth, 1986.
13 Not documented at smelting sites so far.
14 See Reitmaier-Naef, 2018.
15 Anfinset, 2011; Hanning & Pils, 2011; Goldenberg et al., 2011; Hanning, 2012; Hanning in this volume.
16 Stöllner et al., 2011; Pernicka et al. 2016; Rose et al. 2019.
17 In contrast to the study of primary copper metallurgy, the classification of iron smelting and smithing slags by morphological and typological means has become more widely used at least since the 1980s (Sperl 1980) and is now a commonly accepted component of archaeometallurgical studies.
18 Most recently summarised by Hanning et al., 2015.
19 Vossen, 1970, pp.30-31.
20 The use of a different terminology in Styrian research may be related to the history of research, see Sperl, 1980.
21 Hanning et al., 2015; Stöllner et al., 2016.
22 Schaer, 2003, p.29; see also table 1.
23 Addis et al., 2017; Silvestri et al., 2015.
24 Partly correlates with the “coarse, bulky slag” in Schaer, 2003.
25 Judging by the pictures, the “Laufschlacke” type in Kraus 2014 bears a close resemblance to the “massive slag” type.
26 The type definitions and limit values are based on a systematic evaluation of an exemplary sample set. Therefore, they are not exactly identical to those in Schaer 2003, but nevertheless correlate well with the first five of her seven types.
27 On the relevance of magnetism for process reconstruction, see Reitmaier-Naef, 2018, pp.127-128.
28 See Turck in this volume.
29 Davos Tigignas I; Glignia II; Parseiras I; Parseiras II; Son Martegn; Tigignas Sot III; Tiragn; Ual da Val.
30 Dafora; Gneida; Motta Mola; oberhalb Savognin; Son Martegn; Tigignas Sot II.
31 Alp Flix I; Alp Flix II; Alp la Motta; Alp Natons; Brüscheda I; Burgfelsen; Caschegna; Fuortga; Furnatsch; Gruba I; Pardeala; Pareis I; Pareis II; Pareis IV; Plaz II; Pra Miez; Radons; Scalotta I and II; Sot al Crap; Sül Cunfin I and II; Sur Eva I; Val Faller Plaz.
32 Barscheinz III; Bötg da las Serps; Clavè d’Mez II and III; Mot la Bova; Pareis III; Preda.
33 Clavè d’Mez I and IV; Plaz I.
34 Only some 20 slag fragments from the early 1980s are available from the smelting site at Alp Es-cha Dadour.
35 E.g. smelting site S1 Eisenerzer Ramsau: Klemm, 2004; Staudt et al. in this volume; Turck in this volume.
36 Schaer, 2003.
37 Fasnacht, 1991.
38 See Oberhänsli et al. in this volume; Reitmaier-Naef, 2018.
39 Reitmaier-Naef, 2018.
40 The data used in the morphological evaluation were too extensive to be printed here. For the complete dataset see Reitmaier-Naef, 2018.
41 E.g. Herdits, 1997, Pl. pp.13 (lip at the bottom); Staudt, 2017 (lip at the top).
42 Anfinset, 2011; Goldenberg et al., 2011.
43 Hauptmann et al., 1993, 547.
44 Klose 1918, p.31, Fig. 41; Zschocke & Preuschen, 1932, p.79, p.89, Pl. 33a, p.8.
45 Herdits 1997, pp.45-46.
46 Hanning et al., 2015.
47 Anfinset, 2011; Goldenberg et al., 2011; Turck in this volume.
48 For a summarised reconstruction of the “Oberhalbstein process” see Reitmaier-Naef, 2018.
49 We should expect to find complex mechanisms (Stöllner et al., 2016) rather than a linear modification of the smelting process, structures and products as proposed by Eibner, 1992.

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Author

Dr. des. Leandra Reitmaier-Naef – Dep. of Prehistoric Archaeology, Institute of Archaeology, University of Zurich

Correspondence and material requests should be addressed to: leandra.reitmaier@gmx.ch

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Monika Oberhänsli, Mathias Seifert, Niels Bleicher, Werner H. Schoch,
Leandra Reitmaier-Naef, Rouven Turck, Thomas Reitmaier, Philippe Della Casa

Dendrochronological dating of charcoal from high-altitude prehistoric copper mining and smelting sites in the Oberhalbstein Valley (Grisons, Switzerland)

ABSTRACT: *From 2013 to 2019, the prehistoric copper mining region of Oberhalbstein was in the focus of archaeological research carried out by the Department of Prehistoric Archaeology at the University of Zurich in cooperation with the Archaeological Service of the Canton of Grisons. The surveys and excavations of mining and smelting structures unexpectedly yielded numerous large, well-preserved charcoal fragments from conifers (Picea abies/Larix decidua, Pinus cembra, Pinus mugo/sylvestris). A total of 534 charcoal fragments and 7 wooden objects were retrieved from the 23 sites studied. Most of the sites are located between 1695 m and 2450 m a.s.l. The larger charcoal fragments bore up to 200 tree rings, and even fairly small fragments had a considerable number of rings. Dendrochronological analysis allowed us to construct two conifer chronologies that correlated with those from the central and eastern Alps and covered the period between the 12th and the 7th centuries BC. These made it possible to establish accurate calendar dates even for the period of the Hallstatt ^{14}C plateau, which often limits precise radiocarbon dating for that time period. The absolute chronological framework showed that, up to the present state of research, prehistoric copper mining and production in this part of the central Alps took place within two major events: one in the 11th century BC, the other in the 7th or 6th century BC.*

KEYWORDS: ANTHRACOLOGY, HIGH-ALTITUDE SITES, COPPER MINING, CHARCOAL PRODUCTION, LATE BRONZE AGE AND EARLY IRON AGE

Introduction

For some specific mining features in the Oberhalbstein region, Late Bronze Age and Early Iron Age evidence had already become available by the end of the 20th century in the form of radiocarbon dates (Wyss, 1993; Schaer, 2003). When prehistoric mining and smelting processes in the Oberhalbstein Valley became the focus of research again in 2013 (Della Casa et al., 2015; Turck et al., 2014), one of the key questions was their temporal and absolute chronological dimension. At mining and smelting sites, which are predominant within the research project presented here, processes took place which naturally require a lot of wood (fire setting, roasting, smelting). As a consequence, the sites yielded a large amount of charcoal. However, their size and dendrochronological potential greatly exceeded expectations and led to the first extensive dendrochronological analysis of charcoal in Switzerland.

Basically, dendrochronological analysis of charcoal is rarely carried out, because of both the nature of the material and its state of preservation: in many cases, charcoal from soils does not contain a sufficient number of tree rings for dendrochronological analysis due to fragmentation. High-altitude sites can be an exception as slow growing trees are more frequent here, provided that charcoal has survived – as was the case at the sites in the Oberhalbstein project (Fig. 1). In addition to climatic factors, a reason for this slow annual growth of trees may also lie in the high tree density of the exploited woodlands. As a result, even relatively small fragments can bear a large number of tree rings (e.g. Pichler et al., 2013; Pichler et al., 2011).

Radiocarbon analysis also yielded Hallstatt period dates for several sites in the Oberhalbstein project (Turck et al., in press; Turck et al., 2014, pp.223). For various methodological reasons, they were not very precise: dates scattered widely within the Hallstatt plateau (c. 750 to 400 BC) on the ^{14}C calibration curve hamper any attempts to achieve a more precise chronological resolution (e.g. Jacobsson et al., 2019). A further difficulty was that it was not known where on the tree trunk the annual rings of each radiocarbon-dated charcoal sample had originated from. In extreme cases, it is possible that several centuries lie between the heartwood rings that have been radiocarbon

Fig. 1: Sample no. 87854 with 161 tree rings, dated to the end year 685 BC, from the site at Marmorera, Gruba I. Less than 2 cm in length (photo: ADG).

dated and the outermost tree ring, which would provide the date for the event or archaeological feature that is actually being examined. This problem is known as the *old-wood effect* and has been extensively discussed since the late 1970s by researchers attempting to obtain absolute dates for archaeological timbers (Warner, 1990; Schiffer, 1986; most recently: Palincas, 2017). The *old-wood effect* has particularly serious consequences for charred wood from very old tree individuals, from which the majority of the dendrochronologically examined samples presented here originated. This obviously raised the question of whether waney edges were present, which is crucial to eliminating any potential for *old-wood effect*, how they could be firmly identified in charcoal in general and how well they were preserved in this particular case. Another set of questions to be explored were the wood species composition and the function and material value of the charcoal within the mining and copper production context: when it comes to mining and firing processes, the question always arises as to whether wood or (intentionally) charred wood was used (Hanning et al., 2015). From the point of view of dendrochronology, another goal was to establish the first confirmed reference chronology for the earlier stages of the Iron Age in the Grisons. The primary aim, however, was to establish as detailed a chronological framework as possible for the mining activities and copper production that took place in the valley and to reconstruct the *chaîne opératoire* (Turck, 2019; Reitmaier-Naef, 2019; Della Casa et al., 2015; Turck et al., 2014).

Material and methods

Out of approximately 80 archaeological sites in the Oberhalbstein Valley, 23 yielded charcoal fragments, some in significant numbers. In addition, seven fragments of wood, six of which could be identified as artefacts, had been preserved in waterlogged conditions (Reitmaier-Naef et al., in press). A total of 541 samples were dendrochronologically examined. The majority of samples were retrieved during excavations and surveys carried out between 2013 and 2019. As part of the project, other finds from mining contexts excavated earlier were also taken into account to determine their suitability for dendrochronological analysis (Reitmaier-Naef, 2018). The sites which yielded the samples that were suitable for dendrochronological examination were located at altitudes of between 1200 m and 2500 m a.s.l. (cf. Tab. 1). Three smelting sites were identified as the most important in terms of the amount and quality of dendrochronological samples: Gruba I (203 samples), Val Faller Plaz (96 samples) and Pareis I (52 samples). Two mines were also well represented: Cotschens and Avagna-Ochsenalp (Tab. 1) (published separately: Reitmaier-Naef et al., in press). With a total of 351 samples these five sites yielded just under two thirds of all samples examined as part of the project. The mining sites excluded (Cotschens, Avagna-Ochsenalp), they provided as much as 80% of all samples. All were stratified samples from large-scale excavations. Each charcoal sample with at least 25 annual rings was included in the analysis. Most charcoal fragments were extraordinarily well preserved, both in terms of their size – up to 5 cm in length – and in terms of their stability. The growth rings were very narrow (cf. Fig. 5e for mean values of tree ring widths) and some samples bore up to 200 tree rings. Most charcoal fragments from the Oberhalbstein Valley came from tree trunks.

Both their charred state and narrow growth rings posed a challenge: determination of the wood species was handicapped and it was difficult to identify possible examples of waney edges. The parameters for determination of the wood species and waney edges, therefore, had to be narrowly defined.

1) Features that are relevant for species determinations are more clearly visible in earlywood than in latewood cells, because the growth pattern in the former is less dense than in the latter. The narrow-ringed samples contain fewer earlywood cells, with some only bearing one earlywood and one latewood cell, so that because of charring the features relevant for wood species determination are often excellently preserved, but hardly visible.

Charring also makes sapwood impossible to recognise, either with the naked eye or under the microscope, and hampers the distinction between it and heartwood. In uncharred wood, it is possible to distinguish between *Larix decidua* and *Picea abies* by virtue of the fact that the sapwood in larch is distinctly lighter in colour than the heartwood, whereas in *Picea abies* the same distinction cannot be made. This distinguishing feature, however, does not occur when the wood is charred.

Previous wood anatomical studies on the microscopic distinction between *Larix decidua* and *Picea abies* were revealed to be impracticable (cf. Anagnost et al., 1994). Their identifying anatomical features overlap in that *Picea abies* is characterised by a rather continuous transition from early to latewood with bordered pits usually arranged

	context quality	altitude ma.s.l.	total number of samples	*Larix decidua/ Picea abies*	*Picea abies/ Larix decidua*	*Pinus cembra*	*Pinus mugo/ Pinus sylvestris*	species indet.	number of undated samples	number of dated samples	youngest end year	datings with waney edge
MINING SITES												
Marmorera, Cotschens	sondage (2017)	2275	19	10	7	1	1		16	3	1131 BC, 67 BC	
Marmorera, Gruba II, Pinge 1	excavation (2016-2018)	1849	15	9	6				15			
Marmorera, Gruba II, Pinge 3	excavation (2016-2018)	1849	13	13					11	2	1494 AD	
Marmorera, Vals	sondage (2014; 2016)	1748	7	3	2	2			6	1	745 BC	
Tinizong-Rona, Avagna-Ochsenalp	sondage (2015; 2017)	2487	72	12	60				46	26	1043 BC	certain, autumn/winter: 1061 BC
SMELTING SITES												
Bivio, Brüscheda I	survey (2014)	2047	1				1		1			
Bivio, Sur Eva I	survey (2017)	2015	2		1	1			2			
Cunter, Dafora	sondage (1974)	1185	9				9		9			
Marmorera, Alp Natons	excavation (2015)	1948	5	1	3	1			3	2	615 BC	
Marmorera, Gruba I	excavation (2013-2017)	1845	203	140	46	16	1		141	62	607 BC	certain, autumn/winter: 634 BC, uncertain: 607 BC, 614 BC
Marmorera, Gruba III	survey (2016)	1841	9	1	7			1	7	2	613 BC	uncertain: 613 BC
Marmorera, Pardeala	excavation (1952)	1635	1	1					1			
Marmorera, Pareis I	sondage (2014-2015; 2017)	1696	52	20	28	3		1	45	7	614 BC	
Marmorera, Scalotta I	sondage (2014)	1590	17	3	14				15	2	393 AD	
Mulegns, Val Faller Plaz	excavation (2013; 2016)	1764	96	52	24	20			83	13	621 BC	certain, autumn/winter: 642 BC, uncertain: 621 BC
Riom-Parsonz, Tigignas Sot II	survey (2006)	1491	2	1	1				1	1	636 BC	
Riom-Parsonz, Tigignas Sot III	survey (2006)	1477	4	2	2				2	2	636 BC	uncertain: 636 BC
Savognin, Parseiras II	survey (2015)	1387	1		1				1			
Tinizong-Rona, Mulegn	survey (1995)	1247	1		1				1			
CHARCOAL LAYER (INDET.)												
Bivio, Drauscha	survey (2017)	1912	1		1				1			
Marmorera, Survey (Tges Alva/Pareis)	survey (2014)	1705	1		1				1			
Marmorera, Survey (Pareis)	survey (2014)	1841	1		1				1			
Savognin, Parnoz	survey (1997)	1467	9	5	4				9			
TOTAL			**541**	**273**	**210**	**44**	**12**	**2**	**418**	**123**		

Tab. 1: Overview of the wood species and dendrochronological dates (graphic representation: ADG).

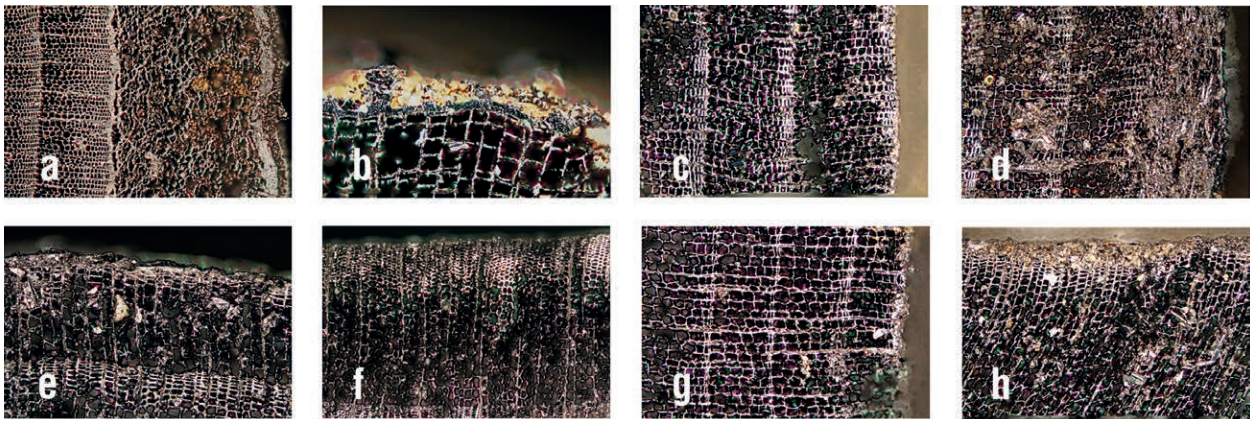

Fig. 2: Some examples of positively identified and/or uncertain waney edges. Width of the image sections: 5 X magnification: 1.7 mm, 10 X: 0.85 mm, 20 X: 0.425 mm (Photos and graphic W. H. Schoch/ADG). a) 87889; Pareis I; Picea abies/Larix decidua; undated; complete bark, autumn/winter waney edge, 5 X magnification. b) 87845; Gruba I; Picea abies/Larix decidua; 634 BC; remnants of bast; autumn/winter waney edge, 20 X magnification. c) 88838; Tigignas Sot III; Picea abies/Larix decidua; 636 BC; no remnants of bast, yet probably with a waney edge, with intact final growth ring cells over the whole tangential surface; classified as "with an uncertain waney", 10 X magnification. d) 88792, Pareis I; Larix decidua/Picea abies; undated; remnants of bast; autumn/winter waney edge, 10 X magnification. e) 88219; Val Faller Plaz; Larix decidua/Picea abies; undated; no remnants of bast, yet probably with waney edge; final growth ring intact over the whole tangential surface; classified as "with an uncertain waney", 10 X magnification. f) 88217; Val Faller Plaz; Larix decidua/Picea abies; undated; no remnants of bast; final growth ring fully developed and intact over the whole tangential surface; autumn/winter waney edge, 5 X magnification. g) 88169; Val Faller Plaz; Picea abies/Larix decidua; undated; classified as "with an uncertain waney", 10 X magnification. h) 88164; Val Faller Plaz; Picea abies/Larix decidua; undated; bast remnants; autumn/winter waney edge, 10 X magnification.

in a single row on the tracheid walls. *Larix decidua*, on the other hand, shows quite an abrupt transition from early to latewood and often has bordered pits in double rows (Schweingruber, 1990, pp.54, pp.56). For obvious reasons, this criterion is not applicable in wood with extremely narrow rings.

As a consequence, the identifications presented here include both names, whereby the name of the more likely species is mentioned first (e.g. *Larix decidua/Picea abies* and vice versa) (Tab. 1). The same applies to *Pinus sylvestris* or *Pinus mugo*. Anatomical differentiation between *Pinus cembra* and other conifers, on the other hand, was clear. Because of the predominance of *Larix decidua/Picea abies* and *Picea abies/Larix decidua* in the samples presented here, we built our dendrochronological mean curves across species, as long as the correlation matches were satisfactory. In this way, we ensured a sufficiently high replication of our mean curves.

2) In contrast to uncharred wood, the final year of growth, and thus the felling date of the tree, is not easily determined in charred wood samples. Any charcoal fragments suspected of containing a waney edge were examined in detail under a microscope magnified up to 50 times and those that did, in fact, include a waney edge, were photographed. Waney edges were positively identified where remains of bast fibres were definitely present or where the outermost cells were invariably fully developed and intact over the whole tangential surface. If the presence of a waney edge was only probable and there were no remnants of bast, it was described as "uncertain" (Fig. 2). Charcoal fragments often break along the boundaries between growth rings, particularly in earlywood cells, which are softer and slightly less stable than the denser latewood cells. In cursory evaluations, such breaks can easily be mistaken for waney edges. Moreover, the generally rather high degree of fragmentation in charcoal means that any potential waney edges must be detected on particularly small surfaces. Similarly, the maximum trunk diameter and the shape of the timber (e.g. split timber etc.) could not be reconstructed in the material presented here.

In an attempt to deal with a set of questions that present themselves regarding the advantages and/or disadvantages of the use of charcoal and wood in firing processes, we conducted an experiment to examine how wood behaves when it is charred. A recent fragment of larch wood (sample no. 85667; Grisons, Langwies-Medergen Wald, 1990 m a.s.l., dated to 2010, larch, 475 tree rings, pith, 36 sapwood rings, waney edge: spring) was divided into two identical pieces; one was then carbonised (Fig. 3).

At this stage of the project, the deposits which contained the charcoal fragments – in particular Gruba I and Val Faller Plaz – have not yet been attributed to any kind of archaeological sequence. This, however, is a prerequisite if also short series are to be included in the overall analysis. It is not yet clear, whether the samples from each site were retrieved from different archaeological features or how they related to each other from a relative chronological point of view. We therefore decided that a

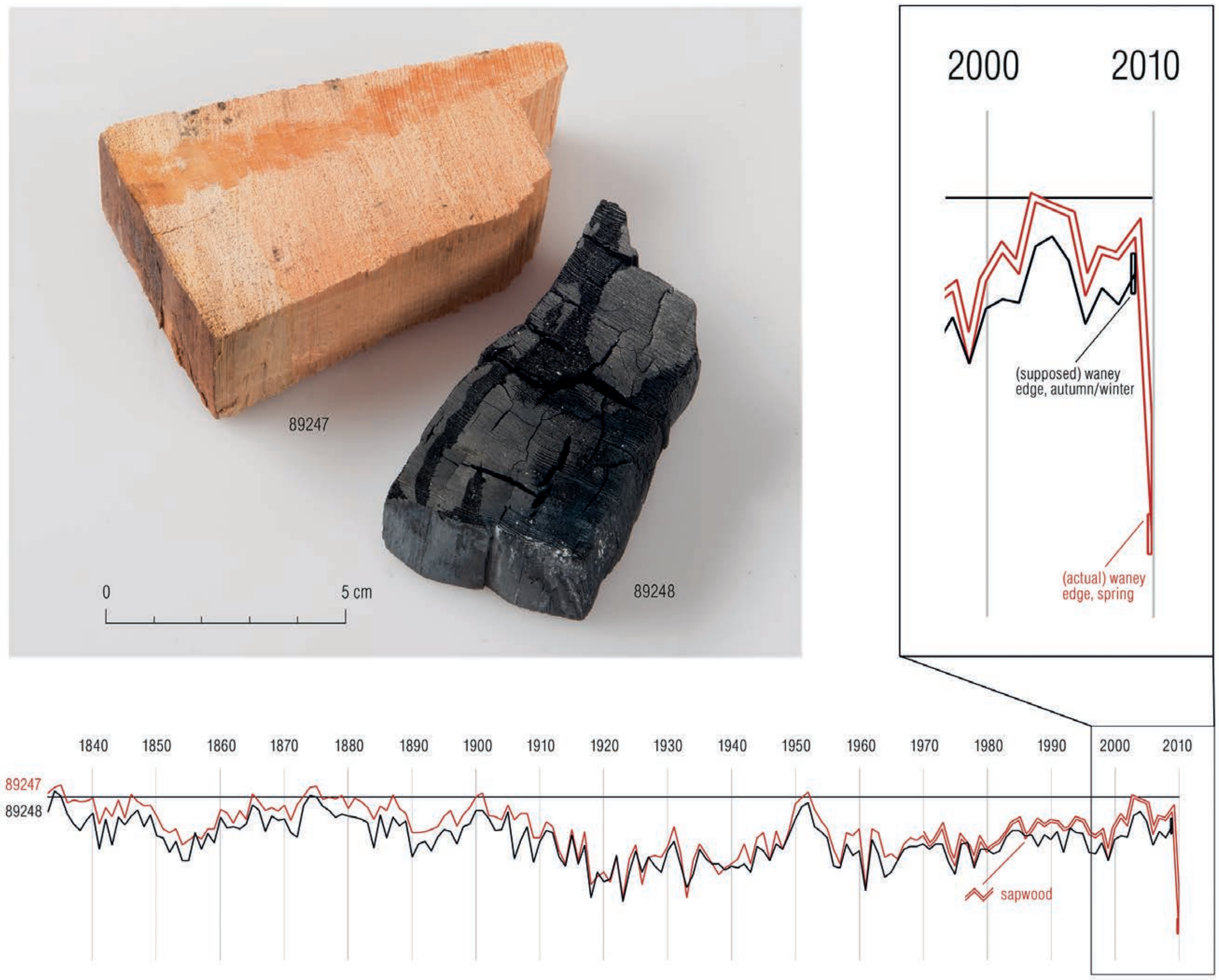

Fig. 3: Charcoal experiment. Recent alpine larch sample, charred and uncharred fragments and the correlation of both series. Values: Gleichläufigkeit 81.3, t-value after Hollstein 10.0 (graphic ADG).

sample must have at least 50 annual rings in order to be taken into account for sites not yet evaluated. Any potential dates from samples with 25 to 49 tree rings will have to be obtained and reviewed at a later date, once they have been firmly associated with one of the phases of use. In the case of Avagna-Ochsenalp and Cotschens, on the other hand, which have been conclusively studied and evaluated with regard to the relative chronological sequence, samples with less than 50 annual rings have already been taken into account and contextualized (Reitmaier-Naef et al., in press).

Our focus therefore was to establish a robust reference chronology, which would ideally be composed exclusively of long and well cross-correlated series. In view of the extraordinarily large number and good quality of the samples, the decision was made to use only the series from Gruba I, which had at least 50 tree rings. The aim of this first step in the analysis was to date the samples from Gruba I and then to date the remaining sites using Gruba I as a reference.

In constructing the Gruba reference mean curve we applied the leave-one-out principle: every series was first checked against the mean curve obtained from all other series. It was then divided into shorter segments for which alternative synchronous positions were checked in the neighbouring years. This allowed us to detect missing rings. Only if a series showed a t-value of at least 5 compared to the master chronology of all other series and only if there were no indications of missing rings, the series in question retained its place in the data set.

Two versions of the mean curve were constructed: one was calculated from the raw values, the other from the detrended series. For detrending prior to calculating the mean curve we used a *cubic smoothing spline* with an interval of 9 years (Cook & Peters, 1980) in order to remove medium and low frequency variability. The strength of the common signal that is contained in the resulting mean curve versions from Gruba I (MK 3940 and 5129) was evaluated using the mean correlation coefficient between all series and the *Expressed Population Signal* in 30-year segments (cf. Fig. 5, EPS: Briffa & Jones, 1990). These calculations were carried out in R (R Core Team 2017) using the DplR package (Bunn, 2008).

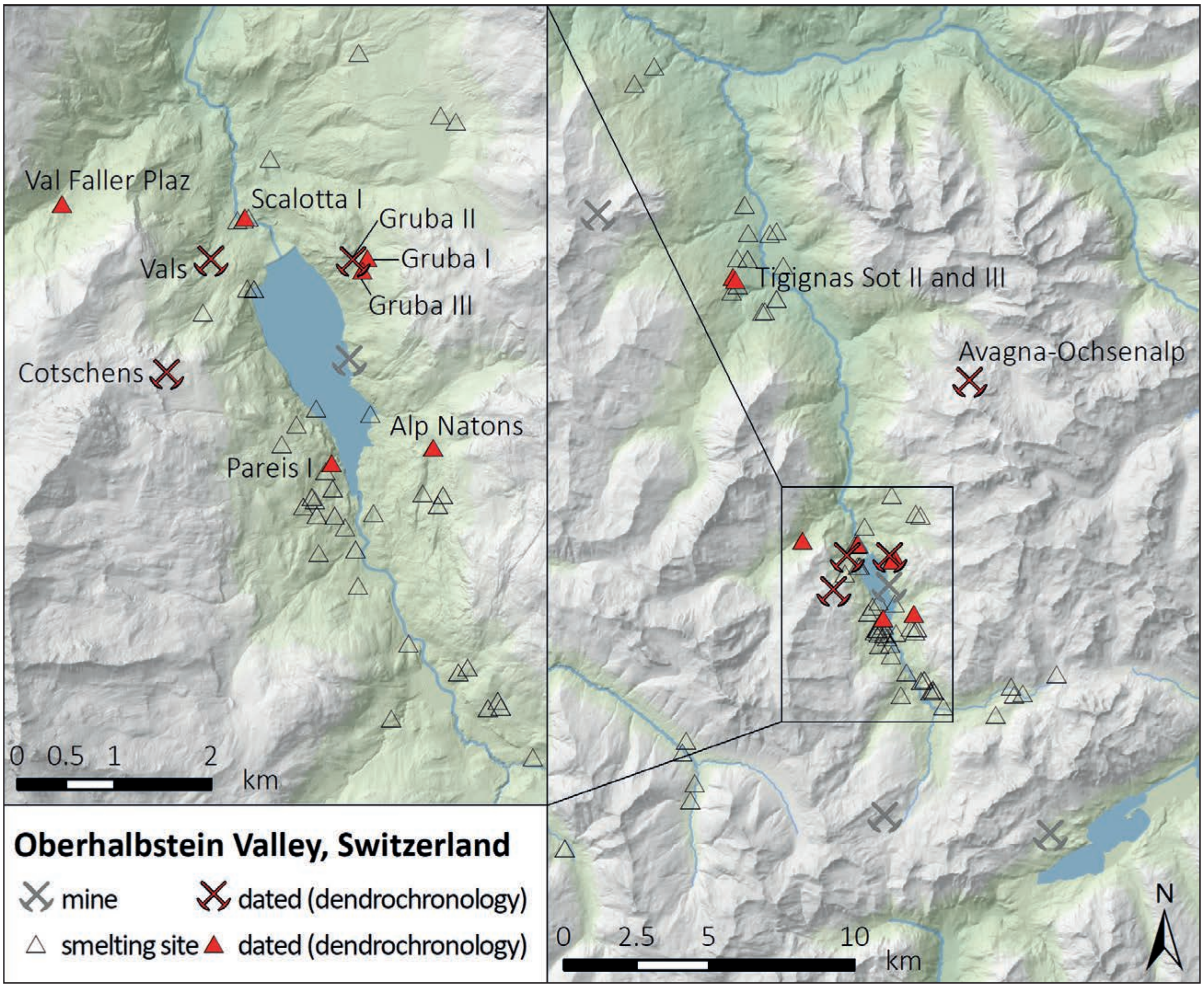

Fig. 4: Location of all sites with dendrochronologically dated samples (graphic L. Reitmaier-Naef).

Results

The vast majority of samples were identified as either *Larix decidua/Picea abies* (51%) or *Picea abies/Larix decidua* (39%), followed by *Pinus cembra* (8%) and a small number of *Pinus mugo/sylvestris* (2%) (Tab. 1). Overall 9 waney edges, autumn/winter in any case, were positively identified whilst a further 9 were labelled as "uncertain" (Fig. 2); a total of 8 samples including a waney edge were dendrochronologically dated (cf. Fig. 7).

Having compared both the dendrochronological series and the fragments themselves, the result of the experiment concerning carbonised wood was that after carbonisation the volume had been reduced by about half and the sample had lost some 75% of its original weight. The waney edges also exhibited differences (Fig. 3). While the last growth cells, which had formed in the spring of 2010, were present in the unburnt piece, they were no longer preserved in the other fragment: during carbonisation, the less robust earlywood cells, which represented the spring growth, had been burnt away completely. Without this background information, one would have assumed that the tree had been felled in the autumn or winter of 2009, simply because the denser and therefore more robust latewood cells had survived the fire, whilst the earlywood cells had not.

A total of 123 individual wood samples (23%) from 12 different sites – 4 mining and 8 smelting sites – were dated as part of the project (Tab. 1, cf. Tab. 2).

With two exceptions (Riom-Parsonz, Tigignas Sot II and III) all sites were located on the upper valley step, clustered around today's Marmorera water reservoir and were excavated as part of the Oberhalbstein project (Fig. 4). Unfortunately, charcoal samples from the associated surveys and from a number of excavations carried out in the 20th century did not yield any useful dendrochronological results.

The majority of samples date from the Hallstatt period. The dates were all obtained on the basis of mean curve MK 5129 consisting of 51 individual wood samples from Gruba I (Fig. 5a-b). It covers a period of 373 years between 980 BC and 607 BC.[1] The first 70 and final

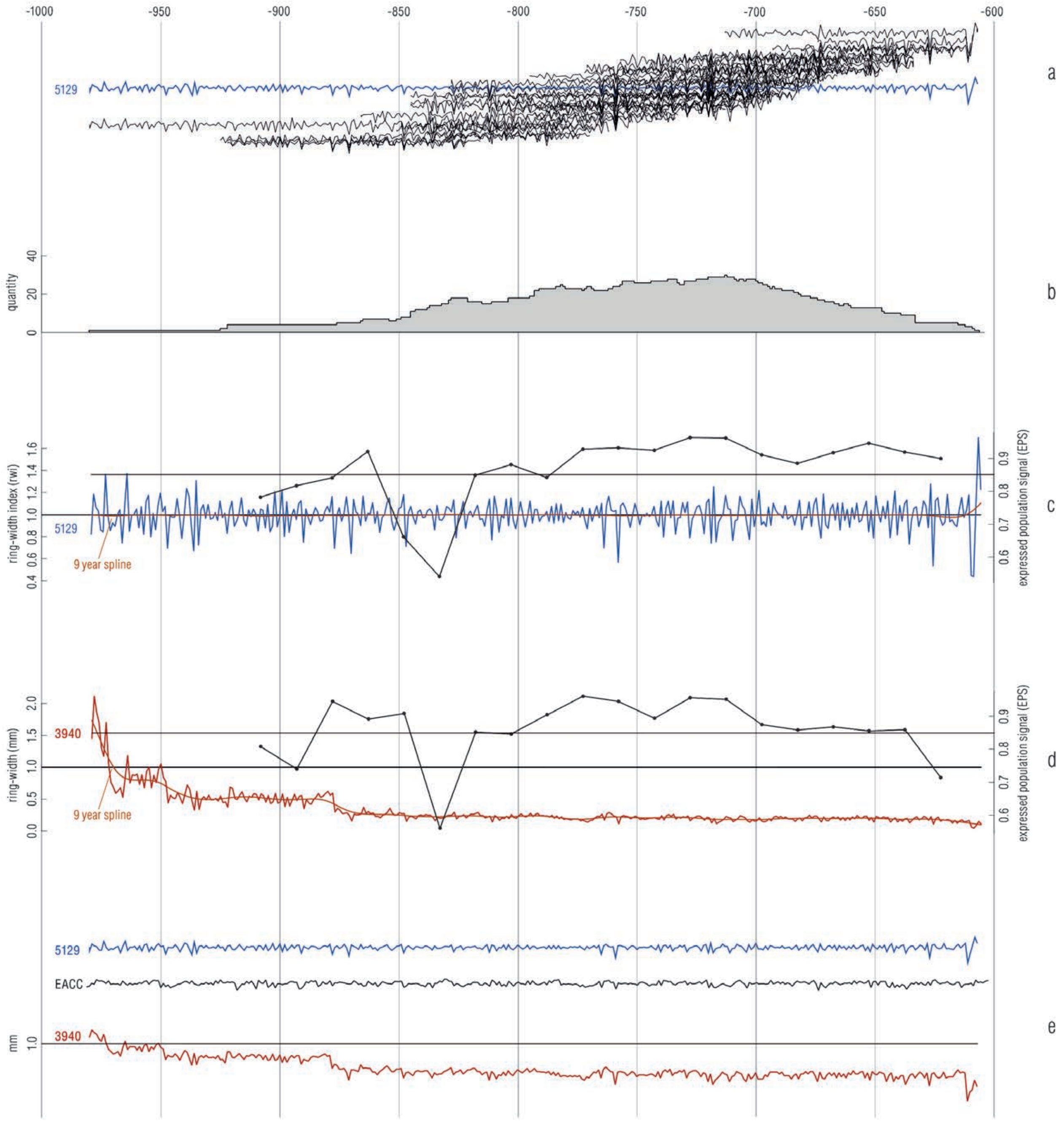

Fig. 5: Marmorera, Gruba I. Superimposed detrended series including the mean curve MK 5129 (graphic representation: ADG). Replication of the mean curves MK 3940 and MK 5129 (graphic representation: ADG). Expressed Population Signal (EPS), detrended series (graphic representation: N. Bleicher/ADG). Expressed Population Signal (EPS), raw data series (graphic representation: N. Bleicher/ADG). Cross-correlations of MK 5129 (Gleichläufigkeit 70.2%, t-value after Hollstein: 13.3) and MK 3940 (Gleichläufigkeit 69.7%, t-value after Hollstein: 13.9) with the Eastern Alpine Conifer Chronology (EACC; K. Nicolussi, University of Innsbruck) (graphic K. Nicolussi/ADG).

15 tree rings were excluded from the evaluation due to poor replication values. The chronology shows a solid *Expressed Population Signal (EPS)* of at least 0.85 for the period between c. 820 BC and 620 BC (Fig. 5c). The period between c. 910 BC and 820 BC was the only section of the mean curve that yielded inferior values. In comparison, the raw data series yielded slightly lower but still quite solid values (Fig. 5d).

Cross-correlation of the detrended mean curve MK 5129 with the *Eastern Alpine Conifer Chronology (EACC),* which goes back uninterrupted to the 8th millennium BC (Nicolussi et al., 2009), was very robust and statistically highly significant, even in the area evaluated by the EPS as non-confident (Fig. 5e). The period between 980 BC and 915 BC did exhibit some areas of *Gegenläufigkeit*. In MK 5129 this period is represented by only one series.

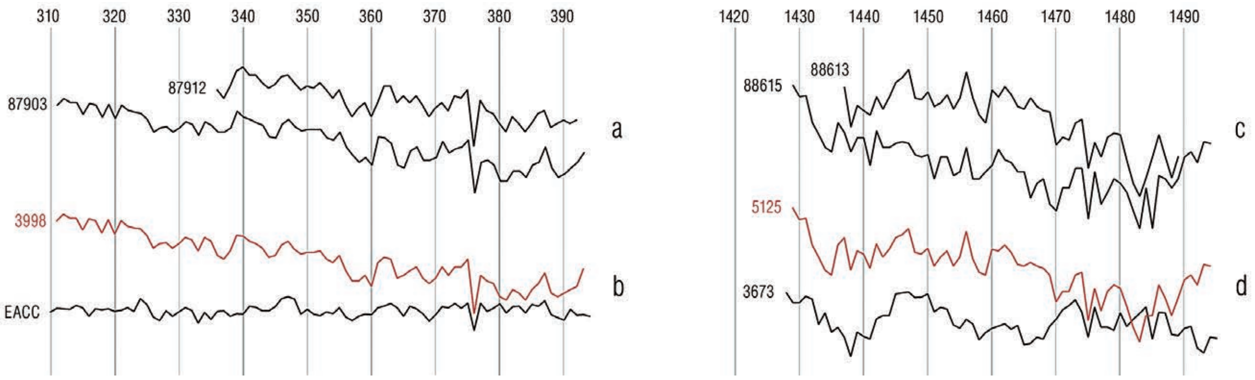

Fig. 6: Overlapping mean curves. Marmorera, Scalotta I. MK 3998 consists of series 87903 and 87912; Gleichläufigkeit 69.9%, t-value after Hollstein 10.0 (graphic representation: ADG). Marmorera, Scalotta I. MK 3998 cross-correlated with the Eastern Alpine Conifer Chronology (K. Nicolussi, University of Innsbruck); Gleichläufigkeit 70.7%, t-value after Hollstein 7.7 (graphic representation: K. Nicolussi/ ADG). Marmorera, Gruba II, Pinge 3. MK 5125 consists of series 88613 and 88615; Gleichläufigkeit 76.9%, t-value after Hollstein 5.4 (graphic representation: ADG). Marmorera, Gruba II, Pinge 3. MK 5125 cross-correlated with mean curve MK 3673 from S-chanf, house no. 25; Gleichläufigkeit 66.2%, t-value after Hollstein 5.1 (graphic ADG).

As expected, the detrended mean curve yielded a higher *Gleichläufigkeit* – though only marginally – and a lower t-value when compared to the raw data series MK 3940 (Fig. 5e).

A further 11 samples from Gruba I as well as a number of samples from other sites were subsequently dated by means of MK 5129 from Gruba I. In order to enhance the quality of these dates, rather rigid parameters were set, with the lowest t-value after Hollstein being 5 and the minimum number of tree rings being 50: the samples came from the sites Val Faller Plaz (13 samples), Pareis I (7 samples), Gruba III (2 samples), Alp Natons (2 samples), Vals (1 sample) and Tigignas Sot II and III (2 samples). With the exception of the two latter sites, which were located at an altitude of 1400 m a.s.l., all samples dating from the Hallstatt period were found at altitudes of between c. 1695 m and 2000 m a.s.l.

All seven waney edges from the Hallstatt period sites were dated to between 642 BC and 607 BC, though the earliest end year date was calculated as 855 BC (cf. Fig. 7). In the case of Gruba I, which yielded three samples with a waney edge, these represented the most recent, the fifth most recent and the eighth most recent of a total of 62 end year dates.

Besides the Hallstatt period, other periods were also represented at various sites: Scalotta I yielded one Late Antique end year date (AD 393)[2] and Gruba II, Pinge 3 one late medieval end year date (AD 1494) (Fig. 6). Prehistoric phases of these two sites are also evidenced by radiocarbon dated charcoal unsuitable for dendrochronological analyses (Turck et al., in press). It was not possible to ascertain the number of tree rings that were missing between the outermost rings and the waney edges.

The results obtained by dendrochronological analysis from the material from the mining sites at Cotschens and Avagna-Ochsenalp are shown here for the sake of completeness but have already been published and contextualised elsewhere (cf. Tab. 2) (Reitmaier-Naef et al., in press).

Discussion

The dates obtained have shown that charcoal as a material can provide important results but is also associated with certain difficulties due to its nature. Because it was not possible to ascertain the degree of fragmentation, it was also not clear whether the wood species distribution was representative of the original number of individuals and in how far it mirrored the species composition of the surrounding woodland in the period concerned. The wood charring experiment further revealed that potential spring/summer waney edges were perhaps not available because the soft earlywood did not survive the charring process, as was the case, at least, in the experiment we conducted. Determinations and interpretations of seasonal dates of charcoal samples must therefore be treated with some degree of circumspection.

A total of 90 samples were retrieved from the sites of Gruba I, Val Faller Plaz, Gruba III, Alp Natons, Pareis I, Tigignas Sot II and III and Vals (Fig. 7), which, thanks to the extremely robust mean curve (MK 5129) from Gruba I, could be dated. Apart from Tigignas Sot II and III (and Cotschens and Avagna-Ochsenalp; Reitmaier-Naef et al., in press), all sites were located at altitudes of between 1695 m and 2000 m a.s.l.; because of the similarly high altitudes, the samples can be expected to cross-correlate well, both within and beyond the site boundaries.

Although seven waney edges is a very small number, they were distributed throughout almost all sites and yielded strikingly similar dates of between 642 BC and 607 BC, thus covering only the final 35 years of a

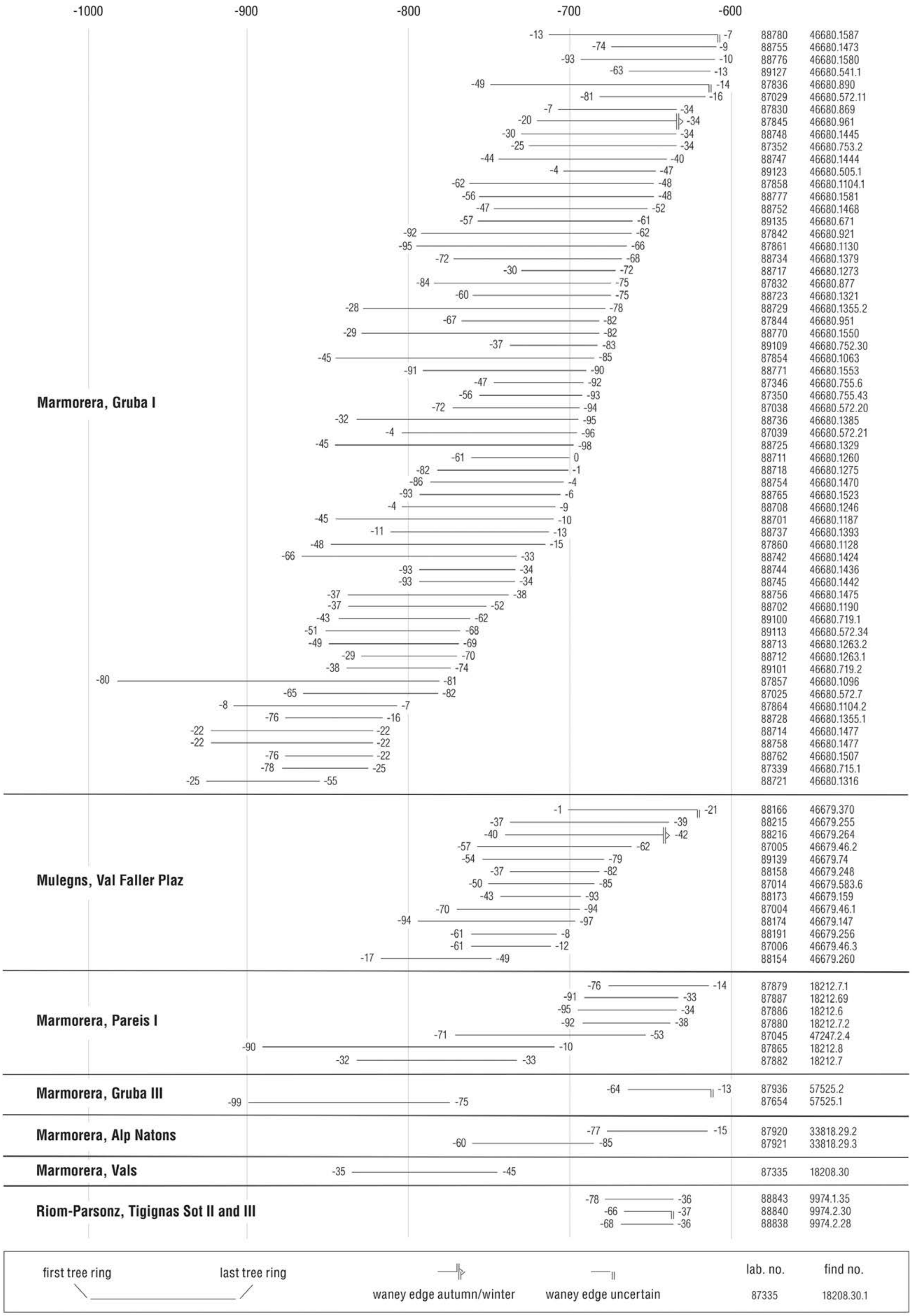

Fig. 7: Bar chart of all samples dating from the Hallstatt period (graphic ADG).

373 year-long mean curve. In the case of Gruba I, which yielded 62 dates in total, the ones with a waney edge were amongst the eight most recent end year dates.

It is as yet unclear whether these end year dates belonged to one or more phases of Gruba I (Turck, 2019). Only if there was a single short phase at Gruba I, all data could be interpreted together, including the end year dates with a waney edge. If that was the case, the entire data set of the series without a waney edge would show how large the range of end year dates can be, thus quantifying the *old-wood effect*. Even if these dates only indicated a *terminus post quem* for the final smelting activity, one might still assume, with the most recent end year being 607 BC, that the local activities took place around the end of the 7th and the first half of the 6th centuries BC.

So far, the data from the other sites with waney edges, i.e. Val Faller Plaz, Gruba III and Tigignas Sot II and III, do not allow such statements, as the number of dated samples is not sufficient. However, based on the most recent end year dates from these sites (Gruba I: 607 BC, Val Faller Plaz: 621 BC, Gruba III: 613 BC, Pareis I: 614 BC), all of which were located quite close to one another and were closely related with regard to their mining contexts, we can postulate a close chronological correlation or perhaps even contemporaneity between them. In case these sites turn out to be multi-phased, at least some of these phases might be synchronous, especially their final phases of use. It is possible, or perhaps even probable, that this also applies to the mining site at Vals, which yielded very little dendrochronologically datable charcoal and only one end year date of 745 BC. We cannot say for certain, but we could be dealing with the *old-wood effect* in this particular case. Tigignas Sot II and III (636 BC) were located at some distance from the other Hallstatt-period sites, which means that the connection to the other sites was based mainly on contextual similarities rather than geographical proximity.

Conclusion

Due to the large number and high quality of samples, dendrochronological analysis has become one of the cornerstones of the project over the past seven years.

Based on the current state of dendrochronological research, we would assume that the Hallstatt period copper mining and production at the sites investigated took place within a short period of time in the late 7th century BC (and/or at the beginning of the 6th century BC). However, this hypothesis rests on only few waney edges and the fact that no younger rings were found. The stratigraphical position has up to now not been taken into account. If the stratigraphical position of some samples should contradict our hypothesis, a critical reappraisal of either the *old wood-effect* or the stratigraphical consistency might become necessary, as taphonomical effects such as bioturbation might also affect the stratigraphical position of charcoal fragments.

We argue that the *old-wood effect* can be minimised by analysing a large number of samples, as shown by the project presented here. The more samples are provided by a site and analysed dendrochronologically, the more restricted the variation of the most recent end year dates becomes – even if there is a lack of dates with a waney edge. Chronologically speaking, it is the sum of all available samples that yields the best possible results.

Gruba I yielded 62 dendrodates (3 with a waney edge; 203 samples in total), Val Faller Plaz provided 13 dendrodates (2 with a waney edge; 96 samples in total). This poor yield is due to the fact that samples with fewer than 50 tree rings have not yet been analysed as part of the project (Gruba I: 56, Val Faller Plaz: 46). Once the relative chronological sequence of the features has been examined and the archaeological context can be used as additional information in the dating process, it will be possible to examine a few more series of samples with less than 50 rings, which may allow us to date the sites with greater precision.

Acknowledgements

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lab. no.	find no.	site	context quality	date	dating quality	waney edge	tree rings	ER no.	site no.	material	wood species	notes	^{14}C and *wiggle-matchings*
MINING SITES													
88581	67457.22.1	Marmorera, Cotschens	sondage (2017)	-67	b		88	67457	1890	wood	*Picea abies/ Larix decidua*	trough; pith	ETH-84250 (tree rings 82-84): 2076±17 BP
88593	18203.1109.3	Marmorera, Cotschens	sondage (2017)	-1137	b		50	18203	1890	charcoal	*Larix decidua/ Picea abies*		*wiggle-matching* with lab. no. 88596; ETH-86920 (tree rings 6-16; values 6-16 of mean curve 5095): 3054±22 BP
88596	18203.1109.6	Marmorera, Cotschens	sondage (2017)	-1131	b		43	18203	1890	charcoal	*Larix decidua/ Picea abies*		*wiggle-matching* with lab. no. 88593; ETH-84251 (tree rings 33-43; values 6-16 of mean curve 5095): 3073±17 BP
88613	56371.303.1	Marmorera, Grubaç II, Pinge 3	excavation (2016-2018)	1489	a		53	56371	1854	charcoal	*Larix decidua/ Picea abies*		
88615	56371.303.3	Marmorera, Gruba II, Pinge 3	excavation (2016-2018)	1494	a		66	56371	1854	charcoal	*Larix decidua/ Picea abies*		
87335	18208.30	Marmorera, Vals	sondage (2014; 2016)	-745	a		91	18208	1885	charcoal	*Larix decidua/ Picea abies*		ETH-58638 (tree rings 1-10): 2660±27 BP; ETH-58639 (tree rings 81-90): 2481±26 BP
87897	18203.1049	Tinizong-Rona, Avagna-Ochsenalp	sondage (2015; 2017)	-1112	b		68	18203	3911	charcoal	*Picea abies/ Larix decidua*		ETH-86921 (tree rings 57-68): 2973±21 BP
88633	67459.2.5	Tinizong-Rona, Avagna-Ochsenalp	sondage (2015; 2017)	-1058	a		52	67459	3911	charcoal	*Larix decidua/ Picea abies*		
88635	67459.2.7	Tinizong-Rona, Avagna-Ochsenalp	sondage (2015; 2017)	-1061	a		36	67459	3911	charcoal	*Picea abies/ Larix decidua*		
88637	67459.2.9	Tinizong-Rona, Avagna-Ochsenalp	sondage (2015; 2017)	-1067	a		57	67459	3911	charcoal	*Larix decidua/ Picea abies*		
88639	67459.2.11	Tinizong-Rona, Avagna-Ochsenalp	sondage (2015; 2017)	-1069	a		38	67459	3911	charcoal	*Picea abies/ Larix decidua*		
88644	67459.2.16	Tinizong-Rona, Avagna-Ochsenalp	sondage (2015; 2017)	-1059	a		61	67459	3911	charcoal	*Larix decidua/ Picea abies*		
88647	67459.2.19	Tinizong-Rona, Avagna-Ochsenalp	sondage (2015; 2017)	-1079	a		24	67459	3911	charcoal	*Picea abies/ Larix decidua*		
88648	67459.2.20	Tinizong-Rona, Avagna-Ochsenalp	sondage (2015; 2017)	-1065	a		40	67459	3911	charcoal	*Picea abies/ Larix decidua*		
88653	67459.2.25	Tinizong-Rona, Avagna-Ochsenalp	sondage (2015; 2017)	-1061	a	autumn/ winter	52	67459	3911	charcoal	*Picea abies/ Larix decidua*	bast remnants	
88655	67459.2.27	Tinizong-Rona, Avagna-Ochsenalp	sondage (2015; 2017)	-1079	a		25	67459	3911	charcoal	*Picea abies/ Larix decidua*		
88656	67459.2.28	Tinizong-Rona, Avagna-Ochsenalp	sondage (2015; 2017)	-1078	a		36	67459	3911	charcoal	*Picea abies/ Larix decidua*		
88658	67459.5.1	Tinizong-Rona, Avagna-Ochsenalp	sondage (2015; 2017)	-1062	a		46	67459	3911	charcoal	*Picea abies/ Larix decidua*		
88659	67459.5.2	Tinizong-Rona, Avagna-Ochsenalp	sondage (2015; 2017)	-1063	a		44	67459	3911	charcoal	*Picea abies/ Larix decidua*		
88662	67459.5.5	Tinizong-Rona, Avagna-Ochsenalp	sondage (2015; 2017)	-1075	a		43	67459	3911	charcoal	*Picea abies/ Larix decidua*		
88668	67459.5.11	Tinizong-Rona, Avagna-Ochsenalp	sondage (2015; 2017)	-1076	a		37	67459	3911	charcoal	*Picea abies/ Larix decidua*		
88671	67459.6.1	Tinizong-Rona, Avagna-Ochsenalp	sondage (2015; 2017)	-1063	a		59	67459	3911	charcoal	*Picea abies/ Larix decidua*		
88674	67459.6.4	Tinizong-Rona, Avagna-Ochsenalp	sondage (2015; 2017)	-1081	a		38	67459	3911	charcoal	*Picea abies/ Larix decidua*		
88675	67459.6.5	Tinizong-Rona, Avagna-Ochsenalp	sondage (2015; 2017)	-1071	a		38	67459	3911	charcoal	*Picea abies/ Larix decidua*		
88676	67459.6.6	Tinizong-Rona, Avagna-Ochsenalp	sondage (2015; 2017)	-1111	a		76	67459	3911	charcoal	*Picea abies/ Larix decidua*		
88678	67459.6.8	Tinizong-Rona, Avagna-Ochsenalp	sondage (2015; 2017)	-1105	a		50	67459	3911	charcoal	*Picea abies/ Larix decidua*		
88684	67459.8.2	Tinizong-Rona, Avagna-Ochsenalp	sondage (2015; 2017)	-1078	a		42	67459	3911	charcoal	*Picea abies/ Larix decidua*		
88687	67459.8.5	Tinizong-Rona, Avagna-Ochsenalp	sondage (2015; 2017)	-1061	a		47	67459	3911	charcoal	*Picea abies/ Larix decidua*		
88689	67459.9.1	Tinizong-Rona, Avagna-Ochsenalp	sondage (2015; 2017)	-1061	a		56	67459	3911	charcoal	*Picea abies/ Larix decidua*		
88691	67459.9.3	Tinizong-Rona, Avagna-Ochsenalp	sondage (2015; 2017)	-1083	a		79	67459	3911	charcoal	*Picea abies/ Larix decidua*		
88692	67459.9.4	Tinizong-Rona, Avagna-Ochsenalp	sondage (2015; 2017)	-1043	a		63	67459	3911	charcoal	*Larix decidua/ Picea abies*		
88695	67459.9.7	Tinizong-Rona, Avagna-Ochsenalp	sondage (2015; 2017)	-1071	a		32	67459	3911	charcoal	*Picea abies/ Larix decidua*		

lab. no.	find no.	site	context quality	date	dating quality	waney edge	tree rings	ER no.	site no.	material	wood species	notes	^{14}C and *wiggle-matchings*
		SMELTING SITES											
87921	33818.29.3	Marmorera, Alp Natons	excavation (2015)	-685	a		76	33818	1870	charcoal	*Picea abies/ Larix decidua*		
87920	33818.29.2	Marmorera, Alp Natons	excavation (2015)	-615	a		63	33818	1870	charcoal	*Picea abies/ Larix decidua*		
87025	46680.572.7	Marmorera, Gruba I	excavation (2013-2017)	-782	a		84	46680	1852	charcoal	*Larix decidua/ Picea abies*		
87029	46680.572.11	Marmorera, Gruba I	excavation (2013-2017)	-616	a		66	46680	1852	charcoal	*Picea abies/ Larix decidua*		
87038	46680.572.20	Marmorera, Gruba I	excavation (2013-2017)	-694	a		79	46680	1852	charcoal	*Pinus cembra*		
87039	46680.572.21	Marmorera, Gruba I	excavation (2013-2017)	-696	a		109	46680	1852	charcoal	*Larix decidua/ Picea abies*		
87045	47247.2.4	Marmorera, Gruba I	excavation (2013-2017)	-653	a		119	47247	1860	charcoal	*Picea abies/ Larix decidua*		
87339	46680.715.1	Marmorera, Gruba I	excavation (2013-2017)	-825	a		54	46680	1852	charcoal	*Picea abies/ Larix decidua*		
87346	46680.755.6	Marmorera, Gruba I	excavation (2013-2017)	-692	a		56	46680	1852	charcoal	*Picea abies/ Larix decidua*		
87350	46680.755.43	Marmorera, Gruba I	excavation (2013-2017)	-693	a		64	46680	1852	charcoal	*Larix decidua/ Picea abies*		
87352	46680.753.2	Marmorera, Gruba I	excavation (2013-2017)	-634	a		92	46680	1852	charcoal	*Picea abies/ Larix decidua*		
87830	46680.869	Marmorera, Gruba I	excavation (2013-2017)	-634	a		74	46680	1852	charcoal	*Larix decidua/ Picea abies*		
87832	46680.877	Marmorera, Gruba I	excavation (2013-2017)	-675	a		110	46680	1852	charcoal	*Larix decidua/ Picea abies*		
87836	46680.890	Marmorera, Gruba I	excavation (2013-2017)	-614	a	uncertain	136	46680	1852	charcoal	*Larix decidua/ Picea abies*		
87842	46680.921	Marmorera, Gruba I	excavation (2013-2017)	-662	a		131	46680	1852	charcoal	*Larix decidua/ Picea abies*		
87844	46680.951	Marmorera, Gruba I	excavation (2013-2017)	-682	a		86	46680	1852	charcoal	*Picea abies/ Larix decidua*		
87845	46680.961	Marmorera, Gruba I	excavation (2013-2017)	-634	a	autumn/ winter	87	46680	1852	charcoal	*Picea abies/ Larix decidua*	bast remnants	
87854	46680.1063	Marmorera, Gruba I	excavation (2013-2017)	-685	a		161	46680	1852	charcoal	*Larix decidua/ Picea abies*		
87857	46680.1096	Marmorera, Gruba I	excavation (2013-2017)	-781	a		200	46680	1852	charcoal	*Picea abies/ Larix decidua*		ETH-69841: 2907±13 BP
87858	46680.1104.1	Marmorera, Gruba I	excavation (2013-2017)	-648	a		115	46680	1852	charcoal	*Larix decidua/ Picea abies*		
87860	46680.1128	Marmorera, Gruba I	excavation (2013-2017)	-715	a		134	46680	1852	charcoal	*Larix decidua/ Picea abies*		
87861	46680.1130	Marmorera, Gruba I	excavation (2013-2017)	-666	a		130	46680	1852	charcoal	*Larix decidua/ Picea abies*		
87864	46680.1104.2	Marmorera, Gruba I	excavation (2013-2017)	-807	a		102	46680	1852	charcoal	*Larix decidua/ Picea abies*		
87867	46680.1096	Marmorera, Gruba I	excavation (2013-2017)	-841	a		140	46680	1852	charcoal	*Picea abies/ Larix decidua*		
87882	18212.7	Marmorera, Gruba I	excavation (2013-2017)	-733	a		100	18212	1860	charcoal	*Larix decidua/ Picea abies*		
88701	46680.1187	Marmorera, Gruba I	excavation (2013-2017)	-710	a		136	46680	1852	charcoal	*Larix decidua/ Picea abies*		
88702	46680.1190	Marmorera, Gruba I	excavation (2013-2017)	-752	a		86	46680	1852	charcoal	*Larix decidua/ Picea abies*		
88708	46680.1246	Marmorera, Gruba I	excavation (2013-2017)	-709	a		96	46680	1852	charcoal	*Larix decidua/ Picea abies*		
88711	46680.1260	Marmorera, Gruba I	excavation (2013-2017)	-700	a		62	46680	1852	charcoal	*Larix decidua/ Picea abies*		
88712	46680.1263.1	Marmorera, Gruba I	excavation (2013-2017)	-770	a		60	46680	1852	charcoal	*Larix decidua/ Picea abies*		
88713	46680.1263.2	Marmorera, Gruba I	excavation (2013-2017)	-769	a		81	46680	1852	charcoal	*Picea abies/ Larix decidua*		
88714	46680.1477	Marmorera, Gruba I	excavation (2013-2017)	-822	a		101	46680	1852	charcoal	*Larix decidua/ Picea abies*		

lab. no.	find no.	site	context quality	date	dating quality	waney edge	tree rings	ER no.	site no.	material	wood species	notes	^{14}C and *wiggle-matchings*
		SMELTING SITES											
88717	46680.1273	Marmorera, Gruba I	excavation (2013-2017)	-672	a		59	46680	1852	charcoal	*Larix decidua/ Picea abies*		
88718	46680.1275	Marmorera, Gruba I	excavation (2013-2017)	-701	a		82	46680	1852	charcoal	*Larix decidua/ Picea abies*		
88721	46680.1316	Marmorera, Gruba I	excavation (2013-2017)	-855	a		71	46680	1852	charcoal	*Larix decidua/ Picea abies*		
88723	46680.1321	Marmorera, Gruba I	excavation (2013-2017)	-675	a		86	46680	1852	charcoal	*Larix decidua/ Picea abies*		
88725	46680.1329	Marmorera, Gruba I	excavation (2013-2017)	-698	a		148	46680	1852	charcoal	*Larix decidua/ Picea abies*		
88728	46680.1355.1	Marmorera, Gruba I	excavation (2013-2017)	-816	a		61	46680	1852	charcoal	*Larix decidua/ Picea abies*		
88729	46680.1355.2	Marmorera, Gruba I	excavation (2013-2017)	-678	a		151	46680	1852	charcoal	*Larix decidua/ Picea abies*		
88734	46680.1379	Marmorera, Gruba I	excavation (2013-2017)	-668	a		105	46680	1852	charcoal	*Picea abies/ Larix decidua*		
88736	46680.1385	Marmorera, Gruba I	excavation (2013-2017)	-695	a		138	46680	1852	charcoal	*Larix decidua/ Picea abies*		
88737	46680.1393	Marmorera, Gruba I	excavation (2013-2017)	-713	a		99	46680	1852	charcoal	*Larix decidua/ Picea abies*		
88742	46680.1424	Marmorera, Gruba I	excavation (2013-2017)	-733	a		134	46680	1852	charcoal	*Picea abies/ Larix decidua*		
88744	46680.1436	Marmorera, Gruba I	excavation (2013-2017)	-734	a		60	46680	1852	charcoal	*Larix decidua/ Picea abies*		
88745	46680.1442	Marmorera, Gruba I	excavation (2013-2017)	-734	a		60	46680	1852	charcoal	*Picea abies/ Larix decidua*		
88747	46680.1444	Marmorera, Gruba I	excavation (2013-2017)	-640	a		105	46680	1852	charcoal	*Larix decidua/ Picea abies*		
88748	46680.1445	Marmorera, Gruba I	excavation (2013-2017)	-634	a		97	46680	1852	charcoal	*Picea abies/ Larix decidua*		
88752	46680.1468	Marmorera, Gruba I	excavation (2013-2017)	-652	a		96	46680	1852	charcoal	*Larix decidua/ Picea abies*		
88754	46680.1470	Marmorera, Gruba I	excavation (2013-2017)	-704	a		83	46680	1852	charcoal	*Larix decidua/ Picea abies*		
88755	46680.1473	Marmorera, Gruba I	excavation (2013-2017)	-609	a		66	46680	1852	charcoal	*Larix decidua/ Picea abies*		
88756	46680.1475	Marmorera, Gruba I	excavation (2013-2017)	-738	a		100	46680	1852	charcoal	*Larix decidua/ Picea abies*		
88758	46680.1477	Marmorera, Gruba I	excavation (2013-2017)	-822	a		101	46680	1852	charcoal	*Larix decidua/ Picea abies*		
88762	46680.1507	Marmorera, Gruba I	excavation (2013-2017)	-822	a		55	46680	1852	charcoal	*Larix decidua/ Picea abies*		
88765	46680.1523	Marmorera, Gruba I	excavation (2013-2017)	-706	a		88	46680	1852	charcoal	*Larix decidua/ Picea abies*		
88770	46680.1550	Marmorera, Gruba I	excavation (2013-2017)	-682	a		148	46680	1852	charcoal	*Larix decidua/ Picea abies*		
88771	46680.1553	Marmorera, Gruba I	excavation (2013-2017)	-690	a		102	46680	1852	charcoal	*Larix decidua/ Picea abies*		
88776	46680.1580	Marmorera, Gruba I	excavation (2013-2017)	-610	a		84	46680	1852	charcoal	*Picea abies/ Larix decidua*		
88777	46680.1581	Marmorera, Gruba I	excavation (2013-2017)	-648	a		109	46680	1852	charcoal	*Picea abies/ Larix decidua*		
88780	46680.1587	Marmorera, Gruba I	excavation (2013-2017)	-607	a	uncertain	107	46680	1852	charcoal	*Picea abies/ Larix decidua*		
89100	46680.719.1	Marmorera, Gruba I	excavation (2013-2017)	-762	a		82	46680	1852	charcoal	*Larix decidua/ Picea abies*		
89101	46680.719.2	Marmorera, Gruba I	excavation (2013-2017)	-774	a		65	46680	1852	charcoal	*Pinus cembra*		
89109	46680.752.30	Marmorera, Gruba I	excavation (2013-2017)	-683	a		55	46680	1852	charcoal	*Larix decidua/ Picea abies*		
89113	46680.572.34	Marmorera, Gruba I	excavation (2013-2017)	-768	a		84	46680	1852	charcoal	*Picea abies/ Larix decidua*		
89123	46680.505.1	Marmorera, Gruba I	excavation (2013-2017)	-647	a		58	46680	1852	charcoal	*Picea abies/ Larix decidua*		

lab. no.	find no.	site	context quality	date	dating quality	waney edge	tree rings	ER no.	site no.	material	wood species	notes	^{14}C and *wiggle-matchings*
		SMELTING SITES											
89127	46680.541.1	Marmorera, Gruba I	excavation (2013-2017)	-613	a		51	46680	1852	charcoal	*Picea abies/ Larix decidua*		
89135	46680.671	Marmorera, Gruba I	excavation (2013-2017)	-661	a		97	46680	1852	charcoal	*Larix decidua/ Picea abies*		
87654	57525.1	Marmorera, Gruba III	survey (2016)	-775	a		125	57525	56328	charcoal	indet.	sample missing	
87936	57525.2	Marmorera, Gruba III	survey (2016)	-613	a	uncertain	52	57525	56328	charcoal	*Picea abies/ Larix decidua*		ETH-69844: 2499±15 BP
87865	18212.8	Marmorera, Pareis I	sondage (2014-15; 2017)	-710	a		181	18212	1860	wood	*Larix decidua/ Picea abies*	toolmarks	
87879	18212.7.1	Marmorera, Pareis I	sondage (2014-15; 2017)	-614	a		63	18212	1860	charcoal	*Picea abies/ Larix decidua*		
87880	18212.7.2	Marmorera, Pareis I	sondage (2014-15; 2017)	-638	a		55	18212	1860	charcoal	*Picea abies/ Larix decidua*		
87886	18212.6	Marmorera, Pareis I	sondage (2014-15; 2017)	-634	a		62	18212	1860	charcoal	*Picea abies/ Larix decidua*		
87887	18212.69	Marmorera, Pareis I	sondage (2014-15; 2017)	-633	a		59	18212	1860	charcoal	*Larix decidua/ Picea abies*		
87903	18191.25.1	Marmorera, Scalotta I	sondage (2014)	393	a		83	18191	1842	charcoal	*Picea abies/ Larix decidua*		ETH-85520 (tree rings 1-10): 1775±24 BP; ETH-75698 (tree rings 70-80): 1780±22 BP
87912	18191.25.15	Marmorera, Scalotta I	sondage (2014)	392	a		57	18191	1842	charcoal	*Picea abies/ Larix decidua*		
87004	46679.46.1	Mulegns, Val Faller Plaz	excavation (2013; 2016)	-694	a		77	46679	2120	charcoal	*Larix decidua/ Picea abies*		
87005	46679.46.2	Mulegns, Val Faller Plaz	excavation (2013; 2016)	-662	a		96	46679	2120	charcoal	*Larix decidua/ Picea abies*		
87006	46679.46.3	Mulegns, Val Faller Plaz	excavation (2013; 2016)	-712	a		50	46679	2120	charcoal	*Larix decidua/ Picea abies*		
87014	46679.583.6	Mulegns, Val Faller Plaz	excavation (2013; 2016)	-685	a		66	46679	2120	charcoal	*Larix decidua/ Picea abies*		
88154	46679.260	Mulegns, Val Faller Plaz	excavation (2013; 2016)	-749	a		69	46679	2120	charcoal	*Larix decidua/ Picea abies*		
88158	46679.248	Mulegns, Val Faller Plaz	excavation (2013; 2016)	-682	a		56	46679	2120	charcoal	*Larix decidua/ Picea abies*		
88166	46679.370	Mulegns, Val Faller Plaz	excavation (2013; 2016)	-621	a	uncertain	81	46679	2120	charcoal	*Picea abies/ Larix decidua*	bast remnants	
88173	46679.159	Mulegns, Val Faller Plaz	excavation (2013; 2016)	-693	a		51	46679	2120	charcoal	*Larix decidua/ Picea abies*		
88174	46679.147	Mulegns, Val Faller Plaz	excavation (2013; 2016)	-697	a		98	46679	2120	charcoal	*Larix decidua/ Picea abies*		
88191	46679.256	Mulegns, Val Faller Plaz	excavation (2013; 2016)	-708	a		54	46679	2120	charcoal	*Larix decidua/ Picea abies*		
88215	46679.255	Mulegns, Val Faller Plaz	excavation (2013; 2016)	-639	a		99	46679	2120	charcoal	*Larix decidua/ Picea abies*		
88216	46679.264	Mulegns, Val Faller Plaz	excavation (2013; 2016)	-642	a	autumn/ winter	99	46679	2120	charcoal	*Larix decidua/ Picea abies*		
89139	46679.74	Mulegns, Val Faller Plaz	excavation (2013; 2016)	-679	a		76	46679	2120	charcoal	*Larix decidua/ Picea abies*		
88843	9974.1.35	Riom-Parsonz, Tigignas Sot II	survey (2006)	-636	b		43	9974	56325	charcoal	*Picea abies/ Larix decidua*		ETH-86922 (tree rings 31-43): 2528±22 BP
88838	9974.2.28	Riom-Parsonz, Tigignas Sot III	survey (2006)	-636	b	uncertain	33	9974	64189	charcoal	*Picea abies/ Larix decidua*		
88840	9974.2.30	Riom-Parsonz, Tigignas Sot III	survey (2006)	-637	b		30	9974	64189	charcoal	*Larix decidua/ Picea abies*		ETH-86923 (tree rings 21-30): 2477±21 BP

Tab. 2: All dated samples from the Oberhalbstein Valley project (graphic ADG).

Notes

1 This article uses the historical time scale, where the year "0" does not exist.

2 Due to insufficient correlation values with local references, *wiggle-matching* samples were taken from sample no. 87903. They resulted in a 2 sigma range of 295-325 cal. AD (plus 3 annual rings) for the more recent tree rings (for raw data cf. Tab. 2). Only then did Kurt Nicolussi check the dendrochronological analysis and achieve a dating on the EACC reference to the end year 393 – which meant that the deviation from the 2 sigma range was several decades. Contamination in the radiocarbon laboratory could be ruled out as a possible cause. Similar deviations for the 4th century AD have recently been observed elsewhere, which suggests that the cause may lie in the course of the calibration curve itself. Cf. Friedrich et al., 2019.

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Authors

Niels Bleicher – Laboratory for Dendrochronology, City of Zurich
Philippe Della Casa – University of Zurich, Institute of Archaeology, Department of Prehistoric Archaeology
Monika Oberhänsli – Laboratory for Dendrochronology, Archaeological Service of the Canton of Grisons
Thomas Reitmaier – Archaeological Service of the Canton of Grisons
Leandra Reitmaier-Naef – University of Zurich, Institute of Archaeology, Department of Prehistoric Archaeology
Werner H. Schoch – Laboratory for Ancient Wood Research, CH-8135 Langnau am Albis
Mathias Seifert – Laboratory for Dendrochronology, Archaeological Service of the Canton of Grisons
Rouven Turck – University of Zurich, Institute of Archaeology, Department of Prehistoric Archaeology

Correspondence and material requests should be addressed to: monika.oberhaensli@adg.gr.ch

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Elena Silvestri, Paolo Bellintani, Andreas Hauptmann

Bronze Age copper ore mining and smelting in Trentino (Italy)

ABSTRACT: *Knowledge about Trentino as a mining district has grown within the last years, based on new excavations at smelting sites, radiocarbon datings and archaeometallurgical analyses of slags. Following a general description of indications for copper mining and smelting in the area during the last phases of the Bronze Age, two new excavations, Valcava and Sant'Orsola both in the Mocheni Valley are briefly presented. The results of eleven new radiocarbon datings from LBA smelting sites are improving the discussion about chronology of the smelting activity in the region. Preliminary results of the analytical part of the research, focused mostly on plate slags, are presented, including bulk composition of plate slag samples and chemical composition (method: SEM-EDX) of Cu-Fe-sulphide inclusions in plate slags from different smelting sites.*

KEYWORDS: COPPER PRODUCTION, SMELTING SITES, FURNACES, CHRONOLOGY, SLAG ANALYSES

Introduction

In 1987, before most of the publications about copper smelting in the area had been published, Reinhard Exel defined the prehistoric exploitation of the copper ore in the eastern part of Trentino as probably even more important than the silver exploitation of Monte Calisio during medieval times (Exel, 1987). The importance of the local copper ores emerged even more thanks to the project of systematic investigation of prehistoric smelting sites in the area carried out by the Deutsches Bergbau-Museum (DBM) Bochum (Germany) and the Ufficio beni archeologici of Trento (UBA) during the 1980s and the 1990s (Cierny, 2008; Metten, 2003). The research, through survey and excavations, showed how large metallurgical activity was during Prehistory, with over 200 smelting sites found and mapped (Fig. 1). Thanks to this research the heritage protection could reach more remote areas of the territory, where most of the smelting sites are located and frequently in danger to be destroyed, mostly by ski tracks and roads construction.

A very important part of the collaboration between Bochum and Trento was the archaeological excavation carried out at Acqua Fredda (near the Redebus Pass in the Mocheni Valley, Trento), at an altitude of about 1,500 m a.s.l. between 1979 and 1995 (Cierny, 2008 and references therein). Here, a large and well-preserved smelting complex with nine smelting furnaces built into stone walls on an artificial terrace has been excavated. It is one of the most important metallurgical sites in the Alpine area. The site is dated, thanks to archaeological findings and 13 radiocarbon datings, to the Late and Final Bronze Age. The analysis of stratigraphy identified two main phases of construction of the furnaces[1]. An area with a large deposit of slags, slag sand (finely crushed slag) and tools (grinding stones, hammer stones) was identified close to the site, with a quantity estimated to be around 800-1000 tons of slags.

During the last years, new excavations have been carried on by the Ufficio beni archeologici (Archaeological Heritage Office) during its activity of heritage protection. The archaeometallurgical research project started again in 2011 with a PhD study at the Ruhr Universität Bochum in collaboration with the DBM and the Ufficio beni archeologici of Trento. It includes field work (excavation, survey) and analytical investigations, mainly focused on plate slags.

The copper ore and the mining activity

A general overview of the evidence by Renato Perini shows that during Prehistory two main metallurgical phases can be distinguished (Perini, 1992; Cierny et al.,

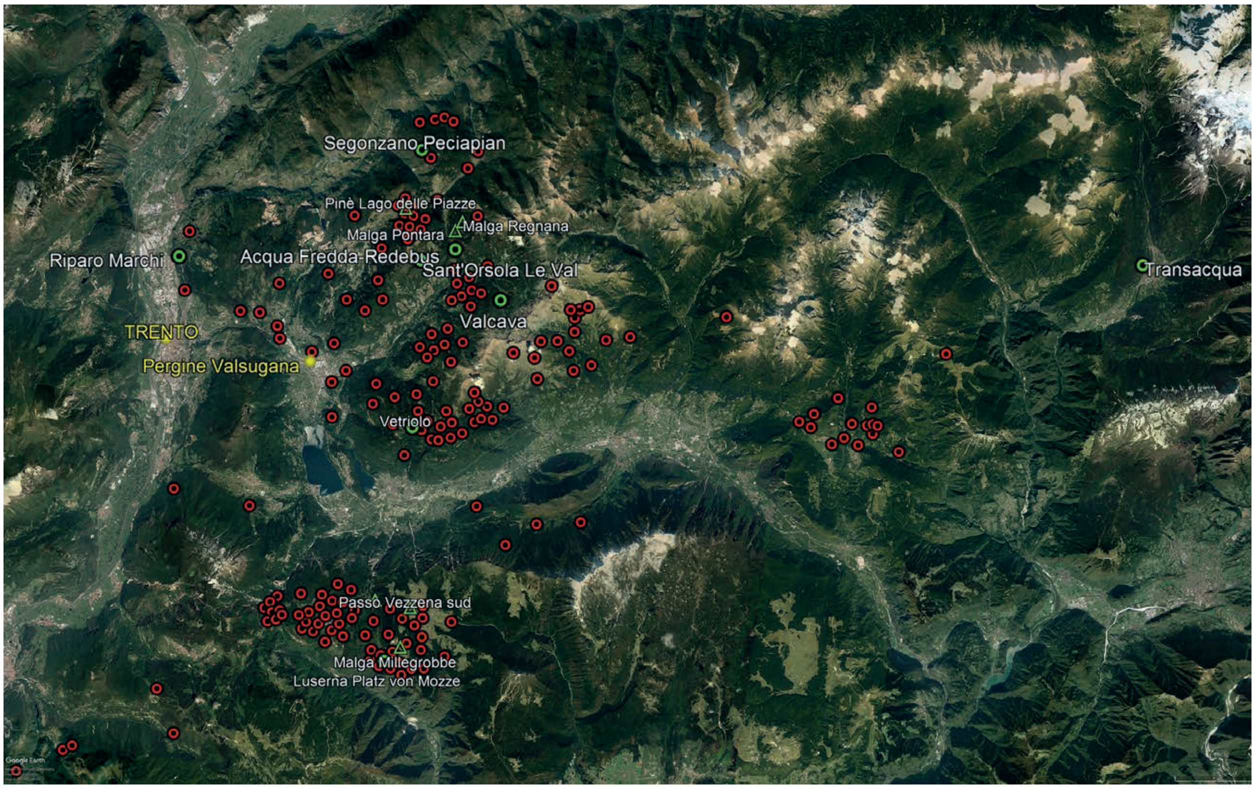

Fig. 1: Map of eastern Trentino with the sites mentioned in the text. The red spots are the so far mapped smelting sites, the green spots are the smelting sites excavated in the last years. The green triangles are the smelting sites where slags have been surface sampled for archaeometrical analyses.

1995; Angelini et al., 2013). The earliest copper smelting sites in Trentino date back to the Copper Age-Early Bronze Age (second half of the third millennium BC). They lie under or near rock shelters on the floor of the Adige Valley or in open areas. Smelting took place in oval-shaped pits coated with clay or square smelting furnaces with open fronts. The second period of copper metallurgy after Perini took place during the Late-Final Bronze Age according to the Italian chronology (second half of the 14th century-12th century BC)[2]. The smelting activity seems to have dramatically improved and moved to mountain areas over 1,000 m a.s.l. This is proven by slag heaps and the remains of smelting furnaces built on slopes near water and timber resources, especially in eastern Trentino (Mocheni Valley, Tesino, Altopiano di Lavarone e Luserna, Vezzena; Fig. 1).

The number of sites belonging to the first phase is quite small (eleven sites found till now) while the activity during the Late Bronze Age includes a large number of smelting sites, with a concentration up to 1 site/km^2 in specific areas. It needs to be specified that only a minor part of these sites is securely dated to Late-Final Bronze Age, on the basis of pottery typology or of ^{14}C datings (Acqua Fredda, Malga Pontara, Cambroncoi, Brombisc, Malga Stramaiolo, Bedelar, Prati di Montagna, Malga Trenca, Val Morta, Luserna Platz or Pletz von Mozze, Segonzano Peciapian, Transacqua, Valcava, Sant'Orsola, Terrebis). The other sites are dated to the same phase due to the morphology of the slags, especially the flat and very homogeneously composed plate slags (in German language called *Plattenschlacken*), typical of this period.

The main area with copper ores leads to the east of Trento along a system of faults ENE-WSW called "Linea della Valsugana" (Valsugana tectonic line), in the central part of the province, to the east of the Monte Calisio, up Mocheni Valley to the North and North-East and north of the Valsugana. It is coinciding with zones for which historic mining is documented (Preuschen, 1973; Šebesta, 1992; Forenza, 2005; Pearce, 2007; Cierny, 2008). There are copper deposits in the western part of the Province also, e.g. Val di Non and Giudicarie, but so far no smelting sites are known, and the research focused so far on the deposits to the east of the Adige Valley.

The copper ore deposits in this area have been discussed by Ernst Preuschen (Preuschen, 1968; 1973 translation in Italian) and Beate Metten (Metten, 2003). Preuschen (1973, pp.122-129) describes the deposits in detail, connecting the medieval mines and mining dumps with the presence of smelting sites, dated to Prehistory on the grounds of slags and stone tools. Many deposits described by Preuschen contain abundant chalcopyrite (Nogarè, Erdemolo, S. Francesco, Cinque Valli, etc.). The smelting sites mapped by him have been afterwards included in Cierny's database (Cierny, 2008).

The ore outcrops show three different types of deposits, with a mixture in different proportions of sulphidic, carbonatic and oxidic ores. Metamorphic rocks like quartz phyllites contain sulphides with pyrite as main mineral. Minor minerals are galena, chalcopyrite and arsenopyrite. In the hydrothermal veins of quartz phyllite and vulcanites the main minerals are arsenopyrite, galena, chalcopyrite, pyrite and sphalerite with malachite, azurite and calcite. Both types of deposits feature quartz. In the deposits related to the Bellerophon formation, small quantities of chalcopyrite, covellite, malachite and azurite can be found also, playing only a minor role during Bronze Age exploitation, together with silver and lead minerals.

Up to now, no data about copper mining during Prehistory is available. A reason for that could be the intensive exploitation of the area during medieval times that could have partly destroyed the traces of former mining activities.

In most cases the smelting sites are in proximity of the mineral outcrops, and they represent so far the only evidence of their exploitation during Bronze Age. There is nevertheless an important exception in this scenario: the Lavarone-Luserna-Vezzena plateau (Altipiani Cimbri). Here there is a high concentration of smelting sites, but there do not seem to be any significant copper deposits in the area (the reasons for the smelting activity in the area are discussed in detail in Pearce, 2007, pp.77-81).

In Vetriolo (Levico, Trento), at an altitude of 1,700 m a.s.l., the only site appearing to have been an area dedicated to the crushing and washing of ore had been discovered by E. Preuschen (Preuschen, 1962; 1973 pp.121, 126, fig. 4 & 7, tav. 1 & 2). The peculiar tools, including large grinding stones with and without vertical incisions, mostly made of porphyry, allowed him to date the site to the Bronze Age (Figure 2). No pottery has been found during the excavation, only two atypical fragments. The dating of the site is based on the morphology of the stone tools only. In the area of the mining dump, heavy, only partially liquified slag cakes can still be found, the so called *Schlackenkuchen* (Fig. 11). Outcrops of chalcopyrite and pyrite are present in the vicinity, smelting sites (at least six known in an area of ca. 10 km^2) and an impressive medieval and modern mining activity, although more focused on the extraction of pyrite, galena and barite (Detomaso, 2005, pp.99-100, 109-110; Gramola, 2000, pp.229-238).

In the adjacent area, Alto Adige/Südtirol, copper smelting is also attested from the third millennium BC (Millan, Gudon, Bressanone/Brixen, Velturno; Angelini, et al., 2013; Tecchiati, 2015 and references therein). Only one major deposit occurs, in Monte Fondoli/Pfundererberg near Chiusa/Klausen, and it seems to have been the source of chalcopyritic charge for all the sites along the Isarco Valley (Artioli et al., 2015, p.81). The more recent metallurgical phase is also attested by smelting sites with plate slags, "slag sand" and stone tools in Luco/Laugen culture contexts (Nothdurfter, 1993, pp.72-75; Anguilano et al., 2002a).

In spite of the difficult context, some hypotheses about the origins of copper ores have been advanced on the basis of chemical and mineralogical analyses of the slags. The analyzed smelting slags reveal a provenance of the raw material from the phyllitic basement of Valsugana (slags from Gaban, Acquaviva, Romagnano, Luserna sites), or from the deposits related to post-variscan volcanism (Val Fersina; Cattoi et al., 2001; D'Amico et al., 1998). Moreover, isotope analyses performed by Artioli and his team led to identify the Valsugana fault (Calceranica, Vetriolo) as the ore provenience area for the slags from Romagnano, La Vela, Gaban and Acquaviva, and the Mocheni Valley as the origin of the mineral processed at Montesei di Serso (Angelini et al., 2013; Artioli et al., 2014; 2015; 2016; Nimis et al., 2012).

Fig. 2: Grinding stone found in Vetriolo, dimensions 57x35 cm, height 18 cm (after Preuschen, 1962, fig. 4).

The destination of the final product, the metal, is one of the most interesting topic of debate between scholars. The last researches based on isotopic data are shedding new light on the importance of the southern Alpine area as possible source of copper on a much larger scale than expected (Artioli et al., 2016; Jung et al., 2011; Jung & Mehofer, 2013; Stos-Gale, 2017).

An interesting case study is the mining district around Pergine Valsugana and Mocheni Valley, for the outcrops but also for the long history of mining activity (Fig. 3). The exploitation started during Prehistory, although we have no direct evidence of it, and had an important phase during medieval times, with residual activity up to the last century (Detomaso, 2005). In the area of Pergine the medieval exploitation was started in the 14th century AD by companies coming from Bohemia. One of the largest medieval mining district in the area is Serso-Viarago (Pergine Valsugana) with a polymetallic ore composed of chalcopyrite, pyrite, galena and sphalerite in quartz gangue, in veins up to 1 m thick. In the 14th century over 10 mines were active. They had been exploited till 1940. One of the mines, still existing, includes seven levels (by that the name "Sette sospiri", "Seven sighs"), the main mineral being chalcopyrite.

During the 14th century AD copper ore was exploited in the area around Pinè, in the Mocheni Valley, Viarago,

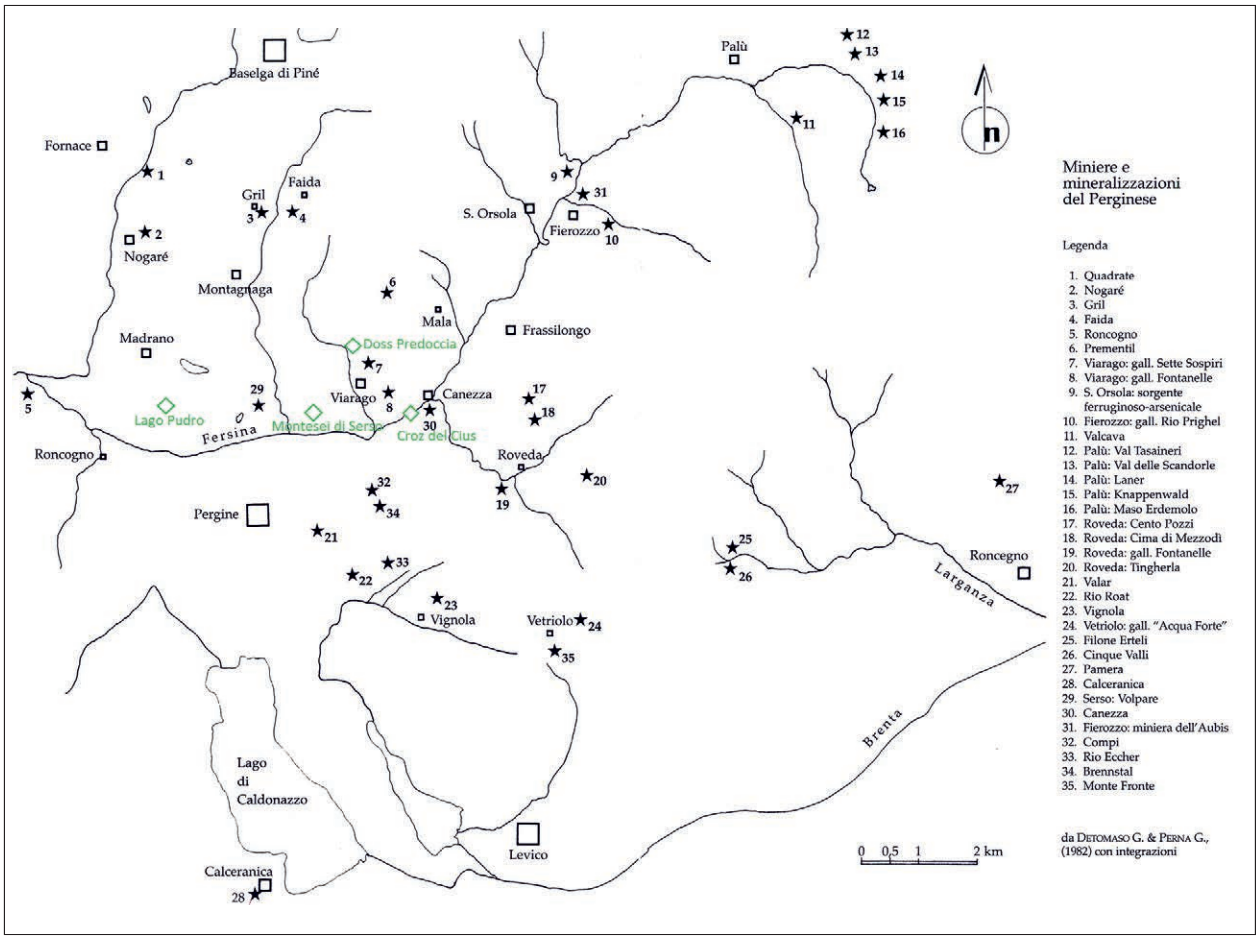

Fig. 3: Map of the area around Pergine Valsugana and the Mocheni Valley (after Forenza et al., 2005). The star symbols indicate the mines and the outcrops exploited during medieval and modern times (not only copper ores); the green symbols are the prehistoric sites cited in the text. For the smelting sites see Figure 1.

Roveda, Falesina, Vignola, Frassilongo (Zammatteo & Zampedri, 2004, p.414). A report written in 1522 states that in the mines in Viarago and Vignola 350 miners were working; Forenza reports 700 persons around 1400 in the area around Pergine (Forenza, 2005). In 1816 G.N. Hoffer writes about copper being still extracted in Valar, Vignola, Palù and Nogarè. According to G. Gasser (1913) there were more than 40 old mines and tests, with extraction of pyrite, sphalerite, galena and chalcopyrite.

Perna (1964, p.176) writes that at Viarago, in the Galleria delle Fontanelle, in 1916 the content of copper was 10,6 % and of silver 0,064 %. He reports that in 1964 the vein was max. 1 m thick and contained up to 6 % of copper. One should consider that at that time the deposits had been mined for centuries, and the veins were considered not exploitable anymore, according to industrial standards.

The same author reports that the mining area in Fierozzo was still working around half of the 19th century with an attempted copper ore extraction; in 1890 researches in Mocheni Valley and at Cinque Valli by an Austrian mining company showed important quantities of copper, lead and zinc minerals potentially to be exploited.

Juxtaposing the data about mining during medieval and modern times with the geological information about copper ores in the area gives a general overview of what could have been the exploitation during Prehistory, even with due caution when comparing exploitation during different ages.

The proxy evidence of mining activity in the area of Pergine and Mocheni Valley is the large number of smelting sites, of which two (Montesei di Serso and Croz del Cius) even belong to the first phase of metallurgy, between Copper Age and Bronze Age.

The human landscape is then completed by the presence of settlements belonging to the Late-Final Bronze Age (Montesei di Serso and Doss Predoccia), and, if we want to consider the enlarged chronology, a hoard from Lago Pudro including a wonderful sword (Bianco Peroni, 1970, tab. 42 no. 284) dated back to 10th century BC (that could be imported from Central Europe, Marzatico, 2001, p.402) and isolated finds like bronze objects and hoards in different localities of the Valsugana.

Fig. 4: General view of the site of Valcava, with the two slag concentrations visible above the Balkof stream (photo: Ufficio beni archeologici PAT, N. Pagan).

Excavations

As mentioned above, the Ufficio beni archeologici has been carrying out excavations at different smelting sites in the last years. A new smelting site, Riparo Marchi, dating back to the so called "first metallurgical phase", during the second half of the third millennium BC, has been found and partly excavated.

The majority of the new excavations are smelting sites dating to Late-Final Bronze Age (Luserna Platz von Mozze, Valcava, Transacqua, and Segonzano Peciapian, Fig. 1).

About Luserna Platz von Mozze, Segonzano and Transacqua short notes have been published already (Bellintani et al., 2010; Silvestri et al., 2014; 2015a; 2015b). Here we are going to present the two sites that have been less described or more recently investigated: Valcava and Sant'Orsola Le Val.

Valcava

In the area of the Mocheni Valley between Palù and Erdemolo, there are many small outcrops of pyrite with chalcopyrite, sphalerite and galena in a quartz-carbonatic gangue, with iron, copper and lead oxides (Lenzi, Tasaineri, Val delle Scandorle, Laner, Knappenwald, Maso Erdemolo, Ai Meus at Valcava, Figs. 1 and 3). The site of Valcava lies in the focal point of this area, less than 1 km from the "Ai Meus" mine.

The site consists of two different concentrations of slags: the southern area is around 110 m in length and between 10 and 30 m in width, with a max thickness of 40 cm, while the area to the north, around 30 m from the first one, is 70 m long and 10-12 m in width (Fig. 4). The area had been compromised by a ski track passing over it, hence the slags are quite spread and fragmented. The slag heaps are mostly consisting of broken plate slags/*Plattenschlacken,* with dimensions between 2-3 and 10 cm. Less slag cakes/*Schlackenkuchen*, sometimes even complete specimens (up to 40 cm in diameter), can be found.

In summer 2012 it was possible to establish that the area with evidence of smelting activity is around 900 m^2. The excavation was focused on the area with the structures, around 200 m^2, but the furnaces have been brought to light, documented and not excavated yet, because the financial support was missing.

Three furnaces have been found, two close to each other and a third one around 15 m far from them (Figs. 5 and 6). At least the two closer to each other were belonging to a complex, or they seem to have been operative at the same time. An evidence of that could be the similar orientation (NW-SE with open front to NE, facing the valley)

Fig. 5: Valcava (Mocheni Valley). Photomosaic of the excavation area, with the three smelting structures shown in red. The burnt clay areas north of the two structures and in between furnace 2 and 3 could be remains of roasting beds. (graphic: N. Pagan Ar.Tech. srl.).

and the belonging of furnace 1 and 2 to the same phase. It cannot be confirmed for sure that furnace 3 belongs to the same phase. Possible remains of at least two roasting beds have been found also. It is clearly evident that the smelting activity continued after the dismissing of furnaces 1 and 2 (and most probably of furnace 3 also), because the structures were completely covered by a thick layer of “slag sand”. The structures belonging to this last phase have not been found yet.

Fig. 6: Valcava (Mocheni Valley). Detail of furnace 1. (photo: Ufficio beni archeologici PAT, N. Pagan).

Sant’Orsola Terme

In the Mocheni Valley, on the mountain above Sant’Orsola Terme, works for a new forest road unearthed a slag heap. This was the starting point for a rescue excavation which took place during summer 2014. Two smelting furnaces have been excavated, singularly standing on an artificial terrace delimited uphill by a stone retaining wall (Fig. 7). In both furnaces the upper part was missing. The lower part was partly dug into the ground and built with a large flat stone to the bottom and stone walls on three sides. The stone structure was then coated with clay.

Both structures show layers of renovation, usually a layer of stones below, and above a layer of burnt clay covered by charcoal. Furnace 1 shows two phases of renovation (Fig. 8) and furnace 2 three phases. In the area around, some stone tools have been found, and some slags. No pottery has been found, besides a decorated body of a vessel that could be most likely dating to the beginning of the Iron Age. The slag heap was close by, downhill, but it hasn’t been investigated. A very interesting structure is a pit, oval shaped, 90x54 cm and 50 cm deep, excavated in the terrace around 1 m from the closest furnace. The pit is filled with layers of slags, quite horizontal, stones and charcoal, but it does not show traces of burnt clay inside (Fig. 9). This

Fig. 7: Sant'Orsola Le Val (Mocheni Valley). View of the area from East, with furnace 2 to the front and furnace 1 in the background. (photo: Ufficio beni archeologici PAT, N. Degasperi).

Fig. 8: Sant'Orsola Le Val (Mocheni Valley). Detail of furnace 1 during the excavation. The different phases of renovation are clearly visible. (photo: Ufficio beni archeologici PAT, N. Degasperi).

Fig. 9: Sant'Orsola Le Val (Mocheni Valley). The pit filled with stones and slags. (photo: Ufficio beni archeologici PAT, N. Degasperi).

is not the first example of pits in a smelting site, and the discussion about the usage of these structures is still open (Hanning et al., 2015).

The position of the structures is the most important information. The use of the geomagnetic prospection was difficult because in all cases, with the exception of Sant'Orsola Le Val, the structures were covered by heaps of slags or "slag sand". The destruction of the furnaces seems to have happened during the frequentation of the sites for metallurgical activity. This is interesting because it clearly shows a sequence of events, with multiple phases of frequentation, even if chronologically limited in time, as the datings show (see below). The state of conservation of the smelting structures in Acqua Fredda seems to be an exception in the panorama of the area: in the other sites furnaces are always at least partly destroyed.

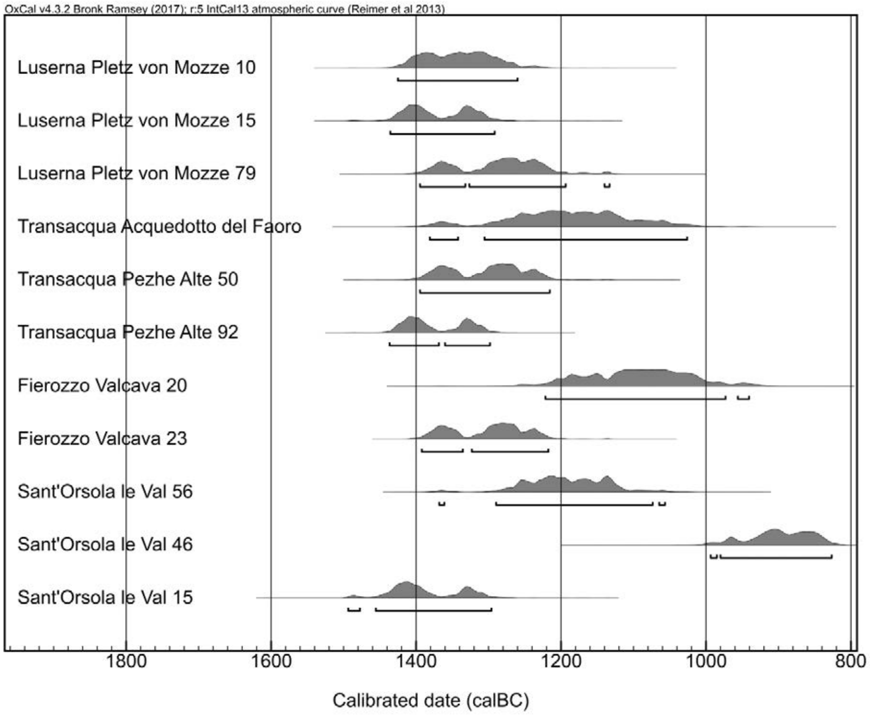

Fig. 10: Diagram of radiocarbon datings of smelting sites from Late Bronze Age. Analyses performed at CIRCE (Center for Isotopic Research on the Cultural and Environmental heritage), Caserta (Italy).

These furnaces are similar to those found at smelting sites in the Alpine area, belonging to partly different periods: at Kurtatsch (Bolzano, Alto-Adige) (Nothdurfter & Hauser, 1986; Hauser, 1986; Nothdurfter, 1993; Anguilano et al., 2009; Schifferle et al., 2014), at Mitterberg, Austria (Stöllner, 2015 and references therein), in the Jochberg area (Nordtirol; Koch Waldner & Klaunzer, 2015 and references therein) and in the Mauken area (Tyrol, Austria: Goldenberg, 2015 and references therein).

The chronology

Eleven new radiocarbon datings (plus those from Riparo Marchi, first metallurgical phase, not presented here), still unpublished, are increasing our knowledge about the metallurgy in Trentino. The results are shown in Fig. 10 and tab. 1, calibrated at 95,4 % with the more recent radiocarbon curve (IntCal13, Reimer, et al., 2013, OxCal 4.3, Bronk Ramsey, 2009).

Other 28 datings are already existing (of which 13 from Acqua Fredda, 13 from other smelting sites in eastern Trentino and two from Lodner Moor/Bozen: Cierny, 2008, pp.68-70, tab. 3; Marzatico et al., 2010, tab. 2, 3, 7; Pearce et al., in press). They confirm the general attribution of the smelting activity to the final phases of Bronze Age, but on the basis of the radiocarbon datings it is possible to hypothesize that the smelting activity actually started during the Middle Bronze Age, in the 16th century BC, and continued till the 11th century BC. In some cases, like Sant'Orsola (see Fig. 10 and tab. 1), Acqua

Site	Sample	Lab.Code	Material	Radiocarbon Age	Unmodelled (BC/AD)	
					From	to
Luserna Platz von Mozze	10	DSH8294_C	charcoal	3080 (33)	-1426	-1261
Luserna Platz von Mozze	15	DSH8293_C	charcoal	3111 (28)	-1436	-1292
Luserna Platz von Mozze	79	DSH8308_C	charcoal	3028 (30)	-1395	-1134
Transacqua Acquedotto del Faoro	15	DSH8317_C	charcoal	2972 (50)	-1382	-1027
Transacqua Pezhe Alte	50	DSH8310_C	charcoal	3039 (27)	-1395	-1216
Transacqua Pezhe Alte	92	DSH8296_C	charcoal	3114 (25)	-1437	-1299
Fierozzo Valcava	20	DSH8304_C	charcoal	2903 (45)	-1222	-941
Fierozzo Valcava	23	DSH8299_C	charcoal	3038 (25)	-1393	-1218
Sant‘Orsola le Val	56	DSH8315_C	charcoal	2975 (32)	-1369	-1057
Sant‘Orsola le Val	46	DSH8307_C	charcoal	2757 (32)	-994	-827
Sant‘Orsola le Val	15	DSH8303_C	charcoal	3127 (31)	-1494	-1297

Tab. 1: Results of the most recent radiocarbon datings.

Fredda, Luserna, Casara Conti Mirafiori (Cierny, 2008; Marzatico et al., 2010), also more recent frequentations have been found.

Sample no. 10 of Luserna Pletz von Mozze is from layer 86, which consists of a lens of charcoal intergrown with lenses of burnt soil and clay, many pieces of plate slags and less numerous small pieces of slag cakes. The layer belongs to the most recent phase of activity. The sample no. 15 was associated with rare plate slags and Luco/Laugen pottery.

The datings from Transacqua Pezhe Alte are confirming the chronological attribution to the Late-Final Bronze Age made during the excavation, based on the pottery (Luco/Laugen A troncoconic vases). Sample no. 50 comes from layer 303, which is part of a large slag heap with stone tools, pottery, pieces of burnt clay and both plate slags and slag cakes. Sample no. 92 comes from layer 515, an ash layer which has been interpreted during the excavation as the bottom of a completely destroyed possible fire structure. The sample from Transacqua Acquedotto del Faoro, a site where a probable roasting bed has been found, comes from layer 1005, a layer of sandy clay completely burnt, above a layer of slags and stones, interpreted as the surface of the roasting bed. This site seems to be more recent than Transacqua Pezhe Alte, but so far it's still too early to get to conclusions, because the hypothesis is based on one dating only, and because the roasting bed, on the same mountain but lower in altitude compared to Pezhe Alte, clearly shows two if not three phases of use and renovation.

The samples from Fierozzo Valcava are, respectively, remains of the pole in a post hole connected to the smelting activity, and charcoal coming from a layer of abandonment of a structure completely destroyed.

The sample no. 15 from Sant'Orsola le Val comes from the layer filling the pit we mentioned above, with slags (*Schlackenkuchen*) and porphyry clasts. Samples no. 46 and 56 are coming from the charcoal lenses inside furnace 2 and 1 respectively, which belong to the most recent phase of both furnaces.

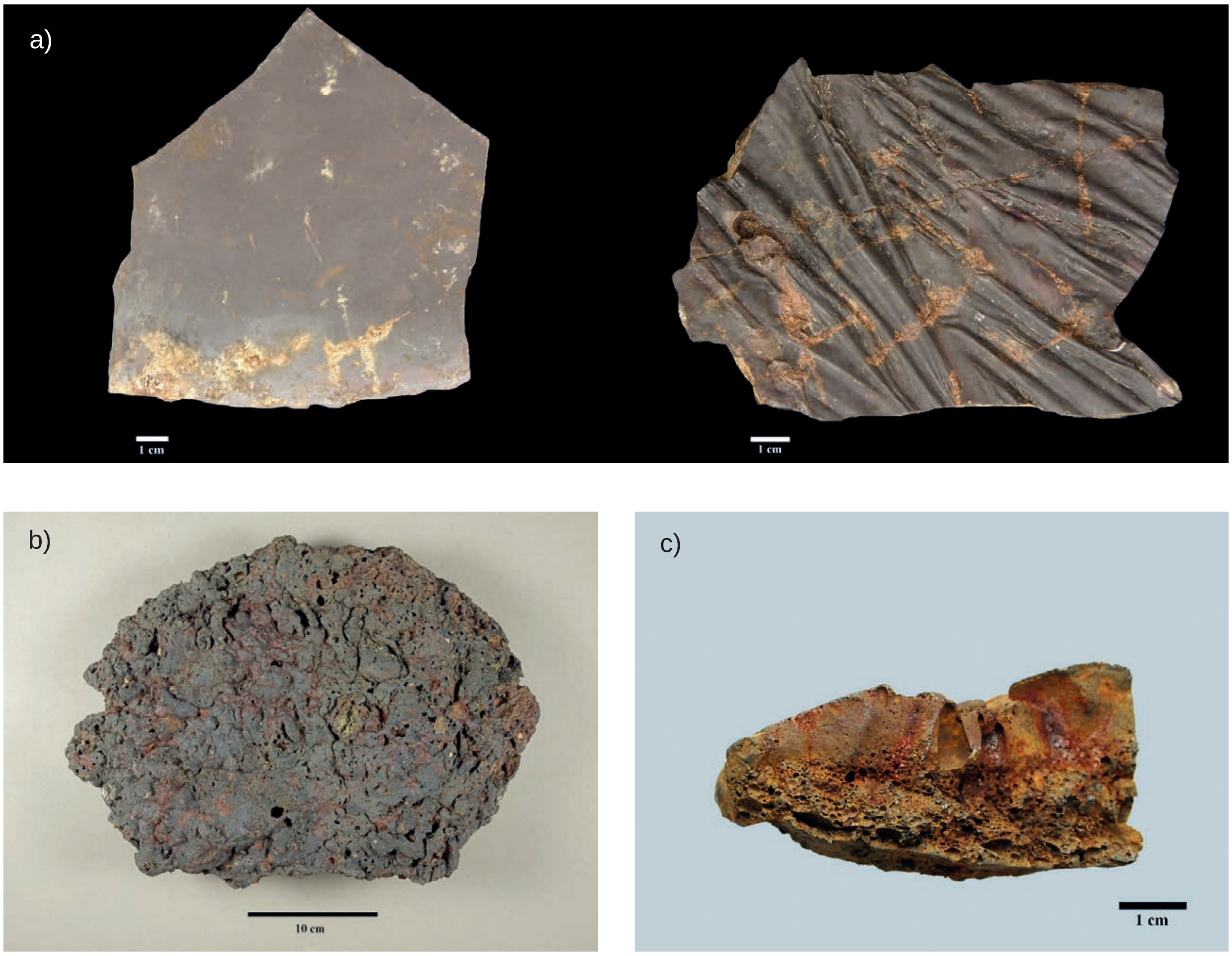

Fig. 11: Different types of slags from the smelting sites in Trentino. A. Plate slags or Plattenschlacken with smooth and wrinkled surface; B. Only partially liquefied slag cake or Schlackenkuchen. On top, the cake shows inclusions of unmelted plate slags that were added as a "flux" for (s)melting. In addition, partly decomposed pieces of sulphidic CuFe-ores embedded in a siliceous gangue were identified. Note, that the slag only in spots shows flow structures. C. massive slag; (photo: DBM Bochum, E. Silvestri).

The slag database[3]

Since the early beginning of the work about copper metallurgy, description and definition of copper slags had been a problem. With the aim to collect as much information as possible about slag formation in the different sites, between 2006 and 2009 a systematic sampling took place at the major sites (Luserna, Segonzano, Transacqua) and data about slags have been inserted in a database. Short notes have been published so far (Bellintani et al., 2010).

The slag database records the visual and macroscopic characteristics of the fragments, in order to recognize typological classes and differences between sites. At the moment the database has 2000 slags recorded, coming from Luserna and Segonzano. They are part of 43 samples inserted, 22 from Luserna, 21 from Segonzano.

The database fields are: slag type, sides (for plate slags), thickness, weight, presence and type of rim, presence/absence of quartz inclusions, max diameter of quartz pieces, charcoal alveola, unreacted ore and slag fragments inclusions. Because it is difficult to recognize the type of the slag if the sample is too small, only pieces of plate slag larger than 4 cm have been recorded in the database. Morphometrical data is also being recorded, as the hypothetical diameter of the slag.

The definition of the slags and the terminology used to address the different kinds of slag is still not defined and homogeneous in the archaeometallurgical literature. So after the work of classification of the slag, a protocol of definition has been established. Most of the slags fit into three main groups, although there is a large variability. The thin plate slags, with a thickness between 0,2 and 0,8 cm, homogeneous with smooth, wrinkled or granular surfaces (Fig. 11a) correspond perfectly to plate slags. There is a variant of the plate slag, with a thickness of ca. 1-1,2 cm. The second type corresponds to the large, inhomogeneously composed slag cakes (Fig. 11b). A third type of slag has been called by us "massive" slag: it is more than 1,8 cm thick, it has a higher density in the centre and a lower density close to the surfaces but the composition is quite homogeneous (Fig. 11 c).

The quantitative analyses are particularly exaustive in Luserna, where a slag heap, composed by layers 110 and 111, has been sampled by 30 to 30 cm excavation trenches. The result are 36 samples, with a total slag weight of 673 kg.

Out of these samples, particularly representative is sample 61 from layer 111, 75 cm thick, described as an example of composition of slag heap. The total weight of the sample is 38,68 kg. The observation of the sample gives a clear idea about the composition of a slag heap: around 80 % are thin plate slags, about 13% are thick (≥ 1 cm) plate slags, and the rest are coarse or undetermined. We described in detail around 100 fragments of plate slags, 65% of which present both smooth surfaces, in 19 % of the cases one surface is smooth and one wrinkled; 6 % show one smooth surface and one with drops on the lower side (dropping down to the molten material below); 5 % one smooth and one granular surface; 5 % one smooth and one irregular. In every site the composition of the slag heaps can vary a lot.

The samples from Segonzano have not been considered here because we excavated part of the "slag sand" heap but not yet the area with slag fragments, dispersed over a much larger area.

The investigation of slags

Only a correlation between archaeology and archaeometry can help answering to the big problem of the formation of the slags (Hauptmann, 2007; 2014). The archaeological data from Jan Cierny´s survey (Cierny, 2008) and from the new excavations carried out by the UBA in the last decade need to be integrated with the archaeometallurgical analyses on the slags.

Other research teams have been investigating the composition of late Bronze Age slags from Trentino and Alto Adige/Südtirol (Metten, 2003; Cattoi et al., 2000; Anguilano et al., 2002a; 2002b; Addis et al., 2016; 2017), giving partly different interpretations of the operative chain.

The project is going to be an in depth examination of the chemical and mineralogical composition of about one hundred slag samples, collected from ten different smelting sites, part of them from excavations and part from the surface collections. The sites are: Segonzano Peciapian, Transacqua, Valcava, Luserna Pletz von Mozze, Malga Millegrobbe, Pinè lago delle Piazze, Malga Pontara, Malga Regnana, Malga Laghetto and Passo Vezzena sud (Fig. 1).

The questions and problems the research is trying to solve are:

- From which metallurgical operations are plate slags (*Plattenschlacken)* resulting? Did they form inside a furnace or have they been tapped?
- What is the difference to a slag cake? Is the difference between the two kinds of slag only due to the cooling or is there a difference in the texture and/or chemical composition?
- What was the reason for processing slags to produce "slag sand" frequently found in the smelting sites in the Alpine area? Is it a product of crushing slag cakes or plate slags? What was extracted, what was the aim of this activity?

Other questions can be correlated:

- Are there differences between slags from the different smelting sites mentioned above?
- Why have plate slags been found only in Recent-Final Bronze Age and not in the more ancient sites? Is it a technological development?
- Why are plate slags and the slag cakes, most of the times, found in different layers in the stratigraphy?

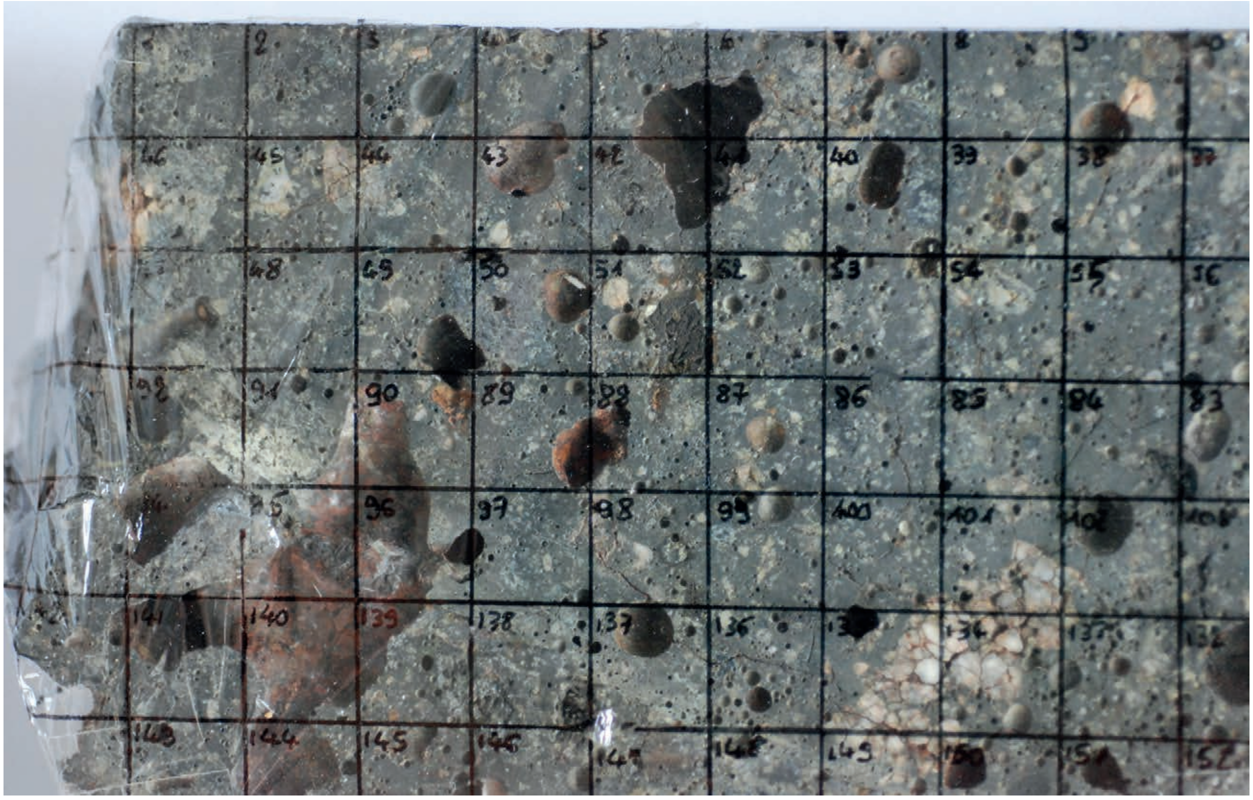

Fig. 12: Luserna, slag cake. The slag cake has been cut in two parts, to demonstrate the heterogeneous texture of this type of slag. Squares of 1 cm have been drawn on the surface, with the help of a transparent plastic foil. The image shows that relics of highly refractive, light minerals (mm- to cm-sized) are distributed throughout the cake. See Figure 17 for the chemical composition of the slag in the different squares (photo: DBM Bochum, E. Silvestri).

Plate slags tend to be in connection with LBA smelting processes, but their formation is still unclear. Surface polished thin sections of 20 samples have been examined by optical and scanning electron microscopy (SEM) to establish the texture of silicate and oxide phases of the slag, and the presence, shape and size of the sulfide inclusions. SEM with an attached EDX-system was used to analyze the bulk composition of the slag by scanning various subareas in the slags, the composition of the sulphidic inclusions (by plane squared scans) and the presence of oxidized silicate phases at the surfaces of the slags to determine the location of their cooling.

In addition, a completely preserved slag cake with a diameter of 20 cm has been cut and investigated in detail, analyzing by portable XRF more than one hundred points on the surface of the inhomogeneously composed slag (Fig. 12). We analysed the most homogeneous areas only, trying to avoid quartz relics, in order to compare the matrix with the one of the plate slags.

Preliminary results

First in a macroscopic observation it can be clearly seen that the plate slags have been cooled on top of a liquid mass, because they have mostly smooth or wrinkled surfaces both above and below. In other cases one of the surfaces (never both of them) shows clearly that the slag cooled down on an irregular, granular surface, probably the ground. The fragments of the plate slags show that the original shape was circular and they frequently have rounded edges with inwardly-twisting rims. The appearance fits perfectly with the description of plate slags/*Plattenschlacken* in the German literature.

The slags have been described on the basis of macroscopical observation, optical microscopy and SEM-EDX analyses combined together. In general, it can be observed that:

- Plate slags are composed mainly of the iron silicate fayalite (Fe_2SiO_4). The texture of the fayalite crystals is varying in size and shape, but frequently it forms needles vertically to the surfaces. In addition, magnetite (Fe_3O_4) and Cu-Fe-sulphide inclusions composed like chalcopyrite ($CuFeS_2$), bornite (Cu_5FeS_4) and digentite (Cu_2S) are distributed throughout the slag. The slags are only 0.5 cm thick in average and rarely contain any macroscopically visible inclusions. They appear to consist of an ideal eutectic composition. The bulk composition values of the analysed samples have been inserted in a FeO (+ CaO + MgO) – Al_2O_3-

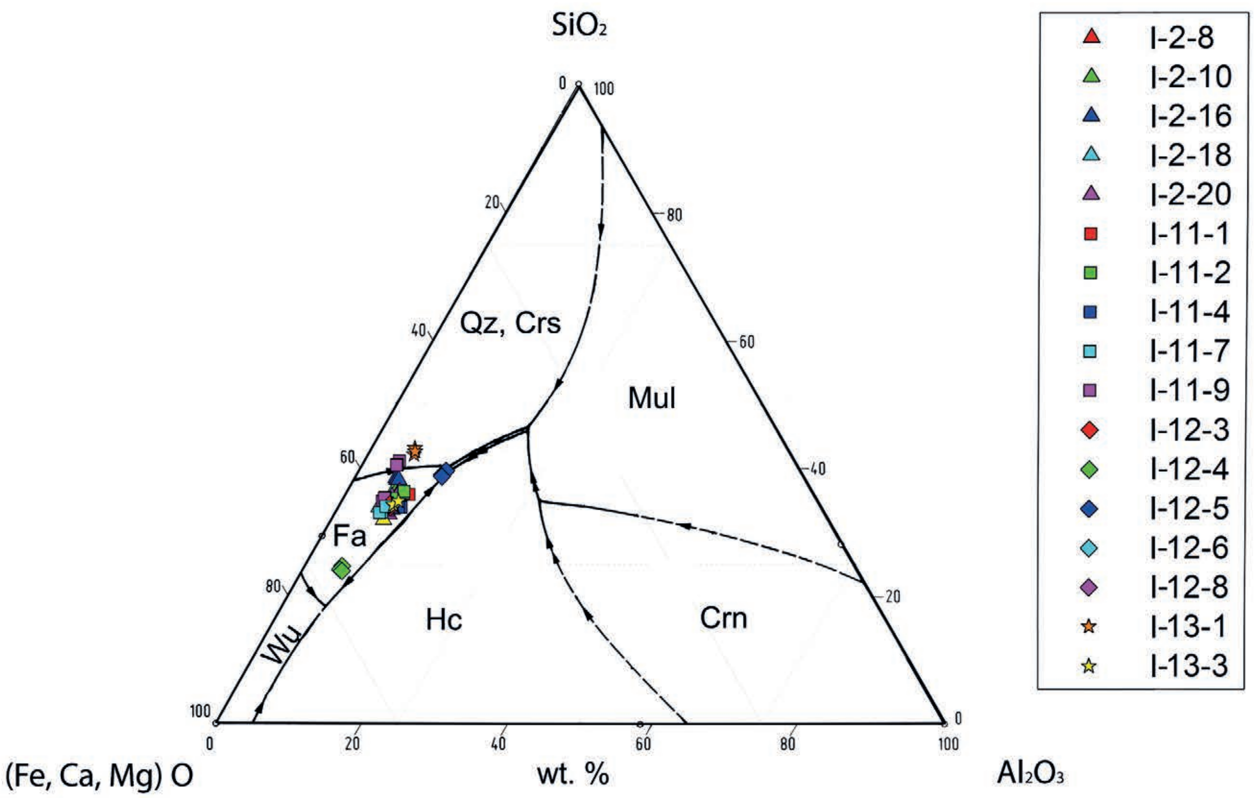

Fig. 13: Phase diagram FeO - Al_2O_3 - SiO_2 (after Osborn & Muan, 1964) showing the bulk composition of plate slag samples from various slag heaps in the Trentino (I Italy, 2 Luserna, 11 Transacqua, 12 Segonzano, 13 Malga Pontara), and sample number. Note that lower MgO and CaO contents were added to FeO.

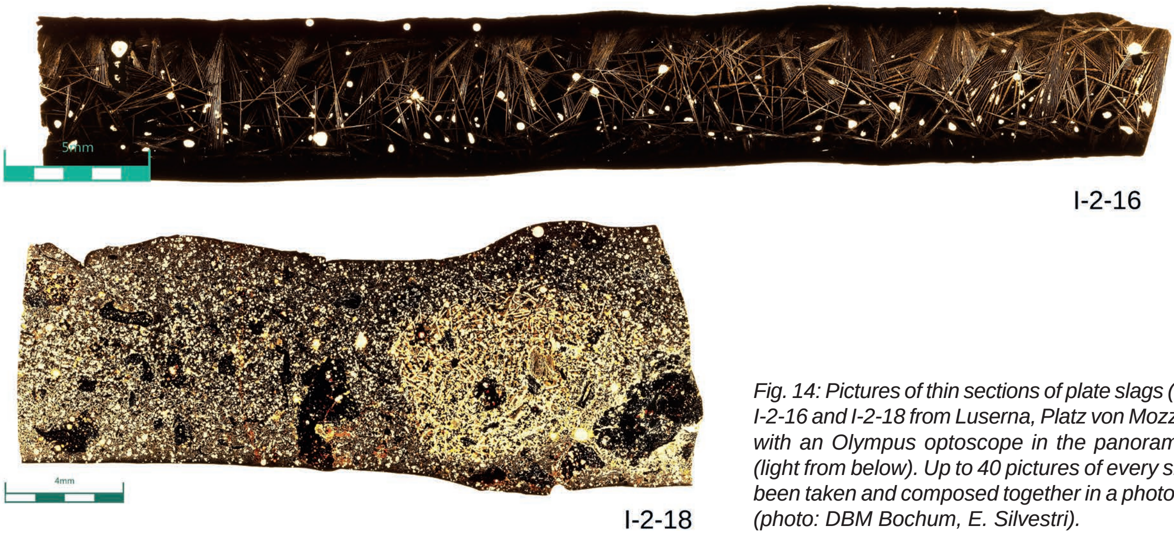

Fig. 14: Pictures of thin sections of plate slags (samples I-2-16 and I-2-18 from Luserna, Platz von Mozze) taken with an Olympus optoscope in the panorama mode (light from below). Up to 40 pictures of every slag have been taken and composed together in a photo mosaic; (photo: DBM Bochum, E. Silvestri).

SiO_2 diagram (Fig. 13). They fit perfectly in the low melting liquidus field of fayalite with an eutectic point around 1150 - 1200 °C.

- The amount of magnetite and Cu-(Fe-)sulphide inclusions can vary, plate slags are not as homogeneous as they seem; different subtypes can be recognized (examples in Fig. 14). Some are really homogeneous and composed mostly by fayalite, with very few inclusions of magnetite and Cu-Fe-sulphides; others contain much more magnetite and Cu-Fe-sulphides, scattered or in agglomerations. The difference is not only in the quantity of Cu-Fe-sulphides included, but also in their size: the inclusions are normally bigger in the latter type.
- The SEM analysis of the mineral phases along the rim of the slag shows the oxidation of the two surfaces,

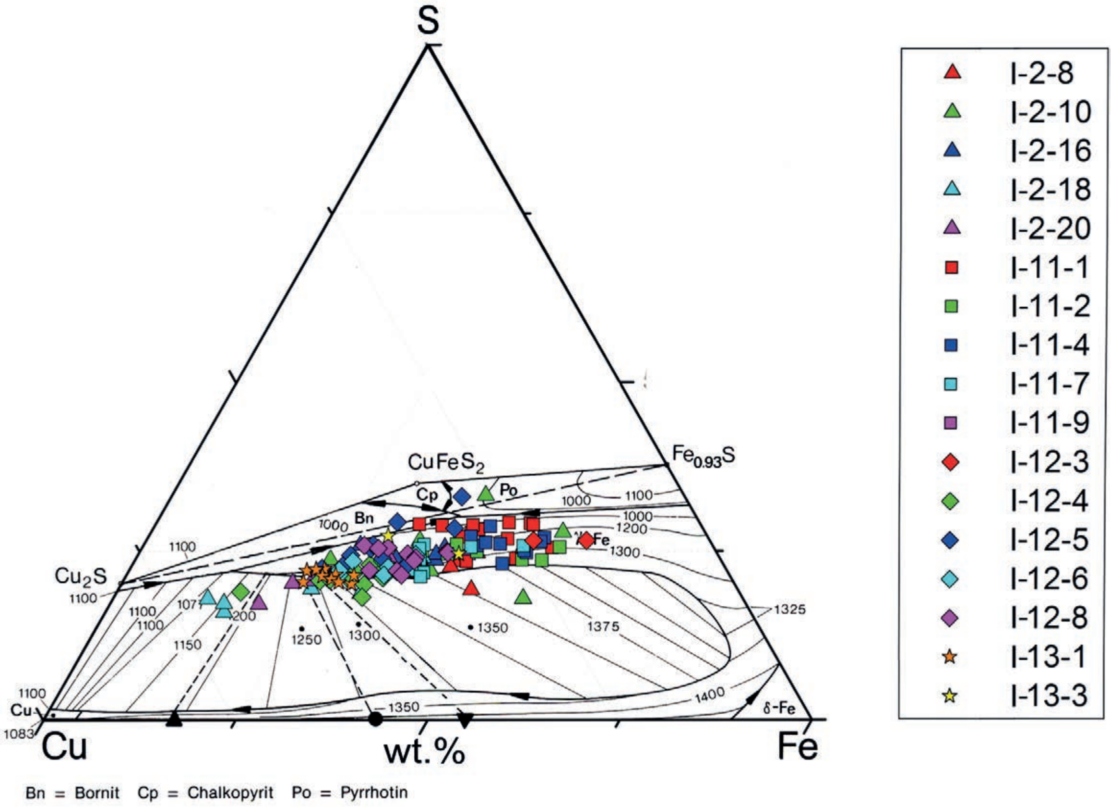

Fig. 15: Chemical composition (method SEM-EDX) of Cu-Fe-sulphide inclusions in plate slags from various localities in the Trentino (for captions see Figure 13), plotted in the lower sulphide area of the Cu-Fe-S diagram (after Schlegel & Schüller, 1952). Note the miscibility gap between the S-rich side (represented almost by the line Cu_2S - $CuFeS_2$ - $Fe_{0.93}S$) and the metal-rich side between Cu and Fe. The majority of the sulphide inclusions have high iron contents. The connection lines (conodes) clearly show that these compositions would exclude a precipitation of copper, i.e., these slags are not suitable to produce copper. Exceptions are a few sulphide inclusions in slags from I-12/6 which are in equilibrium with copper and copper low in iron.

and helps to recognize which one is the upper part of the slag. In several cases both surfaces show traces of oxidation. This makes it difficult to distinguish the upper surface of the slag, in contact with the oxygen, from the bottom. The oxidation seems to be correlated with the different types of surface: the smooth surface shows (almost always) oxidation traces. If the slag has two smooth surfaces it often happens that both of them have oxidation traces. The wrinkled surface may also show traces of oxidation. The irregular and the granular surfaces very rarely present oxidation.

- Cu-Fe-sulphide inclusions are scattered throughout the matrix, with no difference between upper and lower part or particular concentrations, except for magnetite agglomerations. It is important to note that we did not find evidence for any enrichment of matte or metal rims above or below the plate slag.
- The Cu-Fe-sulphide inclusions can be round-shaped prills or, more frequently, irregular shaped with a size of some micrometers only. They consist mostly of chalcopyrite, sometimes with lamellae of bornite, and surrounded by covellite (Fig. 15). These phases were formed by corrosion. Most of the sulphide inclusions, however, were more or less totally corroded and leave a hole in the matrix.

Fig. 16 shows that the Cu-Fe sulphide inclusions are quite homogeneous, usually their size is less than 200 µm.

The most interesting point is that in the slag cakes from Trentino there's no clear separation between liquefied matrix and inclusions, which are scattered throughout the slag without being concentrated, on one or the other side.

- Plate slags normally do not contain inclusions of quartz, with the exception of two analysed samples. Some samples from Acqua Fredda, already analysed by Beate Metten in the 1990s, have been reconsidered under the optical microscope. They seem to contain more quartz. The reason is probably because they have been classified as plate slags but most of them are "massive slag", following our definition.

Quartz grain fractures and inclusions normally contain a lot of Cu-Fe sulphide inclusions. This is coherent with the kind of ore available in the area, containing quartz in the gangue.

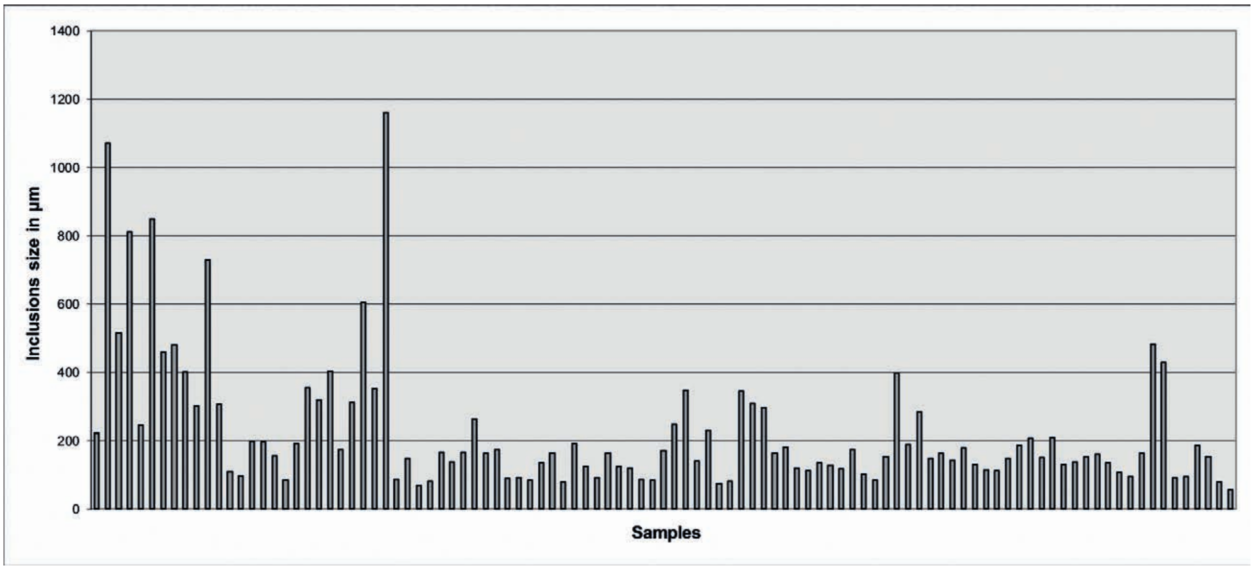

Fig. 16: Diagram showing the size of Cu-Fe sulphide inclusions in plate slags.

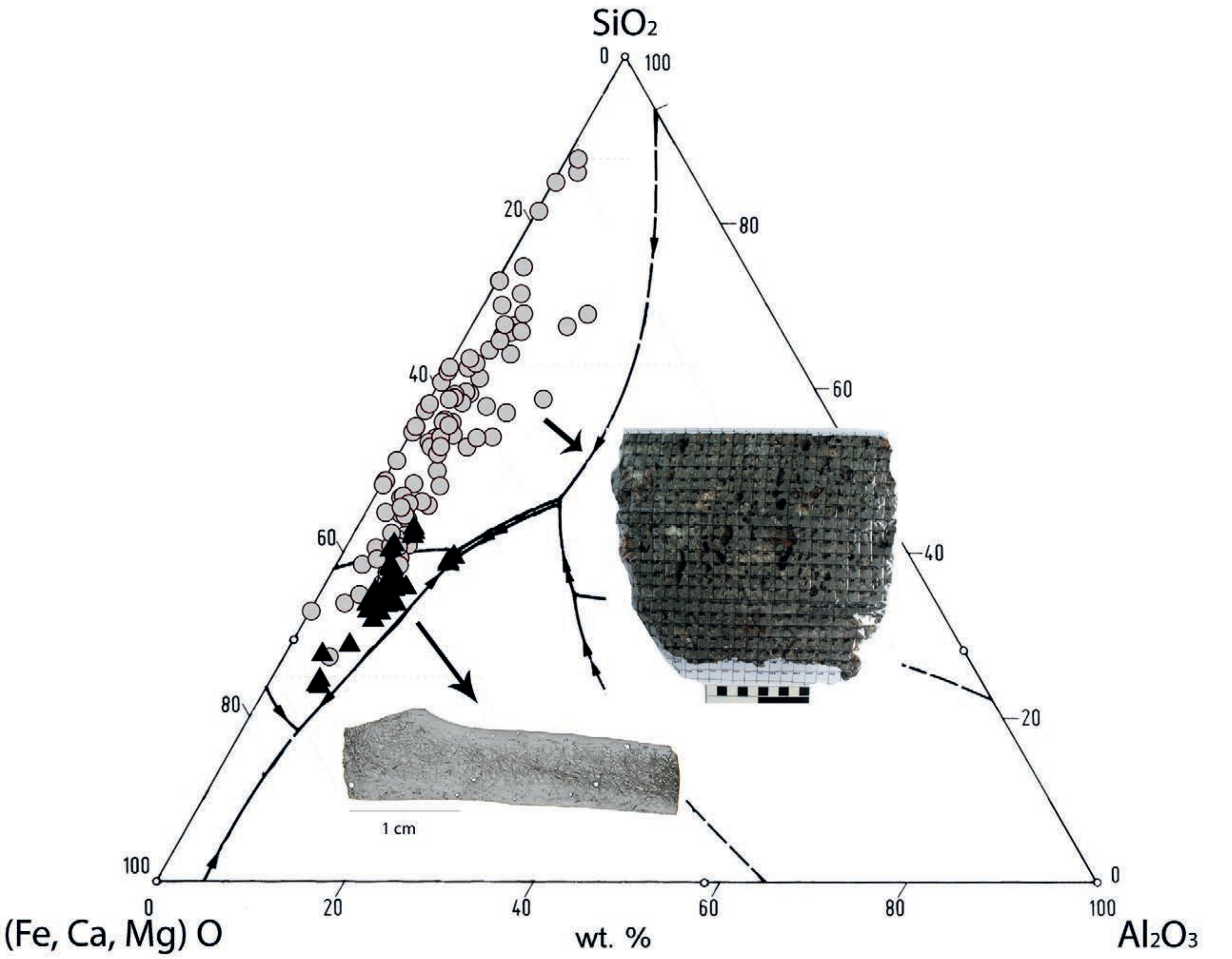

Fig. 17: Plots of the main oxide constituents in the phase diagram SiO_2 – FeO (+CaO+MgO) – Al_2O_3 of plane scans performed on a slag cake (see Figure 12) and various plate slags. Ca. 100 spots were analysed on the slag cake, and 55 in thin sections of plate slags. Methods: pXRF (Niton XL3t), SEM (Zeiss Supra 40 VP). Note development from SiO_2-rich (unmelted) compositions to low melting subareas in the slag cake.

Comparison with the other kinds of slag

The coarse slags (or slag cakes or *Schlackenkuchen*) are much more heterogeneous than the plate slags and contain quartz inclusions, charcoal and non-reacted ore. They can be interpreted as partially liquefied charged material ("immature slag") composed of unmelted "resisters" and fully liquefied subareas with eutectic composition. The liquefied areas of them are composed mainly of fayalite with Cu-Fe sulphide inclusions, apparently not so different from the plate slags/*Plattenschlacken* matrix (Fig. 17).

The so called "slag sand", or better "crushed slag", two samples of which have been analysed, is composed of small pieces of slag (granulometry 1 - 3 mm). Some of these pieces contain fayalite but most of them are composed of quartz. "Slag sand" is found at LBA smelting sites only. It results from slag, probably crushed in order to separate and collect the remaining copper, matte or unprocessed mineral particles.

Conclusions

The research carried out in the last ten years has increased consistently the knowledge about the Bronze Age smelting processes in the southern Alpine area. The new excavations have brought to light the evidence of technological steps unknown before, like the existence of roasting beds as it is common in the northern part of the Alps. The research at the smelting sites showed important differences between sites, which need to be further investigated. The radiocarbon datings confirm the general attribution of the smelting activity to the final phases of Bronze Age, but show in some cases also surprisingly recent frequentation of the sites.

The other field of the research, the investigation of the slag by optical microscopy and SEM-EDX analyses, shows that plate slags predominately consist of fayalite. Hence, they were almost totally liquified around 1150 - 1200 °C and cooled down very quickly. The slag formation was concentrated in the low melting range of the main components of the material system FeO-SiO_2-Al_2O_3. This means that the composition of materials for the formation of plate slags was deliberately and most carefully controlled. Alternatively, plate slag have been automatically formed as a partial liquid in a larger silicate system – perhaps from the slag cakes.

The slag cakes are much more heterogeneous. They are never completely liquified and contain inclusions of (sulphide bearing) quartz and of plate slags (as a flux?). The liquefied areas are free of inclusions and consist mainly of fayalite with Cu-Fe sulphide inclusions, apparently not so different from the plate slags matrix.

The analyses are still in progress, and the focal point of the next steps of the research will be the formation of the different kinds of slags found in the archaeological context. In order to better understand the technological processes applied in the Late Bronze Age Trentino it would be helpful to include any methods of small scaled metallurgy or any ethnographic evidence.

Notes

1 A third phase has been evidenced by radiocarbon datings but no clear evidence of structures has been recorded (Cierny, 2008; Marzatico et al., 2010).

2 The chronology is now under discussion, see paragraph "The chronology" below.

3 In collaboration with Livia Stefan.

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Authors

Elena Silvestri – Ufficio beni archeologici – Soprintendenza per i beni culturali della Provincia autonoma di Trento, Italy
Paolo Bellintani – Ufficio beni archeologici – Soprintendenza per i beni culturali della Provincia autonoma di Trento, Italy
Andreas Hauptmann – Deutsches Bergbau-Museum Bochum, Bochum

Correspondence and material requests should be addressed to: elena.silvestri@provincia.tn.it

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Markus Staudt, Gert Goldenberg, Manuel Scherer-Windisch, Caroline Grutsch, Roman Lamprecht, Bianca Zerobin

The Late Bronze Age smelting site Rotholz in the Lower Inn Valley (North Tyrol, Austria)

ABSTRACT: *Since the 1990s, archaeological investigations of prehistoric copper mines have been conducted in the famous mining district of Schwaz/Brixlegg in the Lower Inn Valley, North Tyrol (Austria). A large number of sites (mainly from the Late Bronze Age and up to the Early Iron Age) have been investigated so far with the aim to record and to analyse this extraordinary prehistoric mining landscape. A focal point of research is the reconstruction of the process chain connected to the prehistoric copper production comprising ore mining, beneficiation, and smelting processes. This paper discusses the final step of metal production, the smelting of copper ores. Whereas dozens of prehistoric mines and several sites with traces of mechanical ore treatment have been examined in the last years, only two smelting sites from the period under consideration are known so far. One of these sites, the smelting site Rotholz (municipality of Buch in Tyrol), could be prospected by geophysical methods (geomagnetic) and partly excavated during several campaigns in 2010 and 2015-2017. A detailed documentation of the archaeological remains could be performed in the frame of the DACH-project "Prehistoric copper production in the eastern and central Alps - technical, social and economic dynamics in space and time" (supported by the Austrian Science Fund FWF, the German research foundation DFG and the Swiss National Research Foundation SNF, 2015-2018). The Rotholz smelting site dates into the 12th/11th cent. BC (Late Bronze Age, Urnfield culture, dated by ^{14}C-analysis). The basic raw material used for the local copper production were fahlores which occur in considerable quantities in the Devonian dolomitic hostrock (Schwazer Dolomit). As a result of the excavations a multiphase roasting bed, a battery of four furnaces, a slag heap (crushed slag, slag sand) and many other informative structures could be uncovered and documented. The findings (ceramic, slags, ores, stone tools, animal bones,…) have been furnished to archaeological and archaeometrical analysis.*

KEYWORDS: LATE BRONZE AGE, COPPER PRODUCTION, SMELTING SITE, FURNACES, ROASTING HEARTHS, SLAG BENEFICIATION, SLAG SAND

Introduction

In the framework of the international DACH-project (see above, the Austrian part being supported by the Austrian Science Fund FWF, project-number: I-1670-G19), the Late Bronze Age smelting site Rotholz (municipality of Buch in Tyrol, Lower Inn Valley) was chosen for detailed archaeological investigations.

Although the archaeological remains of prehistoric copper ore mining in the fahlore mining district of Schwaz/Brixlegg are impressive, numerous and manifold, like fire setted mines, mining pits and dumps (see article Staudt et al., in this volume; Staudt et al, 2017a, 2018b), only two prehistoric smelting sites (Radfeld-Mauk A and Rotholz) are known so far. It is assumed that there must exist much more sites of extractive copper metallurgy in the field, but they are not visible anymore because of natural erosion processes, overprinting by younger mining activities (from late Medieval and more recent times), and particularly by extensive mass movements. The latter are frequent in the zone of the steep hillslopes, which are covered with mighty and instable talus and deposits of mining debris. Wet landslides (Muren) are especially common near springs and along the brooks and streams, places which have been explored also by the prehistoric metallurgists. So it is not astonishing, that the two known smelting sites have been discovered only by coincidence in the succession of forest road constructions.

The evidence of the earliest fahlore smelting in North Tyrol could be observed in Neolithic and Early Bronze Age settlements like the Mariahilfbergl (Brixlegg; Huijsmans & Krauß, 1998, 2015), Kiechlberg (Thaur; Töchterle, 2015), Buchberg (Wiesing; Martinek & Sydow, 2004; Schubert, 2005) and inside the Tischofer Höhle (Kufstein; Mostler, 1969; Neuninger et al., 1970; Harb, 2002; Harb & Spötl, 2015). For this earliest metal production a mix of sulfidic fahlore and secondary (oxidic) copper minerals was probably smelted in small crucibles in open fire pits using blowpipes and clay tuyères (Bartelheim et al., 2002; Martinek & Sydow, 2004; Höppner et al., 2005; Krismer et al., 2015; Hanning et al., 2015; Lutz, 2016). Finds of small tuyères are characteristic features of Copper Age and Early Bronze Age metallurgy (Töchterle et al., 2013). So far only one radiocarbon date from the mining pit field Mauk D (Radfeld) in the Mauken Valley gives direct evidence for early fahlore mining in the district Schwaz/Brixlegg (VERA-1605, Mauk D 239, 3795 ± 35 BP, cal. BC 2400-2050, 2 σ).

During the second fahlore mining boom which started in the 12th century BC (Late Bronze Age) and lasted until the end of the 8th cent. BC (Early Iron Age, see article Staudt et al., in this volume) the extractive metallurgy took place on a more "industrial" scale in the mining districts. Now larger amounts of ore could be processed on smelting sites which show quite similar structures when compared with other excavated sites of this period in the Eastern and Southern Alps (Weisgerber & Goldenberg, 2004). Important requirements for the installation of smelting sites are the availability of fire wood respectively charcoal, clay for the metallurgical constructions, and water for wet-mechanical ore and slag processing.

The two known smelting sites in the fahlore district could only be identified because of forest road constructions cutting through the prehistoric slag heaps. In a drainage trench (Mauk A, Radfeld) and in the batter of a forest road (Rotholz) conspicuous dark sandy layers including reddish burnt stones (fragments of furnace wall), greenish animal bones, slags and slag sand were visible.

The Late Bronze Age smelting site in the Mauken valley (Mauk A, Radfeld) was object of several excavation campaigns between 1994 and 2009 (supported by the Austrian Science Fund FWF), which were accompanied by archaeometrical investigations: geomagnetic prospection, radiocarbon-dating, dendrochronological, archaeozoological and mineralogical/geochemical analysis (Goldenberg & Rieser, 2004; Goldenberg et al., 2012; Goldenberg 2013, 2014, 2015; Schibler et al., 2011). This site yielded archaeological features like a multiphase roasting bed, two furnaces, a water basin/sluice with wooden construction elements for the wet mechanical processing of slag sand, a few postholes, and a big slag heap comprising mainly of slag sand/grit. Beside different types of slag (heterogeneous slag cake fragments respectively tiny bulky pieces of heterogeneous slag, homogeneous platy slag, slag sand and slagged furnace-lining), domestic and technical pottery (from pot bellows) and stone tools (hammer stones, anvil stones, grinding stones), a casting mould made of sandstone, animal bones, a sewing needle made of bronze, some textile fragments and a glass bead could be recovered from the excavations (Goldenberg, 2013; Grömer et al., 2017).

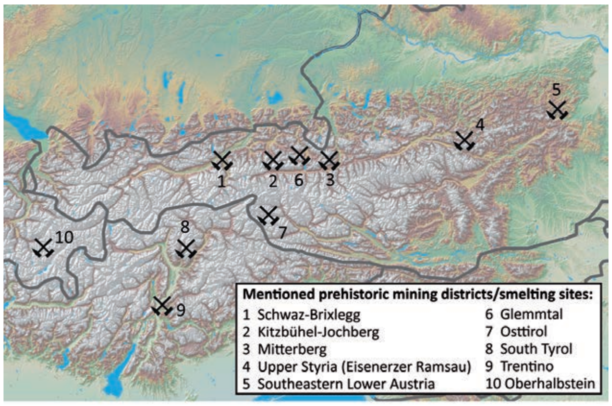

Fig. 1: Mentioned prehistoric smelting districts (graphic: M. Staudt).

Extractive copper metallurgy (primary smelting) could also be observed at the Late Bronze Age settlement site in the gravel quarry Kundl-Wimpissinger (Lang, 1998; Tomedi et al., 2013; Prader, 2013; Patzelt & Weber, 2015). This is the only Late Bronze Age site in North-Tyrol so far where smelting activities could be proved within a settlement. Here also the coeval finds of small blowpipe tuyères and bigger bellow tuyères are extraordinary for Late Bronze Age smelting sites (Staudt & Tomedi, 2015). These finds are indicating a smelting and casting workshop at the same spot. One other smelting site was mentioned and published from the mining district Weißer Schrofen (Rieser & Schrattenthaler, 2007). Recent investigations in the frame of the DACH-project could demonstrate that the slags from this site are the remains from a blacksmith workshop dating into the 15th/16th century AD (see article Staudt et al., in this volume). Indirect evidence of copper ore smelting activities can also be observed in ceramic finds. Especially in the Lower Inn Valley and in the surroundings of the Mitterberg mining district (Salzburg-Bischofshofen) ceramic products are often tempered with slag sand/grit from prehistoric copper smelting sites (Sölder, 1987/88; Reider, 2003; Krismer et al., 2012; Kluwe, 2013; Tomedi et al., 2013; Töchterle et al., 2013; Staudt & Tomedi, 2015; Stöllner et al., 2016; Tropper et al., slag-tempered ceramics and its implications for prehistoric metallurgy in the Lower Inn Valley in this volume).

Considering the large number of smelting sites known from the Mitterberg (Much, 1879; Zschocke & Preuschen, 1932; Eibner, 1972, 1974; Stöllner et al., 2004; Stöllner, 2015), Glemmtal/Viehhofen (Scherer-Windisch et al., 2019; Kyrle, 1918; Preuschen & Pittioni, 1956), Kitzbühel/Jochberg (Pittioni, 1968; Koch Waldner & Klaunzer, 2015; Koch Waldner, 2017), Upper Styria (Preuschen, 1968; Eibner, 1982; Preßlinger & Eibner, 1993; Modl, 2012; Klemm, 2015), Lower Austria (Trebsche, 2015a, 2015b), Virgental/East Tyrol (Preuschen & Pittioni, 1953), South Tyrol (Dal Ri, 1972; Niederwanger, 1984; Niederwanger & Tecchiati, 2000; Nothdurfter, 1993; Lunz, 2005; Nothdurfter & Hauser, 1986), the Trentino (Perini, 1992; Cierny, 2008; Silvestri et al., 2015) and the Oberhalbstein (Schaer, 2001,

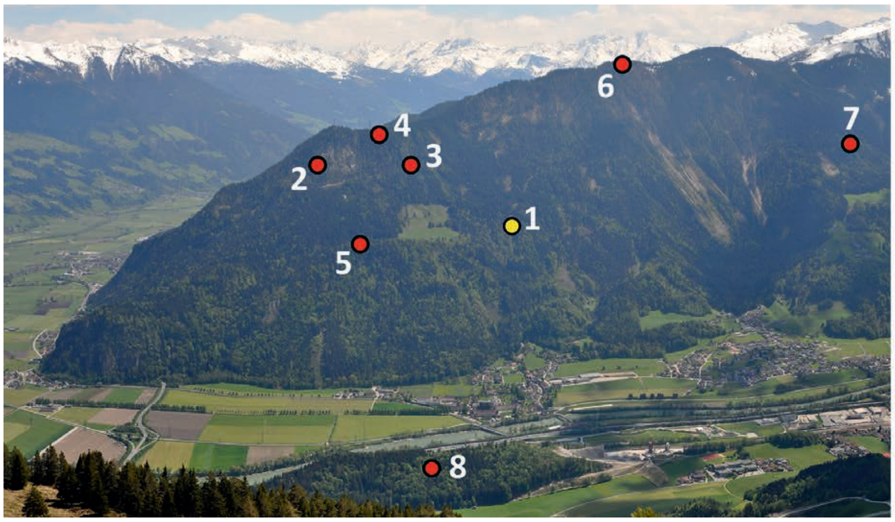

Fig. 2: Potential prehistoric copper mining spots (2-7) in the surroundings of the smelting site Rotholz (1); Early Bronze Age settlement (8) Buchberg Wiesing (graphic/photo: M. Staudt).

2003; Fasnacht, 2004; Wyss, 2004; Turck et al., 2014; Naef, 2015; Reitmaier-Naef et al., 2015; Della Casa et al., 2016) it becomes evident that in the mining district of Schwaz/Brixlegg a lot of smelting sites are still to be discovered (Fig. 1). This is especially the case for the Early Iron Age copper production (8th cent. BC), from which a remarkable number of mines are known, but no contemporaneous smelting sites.

The technical considerations, ethnological aspects and experimental approaches dealing with the different steps of copper production are mainly based on the smelting of chalcopyrite. The investigations are going on since more than a hundred years (Much, 1893; Kyrle, 1918; Klose, 1918; Zschocke & Preuschen, 1932: Czedik-Eysenberg, 1958; Preuschen & Pittioni, 1955; Hampl & Mayerhofer, 1963; Böhne, 1968; Sperl, 1969; Preßlinger et al., 1980; Eibner, 1982; Moesta, 1983; Piel et al., 1992; Herdits, 1997; Metten, 2003; Anfinset, 2011; Modl, 2004, 2011; Goldenberg et al., 2011). According to old chronicles from observations in Asia, three steps (1: first smelting = matting stage, 2: roasting stage and 3: second smelting = reduction stage) are mentioned for the production of copper extracted of chalcopyrite as well as fahlore (Prinsep, 1831; Percy, 1861; Zschocke & Preuschen, 1932; Craddock, 1995; Anfinset, 2011).

Archaeological investigations 2010

The smelting site Rotholz (Fig. 2) is situated at about 950 m a.s.l. in the mining district of Schwaz, west of the Ziller Valley and south of the village Rotholz (municipality Buch in Tyrol). In the vicinity of the nearby Rottenburg castle ruins some Iron Age dress accessories made of bronze have been recorded and prehistoric features therefore are presumed (Zanesco, 2009). The smelting site was first

Fig. 3: The compressed slag sand inside the former washing basins and the appertaining slag dump (in the profile right) at the smelting site Rotholz (photo: M. Staudt).

located by Brigitte Rieser and Hanspeter Schrattenthaler in 2007 while a forest road was constructed (Rieser, 2007). In the course of earth-moving work slag sand/grit layers up to 1 m thick came to light. These layers included fragments of furnace wall, charcoal, tuyère fragments, stone tools, pottery and greenish bones. Also a piston-headed pin which dates from the Ha A1 period (= SB IIa, ca. 1200-1150 BC) was picked up by the discoverer.

In the frame of the special research program SFB HiMAT (the History of Mining Activities in the Tyrol and adjacent areas, impact on environment and human societies, supported by the Austrian Science Fund FWF 2007-2012, project-no. F3106-G02) a first small excavation could be realised in the slope of the forest road in 2010 (Klaunzer et al., 2010a, 2010b; Tomedi et al., 2013; Staudt & Tomedi, 2015). A profile through the slag deposit was documented and at its basis the remains of two washing basins/sluices were uncovered (Fig. 3). These constructions were bordered with wooden planks (in a bad state of preservation) which showed repairs. The inner width

Fig. 4: The wooden constructions (washing basins) filled with fine slag sediments from wet slag sand processing at the smelting site Mauk A (left) and Rotholz (right, photos: G. Goldenberg, M. Staudt).

between the planks is around 50 cm. The excavated part of the basin/sluice is around 2 m long and the structures continue into the documented profile towards the hill side. On the downhill side the former construction was totally destroyed during the forest road construction. A small channel without a wooden structure (refilled with fine and compressed slag sediment) is situated close to the basins/sluices and is covered by the slag dump. It looks like, that the leftover of the slag sand processing in the washing basins/sluices was deposited here.

The two wooden basins are filled up with fine and hardly compressed dark-grey slag sand. Macroscopically this material looks like a kind of sandstone. Tiny charcoal fragments in between the grains are indicating an anthropogenic origin of this material as residues of a technical process. The tiny slag grains can be easily recognised and identified in thin sections under the microscope (Fig. 14, RH25-1_10). The slag sand is a left over from a wet mechanical beneficiation process similar to gold washing. Slag from the ore smelting process was systematically crushed and grinded with stone tools into the grain size of sand. Copper rich inclusions (copper and matte droplets) could then be enriched in the washing basins/sluices by gravity separation. This concentrate could be added again to a furnace charge in order to optimise the overall output of the smelting process.

An extended dump of slag sand up to 0.5 m thick covers the area above and around the washing constructions. It is clear that all types of slag (slag cakes as well as platy slags) were treated for this reason, because – like at the smelting site Mauk A – only a handful of bigger slag fragments could be found in all of the excavation sections

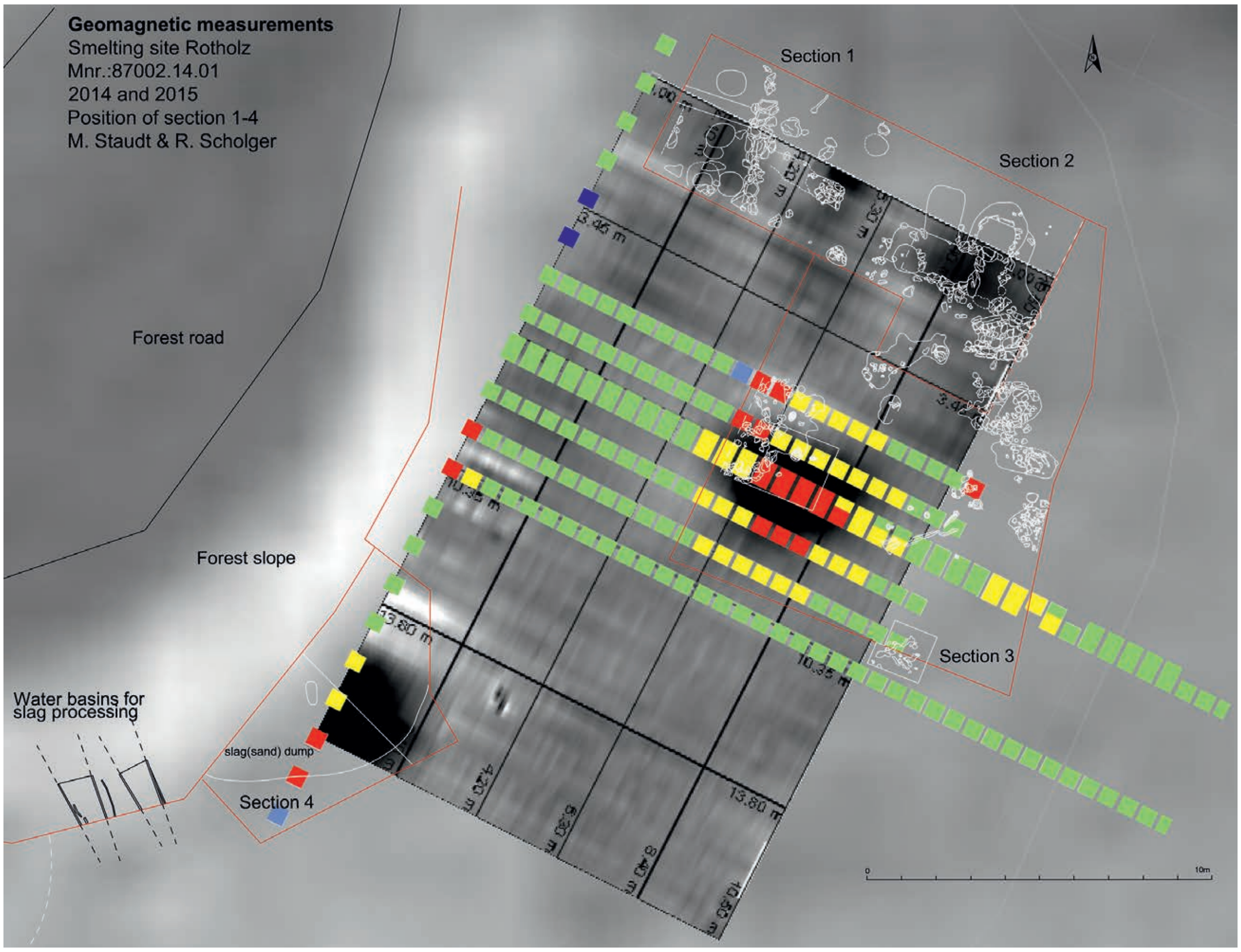

Fig. 5: The results of the geomagnetic measurements (grey area: Innsbruck team, coloured area: Leoben team) with the excavated features in section 1-4 and the documented profile in the slope of the forest road (graphic: M. Staudt, R. Scholger).

from 2010, 2015 and 2016. The slag heap must have been thicker in the western part of its extension where the downhill parts of the washing installations and the slag dump were destroyed by the forest road construction. From this fine grained slag sand heap, greenish animal bones, different stone tools (hammer, picking and grinding stones), technical and domestic pottery (some tempered with slag sand/grit) and just a few bigger slag fragments were picked up.

At the second known smelting site in the Mauken Valley (Mauk A) which is situated 13 km east of the smelting site Rotholz and southeast of Radfeld, a similar wooden basin/sluice for wet mechanical slag processing was excavated by Goldenberg et al. in 1995 and 1997 (Goldenberg & Rieser 2004). Like in Rotholz, it was built into the natural soil (Fig. 4). On the Mauk A site a few pieces of textile were used sealing up the wooden construction (Goldenberg, 2013; Grömer et al., 2017). Also a small slat, which regulated the outflowing water, was preserved. A dendrochronological analysis of one of the planks which bordered the basin/sluice yielded a cutting age of the tree used of around 1010 BC (Nicolussi et al,. 2015). This is one of the youngest dates of this site so far where first smelting activities are assumed to have started already in the 12th century BC. Whether the slag sand beneficiation was a part of the metallurgical process from the beginning or if this technique has been introduced later is still unclear. It could be possible also that the smelters tried to recycle the whole mass of cupriferous slag before they left this site.

On the other hand, just 2 km northeast of the Mauk A smelting site near St. Leonhard, slag sand tempered pottery could be found along with some bronze artefacts which date from around 1200 BC (SB Ib-SB IIa; Staudt et al., 2013). It is supposed that these finds belong to a Late Bronze Age cemetery. The analysed slag temper shows the same intermetallic composition of copper/arsenic/antimony inclusions like at the smelting site Mauk A (Krismer et al., 2012; Tropper et al., in this volume). Because of the adjacency of the two sites and the mineralogical/geochemical analyses of the slags, there is a certain plausibility that the buried people stood in close contact to the nearby miners and smelters community. This in turn would give a clear hint that the technology of slag sand processing at the Mauk A site already started in the 12th century BC within the smelting activities.

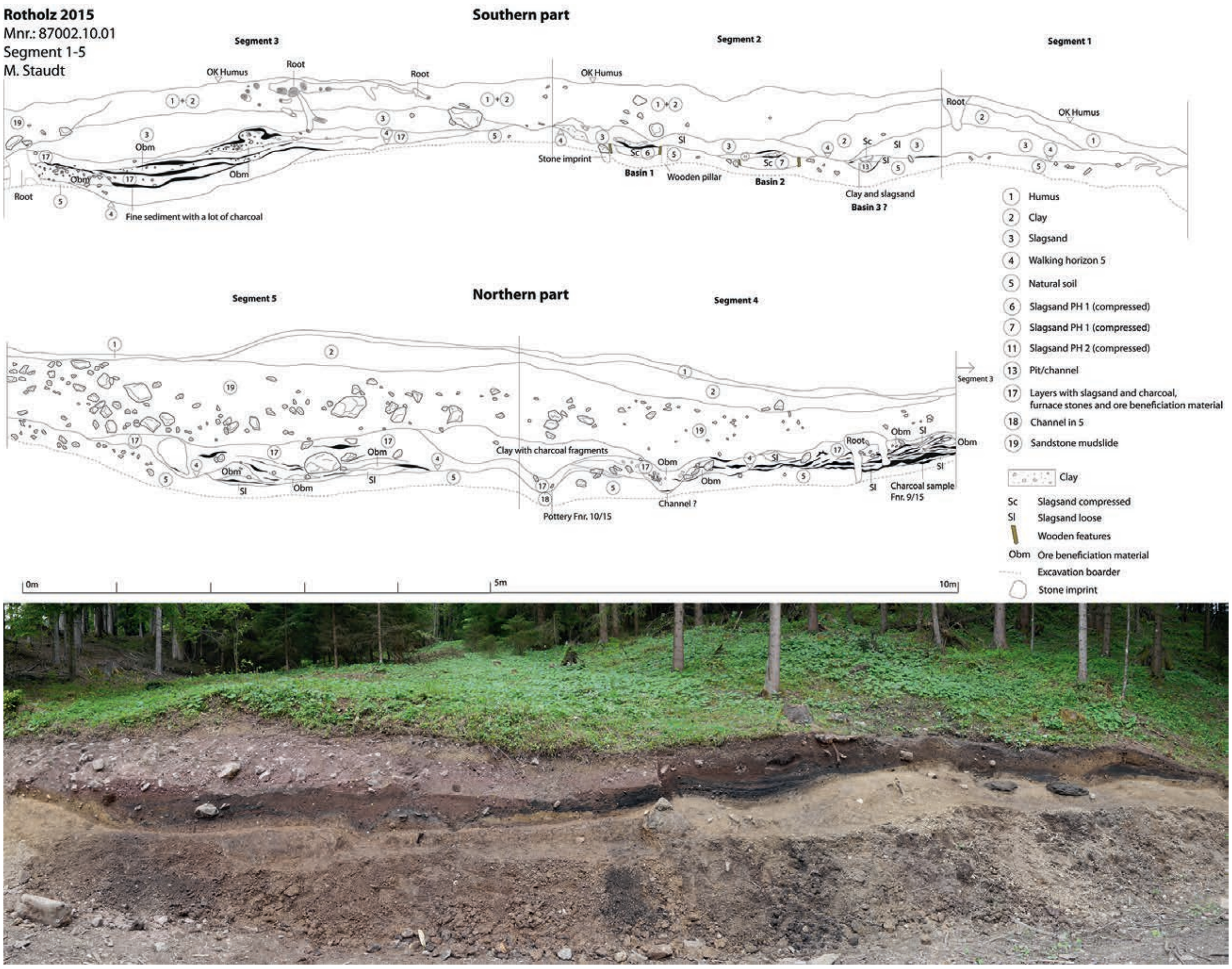

Fig. 6: Profile of segment 1-5 at the forest road; on the right side (southern part), the slag beneficiation features are visible (graphic/photo: M. Staudt).

The archaeological investigations 2015 and 2016 at the smelting site Rotholz

In the framework of a course with students from the Department of Archaeologies, University of Innsbruck, geomagnetic measurements with a 5 channel magnetometer (Sensys) could be undertaken at the smelting site Rotholz on the flat area eastwards above the forest road (Staudt et al., 2016). Robert Scholger (Montanuniversität Leoben) with students from the Department of Geology, University of Innsbruck, did some additional geoelectric and geomagnetic investigations. As a result of the geomagnetic surveys different anomalies could be measured which have been interpreted to indicate the position of slag deposits and structures of the metallurgical installations in the underground (Fig. 5). In addition core drillings up to a depth of 4 m were undertaken by Christoph Spötl and Valerie Göttgens (Department of Geology, University of Innsbruck) in order to obtain information about the stratigraphy of the natural ground as well as the position and depth of prehistoric features and cultural layers (Göttgens, 2015). As a result of the drillings an extended sandstone mudslide could be detected in the underground overlaying the archaeological features with a thickness of more than 1 meter. Furthermore, a red, burned clay layer was recorded in the northern part of the investigated area in a depth of about 1.2 meters which later on turned out to be part of a well preserved roasting bed.

The lateral extension of the prehistoric layers could be excavated and documented at the eastern profile of the side-cut of the forest road. Here the north-south dimension of the smelting site reaches around 20 meters in width (Fig. 6). The profile also shows clearly that the layers on the south side of the profile consist mainly of slag sand/grit deposits. On the north side of the profile slagged furnace stones and burned clay could be documented. Because of these observations, together with the results of the geomagnetic survey and the core drilling, it was concluded that the smelting structures (furnaces and roasting beds) must be situated in the northern part of the investigated area, a few meters eastwards uphill of the forest road. One animal bone taken from the profile

Fig. 7: The three-phase roasting bed and the partly visible furnaces 1 and 2 at the eastern profile of section 2 (photo: M. Staudt).

could be dated by ^{14}C-analysis to 2895 +/- 24 BP (MAMS 25910, cal. BC 1192-1004, 2σ).

According to the promising results of the first investigations two trenches (section 1 and 2) were traced out in the area of the assumed metallurgical structures in 2015 (Fig. 5 and 12). In around 1 meter depth a three-phase roasting bed (23, 28, 30) could be excavated underneath the reddish sandstone mudslide in section 2 (Staudt et al., 2017b). The oldest roasting hearth shows a north-south orientation and was built in the natural soil (5). Therefore, parts of the soil were dug out in the area of the out running slope to get a nearly flat working area for the installation of the metallurgical constructions.

The oldest roasting hearth 1 (30) is 2 meters long and 1 meter wide (reaction space: 0.80 x 1.80 m) and bordered with larger stones (Kellerjoch-Augengneis and red sandstone). The younger roasting hearths 2 (28) and 3 (23) are placed at right angles to and directly above the older structure 1. At the eastern boundary of the roasting hearth 2 (width of reaction space: 0.90 m) the stone construction of the roasting hearth 1 was reused. The back border of the youngest roasting hearth 3 (reaction space: 0.90 x 1.90 m) was slightly displaced 0.50 m westwards from the back border of roasting hearth 2. The youngest phase was destroyed in it's west part by a rootstock and shows nearly the same dimensions (width) like structure 1. Between the boarder stones of phases 2 and 3 clay was placed and flattened. The clay is quite red indicating its exposure to high temperatures and open fires during many runs of the roasting hearths.

The stones of the two younger constructions consist mainly of Kellerjoch-Augengneis. Five of these stone blocks show distinct use marks and represent the broken fragments of a large grinding stone. ^{14}C-analysis of charcoal samples from the roasting hearths 1 and 2 date these structures roughly into the 14th to 12th century BC (roasting hearth 1: 3044 ± 26 BP, MAMS 25908, cal. BC 1399-1218, 2σ; roasting hearth 2: 2995 ± 26 BP, MAMS 25909, cal. BC 1369-1129, 2σ). Considering the state of the art of regional copper production including other mining and smelting sites, dendrochronological investigations, geochemical analysis on bronze artifacts, as well as the development of North Tyrol's urnfield cemeteries it can be supposed that the large-scale smelting activities of the Late Bronze Age did not started before the 12th century BC. The older dates (^{14}C) can probably be argued with the old wood effect (samples taken from heartwood, time-lag between felling and final deposition).

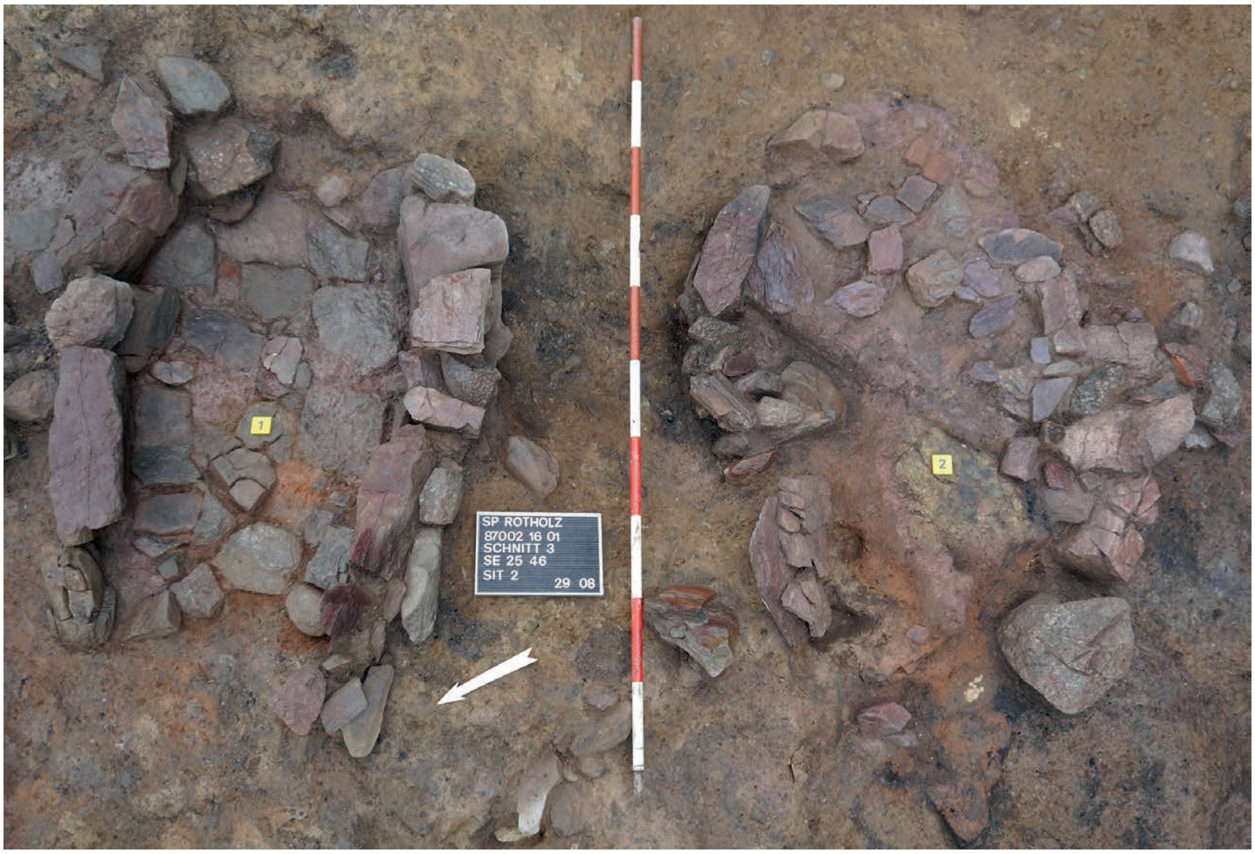

Fig. 8: The excavated furnaces 1 and 2 in section 2-3 (photo: M. Staudt).

In the immediate vicinity south of the roasting hearths in section 2, two smelting furnaces (1 and 2) were partly excavated in 2015 (Fig. 7). Based on these features and on the geomagnetic investigations, section 3 was opened in summer 2016 east- and southwards of the already uncovered smelting structures (Staudt et. al., 2017b, 2018). During this campaign a battery of four smelting furnaces could be uncovered and documented. Furnace 1 is especially well preserved and shows multi-layered stone walls on three sides (Fig. 8). From furnaces 3 (47) and 4 (48) only the bottom parts are left under the overlaying sandstone mudslide which at this place is 1.6 m thick. The furnaces are built mainly with angular sand stones. The reddish stones show high temperature exposure due to the impact of fire and are placed upright in the natural soil. From furnace 1 three layers of stones with a total height of maximal 0.5 m are still preserved. Because of the amount of collapsed furnace stones found inside furnace 1, a minimum height of 1 meter is supposed for the original furnace structure. The bottom of all the furnaces is stone paved with mainly smaller plates of sand stone, phyllite, schist and Kellerjoch-Augengneis. The shape of the constructions is oval and slightly wider at the back part (reaction chamber). The structures of furnace 1 and 2 are east-west orientated and show a length of 1.50 m and a width of 1.00 m (reaction space: 1.30 x 0.70 m; Fig. 8 and 12). Inside the furnaces no slagged clay or stones are left in situ. Such expected slagged stones and clay fragments from the furnace chambers could be found in the near surroundings of the furnaces. In furnace 2 some greenish coloured clay-layer (Cu-oxide minerals, malachite) is a leftover of the copper smelting activities. It is not clear if all four furnaces were used at the same time or alternating. All 4 furnaces were built into the natural soil and belong to the same stratigraphic working layer. Furnaces 3 and 4 show a slightly different orientation with an angular misalignment of about 15 degrees compared to furnaces 1 and 2. This fact and the bad preservation could be an indication that furnaces 3 and 4 were used in an earlier phase. Stratigraphically all of the furnaces belong to the nearby three phase roasting bed. It is noticeable that the furnaces as well as the roasting hearths from Rotholz are built with a different construction technique than those already known from the Mauken Valley smelting site Mauk A. There the roasting beds are paved with flagstones and the 2 uncovered furnaces show a smooth flat bottom made of clay (Goldenberg et al., 2011, 2015). Radiocarbon analyses on charcoal fragments from all four furnaces could be obtained:

- Furnace 1: 2916 ± 24 BP, MAMS 29931, cal. BC 1207-1024, 2σ
- Furnace 2: 2936 ± 22 BP, MAMS 29932, cal. BC 1213-1054, 2σ

Fig. 9: Unexplained structure at the southern profile (left) and probably another younger roasting bed at the western profile (right) of section 3 (photos: M. Staudt).

- Furnace 3: 2939 ± 22 BP, MAMS 29933, cal. BC 1215-1055, 2σ
- Furnace 4: 2994 ± 22 BP, MAMS 29934, cal. BC 1367-1127, 2σ

At the southern profile of section 3 other remains from metallurgical processes came to light. The structure (51) shows a mixture of reddish layers of clay, charcoal and some smaller stones, which were destroyed and relocated by tree roots. The clay fragments are up to 10 cm thick and show strong impact of heat/fire and are definitely not leftovers of a simple fireplace (Fig. 9 and 12). The original structure of this feature is unreproducible and could represent a destroyed smelting furnace or a roasting hearth. 5 m north-west, at the western profile of section 3, another construction with bordering stones and thick layers of burned clay could be excavated. This feature (50) is situated 4.5 m westwards of the furnaces and is also partially destroyed by tree roots in the northern part. The rectangular frame made of stones shows two different reddish layers (Fig. 9 and 12). It looks similar to the other multi-phase roasting hearth in section 3, and the stratigraphic arrangement of the reddish layers is indicating at least two phases. This structure is built on the same working layer which belongs to the furnaces 1 to 4 including the roasting hearth (phases 1 to 3) described above and is therefore stratigraphically younger. The radiocarbon age of a charcoal sample from this structure (2869 ± 22 BP, MAMS 29935, cal. BC 1116-946, 2σ) indicates a younger date than those of the other roasting hearths. Another younger furnace or furnace battery in the nearby area may be expected but no traces have been detected till now. Within the geomagnetic measurements the whole area could not be explored due to the presence of trees and the rising terrain.

Connected to the features from metallurgical activities, a post-hole with wedge stones (53) and an acute pit (49) could be documented. This post-hole could be interpreted as a part of a simple roofing of the furnace battery like it is known from traditional copper ore smelters in Nepal (Anfinset, 2011). The pit does not show any signs of heat impact. It could maybe represent the negative imprint from a clay extracting point as clay was a necessary base material for the construction of the metallurgical installations. In section 3 the remains of a burned wooden plank (55) were found on the surface of the natural soil at the basis of the cultural horizon, representing stratigraphically one of the oldest features of the whole site. A radiocarbon analysis dates this find into the 13th/12th century BC (2983 ± 21 BP, MAMS 29936, cal. BC 1269-1126, 2σ).

In section 2 and west of the multiphase roasting hearth more pits were excavated. One of these depressions (38) is similar to the already described acute pit and was maybe produced for the same reason. Next to it lays a shallow pit (33, max. 20 cm deep) with a flat bottom which is filled up with a layer of charcoal and covered with a layer of stones. Also this feature does not show any impact of heat/fire and therefore has nothing to do with the roasting and smelting process itself. After more recent publications it is supposed that the last step of smelting of sulfidic copper ores is probably done in small pit-hearths (Hanning et al., 2015), but a feature like this has not been identified at the smelting site Rotholz so far.

Fig. 10: The stone wall and the shallow pits for slag beneficiation in the western part of section 1 (photos: M. Staudt).

At the western part of section 1 close to the side-cut of the forest road a north-south orientated dry stone wall (40) made of mainly sand stones was uncovered. The construction shows up to three stone layers and continues into both profiles of section 1. The remaining height of the wall is up to 0.5 m and the mass of collapsed stones is indicating an original height of about 1 m. The function of this structure is not clear. It could either be interpreted as the foundation wall of a former building or as a construction for the stabilization of the slight hillside with the roasting beds above. The wall can be seen in direct connection with several shallow pits (41, 43, 44) which could be uncovered in a regular distance westwards in front of the wall (Fig. 10 and 12). These roundish depressions are aligned next to the wall and orientated north-south. Three of these pits are filled up with hard compact sediment at the bottom, which macroscopically looks similar to the sediments from the slag sand beneficiation basins/sluices. Both materials from the pits and the basins/sluices were examined and compared under the microscope and consist for the major part of small slag fragments mixed with tiny pieces of charcoal

Fig. 11: The slag(sand) dump in section 4 at the forest road with the leftover compressed slag sediment of the washing basins (left) in the background (photos: M. Staudt).

and natural soil (Fig. 14). It is supposed that in these pits a further preparation process with slag sand took place representing a still unknown beneficiation technique. So far comparable features from other contemporaneous smelting sites are unknown. The clay of the older phase of the third pit is slightly reddened by heat. In summary, the ensemble of the wall and the pits can be considered as the leftovers of a former hut / roofed workshop where some special slag treatments took place.

Section 4 was excavated north-east of the wood bordered washing basins/sluices which appeared in the profile of the forest road cut. Here the slag sand dump achieved its biggest thickness confirmed by the geomagnetic measurements. Unfortunately the major part of the slag sand dump was already destroyed by the road building (Rieser, 2007). In consequence of the undocumented destruction only the small leftovers in the south-eastern part of the former slag sand dump (3.5 x 5.0 m) could be investigated (Fig. 5 and 11). In the excavated area the thickness of the cultural layers attains up to 0.6 m maximum. The lower layers consist mainly of slag sand, charcoal, relocated clay and stones. In the upper layer finely grinded slag sand dominates the material. The sandy sediment shows a dark grey rusty colour and is more oxidised at its top part. Inside the dump a few stone tools could be picked up. A big and heavy stone tool (cobble stone, garnet amphibolite, ca. 120 kg) with clear traces of use on two sides can be highlighted amongst these findings. On one side several shallow depressions deriving from crushing slags with hammer stones are apparent (function: anvil stone). On the opposite side a typical slightly concave surface from grinding processes is developed deriving from reducing the slags to the grain size of fine sand (function: mortar stone). Only in the bottom layer small amounts of material from mechanical ore beneficiation processes could be identified. In general all the stone tools described could have been used for the purpose of ore processing as well as slag processing. Especially from the layers in section 4 a lot of greenish animal bones could be collected. These food remains were thrown to the slag dump after the meals. Because of the cuprous salts included in the slag sediments with their antibacterial properties, bones and other organic materials are very well preserved. Geochemical analysis on some of the bones show a distinct enrichment of copper, arsenic and antimony and therefore point out the fact that fahlores have been processed on the site (Rieder, 2014).

Finds from the smelting site

A variety of informative artefacts which are typical for smelting sites of the period under consideration could be found (Fig. 13). Beside the described piston-headed pin (Rieser, 2007) the following materials came to light: food waste (greenish animal bones), fragments of technical and domestic pottery (tuyères, cooking- and dinnerware), stone tools (hammer stones, anvil stones, grinding stones, mortar stones), pieces of fahlore in dolomite, slag fragments, vitrified furnace clay as well as furnace stones and intermediate products from different steps of the pyrometallurgical process like copper matte and/or speiss with copper-arsenic- and copper-antimony-sulphides. The pottery consists mainly of ordinary coarse-ceramic but there are quite a lot of fine-ceramic

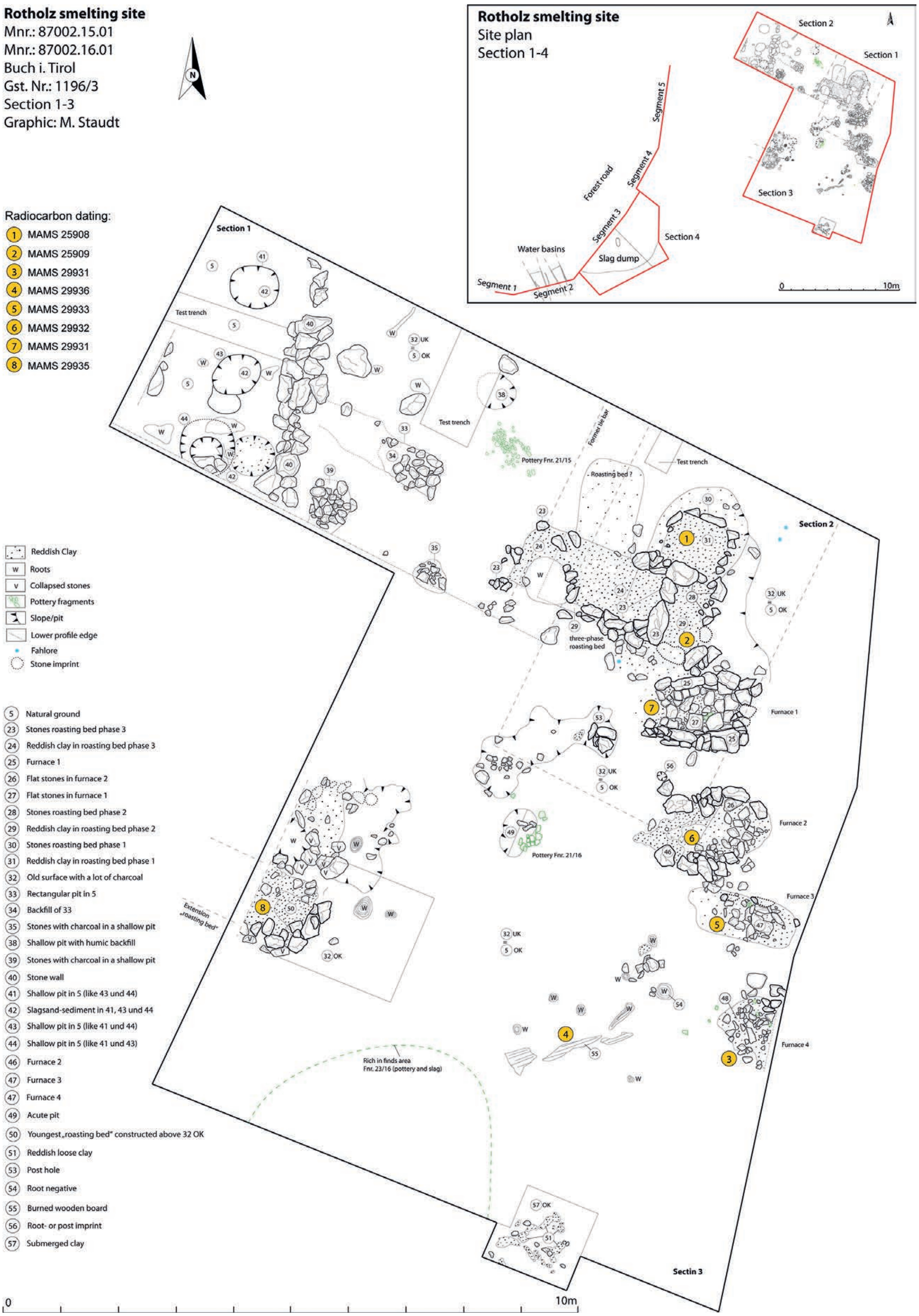

Fig. 12: Plan of the smelting and beneficiation features in section 1-3 (graphics: M. Staudt).

Fig. 13: Finds from the smelting site Rotholz: plate slag (RH8_10, RH20-2_16), heterogeneous slag (RH7-2_15), fahlore (RH13-2_15), fine ceramics (RH4-3_16, RH14-3_15, RH17-16_16, RH17-18_16, RH28_16, RH30_17, RH35-2_17, RH43-2_17), encrusted domestic pottery (RH25_16), fragments of tuyères (RH10_17, RH10-6_17, RH17-20_16) and stone tools (RH3_10, RH31_16; graphics: M. Staudt).

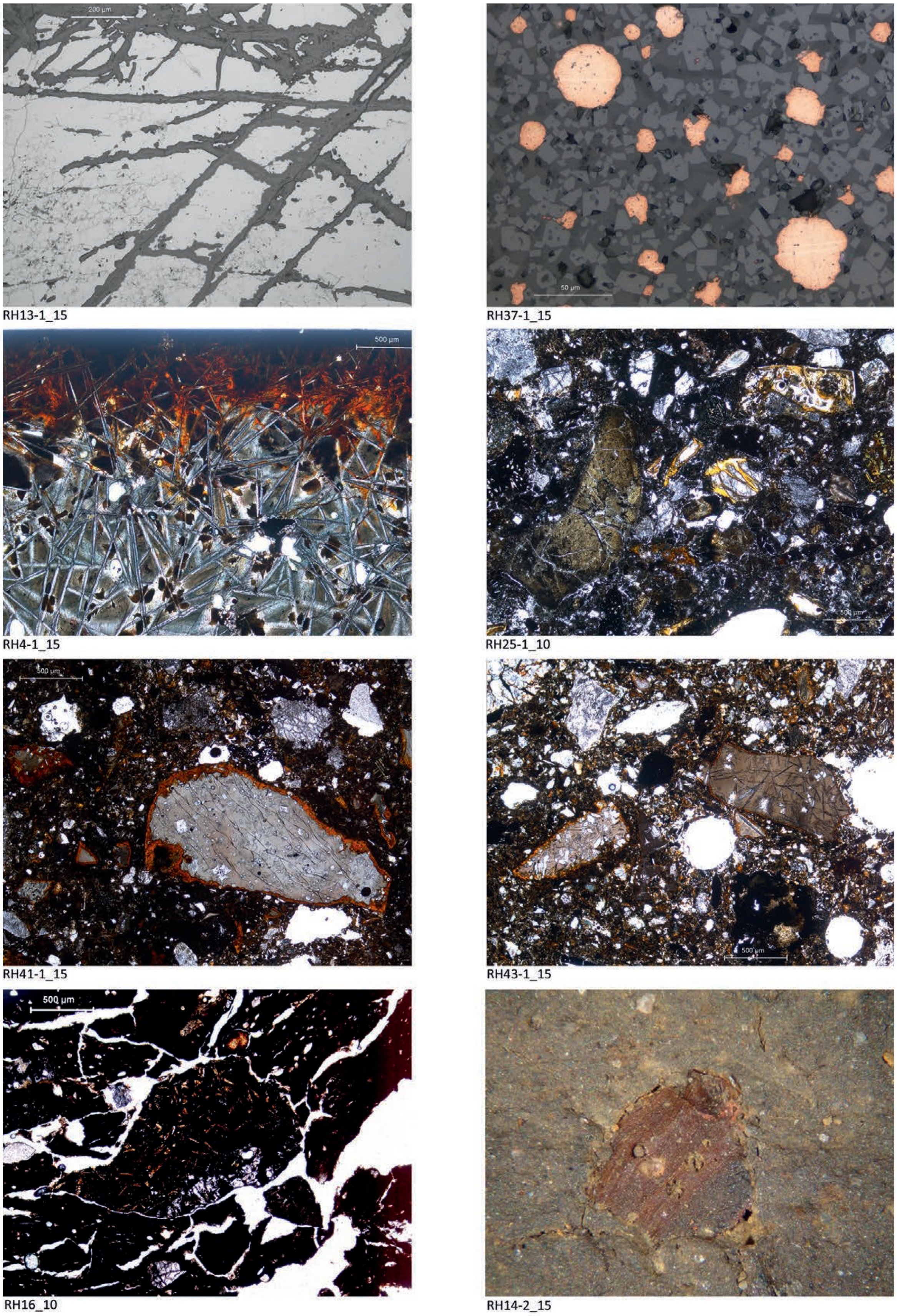

Fig. 14: Microscope pictures of thin sections from Rotholz: Fahlore (RH13-1_15), copper droplets and iron oxides in slag matrix (RH37-1_15), plate slag (RH4-1_15), compressed sediment with slag fragments from washing basin 1 (RH25-1_10), compressed sediment with slag fragments from pit 41 (RH41-1_15), compressed sediment with slag fragments from pit 43 (RH43-1_15), slag temper inside the pottery matrix (RH16_10). Surface microscope picture of slag tempered pottery (RH14-2_15; graphics: M. Staudt, G. Goldenberg, P. Tropper).

fragments in the inventory as well (Fig. 13). In some cases the fine-ceramic is decorated with grooves (RH28_16) and two pieces show an incrustation with a white material (RH25_16, RH35-2_17). Geochemical analyses of such an incrustation from comparable pottery of a Late Bronze Age settlement in the Kauner Valley, North Tyrol, approve the use of a mixture of bone ash, quartz and feldspar partly transformed to the mineral phase apatite (Staudt, 2016). The lower ends of the collected tuyère pieces are never slagged. In total four tuyère fragments show a tiny hole (Fig. 13: RH10-6_17). This fact has also been observed at other prehistoric smelting sites (Töchterle et al., 2013) and could be part of fixing the bellow or a valve system. The domestic pottery from the smelting site Rotholz is many times slag tempered. The temper can be recognised mainly in the coarse-ceramic fragments and the components are sometimes even visible with the naked eye. The metallurgical slags consist mainly of three distinguishable types: heterogeneous slag cakes (fragments, fig 13: RH7-2_15) respectively tiny bulky pieces of heterogeneous slag, homogeneous platy slag (fig13: RH8_10, RH20-2_16) and slag sand. Also some slagged furnace clay has been excavated. In polished sections under the microscope the slag samples show matte and copper inclusions (Fig. 14). Due to the fact that only a very small amount of bigger slag fragments could be observed on the site, it is supposed that all slag types were systematically crushed and grinded to slag sand. The latter then was washed in special washing basins/ sluices and pits, in order to obtain concentrates of metal rich inclusions (matte and copper metal). This material could be smelted again together with a new charge of ore to optimise the overall output of copper metal. By examining thin sections of slag tempered pottery under the microscope, it becomes clear that no selection was done for the comminution of slag.

The use of slag temper in the Late Bronze Age

It seems obvious why the prehistoric potters used slag fragments or slag sand as a temper component:

- large quantities of such materials were available from smelting sites and already in a useable size
- it is a heat proof temper component with a stable shape because it was already heated up to very high temperatures
- it has good thermal conductivity and is therefore well-suited for the production of cooking pottery
- the sharp-edged shape of the crushed and ground slag fragments has perfect binding properties
- maybe it had to do with religious beliefs; similar believes could be observed in Nepal where the traditional copper smelters treat the produced metal as a holy object and broken tuyères are kept for good luck (Anfinset, 2011)

The use of slag temper in the Lower Inn Valley is noticeable in the Early and mainly the Late Bronze Age. Perhaps such a temper addition was used in the Middle Bronze Age as well (Sölder, 1987/88; Töchterle et al., 2013). It can mainly be found in domestic and rarely in grave pottery from the vicinity of the fahlore-mining district. Ceramic finds from this district (mining pits Mauk D, Weißer Schrofen, Rotenstein and Burgstall; smelting sites Mauk A and Rotholz; settlement Kundl-Wimpissinger and cemetery St. Leonhard) prove the intense use of slag temper in the Late Bronze Age. So far only one of the pottery fragments from the Iron Age fire setted mines in the Lower Inn Valley shows this kind of temper (Mauk E, 707 BC) and only one Iron Age slag tempered pottery fragment is known from the cemetery in Kundl. The grave (626) is dated in the Early Iron Age by a serpentine fibula (Lang, 1998). It seems that slag tempered ceramic is typical for the Late Bronze Age and ends around the Early Iron Age. At this stage (end of the 8th century) the latest mining activities could so far be proved through dendrochronological analyses (Goldenberg et al., 2012; see article Staudt et al., in this volume).

It looks like that there is a chronological change in size of the slag temper. Especially in the 12th/11th century BC, the slag temper contains grains with the size of sand. At the final stage of the Late Bronze Age bigger slag temper fragments (up to 1 cm) can be observed at the settlement Kundl Wimpissinger and the mining pits at the Burgstall. Perhaps the early Late Bronze Age pottery is tempered with grinded slag from smelting sites, where slag beneficiation was an important part of the copper production. It is possible that in the final stage of the Late Bronze Age the slag processing stopped for whatever reasons and the slag was just added traditional and because of the positive properties as a surcharge. Maybe at this time the ore was smelted only in settlements (like Kundl-Wimpissinger) and slag beneficiation was not important anymore.

The nearby prehistoric mining districts

Prehistoric copper mining has been proved at the nearby district Weißer Schrofen (Pirkl, 1961; Gstrein, 1978), which is situated just 1.2 km east of the smelting site Rotholz. This is probably the place where some of the smelted fahlore came from (Fig. 2). During the excavations in 2016 at the pit field Weißer Schrofen, a piece of plate slag could be picked up which definitely comes from a prehistoric smelting site. Also the ^{14}C-data from the mining pits at the Weißer Schrofen (12th to 10th century BC) correspond well within the ones from the nearby smelting site Rotholz (see article Staudt et al., in this volume). Just 300 m westwards of this sub-district a few traces of fire setting activities are clearly visible (like the “Kooperatorstollen”; Perger, 1995; Rieser & Schrattenthaler, 2002). Even though this spot is not

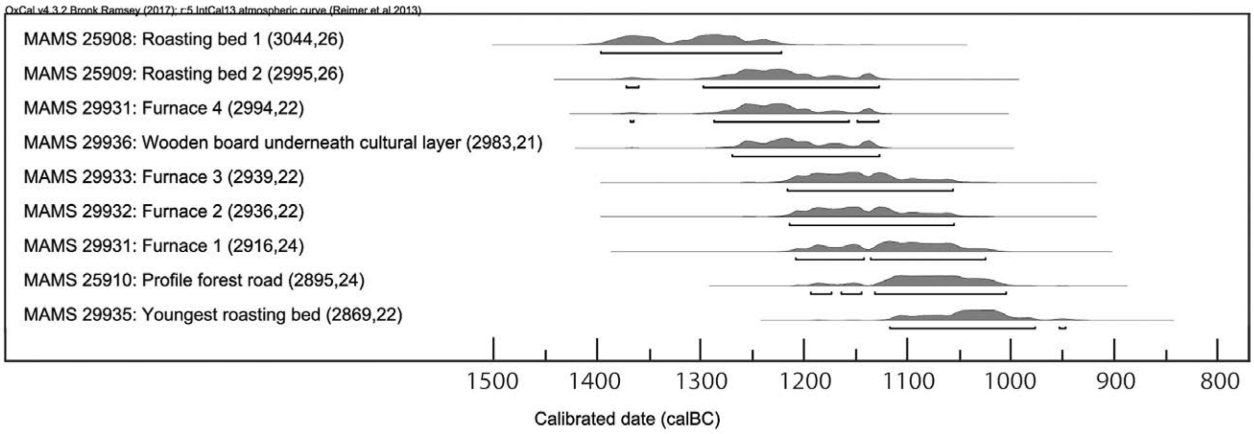

Fig. 15: Calibrated ^{14}C-data from samples of the smelting site Rotholz (graphic: OxCal v4.3.2.).

dated yet, it is supposed that these traces come from prehistoric mining. 200 m westwards of the Larchkopf (1 km east of the smelting site Rotholz) some collapsed furrow pits and former open cast mines could indicate prehistoric work as well. So far nothing is known about modern mining activities in this man made rugged area. Maybe some of the smelted ore also came from the area of todays Raffl farm (Hallersberg) where small fire settings are visible in the Schwazer Dolomit as well. It is conceivable that some fahlore from the Reither Kopf was brought to the smelting site too. This prehistoric mining spot with the remains of big pits is situated 1.2 km southwards (Rieser & Schrattenthaler, 1998/99 & 2002). Prehistoric mining could be detected also along some mining pits in the district Rotenstein (Obertroi) which is situated only 1.2 km southwest of the excavated smelting features (see article Staudt et al., in this volume; Rieser & Schrattenthaler, 1998/99, 2002).

Conclusions

The ^{14}C-data from the smelting site Rotholz are documenting metallurgical activities in the period from the 13th to the 11th century BC (Fig. 15). Considering the possible “old wood effect“, it is supposed that the earliest smelting activities started around the beginning of the 12th century BC, like it could be demonstrated for the second known smelting site Mauk A. The complex smelting site Rotholz, with many different structures of technical processes (smelting, roasting, ore/slag beneficiation), represents an industrial-like copper production. The slag beneficiation played a very important role. This can be concluded by examining the features like the shallow pits, the wooden basins and the slag sand heap. For all the different kind of work a well organised subsistence strategy concerning ore, wood, and food supply is essential. It is supposed, that the smelters were specialists in their field. These activities are based on the transfer of knowledge, which probably came from other mining districts like Mitterberg and/or Kitzbühel-Jochberg, where the copper production based on chalcopyrite deposits was already well established before. A traditional association and a specific technical transfer of those smelters from the different districts can be seen by the phenomenon of slag tempered pottery which spreads between the Lower Inn Valley and the Mitterberg mining district (Sölder, 1987/88; Töchterle et al., 2013; Stöllner et al., 2016; see Tropper et al., in this volume). The smelting activities at the two known smelting sites in the Lower Inn Valley lasted for more than one century. Fahlore from the surrounding ore deposits was smelted in these strategically well placed spots where wood, clay and water as well as food supply was available. It is also evident that there must exist more still unknown smelting sites, which are considered to be buried underneath massive mudslides. Such observations can be made at different archaeological sites along the Lower Inn Valley (for example: mining pit field Mauk D, Goldenberg, 2014; mine Mauk B, Goldenberg & Rieser, 2004, Staudt et al., 2017a; settlement Kundl-Wimpissinger, Patzelt & Weber, 2015). These earth movements caused by erosion can partly be explained as a result of large scale deforestation accompanying the extensive prehistoric, late medieval and modern mining activities.

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Authors

Markus Staudt – Department of Archaeologies, University of Innsbruck
Gert Goldenberg – Department of Archaeologies, University of Innsbruck
Manuel Scherer-Windisch – Department of Archaeologies, University of Innsbruck
Caroline Grutsch – Department of Archaeologies, University of Innsbruck
Roman Lamprecht – Department of Archaeologies, University of Innsbruck
Bianca Zerobin – Department of Archaeologies, University of Innsbruck

Correspondence and material requests should be addressed to: Markus.staudt@uibk.ac.at

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Peter Tropper, Markus Staudt, Ulrike Töchterle, Matthias Krismer, Gert Goldenberg

Encapsulated industrial processes: slag-tempered ceramics and its implications for prehistoric metallurgy in the Lower Inn Valley (North Tyrol, Austria)

ABSTRACT: *The use of slag-tempered ceramics is a characteristic feature of prehistoric inner-Alpine settlements associated with Cu-ore deposits. Slag-tempered ceramic fragments from three sites in the Lower Inn Valley were investigated with mineralogical, petrographical and geochemical methods: (1) the hilltop settlement Kiechlberg near Thaur, (2) the gravel quarry Kundl-Wimpissinger and (3) the cemetery St. Leonhard site, latter both in the vicinity of Kundl. The Kiechlberg (1) site is a small hill on the south face of the Karwendel mountain range, a few kilometers northeast of Innsbruck. Superficial finds of artefacts and metallurgical slags led to first archaeological excavations in the frame of the Special Research Program HiMAT (supported by the Austrian Science Fund FWF). On the Kiechlberg, a huge amount of ceramic and flint artefacts as well as metal objects made of copper and bronze were collected during the investigation of a prehistoric layer of debris, indicating an occupation of the site from Late Neolithic up to Early and Middle Bronze Age. One specific feature was the occurrence of slag-tempered ceramic fragments. The slag fragments are <5 mm in size and often occur greenish due to alteration of Cu-minerals. The slag mineral assemblage is olivine + clinopyroxene + spinel + Cu-droplets. Chemical compositions of the Cu metal droplets are identical to compositions from slag samples from the site itself. At the gravel quarry Wimpissinger (2) near Kundl a Late Bronze Age settlement was discovered with a metal workshop containing slag residues and ceramic fragments. In these ceramic fragments slag temper was also found. The mineralogy of the analyzed slag fragments as well as the slag temper indicates that the ore used to produce Cu-metal came from the nearby fahlore-group mineral deposits of Brixlegg (embedded in Devonian dolomites, "Schwazer Dolomit"). Significant amounts of Ni and Co also indicate that ores of Triassic age ("Schwazer Trias") were also used. On the south side of the Inn Valley near the village of St. Leonhard (3) near Kundl (Tyrol, Austria) a few pieces of bronze and pottery have been discovered on a field. Here, a Late Bronze Age (Urnfield period) burial site is suggested. Because of the greenish spots observed on one of the pottery fragments it was assumed that some of the jars could have been tempered with slag sand. Slag sand/grit is a by-product of copper ore smelting processes and can be found in the copper smelting sites Mauk A in the nearby Mauken Valley, only two kilometres southwest, as well as at the smelting site in Rotholz (Buch i. T.). Mineralogical investigations of ceramic fragments confirm the first assumption that in the three above mentioned sites primarily slag fragments were used as temper. The slag temper has a characteristic chemical/mineralogical composition. The metal/copper inclusions in the slag have typical "fahlore-signature" containing Sb and As. The chemical composition and textures of the silicate phases are comparable to the Late Bronze Age copper slags from the adjacent site "Mauk A". Chemical analysis of the slag-tempered fragments from all three sites indicate so far that local fahlore-group minerals from the Lower Inn Valley have been used.*

KEYWORDS: CERAMICS, SLAG TEMPER, ARCHAEOMETALLURGY, KIECHLBERG, KUNDL-WIMPISSINGER, HIMAT

Introduction

Investigations of ceramic fragments in the Alps have a long tradition (e.g. Maggetti, 2005). Ceramic provenance analysis begins with the petrographic study of the ceramics itself (e.g. Quinn, 2009). Sometimes petrographic analysis of the temper alone, due to the presence of some mineral inclusion distinctive enough, is sufficient to determine regions of source procurement and hence manufacture (Peacock, 1969; Shepard, 1956). For instance, the Kiechlberg revealed a large number of ceramic fragments and stylistically the different ceramic fragments can be attributed to the following groups (Töchterle, 2015): 1.) The Polling group (4,100-3,900 BC), which has already been found at Brixlegg-Mariahilfbergl, Innsbruck-Norer Sandgrube and Thaur-Kiechlberg. 2.) The „Vasi a Bocca Quadrata" (Isera II, 4,200-3,800 BC) south of the Alps. 3.) The Pfyn and Altheim style (3,800-3,300 BC) and 4.) local manufacture from Early Bronze Age (2,200-1,600 BC). Since petrographic investigations of prehistoric

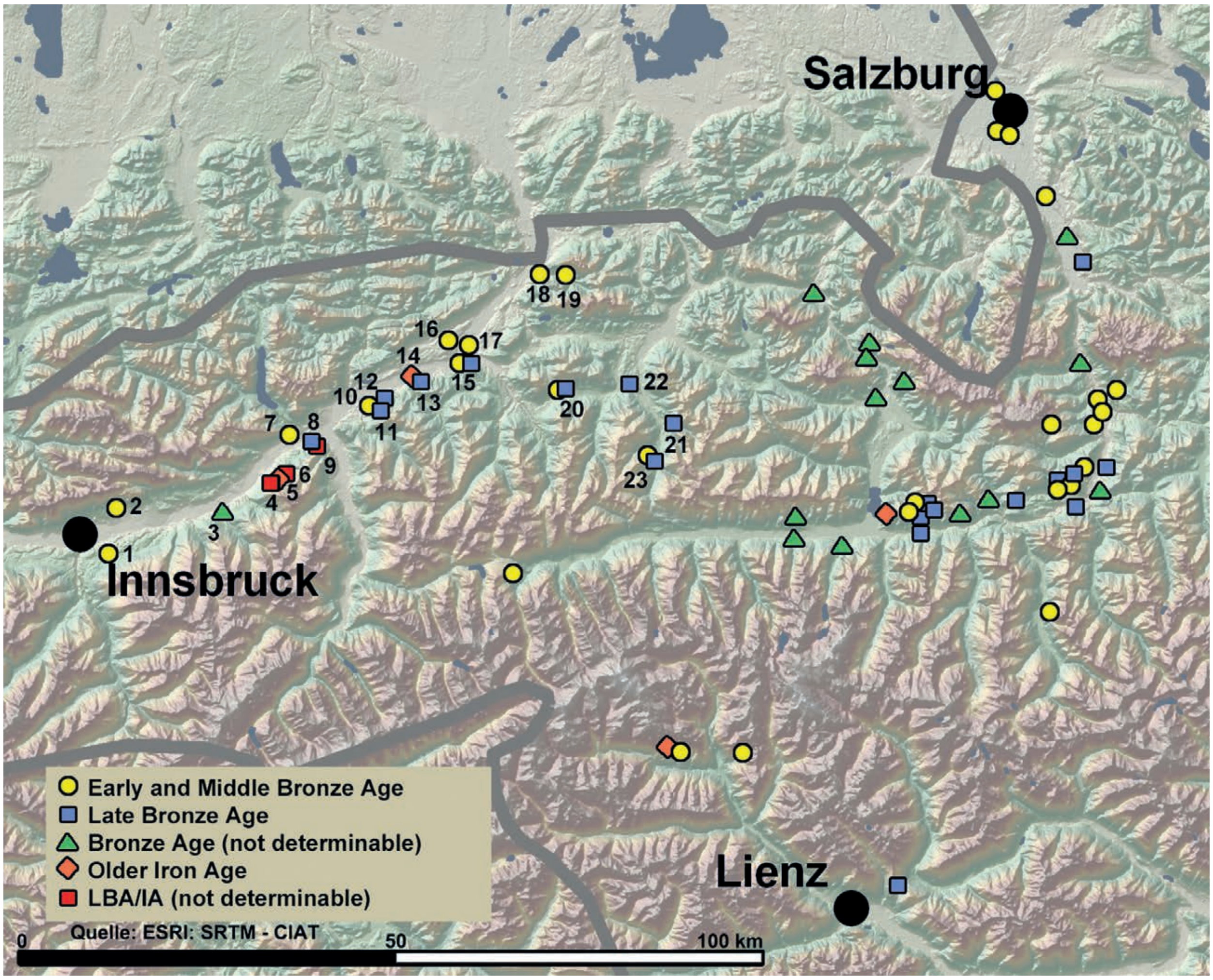

*Fig. 1: Map showing the distribution of Bronze Age/Iron Age slag-tempered ceramics in North Tyrol***:** *1: Goldbichl, Igls; 2: Kiechlberg, Thaur; 3: Stadlerhof, Weer; 4 + 5: Blutskopf/Gallzeiner Joch, Gallzein; 6: Obertroi, Buch in Tirol; 7: Buchberg, Wiesing; 8: Smelting site Rotholz, Buch in Tirol; 9: Weißer Schrofen, Strass im Zillertal; 10: Hochkapelle-Mariahilfbergl, Brixlegg; 11: Smelting site Mauk A und Pingenfeld Mauk D, Radfeld; 12: St. Leonhard, Kundl; 13: Wimpissinger-quarry (settlement), Kundl; 14: Wimpissinger-cemetery, Kundl; 15: Inntalmilch, Wörgl; 16: Siedlung, Angath; 17: Grattenbergl, Kirchbichl; 18: Festungsberg, Kufstein; 19: Tischofer Höhle, Ebbs; 20: Götschen, Brixen im Thale; 21 Kelchalm, Aurach; 22 Tiefenbrunner Feld, Kitzbühel; 23 Smelting site SP9 (Wurzhöhe), Jochberg. Sources: 5, 7, 10, 16, 19 Sölder 1987/88, 2015; 1-3, 15, 17, 20 Töchterle et al. 2013; 4, 6, 8, 9, 18, 21 Staudt pers. comm.; 12 Krismer et al. 2012; 13 Prader 2013; 14 Lang 1998; 11 Goldenberg 2014; 22 Huijsmans 1994; 23 Preuschen & Pittioni 1955.*

ceramic fragments in the Tyrol have only been done at the Mariahilfbergl, Brixlegg (Huijsmans, 2001), Buchberg, Wiesing (Martinek, 1996), Mauken Valley, Radfeld (Mauk A, Reider, 2003), Mairhof, Kaunerberg (Staudt, 2016) and Pirchboden, Fritzens (Ciresa, 2006), there is an absolute need to increase the database. One peculiar feature observed during the investigations of the research centre HiMAT (The History of Mining Activities in the Tyrol and adjacent areas: Impact on Environment and Human Societies) is the use of metallurgical products as ceramic temper. So far it seems that slag sand tempered ceramic is an alpine phenomenon and can be found in technical ceramics (tuyères and crucibles), domestic pottery from settlements as well as in grave goods (ceramics) since the Early Bronze Age up to the Early Iron Age (Sölder, 1987/1988, Töchterle et al., 2013; also Stöllner et al. 2016, pp.83-87). In the Inn Valley such findings can be located near the fahlore-group mineral mining district Schwaz-Brixlegg (Preuschen & Pittioni, 1955; Gstrein, 1981, 1988; Sölder, 1987/1988; Huijsmans, 1994; Rieser & Schrattenthaler, 1998/1999, 2004; Goldenberg & Rieser, 2004; Goldenberg et al., 2012; Goldenberg, 2013, 2014, 2015; Töchterle, 2015). Within the framework of the research centre HiMAT (since 2007) and the international DACH-project “Prehistoric copper production in the eastern and central Alps – technical, social and economic dynamics in space and time” (supported by the Austrian Science Fund FWF, the German Research Foundation DFG and the Swiss National Science Foundation SNF, 2015-2018) comprehensive investigations on prehistoric copper production were done on the mining area Schwaz-Brixlegg over the past years. This lead to the identification of so far 23 sites where metallurgical remains were used as ceramic temper in Tyrol. Most of these sites, 19 of them, are found in the Lower Inn Valley as shown in Fig. 1. The westernmost occurrence of slag-tempered ceramics in the Lower Inn Valley is at the Early Bronze Age hilltop-settlement at the Kiechlberg (Thaur) about 30 km west of the important fahlore-group mineral deposits in the Tyrolean Lower Inn Valley (Krismer et al., 2010, 2012a; Töchterle, 2015). Most of the sites containing slag-tempered ceramic centre around the mining district Schwaz-Brixlegg and in the course of recent investigations new locations dating into the Late Bronze Age/Early Iron Age could be identified inside the mining district, the most prominent being the sites near Kundl and St. Leonhard. The dimensions of the slag fragments found inside the ceramic strongly vary from small grain sizes of <2 mm up to a size of 1 cm.

Prominent examples of archaeological sites with slag-tempered ceramics

Archaeological background

(1) Kiechlberg: The Kiechlberg (1028 meters a.s.l.) is a small hill at the foot of the Karwendel mountain range, 400 metres above the Inn Valley a few kilometres northeast of Innsbruck. Superficial finds of prehistoric artefacts and metallurgical slag led to first archaeological excavations, which started in 2007 within the frame of the Special Research Programme HiMAT. A huge amount of ceramic and flint artefacts as well as copper and bronze objects were collected during the investigation of a prehistoric layer of debris, indicating a multiphase-occupation of the site from the Late Neolithic up to the Middle Bronze Age. On the steep northern slope of the Kiechlberg a massive deposit of cultural layers contains metallurgical finds. The radiocarbon samples of the oldest layers deposited on the bedrock and postglacial sediments and particularly poor metallurgical finds provide the earliest data of 4050-3810 cal. BC (2σ) and 4230-3970 cal. BC (2σ) (VERA-4457: 5170 ± 35 BP; VERA-4911: 5255 ± 40 BP; Töchterle, 2015). According to the assemblage with numerous fine-decorated potteries of the Polling group in today's South Bavaria, they confirm the first settlement activities on the Kiechlberg between the 5th and 4th mill. BC. More recent data (3020–2870 cal. BC (2σ), VERA-4455: 4300 ± 35 BP; 2470–2200 cal. BC (2σ), VERA-4454: 3875 ± 40 BP; 2200–1950 cal. BC (2σ), VERA-4458: 3680 ± 35 BP) originate from the upper layers, which represent the Copper Age and Early Bronze Age occupation but without chronological order. Especially in these upper layers slag and copper-rich semi-products are abundant. Metallurgical remains on the top of the hill only occur in Early Bronze Age context (1880-1620 cal. BC (2σ), VERA-4906: 3425 ± 40 BP). One bronze pin and a radiocarbon date (1630-1430 cal. BC (2σ), VERA-4907: 3260 ± 40 BP) of a posthole indicate the Middle Bronze Age as the final phase of the prehistoric presence. Metallurgical artefacts, such as copper ore fragments, copper slag, raw copper as well as finished copper- and bronze artefacts are concentrated mainly in Late Copper Age to Early and Middle Bronze Age layers (Töchterle, 2015; Krismer et al., 2010, 2012a). Within these artefacts slag-tempered ceramic fragments from the Early Bronze Age occur (Fig. 2). Often these fragments can be spotted due to their alteration to a green copper carbonate-hydroxide mineral, malachite. The small amount of slag and the presence of slagged and thermally altered ceramic fragments might indicate a small-scale workshop for copper production. Most probable sulfide-rich ores were smelted in crucibles in a hearth fire with blowpipes.

(2) St. Leonhard: On the south side of the Inn Valley near the hamlet of St. Leonhard a few bronze artefacts and pottery have been discovered on a field. Due to the high quantity of findings and to the fact that some of the artefacts show partial signs of the effects of fire, a Late Bronze Age burial site is suggested. Most of the bronze objects were identified as dress accessories, like belt hooks, arm-rings and some globe-headed pins. The finding of a tang knife represents typical Urnfield period burial equipment. Analysis of the pottery fragments suggests large wide-mouthed and round-bodied vessels (urns). All of the artefacts date to the Urnfield period around the 13th -12th century BC (Staudt et al., 2013). The cemetery is situated on the eastern part of the Schwaz-Brixlegg fahlore-group mineral mining district just 2 km (linear distance) north of the smelting site Mauk A (Krismer et al., 2012b, 2012d; Krismer et al., 2015). Because of small greenish spots observed on the surface of one of the pottery fragments it was assumed that some of the vessels could have been tempered with slag sand. Some pieces of slag are even visible with the naked eye due to their brown colour and/or alteration to malachite (Fig. 3). This is the first cemetery where slag sand-tempered ceramics has been observed in Tyrol so far. Late Bronze Age layers, which have been discovered nearby the church of St. Leonhard in the 1950´s could represent the corresponding settlement (Bachmann, 1956).

(3) Kundl-Wimpissinger: Just 4 km east of St. Leonhard in the gravel quarry Wimpissinger in Kundl, three thick cultural layers could be documented at the east slope. Below two layers of an Iron Age settlement, remains of a Late Bronze Age settlement and metallurgical activities were found during archaeological investigations in 1977 (Lang, 1998). Abundant metallurgical artefacts such as different pieces of slag (also plate slag), secondary copper minerals, crucible fragments, pieces of tuyères (from blowpipes and big tuyères) and slagged furnace clays were found in the Late Bronze Age layer (Staudt

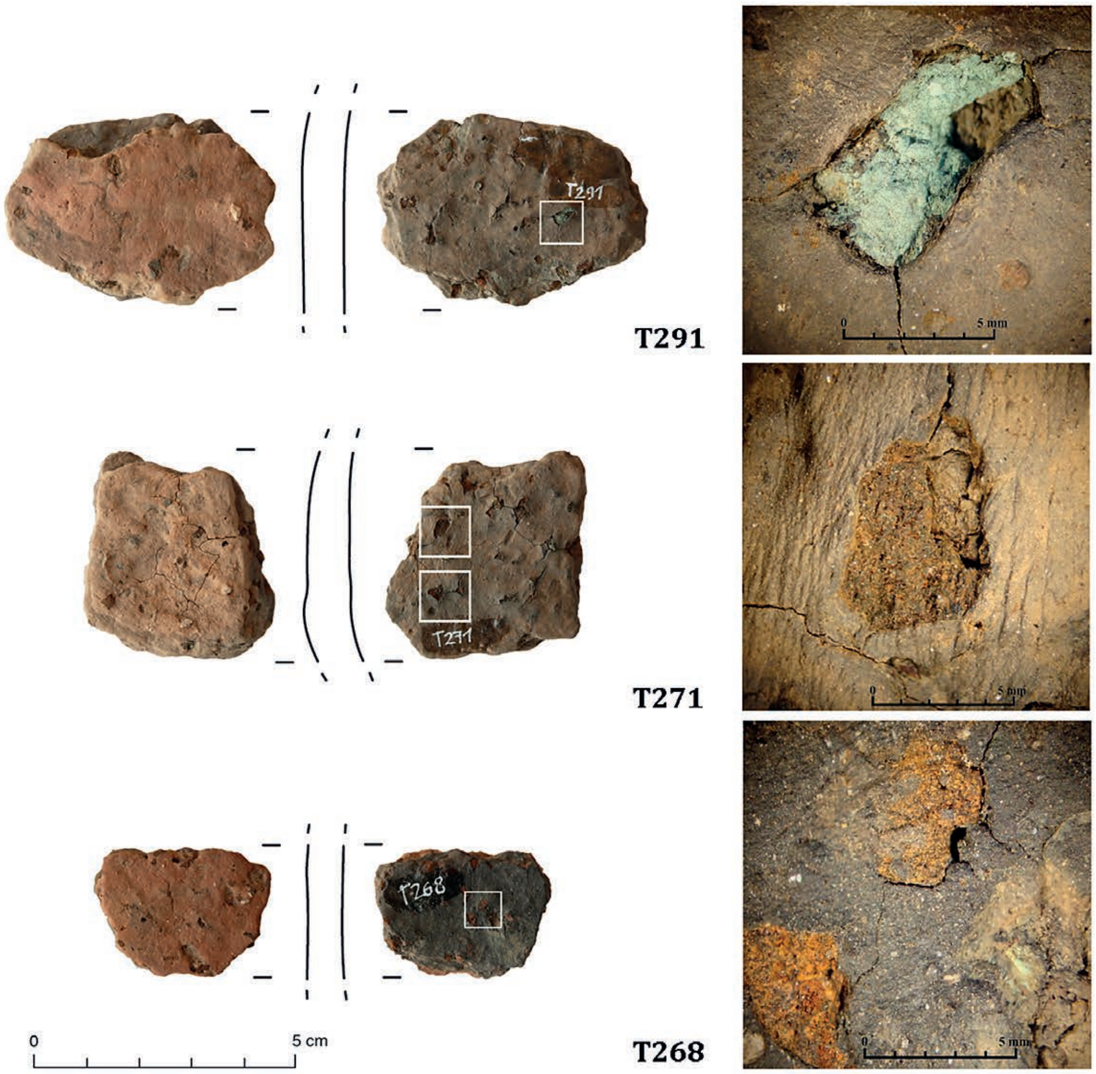

Fig. 2: Photographs of ceramic fragments from the Kiechlberg and the positions of slag temper fragments (left). Close-up of the slag fragments (right). In sample T291 the alteration of the slag fragment to the copper carbonate-hydroxide mineral malachite can be seen.

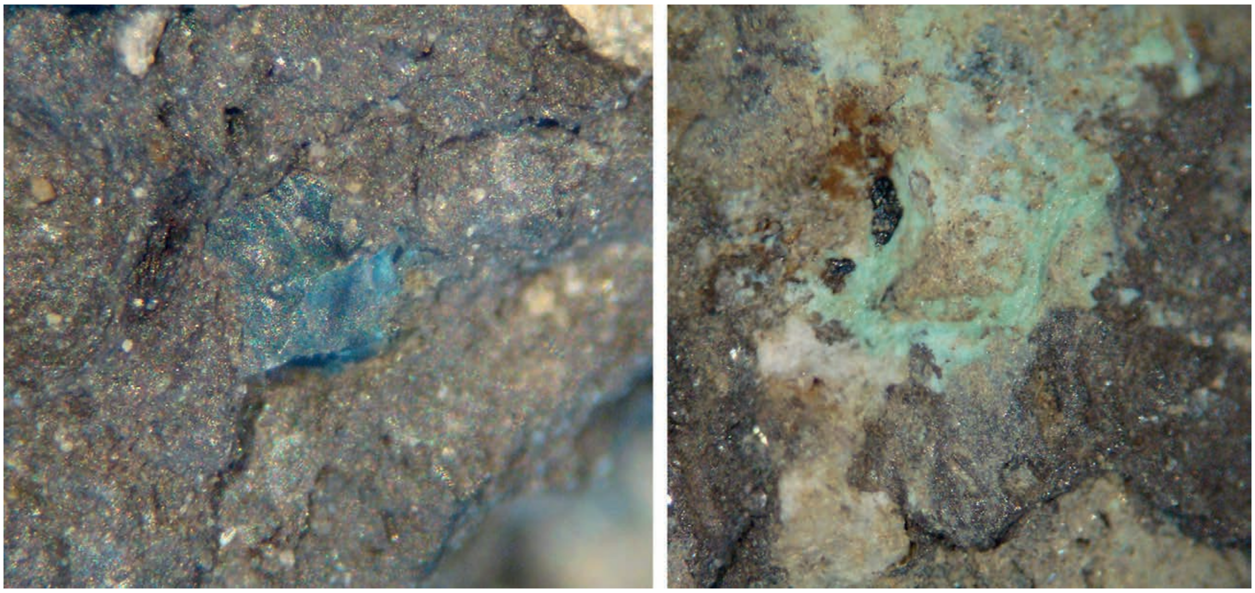

Fig. 3: Close-up photograph of slag-temper fragments visible on the surface of ceramic fragments (blue, left image and brown, right image, partly altered to green malachite) from the cemetery of St. Leonhard. The width of both images corresponds to approximately 1 cm.

Fig. 4: Photograph of a ceramic fragment with visible slag-temper fragments on the surface (dark aggregates indicated with black arrows) from Kundl-Wimpissinger (sample W1).

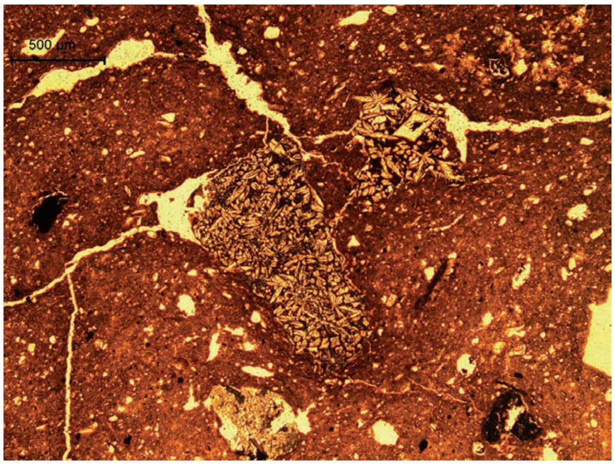

Fig. 5: Microphotograph of slag fragments showing aggregates of clinopyroxene crystals in sample T005-013 from the Kiechlberg.

& Tomedi, 2015). Further some constructions made of stone and reddened clay in combination with surrounding pieces of smelting slags were also documented and could represent remnants of smelting furnaces (Lang, 1998). The same Late Bronze Age settlement layer also was identified at the west slope profile of the gravel quarry (Weber, 2003; Patzelt & Weber, 2015; Tomedi, et al. 2013). The Bronze Age horizon is as far as 7 m below today's surface and approximately 5 m underneath the Iron Age layers. This demonstrates huge masse movements (land slides) already in prehistoric times and later on. During these investigations it was possible to recover two big storage vessels, which were filled with pieces of pottery, which contains tiny, dark slag fragments (Fig. 4), slagged furnace clay, secondary copper minerals and animal bones from the deepest layer in the steep slope of the quarry. Patzelt's five radiocarbon analyses of charcoal, taken from the Late Bronze Age layer and the storage vessels yield a time period from the 11th to the 9th century BC (Patzelt & Weber, 2015; Staudt & Tomedi, 2015). The collected samples present different pieces of slags and in some of the fragments pieces of dolomite were still visible. This could be a sign for a first smelting process, where remains of the ore-bearing host rock (dolomite) did not completely melt. These slags together with other findings of metallurgical activities (clay tuyères from small blow pipes as well as big bellows and small pieces of fahlore-group mineral ores) definitely document smelting activities in the settlement (Staudt & Tomedi, 2015). This is the first Late Bronze Age settlement where this kind of metallurgical activities (primary smelting) could be proven in North Tyrol. During the investigations at Kundl-Wimpissinger many slag-tempered ceramic fragments were documented in the Bronze Age layers. On one ceramic fragment (Nr. 3) from the underlying Iron Age cemetery in Kundl (Fig. 1) slag temper is visible (area 626, Nr. 1867, Lang, 1998). The piece of pottery was found together with a serpentine fibula with loop, which dates in the Hallstatt period (Ha D2, 6th century BC) and is so far the youngest known slag tempered pottery fragment in the Inn Valley. By looking at pictures from the excavation it is obvious that some of the graves were covered with smelting/ore preparation tools like grinding and anvil stones. It could be possible that some of the buried Early Iron Age people were miners too. Latest investigations by dendrochronology on some mines in the district Schwaz-Brixlegg prove the youngest exploitation activities till the end of the 8th century BC (youngest dated tree ring: 707 BC; Nicolussi & Pichler, 2013; Nicolussi et al., 2015).

Petrography of slag tempered ceramic fragments

(1) Kiechlberg: Petrographical and mineral-chemical investigations were made of the slag fragments contained in the ceramic material (Trauner, 2010; Doberer, 2014). The slag fragments show randomly oriented crystals and occur in a fine-grained reddish matrix (Fig. 5). As temper, rock fragments and crystal fragments dominate. The rock fragments show sizes of up to 500 µm and most of them are orthogneiss and quartzite fragments. In addition abundant recycled ceramic fragments also occur. The crystal fragments are mostly quartz, feldspar and mica and their size is below 50 µm. The slag assemblage is olivine + clinopyroxene (Fig. 6a) + spinel (magnetite) ± melilite (akermanite $Ca_2MgSi_2O_7$-gehlenite $Ca_2AlSiAlO_7$ solid solutions) + Cu-droplets + glass. The Cu-droplets often occur as tiny inclusions in clinopyroxene (Fig. 6b) are ca. 10-30 µm in size and show a chalcosine or digenite rim. Rarely Sb_2O_3 and Ag_2S occur.

(2) St. Leonhard: Mineralogical investigations of ceramic fragments confirm the first assumption that primarily slag fragments were used as temper (Krismer et al. 2012c;

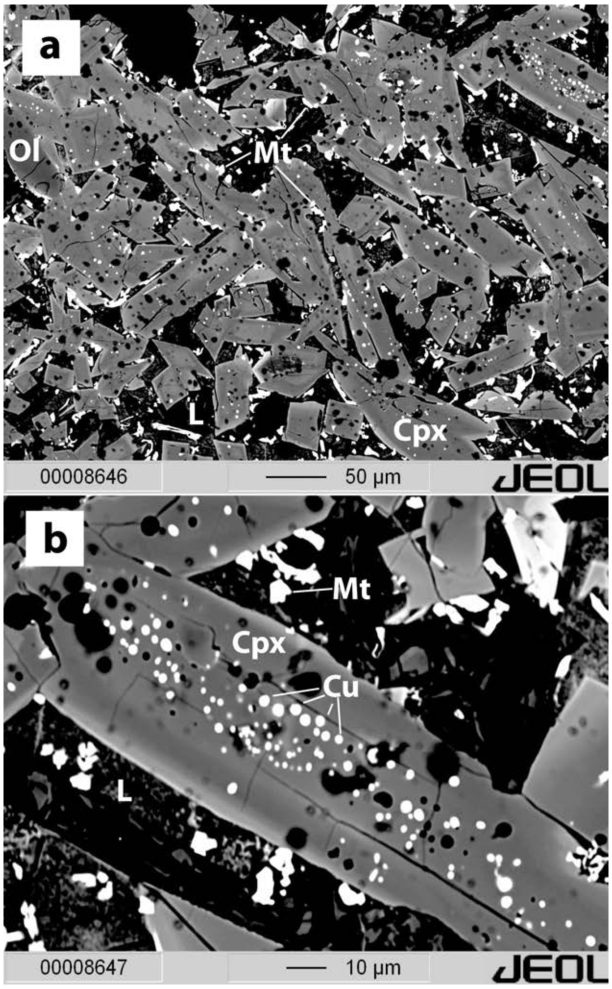

Fig. 6: Backscatter electron (BSE) images of a slag fragment from the Kiechlberg (sample T005-013). (a): overview of the mineral assemblage clinopyroxene (Cpx) + olivine (Ol) + magnetite (Mt) + glass (L). (b): close-up of a clinopyroxene (Cpx) crystal with abundant tiny Cu-inclusions.

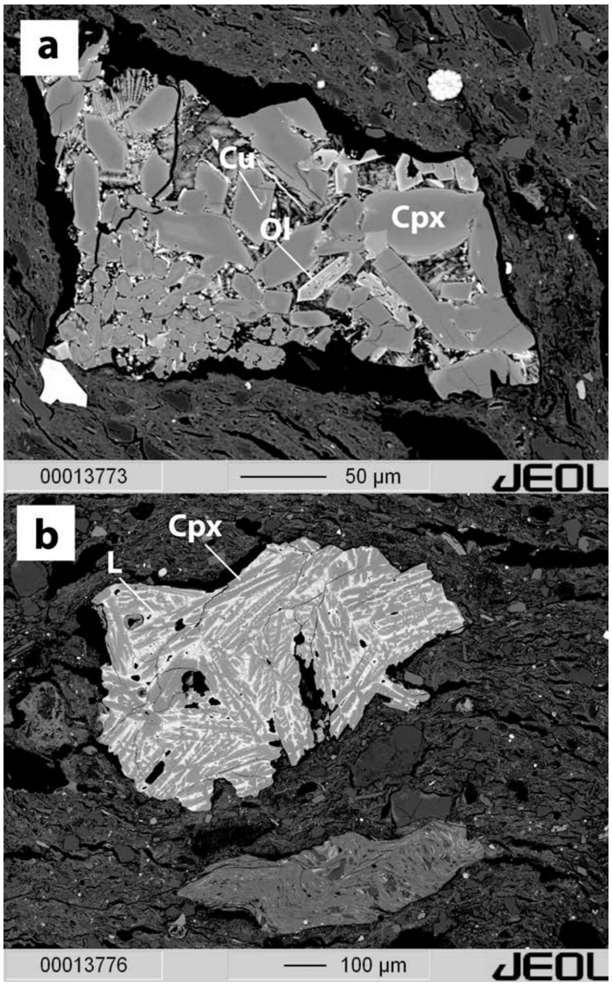

Fig. 7: Backscatter electron (BSE) images of slag fragments from the cemetery St. Leonhard (a: sample SL3; b: sample SL4). (a): slag fragment with the mineral assemblage clinopyroxene (Cpx) + olivine (Ol). Rarely clinopyroxene contains very tiny Cu-droplets (sample SL3). (b): slag-fragment with the mineral assemblage clinopyroxene (Cpx) + glass (L). Directly below a quartzphyllite temper fragment can be seen (sample SL4).

Krismer & Staudt, 2012). The coarser temper components consist mostly of two types of polycrystalline aggregates: slag fragments and rock fragments The size of these coarse temper fragments ranges from a few hundred up to thousands µm. Finer temper fragments with a size below 100 µm consist mostly of monomineralic quartz and feldspar fragments. The rock fragments consist of quartzphyllites with the mineral assemblage muscovite + chlorite + K-feldspar + albite + quartz + rutile + zircon (Fig. 7b). The slag temper has a characteristic chemical/mineralogical composition. Most slag fragments consist of minor skeletal crystals of olivine, and clinopyroxene (Fig. 7a), or only of clinopyroxene + glass (Fig. 7b). In addition to the silicate minerals, spinel (magnetite) also occurs. Rounded Cu-rich droplets occur in the slags. Close examination of the Cu-rich droplets yields a Cu-core and a rim of chalcosine (Cu_2S).

(3) Kundl-Wimpissinger: The slag fragments are clearly visible without a microscope and the size of the slag grains is sometimes up to 1 cm (Fig. 4). Nearly all of the recovered ceramic artefacts from the quarry Wimpissinger show slag (plate slag) as the main tempering material (Prader, 2013). For instance, in the pottery sample W1 sharp-edged homogeneous slag fragments of plate slag with iron silicate (fayalite) crystals and iron oxides in a glassy matrix are clearly visible. Subordinately rock fragments and crystal fragments occur as temper. The rock fragments are also quartzphyllites have a size of up to 500 µm and consist of the mineral assemblage muscovite + chlorite + K-feldspar + plagioclase + quartz + rutile + epidote + allanite. The crystal fragments (quartz, feldspar, mica) are much smaller and show a size of 10-50 µm. No specific orientation of the fragments was observed. The slag fragments show a size of 300 to 400 µm and

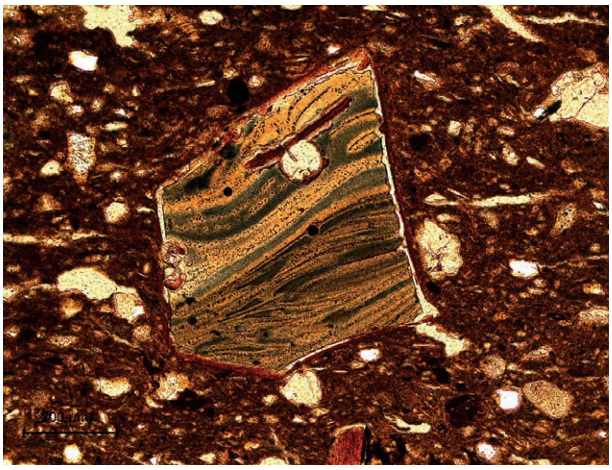

Fig. 8: Microphotograph of a slag fragment showing layers of glass with color ranging from dark grey to light brown in sample W-4 from Kundl-Wimpissinger.

consist mostly of glass, which shows a characteristic schlieren-texture with colours ranging from dark grey to light brown (Fig. 8). Only very few clinopyroxene crystals occur in the glass matrix (Fig. 9a). Within the glass small composite Cu-droplets with sizes between 5 and 30 µm occur. By using a larger magnification, copper droplets in the matte could be identified (Fig. 9b). The Cu-droplets are composite aggregates and contain Cu- and Sb-As-rich Cu intergrowth in the core and chalcosine (Cu_2S) at the rim.

Mineral chemistry of slag tempered ceramic fragments

For standard elemental analyses of sulfide, oxide and silicate the electron microprobe JEOL JXA 8100 SUPERPROBE with five WDS detectors and a Thermo Noran EDS system was used at the Institute of Mineralogy and Petrography of the University of Innsbruck. To cover the whole range of possible elements in the sulfides and sulfosalts, an analysis set-up with 21 elements (S, Cu, Fe, Zn, Hg, Mn, Mo, Cd, Ni, Pb, Co, Au, Ag, Ge, In, As, Sb, Bi, Se, Sn, Te) was developed. Oxide and silicate phases were measured by a routine including the elements O, Si, Mg, Fe, Mn, Cr, Ca, K, Na, Ba, Sr, Al, Ti, P, Zn, Cl, F, Sb, As, Cu, Ba and Zn. The analytic conditions were 15 kV acceleration voltage and 10 nA beam current.

(1) Kiechlberg: Extensive electron microprobe analysis was done on the olivines and they show a highly variable Fe content ranging between 5 and 48 wt.% FeO, which corresponds to 5-66% fayalite (Fe_2SiO_4) component (Trauner, 2010; Doberer, 2014). CaO contents range from 2 to 4 wt.% and ZnO contents are slightly higher with 2-8 wt.%. Olivines often occur chemically zoned with Zn-rich cores as shown in Fig. 10. For example olivin

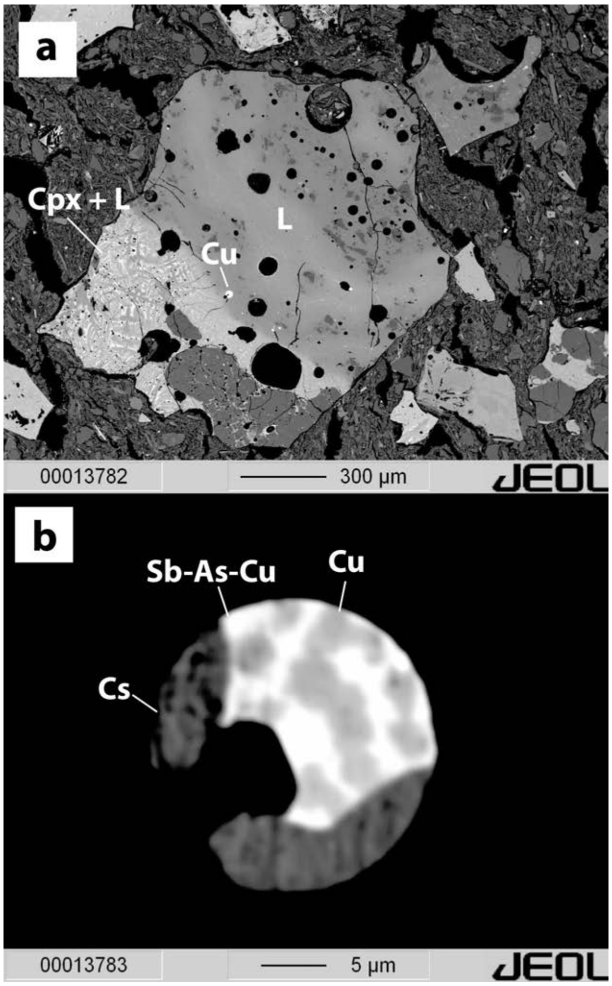

Fig. 9: Backscatter electron (BSE) images of a slag fragment from Kundl-Wimpissinger (sample W5). (a): slag fragment with the mineral assemblage clinopyroxene (Cpx) + glass (L). A small Cu-droplet is visible in the glass matrix. (b): close-up of the composite Cu-droplet showing a small-scale intergrowth between Cu and Sb-As-bearing Cu. The rim of the droplet is chalcosine (Cs).

composition from sample T268 changes from 6.31 wt.% FeO, 46.63 wt.% MgO, 3.97 wt.% CaO and 5.75 wt.% ZnO in the core to 18.67 wt.% FeO, 37.66 wt.% MgO, 4.11 wt.% CaO and 3.10 wt.% ZnO in the rim. This indicates a strong increase in the Fe component accompanied by a decrease in the Mg component and Zn component from core to rim.

Figure 10 clearly shows discontinuous chemical zoning with respect to ZnO, FeO and MgO (Doberer, 2014). This is indicative of a sequence of mineral reactions taking place during firing whereby a Zn-rich phase (e.g. fahlore-group minerals) breaks down in a first step and releases ZnO. It is also interesting that ZnO occurs in melilites with up to 13 wt.%. Most Cu-droplets show significant amounts of Sb and As and FeAsSb compounds sometimes occur. Most Cu-droplets contain 60 wt.% Cu, 30 wt.% Sb and ca. 10 wt.% As but in one sample a droplet with Cu and Sb contents of 48 wt.% and 4 wt.% As occurs. Although

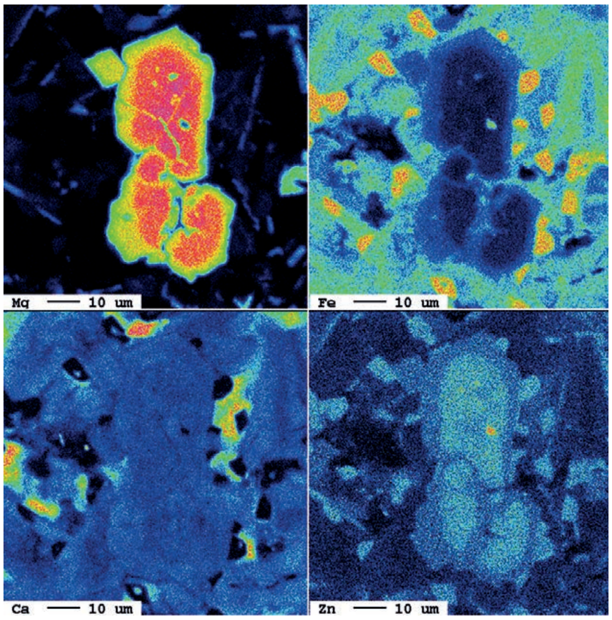

Fig. 10: Elemental distribution maps of MgO (upper left), FeO (upper right), CaO (lower left) and ZnO (lower right) of an olivine crystal from a slag fragment from sample T268 from the Kiechlberg. Note that almost no chemical zoning occurs in CaO.

the As contents are mostly below 10 wt.% one droplet contains up to 30 wt.% As!

(2) St. Leonhard: The chemical composition of the silicates is in the chemical system Ca-Fe-Mg-Si-O and the glass matrix contains in addition to these elements Zn, Al, Na and Ba contents (Krismer et al., 2012c). Zn also occurs up to a few wt.% ZnO in the silicate phases. The Cu-droplets show chemical compositions in the system Cu-Sb-As-S. Microprobe analysis yielded ca. 70-90 wt.% Cu and 10-30 wt.% Sb + As. Thus the metal/copper inclusions in the slag have a typical “fahlore-signature” containing antimony (Sb) and arsenic (As). The chemical composition and textures of the silicate phases are comparable to the Late Bronze Age copper slag’s from the close Mauk A site.

(3) Kundl-Wimpissinger: Chemically the slag shows variations in the SiO_2 content from 44 to 58 wt.% and elevated Mg- and Ca-contents of 6-10 wt.% MgO and 9-19 wt.% CaO (Prader, 2013). In addition, the glass contains little Al with contents of 3-4 wt.% Al_2O_3 and relatively low Fe contents of 9-17 wt.% FeO. A noticeable exception is the relatively high MnO content of 4-6 wt.%. The glass also contains up to 7 wt.% ZnO. The clinopyroxenes are diopside ($CaMgSi_2O_6$)-hedenbergite ($CaFeSi_2O_6$) solid solutions and contain no Al. The composition of the Cu-droplets is 70-98 wt.% Cu and <30 wt.% Sb, As and very little Ag. The Ag contents range up to 0.5 wt.% Ag. The As-content varies between 0.4 und 16 wt. % and the Sb-content varies between 0.1 und 19 wt.%. Low Fe-contents of 0.2 and 1.6 wt.% and Mn of 0.1 and 0,8 wt.% were also analysed. Trace contents of Pb, Bi and Co were also detected.

Discussion

Pernicka and Lutz (2015) show that at the beginning of the Early Bronze Age the fahlore copper of the Lower Inn Valley played a dominating role not only in this region but also in the northern foothills of the Eastern Alps and even further to the North. From the late Early Bronze Age on and during the Middle Bronze Age fahlore copper is replaced by the east Alpine copper of the Mitterberg type, produced mainly from chalcopyrite ores. Fahlore copper reappears in the Late Bronze Age and is then used parallel to east Alpine copper. In this period mixing of chalcopyrite copper and fahlore copper is also common (Pernicka & Lutz, 2015). Fahlore-group mineral deposits of the Lower Inn Valley in the Schwaz-Brixlegg area were primarily mined during the Early and Late Bronze Age, while during the late Early Bronze Age and the Middle Bronze Age chalcopyrite was preferred from Mitterberg district (Salzburg) (Höppner et al., 2005; Sperber, 2004; Stöllner et al., 2012; Hanning et al., 2015) or similar ore deposits (e. g. Kelchalm near Kitzbühel). In the Late Neolithic and Early Bronze Age copper ore smelting is evident only in settlements on a small scale. Although, extensive trade of copper from the Lower Inn Valley emerged in the Early Bronze Age (Ösenring copper), thus leading to an intensive exchange between the cultures and causing significant effects on the economic and social structures of the society.

The chemical composition of slag and raw metals found at the Kiechlberg site confirm Fe-Zn tetrahedrite-tennantite (fahlore-group mineral) smelting in the Early Bronze Age (Krismer et al., 2012e). The mineralogy and chemical composition of the slag-temper fragments also fit this observation very well. The slag temper also contains fine metallic inclusions with sizes of 10-30 µm, which are sulfidic Cu-Fe droplets with significant amounts of Sb and As as well as low amounts of Ag. Krismer et al. (2012e) concluded that smelting fahlore-group minerals results in impure Cu with a composition of 75-80% Cu + Ag and 25-20% Sb + As, which was observed in a sample. This chemical signature and the presence of ore fragments from the mining area of Brixlegg at the Kiechlberg site can be regarded as evidence for the smelting of fahlore-group minerals from the 30 km distant copper ore deposits of Schwaz/Brixlegg. Slag textures and mineralogy also indicate that the process was relatively reducing below the $2Sb + 1.5O_2 \rightarrow Sb_2O_3$ reaction producing Sb-rich (>10 wt.% Sb in metal) raw copper. The occurrence of Ca-rich slag phases such as minerals of the melilite group and significant Ca- and Mg-contents of the olivines indicate that dolomitic gangue was present during smelting, which fits the Brixlegg ore deposit (Arlt & Diamond, 1998; Krismer et al., 2011). In addition, inhomogeneous slag remains containing high amounts of sulfide- and metal inclusions suggest a poor separation of metal, matte (copper sulfide, chalcosine) and silicate/oxide melt during the smelting process. This indicates that for instance the reaction $Cu_2S + O_2 \rightarrow 2\ Cu + SO_2$ did not run to completion due to the presence of still abundant S_2. Similar conclusions can be drawn for the slag temper fragments from the Late Bronze Age sites St. Leonhard and Kundl-Wimpissinger. Textures, mineralogical and chemical composition of the slag-temper fragments from St. Leonhard fit the observations in the slags from the smelting site Mauk A very well. Except for the slag temper fragments from Kundl-Wimpissinger, the slag fragments most likely represent slag sand fragments.

These observations from the Late Bronze Age period support demographic studies of population development by Sperber (1992, 2004) based on investigations on the Late Bronze Age cemetery of Volders. He proposed that the increase and decrease of the population in the Late Bronze Age correlates with the fahlore-group mineral mining activities in the district Schwaz-Brixlegg. Based on different grave constructions as well as grave goods (black copper, slags and metalworking tools) from another Late Bronze Age cemetery in Fiecht-Au it is assumed that immigrants from the northern foothills of the Alps came to Tyrol for the reason of copper mining and metalworking (Sölder, 2015). The reason why the prehistoric people used slag tempered ceramic lies in the physical properties of these slag fragments. For ceramic objects associated with firing processes like tuyères and crucibles as well as cooking pottery it is best to use these already heat proof temper components. Since slag represents already a high temperature product it will not suffer again from shrinking during ceramic firing and thus its shape will not deform easily due to low expansion properties. This temper property will significantly reduce the danger of cracking during ceramic burning. In addition the sharp-edged shape of the crashed and grinded slag fragments has perfect binding properties with the fine-grained clay matrix. On the other hand the easy availability of these temper fragments from dumps of the smelting sites and their already homogenous size after grinding makes it also an attractive material as temper.

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Authors

Peter Tropper – Institute of Mineralogy and Petrography, University of Innsbruck
Markus Staudt – Institute of Archaeologies, University of Innsbruck
Ulrike Töchterle – Institute of Archaeologies, University of Innsbruck
Matthias Krismer – Institute of Mineralogy and Petrography, University of Innsbruck
Gert Goldenberg – Institute of Archaeologies, University of Innsbruck

Correspondence and material requests should be addressed to: peter.tropper@uibk.ac.at

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Erica Hanning

Slag heap quantification: re-evaluating the Mitterberg smelting sites

ABSTRACT: *The Mitterberg Mining District near St. Johann i. Pongau, Salzburg, Austria belongs to one of the most intensively investigated Bronze Age copper production landscapes in the eastern Alpine region. Starting 2006, a new series of prospection and excavation campaigns were initiated, which included, among others, a program of intensified prospection and sampling of the smelting sites.*

The combination of geomagnetic surveys, systematic coring and sampling of the slag heaps proved to be an effective way to quantify smelting sites, allowing the efficient investigation of a larger area and creating a more detailed view of a complex copper production landscape, without the need of a full excavation of the archaeological site. The study has also highlighted the importance of taking the depositional context into account, in order to gauge the amount of metallurgical debris actually present. When morphology and depositional characteristics of the slag heap were not taken into consideration, there can be a substantial overestimation of slag at the smelting site, which would in turn lead to a gross overestimation of the theoretical metal production output.

KEYWORDS: BRONZE AGE, METALLURGY, COPPER SMELTING, SLAG, GEOMAGNETIC PROSPECTION, MITTERBERG

Location and Dating of the Smelting Sites

The Mitterberg Mining District near St. Johann i. Pongau, Salzburg, Austria belongs to one of the most intensively investigated Bronze Age copper production landscapes in the eastern Alpine region. In 2006, the Deutsches Bergbau-Museum Bochum, in conjunction with the SFB HiMAT (History of Mining Activities in the Tyrol and adjacent areas, University of Innsbruck) initiated a new series of prospection and excavation campaigns in order to continue the over 180 years of archaeological investigation of the mining landscape (see Stöllner, 2009; 2015; Stöllner et al., 2011). As part of this work, a series of prospection campaigns were carried out in order to investigate the smelting sites, which are recognizable by their slag heaps and are scattered throughout the Mitterberg Mining District and its hinterland. Over 200 smelting sites are known from the literature (Zschocke & Preuschen, 1932; Preuschen & Pittioni, 1955, 1956; Pausweg, 1976; Krauß, 2004, 2001, 1991; Eibner, 1993; Günther et al., 1993; Günther, 2007, Neuniger et al., 1969) and prospection surveys in this greater area, 190 of which fall within the area mapped out by Zschocke and Preuschen in the early 20th century (Fig. 1, area outlined in grey). At least 45 of the known smelting sites have been classified in the literature as iron smelting, and belong to a later period of iron mining and production that began most likely during the Medieval Period[1]. The remaining sites are assumed to belong to prehistoric copper production.

The smelting sites are scattered throughout the landscape between the different ore veins, sometimes at great distance from the nearest known ore source, most likely in order to take advantage of the surrounding forests for the fuel-intensive smelting process. Moreover, they are almost always near a source of water, such as a stream or spring, often with several sites situated along a single watercourse (see for example Fig. 2, No 12, 13, 14, 15).

Especially during the Middle to Late Bronze Age, the layout and construction of the smelting sites, as well as the external appearance of the slags show a surprising level of conformity, pointing to certain amount of standardization of the sulfide copper smelting process across the eastern Alpine region. A “typical” Middle to

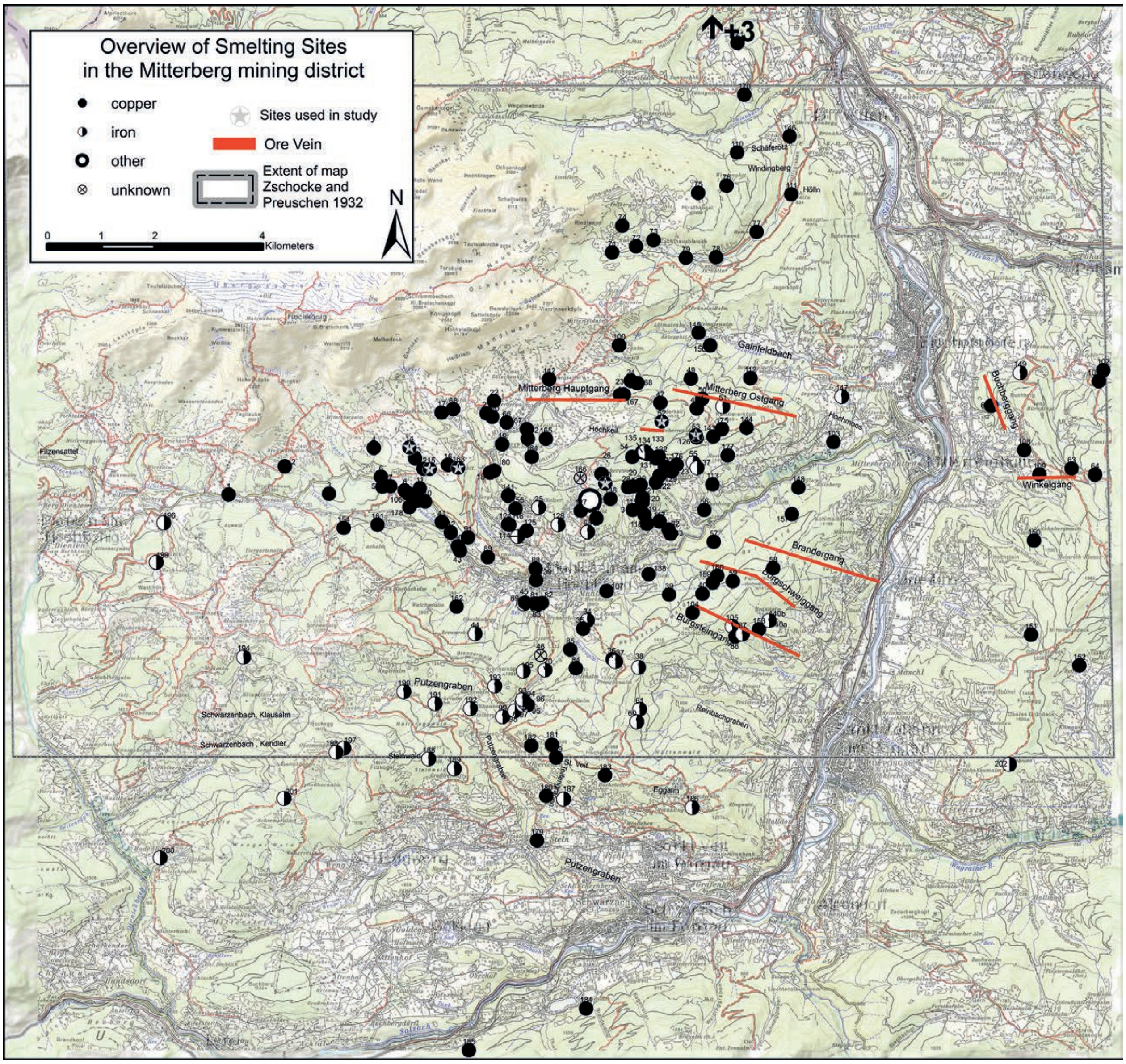

Fig 1: Overview of Mitterberg Mining District and surrounding regions. The area mapped out by Zschocke and Preuschen (1932) is outlined in grey (graphics: E. Hanning, DBM).

Late Bronze Age eastern Alpine smelting site is usually located near a source of water and is comprised of three general elements: roasting beds, furnaces and slag heaps. The roasting beds (Fig. 3a) were carefully leveled with a clay coated floor and often delimited by stones. The furnaces (Fig. 3b) were usually located below the roasting beds, often in pairs, or sometimes as batteries of several furnaces in a row. They were typically dug into the slope, with stone-and-clay walls on at least three sides, a low clay threshold is usually all that has been preserved of the front wall, which was presumably destroyed in order to extract the smelting products. Slag heaps were usually situated below the furnaces where the product of the smelt was separated and the waste (slag) was discarded.

To date, circa 20 smelting sites have been dated via ^{14}C. The majority of the ^{14}C dates fall into the Middle Bronze Age, with three outliers dating to the end of the Early Bronze Age and two into the Late Bronze Age (Fig. 4) (Stöllner, 2009; 2015; Stöllner et al., 2010; Pernicka, et al. 2016). Moreover, the smelting sites can also have several phases of use over a long time-span. For example, excavations at the smelting site “Brennerwald” (Fig. 2, No 162) revealed at least four different phases of furnaces, while the two radiocarbon dates from the site span roughly two centuries (Herdits, 1997, Herdits & Löcker, 2004); a similar spread of about 200 years can be seen from ^{14}C samples taken from different depths at Site 14 (Fig. 4, No 14), and those from Site 15 (Fig. 4, No 15). At this time, it is not known if smelting was continuous over several centuries

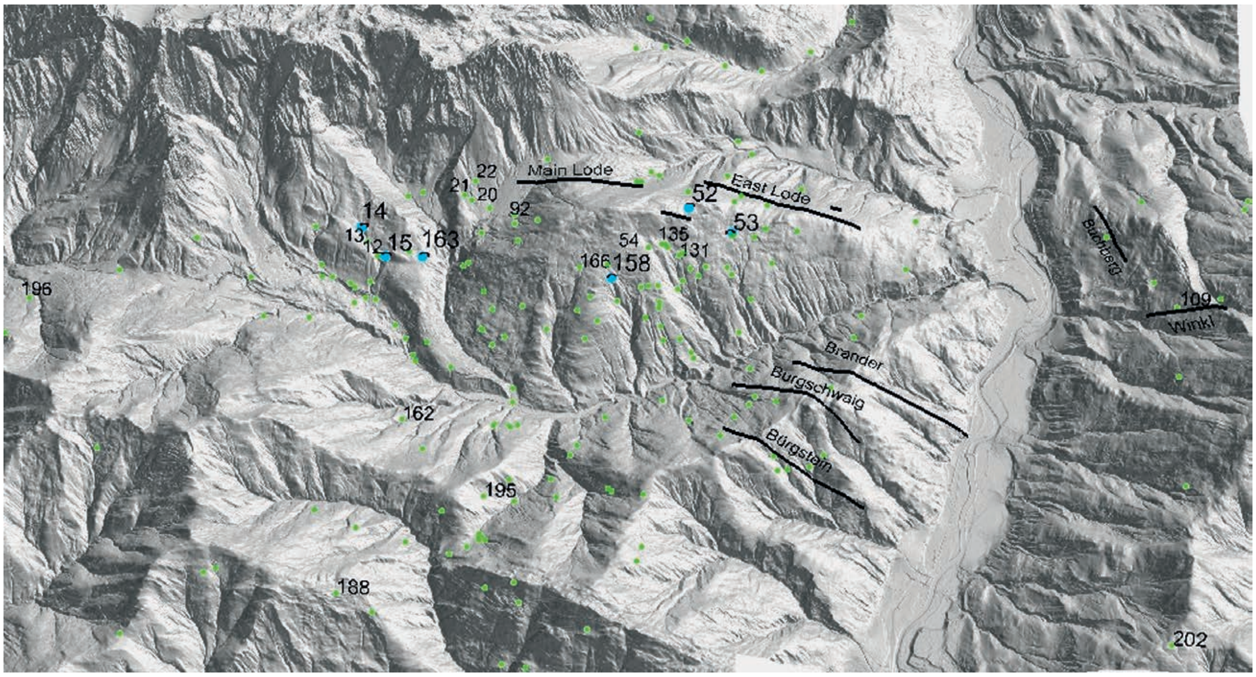

Fig 2: Close-up of the Main Lode area, with the position of the smelting sites and ore veins mentioned in the text (graphics: E. Hanning).

or if the sites went through cycles of abandonment und subsequent revitalization. However, the longevity of the smelting sites hints at a transference of knowledge over many generations - not only about the location of the site, but also the construction of the metallurgical installations and the operational sequence of smelting the ore (Stöllner et al., 2016, pp.80-83).

Intensive prospection of the smelting sites and calculation of slag heap volume

Between 2007 and 2009 (Stöllner et al., 2009; Hanning, 2013, DBM, 2015), four prospection campaigns were carried out where circa 30 smelting sites mentioned in the literature were relocated, while 6 previously unpublished sites were also recorded. 6 smelting sites (Fig. 1 and 2, No 14, 15, 52, 53, 158, 163) were then chosen around the area of the Main Lode for an intensified prospection program[2].

Calculation of the amount of slag can give information about the productivity of each individual site. Quantification can be done, for example, by extensive excavation of the site and by measuring all pieces of slag present (ex. Herdits, 1997, Klemm, 2015). This method is however, expensive, time consuming and leads to the ultimate destruction of the site. Other less or non-invasive methods that have been used on smelting sites include coring and/or subsampling via smaller sondages, GIS-based surface modeling, magnetometry and magnetic susceptibility surveys, induced polarization, electrical resistivity tomography and ground penetrating radar, and/or a combination thereof (ex. Rothenberg & Palmero, 1986; Perret & Serneels, 2009; Humphris & Carey 2016; Powell, et al 2002; Florsch, et al. 2011; Günther & Martin, 2016; Qi et al., 2018, Ullrich et al., 2007; 2015). Like the work carried out by Humphris and Carey (2016), a variety of methods including field surveys, geophysical prospection, coring and small sondages for sample collection were used in the current study to gain more information about the overall state of preservation, size and amount of slag present at the smelting sites.

Gradiometer survey

Although slag remains eroded out onto the surface point to the general location of the smelting sites, their full extent and location of the metallurgical installations (i.e. furnaces, roasting beds and slag heaps) is usually obscured by varying amount of sediment and flora. However, the strong magnetic anomalies created by the metallurgical remains make them ideal candidates for geomagnetic prospection: both the roasting beds and smelting furnaces are subjected to relatively high temperatures and the baked clay linings and/or natural clay of the soil surrounding the structures have acquired a high thermoremanent magnetization (TRM) during their firing. Likewise, other metallurgical material, in particular the slag, is also characterized by a higher magnetic susceptibility than its surroundings, which show up as positive magnetic anomalies on the gradiometer survey. All of the six smelting sites were measured using a single

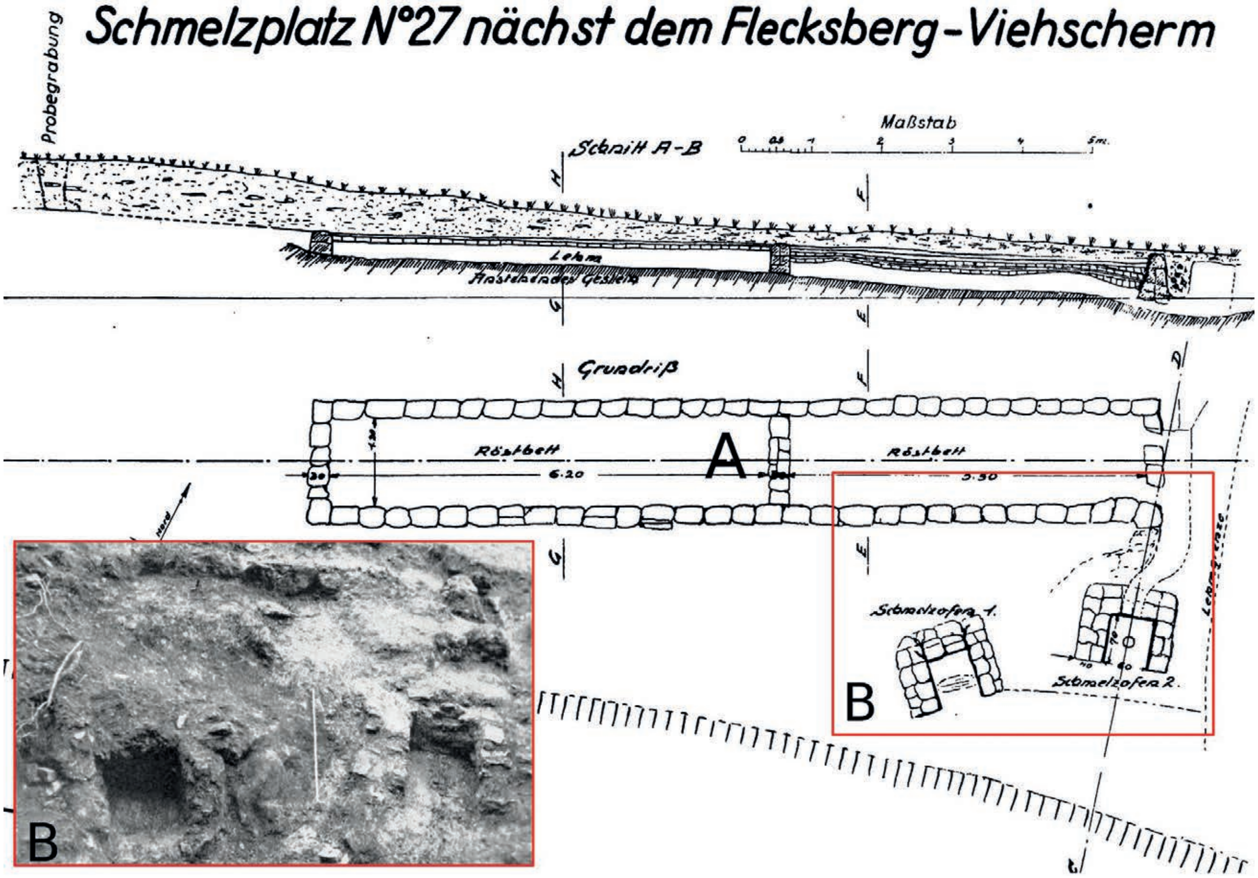

Fig 3: Drawing and photograph of a "typical" smelting site with roasting bed (A) and smelting furnaces (B and photo insert). Modified after Zschocke & Preuschen, 1932, pl. III and V.

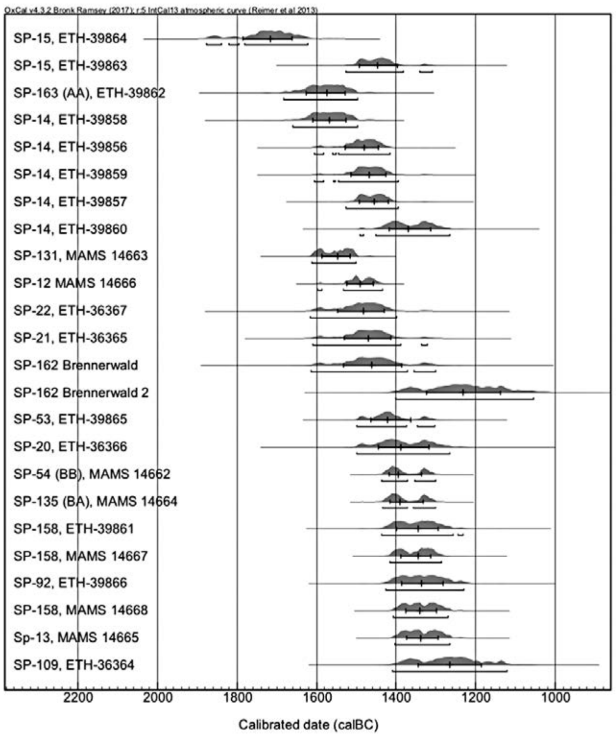

Fig 4: C^{14} dates from the smelting sites. Modified after Stöllner, 2009; Pernicka et al., 2016. Generated using OxCal v4.3.2.

channel handheld fluxgate gradiometer (B. Sikorski, B. Song, Ruhr Universität Bochum); additionally, one site (Fig. 3, No 52) was also remeasured using a 6-channel Foerster FEREX gradiometer mounted on a hand pulled cart (Eastern Atlas GmbH, B. Ullrich).

In many cases, it is possible to interpret the position of the roasting beds, furnaces and slag heaps from the geomagnetic anomalies (for example Smelting Site 52, Fig. 5 left). This is mainly due to the fact that many the Middle to Late Bronze Age smelting sites have an extremely similar organizational plan (see above). The long rectangular roasting beds present as a linear positive magnetic anomaly; the smelting furnaces were positioned just below these, usually grouped in pairs or several in a row, and appear as a series of round to ovoid magnetic anomalies; the slag heaps are located downslope from the furnaces, and – due to their heterogeneous composition – take the form of an irregularly shaped mass with a magnetic signature that varies greatly within the heap. In other cases, the overlapping of several different phases of furnaces and slag heaps, as well as destruction of the site through subsequent land use make it impossible to discern the position of the furnace batteries and roasting beds from the geomagnetic anomalies alone (Smelting Site 53, Fig. 5 right). In such cases, further investigation

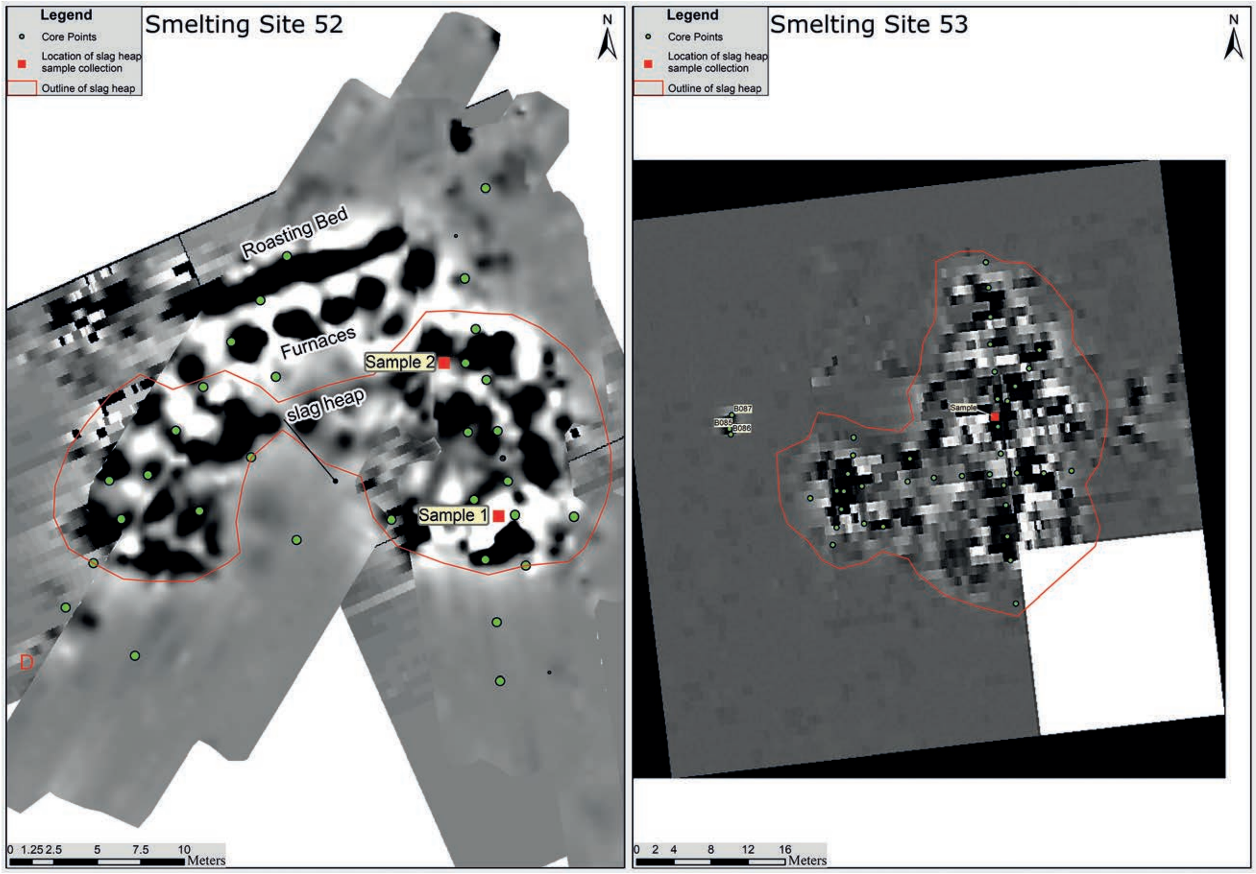

Fig 5: Two examples of geomagnetic surveys from the smelting sites. The position of the cores are marked in green, the circumferences of the slag heap are outlined in red and the location of the sample collection is marked with a square. Left: Smelting Site 52. The position of the roasting beds, furnaces and slag heaps can be clearly interpreted from the geomagnetic anomalies. Right: Smelting Site 53: overlapping of the different archaeological features makes it difficult to properly identify the metallurgical installations without further coring or sondages (graphics: E. Hanning, DBM).

in the form of coring or sondages are necessary in order to interpret the composition and function of the anomalies seen on the magnetogram.

Coring and calculation of the slag heap volume

Systematic coring was also done at the 6 sites in order to calculate the volume of the slag heaps, as well as to confirm the type and position of the pyrometallurgical installations interpreted from the geomagnetic surveys. Two types of corers were used: a hand driven slit corer (= Pürkhauer corer) and a motor driven percussion corer (= Cobra corer). The Pürkhauer corer has the advantage of being relatively light, easily taken into the field. The fine stratigraphy is also preserved without a large amount of compression of the individual layers. It does not do well, however, with coarse material such as large pieces of slag or stone, which are frequent in mining tips and slag heaps and inhibit the passage of the corer. For this reason, the larger Cobra corer was also used, which can literally punch through most material and retain coarse sediment in the sampling chamber. Using alternating Pürkhauer and Cobra coring points, it was possible to gain information about the coarse material in the slag dumps, while correcting the depth and position of the finer stratigraphy.

In this way, information about the depth and thickness of the archaeological layers could be obtained from the core profiles, while the boundaries of the slagheap could be interpreted by marking the edges of the strong magnetic anomalies created by the slag in the geomagnetic survey (Fig. 5, red outline). By combining this information - the circumference of the slagheap estimated from the magnetometer survey and its thickness from the core profiles - it was possible to give an approximation of the volume of the slag heap with minimal impact to the site. A 3-dimensional model was then generated using the x and y coordinates taken from the core positions and from points placed around the magnetic anomaly marking the position of the slag heap (Fig. 6). The z coordinates were calculated by taking the thickness

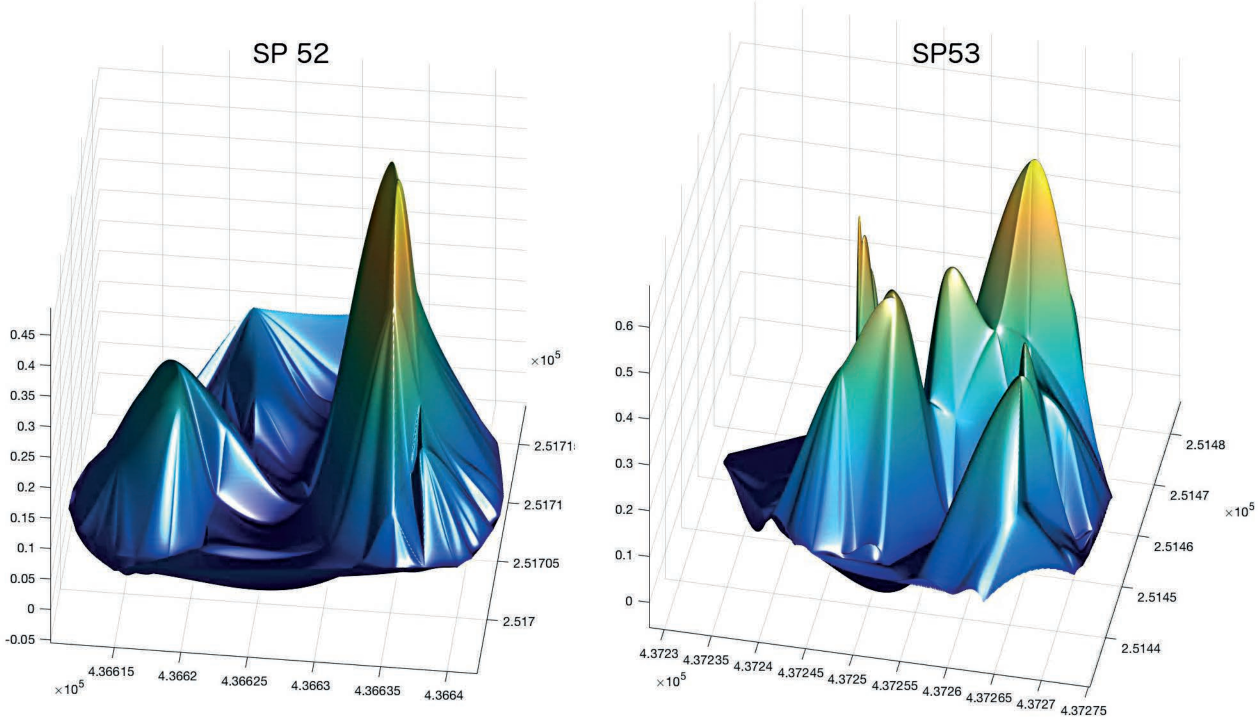

Fig 6: Examples of the 3-dimensional model of the slag heap used for the calculation of their volume. X and Y axes give the coordinates of the slag heap while the z axis presents its thickness in meters. The model is not a reconstruction of the actual 3D shape of the slag heap, but rather its thickness. The model was generated in MatLAB using a cubic interpolation (graphics: E. Hanning).

of the archaeological layers from the core profile. This does not, however, generate a model of the actual 3-dimensional shape of the slagheap, but is instead a model of its thickness. This was done due to the fact that at most points along the perimeter of the slagheap, (as seen by low or absent geomagnetic anomalies) do not have a depth – only an x and y coordinate taken from the magnetometer survey. Trying to recreate a 3D model of the true shape of the slagheap from this information would create a body in which the edges would be pulled unnaturally upwards towards the surface, skewing the model. When using the thickness instead of the actual depth of the archaeological layers, the points along the perimeter and outside the slagheap have a z-value of 0, and thus do not contribute to the volume calculation. The information was then graphed using a mesh plot in MatLAB with a bounding box sufficiently large enough to encompass the entire area. The surface between the points was interpolated using 4 different types of triangulation-based interpolation methods[3]; the resulting plots are comprised of a series of peaks and valleys which correspond to the thickness of the slag heap at a given x-y coordinate (Fig. 6). The area under the resulting mesh surface was then "filled" with virtual cubes measuring 5x5x5cm in order to estimate its volume and thus the volume of the slag heap. A table of the calculated surface areas and volumes can be seen in Table 1. As the different interpolation methods generated different mesh surfaces, the resulting calculated volumes also varied (between ca. 2-4m^3). As a result, an average of the four calculated volumes for each slagheap was also taken; the average value is given in Table 1, b.

Calculation of amount of slag and slag typology

However, due to the fact that the slag heap is composed of a mixture of slag, and non-slag material (such as stone, sediment, organics, ceramic, and water), estimation of the heap volume does not necessarily directly correspond to the amount of slag at the site. Thus, in order to gain a better estimate of the amount of slag in comparison to other material, a vertical sample was taken from the center of the dump, taking ca. 0.01m^3 of material for every 10cm of depth[4]. Each stratified 10cm sub-sample was placed in a separate sack and evaluated individually. The total volume[5] of the sample was recorded using the water displacement method and was then wet sieved using standardized mesh sizes ranging from 0.25mm up to 22.5mm. All pieces of slag above 22mm were individually recorded in a database, recording their characteristics such as external appearance, size, weight, density, porosity, number of original surfaces, type and size of inclusions, color, and magnetism (Fig. 7). For

Fig 7. Left: selection of slag pieces in the slag heap sample. Right: Section through a larger piece of slag. Unmelted pieces of ore and gangue material are clearly visible as white inclusions in the slag.

	A	B	C	D	E
Site	Slag Heap Surface Area m²	Slag Heap Volume m³	Average Slag Density t/m³	Packing Factor (Slag vs other Material)	Amount of Slag (B xC x D) tonne
14	507	40	2.61	0.31	32
15	424	53	2.91	0.47	72
52	310	38	2.87	0.44	48
53	845	140	2.3	0.66	213
158	330	74	2.21	0.45	74
163	441	79	2.68	0.51	108

Tab. 1: Estimation of the amount of slag present at the smelting sites.

	Slag vs Other Material from Slag Heap Sample (Vol %)			
Site	Water and Sediment <0,25 mm	Mixed Material >0,25 <2 mm	Non-Slag Components >2 mm	Slag >2 mm
14	35	18	16	31
15	18	28	7	47
52	15	21	20	44
53	15	10	9	66
158	6	35	14	45
163	17	18	14	51

Tab. 2: Slag vs. other Material in the slag heap samples, by Vol%.

the smaller sieve fractions, the slag was also sorted out by hand[6]; the weight and volume of the pieces of slag were recorded in bulk. Additionally, both XRD and XRF analysis (D. Kirchner, DBM) were done on powdered samples taken from the different sorted sieve fractions to give information of the bulk mineral and chemical content from the different sites.

The weight, volume and average density of the slag in the sample can then be used to estimate the amount of slag in that heap as a whole.

The determination of the amount of slag vs. other material is analogous to the "packing factor", found in an equation put forward by Bachmann (1982, p.5) for the calculation of the amount of slag found at a site: *Slag-covered area* x *depth* x *specific gravity of the slag*[7] x *packing factor* = *amount of slag* (*metric tons*). When the slag density and packing factor are unknown, Bachmann puts forward an average value of 3.5g/cm³ for the slag and a packing factor of 0.8 (i.e. 80% of the slag dump is comprised of slag). However, the average of the apparent particle densities[8] of the slag varied from 2.2 to 2.9 g cm³ (Tab. 1, C), much lower than the value put forward by Bachmann, mainly due to the bulk of the slag at the sites being quite porous.

This very detailed recording of the samples led to some interesting results. In particular, it becomes apparent that the slag heaps have a large quantity of non-slag components, including ground moisture, sediment, stones, and organic material. As a result, the packing factor (Tab. 1, D), which was calculated by taking the bulk volume of all slag above 2mm in diameter and dividing it by the total soil volume - i.e. the combined volume of the solids, liquids, pores and inter-particle voids present in the sample through the slag heap (for terminology, see Webb, 2001; Hanning, in prep.) - was also much lower than what was put forward by Bachman. This was due to the fact that non-slag components made up ca. 30 to 60 % of the volume of the samples, depending on the site (Tab. 2). The packing factors and estimation of the total amount slag at each site can be seen in Table 1, D.

Thus, the calculation of the amount of slag at each site is well below what it would have been when using the above-mentioned average density (3.5) and packing factor (0.8) put forward by Bachmann. For example, at smelting Site 15, only 47 vol% of the slag heap sample was comprised of slag, with an average density of 2.91 t/m^3. Using the information gained from the cores and geomagnetic surveys, the slag heap volume was calculated to be ca. 53 m^3. Thus, the calculated amount of slag at the site would be 72 tons. If the generic packing factor (0.8) and slag density (3.5) put forward by Bachmann are used, then there would be an estimated 148 tons of slag at the site - over twice the amount.

These numbers must of course also be viewed as an approximation, as the slag heaps are far from homogenous and some material would have been transported away from the site, either by erosion or subsequent use of the land for agriculture or other activities. Ideally the method should be double checked by fully excavating the site and weighing the full amount of slag and sediment present, which is not only extremely time consuming and labor intensive, but would also lead to the complete destruction of the archaeological deposit.

Estimation of copper production – possibilities and limitations

Previous estimations of prehistoric copper production in the Mitterberg area have been calculated using the theoretical amount of copper present in the exploited ore minus copper loss during mining, beneficiation and smelting (see Stöllner et al., 2011; Pernicka et al., 2016, 27), as well as trying to calculate the amount of metal produced via a copper:slag ratio (Kyrle, 1918, p.46-47). One of the motives for the estimation of the amount of slag found at each smelting site is in part to try to estimate the amount of metal being produced there through calculation of the copper to slag ratio. However, this is not as straight forward as it seems. The metal:slag ratio is dependent on several variables, including the composition of the charge, the operational sequence and efficiency of the smelting process. Kyrle's estimation of a slag to copper ratio of 4:1 (Kyrle, 1918, pp.46-47) should be met with some skepticism, as he estimated that one conglomerate of furnace slag equated to one plano-convex ingot, ignoring the theory that the process most likely had multiple steps, each producing a certain amount of waste product in the form of slag. From the archaeological remains, the use of a multi-step roast-reduction process can be surmised, though the exact allocation to a specific slag type to a specific step in the process has long been debated (ex. Eibner, 1982; Metten, 2003; Hanning et al., 2015, Silvestri et al., 2015; Zschocke & Preuschen, 1932, p.73-95; Czedik-Eysenberg, 1958; Preßlinger et al., 1988).

The use of a mass balance equation is one possible way to approximate the copper to slag ratio, and has been used for production estimations for both copper and iron metallurgy (ex. Kronz, 2000, Maldonado & Rehren, 2009). Based on the principle of mass conservation, a simple mass balance equation for a smelting process can be written as furnace charge + fuel ash + furnace clay = matte (and/or) metal + slag + unreacted furnace charge. However, the furnace charge would not have contained pure copper ore. It is known that the main copper-bearing ore in the Mitterberg area was chalcopyrite ($CuFeS_2$), associated with Pyrite (FeS_2) and a host of other accessory minerals in a gangue of quartz (SiO_2), dolomite ($CaMg(CO_3)_2$), siderite ($FeCO_3$) and ankerite ($Ca(Fe,Mg,Mn)(CO_3)_2$) (Pernicka et al., 2016, p.22; Günther et al., 1993 p.44; Weber et al., 1972). Analysis of slag pieces from the smelting sites often show slag conglomerates containing large pieces of partially melted gangue material (mainly quartz and Fe/Mg oxides) encapsulated in a fayalitic matrix (Fig. 7 right) (ex. Metten, 2003, p.77-81; Viertler, 2011; Zschocke & Preuschen, 1932). Evidence of large Bronze Age ore beneficiation sites in the Mitterberg area (Stöllner et al., 2010) point to an ore enrichment process that would have a positive effect on the metal to slag ratio. However, the smelting charge did not contain pure chalcopyrite - a host of associated minerals from the ore vein, as well as a certain amount gangue material from an incomplete separation of the ore was also intentionally or unintentionally introduced into the smelt. Silica-bearing minerals (such as quartz from the gangue) are an essential part of the smelting process as they are needed to remove the iron from smelt in the form of slag. Ash from the fuel, as well as parts of the furnace lining will also contribute to the smelting remains. Additionally, slag from previous smelts can be added to help recuperate copper loss and act as a flux (see Hanning et al., 2015; Herdits, 1997; Silvestri et al., 2015). For each step in the process, a new mass balance equation would have to be calculated, and the slag from all processes totalized. Mass balance calculations for the Mitterberg slag have not yet been carried out in detail and remain a desideratum for future work.

Maldonado and Rehren (2009) calculated the copper to slag ratio of about 1:3.75 for the copper smelting in Itziparátzico Mexico by assuming that the iron content of the slag originated almost exclusively from the chalcopyrite

($CuFeS_2$) in the ore (Maldonado & Rehren, 2009, pp.2004-2006). This is not completely viable for the Mitterberg ore due to the introduction of additional iron from pyrite (FeS) and siderite ($FeCO_3$) which are naturally associated with the ore and gangue (Weber et al., 1972, Pernicka et al., 2016; Günther et al., 1993, Günther, 2007).

Attempts have also been made to recreate the alpine copper smelting process through experimental archaeology (Hanning, in prep.; Herdits, 1997; Rose et al., 2018). Comparison of the experimental slag to the original can help by creating comparable slag where charge composition is known. However, it must be considered that the copper to slag ratio and metal output from such experiments is probably much worse than what an experienced smelter could produce. This is mainly due to the fact that the ore available today is usually of a much poorer quality and the process was most likely much less efficient due to lack of smelting experience on the part of the investigators running the experiments.

Another option is to look at written accounts of pre-industrial era copper smelting. However, emphasis is often put onto the description of the process and little empirical data is given to the amount of slag produced. One exception to this is a study on the traditional chalcopyrite smelting in a small-scale bowl-type furnace in Nepal (Anfinset, 2011). Although the process cannot be compared exactly to the Bronze Age smelting remains, it can give a point of comparison. The measured slag to copper ratio was quite high, ranging from1:15.2 to 1:10.1, depending on the smelt (Anfinset, 2011 p.58).

As can be seen the copper to slag ratio from the ethnographic account from Nepal is markedly higher than the theoretical calculations listed above. At the moment the spread between the lowest theoretical copper to slag ratio of ca. 1:4 and the highest known values from ethnographic examples of ca. 15:1 creates too great of a margin of error. For example, the calculated tonnage of slag at smelting site 14 was calculated to be 32 tons. This would equate to a copper output at the site between 8 tons (copper:slag ratio of 1:4) and 2.1 tons (copper:slag ration of 1:15) of metal depending on which copper to slag ratio is taken. Considering that the stratified radiocarbon dates for Site 14 span roughly 180 years, this would equate to only 44 to 11 kg of metal per season, if the site was actually used on a yearly basis. Combining the calculation from the 6 sites from the study equates to 547 tons of slag, which would be the equivalent of between 137 and 36 tons of copper, depending on the ratio used. Roughly 154 copper smelting sites are known form the greater Mitterberg mining area to date (DBM 2015; Hanning, in prep). Taking the mean volume of ca. 90 tons of slag from the 6 investigated sites and multiplying by 154 smelting sites gives a total of 13,860 t of slag, which could equate to between ca. 3,500 and 925 tons of copper metal produced at the known smelting sites. Zschocke and Preuschen calculated an output for the Mitterberg Main Lode ore vein to be ca 11,000 t (Zschocke & Preuschen, 1932, pp.100-103), while Stöllner et al. (2011, p.125) put the output for the Main Lode to be ca. 14,700, and a total prehistoric copper production of the Mitterberg mining district at 23,000 t. (Pernicka et al., 2016, 27).

The discrepancy in the numbers can be accounted for in several ways. First of all, one must consider that most likely not all of the copper smelting sites are known; even smelting sites documented in the 1930's are not always relocatable today due to destruction from subsequent land use (road building, etc.), erosion or reburial through natural sedimentation processes. Likewise, it is very likely that only a portion of the metallurgical debris is still in situ: there is considerable erosion on the steep alpine slopes, as well as deliberate extraction of material (for example for use as road fillers, or to even out the land for better pasturage) from the sites over the millenia have taken their toll. Furthermore, the above study has also shown that the investigated smelting sites have a large variability in both their size and amount of slag present; the amount of slag at the sites from this study can be seen as a conservative estimation, full excavation could lead to a larger volume of slag and thus a larger production output. Also, as stated above, the slag to copper ratio is at the moment not well known, which again brings error into such calculations.

Conclusion

The combination of geomagnetic surveys, systematic coring and sampling of the slag heaps has proved to be an effective way to quantify smelting sites, allowing the efficient investigation of a larger area and creating a more detailed view of a complex copper production landscape. The study has also highlighted the importance of taking the depositional context into account, in order to gauge the amount of metallurgical debris actually present at the site. When morphology and depositional characteristics of the slag heap were not taken into consideration, there was a substantial overestimation of slag at the smelting site. Moreover, before the hypothetical copper production at the sites can be calculated, more work has to be done on calculating a viable copper:slag ratio through further investigation of slag composition, mass balance calculations and experimental archaeological reconstructions.

Notes

1 The first written documentation of iron mining in Dienten am Hochkönig, just to the west of the Miterberger mining district, date to the second half of the 12th century AD (Günther & Krauß, 2004, 134). However, 5 iron smelting sites have been dated via ^{14}C analysis from the late Early Medieval to early High Medieval periods (Hanning, in prep. cat No 166; DBM 2015, cat. No 100; Krauß, 2004, pp.11-13).

2 The results of the survey are being studied as part of the author's PhD thesis (Hanning, in prep.).

3 The interpolation methods used were nearest neighbor, natural neighbor, linear and cubic. For documentation of Interpolate Scatted Data in MatLAB, see https://www.mathworks.com/help/matlab/ref/griddata.html and https://www.mathworks.com/help/matlab/math/interpolating- gridded-data.html.

4 Due to the problem that large pieces of slag and stone in the heaps made it impossible to create a straight-sided test pit through the slag heap, a test pit with a larger dimension as the sample was dug down, taking a 32x32cm sample every 10 cm of depth.

5 The total volume in this case refers to the combined volume of solids, closed pores, and inter-particle voids, which may contain air or water or both http://www.soilquality.org.au/factsheets/bulk-density-measurement

6 For sieve fraction below 8mm, a smaller representative sample was taken and the slag fragments were separated by hand. The mass fraction of slag in the representative sample was then used to estimate the total amount of slag in the sieve fraction. The presence of slag in the sieve fractions below 2 mm was checked using XRD analyses by looking for fayalite-like phases, which are almost always present in the Bronze Age copper slag from Mitterberg (ex. Viertler, 2011), but not present as naturally occurring mineral in the local rocks. Quantification of slag in the sieve fractions below 2 mm was not possible that this time. However, examination of a sample of the sieve fraction under the microscope showed that the slag particles did not make up a significant amount of the sediment and thus were not included in the calculations.

7 Bachmann mistakenly refers to the specific gravity of the slag, which is a ratio and is a unitless value. For the calculation of the weight of the slag present at the site, one needs to take into account the density of the slag, which is the amount of mass per volume.

8 Since most pieces of slag are of irregular shape and tend to have both open and closed pores, the apparent particle density of the slag was used – i.e. the dry weight of the piece of slag divided by the exterior volume, including pores (Webb, 2001 p.4). This was calculated using a variance of the standard test method for bulk density of refractory brick and insulating firebrick (ASTM C20-00, 2015).

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Author

Erica Hanning – Römisch-Germanisches Zentralmuseum, Mainz

Correspondence and material requests should be addressed to: hanning@rgzm.de

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Roland Haubner, Susanne Strobl, Peter Trebsche

Metallographic analyses from the late Urnfield period copper mining settlement at Prigglitz-Gasteil in Lower Austria

ABSTRACT: *The site of Prigglitz-Gasteil represents the largest Late Bronze Age mining settlement in Lower Austria, occupied from about 1050 to 900 BC. According to excavations from 1956 to 1958 and from 2010 to 2014, all metallurgical production steps, from copper ore to bronze, are attested at the site.*

Copper slag from an early production step is very inhomogeneous and contains large quartz inclusions. From the slag´s microstructure and composition a solidification temperature of approximately 1350 °C can be assumed. Black copper with a total sulphur content between 1 and 1.2 wt.% S consists of Cu and network-like arranged Cu_2S*.*

On the surface of a bronze slag a particle containing Sn and O was observed. From the slag composition a melting temperature between 1120 and 1090 °C is assumed. A corroded bronze droplet was investigated as well. The original microstructure of the metallic bronze is still visible in the corrosion products. Due to a special corrosion process about 25 wt.% Sn was observed in the corrosion products. With regard to other objects like casting molds it can be demonstrated that bronze casting took place at Prigglitz-Gasteil.

KEYWORDS: LATE BRONZE AGE; MINING SETTLEMENT; COPPER SLAG; BLACK COPPER; BRONZE SLAG; BRONZE DROPLET

Introduction

The Late Bronze Age mining settlement of Prigglitz-Gasteil is located at the easternmost fringe of the Alps in the district of Neunkirchen in Lower Austria (Fig. 1a). The site was occupied during the late Urnfield period (ca. 1050 to 900 BC). It reached a maximum extent of about 3 hectares, thus representing the largest mining settlement in Lower Austria (Trebsche, 2013; 2014a; 2015a; 2015b; Trebsche & Pucher, 2013; Haubner et al., 2015).

In contrast to the western parts of the Austrian Alps, prehistoric mining research in Lower Austria only started in the 1920s (Mühlhofer, 1935; 1952). The first direct evidence of prehistoric copper production was found in the 1950s by archaeologist Franz Hampl and geologist Robert Mayrhofer (Hampl, 1953; 1976; Hampl & Mayrhofer, 1958; 1963). The copper mining site of Prigglitz-Gasteil (Cu I) was discovered in 1955 (Fig. 1b). Hampl and Mayrhofer dug 15 narrow trenches there in 1956 and 1958. In 1959, they continued their excavation at the nearby copper smelting site of Prigglitz-Gasteil Cu II (Hampl & Mayrhofer, 1963, pp.74-75). Hampl distinguished the large mining settlement at site „Cu I“ and the small copper smelting site „Cu II“. If there is no precise indication, we use the name Prigglitz-Gasteil to refer to the site „Cu I“. Peter Trebsche resumed fieldwork at Prigglitz-Gasteil in 2010. Altogether, in five summer campaigns from 2010 to 2014, two areas of approximately 210 m^2 were excavated on two different terrain terraces that had not been studied previously (Fig. 1c). The excavations revealed that the occupation floors were extraordinarily well preserved. The annually published excavation reports are also available online (Trebsche, 2010-2014; https://uibk.academia.edu/Peter Trebsche).

Excavations at Prigglitz-Gasteil brought to light only a few chronologically significant small finds, so the absolute chronology of the site depends on radiocarbon dating. A small series of nine C^{14} samples showed that the final occupation phase lasted from the middle of the 11th to the end of the 10th century BC (Trebsche, 2015a).

Thanks to its outstanding state of preservation, the site of Prigglitz-Gasteil allows for a multi-faceted approach to copper mining, bronze working and its social aspects. Fortunately, the Late Bronze Age features have not been damaged by later mining activities. The excavations from 2010 to 2014 yielded abundant material for the study of miners' daily life and nutrition, for the reconstruction of dwellings and workshops, and for the spatial analysis of a mining settlement. They also provide completely new insights not only into metal production, but also into the

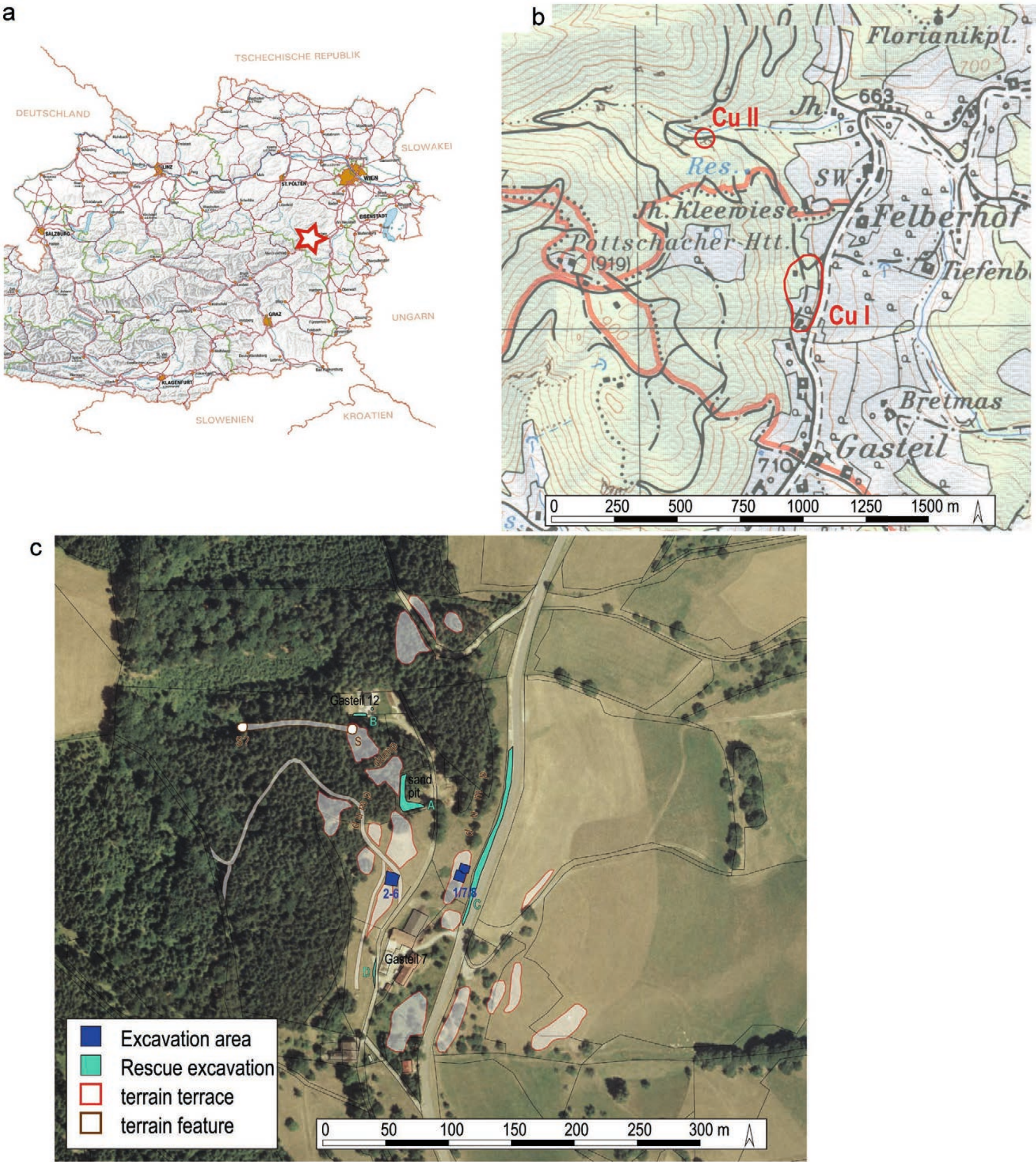

Fig. 1: Prigglitz-Gasteil (a) Location of the site in Austria; (b) topographic map of sites Cu I and Cu II in the cadastral area of Prigglitz; (c) plan of site Prigglitz-Gasteil Cu I.

operation and supply of a mine (butchering, manufacture of tools, timber procurement etc.). Archaeozoological analysis of the animal bones from the Prigglitz-Gasteil site shows striking parallels with pork processing at the contemporaneous Hallstatt salt mine (Trebsche & Pucher, 2013).

During the excavations, only indirect evidence for copper ore mining was found such as coarse dump layers and miners' tools (antler picks and hammers). The main local ores are chalcopyrite, pyrite and siderite. At present, it is unclear which mining technique (open cast mining, open-trench extraction or underground working) was employed at Prigglitz-Gasteil. Unfortunately, there are no terrain features such as pits or sunken shafts visible at the site. Although several prospection techniques have already been employed (archaeological field surveys, aerial photography, analysis of LiDAR terrain models, geomagnetic surveys), no direct traces

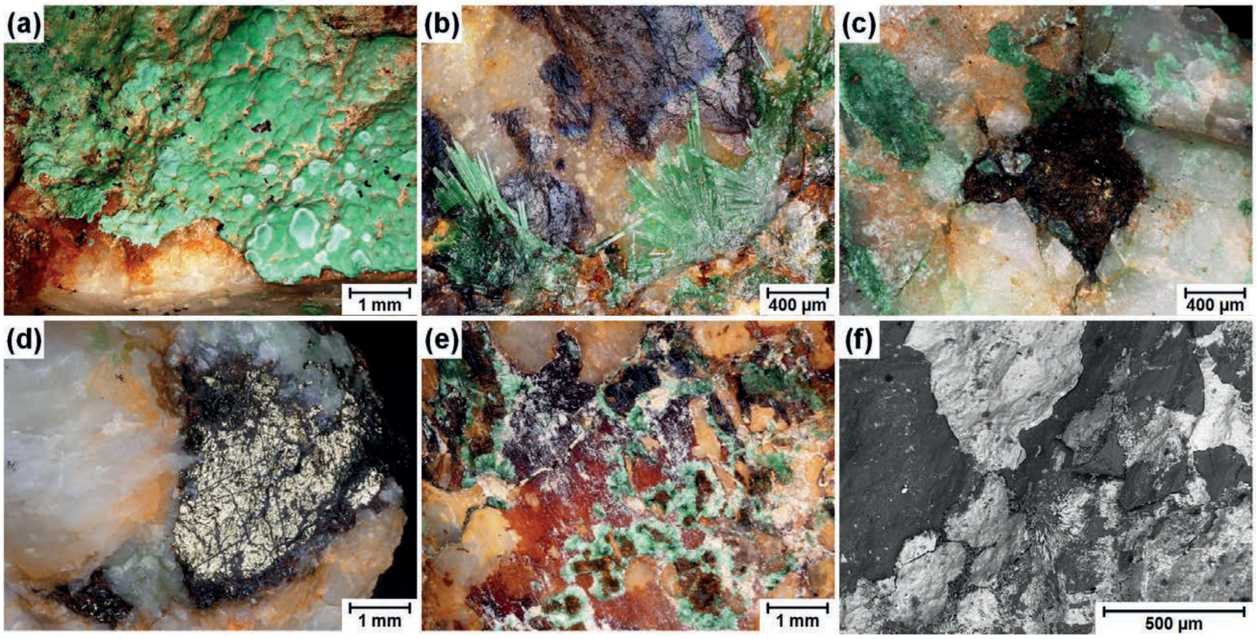

Fig. 2: Ore samples from Prigglitz-Gasteil Cu I in 3D-OM; (a) nodular malachite and quartz; (b) needle-like malachite; (c) limonite inclusion, (d) chalcopyrite in quartz; (e) mixture of malachite, cuprite and limonite; (f) SEM-BSE, cupreous regions are bright.

of copper mines were detected. In 2013 and 2014, 18 percussion drillings were conducted to a maximum depth of 10 m which was not enough to reach the underlying bedrock (Trebsche, 2014a; 2014b; 2014c). Therefore, geoelectric prospections and core drillings into greater depth should be conducted in the future in order to investigate the stratigraphy of the mining dumps and to localise the underground workings and the copper vein (in case there is some copper ore left).

Considering the extraordinary size (3 ha) of the copper production site at Prigglitz-Gasteil, it seems possible that not only local ores were processed. To test this hypothesis, several surveys of copper ore deposits in the region (district of Neunkirchen) have been conducted by Michael Götzinger (Institute of Mineralogy, University of Vienna) and Uwe Kolitsch (Mineralogical Department, Museum of Natural History of Vienna) since 2012, supported by local mineral collectors (Niedermayr et al., 2014, pp.121-124).

Following copper ore extraction, the next steps in the chaîne opératoire are ore beneficiation, smelting, alloying and casting of bronze objects. All these steps are attested at the site of Prigglitz-Gasteil, with more than 146 copper or bronze fragments, droplets and intact bronze artefacts as well as approximately 400 pieces of different slag types. However, these finds cannot be interpreted by macroscopical investigation alone but require archaeometallurgical analyses. Considering the great number of metallurgical finds, archaeometallurgical analyses are planned in three steps: The first step aims to investigate from which stage of the copper production process these remains originate (Eibner, 1992). The second step is to characterize the local copper ores and ore specimens from neighbouring deposits with the aid of trace elements and lead isotopes. This should provide the basis for identifying products of the Prigglitz-Gasteil copper mine in regional or supra-regional contexts. The third step is to investigate local bronze working techniques using metallographic analyses.

In this paper, the results of four metallographic analyses will be presented. These samples were chosen from different find categories and allow for a preliminary orientation. In the future, a representative number of samples will be selected to further investigate each copper production step at the site of Prigglitz-Gasteil.

Archaeological context of the analysed samples

One piece of coarse slag (no. 1, inventory number UF-11901, Fig. 3) was selected for archaeometallurgical analysis from the site Prigglitz-Gasteil Cu II. This site probably represents a small smelting site contemporaneous with the large mining settlement at site Cu I. It is located approximately 700 m northwest of the site Cu I in the so-called Klausgraben (Fig. 1b) and was investigated in 1959 by Franz Hampl (Hampl & Mayrhofer, 1963, pp.74-75).

The piece of black copper (no. 2, Fig. 4) was found by Reinhard Lang near the farmstead Gruber in the area of the site Prigglitz-Gasteil Cu I in the years 2000–2010. Lacking a stratigraphic context, this surface find cannot be dated with absolute certainty, but most probably it originates from the Late Bronze Age as the vast majority of finds from the site does.

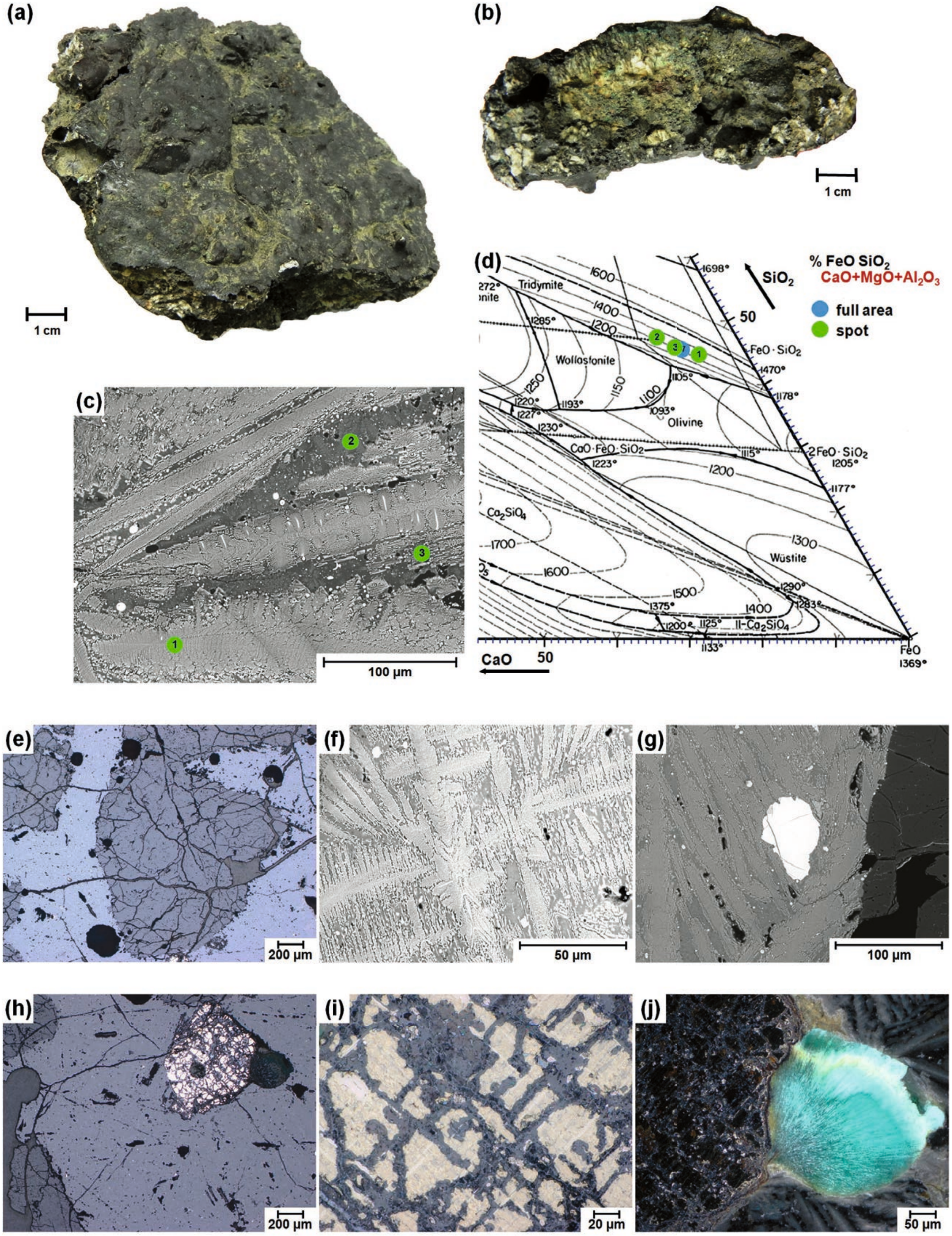

Fig. 3: Slag sample from Prigglitz-Gasteil Cu II; (a) front view and (b) side view; (c) SEM image of the slag with marked spots for the EDX analysis; (d) FeO-SiO_2-CaO(MgO-Al_2O_3) phase diagram showing the elemental composition of the EDX measurements shown in (c); (e) LOM image showing the distribution of darker quartz and brighter slag; (f) dendritic slag microstructure in SEM; (g) chalcopyrite inclusion in the slag (SEM); (h-j) copper and cupreous inclusions (LOM).

The fragment of a platy slag (no. 3; inventory number UF-22692.1896. Fig. 5) and a bronze droplet (no. 4; inventory number UF-22692.1778, Fig. 6) also come from site Prigglitz-Gasteil Cu I. They were found during the 2013 excavation campaign and belong to stratigraphic unit 916 in excavation area 6 located on the upper terrain terrace. The stratigraphy of the upper terrain terrace can be divided into four phases: in the first phase, fine-grained dump layers indicate the beneficiation of copper ores; during the second phase, these dumps were levelled horizontally to construct a working platform or terrace. Several hearths and postholes were documented on this terrace which was covered by a sequence of different layers. The older layers in this sequence provide evidence for copper or bronze metallurgy, including the fragment of a stone casting mould for a bronze knife (see Trebsche, 2015a, pp.49, fig. 2/7). Copper based artefacts and platy slags concentrated mainly in a greyish layer with lots of charcoal (stratigraphic unit 916) from where the two mentioned samples were selected. Later, the use of this working terrace changed and large amounts of animal bones were deposited. The whole sequence comprised at least 23 charcoal layers indicating (local) fire events. In the following third phase, fine-grained material from ore beneficiation was dumped again covering the mentioned terrace. After that, a cultural layer with postholes belongs to the fourth phase. A layer of coarse dump material was deposited onto the cultural layer. Finally, in the fifth phase, a working pit was dug into the terrace. While the first four phases can be dated to the late Urnfield period by radiocarbon samples, the fifth and last phase belongs to the medieval period (Trebsche, 2015a, pp.48-51).

Archaeometallurgical analyses

Copper ore samples, slags and metallic copper alloys were analysed by metallographic methods.

For metallographic investigations the different samples were cut and vacuum infiltrated with epoxy resin. After plane grinding, the samples were fine grinded and polished using 9, 3 and 1 µm diamond suspensions. The prepared samples were finally examined by an inverse light optical microscope (LOM).

Further investigations of original and polished samples were carried out with a FEI QUANTA 200 K scanning electron microscope (SEM) which was equipped with an energy dispersive X-ray detector (EDX). For SEM images, only the back scattered electron mode (BSE) was used. A digital 3D optical microscope (Keyence, 3D-OM) was used to investigate the sample´s surface.

Copper ores

During the excavation campaign in 2014, several ore samples were collected by Roland Haubner from the excavated material. At first, the surfaces of the samples were investigated by 3D-OM and afterwards samples were crushed to sizes which were acceptable for the SEM-EDX analysis.

The images in Fig. 2 reveal different copper ores. Generally, the gangue associated with the copper ores in the investigated samples was quartz. In some areas the quartz is covered by nodular malachite (Fig. 2a). In voids the malachite forms needle-like crystals (Fig. 2b). Due to long-time storage of the samples in the mine dump, original ore and oxidized material are mixed. In Fig. 2c a limonite inclusion and in Fig. 2d a chalcopyrite ore inclusion can be seen. A mixture of malachite, cuprite and some limonite is shown in Fig. 2e. Using SEM-EDX in backscattered mode, the cupreous regions are bright in contrast to the darker quartz. Additionally, other minerals such as pyrite, oxidized pyrite (limonite), titanite ($CaTiO_3$) and cinnabarite (HgS) were locally observed. Similar results were described by Michael Götzinger and Uwe Kolitsch (cf. Niedermayr et al., 2014, pp.121-124).

Slag lump from copper smelting (no. 1)

The surface of the slag in Fig. 3a has a comparatively homogeneous appearance but the side view shows a mixture of slag and quartz (Fig. 3b). The quartz particles reach a dimension of several mm. After metallographic preparation, the darker quartz is clearly distinguishable from the brighter slag (Fig. 3e). In LOM many cracks are observed in the quartz and some cavities in the slag. We assume that this piece of slag was formed when molten slag was removed from the furnace and accidentally came into contact with quartz sand outside the furnace. In this case, the quartz cannot be related to the copper ore which was filled into the furnace. This is plausible, because XRD analysis showed no cristobalite which should be formed during the high-temperature treatment in the furnace. Additionally the microstructure show no distinct reaction zones between quartz and slag. The slag´s microstructure consists of fine dendrites and the interdendritic space is filled with a glass phase (Fig. 3f). To get information about the melting temperatures of the slag local SEM-EDX measurements are necessary (Haubner et al., 2017; Haubner & Strobl, 2017). Thus, the full area of Fig. 3c and several spots were measured and the calculated results were plotted in the conventional FeO-SiO_2-CaO phase diagram (Fig. 3d), note that for the calculation MgO and Al_2O_3 were added to CaO (Haubner, Strobl and Klemm, 2017). For comparison all EDX results of the discussed copper slag and a bronze slag, which will be described later, are summarized in Table 1. The full area and the single spots are located in the tridymite and FeO-SiO_2 region. Melting temperatures above 1200 °C are realistic for this slag. The brighter dendritic material (spot 1) shows the stoichiometry of $FeSiO_3$ containing some impurities. In the phase diagram this spot is located right from the full area spot. Spot 2 was measured in the

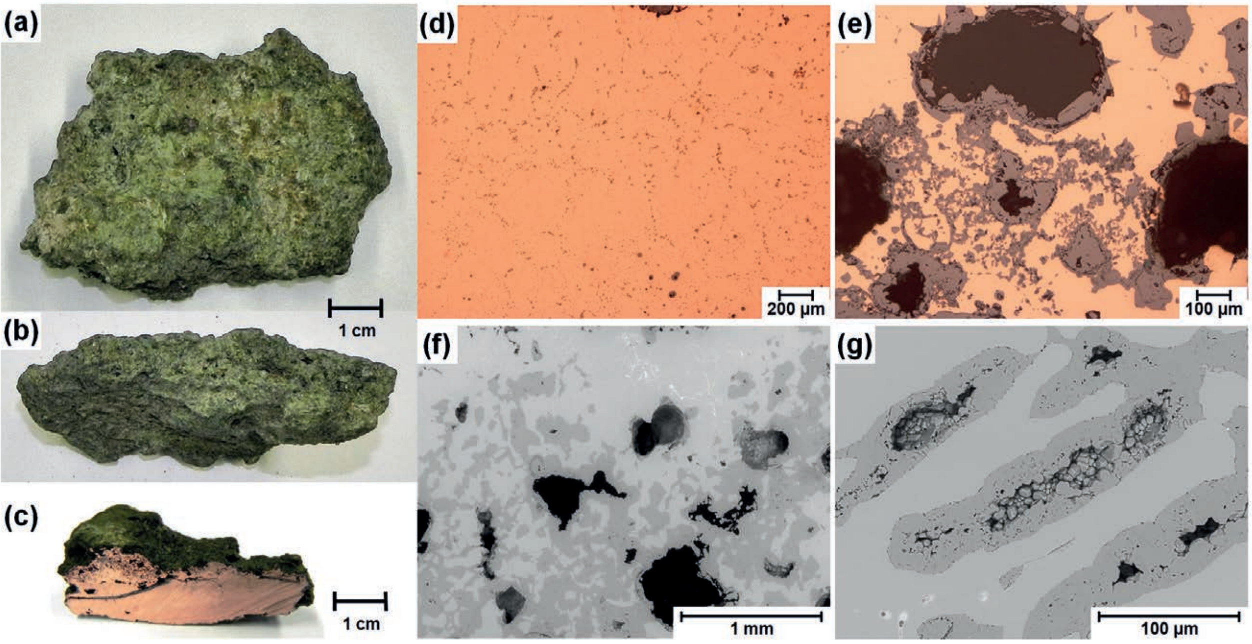

Fig. 4: Black copper lump Prigglitz Gasteil Cu I; (a) front view; (b) side view; (c) cross section; (d) homogeneous copper with Cu_2S inclusions (LOM); (e) inhomogeneous region containing holes, sulfides and oxides (LOM); (f, g) SEM images showing the inclusions in metallic copper.

Mas. %	slag from copper smelting					slag from bronze production			
	area	spot 1	spot 2	spot 3		area	spot 1	spot 2	spot 3
Fe	38,9	41,9	35,3	37,7		40,7	46,6	36,9	38,2
Si	23	22,8	24	23,1		17,1	16,1	18,5	17,2
Ca	2,3	--	4	3,3		4,5	2,6	5,8	5,4
Mg	1,3	2,3	--	0,8		1,2	3,1	--	--
Al	2	1,8	2,9	2,3		2,8	--	3,3	3,3
Mn	--	--	--	0,8		--	--	--	--
K	1,1	1,4	1,3	1		1,4	--	1,7	1,9
S	0,6	0,3	0,9	0,6		0,8	--	--	--
O	29,5	29,4	31,6	30,3		28,1	27,9	30,1	28,8

Tab. 1: Original EDX results from area and spot measurements of slag samples.

darker glass phase area and contains higher amounts of CaO and Al_2O_3. This spot is located left of the full area spot. As assumed, spot 3 is located between spot 1and 2 and the elemental composition is near the full area spot.

The composition $FeSiO_3$ suggests the presence of pyroxene crystals, but it was not possible to identify this phase by crystallographic methods. During solidification the crystallization of fayalite (Fe_2SiO_4) and additional quartz is assumed. From the phase diagram a slightly higher solidification temperature (about 1350 °C) for the FeO-SiO_2 mixture can be assumed compared with the glass phase solidification temperature (about 1320 °C).

In the slag some copper and cupreous inclusions were observed (Fig. 3g) and a large bright particle was identified as chalcopyrite. Other inclusions are partly reduced to copper and contain mixtures of metallic copper and chalcopyrite (Fig. 3h, i). During long-time storage of the slag in the dump, malachite had been formed in some areas by oxidation (Fig. 3j).

Black copper after smelting (no. 2)

We assumed that the lump shown in Fig. 4a, b (front and side view) contains metallic copper due to its relatively high weight of 274 g. After sectioning the lump it was identified as metallic copper (Fig. 4c). The lower part has a homogeneous appearance but at the left side there is a crack and the material at the top appears porous and inhomogeneous.

The homogeneous copper shown in Fig. 4d contains fine, network-like arranged, scarlet inclusions which were

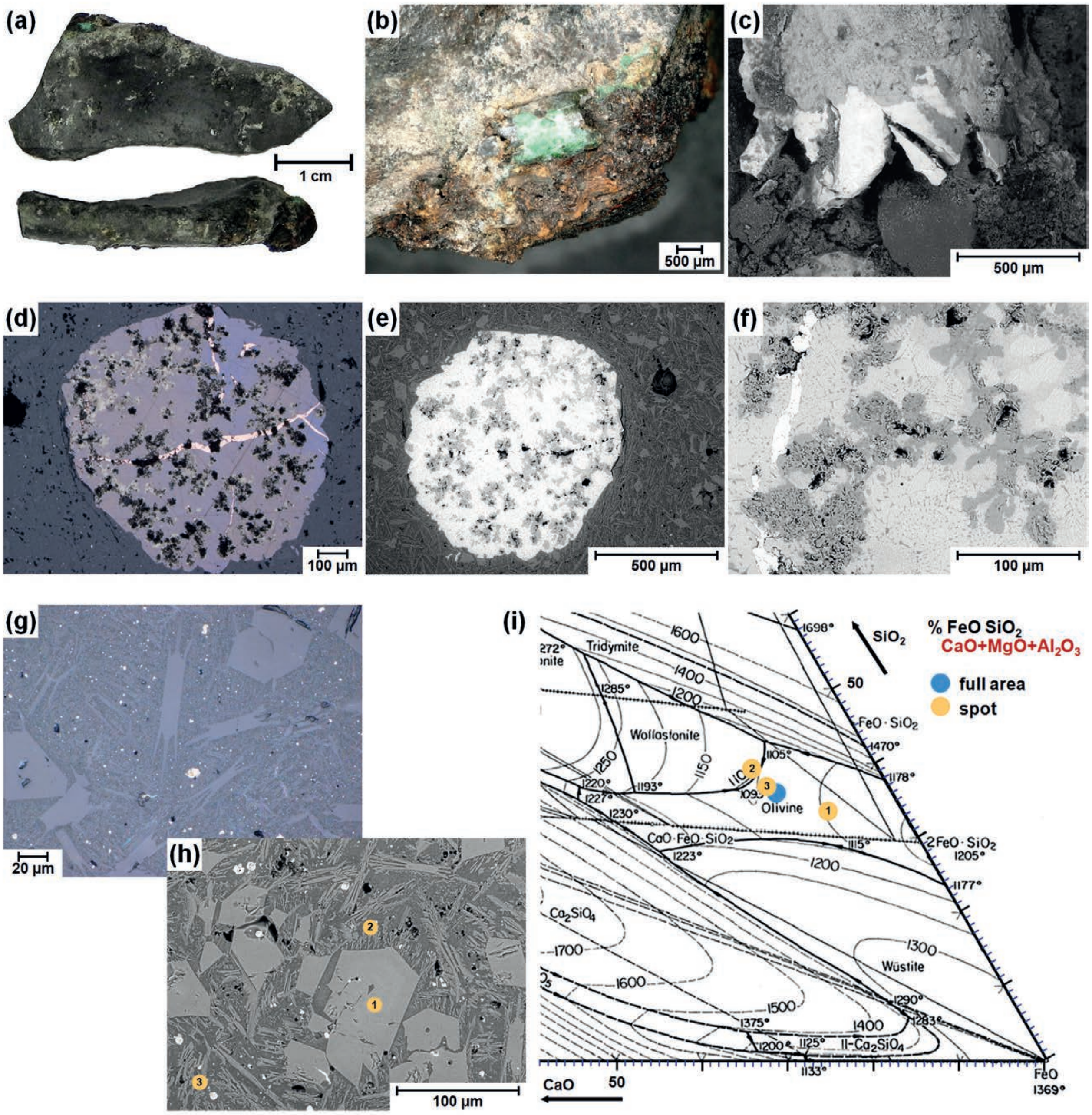

Fig. 5: Platy slag from Prigglitz-Gasteil (Pr 1896); (a) front and side view; (b) surface with Sn rich particle (3D-OM); (c) Sn rich particle in SEM); (d) copper rich inclusions (LOM); (e, f) SEM-BSE pictures of the Cu-rich inclusion; (g) slag microstructure in LOM; (h) SEM picture with indicated spots for EDX measurements; (i) phase diagram showing the elemental composition of the EDX measurements shown in (h).

identified by EDX as Cu_2S. The total sulphur content for the full area is between 1 and 1.2 wt.% S in Cu. The microstructure is characteristic for a Cu-melt during solidification where pure Cu is crystallizing first and S is concentrated in the melt. At last Cu_2S and Cu are crystallizing according to the Cu-S phase diagram (Massalski, 1990; Schumann, 1967).

The porous and inhomogeneous region shows large holes surrounded by a dark phase in metallic copper (Fig. 4e).The SEM-EDX analyses identify the large grey areas as Cu_2O (Fig. 4f, g). Additionally, in the copper and in the Cu_2O fine Cu_2S particles were observed, but the absence of Cu corrosion products like malachite indicates that the Cu_2O was formed during solidification.

In the copper phase several bright spots are visible, where Sb and O were identified (Fig. 4f, g), which means that some fahlore was used for Cu smelting. In this black copper sample, no As was detected, although As is another typical element in fahlores (Kharbish et al., 2007) and copper ingots produced from fahlores (Ertl et al., 2017; Haubner et al., 2017).

Slag from bronze production (no. 3)

A platy slag excavated 2013 near a fireplace was investigated (Fig. 5a). In LOM a green particle with approximately 3 mm length and 1 mm width was observed near the edge of this slag sample (Fig. 5b). SEM-EDX analyses show that the particle´s core is Sn- and O-enriched and is covered by malachite (Fig. 5c). It was not possible to identify this particle as SnO_2 ore, but it was a first hint that this slag was a by-product of the Sn bronze production. This extraordinary observation requires further investigations of much more platy slags which will be performed in the next stage of our research.

This slag is quite compact because during the metallurgical process it was completely molten. After metallographic preparation, LOM and SEM images of the cross sections are shown in (Fig. 5g, h). Area and spot measurements by EDX allow the appraisement of the melting point from the phase diagram in Fig. 5i. The microstructure is characterized by large, compact olivine crystals with mainly Fe- and small amounts of Mg- and Ca-silicate (Fig. 5i spot 1). The elongated crystals are olivine as well but they crystallized later together with the glass phase (Fig. 5i spot 2 and 3).

As shown in the FeO-SiO_2-CaO phase diagram, the melting temperatures for the different slag phases are between 1120 and 1090 °C. But this is only a rough estimation because the other trace elements Mg, Al, K and S in the slag also have an influence on the melting respectively solidification temperatures.

In the slag cupreous inclusions were additionally observed (Fig. 5d, e). In the SEM-BSE image (Fig. 5f) the white veins were identified as Cu, the light grey areas are chalcopyrite and the dark grey areas are FeS (pyrrhotite).

Bronze droplet (no. 4)

During the excavation period of 2013, approximately 100 copper alloy droplets were found near a fireplace (Trebsche, 2014b). For analytical investigations, a droplet with corrosion products on its surface was selected (Fig. 6a). In SEM-BSE on the droplet´s surface the corroded microstructure of Sn-bronze was already visible (Fig. 6b). The corrosion products are greyish and the metallic phase is bright. EDX measurements showed that the different areas vary considerably in their Cu and O content, in contrast the Sn amount with 25 wt.% is almost constant. An explanation for this Sn-enrichment is that reactions of Sn and Cu occurred: Sn forms insoluble SnO_2 and Cu forms Cu^+ ions, which are soluble and transported to other locations (Haubner et al., 2017).

For metallographic investigations the droplet was mounted in araldite and in a first step the surface area was polished. Mixtures of metallic and corroded areas became visible in LOM (Fig. 6e) and SEM (Fig. 6d). The original microstructure of the bronze was dendritic, but currently the copper dendrites are corroded - forming malachite - and the interdendritic Sn-enriched areas remain metallic. Using polarized light in LOM, the metallic areas can be distinguished well from the green malachite and the red Cu_2O (Fig. 6f).

After further polishing of the droplet it became clear that this droplet was fully corroded and no metallic bronze core was observed (Fig. 6b). But at the rim of the droplet metallic areas were detected beneath a scale layer (Fig. 6g). Using polarized illumination in LOM, the distribution of malachite (green) and Cu_2O (orange-red) is well visible (Fig. 6h). Why metallic phases are found at the surface but not in the core of the droplet is yet unknown. The corroded core of the droplet shows a dendritic structure, which had been formed during the bronze solidification (Fig. 6i). In polarized light the oxidized copper dendrites are orange-red, the Sn-enriched interdendritic areas are scarlet and near the surface Cu_2O reacted to green malachite by further oxidation (Fig. 6i).

Conclusions

At the archaeological site Prigglitz-Gasteil the metallurgical production steps of copper alloy, from ore to bronze, are proven. This investigation presents analytical results from cupreous ores, copper slag, black copper, bronze slag and bronze droplets.

Ores: In the investigated samples, the gangue associated with the copper ores was quartz which contained nodular or needle-like malachite and cuprite. Limonite and chalcopyrite inclusions were found occasionally. Other minerals such as pyrite, titanite ($CaTiO_3$) and cinnabarite (HgS) were locally observed.

Copper slag (no. 1): The slag lump is very inhomogeneous and contains large quartz inclusions. This is typical for primary copper smelting slags (“slag cakes”) where unmolten quartz relics from the gangue are to be expected.The slag´s microstructure consists of fine olivine dendrites, and the interdendritic space is filled with a glass phase. SEM-EDX measurements showed that the SiO_2 content is high in this slag. From the phase diagram solidification temperatures of approximately 1350 °C can be assumed.

Black copper (no. 2): This piece of metallic copper contains network-like arranged Cu_2S inclusions, and the total sulphur content is between 1 and 1.2 wt.% S. Locally, holes surrounded by Cu_2O were observed. The absence of Cu corrosion products like malachite indicates that the Cu_2O was formed during solidification. In the copper phase Sb was identified. This indicates that fahlore was used for Cu smelting. As to our present knowledge, at Prigglitz-Gasteil fahlore occurs only very rarely compared with the dominating sulphidic copper ores. The only fahlore specimens were found during core drillings in 2017. It cannot be excluded, however, that the piece of black copper was transported from somewhere else into the mining settlement.

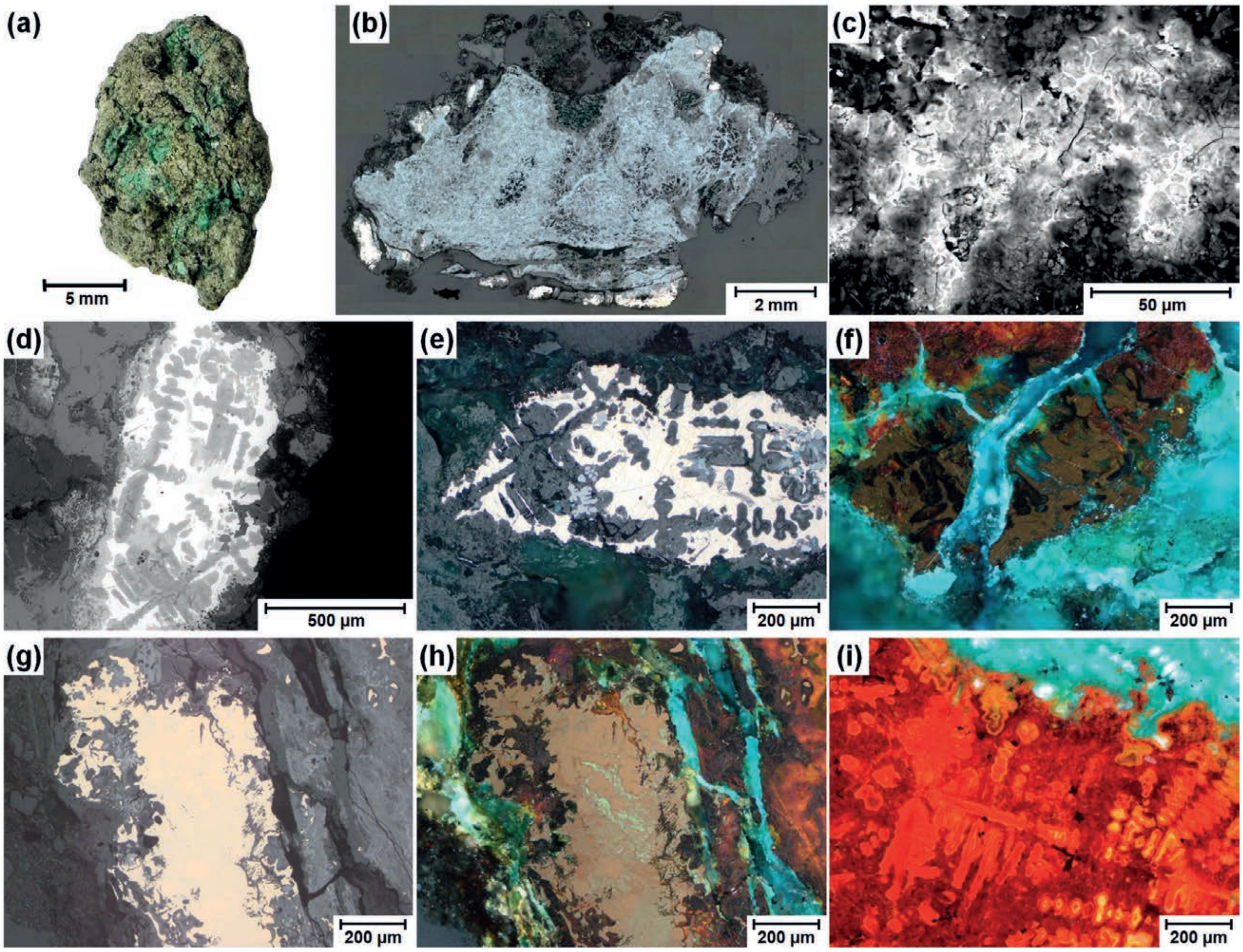

Fig. 6: Bronze droplet (P1778); (a) front view; (b) metallographic cross section (LOM); (c) droplet surface (SEM-BSE); (d – f) microstructure near the droplet surface (SEM and LOM); (g – i) cross section near the droplet center (LOM) – (g) metallic bronze (h) same location in LOM with polarized light (i) corroded bronze in the center of the droplet.

Bronze slag (no. 3): On the surface of this slag a particle containing mainly Sn and O was found. This platy slag is compact and was completely molten during production. The microstructure is characterized by large, compact and elongated olivine but the elongated crystals solidified later together with glass phase. According to the phase diagram, the melting temperatures for the different slag phases are located in the olivine area and are between 1120 and 1090 °C. In the slag inclusions of cupreous phases, chalcopyrite and FeS were identified.

Bronze droplet (no. 4): On the droplet´s surface the corroded microstructure of Sn-bronze is already visible. While the Cu- and O-content varies, the Sn amount with 25 wt.% is almost constant. The original microstructure of the bronze was dendritic, but currently the droplet is corroded, forming mainly Cu_2O. The dendrites are still visible due to the interdendritic Sn-enriched areas showing different colours. Using polarized light green malachite, formed by further oxidation, and red Cu_2O can be distinguished.

The platy slag (no. 3) and the bronze droplet (no. 4) from layer 916 on the upper terrace confirm that bronze was cast at the site of Prigglitz-Gasteil. Therefore in the mining settlement, not only copper was produced but also copper alloys and bronze objects. The fragment of a stone casting mould (see Trebsche, 2015a, 49 fig. 2/7) for knife production provides the evidence of bronze casting. Interestingly, bronze casting took place between two periods of ore beneficiation as attested by the local stratigraphy in the upper terrain terrace. At present, it remains unclear whether bronze casting was a regular or an occasional activity at the Prigglitz-Gasteil site, and whether the bronze objects were cast for local use or for regional trade.

Acknowledgement

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Authors

Roland Haubner – Technische Universität Wien, Institute of Chemical Technologies and Analytics
Susanne Strobl – Technische Universität Wien, Institute of Chemical Technologies and Analytics
Peter Trebsche – University of Innsbruck, Institute of Archaeologies

Correspondence and material requests should be addressed to: roland.haubner@tuwien.ac.at

Raw products, metal provenance and metal exchange

Photomontage: Bronze Age to Early Iron Age axes of the Salzach- and Inn-Valley on top of a slag from the Oberhalbstein mining district, photos: C. Grutsch, L. Reitmaier-Naef, T. Rabsilber

Der Anschnitt, Beih. 42, S. 335–362, 2019

Caroline O. Grutsch, Joachim Lutz, Gert Goldenberg, Gerald Hiebel

Copper and bronze axes from Western Austria reflecting the use of different copper types from the Early Bronze Age to the Early Iron Age

ABSTRACT: *First evaluations of analytical data from East Alpine prehistoric metal artefacts have shown that a use of different types of copper can be expected varying in time and space (Sperber, 2004, Möslein, 2008). These studies mainly emphasise a change from the use of fahlore based copper in the Early Bronze Age to the major use of chalcopyrite based copper in the Middle Bronze Age, with a shift in the Hallstatt A2 period, when both materials were used to produce bronze (Lutz & Pernicka, 2013, Pernicka & Lutz, 2015, Lutz, 2016).*

In the following these general observations are specified for a defined area and a certain object group. Copper and bronze axes from Western Austria (Vorarlberg, Tyrol, Salzburg, Upper Austria) have been chosen as these objects are available in all periods and regions and contain a representative amount of copper. The above mentioned succession of fahlore copper use, chalcopyrite copper use and the use of both materials is also observed within the examined axes. A more detailed picture evolves regarding the Late Bronze Age and the Early Iron Age, when the use of fahlore copper is mainly observed in bronzes based on diluted fahlore copper and not on pure fahlore copper. This is particularly notable as a big Late Bronze Age/Early Iron Age fahlore production center – Schwaz/Brixlegg – lies in the heart of the examined area.

Regarding alloying practice, two observations are remarkable: In the Late Bronze Age (Ha A1-B3) the average tin content drops significantly, correlated to the reuse of fahlore copper. In the Early Iron Age (Ha C1-D2), the alloying practice changes again and the tin content in the axes rises to a level like in the Middle Bronze Age, but also the lead contents rise.

KEYWORDS: EASTERN ALPS, WESTERN AUSTRIA, COPPER AND BRONZE AXES, EARLY BRONZE AGE TO EARLY IRON AGE, ARCHAEOMETALLURGICAL ANALYSES, COPPER TYPES, ALLOYING, EXCHANGE NETWORKS

Premises

The DACH-project[1] (2015-2018) "Prehistoric copper production in the Eastern and Central Alps – technical, social and economic dynamics in space and time" financed by the Austrian Science Fund (FWF), the German Research Foundation (DFG) and the Swiss National Science Foundation (SNF) gives the frame for the below presented work. It is a joint project of the Universities of Innsbruck (Research Centre HiMAT[2]), Bochum and Zürich, the Deutsches Bergbau-Museum Bochum (DBM), the Curt-Engelhorn Zentrum Archäometrie gGmbH (CEZA) Mannheim and the Archäologischer Dienst Graubünden.

Spadework and hypothesis

First evaluations of analytical data from East Alpine prehistoric artefacts have shown that a use of different types of copper (fahlore based, chalcopyrite based) can be expected varying in time and space and produced in different copper districts (Sperber, 2004, Möslein, 2008). These studies mainly emphasise a change from fahlore copper use in the Early Bronze Age to the major use of chalcopyrite copper in the Middle Bronze Age, with a shift in Hallstatt A2 period, when both materials were used (Lutz & Pernicka, 2013, Lutz, 2016). For these developments not only the technical progress but also demand-orientated decisions and other influences must be taken into consideration.

In the following these general observations are specified for a certain object group in a defined area (axes of western Austria[3] and adjacent areas). Furthermore examinations regarding standardized tin alloying and a relation between low tin-contents and high trace element contents are conducted. The use of lead within the bronze alloys is also examined.

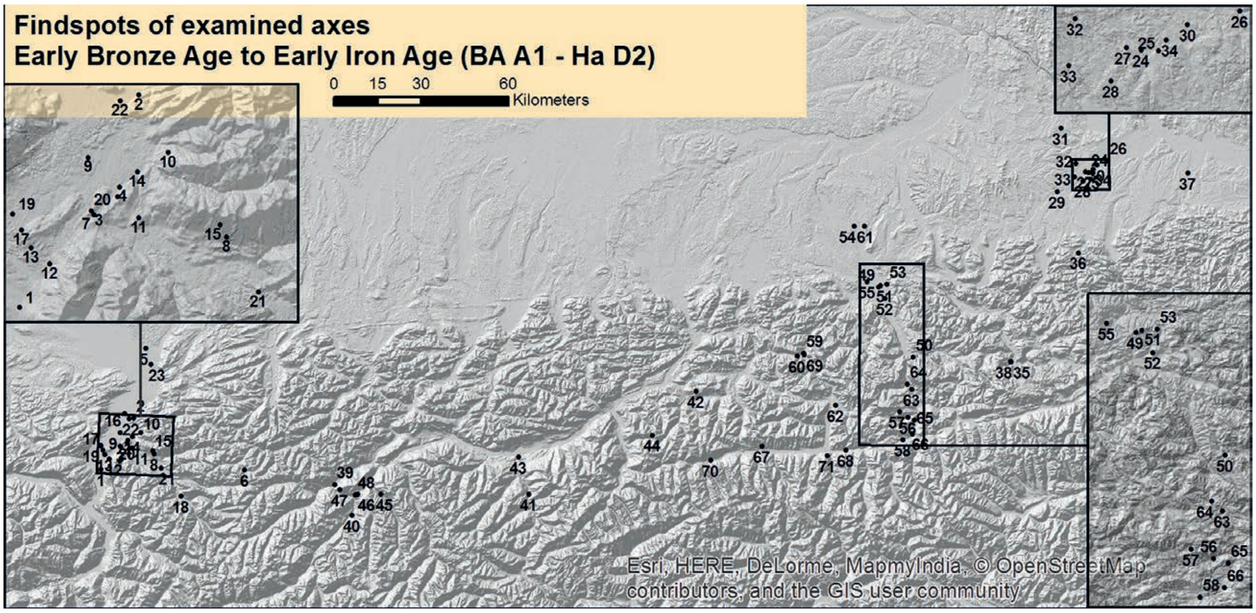

Fig. 1: Distribution map of the 175 examined axes. For corresponding site names see Tab. 1.

Goals

Since the 1950's hundreds of chemical and isotope analyses of ores and artefacts have been produced (Otto & Witter,1952, Junghans et al,1960 and 1968, Ottaway, 1982, Rychner & Kläntschi,1995, Krause, 2003, Kienlin, 2008, Pernicka et al, 2016, Möslein & Pernicka in this volume), complemented by data created within the HiMAT project within the last decade.

The aim of the work at hand is a consolidating research for Western Austria, bringing together the archaeological data with the geochemical data. There is revealing work for either special periods or parts of Western Austria (e .g. Ottaway, 1982, Sperber, 2004, Kienlin, 2008, Möslein, 2008, Lutz & Schwab, 2014) or on the scale of an overview (Pernicka & Lutz, 2013, Lutz, 2016), but no detailed research on the developments within one object group from the Early Bronze Age to the Early Iron Age. The Axes of Western Austria were chosen for this approach as they were in use during all periods of interest in all regions and they embody a representative mass of copper.

On the basis of 175 axes and by combining the archaeological with the geochemical data the work investigates:

1. the chronological development of the use of different copper types in the Eastern Alps from the Early Bronze Age to the Early Iron Age and
2. the chronological development of alloying practices in the Eastern Alps from the Early Bronze Age to the Early Iron Age.

Material

The 175 axes discussed, derive from the vorarlberg museum[4] (28 axes), Northern Tyrol (94 axes), Salzburg (32 axes)[5] and Upper Austria (21 axes) (Tab. 1, Fig. 1). The earliest pieces date to Bronze Age A1, the latest to Hallstatt D2 (Fig. 2). Therefore the material covers about 1700 years of regional copper and bronze production.

All analyses are either measured or remeasured by the CEZA or the TU Bergakademie Freiberg[6] using XRF and are therefore comparable, except 10 older analyses[7] (Otto/Witter, 1952). The latter are not used for the element plots, as the data is not well comparable. They are only included in the interpreting histogram (Fig. 8), as the assignment to a copper type was possible. This means that for Northern Tyrol and Salzburg analyses from Otto and Witter (10 objects), the SSN-project[8] (16 objects) and the HiMAT-project[9] (100 objects) are used. 18 objects from the vorarlberg museum as well as the axes from Upper Austria (21) have been sampled and analysed within the DACH-project[10] (for these analyses see Tab. 3). 10 samples from the vorarlberg museum derive from the SAM-project[11] and have been remeasured at the CEZA for the study at hand.

As within the HiMAT-project two big hoard finds were analysed, there is an accumulation of data for the Middle Bronze Age and the beginning Late Bronze Age (BA B1-D1) for Northern Tyrol (46 axes from the hoard find Moosbruckschrofen/Piller (Tomedi, 2001 and 2007)) and for the Early Iron Age (Ha C1-D2) in Northern Tyrol (38 axes from the so called Kathreinfund/Fließ (Sydow, 1995)). In Upper Austria 4 of the analysed pieces derive

Fig. 2: Selection of characteristic axe types sampled to illustrate the typo-chronological development of axes in the Eastern Alps from BA A1 to Ha C1-D2 (types from upper left to bottom right: Salez A, Langquaid II/Koblach, Absatzbeil mit gedrungen herzförmiger Rast, Freudenberg/Elixhausen, Freudenberg/Retz, Lappenbeil mit herabgezogenen Lappen, Breites mittelständiges Lappenbeil, Winkel- und bogenverziertes Tüllenbeil, Hallstatt). For corresponding data see Tab. 1, for corresponding find spots see Fig. 1. Red crosses mark the sampling positions if the objects have been sampled within the DACH-project.

from the Oberösterreichische Landesmuseum and 17 from the Stadtmuseum Wels – this explains the accumulation of sampled objects in the vicinity of Wels. In Vorarlberg there are find concentrations around the rivers Ill and Rhine. This may actually reflect the prehistoric picture, although an academic void for nowadays sparsely populated areas due to missing investigations and chance finds has to be taken into account.

Methods

As already mentioned the main target of this work is to merge the archaeological data with the geochemical data. The archaeological part comprises the material selection, typological determination, artefact dating, photo and drawing documentation, weighing of artefacts and object sampling. The geochemical part includes sample preparation, analysing and determination of copper types. Conclusions are drawn in close cooperation between archaeologists and geologists/geochemists.

Artefact selection not only depends on the availability of prehistoric axes in the questioned area but also on the accessibility and the possibility of sampling. For Vorarlberg and Upper Austria cooperation with the vorarlberg museum (G. Grabher), the Oberösterreichisches Landesmuseum (J. Leskovar) and the Stadtmuseum Wels (R. Miglbauer) was agreed, otherwise it would have been very difficult to obtain material and analyses. For the Tyrol and Salzburg the predominant aim was to process the already existing data[12]. For South Tyrol work is in progress[13] but cannot be presented yet. Objects from Southern Bavaria[14] which also should be considered when speaking about the Eastern Alps have been sampled and are dealt with in the SSN-project (Möslein/Pernicka in this volume).

Sampling of the objects is done with the Proxxon TBM 220 with a 1.5 mm drill. After carefully removing the patina, about 40 mg of fresh metal drillings are gained. Afterwards the drill holes are sealed with a colour-coordinated restoration wax[15].

As this paper exclusively deals with the differentiation of chalcopyrite copper from fahlore copper and with tin contents in relation to trace and minor element contents deriving from the ore, X-ray Fluorescence Analyses (XRF) are sufficient. All ore analyses plotted in the diagrams are Neutron Activation Analyses (NAA).

The alloy composition of the metal samples was determined by energy-dispersive XRF analysis following the quantification and correction procedures of Lutz & Pernicka (1996). Ore samples were irradiated together with appropriate neutron flux monitors and standard materials in the TRIGA reactor of the Institute for Nuclear Chemistry of the University of Mainz. The measurement of the activated ore samples (gamma-radiation) was carried out at the CEZA in Mannheim using Ge-detectors. The NAA-method used is published in Kuleff & Pernicka (1995).

The two main East Alpine copper sources are fahlore and chalcopyrite deposits with their secondary minerals. The discrimination of copper produced from fahlores and copper produced from chalcopyrite is based on trace element contents, especially silver and antimony. Plotting the silver and antimony contents of East Alpine fahlores and chalcopyrite, results in two well distinguishable groups – silver and antimony rich fahlores, but silver and antimony poor chalcopyrite. This picture is reproduced when plotting the silver and antimony contents of prehistoric raw copper (plano-convex copper ingots), which has some clear advantages to distinguish different copper types (Fig. 3). As prehistoric mining areas are often inaccessible, altered or largely exploited, sometimes only small remains of ores on mining heaps can be sampled. Furthermore each ore sample represents only one possible composition, deriving from an usually very heterogeneous ore body. To understand the whole system, it is of course essential to characterize the ores of a mining district. But raw copper in contrast to an ore sample depicts a deposit already homogenized through beneficiation and smelting. Furthermore it also reflects the smelting process.

There are 192 analysed plano-convex copper ingots (raw copper) not only from the Inn Valley, but also from the Alpine foothills, North Tyrol and Salzburg[16] (Figs. 4 and 5), which illustrate the composition of the prehistorically produced copper of this region very well (Lutz 2016). This set of data is the basis for the following calculations.

The analyses have shown that the average silver content in fahlore copper (FC) is a hundred times higher than the one in chalcopyrite copper (CC). As only one plano-convex copper ingot has a silver content of 0.2 to 0.3 mass% silver, the statistic distribution divides silver rich from silver poor copper at 0.22 mass% silver, with two peaks at around 0.01 and 1.0 mass% (Fig. 4). The median silver contents for the two groups received, are 0.008 mass% silver in chalcopyrite copper and 0.82 mass% silver in fahlore copper. Consequently the silver content is an appropriate tool to distinguish objects made of alpine fahlore copper from those made of alpine chalcopyrite copper. Even more since silver is not lost during further processing (melting/remelting) and can be measured precisely with XRF-analyses (detection limit of 20 ppm). Although antimony gets lost during smelting, there is still a substantial content-difference observed in the casting cakes. Therefore raw copper obtained from fahlores comprises about 300 times higher antimony contents on average than raw copper obtained from chalcopyrite[17]. Consequently also increased antimony contents are expected in objects made of fahlore copper, though it is more difficult to estimate at what height, as it was one aim of further processing to get rid of the antimony. While arsenic is also a significant component of fahlores, it is not that useful for differentiation. Especially the chalcopyrite from Mitterberg occurs together with gersdorffite (NiAsS). Thus a lot of arsenic (and also nickel) can arise in chalcopyrite copper objects produced from Mitterberg ores.

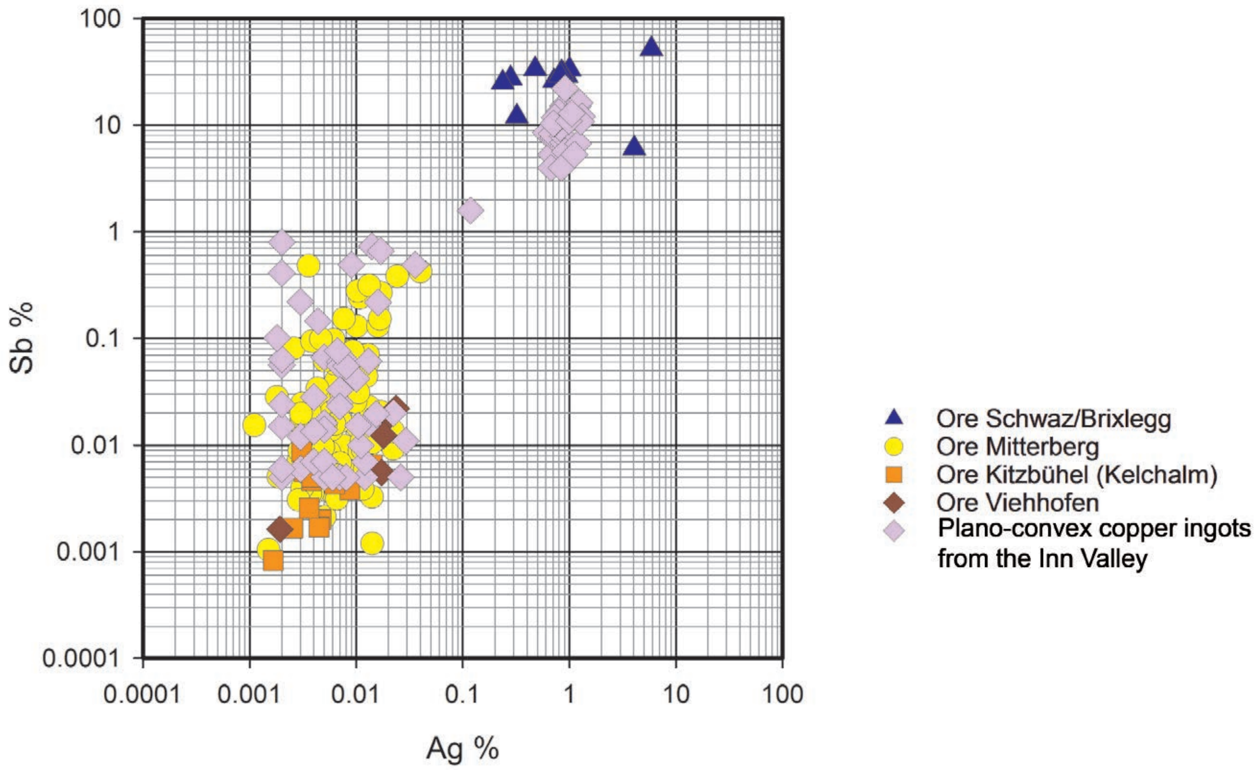

Fig. 3: Plotting silver versus antimony emerges two very well distinguishable groups of silver and antimony rich and poor ores and raw copper (plano-convex copper ingots). For the silver and antimony rich fahlore-group it is also evident, that antimony gets lost during processing, while silver gets homogenized.

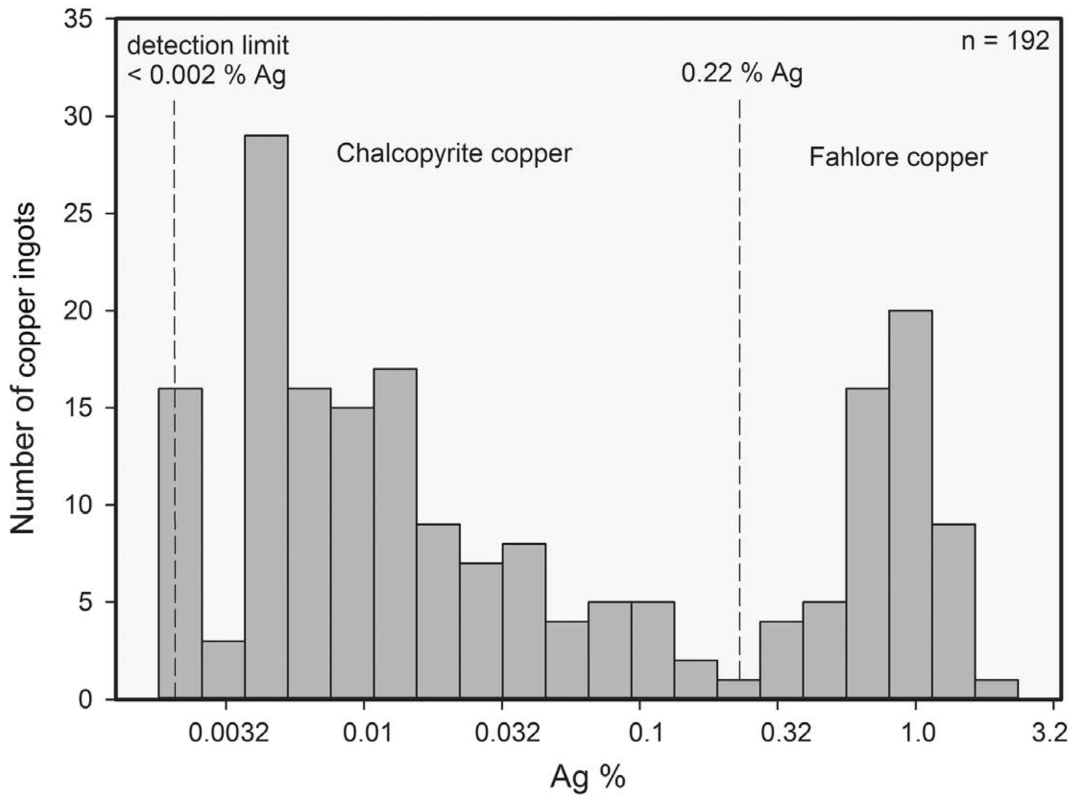

Fig. 4: Silver content (logarithmic) in 192 East Alpine casting cakes. The two peaks represent two types of copper. Nonetheless all gradations are present, though only within a few pieces.

First results

Merging the data basically means bringing together the archaeological information (typology, chronology and chorology of the artefacts) with the geochemical information (ore resources, copper types). Hence an evaluation of the chronological and spatial development of fahlore copper / chalcopyrite copper use is possible.

Development of fahlore and chalcopyrite copper use in the Eastern Alps from the Early Bronze Age to the Early Iron Age

Chronology

Axes are an object group for which fine dating is not always possible as most of them derive from single or hoard finds, especially after the Early Bronze Age. For hoard finds it becomes increasingly obvious, that one single deposit can cover a long time span, sometimes 200 or 300 years. Circular reasoning led to misinterpretation and objects, among them also axe types, are misdated, referring to the youngest piece in a hoard. (On these issues e.g. Tomedi, 2007, Hansen, 2016). In this paper lifespans of types (Tab. 1) are used, which are merged to succeeding dating groups (Tab. 2). Axes for example which can clearly be assigned to BA A1 will of course be found in the first group "Beginning Early Bronze Age". If an axe type can derive from either BA A1 or A2, it will be found in the next group "Early Bronze Age" – as we cannot decide to put it either into A1 or A2 – thus considering the lifespan of an axe-type but also a tendency of an object to be of later origin. Because of this, some developments in the succession of copper types might be expressed slightly weakened. On the other hand presumed fine dating can be avoided and at least the succession of copper types is depicted correctly.

As quite a few axes of the type Freudenberg are included, a short comment shall be attached. According to Mayer the majority of Freudenberg axes is – consistent with the youngest objects in some hoard finds[18] – dated to the early Urnfield period, with a possible maximum life span of this type from BA C to Ha A1 (Mayer, 1977, 141). "*In contrast*" the grave finds containing Freudenberg axes date to the Middle Bronze Age (Mayer 1977, pp. 142-144, Pászthory & Mayer,1998, 97 f.). In addition there is a terminus ante quem for a Freudenberg axe from the ritual site for burnt offerings (*Brandopferplatz*) Piller Höhe/Tyrol (HiB161). The layer covering the axe is radiocarbon-dated to the Middle Bronze Age as follows: 1504-1311 cal. BC (2σ) (IntCal 13, 3158 +/- 34 BP) or 1504-1383 cal. BC (89,3%) (IntCal 13, 3158 +/- 34 BP)[19] (Tschurtschenthaler &Wein,1998). In the work at hand the Freudenberg axes which cannot be fine dated based on their variation or other information are therefore placed into the group „End of Middle Bronze Age / beginning Late Bronze Age".

Chronological development of fahlore copper and chalcopyrite copper use

Plotting the silver and antimony contents of the chronologically grouped axes displays the following developments through time (Fig. 5).

The earliest axes (dating group 1) show high silver and antimony contents. These objects are all made of fahlore copper, which does not surprise due to the known technical standard in this period.

But the next two phases plotted in the same diagram (dating groups 2, 3), show a development towards silver and antimony poor copper, with still some silver rich objects. This trend reaches its climax in the Middle Bronze Age and the earlier phase of the Late Bronze Age (dating groups 4, 5, 6). Not a single axe has more than 0.1 mass% silver. The antimony content is slightly varying, but besides one piece it is significantly below 1 mass%.

Plotting the data of the latest examined axes, dating to the later phase of the Late Bronze Age and the Early Iron Age (dating groups 7, 8), reveals at first sight a confusing result. Nearly all pieces neither fit the silver and antimony rich nor the silver and antimony poor raw material group, but lie somehow in between. Compared to the ores of the East Alpine copper districts, it clearly shows that the bulk of these axes cannot be made of chalcopyrite copper as the silver and/or antimony contents are too high. In contrast these contents are too low to derive from fahlores (Fig. 6, left side). This is also visible compared to the plano-convex copper ingots (Fig. 6, right side). Only a few casting cakes which lie in between the two bulks seem to fit. Having a closer look to the composition of these objects in between, they show a somehow diluted fahlore copper signature. They have clearly too much silver and antimony to derive from chalcopyrite[20], but also clearly less than expected for copper produced from fahlores, as the silver content cannot drop. Hence the copper type "diluted fahlore copper" (DFC) or "mixed copper" shall be introduced.

As fahlore copper and chalcopyrite copper are primarily defined by the silver content, this is also the determining parameter for the "diluted fahlore copper" or "mixed copper". Looking at the ores from the chalcopyrite deposits Mitterberg, Kitzbühel and Viehhofen and especially the silver poor casting cakes, the silver content varies from 0.002 mass%[21] to 0.05 mass%. The fahlores from Schwaz/Brixlegg show a very high variation due to the inhomogeneity of ore deposits. Therefore the calculations are based on the silver and antimony rich plano-convex copper ingots, which are considered to be more representative for the entire fahlore deposit than individual ore samples. These pieces have a silver content from 0.5 mass% to 1.3 mass% (with one statistical outlier containing 2.3 mass%). Therefore the limits for "diluted fahlore copper" where defined as follows: The silver content must not be less than 0.1 mass% and not higher than 0.5 mass%. For the lower limit the maximum of 0.05 mass% silver was multiplied by a safety factor of 2, not to include too many chalcopyrite copper objects as

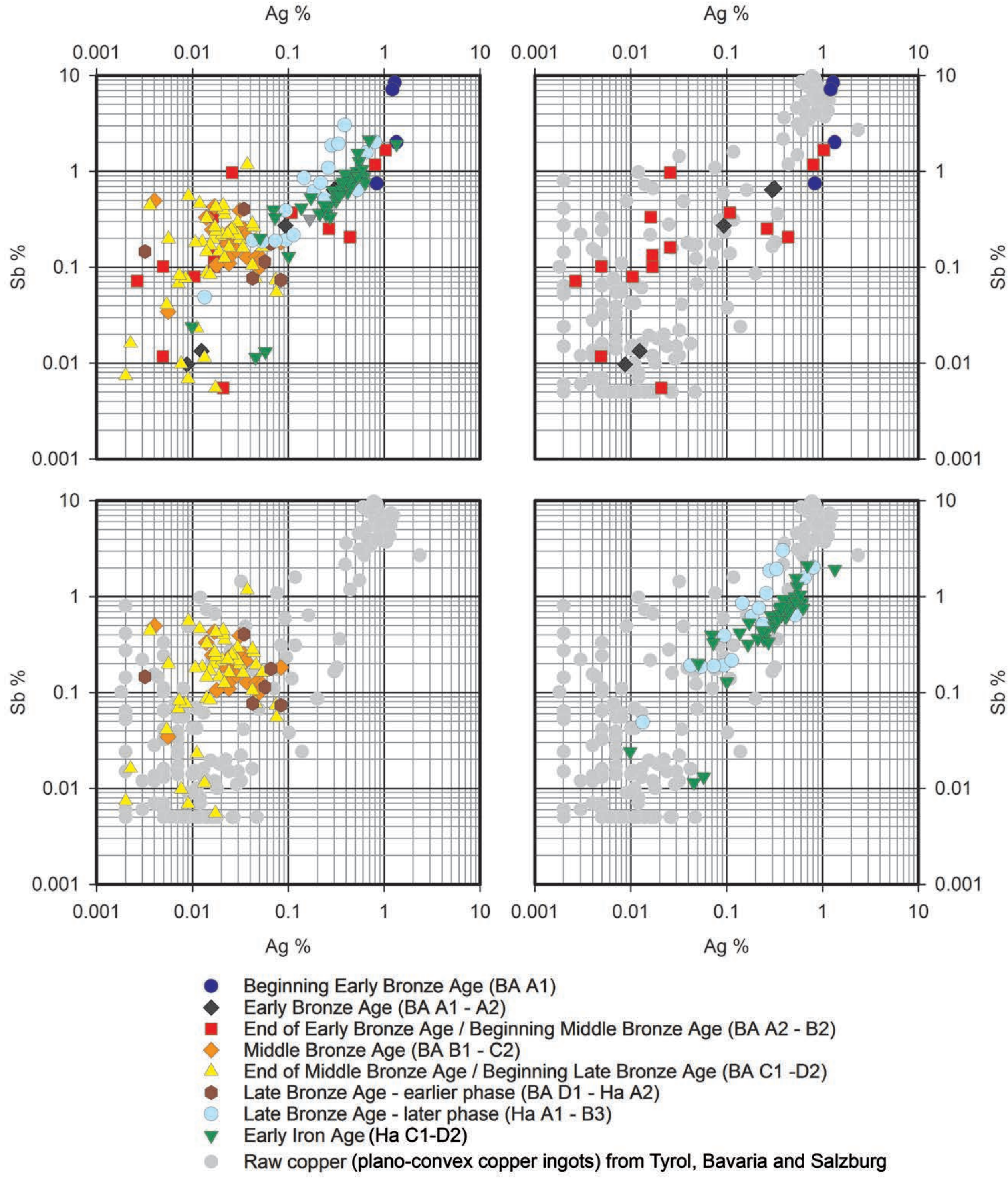

Fig. 5: Silver versus antimony for 165 East Alpine axes through time (as mentioned without Otto/Witter samples) and 192 East Alpine casting cakes. For the latter the two groups of silver/antimony-rich and -poor material are evident.

the maximum and minimum silver contents can vary by a factor of 4 downward and a factor of 6 upward (based on the median for chalcopyrite copper of 0.008 mass%). Variation for the fahlore copper casting cakes is much lower with the factors of 1.6 down- and upward (based on the median of 0.82 mass% silver). Therefore no safety factor was taken into account.

For now these calculations of course only lead to a valuation of the quantity of "diluted fahlore copper" or "mixed copper" objects – but whether the limits have to be corrected slightly, it is obvious that there is a group of objects which lies in between what the known chalcopyrite or fahlore deposits are expected to produce. In the following we will operate with these limits.

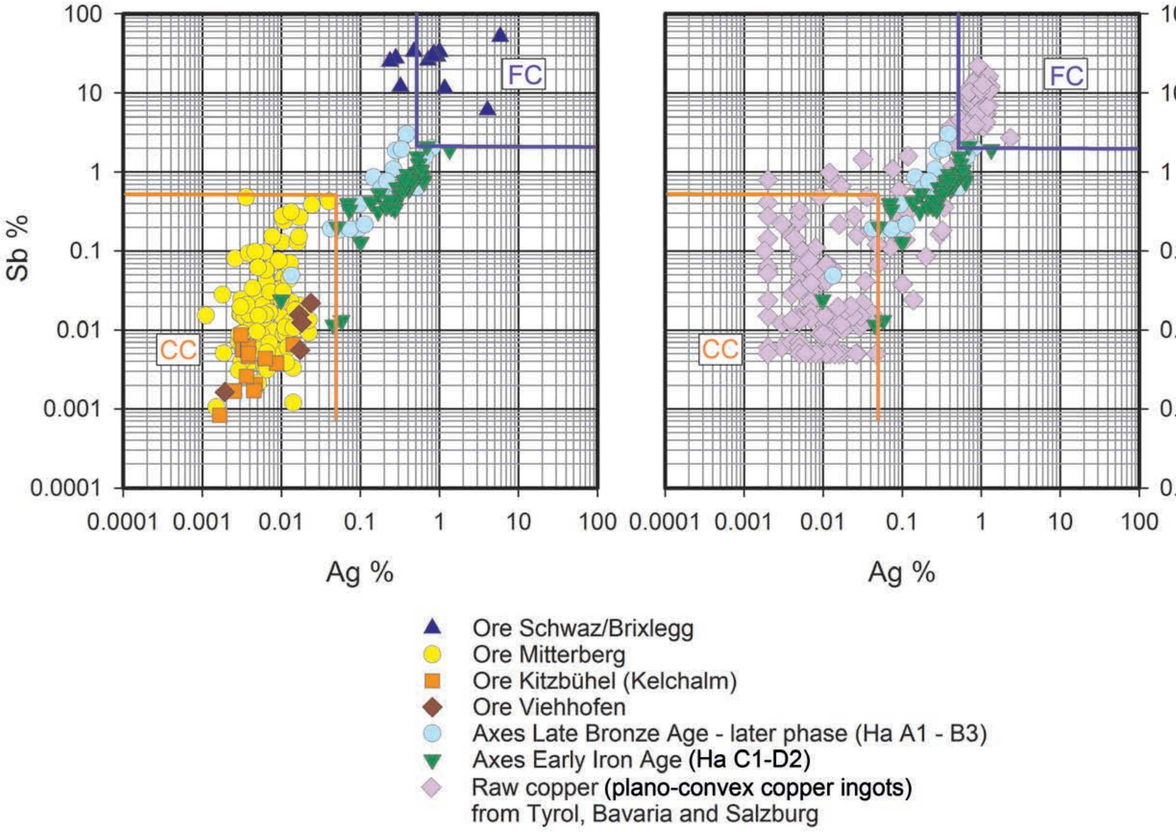

Fig. 6: Most of the axes from the later phase of the Late Bronze and Early Iron Age neither fit the silver / antimony contents expected for chalcopyrite copper nor for fahlore copper.

At the moment it cannot be decided whether this "diluted fahlore copper" originates from mixing chalcopyrite copper with fahlore copper[22] or if it represents polymetallic deposits where chalcopyrite and fahlore occur together, sometimes interwoven. Such deposits are known for example from Leogang, Kitzbühel or Navis (for the last cf. Grutsch et al. in this volume). The use of such ores would also explain the few copper ingots with the chemical signature of "diluted fahlore copper" (see also Figs. 4, 5, 6). Anyhow intentional mixing of fahlore copper with chalcopyrite copper seems more likely for the majority of objects, not least because the mainly exhausted deposits and the archaeological record from smelting sites show a specialisation on either fahlore or chalcopyrite processing. In return the possibility of recycling does not seem very likely, as the chemical signatures of these objects are quite uniform and alloying with tin, especially for Early Iron Age axes, is quite standardized, which would not have been easy to manage, when mixing together objects with unknown composition. Furthermore if recycling would have played a major role, the changes throughout time would not be that visible. Anyway specific recycling of fahlore copper in these periods would not have been easy as for 300 years none has been produced.

Charting the obtained data in a histogram, the succession of copper types through time is even more evident, especially the chalcopyrite copper domination in the Middle Bronze Age and the beginning Late Bronze Age and the reuse of fahlore copper from Ha A1 on (Figs. 7 and 8).

Fig. 7 depicts the amounts of fahlore copper and chalcopyrite copper per period in *purely arithmetical terms*, based on the median silver contents. The percentage of fahlore copper in use during BA A1 (dating group 1) shrinks from 100% to about only 10% already during the following period (dating group 2). Throughout the succeeding epochs (dating groups 3, 4, 5) there is some kind of "fahlore copper background noise", becoming a clear signal again only in Ha A1 (dating group 7, already slightly visible in dating group 6). But even in the later phase of the Late Bronze Age and the beginning Iron Age (dating groups 7, 8) chalcopyrite copper remains the dominant copper type.

If the classification is not solely conducted on the statistically obtained silver medians, but *each piece assigned to a defined copper type*[23] including "diluted fahlore copper", a somewhat different picture evolves (Fig. 8).

As this diagram also contains the Otto/Witter samples mentioned above, there are some very early axes made of arsenical copper (AC) in retrospective of the Chalcolithic, together with pure fahlore copper objects in BA A1. But already in BA A2 chalcopyrite copper comes in use, though there is still fahlore copper available. A few pieces made of mixed copper are also observed until

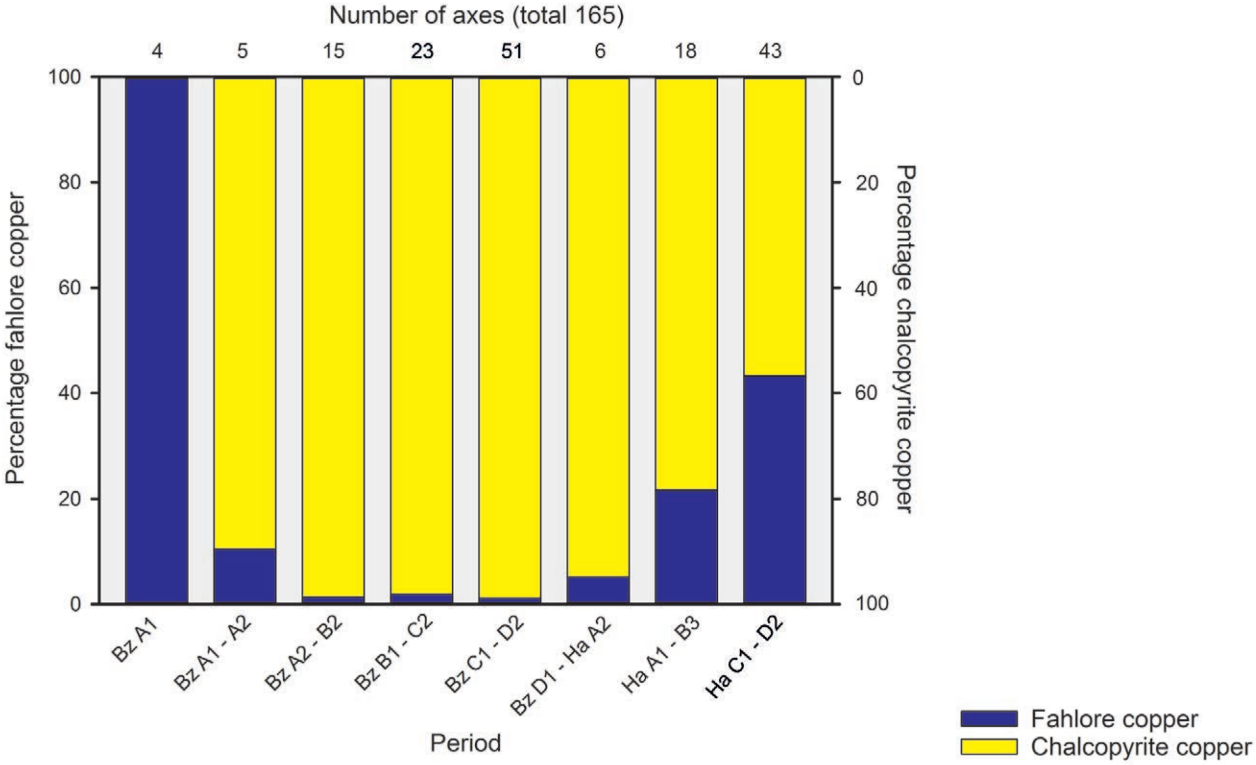

Fig. 7: Fahlore copper and chalcopyrite copper amounts within the axes, calculated on the statistically obtained silver medians of the two copper types. Though the use of fahlore copper rises again in the later periods, chalcopyrite remains the most relevant copper ore (for explanation of overlapping periods see Tab. 2).

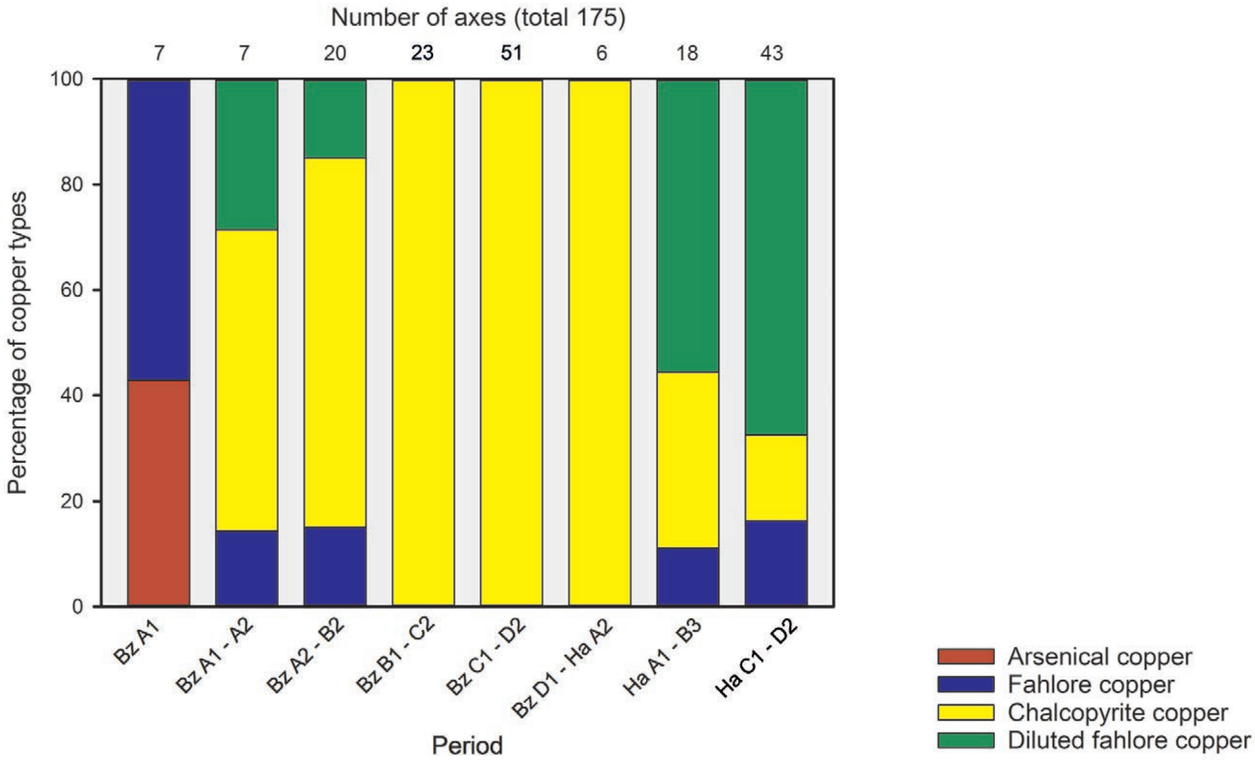

Fig. 8: Differentiated use of fahlore and chalcopyrite copper from the Early Bronze Age to the Early Iron Age (for explanation of overlapping periods see Tab. 2). 10 Otto/Witter samples have been included here as the determination of the copper type was possible.

BA B2. Thereby copper types must not be related to axe types, not even if they are found in one hoard. From six pieces of the type Langquaid for example one is based on fahlore copper, three on chalcopyrite copper and two on diluted fahlore copper. Three pieces of this type where found in the hoard Koblach-Kadel – two of them are based on diluted fahlore copper, one on chalcopyrite copper. If the diluted fahlore copper in this period actually depicts mixed East Alpine copper sources or probable import, has to be discussed elsewhere, as for the Early Bronze Age a big variety of copper suppliers has to be taken into account.

After the early Middle Bronze Age chalcopyrite copper is the utterly dominant copper type in use for about 300 years. For 23 Middle Bronze Age axes and 51 axes from the end of the Middle Bronze Age / beginning Late Bronze Age the maximum, median and minimum nickel, arsenic, silver and antimony contents are compared (Fig. 9). The minimum values drop significantly at the end of the Middle Bronze Age / beginning Late Bronze Age. It becomes apparent that new chalcopyrite copper producers, characterized by lower trace element contents in the ore, appear. This can be explained on the basis of the mining archaeological record (Stöllner et al., 2016). Slightly higher[24] nickel and arsenic but also antimony values are known from the Mitterberg, while particularly pure chalcopyrite copper can derive from the Kitzbühel and Viehhofen districts (Lutz et al, 2009, Lutz, 2013 and 2016). Therefore these results probably display copper from Kitzbühel and Viehhofen from the end of the Middle Bronze Age on, which fits the time of production at least for the Kitzbühel district very well (Koch Waldner & Klaunzer, 2015). The quite constant median values would depict the still ongoing production at the Mitterberg.

As far as the examined axes provide information, fahlore copper has its revival not earlier than in Ha A1. Notably it is mainly recognized in diluted fahlore copper objects not in pure ones, which is also true for the next period, the Early Iron Age (dating group 8). This is especially striking, as for these periods there is plenty of evidence for fahlore mining and processing from the Schwaz/Brixlegg district (Staudt et al., in this volume). It seems that fahlore copper on its own was not competitive, but in demand when mixed with chalcopyrite copper, which was already suggested by Sperber (2004).

But why is there a comeback of fahlore copper at all after several hundred years of chalcopyrite copper use? The Mitterberg and Kitzbühel districts both show a decline in production during Ha A1 whereby production in Kitzbühel seems to end in this period as far as we know at the moment (Koch Waldner & Klaunzer, 2015), whereas the Mitterberg keeps producing on a smaller scale also during Ha B and the Early Iron Age (Breitenlechner et al., 2014, Stöllner, 2009). On the other hand there is still plenty of chalcopyrite copper available in both periods, possibly also coming from the Southern Alps, where production starts in Laugen-Melaun A (Cierny, 2008). The axes of the Ha C-D hoard find from Fließ/Tyrol[25] for example

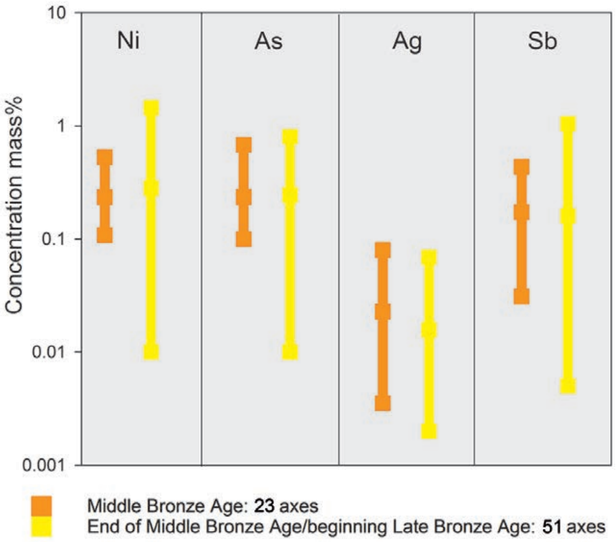

Fig. 9: Maximum, median and minimum nickel, arsenic, silver and antimony contents of the axes show that at the end of the Middle Bronze Age / beginning Late Bronze Age (dating group 5) a type of chalcopyrite copper with fewer trace elements appears.

have a total weight of 20.36 kg, thereof 0.85 kg bronze based on chalcopyrite copper, 2.1 kg based on fahlore copper and 17.41 kg based on diluted fahlore copper. Less the median tin content of 10.6 mass% this leaves 1.88 kg of fahlore based copper, 0.77 kg of chalcopyrite based copper and 15.56 kg of diluted fahlore copper, the latter with a median silver content of 0.36 mass%. Based on the silver medians for fahlore copper (0.82 mass%) and chalcopyrite copper (0.008 mass%) this means that for these axes in total still 9.58 kg of chalcopyrite copper is needed, opposing 8.63 kg of fahlore copper. This picture gets even clearer looking not only at the axes but at the hoard find in total: 61% of the copper is chalcopyrite copper accompanied by only 39% of fahlore copper[26]. Therefore a decline of chalcopyrite copper production cannot be the only reason for the comeback of fahlore copper. Maybe chalcopyrite copper just could not supply the increased demand and fahlore copper is produced additionally. Another explanation could be an insufficient tin supply, which revaluates fahlore copper with its trace elements probably used as tin substitutes. (Lutz & Schwab, 2014, Lutz, 2016).

Spatial development of fahlore copper and chalcopyrite copper use

From Upper Austria no BA A1 axes were available for the investigations. The three BA A1 axes from Salzburg are made of arsenical copper. Four from the vorarlberg museum are made of fahlore copper.

But then it gets interesting. There seems to be a slight east-west divide in the early use of chalcopyrite copper. While the investigated objects dating to BA A2-B1 from the Tyrol are still dominated by fahlore copper (4 pieces), in Salzburg and Upper Austria there is only chalcopyrite copper in use (4 pieces), with the earliest piece dating to BA A1-A2 from Aigen/Salzburg. Notably the BA A2 axes from Vorarlberg already represent chalcopyrite copper (3 pieces) and two are based on diluted fahlore copper. From the vorarlberg museum there are no axes based on pure fahlore copper in this period. While the picture for the Tyrol and Salzburg/Upper Austria seems consistent with their relative vicinity to specialized fahlore copper or chalcopyrite copper production centres respectively, the situation in Vorarlberg seems remarkable. After BA A2 all regions get dominated by chalcopyrite copper. Only 2 pieces from Vorarlberg and 1 piece from Upper Austria still contain fahlore copper within objects based on mixed copper. (Fig. 10 a) These conclusions are so far drawn only on a small number of objects, which has to be broadened.

In the Middle Bronze Age and the earlier phase of the Late Bronze Age all regions are dominated by chalcopyrite copper (Fig. 10 b).

Diluted fahlore copper is the dominant copper type in the later phase of the Late Bronze Age and the beginning Iron Age (dating groups 7, 8), even in the Tyrol, though intense fahlore copper production at that time is proved in Schwaz/Brixlegg (Staudt et al. in this volume). At least the few pure fahlore copper axes are from the Tyrol (7 pieces) but also from Salzburg (2 pieces), dating to Ha B2, Ha B3 and Ha C1-D2. Pure chalcopyrite copper is present in all regions and phases of this time segment (Fig. 10 c).

Chronological development of alloying techniques in the Eastern Alps from the Early Bronze Age to the Early Iron Age

The earliest alloyed pieces (5 objects dating to BA A2) have a median tin content of 6.7 mass%. This value rises to 10 mass% within BA A2-B2. Notably three unalloyed flanged axes from the Tyrol[27] dating to this time segment are all made of fahlore copper, which indicates, that these artefacts rather date to BA A2 within their possible lifespan (BA A2-B1). Furthermore there are seven axes with pretty high tin contents of more than 10 mass% - one even with 14 mass% tin (Fig. 11).

While in the Middle Bronze Age and the earlier phase of the Late Bronze Age some statistical outliers still display similar minimum and maximum tin contents like in the periods before, the majority of objects (61 of 80 pieces) is alloyed with 8 to about 12 mass% tin, with a median in these periods of 9.7 mass%. Chalcopyrite copper and tin supply seem very stable and alloying quite standardized in this era. This can be considered as one reason which made the success of chalcopyrite copper possible (cf. Kienlin, 2008) (Fig. 11).

In the later phase of the Late Bronze Age changes can be observed: 55% of the objects now have a tin content less than 8 mass% and the median drops to 7.2 mass%. Maybe tin supply is not able to keep up with the risen bronze demand already mentioned as one possible reason for revived fahlore copper production (Fig. 11).

In the Early Iron Age tin supply seems more stable again. 41 of 43 axes dating to this period are alloyed with more than 8 mass% tin, leading to a median of 10 mass%. As during all periods, there are statistical outliers, one with 6.2 mass% and one with only 3.2 mass%. Remarkable are the high lead contents in the Early Iron Age. While in all other periods nearly all objects (except 10) have a lead content lower than 0.5 mass%, most of the Ha C1-D2 axes lie above 0.5 mass% lead, with an accumulation of axes around 1 mass%. Tin concentrations in the Middle Bronze Age and earlier phase of the Late Bronze Age are very similar to the ones in Ha C1-D2, but lead contents differ significantly. Consequently the lead does not come into the objects as a natural component of tin, at least not in the amount claimed. Examinations on the so called Kathreinfund, the Ha C-D hoard from Fliess – from which most of the examined axes derive (38 of 43) – showed that there is a positive correlation between the lead content and fahlore copper, meaning the lead comes into these objects together with the fahlore copper component – whereby the lead isotopes fit the Brixlegg district very well (Lutz et al., 2011, Lutz & Schwab, 2014). On the other hand, when comparing the axes based on fahlore and diluted fahlore copper from the later phase of the Late Bronze Age to the ones from the Early Iron Age, a significantly different median lead content is observed (0.28 mass% for the former versus 0.77 mass% for the latter) (Fig. 11). It would be worthwhile to examine if this could correlate with different working zones within the Schwaz and Brixlegg mining districts.

Another explanation for the risen lead contents in the Early Iron Age would be that tin diluted with lead is exchanged, as reaction to risen demand. Tin alloyed with 10% of lead would yield to 1% lead in a bronze object with 9 % tin, which would not change bronze-quality significantly from a technical point of view (Dies, 1967). The latter would be an argument against intentional admitting of such a small amount of lead for any other reason than for saving tin.

While tin and lead do not seem to correlate, there is a negative correlation of tin and the fahlore copper determining elements silver and antimony within the examined axes in the later phase of the Late Bronze Age (Fig. 12). This was already shown for objects from Northern Tyrol, Southern Bavaria and Salzburg (Stöllner et al., 2016, esp. Figs. 16a and b). The more silver and antimony, the less tin – indicating selective alloying in the sense of saving tin when using fahlore copper, which is naturally alloyed with arsenic and antimony. These elements can substitute tin to some extent. Therefore the axes based on diluted fahlore copper or pure fahlore copper respectively have a median tin content of only 6.0 mass%. On the opposite axes based on chalcopyrite copper are alloyed with a median tin content of 9.6 mass%. This is also visible during the Early Iron Age – though minimized – when tin supply seems to be sufficient again.

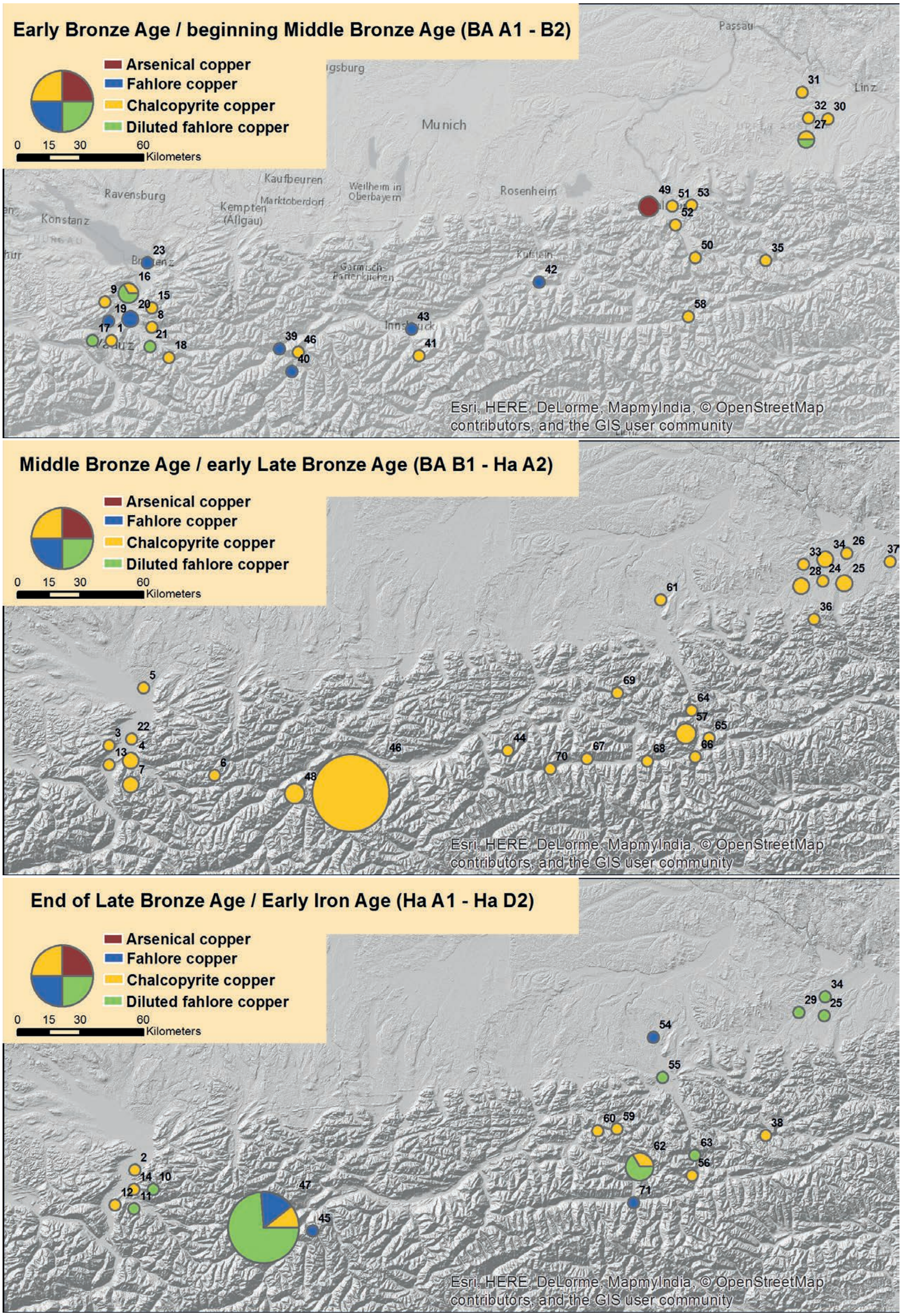

Fig. 10 a / b / c: Chronological and spatial development of the use of different copper types in the Eastern Alps.

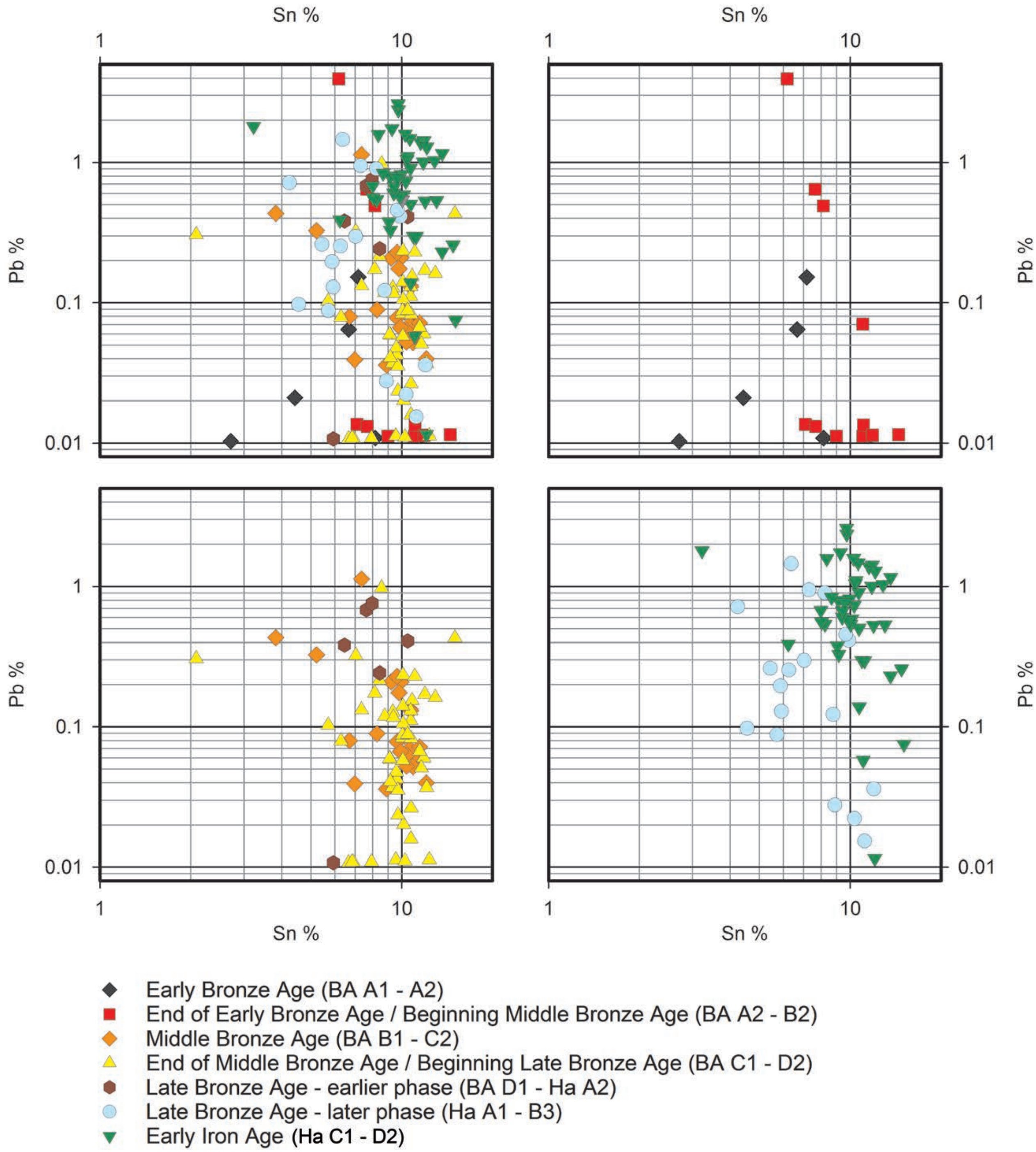

Fig. 11: Tin compared to lead contents through time show no correlation between the two elements. A rise of lead contents in the Early Iron Age is apparent, which could depict a lead rich copper source or tin diluted with lead.

It should also be mentioned that mixing tin-bronze scrap metal based on chalcopyrite copper with fresh fahlore copper could yield a similar composition. Anyhow this practice might not have played a major role as recycling is not observed on large scale anyways, as already discussed above.

Finally nearly no correlation of tin with silver and none with antimony is observed in the chalcopyrite copper dominated periods.

Summary

The analyses of 175 Early Bronze Age to Early Iron Age axes show a differentiated and sequential use of copper ores and tin in correlation to each other in Western Austria. According to the technical development of metallurgy the earliest phase of the Bronze Age (BA A1) is characterized by the use of fahlore copper complemented by arsenical copper. In BA A2 chalcopyrite copper appears though

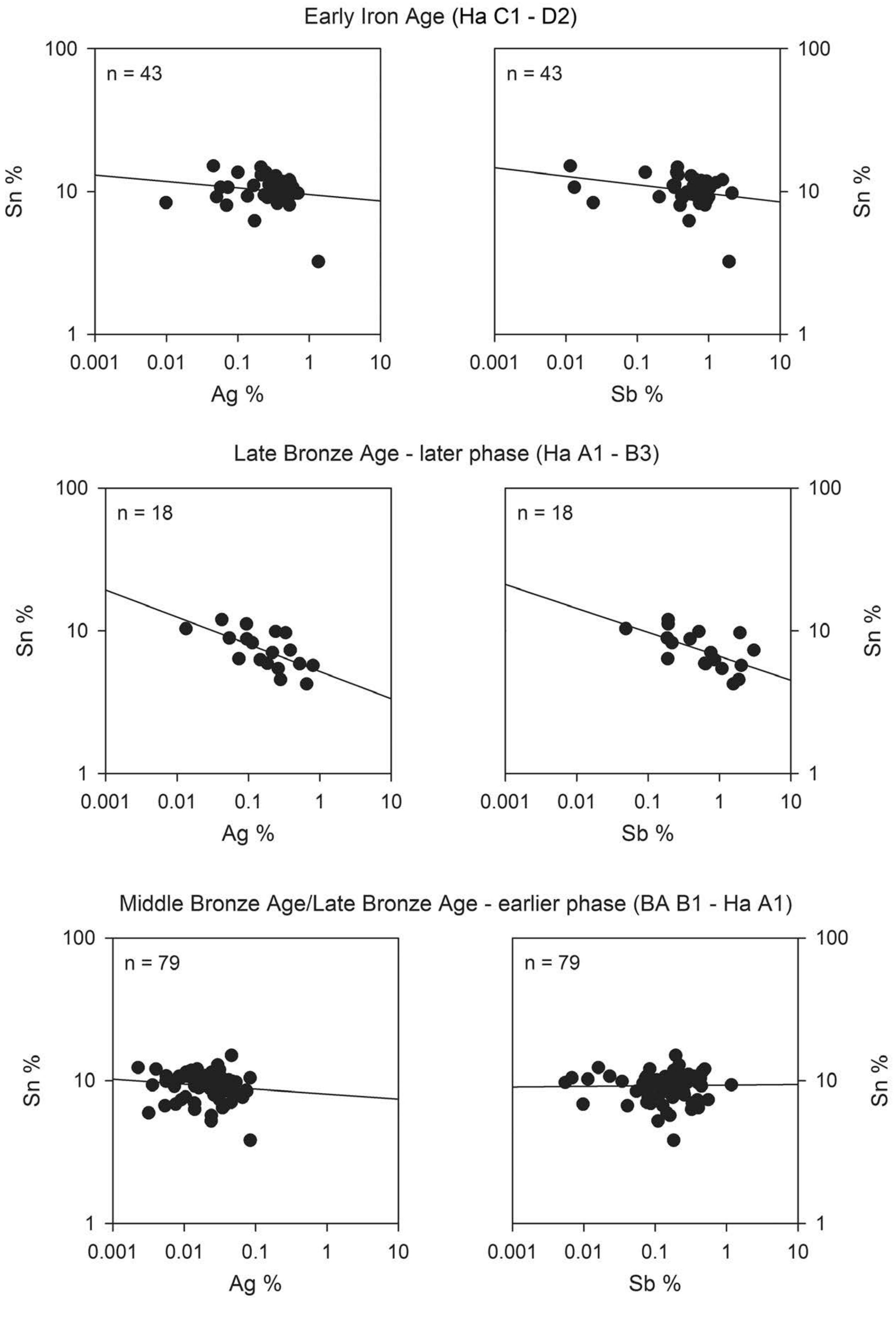

Fig. 12: Correlation of tin and the typical fahlore copper elements silver and antimony. Especially during the later phase of the Late Bronze Age negative correlation shows very well, that tin was intentionally saved when using fahlore copper.

until BA B1 fahlore copper is still in use. From BA B2 on chalcopyrite copper clearly dominates the metal supply for more than 300 years. Until Ha A1 there is not a single axe made of fahlore copper, even not in the variant of diluted fahlore copper. It seems that due to the chalcopyrite copper supply[28] together with a regular tin supply fahlore copper is no longer of interest. The previously popular fahlore copper as a natural alloy falls behind, as objects with the same or better properties can be produced more easily with the purer chalcopyrite copper and tin (see also Kienlin, 2008). After its comeback in Ha A1 it is first recognized within diluted fahlore copper, from Ha B2 on also as pure fahlore copper. Anyway the axes do not show a replacement of chalcopyrite copper by fahlore copper, although with the Schwaz/Brixlegg district there is a potent fahlore copper producer for that period and region. The amount of the available chalcopyrite copper is still remarkable. As the Kitzbühel district does not seem to produce anymore at that time and production at the Mitterberg takes only place on a smaller scale other chalcopyrite dominated mining districts, like in the Trentino, must be taken into account as important copper suppliers.

Regarding alloying, two observations can be pointed out. From Ha A1 on the by than quite standardized tin contents decrease contemporaneous with the reuse of fahlore copper. It cannot be decided yet, whether fahlore is reused to compensate a declining tin supply, or due to an increasing bronze demand, which only secondarily allows to economize tin when using fahlore copper. As mentioned also recycling would be a possibility, though unlikely. In the Early Iron Age not only tin contents rise again, but also lead contents increase to a median value of 0.68 mass%[29] in contrast to a median of 0.08 mass% for all periods before. Whether this is also a hint on a problematic tin supply, which maybe was petered with lead, or if the lead comes in together with a new type of copper, needs to be investigated. Intentionally alloying with lead seems rather unlikely as mentioned above.

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Notes

1 D - Germany, A – Austria, CH – Switzerland.

2 History of Mining Activities in the Tyrol and Adjacent Areas - Impact on Environment & Human Societies.

3 Including Vorarlberg, North Tyrol, Salzburg and Upper Austria and therefore covering large parts of the Eastern Alps.

4 23 of them deriving from Vorarlberg itself, 4 from Liechtenstein, 1 from Switzerland and 1 from the Bodensee/Germany.

5 Kindly provided by courtesy of Thomas Stöllner, Ruhr-University and DBM Bochum (cf. also Stöllner et al., 2016).

6 At the time of the measurements each under the direction of Ernst Pernicka.

7 Cf. Tab. 1.

8 Research of *the Bayerisches Landesamt für Denkmalpflege* on the Middle and Late Bronze Age copper supply in Southern Bavaria, Salzburg and North Tyrol; measured at the TU Bergakademie Freiberg, Ernst Pernicka.

9 Measured at the Curt-Engelhorn-Centre Archaeometry Mannheim.

10 At the Curt-Engelhorn-Centre Archaeometry Mannheim.

11 Studien zu den Anfängen der Metallurgie (Junghans et al., 1960).

12 Sampling of additional objects from the Tiroler Landesmuseum Ferdinandeum was not possible.

13 Thanks to the cooperations with the Amt für Bodendenkmäler, Autonome Provinz Bozen – Südtirol, Catrin Marzoli, Umberto Tecchiati, the Palais Mamming Museum, Elmar Gobbi, the Soprintendenza per i beni culturali, Franco Marzatico and the Museo Castello del Buonconsiglio Laura Dal Prà, Silvano Zamboni.

14 As well as further objects from Salzburg and Northern Tyrol.

15 Kindly provided by Ulrike Töchterle, Restauration, Institute for Archaeologies, University of Innsbruck.

16 HiMAT and SSN data.

17 The median antimony content for the fahlore copper ingots is 6.7 mass%, for the chalcopyrite copper ingots 0.02 mass%.

18 E.g. Riedhöfl, though this deposit also contains clearly Middle Bronze Age objects.

19 *„Probe 342/94: konv. 14C Alter BP: 3158 +/-34, kal. Alter 1 Sigma: BC 1435 – 1400“* (Tschurtschenthaler/Wein 1998, footnote 21, no laboratory code given).

20 As silver is a precious metal contents rise very slightly from ore to object, but not to this extent. Antimony contents would drop anyways.

21 Which is the detection limit for silver with XRF-analyses.

22 Already discussed for the Kathreinfund/Fließ (Lutz et al., 2011).

23 See definitions mentioned above based on the silver contents: less than 0.1 mass% for chalcopyrite copper, equal or more than 0.1 mass% to equal or less than 0.5 mass% for diluted fahlore copper or mixed copper respectively, more than 0.5 mass% for fahlore copper.

24 In terms of chalcopyrite copper, not in comparison with fahlore copper.

25 The so called Kathreinfund, which also includes some italic types (Sydow, 1995).

26 Interestingly the median silver content of all objects within the hoard find is only 0.27 mass%, which means that in comparison to other objects a slightly higher fahlore copper portion was used for the axes.

27 No. HiB063, HiB066 and HiB067.

28 The Mitterberg district starts its production in the 17th century (Stöllner et al., 2016).

29 For all axes, including the ones based on chalcopyrite copper.

DACH-No.	Axe type/variation		Dating	Dating Group	Copper type	Findspot, province or country	No. map	Analysed by	Literature	Inventory-No.
HiB008	RLB	Norddeutscher Typ	BA B1-B2	3	CC	Schaan, FL	1	CEZA	Abels (1972, No. 433)	PR 632
HiB009	LPB	Haidach/Trössing	Ha A1-B3	7	CC	Götzis/Ruine Neumontfort, Vbg.	2	CEZA	Mayer (1977, No. 700); Heeb (2012)	PR 561
HiB010	LPB	Grigny	Ha A1	6	CC	Feldkirch/Tosters, Vbg.	3	CEZA	Mayer (1977, No. 621); Heeb (2012)	PR 596
HiB011	LPB	breites mittelständiges	Ha A1	6	CC	Feldkirch/Bickel'sche Ziegelei, Vbg.	4	CEZA	Mayer (1977, No. 622); Heeb (2012)	PR 587
HiB012	LPB	Freudenberg/Retz	BA C2-D1	5	CC	Lindau/Bodensee, GER	5	CEZA	Pászthory & Mayer (1998, No. 518)	PR 573
HiB013	LPB	herabgezogene Lappen	BA C2-D1	5	CC	Stutz, Vbg.	6	CEZA	Mayer (1977, No. 631)	PR 617
HiB014	LPB	herabgezogene Lappen	BA C2-D1	5	CC	Feldkirch, Vbg.	7	CEZA	Mayer (1977, No. 626)	PR 563
HiB015	LPB	breites mittelständiges	Ha A1	6	CC	Feldkirch/Bickel'sche Ziegelei, Vbg.	4	CEZA	Mayer (1977, No. 620), Heeb (2012)	PR 588
HiB016	LPB	herabgezogene Lappen	BA C2-D1	5	CC	Feldkirch, Vbg.	7	CEZA	Mayer (1977, No. 625)	PR 1939.1
HiB017	RLB	Langquaid I/Linz-St. Peter	BA A2	2	CC	Schnifis/Bassigg, Vbg.	8	CEZA	Mayer (1977, No. 270); Heeb (2012)	without No.
HiB018	RLB	Möhlin/A	BA B1	3	CC	Feldkirch/Paspels, Vbg.	9	CEZA	Heeb (2012, No. 303)	PR 1988.1
HiB019	OS LPB	mit Öse	Ha B2-B3	7	DFC	Zwischenwasser, Vbg.	10	CEZA	Mayer (1977, No. 791); Heeb (2012)	PR 604
HiB021	OS LPB	mit Schulterbildung	Ha C1-C2	8	DFC	Göfis, Vbg.	11	CEZA	Mayer (1977, No. 898); Heeb (2012)	PR 556
HiB022	LPB	Hallstatt	Ha C1-D2	8	CC	Nendeln, FL	12	CEZA	Gridling (2016)	PR 564
HiB023	LPB	abgesetzter hoher Oberteil	BA D1-D2	6	CC	Eschen-Nendeln, FL	13	CEZA	Frei (1954/55, Taf. XXVII, 5)	PR (19)19.1*
HiB024	LPB	Hallein	Ha C1	8	CC	Rankweil, Vbg.	14	CEZA	Mayer (1977, No. 884); Heeb 2012)	PR 626
HiB025	RLB	Neerach/A	BA B2	3	CC	Dünserberg, Vbg.	15	CEZA	Heeb (2012, No. 293)	PR 1993.3
HiB026	RLB	Langquaid II/Koblach	BA A2	2	DFC	Koblach-Kadel, Vbg.	16	TUF	Mayer (1977, No. 277); Heeb (2012)	PR (19)58.1
HiB027	RLB	Langquaid II/Koblach	BA A2	2	DFC	Koblach-Kadel, Vbg.	16	TUF	Mayer (1977, No. 275); Heeb (2012)	PR (19)58.2
HiB028	RLB	Langquaid II/Koblach	BA A2	2	CC	Koblach-Kadel, Vbg.	16	TUF	Mayer (1977, No. 276); Heeb (2012)	PR (19)58.3
HiB029	RLB	Nehren/A	BA B1	3	DFC	Gamprin/Bendern, FL	17	TUF	Abels (1972, No. 435); Heeb (2012)	PR 580
HiB030	RLB	Langquaid II	BA A2	2	CC	Gantschier/Hosensee, Vbg.	18	TUF	Mayer (1977, No. 287)	PR 1956.1688**
HiB031	RLB	Salez/A	BA A1	1	FC	St. Gallen/Salez, CH	19	CEZA	Abels (1972, No. 29); Heeb (2012)	PR 569
HiB032	RLB	Salez/D	BA A1	1	FC	Feldkirch/Levis, Vbg.	20	TUF	Mayer (1977, No. 231); Heeb (2012)	PR 621
HiB033	RLB	Regensburg/Nüziders	BA B1	3	DFC	Nüziders, Vbg.	21	TUF	Mayer (1977, No. 298); Heeb (2012)	PR 567
HiB034	RLB	Salez/A	BA B2-C1	4	CC	Koblach/Ruine Neuburg, Vbg.	22	TUF	Mayer (1977, No. 315); Heeb (2012)	PR (19)13.1
HiB035	RLB	Neyruz	BA A1	1	FC	Bregenz/Rieden-Vorkloster, Vbg.	23	TUF	Mayer (1977, No. 221); Heeb (2012)	PR (19)58.5
HiB037	RLB	Salez/D	BA A1	1	FC	Feldkirch/Levis, Vbg.	20	TUF	Mayer (1977, No. 232); Heeb (2012)	PR 620

DACH-No.	Axe type/variation		Dating	Dat-ing Group	Cop-per type	Findspot, province or country	No. map	Ana-lysed by	Literature	Inventory-No.
HiB038	LPB	Freudenberg/Retz	BA C2-D1	5	CC	Wels/Rosenau, OÖ	24	CEZA	Mayer (1977, No. 552)	10619
HiB039	LPB	Freudenberg/Retz	BA C2-D1	5	CC	Thalheim bei Wels/Aschet, OÖ	25	CEZA	Mayer (1977, No. 572)	14004
HiB040	LPB	Freudenberg	BA C1-D2	5	CC	Thalheim bei Wels/Aschet, OÖ	25	CEZA	Mayer (1977, No. 499)	48
HiB041	LPB	Freudenberg	BA C1-D2	5	CC	Wels/Schafwiesen, OÖ	26	CEZA	Mayer (1977, No. 498)	13473
HiB043	RLB	Norddeutscher Typ	BA B1-B2	3	DFC	Wels/Brandln, OÖ	27	CEZA	Mayer (1977, No. 317)	13525
HiB044	RLB	Norddeutscher Typ	BA B1-B2	3	CC	Wels/Brandln, OÖ	27	CEZA	Mayer (1977, No. 318)	13538
HiB047	LPB	Greiner Strudel/ Niederalm	BA C2-D1	5	CC	Steinhaus/Traunleiten, OÖ	28	CEZA	Mayer (1977, No. 615)	14901
HiB049	TB	mit Öse	Ha A2-B2	7	DFC	Stadl Paura/Lambach, OÖ	29	CEZA	Mayer (1977, No. 1024)	13763
HiB050	RLB	Mägerkingen/Wels	BA B1-B2	3	CC	Wels/Pernau, OÖ	30	CEZA	Mayer (1977, No. 324)	1253
HiB051	ABB	offener Absatz	BA A2-B1	3	CC	St. Thomas, OÖ	31	CEZA	Mittermaier (2017)	217904
HiB052	ABB	gedrungen herzför-mige Rast	BA A2-B1	3	CC	Gunskirchen/Fernreith, OÖ	32	CEZA	Mayer (1977, No. 388)	13762
HiB053	LPB	Freudenberg/Amlach	BA C2-D2	5	CC	Gunskirchen, OÖ	33	CEZA	Mayer (1977, No. 601)	14764
HiB054	TB	winkel- und bogenver-ziert	Ha A2-B3	7	DFC	Wels, OÖ	34	CEZA	Mayer (1977, No. 1064)	13353
HiB055	TB	ohne Öse	BA D1-Ha A1	6	CC	Steinhaus/Traunleiten, OÖ	28	CEZA	Mayer (1977, No. 1032)	12043
HiB056	ABB	langgestreckt herzförmige Rast	BA C1-D1	5	CC	Wels, OÖ	34	CEZA	Mayer (1977, No. 418)	12063
HiB057	LPB	Freudenberg/ Elixhausen	BA B1-C2	4	CC	Wels, OÖ	34	CEZA	Mayer (1977, No. 514)	10618
HiB058	TB	winkel- und bogenver-ziert	Ha A2-B3	7	DFC	Thalheim bei Wels/Aschet, OÖ	25	CEZA	Mayer (1977, No. 1073)	10617
HiB059	ABB	gedrungen herzför-mige Rast	BA A2-B1	3	CC	Hallstatt/Rudolfsturm, OÖ	35	CEZA	Mayer (1977, No. 377)	A669
HiB060	ABB	spitze Rast	BZ B1-C1	4	CC	Viechtwang/Mühldorf, OÖ	36	CEZA	Mayer (1977, No. 429)	A642
HiB061	NSA	B3/Tîrguşor	BA D1-Ha A2	6	CC	Linz/Kronstorf, OÖ	37	CEZA	Mayer (1977, No. 86)	A3143
HiB062	TB	meißelartig	Ha C1-C2	8	CC	Hallstatt/Gräberfeld, OÖ	38	CEZA	Mayer (1977, No. 1160)	A2672
HiB063	RLB	Emmerberg	BA A2-B1	3	FC	Perjen, Tir.	39	O/W	Mayer (1977, No. 307)	TLM 62
HiB064	RLB	Langquaid II	BA A2	2	FC	Ried im Oberinntal, Tir.	40	O/W	Mayer (1977, No. 290)	TLM 1131
HiB065	RLB	Mägerkingen/A	BA B1-B2	3	CC	Matrei am Brenner/ Mühlbachl, Tir.	41	O/W	Mayer (1977, No. 321)	TLM 8933
HiB066	RLB	Randleistenbeil	BA A2-B1	3	FC	Hopfgarten/Hohe Salve, Tir.	42	TUF	Huijsmans (1994); Wada (1975)	TLM 29
HiB067	RLB	Emmerberg/Wilten	BA A2-B1	3	FC	Innsbruck/Berg Isel, Tir.	43	TUF	Mayer (1977, No. 308)	TLM 30
HiB068	LPB	breites mittelständiges	BA C1-D2	5	CC	Alpbach/Steinberg Alpe, Tir.	44	TUF	Mayer (1977, No. 624)	TLM 34
HiB069	OS LPB	ohne Öse	Ha B2-B3	7	FC	Ritzenried im Pitztal, Tir.	45	TUF	Mayer (1977, No. 921)	TLM 18.407

DACH-No.	Axe type/variation		Dating	Dat-ing Group	Cop-per type	Findspot, province or country	No. map	Ana-lysed by	Literature	Inventory-No.
HiB070	RLB	Grenchen	BA B2-C1	4	CC	Piller/Moosbruckschrofen, Tir.	46	CEZA	Tomedi (2001, 79)	PM 017
HiB071	RLB	Grenchen	BA B2-C1	4	CC	Piller/Moosbruckschrofen, Tir.	46	CEZA	Tomedi (2002a, 78)	PM 029
HiB072	RLB	Grenchen	BA B2-C1	4	CC	Piller/Moosbruckschrofen, Tir.	46	CEZA	unpublished	PM 052-071
HiB073	RLB	Grenchen	BA B2-C1	4	CC	Piller/Moosbruckschrofen, Tir.	46	CEZA	Nicolussi Castellan (2002, 48)	PM 057
HiB074	RLB	Grenchen	BA B2-C1	4	CC	Piller/Moosbruckschrofen, Tir.	46	CEZA	unpublished	PM 060
HiB076	RLB	Grenchen	BA B2-C1	4	CC	Piller/Moosbruckschrofen, Tir.	46	CEZA	unpublished	PM 082
HiB077	RLB	Grenchen	BA B2-C1	4	CC	Piller/Moosbruckschrofen, Tir.	46	CEZA	Tomedi (2001, 77)	PM 083-145
HiB078	RLB	Grenchen	BA B2-C1	4	CC	Piller/Moosbruckschrofen, Tir.	46	CEZA	unpublished	PM 099
HiB079	RLB	Grenchen	BA B2-C1	4	CC	Piller/Moosbruckschrofen, Tir.	46	CEZA	unpublished	PM 103
HiB080	RLB	Grenchen	BA B2-C1	4	CC	Piller/Moosbruckschrofen, Tir.	46	CEZA	Nicolussi Castellan (2002, 49)	PM 122
HiB081	RLB	Grenchen	BA B2-C1	4	CC	Piller/Moosbruckschrofen, Tir.	46	CEZA	unpublished	PM 123-288
HiB083	RLB	Grenchen	BA B2-C1	4	CC	Piller/Moosbruckschrofen, Tir.	46	CEZA	unpublished	PM 126
HiB084	RLB	Grenchen	BA B2-C1	4	CC	Piller/Moosbruckschrofen, Tir.	46	CEZA	unpublished	PM 127
HiB085	RLB	Grenchen	BA B2-C1	4	CC	Piller/Moosbruckschrofen, Tir.	46	CEZA	unpublished	PM 134-336
HiB087	RLB	m. z. Schneide herabg. Lappen	BA C1-D1	5	CC	Piller/Moosbruckschrofen, Tir.	46	CEZA	unpublished	PM 213
HiB088	RLB	Grenchen	BA B2-C1	4	CC	Piller/Moosbruckschrofen, Tir.	46	CEZA	unpublished	PM 224
HiB090	RLB	Grenchen	BA B2-C1	4	CC	Piller/Moosbruckschrofen, Tir.	46	CEZA	Tomedi (2002a, 77)	PM 242
HiB091	RLB	Grenchen	BA B2-C1	4	CC	Piller/Moosbruckschrofen, Tir.	46	CEZA	unpublished	PM 324
HiB092	LPB	Freudenberg	BA C1-D1	5	CC	Piller/Moosbruckschrofen, Tir.	46	CEZA	unpublished	PM 004
HiB093	LPB	Freudenberg	BA C1-D1	5	CC	Piller/Moosbruckschrofen, Tir.	46	CEZA	unpublished	PM 033
HiB094	LPB	m. z. Schneide herabg. Lappen	BA C1-D1	5	CC	Piller/Moosbruckschrofen, Tir.	46	CEZA	unpublished	PM 034
HiB095	LPB	Kösching	BA C1-D1	5	CC	Piller/Moosbruckschrofen, Tir.	46	CEZA	unpublished	PM 090
HiB096	LPB	Freudenberg	BA C1-D1	5	CC	Piller/Moosbruckschrofen, Tir.	46	CEZA	Tomedi (2002b, 44)	PM 093
HiB097	LPB	Freudenberg	BA C1-D1	5	CC	Piller/Moosbruckschrofen, Tir.	46	CEZA	unpublished	PM 095
HiB098	LPB	Freudenberg	BA C1-D1	5	CC	Piller/Moosbruckschrofen, Tir.	46	CEZA	unpublished	PM 112
HiB099	LPB	Guntramsdorf	BA C2-D2	5	CC	Piller/Moosbruckschrofen, Tir.	46	CEZA	unpublished	PM 113
HiB100	LPB	Freudenberg	BA C1-D1	5	CC	Piller/Moosbruckschrofen, Tir.	46	CEZA	unpublished	PM 135
HiB101	LPB	Freudenberg	BA C1-D1	5	CC	Piller/Moosbruckschrofen, Tir.	46	CEZA	unpublished	PM 136

DACH-No.	Axe type/variation		Dating	Dat-ing Group	Cop-per type	Findspot, province or country	No. map	Ana-lysed by	Literature	Inventory-No.
HiB102	LPB	Freudenberg	BA C1-D1	5	CC	Piller/Moosbruckschrofen, Tir.	46	CEZA	unpublished	PM 148
HiB103	LPB	Freudenberg	BA C1-D1	5	CC	Piller/Moosbruckschrofen, Tir.	46	CEZA	unpublished	PM 157
HiB105	LPB	Freudenberg	BA C1-D1	5	CC	Piller/Moosbruckschrofen, Tir.	46	CEZA	unpublished	PM 169
HiB106	LPB	Freudenberg	BA C1-D1	5	CC	Piller/Moosbruckschrofen, Tir.	46	CEZA	Nicolussi Castellan (2002, 49)	PM 170
HiB107	LPB	Kösching	BA C1-D1	5	CC	Piller/Moosbruckschrofen, Tir.	46	CEZA	unpublished	PM 172
HiB108	LPB	Freudenberg	BA C1-D1	5	CC	Piller/Moosbruckschrofen, Tir.	46	CEZA	unpublished	PM 175
HiB109	LPB	Freudenberg	BA C1-D1	5	CC	Piller/Moosbruckschrofen, Tir.	46	CEZA	unpublished	PM 185
HiB110	LPB	Freudenberg	BA C1-D1	5	CC	Piller/Moosbruckschrofen, Tir.	46	CEZA	unpublished	PM 192
HiB111	LPB	Freudenberg	BA C1-D1	5	CC	Piller/Moosbruckschrofen, Tir.	46	CEZA	unpublished	PM 208
HiB112	LPB	Freudenberg	BA C1-D1	5	CC	Piller/Moosbruckschrofen, Tir.	46	CEZA	unpublished	PM 214
HiB113	LPB	Freudenberg	BA C1-D1	5	CC	Piller/Moosbruckschrofen, Tir.	46	CEZA	unpublished	PM 215
HiB114	LPB	Freudenberg	BA C1-D1	5	CC	Piller/Moosbruckschrofen, Tir.	46	CEZA	unpublished	PM 219
HiB116	LPB	Freudenberg	BA C1-D1	5	CC	Piller/Moosbruckschrofen, Tir.	46	CEZA	Nicolussi Castellan (2002, 48)	PM 325
HiB117	ABB	langgestreckt herzförmige Rast	BA C1-D1	5	CC	Piller/Moosbruckschrofen, Tir.	46	CEZA	unpublished	PM 014
HiB118	ABB	langgestreckt herzförmige Rast	BA C1-D1	5	CC	Piller/Moosbruckschrofen, Tir.	46	CEZA	unpublished	PM 059
HiB119	ABB	langgestreckt herzförmige Rast	BA C1-D1	5	CC	Piller/Moosbruckschrofen, Tir.	46	CEZA	Tomedi (2002b, 44)	PM 084
HiB120	ABB	langgestreckt herzförmige Rast	BA C1-D1	5	CC	Piller/Moosbruckschrofen, Tir.	46	CEZA	Tomedi (2001, 77)	PM 257
HiB122	RLB	Cressier	BA B1-B2	3	CC	Piller/Moosbruckschrofen, Tir.	46	CEZA	Tomedi (2002b, 44)	PM 188
HiB123	LPB	Hallstatt	Ha C1-D2	8	DFC	Fließ/Kathrein Hof, Tir.	47	CEZA	Sydow (1995)	1
HiB124	LPB	Hallstatt	Ha C1-D2	8	DFC	Fließ/Kathrein Hof, Tir.	47	CEZA	Sydow (1995)	2
HiB125	LPB	Hallstatt	Ha C1-D2	8	DFC	Fließ/Kathrein Hof, Tir.	47	CEZA	Sydow (1995)	3
HiB126	LPB	Hallstatt	Ha C1-D2	8	DFC	Fließ/Kathrein Hof, Tir.	47	CEZA	Sydow (1995)	4
HiB127	LPB	Hallstatt	Ha C1-D2	8	DFC	Fließ/Kathrein Hof, Tir.	47	CEZA	Sydow (1995)	5
HiB128	LPB	Hallstatt	Ha C1-D2	8	DFC	Fließ/Kathrein Hof, Tir.	47	CEZA	Sydow (1995)	6
HiB129	LPB	Hallstatt	Ha C1-D2	8	DFC	Fließ/Kathrein Hof, Tir.	47	CEZA	Sydow (1995)	7
HiB130	LPB	Hallstatt	Ha C1-D2	8	FC	Fließ/Kathrein Hof, Tir.	47	CEZA	Sydow (1995)	8
HiB131	LPB	Hallstatt	Ha C1-D2	8	CC	Fließ/Kathrein Hof, Tir.	47	CEZA	Sydow (1995)	9
HiB132	LPB	Hallstatt	Ha C1-D2	8	DFC	Fließ/Kathrein Hof, Tir.	47	CEZA	Sydow (1995)	10

DACH-No.	Axe type/variation		Dating	Dating Group	Copper type	Findspot, province or country	No. map	Analysed by	Literature	Inventory-No.
HiB133	LPB	Hallstatt	Ha C1-D2	8	DFC	Fließ/Kathrein Hof, Tir.	47	CEZA	Sydow (1995)	11
HiB134	LPB	Hallstatt	Ha C1-D2	8	FC	Fließ/Kathrein Hof, Tir.	47	CEZA	Sydow (1995)	12
HiB135	LPB	Hallstatt	Ha C1-D2	8	DFC	Fließ/Kathrein Hof, Tir.	47	CEZA	Sydow (1995)	13
HiB136	LPB	Hallstatt	Ha C1-D2	8	DFC	Fließ/Kathrein Hof, Tir.	47	CEZA	Sydow (1995)	14
HiB137	LPB	Hallstatt	Ha C1-D2	8	DFC	Fließ/Kathrein Hof, Tir.	47	CEZA	Sydow (1995)	15
HiB138	LPB	Hallstatt	Ha C1-D2	8	FC	Fließ/Kathrein Hof, Tir.	47	CEZA	Sydow (1995)	16
HiB139	LPB	Hallstatt	Ha C1-D2	8	FC	Fließ/Kathrein Hof, Tir.	47	CEZA	Sydow (1995)	17
HiB140	LPB	Hallstatt	Ha C1-D2	8	CC	Fließ/Kathrein Hof, Tir.	47	CEZA	Sydow (1995)	18
HiB141	LPB	Hallstatt	Ha C1-D2	8	DFC	Fließ/Kathrein Hof, Tir.	47	CEZA	Sydow (1995)	19
HiB142	LPB	Hallstatt	Ha C1-D2	8	CC	Fließ/Kathrein Hof, Tir.	47	CEZA	Sydow (1995)	20
HiB143	LPB	Hallstatt	Ha C1-D2	8	DFC	Fließ/Kathrein Hof, Tir.	47	CEZA	Sydow (1995)	21
HiB144	LPB	Hallstatt	Ha C1-D2	8	DFC	Fließ/Kathrein Hof, Tir.	47	CEZA	Sydow (1995)	22
HiB145	LPB	Hallstatt	Ha C1-D2	8	DFC	Fließ/Kathrein Hof, Tir.	47	CEZA	Sydow (1995)	23
HiB146	LPB	Hallstatt	Ha C1-D2	8	DFC	Fließ/Kathrein Hof, Tir.	47	CEZA	Sydow (1995)	24
HiB147	LPB	Hallstatt	Ha C1-D2	8	DFC	Fließ/Kathrein Hof, Tir.	47	CEZA	Sydow (1995)	25
HiB148	LPB	Hallstatt	Ha C1-D2	8	FC	Fließ/Kathrein Hof, Tir.	47	CEZA	Sydow (1995)	26
HiB149	LPB	Hallstatt	Ha C1-D2	8	DFC	Fließ/Kathrein Hof, Tir.	47	CEZA	Sydow (1995)	27
HiB150	LPB	Hallstatt	Ha C1-D2	8	FC	Fließ/Kathrein Hof, Tir.	47	CEZA	Sydow (1995)	28
HiB151	LPB	Hallstatt	Ha C1-D2	8	DFC	Fließ/Kathrein Hof, Tir.	47	CEZA	Sydow (1995)	29
HiB152	LPB	Hallstatt	Ha C1-D2	8	DFC	Fließ/Kathrein Hof, Tir.	47	CEZA	Sydow (1995)	30
HiB153	LPB	Hallstatt	Ha C1-D2	8	DFC	Fließ/Kathrein Hof, Tir.	47	CEZA	Sydow (1995)	31
HiB154	LPB	Hallstatt	Ha C1-D2	8	CC	Fließ/Kathrein Hof, Tir.	47	CEZA	Sydow (1995)	32
HiB155	LPB	Hallstatt	Ha C1-D2	8	DFC	Fließ/Kathrein Hof, Tir.	47	CEZA	Sydow (1995)	33
HiB156	LPB	Hallstatt	Ha C1-D2	8	DFC	Fließ/Kathrein Hof, Tir.	47	CEZA	Sydow (1995)	34
HiB157	LPB	Hallstatt	Ha C1-D2	8	DFC	Fließ/Kathrein Hof, Tir.	47	CEZA	Sydow (1995)	35
HiB158	LPB	Hallstatt	Ha C1-D2	8	DFC	Fließ/Kathrein Hof, Tir.	47	CEZA	Sydow (1995)	36
HiB159	LPB	Hallstatt	Ha C1-D2	8	DFC	Fließ/Kathrein Hof, Tir.	47	CEZA	Sydow (1995)	37
HiB160	LPB	Hallstatt	Ha C1-D2	8	DFC	Fließ/Kathrein Hof, Tir.	47	CEZA	Sydow (1995)	38

DACH-No.	Axe type/variation		Dating	Dat-ing Group	Cop-per type	Findspot, province or country	No. map	Ana-lysed by	Literature	Inventory-No.
HiB161	LPB	Freudenberg/ Niedergößnitz	BA C1	4	CC	Piller/Pillerhöhe, Tir.	48	CEZA	Tschurtschenthaler & Wein (1998)	-
HiB162	LPB	mittelständig	BA C1-D1	5	CC	Piller/Pillerhöhe, Tir.	48	CEZA	Fundberichte Österreich 33 (1994)	-
HiB163	LPB	mittelständig	BA C1-D1	5	CC	Piller/Pillerhöhe, Tir.	48	CEZA	Fundberichte Österreich 33 (1994)	-
HiB164	FB	Salzburg/Rainberg	BA A1	1	AC	Salzburg/Mönchsberg, Sbg.	49	O/W	Mayer (1977, No. 186)	2658
HiB165	FB	Salzburg/Rainberg	BA A1	1	AC	Salzburg/Mönchsberg, Sbg.	49	O/W	Mayer (1977, No. 187)	2659
HiB166	FB	Salzburg/Rainberg	BA A1	1	AC	Salzburg/Mönchsberg, Sbg.	49	O/W	Mayer (1977, No. 188)	2660
HiB167	RLB	Mägerkingen/A	BA B1-B2	3	CC	Golling/Pass Lueg, Sbg.	50	O/W	Mayer (1977, No. 322)	282
HiB168	RLB	Salzburg	BA B1	3	CC	Salzburg, Sbg.	51	O/W	Mayer (1977, No. 299)	334/24
HiB169	RLB	Salzburg/Hellbrunn	BA B1	3	CC	Salzburg/Hellbrunner Berg, Sbg.	52	O/W	Mayer (1977, No. 301)	2515
HiB170	RLB	Emmersdorf/ Bürglstein	BA A1-A2	2	CC	Aigen/Parsch, Sbg.	53	O/W	Mayer (1977, No. 293)	20
HiB171	OS LPB	mit Öse	Ha B3	7	FC	Lamprechtshausen/ Bürmoos, Sbg.	54	TUF	Mayer (1977, No. 789)	16
HiB172	OS LPB	mit Öse	Ha B3	7	DFC	Wals-Siezenheim/ Siezenheim, Sbg.	55	TUF	Mayer (1977, No. 792)	125/69
HiB173	LPB	Bad Goisern	Ha B1-B2	7	CC	Bischofshofen/Salzach, Sbg.	56	CEZA	Mayer (1977, No. 735)	1726
HiB174	LPB	Freudenberg/Retz	BA C2-D1	5	CC	Mühlbach a. Hochkönig/ Mitterberg, Sbg.	57	TUF	Mayer (1977, No. 558)	1723
HiB175	LPB	Freudenberg/Retz	BA C2-D1	5	CC	Mühlbach a. Hochkönig/ Mitterberg, Sbg.	57	TUF	Mayer (1977, No. 566)	1725
HiB176	LPB	Freudenberg/ Obertraun	BA C1-D2	5	CC	Mühlbach a. Hochkönig/ Mitterberg, Sbg.	57	TUF	Mayer (1977, No. 580)	1724
HiB177	RLB	Randleistenbeil	BA B1-B2	3	CC	Schwarzach, Sbg.	58	CEZA	Stöllner et al. (2016, Fig. 10, 2)	8/89
HiB178	LPB	Bad Goisern/Bad Aussee	Ha B1	7	CC	Lofer, Sbg.	59	CEZA	Mayer (1977, No. 763)	5223
HiB179	LPB	Bad Goisern/Bad Aussee	Ha B1	7	CC	Lofer/Pass Strub, Sbg.	60	CEZA	Mayer (1977, No. 762)	679
HiB180	LPB	Greiner Strudel/ Niederalm	BA C2	4	CC	Lamprechtshausen/Nopping, Sbg.	61	TUF	Mayer (1977, No. 616)	123/69
HiB181	OS LPB	ausschwingende Schneide	Ha B1	7	CC	Saalfelden/Magnesitfeld, Sbg.	62	TUF	Moosleitner (1991, Taf. 18, 8)	-
HiB182	OS LPB	ausschwingende Schneide	Ha B1	7	CC	Saalfelden/Magnesitfeld, Sbg.	62	TUF	Moosleitner (1991, Taf. 18, 6)	-
HiB183	OS LPB	ausschwingende Schneide	Ha B1	7	DFC	Saalfelden/Magnesitfeld, Sbg.	62	TUF	Moosleitner (1991, Taf. 18, 7)	-
HiB184	OS LPB	ausschwingende Schneide	Ha B1	7	DFC	Saalfelden/Magnesitfeld, Sbg.	62	TUF	Moosleitner (1991, Taf. 18, 5)	-
HiB185	OS LPB	ausschwingende Schneide	Ha B1	7	DFC	Saalfelden/Magnesitfeld, Sbg.	62	TUF	Moosleitner (1991, Taf. 18, 2)	-
HiB186	LPB	mittelständig	Ha B1	7	DFC	Saalfelden/Magnesitfeld, Sbg.	62	TUF	Moosleitner (1991, Taf. 18, 4)	-
HiB187	LPB	Hallstatt/Wörschach	Ha B1-B3	7	DFC	Werfen, Sbg.	63	CEZA	Mayer (1977, No. 850)	15
HiB188	LPB	Freudenberg/ Niedergößnitz	BA C1-D1	5	CC	Werfen/Tenneck, Sbg.	64	CEZA	Mayer (1977, No. 541)	121/69

DACH-No.	Axe type/variation		Dating	Dating Group	Copper type	Findspot, province or country	No. map	Analysed by	Literature	Inventory-No.
HiB189	-	Fragment	BA C1-D2	5	CC	Mühlbach a. Hochkönig/ Einödberg, Sbg.	65	CEZA	Stöllner et al. (2016, 104)	531/81
HiB190	LPB	Freudenberg/ Niedergößnitz	BA C1-D1	5	CC	St. Johann im Pongau/ Halldorf, Sbg.	66	CEZA	Mayer (1977, No. 547)	1/69
HiB192	LPB	Freudenberg/Rosenau	BA C1-D2	5	CC	Stuhlfelden/Dürnberg, Sbg.	67	CEZA	Mayer (1977, No. 521)	1261
HiB193	ABB	gedrungen herzförmige Rast	BA B1-C2	4	CC	Gries im Pinzgau, Sbg.	68	CEZA	Mayer (1977, No. 392)	285
HiB194	LPB	breites mittelständiges	BA C1-D2	5	CC	Gumping bei Lofer, Sbg.	69	CEZA	Mayer (1977, No. 623)	281
HiB195	LPB	Gmunden	BA C1-D2	5	CC	Neukirchen im Pinzgau, Sbg.	70	CEZA	Mayer (1977, No. 472)	6082
HiB196	LPB	Lappenbeil	Ha C1-C2	8	FC	Salzburg/Brucker Berg, Sbg.	71	CEZA	Stöllner et al. (2016, Fig. 11, 21)	81/86

*also: 1901.1 (519)
**also: 1957.1688

HiB008 to HiB037: vorarlberg museum
HiB038 to HiB058: Stadtmuseum Wels
HiB059 to HiB062: Oberösterreichisches Landesmuseum
HiB063 to HiB069: Tiroler Landesmuseum Ferdinandeum
HiB070 to HiB163: Archäologisches Museum Fließ
HiB164 to HiB180, HiB187 to HiB196: Salzburg Museum
HiB181 to HiB186: Museum Schloss Ritzen Saalfelden

Abbreviations:
FB = Flachbeil (flat axe)
RLB = Randleistenbeil (flanged axe)
ABB = Absatzbeil (palstave)
LPB = Lappenbeil (winged axe)
OS LPB = oberständiges Lappenbeil (end-winged axe)
TB = Tüllenbeil (socketed axe)
NSA = Nackenscheibenaxt
m. z. Schneide herabg. Lappen =
mit zur Schneide herabgezogenen Lappen

FL = Fürstentum Liechtenstein
GER = Deutschland
CH = Schweiz
Vbg. = Vorarlberg
OÖ = Oberösterreich
Tir. = Tirol
Sbg. = Salzburg

Tab. 1: Short-catalogue of the analysed axes. For corresponding Dating Groups see Tab. 2.

No.	Group	Included lifespans	Definition
1	Beginning Early Bronze Age	BA A1	solely dating to BA A1
2	Early Bronze Age	BA A1-A2	mainly BA A2 lifespans not reaching BA B1
3	End of Early Bronze Age / Beginning Middle Bronze Age	BA A2-B1 BA B1-B2	mainly BA B1 - B2 lifespans neither reaching BA A1 nor C1
4	Middle Bronze Age	BA B1-C1 BA B1-C2 BA B2-C1	mainly BA C1 lifespans neither reaching A2 nor D1
5	End of Middle Bronze Age / Beginning Late Bronze Age	BA C1-D1, BA C1-D2 BA C2-D1, BA C2-D2	mainly BA C2 - D1 lifespans neither reaching BA B2 nor Ha A1, nor solely dating to BA C
6	Late Bronze Age (earlier phase)	BA D1-D2 BA D1-Ha A1 BA D1-Ha A2	mainly BA D2 - Ha A1 lifespans neither reaching BA C2 nor Ha B1, nor solely dating to Ha A
7	Late Bronze Age (later phase)	Ha A1-B3, Ha A1-B1 Ha A2-B2, Ha B1-B2 Ha B1-B3, Ha B2-B3	mainly Ha A2 - B3 lifespans neither reaching BA D2 nor Ha C1
8	Early Iron Age	Ha C1-D2	dating to Ha C1-D2

Tab. 2: Chronology-groups used in this paper and their definition. For dating of every single axe see Tab. 1.

DACH-No.	SAM No.	Lab.-No.	Cu %	Mn %	Fe %	Co %	Ni %	Zn %	As %
HiB008	-	MA-155015	91	< 0,01	< 0,05	0,02	0,21	< 0,1	0,88
HiB009	-	MA-155016	91	< 0,01	< 0,05	0,05	0,35	< 0,1	0,12
HiB010	-	MA-155017	90	< 0,01	0,07	0,05	0,12	< 0,1	0,20
HiB011	-	MA-155018	92	< 0,01	0,28	0,05	0,02	< 0,1	0,06
HiB012	-	MA-155019	96	< 0,01	< 0,05	0,05	0,70	< 0,1	0,63
HiB013	-	MA-155020	90	< 0,01	0,47	0,05	< 0,01	0,1	0,05
HiB014	-	MA-155021	92	< 0,01	0,09	0,05	0,29	< 0,1	0,20
HiB015	-	MA-155022	92	< 0,01	< 0,05	0,04	0,06	< 0,1	0,09
HiB016	-	MA-155023	92	< 0,01	0,10	0,04	0,06	< 0,1	0,15
HiB017	-	MA-155024	92	< 0,01	0,08	0,02	0,19	< 0,1	0,20
HiB018	-	MA-155025	89	< 0,01	0,21	0,03	0,28	< 0,1	0,22
HiB019	-	MA-155026	89	< 0,01	< 0,05	0,06	0,32	< 0,1	0,31
HiB021	-	MA-155028	92	< 0,01	0,11	0,14	0,50	< 0,1	0,30
HiB022	-	MA-155029	91	< 0,01	< 0,05	0,09	0,20	< 0,1	0,29
HiB023	-	MA-155030	92	< 0,01	< 0,05	0,05	0,06	< 0,1	0,16
HiB024	-	MA-155031	91	< 0,01	< 0,05	0,04	< 0,01	0,1	0,19
HiB025	-	MA-155032	93	< 0,01	< 0,05	0,02	0,24	0,1	0,30
HiB026	SAM 2763	FG-810002	95	n.a.	< 0,05	0,01	0,41	< 0,1	0,73
HiB027	SAM 2764	FG-810003	93	n.a.	< 0,05	< 0,01	0,45	< 0,1	0,80
HiB028	SAM 2765	FG-810004	92	n.a.	< 0,05	< 0,01	0,45	< 0,1	0,62
HiB029	SAM 2766	FG-829994	89	n.a.	< 0,05	< 0,01	0,61	< 0,1	0,51
HiB030	SAM 2767	FG-829992	97	n.a.	0,26	0,05	0,04	< 0,1	0,17
HiB031	SAM 2768	MA-160001	84	n.a.	< 0,05	0,60	4,4	< 0,1	2,57
HiB032	SAM 2769	FG-829996	96	n.a.	< 0,05	0,02	0,34	< 0,1	0,69
HiB033	SAM 2770	FG-810007	89	n.a.	< 0,05	< 0,01	0,31	< 0,1	0,16
HiB034	SAM 2771	FG-810005	92	n.a.	0,05	0,02	0,53	< 0,1	0,51
HiB035	SAM 2772	FG-829995	94	n.a.	< 0,05	0,07	1,69	< 0,1	0,35
HiB037	SAM 2774	FG-829997	88	n.a.	< 0,05	< 0,01	< 0,01	< 0,1	3,90
HiB038	-	MA-162786	88	< 0,01	0,06	0,03	0,32	< 0,3	0,18
HiB039	-	MA-162787	90	< 0,01	0,10	0,03	0,31	< 0,3	0,15
HiB040	-	MA-162788	89	< 0,01	< 0,05	0,04	0,40	< 0,3	0,29
HiB041	-	MA-162789	88	< 0,01	0,25	0,07	0,73	< 0,3	0,35
HiB043	-	MA-162791	90	< 0,01	0,05	0,05	0,65	< 0,3	0,73
HiB044	-	MA-162792	88	< 0,01	0,06	0,04	0,59	< 0,3	0,48
HiB047	-	MA-162795	92	< 0,01	0,11	0,03	0,31	< 0,3	0,38
HiB049	-	MA-162797	93	< 0,01	< 0,05	< 0,01	0,05	< 0,3	0,35
HiB050	-	MA-162798	88	< 0,01	0,21	0,02	0,37	< 0,3	0,54
HiB051	-	MA-162799	87	< 0,01	< 0,05	0,01	0,24	< 0,3	0,23
HiB052	-	MA-162800	88	< 0,01	0,23	0,04	0,31	< 0,3	0,54
HiB053	-	MA-162801	94	< 0,01	0,05	0,04	0,34	< 0,3	0,22
HiB054	-	MA-162802	88	< 0,01	0,12	0,16	0,50	< 0,3	0,97
HiB055	-	MA-162803	92	< 0,01	0,09	0,05	0,27	< 0,3	0,56
HiB056	-	MA-162804	90	< 0,01	0,20	0,07	0,49	< 0,3	0,76
HiB057	-	MA-162805	93	< 0,01	0,09	0,03	0,25	< 0,3	0,14
HiB058	-	MA-162806	88	< 0,01	< 0,05	0,07	0,39	< 0,3	0,43
HiB059	-	MA-162807	89	< 0,01	< 0,05	0,02	0,52	< 0,3	0,39
HiB060	-	MA-162808	88	< 0,01	0,08	0,08	0,27	< 0,3	0,53
HiB061	-	MA-162809	93	< 0,01	< 0,05	0,03	0,47	< 0,3	0,24

Tab. 3: Samples and analyses conducted within the DACH-project and relevant for this paper (Sampling: Caroline Grutsch, Analyses: Joachim Lutz).

Se %	Ag %	Cd %	Sn %	Sb %	Te %	Pb %	Bi %	Inventory No.
< 0,01	0,019	< 0,005	7,4	< 0,005	< 0,005	0,45	< 0,01	PR 632
< 0,01	0,049	0,012	8,1	0,169	< 0,005	0,03	< 0,01	PR 561
< 0,01	0,075	< 0,005	9,4	0,066	< 0,005	0,37	0,03	PR 596
< 0,01	0,039	< 0,005	7,7	0,070	< 0,005	0,22	0,02	PR 587
< 0,01	0,042	< 0,005	2,0	0,252	< 0,005	0,29	0,01	PR 573
< 0,01	0,067	< 0,005	7,8	0,066	< 0,005	0,88	0,02	PR 617
< 0,01	0,042	< 0,005	6,5	0,071	< 0,005	0,30	0,02	PR 563
< 0,01	0,060	0,005	7,0	0,162	< 0,005	0,63	0,03	PR 588
< 0,01	0,069	< 0,005	7,7	0,050	0,006	0,20	0,04	PR 1939.1
< 0,01	0,008	0,007	7,5	0,009	< 0,005	< 0,01	< 0,01	without No.
< 0,01	0,004	< 0,005	9,8	0,011	< 0,005	< 0,01	< 0,01	PR 1988.1
< 0,01	0,214	< 0,005	8,8	0,46	< 0,005	0,37	0,01	PR 604
< 0,01	0,159	< 0,005	5,7	0,49	< 0,005	0,36	0,02	PR 556
< 0,01	0,064	< 0,005	7,3	0,36	< 0,005	0,62	0,02	PR 564
< 0,01	0,052	< 0,005	7,3	0,105	0,006	0,70	0,02	PR (19)19.1*
< 0,01	0,009	0,013	7,6	0,022	< 0,005	1,43	< 0,01	PR 626
< 0,01	0,016	< 0,005	6,6	0,094	< 0,005	0,01	< 0,01	PR 1993.3
< 0,01	0,283	n.a.	4,2	0,61	< 0,005	0,02	0,01	PR (19)58.1
< 0,01	0,294	n.a.	6,2	0,62	< 0,005	0,06	0,01	PR (19)58.2
< 0,01	0,086	n.a.	6,6	0,250	< 0,005	0,14	0,01	PR (19)58.3
< 0,01	0,235	n.a.	8,0	0,225	< 0,005	< 0,01	< 0,01	PR 580
< 0,01	0,012	n.a.	2,60	0,013	< 0,005	0,01	< 0,01	PR 1956.1688**
< 0,01	1,08	n.a.	< 0,005	7,1	< 0,005	0,20	0,01	PR 569
< 0,01	0,80	n.a.	0,92	0,72	< 0,005	0,01	< 0,01	PR 621
< 0,01	0,39	n.a.	5,5	0,185	< 0,005	3,5	< 0,01	PR 567
< 0,01	0,022	n.a.	4,8	0,101	< 0,005	0,30	< 0,01	PR (19)13.1
< 0,01	1,26	n.a.	0,013	1,89	< 0,005	0,02	< 0,01	PR (19)58.5
< 0,01	1,07	n.a.	< 0,005	6,3	< 0,005	0,02	0,17	PR 620
< 0,01	0,028	n.a.	10,6	0,174	< 0,005	0,15	< 0,01	10619
< 0,01	0,038	n.a.	9,1	0,094	< 0,005	0,21	< 0,01	14004
< 0,01	0,026	n.a.	9,8	0,261	< 0,005	0,20	0,01	48
< 0,01	0,017	n.a.	9,6	0,187	< 0,005	0,14	< 0,01	13473
< 0,01	0,097	n.a.	6,9	0,34	< 0,005	0,58	< 0,01	13525
< 0,01	0,014	n.a.	9,8	0,296	< 0,005	0,01	< 0,01	13538
< 0,01	0,008	n.a.	6,7	0,51	< 0,005	0,12	< 0,01	14901
< 0,01	0,262	n.a.	4,2	1,74	0,007	0,09	0,03	13763
< 0,01	0,023	n.a.	10,4	0,85	0,008	< 0,01	< 0,01	1253
< 0,01	0,002	n.a.	12,6	0,062	< 0,005	< 0,01	< 0,01	217904
< 0,01	0,004	n.a.	10,4	0,089	< 0,005	< 0,01	< 0,01	13762
< 0,01	0,023	n.a.	5,3	0,151	< 0,005	0,10	< 0,01	14764
< 0,01	0,34	n.a.	6,4	2,66	0,022	0,83	0,01	13353
< 0,01	0,032	n.a.	5,9	0,37	0,006	0,35	0,03	12043
< 0,01	0,003	n.a.	8,3	0,39	0,010	0,03	< 0,01	12063
< 0,01	0,034	n.a.	6,2	0,119	< 0,005	0,07	< 0,01	10618
< 0,01	0,291	n.a.	8,5	1,71	0,020	0,40	< 0,01	10617
< 0,01	0,015	n.a.	10,0	0,119	< 0,005	< 0,01	< 0,01	A669
< 0,01	0,004	n.a.	10,6	0,43	0,006	0,04	< 0,01	A642
< 0,01	0,003	n.a.	5,5	0,136	< 0,005	< 0,01	< 0,01	A3143

„<“ = detection limit
n.a. = not analyzed

*also: 1901.1 (519)
**also: 1957.1688

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Authors

Caroline O. Grutsch – Department for Archaeologies, University of Innsbruck
Joachim Lutz – Curt Engelhorn Centre of Archaeometry gGmbH, Mannheim
Gert Goldenberg – Department for Archaeologies, University of Innsbruck
Gerald Hiebel – Department for Basic Sciences in Engineering Science, University of Innsbruck

Correspondence and material requests should be addressed to: caroline.grutsch@student.uibk.ac.at or talitha-cumi@gmx.at

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Joachim Lutz, Sebastian Krutter, Ernst Pernicka

Composition and spatial distribution of Bronze Age planoconvex copper ingots from Salzburg, Austria

First results from the “Salzburger Gusskuchenprojekt”

ABSTRACT: *Planoconvex copper ingots (also named “casting cakes” and “bun ingots”) were found in huge amounts in the Salzach and Saalach Valleys, but also at the Mitterberg and in the Saalfelden district. 103 of these ingots (partly fragments) were analysed chemically and about 50 complete or nearly complete ingots were classified by means of their shapes and sizes into six different morphological types. A coarse chronology of these morphological types was developed. The chemical data was statistically analysed (cluster analysis) and four main metal groups were defined. As might be expected, the largest group corresponds to chalcopyrite copper and ores from the Mitterberg district. Ingots made of fahlore copper or “diluted fahlore copper” are rare and occur only in the later periods. Previous analytical investigations of bronze finds and archaeological excavations of prehistoric mines have shown a reappearance of fahlore copper in the Late Bronze Age. Thus, the coarse chronology of copper varieties analysed in the ingots matches the overall picture. The analytical results also provide the opportunity to characterize the chalcopyrite copper from the Mitterberg district much better than it was hitherto possible.*

KEYWORDS: BRONZE AGE, SALZBURG, PLANOCONVEX INGOTS, COPPER, GEOCHEMISTRY, LEAD ISOTOPES

Introduction

The rich copper ore deposits in the Eastern Alps, especially in Tyrol and Salzburg, are considered as important sources for copper in prehistoric Europe (Pernicka et al., 2016; Lutz, 2016; Stöllner, 2009). In the past decades several archaeometallurgical and analytical projects in this region attempted to link prehistoric metal artefacts with copper ores based on the geochemical characteristics of the ore deposits that have been exploited in ancient times. Most notable for the analytical attempts are the SSN project (“Bronze Age copper supply in Southern Bavaria, Salzburg and North Tyrol”; Möslein & Pernicka, 2018, this volume) and the HiMAT project (“History of Mining Activities in Tyrol and Adjacent Areas”; Lutz, 2016; Lutz & Pernicka, 2013). In the SSN project mainly metal finds were analysed, whereas later in the HiMAT project the focus was more on excavations and ore analyses, especially in the well-known prehistoric mining areas at the Mitterberg district (Zschocke & Preuschen, 1932; Eibner, 1994; Stöllner et al., 2012; Stöllner et al., 2016), the Viehhofen area northwest of Zell am See, the Kitzbühel district (Pittioni 1976; Goldenberg, 2004) and the fahlore deposits in the Inn Valley near Schwaz and Brixlegg (Martinek & Sydow, 2004; Rieser and Schrattenthaler, 1998/1999; Goldenberg et al., 2012). During the Bronze Age, especially in the Middle and Late Bronze Age, these ore deposits were mined on a large scale. But it is still not clear which role each deposit played, as it is often difficult or nearly impossible to collect enough ore samples to fully characterize a large deposit. Most old mines are nowadays inaccessible and old mining dumps are often reworked by mineral collectors.

Analyses of raw copper ingots (or “casting cakes”) found or excavated in the vicinity of the deposits are an important supplement to ore analyses as they often provide much more reliable data for provenance studies of prehistoric metal artefacts than analyses of the ores. They represent the original raw metal that has been smelted and afterwards was traded and distributed to areas outside the Alpine regions. Furthermore, geochemical and isotopic patterns measured in ores may be altered to some degree during processing and smelting. Therefore, the raw copper ingots often provide a better geochemical “fingerprint” than ores. After analysis of about 100 ingots it is now possible to calculate reliable values for element concentrations in chalcopyrite copper, especially from the Mitterberg district. (JL, EP)

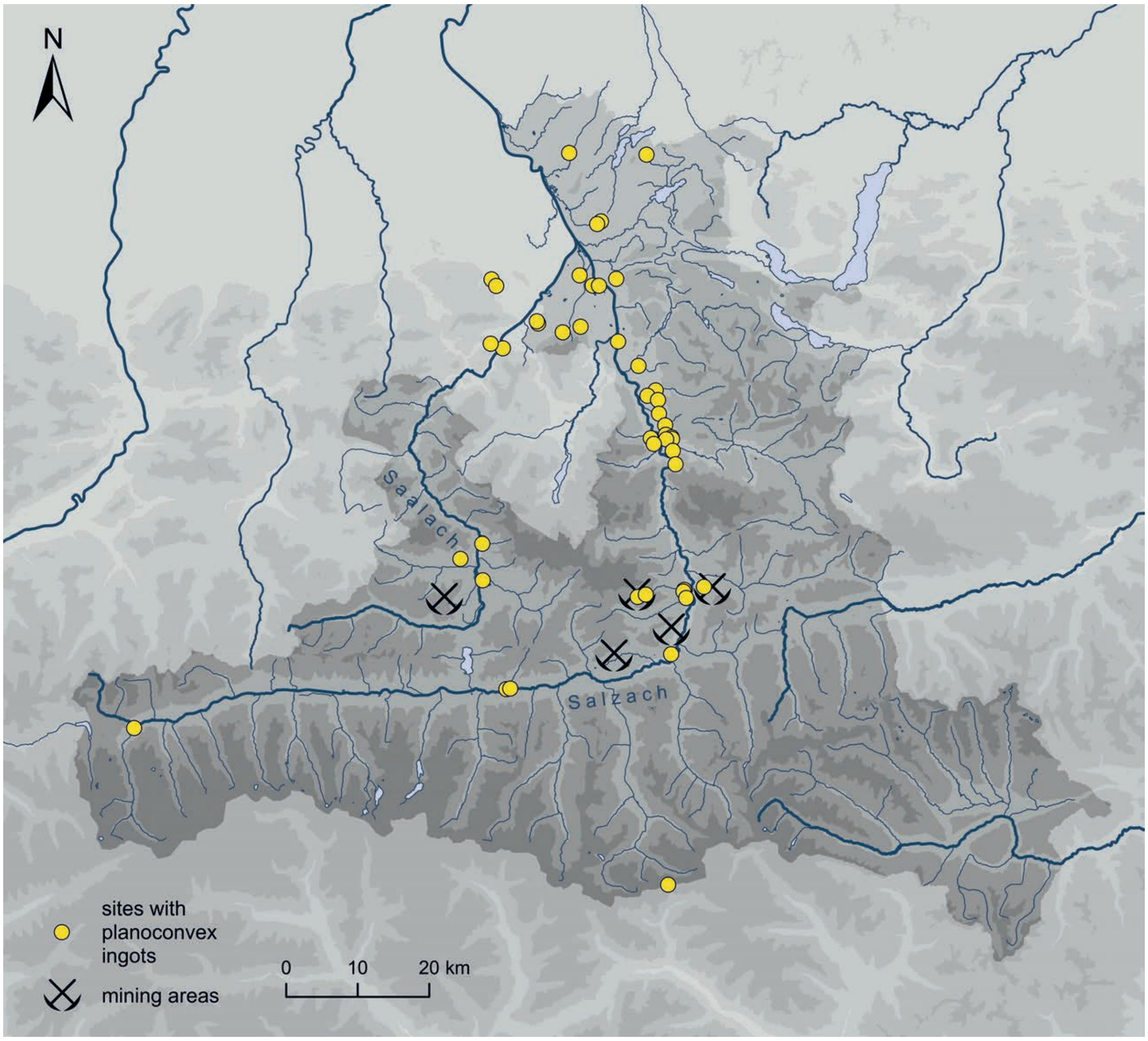

Fig. 1: Distribution of planoconvex ingots in the Salzach and Saalach Valleys (© SAGIS, OSM, Sebastian Krutter).

Planoconvex ingots in the Salzach and Saalach Valleys

In the Salzach and Saalach Valleys there are overall 46 archaeological sites known where about 1,000 complete planoconvex copper ingots and their fragments with a total weight of about 300 kg were found. Besides two isolated accumulations in the Mitterberg region as well as in the Saalfelden basin, the sites with planoconvex ingots cluster mainly in the northern Salzach Valley, in the Salzburg Basin and the Alpine Foreland along the main distribution route of the Alpine copper (Fig. 1). The majority of the planoconvex ingots was found in hoards consisting only of ingots and their fragments, which are located in special environmental situations such as elevated terrain terraces and passes, but rarely within mining areas. The planoconvex ingots were usually deposited in simple earth pits containing up to 17 complete planoconvex ingots, such as known from the hoard Saalfelden-Wiesersberg (Krauß, 1998/1999). Occasionally the pits are covered with stone slabs and the ingots are arranged in a special way and sometimes even organic wrappings and ceramic vessels are preserved. Hoards of planoconvex ingots are also known from fluviatile, lacustrine and palustrine environments and in addition, a few small fragments of planoconvex ingots were found inside some Bronze Age settlements. (SK)

Classification and dating

Due to a combination of unfavourable preservation conditions in form of mostly small fragments and archaeological contexts without any associated dateable finds,

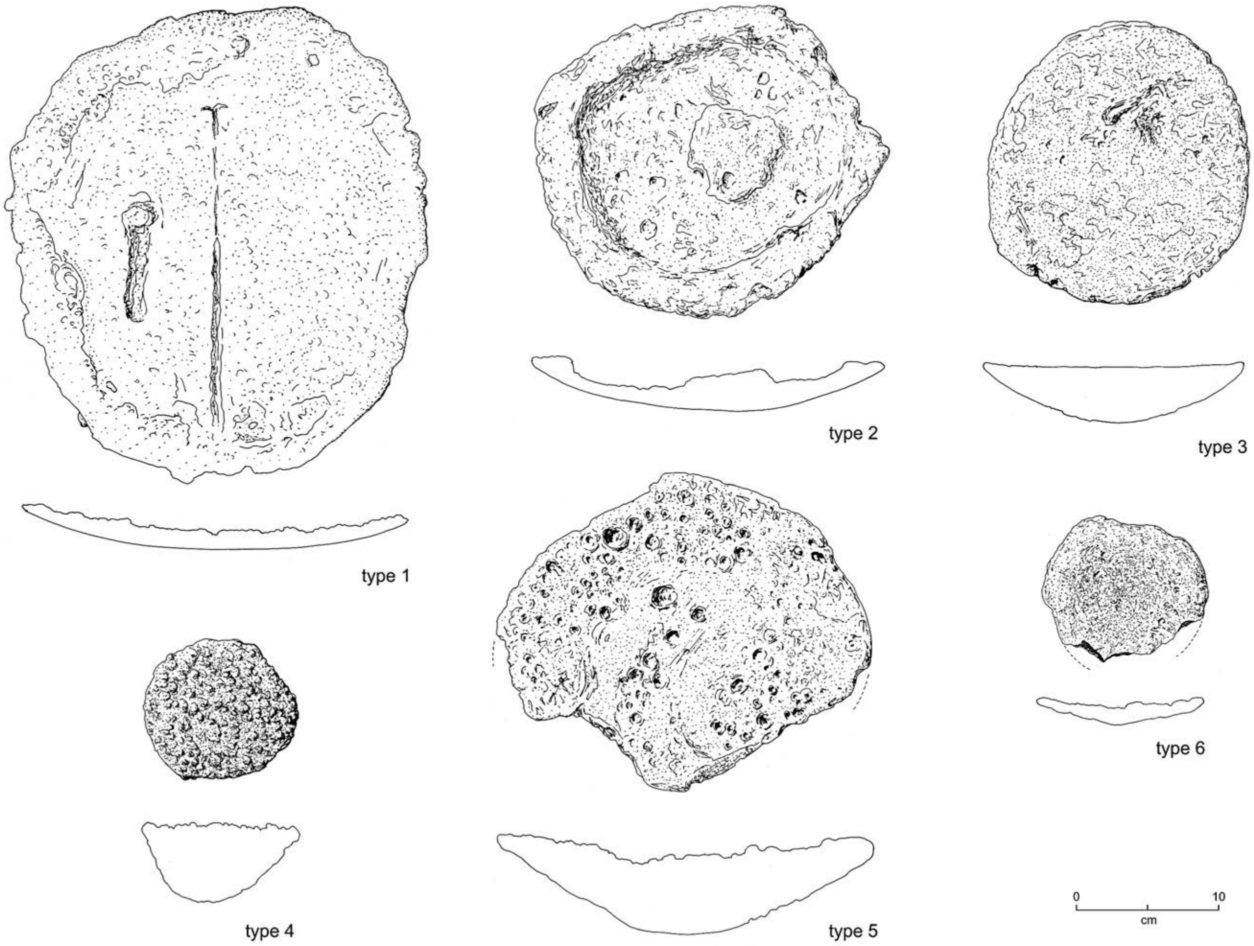

Fig. 2: Types of planoconvex copper ingots from the Salzach and Saalach Valleys (© Salzburg Museum, Franz Krois).

planoconvex ingots and their fragments are usually very difficult to classify and date. This is why they have been generally assigned to the Late Bronze Age in most cases. According to this framework, various basic investigations with different methodological approaches in several regions of central Europe have been published (e.g. Bachmann & Jockenhövel, 2004; Czajlik, 1996; Kyrle, 1918; Modl, 2019; Nessel, 2014; Primas & Pernicka, 1998; Reinecke, 1938; Le Carlier de Veslud et al., 2014).

Considering their comparatively good preservation and the spatial proximity to the Bronze Age copper mining regions, the planoconvex ingots of the Salzach and Saalach Valleys offer a unique basis for a typological study. Hence, the ingots could be separated into six different types (Fig. 2-3) based on a combination of morphometric attributes such as diameter, thickness, basic form, form of the cross-section and form of the casting edges. Due to a lack of typological relevance, the weight as well as the chemical composition could not be used as diagnostic attributes within this classification. Based on radiocarbon dates of charcoal remains from the surface of some ingots and some dateable associated metal finds from hoards and typological parallels in the Alpine piedmont the different types range from the Early Bronze Age up to the Late Bronze Age. Characteristic for the Early and the beginning Middle Bronze Age (BzA2-BzB) are planoconvex ingots of type 1 showing an oval basic form, a bowl-formed cross section and a very distinctive bulging casting edge. Besides a smaller diameter and an almost round basic form, planoconvex ingots of type 2 reveal a close relationship to type 1 and can be considered contemporary. The "classic" planoconvex ingots are represented by type 3 of this classification showing a planoconvex cross-section and a round or oval basic form. Ingots of this type appear over the whole Bronze Age and can be further divided into two variants with different thicknesses and basic forms: Variant 3a is clearly thinner than variant 3b and frequently shows an oval basic form, while variant 3b occurs only with a round basic form and chronologically appears mainly in the Late Bronze Age (BzD-HaB). Planoconvex ingots of type 4 also belong to the Late Bronze Age (BzD-HaB) and are characterised by a planoconvex cross-section and an almost round basic form, but differ from the previous type by a clearly smaller diameter and a larger thickness. In contrast, the largest as well as the heaviest planoconvex ingots within the Salzach and Saalach Valleys are represented by type 5, which shows a round basic form, a planoconvex

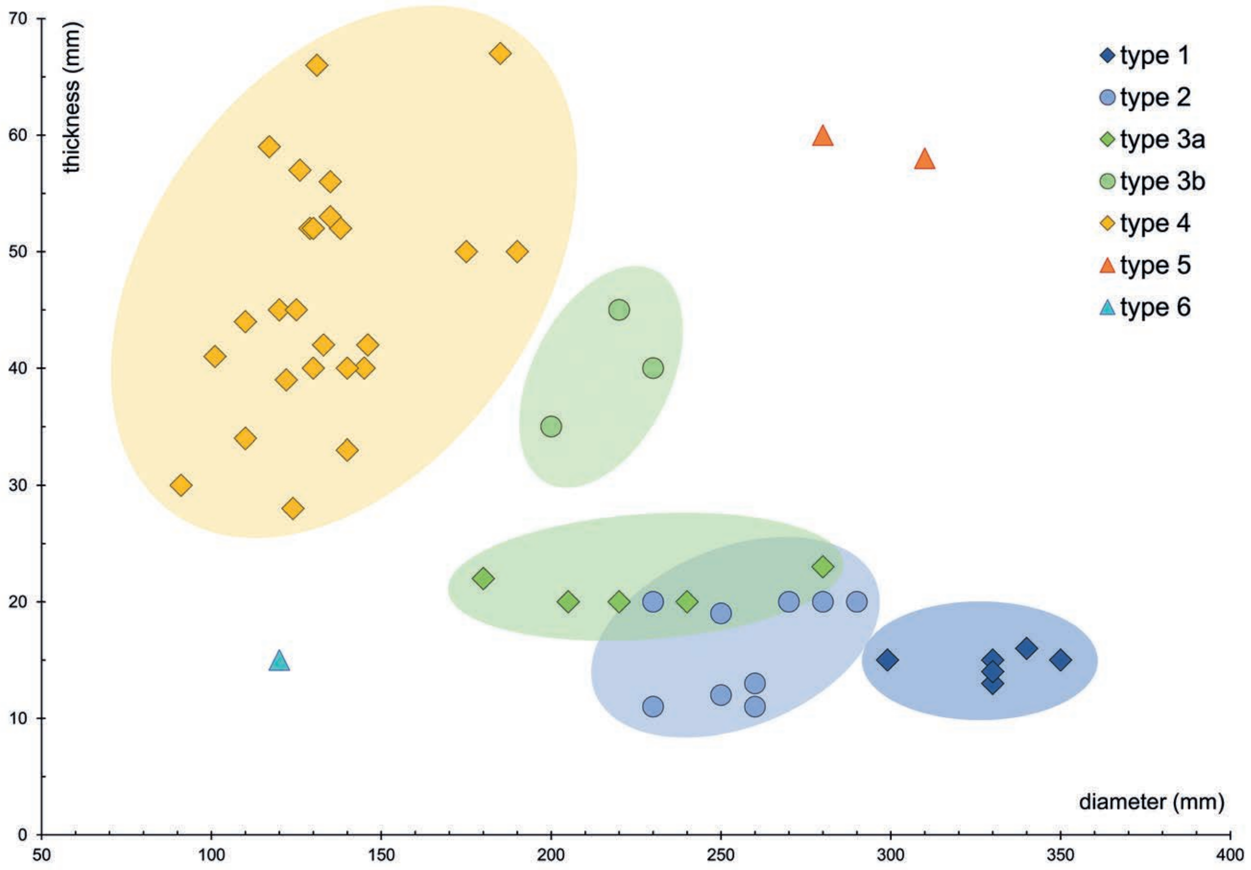

Fig. 3: Metric attributes of planoconvex copper ingots from the Salzach and Saalach Valleys. The diagram includes only planoconvex ingots and fragments whose preservation conditions allow a secure recording of the diameter and the thickness. (© Sebastian Krutter).

cross-section and are dateable also to Late Bronze Age (BzD-HaB). Contemporaneous to the previous type, type 6 is characterised by a round basic form, an almost bowl-formed cross-section and very small dimensions.

Based on the defined types, for the planoconvex ingots of the Salzach and Saalach Valleys a morphometric evolution from the Early to the Late Bronze Age can be stated, within which the diameter becomes smaller and the thickness larger. Furthermore, a change from oval to almost round basic forms is recognisable. Contrary to the previous traditional dating of planoconvex ingots into the Late Bronze Age and especially the Urnfield period, it can now clearly be shown that planoconvex ingots already occurred in the Early Bronze Age and have played much earlier an important role as trading form of raw copper than supposed so far. (SK)

Data and analysis techniques

The chemical analyses of ingots evaluated in this paper were performed during the last 15 years in the frame of different archaeometallurgical projects. Therefore, also different analytical methods and instruments were used. Several hoards with ingots was discovered in Kuchl-Benzbichl and metal samples were analysed at the TU Bergakademie Freiberg in Saxony in 2003. Some ingots were analysed as part of the SSN project (Möslein & Pernicka, 2019, this volume), also at the TU Freiberg. Later, a few ingots from Salzburg were investigated during the HiMAT project (Oeggl et al., 2012) together with a number of artefacts from the Salzach Valley (Stöllner et al. 2016). The dataset was then completed in the last years with a series of analyses for the "Salzburger Gusskuchenprojekt" funded by the Landesarchäologie Salzburg. These analyses were also carried out at the Curt-Engelhorn-Zentrum Archäometrie in Mannheim.

All ingots were sampled with a small steel drill. Afterwards the alloy composition was determined by energy-dispersive X-ray fluorescence analysis (XRF) using different XRF spectrometers, but always following the quantification and correction procedures of Lutz & Pernicka (1996). Therefore, the data is well comparable. In some ingot samples lead isotope ratios were determined using multi-collector ICP-MS following the procedure described by Niederschlag et al. (2003).

The ore samples from the Mitterberg district (Pernicka et al., 2016), the Kelchalm near Kitzbühl, Viehofen and Schwaz/Brixlegg (Höppner et al., 2005) used for com-

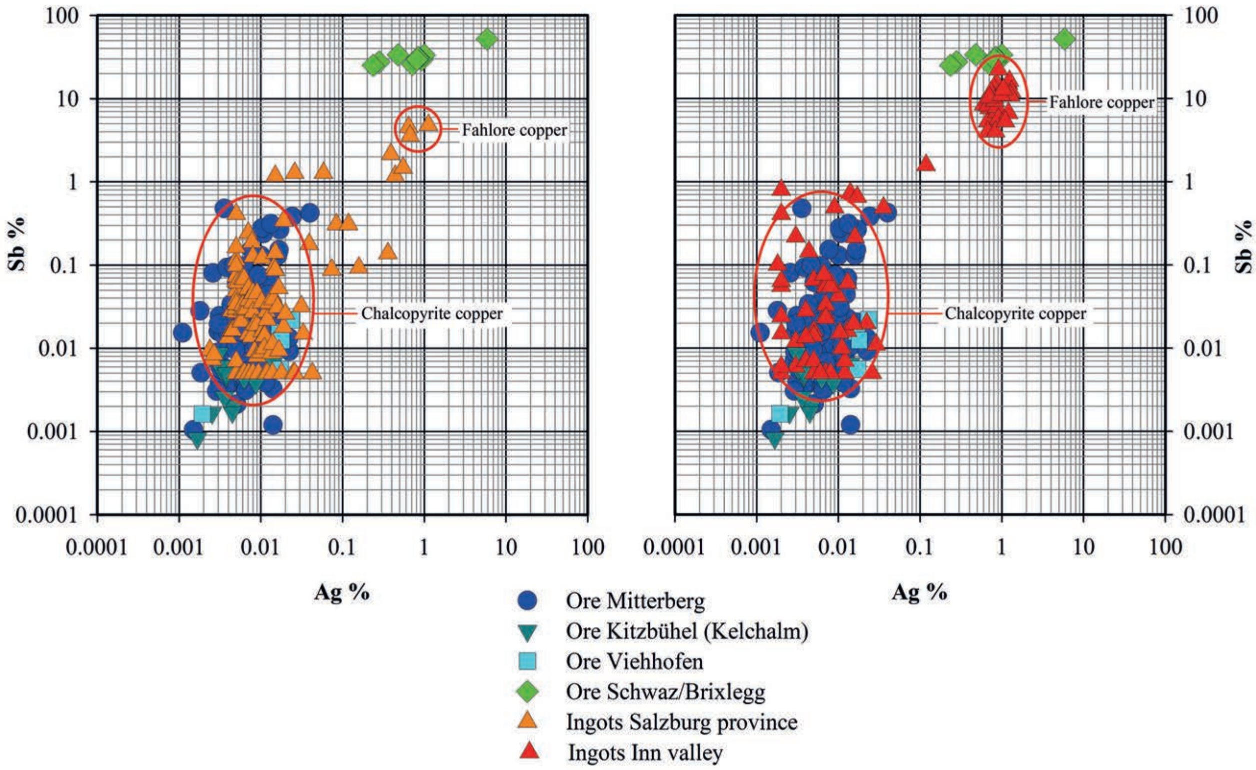

Fig. 4: Concentrations of silver and antimony in fahlores from the Inn Valley (Schwaz/Brixlegg) and in chalcopyrite ores from Mitterberg, Kitzbühel and Viehhofen compared with copper ingots from Salzburg (left) and from the Inn Valley (right). The concentration of antimony in fahlore copper ingots is lower than in the fahlores because it was the aim of the fahlore smelting process to reduce the high antimony contents. While most of the ingots from Salzburg consist of chalcopyrite copper, the proportion of fahlore copper is much higher in ingots from the Inn Valley. This reflects the geographic location of the main fahlore deposits in the west and the most important chalcopyrite deposits more in the east. (© CEZA, Joachim Lutz).

parison were analysed chemically by neutron activation analysis (NAA, for Fe, Co, Ni, Cu, As, Sb, Ag, Au, Se, Te, Zn, Sn) and inductively-coupled plasma mass spectrometry with a quadrupole ion filter (QICP-MS, for Pb, Bi). Furthermore, the lead isotope ratios were determined in some of the ore samples and in addition also in some slag samples from the Mitterberg district. These ore and slag analyses were carried out during the HiMAT project. (JL, EP)

Regional trends in composition

Most of the raw copper ingots discovered in the last hundred years were found in the eastern Alpine foreland and the Inn and Salzach Valleys, especially where the valleys open to the foreland. From the Inn Valley a series of ingots was analysed during the SSN project and this offers the opportunity to compare the composition of ingots from the Inn Valley with those from Salzburg (Fig. 4). In both series ingots of the main copper varieties (chalcopyrite copper, fahlore copper and copper with mixed patterns) occur, but the proportion of the copper varieties differs. In the west (Inn Valley) much more fahlore copper ingots occur whereas in the east (Salzburg) only three fahlore copper ingots were discovered. In Salzburg, most ingots consist of chalcopyrite copper. This reflects the geographic location of the main fahlore deposits (Schwaz and Brixlegg) in the Inn Valley. In Salzburg, chalcopyrite is the predominant copper mineral and fahlore mineralisations are of minor importance. (JL, EP)

Cluster analysis

The chemical data of the Salzburg copper ingots performed with XRF were statistically analysed with cluster analysis (statgraphics software). The elements Co, Ni, As, Ag, Sb and Bi (logarithmic values) were selected for clustering as they were detected in most samples (except Bi which was only detected in fahlore copper ingots and some ingots with mixed patterns). Detection limits were transformed into estimated values (half of the detection limit) to prevent the loss of objects for classification due to missing values. 103 analyses were clustered with the group average clustering method using Euclidean distance metric. The best results were observed on a clustering level with four groups (Fig. 5):

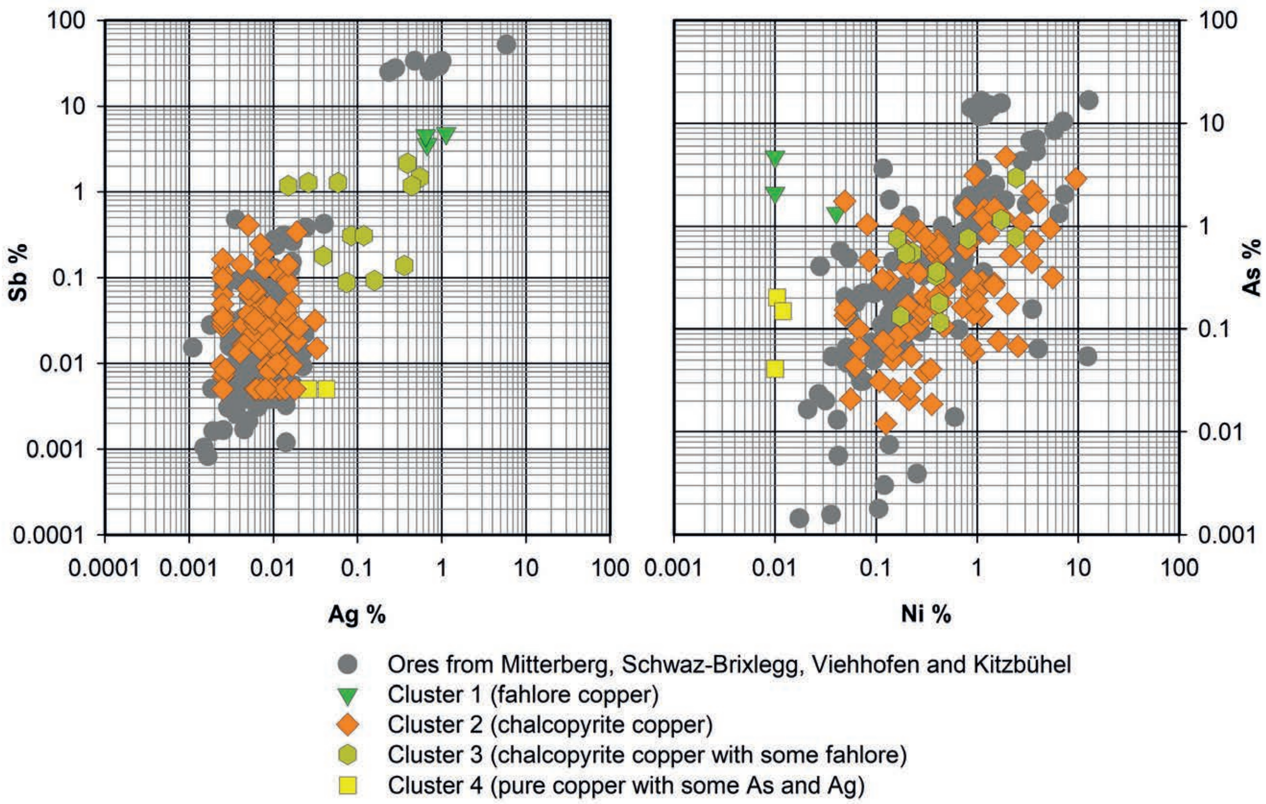

Fig. 5: Concentrations of silver and antimony in ingots from Salzburg (left) and of nickel and arsenic (right) for the four different cluster groups. (© CEZA, Joachim Lutz).

Cluster 1 includes only three ingots of fahlore copper with typically high values of arsenic, antimony and silver and also some bismuth. The concentrations of cobalt and nickel are very low and mostly below detection limits.

Cluster 2 is the largest group with 85 chalcopyrite copper ingots. They match perfectly with the data of the chalcopyrite ores from the Mitterberg (Fig. 5). This result was expected as the Mitterberg is the predominant copper deposit in the region with extensive prehistoric mining remains.

Cluster 3 includes 12 ingots with trace element patterns plotting between the fahlore cluster 1 and the chalcopyrite cluster 2. This variety of copper might be a mixture of fahlore copper and chalcopyrite copper in some cases, but then it should contain also some bismuth from the fahlore copper. But only in two ingots of this "mixed" copper variety bismuth was detected. More likely, fahlore minerals were part of the primary ore paragenesis. Six of these ingots derive from a hoard discovered near Saalfelden. Possibly those ingots derive from the nearby located deposit Leogang, where both chalcopyrite and fahlore occur.

Cluster 4 (3 ingots) is possibly just a variety of chalcopyrite copper with relatively high silver and arsenic contents but low nickel concentrations. Astonishingly they derive all from Anger in Southern Bavaria near the Austrian border, but were found at two different sites. (JL, EP)

Lead isotope analysis

In a small series of copper ingots also lead isotope ratios were determined and compared with copper ores from the Mitterberg (Fig. 6, left diagram). Lead isotope ratios of ores from the Mitterberg show a large variation (especially the Mitterberg Main Lode) due to low lead contents combined with occasionally high uranium concentrations. The variation of lead isotopes in the ingots is smaller because a greater amount of ore was homogenized during processing and smelting. In contrast, the variation of the ingots is nearly congruent with the variation of the Mitterberg slags (Fig. 6, right diagram), as they are also smelted from of a greater amount of ore like the ingots. (JL, EP)

Results

With the data of the chalcopyrite copper ingots it is now possible to define exact concentration ranges for trace elements in copper from the Mitterberg district (Tab. 1) as it was produced and distributed in prehistory. Typical copper from the Mitterberg contains about a percent of arsenic and nickel (these elements are correlated) but only traces of silver and antimony.

	Co %	Ni %	As %	Ag %	Sb %	Bi %	$^{208}Pb/^{206}Pb$	$^{207}Pb/^{206}Pb$	$^{206}Pb/^{204}Pb$
Min	<0.01	0.05	0.012	0.002	<0.005	<0.01	1.9611	0.76957	18.632
Max	0.46	9.5	3.1	0.020	0.41	<0.01	2.0918	0.82093	20.498
Median	0.04	0.40	0.32	0.007	0.028	<0.01	2.0509	0.84088	19.104

Tab. 1: Chemical and lead isotopic characteristics of chalcopyrite copper from the Mitterberg district. The ingots from Saalfelden were omitted for the calculation of the values, as they possibly may not derive from the Mitterberg mining district. (© CEZA, Joachim Lutz).

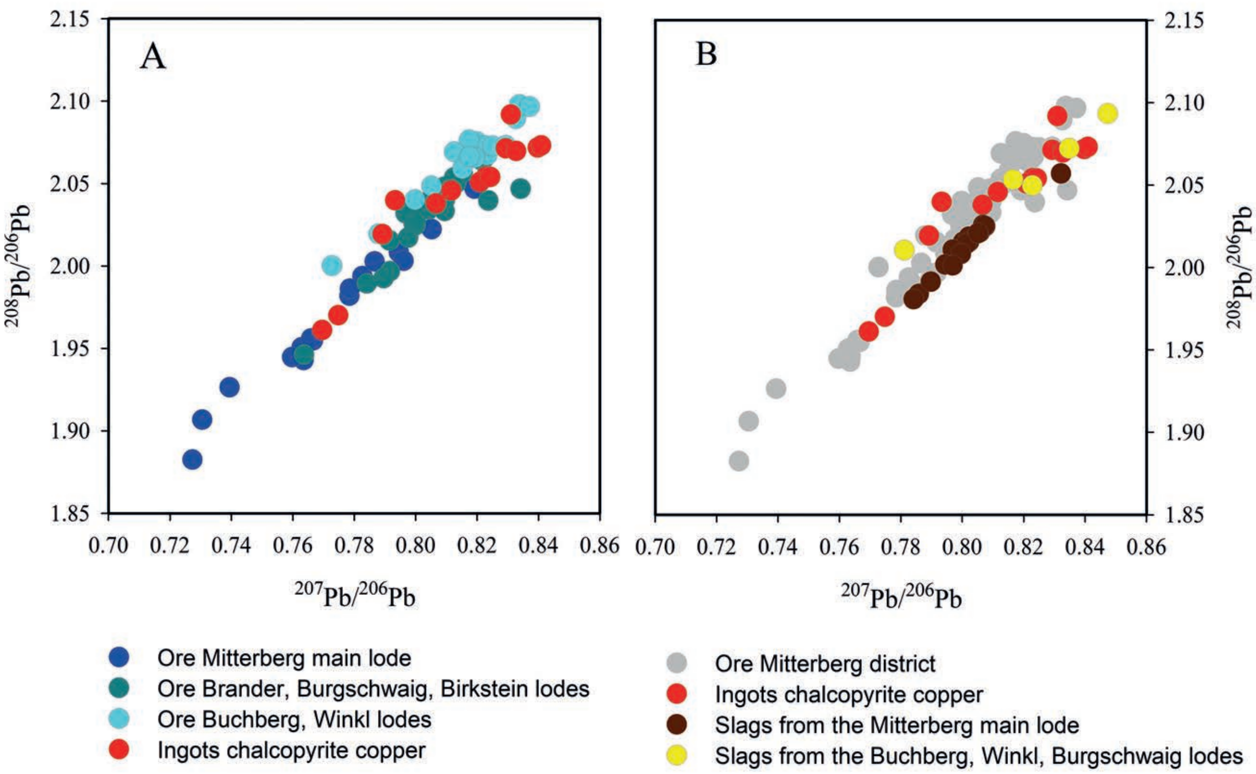

Fig. 6: Lead isotope ratios in ores from the Mitterberg district compared with some chalcopyrite copper ingots from Salzburg (left). The variation of lead isotope ratios is greater in the ores. In contrast, the scattering range of the copper ingots and slags from the Mitterberg region is almost identical. During processing and smelting of ores a greater amount of ore is homogenized. Therefore, the scattering range is smaller in slags and ingots compared with relatively small ore samples that were used for characterizing ore deposits. (© CEZA, Joachim Lutz).

Despite the fact that most ingots consist of chalcopyrite copper, it is interesting to see how the other copper varieties are distributed among the different morphological types in Salzburg (Fig. 7). The chalcopyrite copper (cluster 2) is present in all types, whereas the fahlore copper (cluster 1) and the copper with "mixed" patterns (cluster 3) tend to occur only in the later types. Cluster 4 occurs only with type 2. Analytical investigations of bronze finds and archaeological excavations of prehistoric mines have proven a re-appearance of fahlore copper in the Late Bronze Age. Thus, the chronology of copper varieties in the ingots matches the overall picture. (JL, EP)

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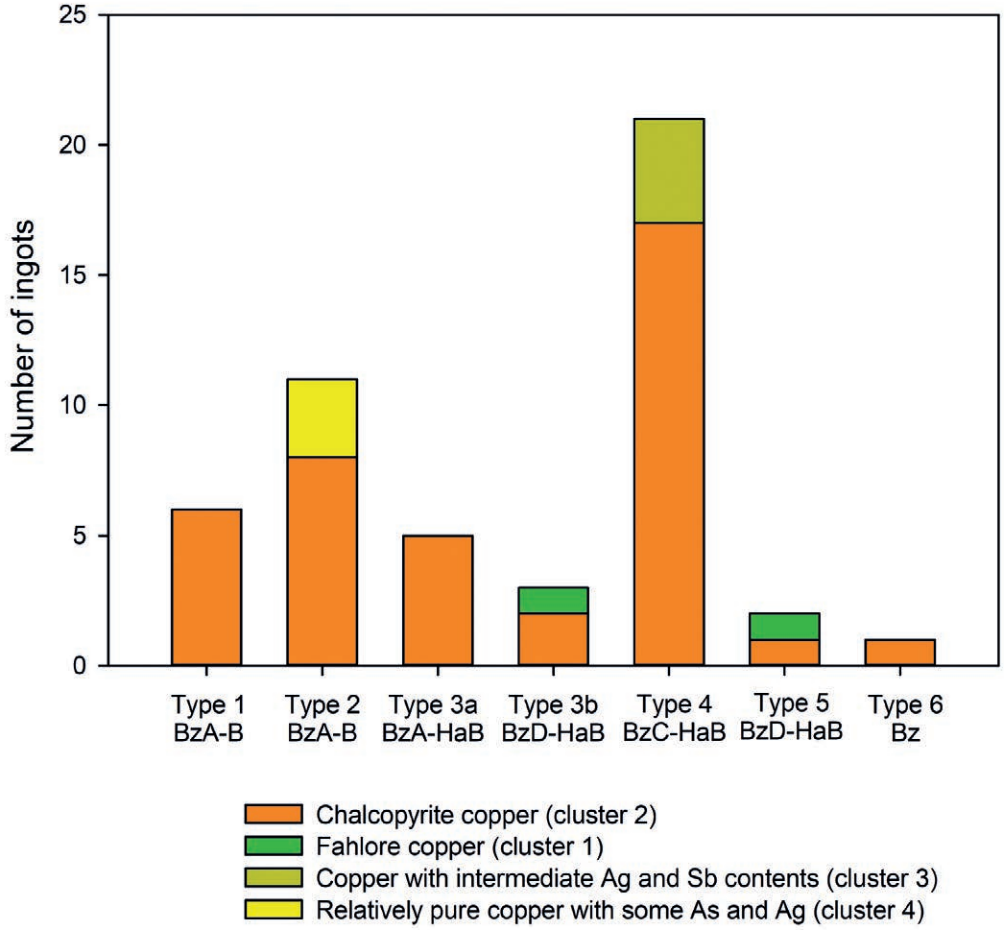

Fig. 7: Number of ingots of the different types analysed. The total number of analyses is larger, but many fragments could not be assigned to a certain type. Most ingots consist of chalcopyrite copper. Ingots made of fahlore copper or "diluted fahlore copper" are rare and occur only in the later periods. (© CEZA, Joachim Lutz).

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Authors

Joachim Lutz – Curt Engelhorn Centre of Archaeometry gGmbH, Mannheim
Sebastian Krutter – Landesarchäologie Salzburg, c/o Salzburg Museum
Ernst Pernicka – Curt Engelhorn Centre of Archaeometry gGmbH, Mannheim

Correspondence and material requests should be addressed to: joachim.lutz@ceza.de

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Daniel Modl

Recording plano-convex ingots (Gusskuchen) from Late Bronze Age Styria and Upper Austria – A short manual for the documentation of morphological and technological features from production and partition

ABSTRACT: *The plano-convex ingot (in short PCI) or casting cake (German: Gusskuchen) is the most common ingot type for copper and its alloys in Late Bronze Age in Central Europe. The PCIs were formed in an open casting process by pouring molten metal into a shallow pit in the ground or in a specific casting form. Because of their simple production this raw metal type is found across a wide chronological and geographical range and was used for several metals. Despite their importance for the reconstruction of prehistoric copper metallurgy, the PCIs are often described insufficiently, which complicates major comparative studies. The following study attempts to remedy this by presenting a recording system with a uniform terminology, which presents all important measurable parameters and visible morphological and technological features on the surface of the PCIs, supported by results from chemical analyses, metallographic examinations or imaging techniques, for a better understanding of their production and partition.*

KEYWORDS: LATE BRONZE AGE, PLANO-CONVEX INGOT, CASTING CAKE, RAW METAL, COPPER, METAL CASTING, RECORDING SYSTEM

Introduction

In Bronze Age metallurgy, plano-convex ingots (in short PCIs) representing semi-products are important links between producers and consumers and provide various technological information concerning production and processing. However, their recording is inconsistent: a handful elaborate publications and regional studies, partially with scientific analyses, are in contrast with numerous short descriptions with very rudimentary or vague data. The lack of basic information, such as size, weight or shape, the inconsistent definition of top and base side, the use of a diverse vocabulary and missing illustrations or photos in the publications not only complicated a reliable comparison of individual pieces, but also the realisation of transregional studies. The following paper attempts to remedy this by presenting a manual with appropriate terminology, which is designed to facilitate comparative work on morphological and technological features by an accurate description, and to address the major issues in the study of the production and partition of PCIs.

This manual is in turn part of an ongoing project in which the author undertook chemical analyses (ICP-AES/OES), metallographic examinations, imaging techniques (SEM, CT scanning) and radiocarbon dating (on trapped charcoal) on more than 100 PCIs and their fragments, as well as related metal ingots (e.g. rod ingots) from Bronze Age/Urnfield Period hoards, settlements and a burnt offerings site from Salzkammergut in Styria and Upper Austria (on the finding area: Modl, 2008; 2013; Windholz-Konrad, 2003; 2012; 2018). The manual is presented to the scientific community before the final publication of the project's outcome and should serve as stimulation for a better documentation of PCIs in the future. Before continuing with the manual, it is necessary to define PCIs, recap the current state of research and introduce the methodology.

Plano-convex ingots

Terminology

The regular 'plano-convex ingot' is characterised by a flat topside and a bulged underside. This raw metal type is often, contrary to the direction of production, referred to as 'bun ingot', which implies the opposite orientation of concavity (cf. Weisgerber & Yule, 2003, p.49; Weisgerber, 2004, p.31; Modl, 2010, p.127). In the countries around the Adriatic Sea, PCIs are sometimes assigned to a precoin monetary metal called 'aes rude', a Latin term (cf. Trampuž Orel et al., 2002, p.63; Murgan, 2014, p.66). Their traditional German name is 'Gusskuchen', a term which is very appropriate because it describes the production process well, but is not really common in the English-speaking world, like the sometimes used direct translation 'casting cake' (e.g. Romanow, 1995; Nessel, 2014; Stöllner et al., 2016). The author has therefore decided – contrary to his own linguistic usage – to apply the term 'plano-convex ingot' in this paper (German: plankonvexer Barren) or the acronym 'PCI', which refers to a formal criterium, the cross-section. The author understands this term as a hypernym, because this raw metal type can have a technically related variability of shapes.

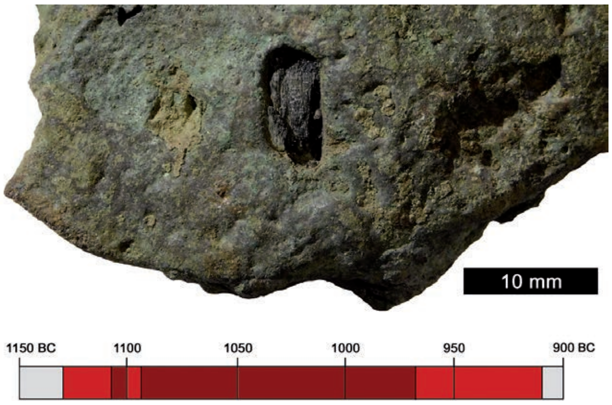

Fig. 1: Radiocarbon dating of a charcoal from the base side of a PCI from hoard IV (CNr. 6; Ha B1/B3; see Windholz-Konrad, 2018, p.124, 158, tab.7/13) in the finding area 'Kainischtraun' near Bad Aussee, Styria, with a calibrated date between 1100 and 1100 BC or 1090 and 975 BC at 68,2% probability and 1130 and 915 BC at 95,4% probability (VERA-6251) (graphic: D. Modl).

Historical and geographical frame

The PCI is formed in an open casting process by pouring molten metal into a shallow pit in the ground or in a specific casting form (subsequently referred to as "mould"). Because of the simple production of ingot and mould, this raw metal form is found across a wide chronological and geographical range and was used for several metals, such as copper and its alloys, as well as lead, tin, silver and gold.

Smelted copper with plano-convex shape has been known since early metallurgic times in the Middle East and Europe (e.g. Schubert & Schubert, 1999, p.668, fig.1/1, 2/1-2). In the course of the Bronze Age, the PCI is evidenced throughout Europe and the Mediterranean, especially in hoards and as shipwreck cargo material (see Muhly et al., 1977; Rothenberg, 1990, pp.65-66; Hauptmann et al., 2002; Hauptmann & Maddin, 2005; Müller-Karpe, 2005, pp.486-487; Yahalom-Mack et al., 2014; Lehner & Schachner, 2017, pp.413-415; Wang et al., 2018, pp.102-117). In Central Europe during the Early/ Middle Bronze Age transition, the heterogeneous PCI replaced the standardised ingots with fixed denomination (like loop or neck-rings/Ösenringe; rib ingots/Rippen-/ Spangenbarren) and evolved to the preferred raw metal form for copper and its alloys (see Möslein, 1998, p.252, pp.256-257). In the Late Bronze Age Mediterranean the PCI remained subordinate to the so called ox-hide ingots (Ochsenhautbarren; see Sabatini, 2016, pp.15-62).

In prehistoric times, this form was additionally produced in larger number in the Persian Gulf area (see Prange, 2001, pp.11-15, 31-33; Craddock et al., 2003; Weisgerber & Yule, 2003), in India (see Yule, 1985, p.44, tab.26/357-360; Pigott, 1999, p.123) and even in South-East Asia (see Bennett, 1998, p.337, 345) and China (see Wang et al., 2019, [p.2409, 2411, fig. 2/7]). Also in Roman times and especially between the Late Medieval to Early Modern Periods, ingots were increasingly produced in similiar form in Europe, as documented in the cases of the ancient copper ingots found in Northern Wales (see Tylecote, 1986, pp.22-24, tab.10-11, fig.10) and along the Languedoc shore in France (see Rico et al., 2005; Klein et al., 2007) or the hemispherical bars from the Portuguese trade vessel 'Bom Jesus' at the Namibian coast (see Hauptmann et al., 2016). PCIs were also the bottom part of a medieval 'Reißscheiben' cast, which were called 'Könige' (see Hänsel & Schulz, 1980, pp.13-17; Werson, 2015, pp.66-68, 87-88). Because of the partly identical shape and production technique, studies on non-prehistoric and non-European PCIs are of great interest for the analysis of Central European pieces from the Bronze Age.

Traditionally, the PCIs in Central Europe were dated to the Late Bronze Age/Urnfield period and judged to be chronologically insensitive. However, their time frame is much broader than the evaluation of metal hoards indicates (see Neumann, 2015, pp.145-147) and includes all time stages between the Early Bronze Age and the Hallstatt period. For individual regions even convincing chronologies for different types could be determined on the basis of morphometric data from complete PCIs (Krutter, 2015; Lutz et al., 2019, this volume). Basically, it turns out that in the Early Bronze Age, the PCI were the largest and then became smaller but thicker during the Bronze Age.

The dating of single ingot fragments without archaeological context, however, is still hampered by the lack of a clear chronological framework. Only very rarely the radiocarbon method has been used for dating charcoals embedded in the surfaces of PCIs (e.g. Wischenbarth, 2004, pp.149-150; Galili et al., 2013, p.171; Armada & García-Vuelta, 2015, pp.372-382; Jansen & Löffler, 2016, pp.130-131; Lutz et al., 2019, this volume). In the course of the project presented here, such an investigation was undertaken, which revealed a dating frame from the older to the younger Urnfield period (Ha A2-Ha B2) for a small PCI from a hoard in the Styrian Salzkammergut (Fig. 1;

cf. Windholz-Konrad 2003, pp.82-84, p.102, fig.60; 2018, p.124, 158, tab.7/13).

Metal composition and ingot manufacturing/partitioning

Metal analysis of Bronze Age PCIs in Central Europe revealed that they are originally made of chalcopyrite copper, fahlore copper or, less common, a mixture of both types, all of different composition (see Trampuž Orel et al., 1996, pp.178-211; Klemenc et al., 1999; Bachmann et al., 2002/03, pp.94-99; Sperber, 2004, pp.312-315, 318-321; Trampuž-Orel & Drglin, 2005; Pernicka et al., 2016, pp.31-34; Stöllner et al., 2016, pp.87-88, 92, fig.14, tab. 2; Radivojević et al., 2018; Möslein & Pernicka, this volume). As changeable copper contents and varying amounts of minor elements (arsenic, antimony, nickel, iron, tin, lead) show, impure and partly refined copper (black copper or blister copper), as well as nearly pure copper and even alloyed copper were used for their production. This material inhomogeneity and the fact that the PCIs display a surprisingly large variety in shape, size and weight, their interpretation as bars and subsequently as potential premonetary currency, or 'special purpose money', was controversially discussed.

However, an ingot is not defined by its quality or value, because rather practical reasons are crucial. The size and shape must merely be suitable for storing, transporting and further processing, a purpose fullfilled by PCIs. Another criterion relates to the production technique, as ingots are manufactured in an independent casting process (see Drescher, 1976, p.60; Ottaway, 1994, p.115; Primas & Pernicka, 1998, pp.29-32; Kuijpers, 2008, pp.73-77; Nessel, 2017, pp.169-170, 192). According to research tradition, the PCIs have been viewed as a primary product of copper extraction (see Tylecote, 1976, p.166, 170; Ottaway, 1994, p.98, fig.13 and the graphic in Eibner, 1982a, p.406, fig.3), forming during smelting at the bowl-shaped base of a furnace beneath a well-seperated layer of slag.

However, this formation process cannot be reconstructed in archaeological experiments (see Hanning, 2012; Modl, 2015) and is also in contradiction with features on the top surface of most of the PCIs. While the concentration of the ore into a copper-iron sulphide matte was well trialled in smelting experiments, the efficient converting of the matte into metallic copper and the formation of a homogenous copper cake as well as the purification of the metal by refining (e.g. oxidation, poling or melting with lead; see Rostoker, 1975, pp.312, 314; Eibner, 1982b, pp.309-311; Preßlinger, 2004, p.326) is to date inadequately replicable (summarising Hanning et al., 2015). In addition, apart from different slags just a few metallic semi- and endproducts from the smelting sites, mining settlements or nearby hoards are known for these last process steps and hardly any facilities, like pit or hearth furnances or crucibles for such pyrometallurgical operations are documented. The same applies also for the production of the alloy bronze by co-smelting of copper and metallic tin, by cementation of copper with the tin oxide cassiterite (SnO_2) or by co-smelting a mixture of copper and tin ores, which is also hardly detectable in the archaeological record but good to repeat in archaeological experiments (see Herdits et al., 1995, pp.78-85; Rovira et al., 2009, pp.407-414).

Currently, it can be assumed that the end product of the smelting process were probably amorphous copper lumps or smaller prills mixed with slag which needed to be remelted and recast. Therefore the PCI in its usual form was not the primary product of smelting, it is rather the product of a secondary casting process between refining, alloying and recycling in which the metal is cast into a bowl-shaped mould. Whether the pour was carried out by use of crucibles or by discharging molten metal from the bottom of the furnance into a forehearth or a tapping pit will be the subject of further discussions (Fig. 2/A-B; see Modl, 2010, pp.129-132, 138-140; Holdermann & Trommer, 2010, pp.792-795).

Such moulds are to date unknown in Europe. The only validated finds of clay moulds for casting a PCI are known from the Iron Age site 30 at Timna (Israel; see Rothenberg, 1987; 1990, p.54, 67, fig.81-82), while small casting pits were detected at the Bronze Age settlement Maysar-1 (Oman; see Weisgerber, 1981, p.209, fig.38; Weisgerber & Yule, 2003, p.48; Weisgerber, 2004, p.22). The fact that the majority of the PCIs were actually cast is indicated for example by flow structures at their top surface or an internal multilayer structure, formed by repeated or interrupted casting batches. Their varying purity (mostly between 94-98 wt% copper) and alloying degree as well as different contents of copper oxides and sulphides or an arsenic loss reflect that the PCIs are not the result of a simultaneous manufacturing process but rather products of an entire series of pyrometallurgical processes commencing with copper smelting and continuing with several refining, alloying or recycling procedures, while PCIs are being poured and broken up again and again (Fig. 3). A special position among the PCIs is occupied by pieces which consist of recycled metal and are possibly produced in two ways: by casting molten metal in a mould filled with scrap metal, or by adding scrap metal into an existing melt (Fig. 2/C-D).

For the definition of the PCI as an ingot the metal quality and production stage play only a subordinate role, but an almost plano-convex shape and a minimum size are more determining factors. For this reason some foundry remains should not be included in the group of PCIs. These include, for example, casts or remains of the bottom of crucibles or ceramic vessels ('reguli') with a plano-convex cross-section, but with a diameter of only a few centimeters (e.g. Czajlik, 1996, p.171, fig.16; Bachmann et al., 2002/03, p.90, fig.10/D/2-6; Weisgerber, 2004, p.31; Czajlik, 2006, p.58, fig.6; Kytlicová, 2007, p.163, tab.138/D/3-5; Lauermann & Rammer, 2013, p.96, tab.23/3-4; Le Carlier de Veslud et al., 2014, pp.514-515),

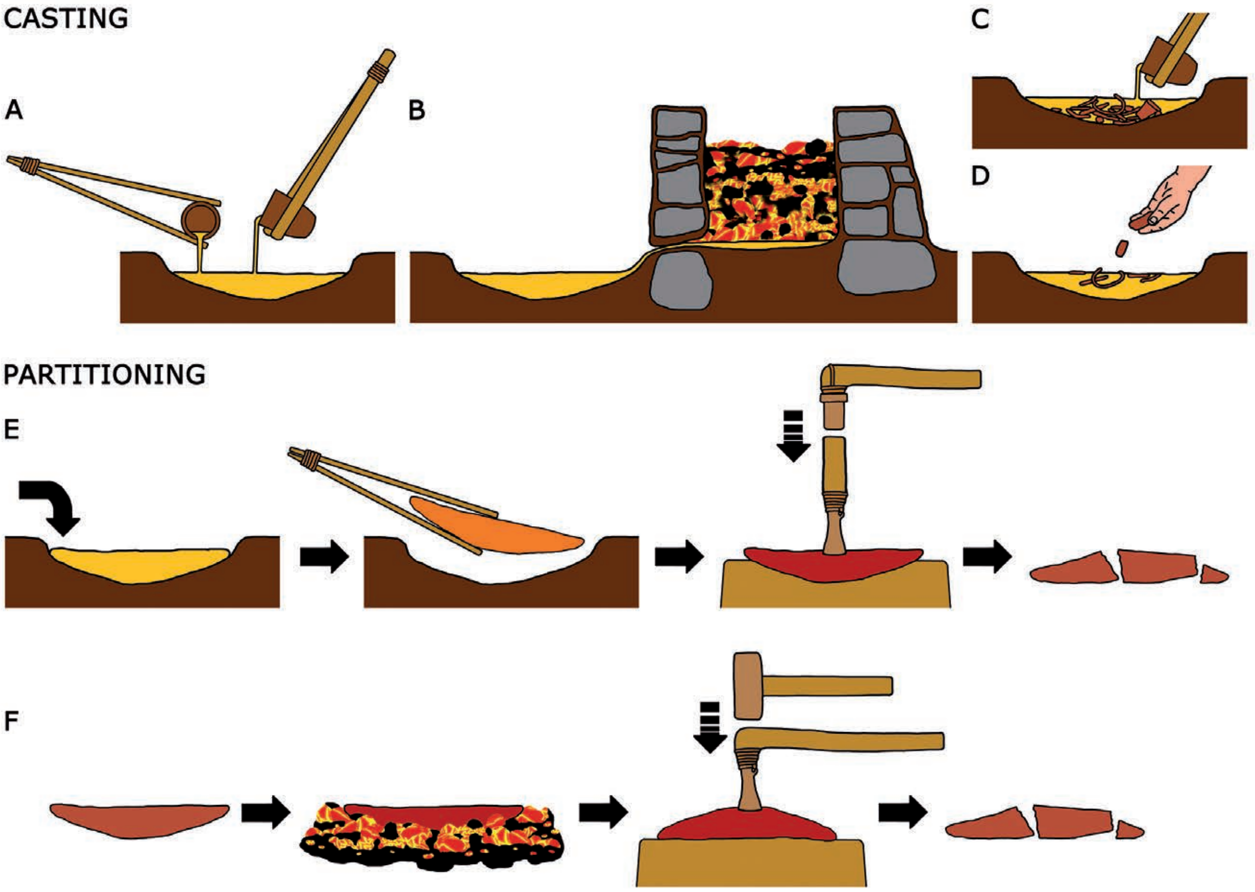

Fig. 2: Simplified representation of the possible casting techniques for the production of PCIs by (A) using crucibles or (B) by discharging molten metal from a furnace into a bowl-shaped mould, forehearth or tapping pit, as well as the manufacturing of PCIs out of recycled metal (C) by casting molten metal in a with scrap metal fullfilled mould or (D) by adding scrap metal into a existing melt. Furthermore the two potential options for the partitioning of PCIs by using a hammer and different cutting tools are depicted with the (E) primary partitioning immediately after the casting and the (F) secondary partitioning by reheating the PCI (graphic: D. Modl).

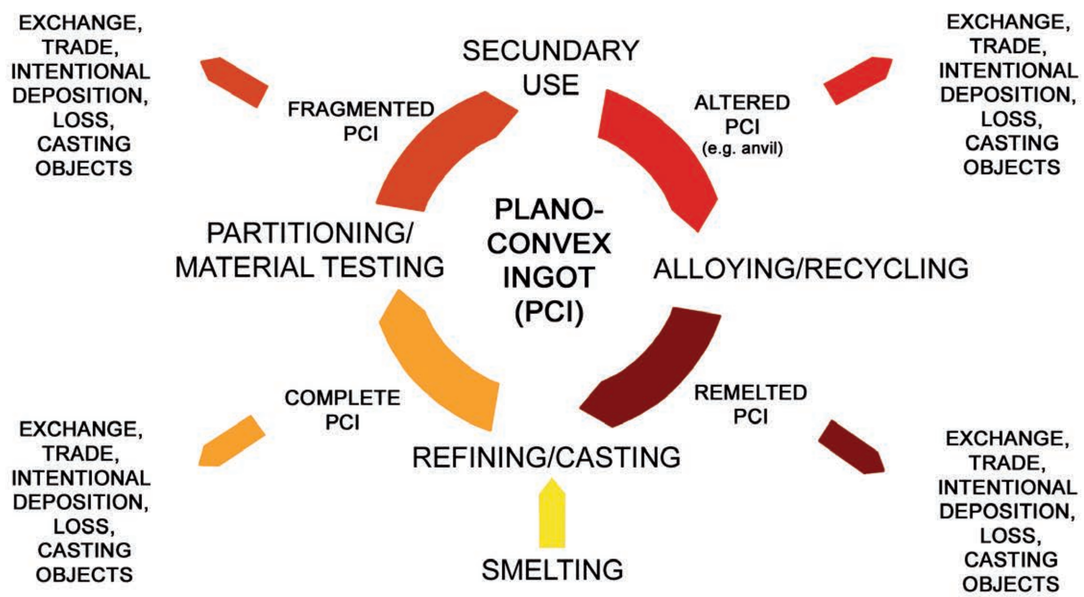

Fig. 3: Visualisation of the production and processing cycle of PCIs (graphic: D. Modl).

amorphous smelting waste (e.g. Gruber & Preßlinger, 1983, pp.1255-1256; Preßlinger & Eibner, 2004, pp.70-71) and socket-shaped castings ('tüllenförmige Gusskuchen'; e.g. Höglinger, 1996, p.77, 141, tab.27/515; Engelmann, 1997, p.31, 75, 114, fig.48-49, tab.19/14; Pühringer, 2000, pp.195-197).

Most of the PCIs in Late Bronze Age hoards are fragmented (see Modl, 2010; Nessel, 2014; 2017). This is the result of a targeted breaking in red-hot state immediately after casting (primary partitioning) or after a later heating in a charcoal fire (secondary partitioning) when they were traded, processed, hoarded or sacrificed. Principally the PCIs show various deformations and tool marks that suggest the use of different hammers, axes and chisels during the dividing process. The partition did probably not take place directly in the casting pit, but rather a hard base like a wooden block or a stone was used here (Fig. 2/E-F).

State of research

Already around the middle of the 19th century, antiquarians in Austria and Hungary comprehend 'Gusskuchen' or PCIs as own archaeological object group (see Pratobevera, 1856, p.27; Érdy, 1861, p.38). A more detailed typological classification of the PCIs based on metrical data and including technological features commenced in Europe in the 1970s and 1980s with the analysis of Late Bronze Age hoards (see Stein, 1976, p.22, 28; Rusu, 1981, pp.375-379, 382-384; Mozsolics, 1984, pp.35-39).

Of particular importance is the paper of Czajlik (1996), who was the first to combine qualitative and quantitative aspects of PCIs from western Hungary, including shape, cross-section, size, weight, metal composition and manufacturing technique. Besides an inconsistent typology, this important and influential study presents an implausible reconstruction of the production process that results in an inverted orientation of the PCIs, which the author sees mainly confirmed in density differences in their inside. However, this approach must be rejected because he did not consider various degassing effects in the core and on the surface as well as the pouring in different batches, which can explain the density differences and speaks against the proposed manufacturing process.

Thanks to experimental archaeological investigations particularly into the production of ox-hide ingots, where PCIs were sometimes by-products, we know more about the manufacturing of copper ingots in different mould materials (see Tylecote, 1976, p.164; Merkel, 1986a; 1990, pp.107-109, 113-116; Craddock et al., 1997; Van Lokeren, 2000; Bunk & Kuhnen, 2008; Larson, 2009; Modl, 2010, pp.138-140; Laschimke & Burger, 2012; Galili et al., 2013, p.21; Hauptmann et al., 2016). Just a few years ago, also in the course of archaeological experiments, some authors began to study the partitioning of copper ingots with different techniques and tools, however, too many questions remained unanswered regarding optimal processing temperature or fracture behavior due to the chemical composition of the ingots (see Merkel, 1986b, p.269; Van Lokeren, 2000, p.275; Modl, 2010, pp.140-146; 2011, pp.147-155; Hauptmann et al., 2016, p.758). Based on this work, the fragments of PCIs got more into the focus of research, which made it possible to distinguish several fracture patterns or weight ratios in European hoards (see Primas & Pernicka, 1998, pp.45-50; Pühringer, 2000, pp.203-214; Modl, 2010, pp.147-148; Nessel, 2014, pp.404-409; 2017, pp.175-192; Reiter & Linke, 2016, pp.150-151, fig.22-23).

Over the last two decades, for many European countries, such as Spain (Montero-Ruiz et al., 2010/11), France (Czajlik, 2006, pp.52-62; Le Carlier de Veslud et al., 2014), England (Loughton, 2017; Wang et al., 2018, pp.102-117), Switzerland (Rychner, 1984), Germany (Reinecke, 1938; Wischenbarth, 1995; Primas & Pernicka, 1998; Bachmann et al., 2002/03), Czech Republic (Salaš, Stránský & Winkler, 1993; Kytlicová, 2007, pp.162-164), Austria (Klose, 1918, pp.31-33; Sperl, 1988, pp.111-114; Höglinger, 1996, pp.76-77; Pühringer, 2000, pp.179-205; Windholz-Konrad, 2003, pp.66-68; 2018, pp.44-46; Modl, 2010, pp.127-137; Krutter, 2015), Hungary (Hampel, 1896, pp.180-187; Mozsolics, 1981; 1984; Czajlik, 1996; 2012, pp.64-77, 85-98; Tarbay, 2016, pp.97-101), Italy/Sardinia (Stech, 1989; Lo Schiavo, 1990; Begemann et al., 2001; De Marinis, 2006; Jung et al., 2011, pp.237-241, 242-245), Slovenia (Turk, 2000, pp.141-146), Croatia (Bertol & Farac, 2012; Karavanić, 2017, pp.102-109), Bosnia-Herzegovina (König, 2004, p.90, 124, 153), Romania (Rusu, 1981, pp.375-379, 382-384), Bulgaria (Leshtakov, 2007, pp.452-453; Doncheva, 2012, pp.679-683, 688), Greece (Mangou et al., 2000) and Ukraine (Kobal', 2000, pp.70-71) some hoard analyses and regional studies were carried out not only allowing a more elaborate differentiation between several raw metal forms, but also permitting a more refined dating of the PCIs. These studies are supplemented by detailed metallographic examinations and chemical analyses (e.g. Tylecote, 1976, pp.160-165, 169-170; Gruber & Preßlinger, 1983; Angerbauer, 1985, pp.49-60; Maddin & Merkel, 1990, pp.42-199; Roman, 1990, pp.176-181; Scott, 1991, p.97; Czajlik et al., 1995; 1999; Trampuž-Orel et al., 2002; Franceschi et al., 2004; Preßlinger, 2003, p.68; 2004, pp.327-328; Wischenbarth, 2004; Ciugudean et al., 2006, pp.98-100; Jansen & Löffler, 2016; Reiter & Linke, 2016, pp.161-165; Haubner et al., 2017; Wang et al., 2018, pp.106-115; Windholz-Konrad & Modl, 2018, pp.47-48), which make their manufacturing process more transparent or allow conclusions about the origin of the copper from chalcopyrite or fahlore.

Recording system

The following manual lists important measurable parameters and visible features of PCIs and illustrates that it is possible to draw conclusions about their production or

<table>
<tr><th></th><th>COMPLETE PCI (without fracture surface)</th><th>FRAGMENTED PCI</th></tr>
<tr><td rowspan="25">VERBAL DESCRIPTION / VISUAL DOCUMENTATION</td><td colspan="2">FORM AND PRESERVATION</td></tr>
<tr><td>PRIMARY SHAPE
round, ovoid, drop-shaped (triangular), sub-rectangular, irregular

PRIMARY CROSS-SECTION
flat/flat (flat, rectangular), flat/convex (plano-convex, hemispherical, catenary, triangular/conical, trapezoid, bun-shaped, bell-shaped, bell-shaped/constricted, asymmetrical), concave/convex (curved, shrunken, bell-shaped/campanulate), convex/convex (umbonate, biconvex), multi-poured ingots (vacancies at the top/bottom, flat slabs with hook-shaped edges), ingots with large cavities, not definable</td><td>SECONDARY SHAPE
half, circular segment, quarter, eighth, wedge-shaped segment, pieces in varying geometric shapes (e.g. rectangular, quadratic, triangle, trapezoid, polygon), D-shaped edge piece, amorphous piece

SECONDARY CROSS-SECTION
complete or half cross-section, edge piece, slope piece, core piece, not definable</td></tr>
<tr><td colspan="2">CASTING EDGE
pointed, rounded, edged, tapered, steep, stepped, hook-shaped, bead-shaped, not definable</td></tr>
<tr><td>DIMENSIONS
major/minor diameter (ma./mi. diam.), thickness (th.), weight (wt.)</td><td>DIMENSIONS
length (l.), width (w.), thickness (th.), weight (wt.), rec. diameter (diam.)</td></tr>
<tr><td colspan="2">SIZE GROUP
large (size class 1: >20 cm diam., >3 cm th., >4 kg w.), medium (size class 2: 15-25 cm diam., 2-4 cm th., 2-5 kg w.), small (size class 3: <15 cm diam., <3 cm th., <2 kg w.), not definable</td></tr>
<tr><td colspan="2">MAGNETISM
not magenitc, slightly magnetic, strong magnetic</td></tr>
<tr><td colspan="2">PATINA
colour, texture, special features (e.g. oxidation coatings, rust spots, fire patina)</td></tr>
<tr><td colspan="2">CASTING SURFACE AND PARTITION FEATURES</td></tr>
<tr><td colspan="2">TEXTURES - TOP SURFACE
smooth, grainy or wrinkly surface, slight swellings or spherical bulges, burst/collapsed blisters, deep bubble craters/holes, cooling cracks</td></tr>
<tr><td colspan="2">IMPRINTS/COATINGS - TOP SURFACE
embedded charcoals or their imprints, slag coating, non-existent</td></tr>
<tr><td colspan="2">TEXTURES - BASE SURFACE
smooth, porous or pitted surface</td></tr>
<tr><td colspan="2">IMPRINTS/COATINGS - BASE SURFACE
embedded sand/grit, burned clay/ceramic or charcoals or their imprints, slag coating, non-existent</td></tr>
<tr><td colspan="2">POURING CHARACTERISTICS - TOP SURFACE
directed or concentric flow textures, concentration of pores and shrink holes, extensions, half-smelted and protruding objects on the surface</td></tr>
<tr><td colspan="2">TOOLMARKS / DEFORMATIONS
round punctures from wooden poles, scratches and notches from axes or chisels (blade length), marks from hammers with round or elongated fins (diameter of the imprints), mushroom head, deformations/flattenings, stress cracks, straight breaking edges</td></tr>
<tr><td colspan="2">INNER STRUCTURE AND FRACTURE SURFACE</td></tr>
<tr><td></td><td>GENERAL HOMOGENEITY
homogenous, heterogeneous, not definable</td></tr>
<tr><td></td><td>SHAPE - MACROPORES
spherical, ovoid, drop-shaped, elongated, irregular, connected pores</td></tr>
<tr><td></td><td>SIZE - MACROPORES
small pores (<3 mm), medium pores (3-15 mm), large pores (>15 mm), pores of all size classes, no pores visible</td></tr>
<tr><td></td><td>DENSITY - MACROPORES
low porosity (<5 vol%), medium porosity (5-15 vol%), high porosity (>15 vol%), non-porous</td></tr>
<tr><td></td><td>DISTRIBUTION - MACROPORES
uniformly/unevenly distributed, on the top side/base side, along a internal cooling rim</td></tr>
<tr><td></td><td>MACROSCOPIC INCLUSIONS
slag, charcoil, non-existent</td></tr>
<tr><td></td><td>GRAIN STRUCTURE
columnar grains, equiaxed grains, no grain structure visible</td></tr>
<tr><td>CASTING LAYERS
circumferential necking on the surface of the base side</td><td>CASTING LAYERS
two-layered, multi-layered, no layering visible</td></tr>
<tr><td></td><td>FRACTURE TYPES
comminuted fracture, unilateral V-notched fracture, bilateral V-notched fracture, splitting, not definable

FRACTURE EDGE
vertical, slanting, stepped, irregular</td></tr>
<tr><td></td><td>FRACTURE SURFACE PRESERVATION
sharp-edged (grainy/columnar/spiky), rounded (by annealing)</td></tr>
<tr><td rowspan="10">ADDITIONAL SCIENTIFIC ANALYSIS</td><td colspan="2">CHEMICAL/ISOTOPIC ANALYSIS</td></tr>
<tr><td colspan="2">atomic absorption spectroscopy (AAS), neutron activation analysis (NAA), energy dispersive X-ray fluorescence spectrometry (EDXRF), scanning electron microscopy with energy dispersive X-ray spectroscopy (SEM-EDS), inductively coupled plasma – atomic emmission spectroscopy (ICP-AES/OES), mass spectroscopy (ICP-MS), lead isotope analyses (LIA)</td></tr>
<tr><td colspan="2">METALLOGRAPHIC EXAMINATIONS</td></tr>
<tr><td colspan="2">macroscopic, light microscopic and/or electron microscopic structural examination of an etched microsection, hardness test</td></tr>
<tr><td colspan="2">IMAGING TECHNIQUES</td></tr>
<tr><td colspan="2">scanning electron microscopy (SEM), industrial computed tomography (CT), neutron tomography (NT)</td></tr>
<tr><td colspan="2">DATING METHODS</td></tr>
<tr><td colspan="2">radiocarbon dating of enclosed charcoal</td></tr>
<tr><td colspan="2">ARCHAEOBOTANICAL ANALYSIS</td></tr>
<tr><td colspan="2">wood identification on enclosed charcoal</td></tr>
</table>

Fig. 4: 'Checklist' for the recording of complete and fragmented PCIs with additional scientific analysis (graphic: D. Modl).

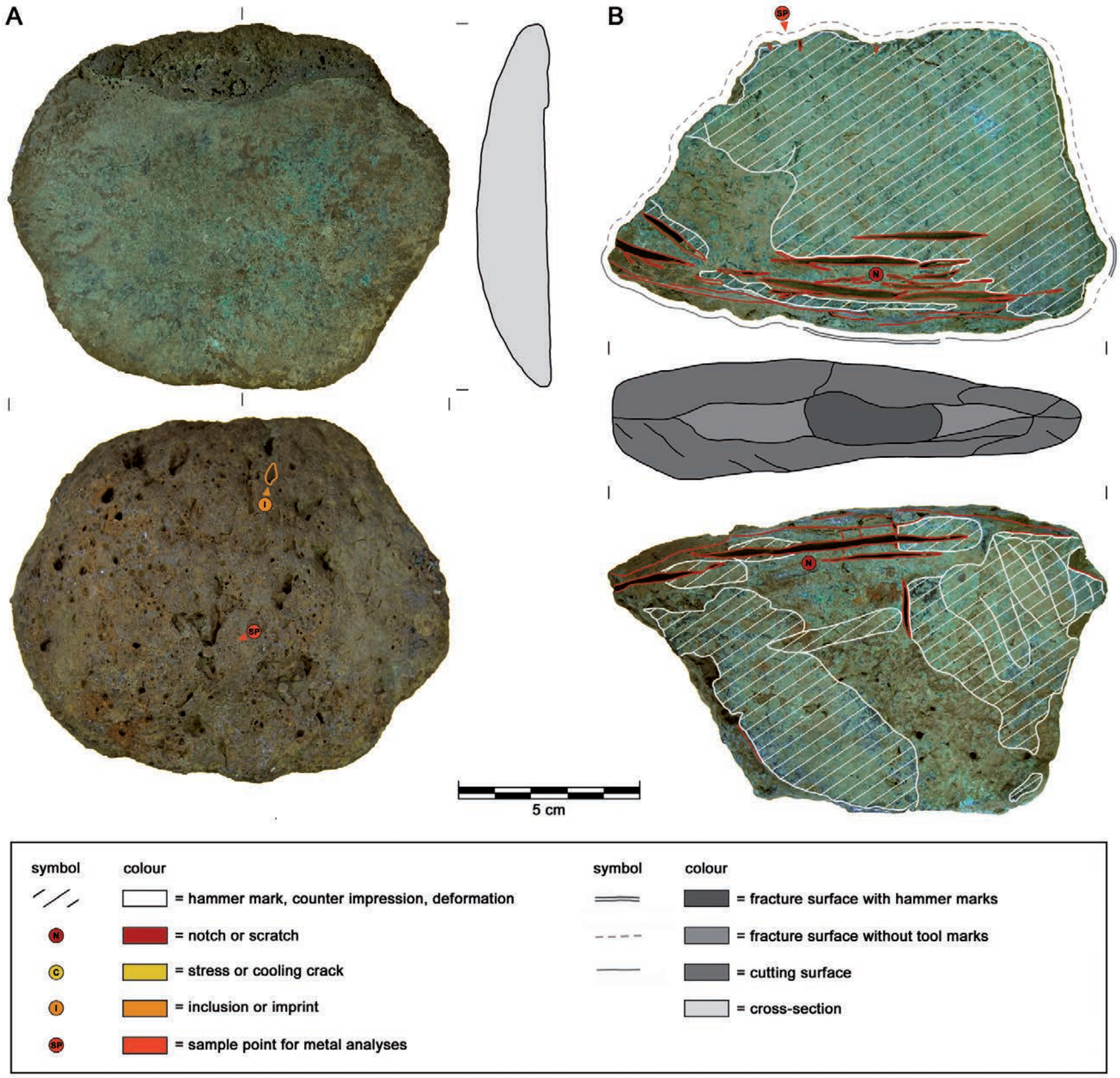

Fig. 5: Examples for the visual documentation of PCIs: (A) PCI from hoard XIX (CNr. 37; Bz D/Ha 1; see Windholz-Konrad, 2018, p.151, 175, tab.51/8) from the finding area 'Hallstatt-Seeufer', Upper Austria, (B) fragment of a PCI from hoard I (CNr. 11; Bz D/Ha A1/A2; see Windholz-Konrad, 2018, p.130, 160, tab.13/82) beneath the so-called 'Rabenwand' near Bad Aussee, Styria, together with a legend for the used symbols and colours (graphic: D. Modl).

partition by simple observation even without elaborate scientific laboratory analyses. In addition, the manual attempts to define a documentation standard that enables comparative studies. The practical work requires no equipment more sophisticated than a digital camera, photo scale, calliper, triangel ruler, circular graph paper, magnifying glass, neodymium magnet (N35) and a strong desk lamp.

However, the suggested approach cannot replace any scientific investigations if one wants to obtain more detailed information about smelting technology and material composition. For this purpose imaging techniques, like industrial computed tomography (CT) or neutron tomography (NT) and metallographic examinations with a hardness test (Brinell, Rockwell or Vickers) as well as quantitative chemical or isotopic analyses have to be applied (see Hauptmann, 2008; Pernicka, 2014; Pollard & Bray, 2014). Various methods were in use for the trace element analysis and provenance studies of copper PCIs, like atomic absorption spectroscopy (AAS), neutron activation analysis (NAA), energy dispersive X-ray fluorescence spectrometry (EDXRF), proton-induced X-ray emission (PIXE), electron probe micro analysis (EPMA)/ scanning electron microscopy with energy dispersive X-ray spectroscopy (SEM-EDS), inductively coupled plasma – atomic emmission spectroscopy (ICP-AES/OES) or mass spectroscopy (ICP-MS) and lead isotope analyses (LIA). Especially the impure and partly refined coppers (black copper) are most suitable for provenance studies because their geochemical fingerprint was not altered by alloying, mixing or recycling.

Furthermore it is possible to date the PCIs directly over charcoal inclusions and to determine the firewood used in their production through archaeobotanical analysis. Additional information can be obtained by comparing original PCIs with specimens from archaeological experiments.

The following manual was developed on the basis of scholarly literature and tested on an archaeological record from Styria and Upper Austria, which is a total of two dozen complete PCIs and quarter pieces as well as over 1000 fragments from the Bronze Age. The recording system describes a large number of external qualities by using a uniform terminology under the three headings of 'form and preservation', 'casting surface and partition features' as well as 'inner structure and fracture surface' which have been summarised in a useful 'checklist' (Fig. 4). This content outline shows that the recording system is not designed as a rigid typological study, but rather explains the individual characteristics of PCIs, which should allow for their better description in find catalogues.

For the visual documentation of the PCIs photographs of the top and base side and drawings of the cross-sections in scale of 1:1 or 1:2 were used (Fig. 5). With colored lines, hatchings and symbols, the sampling points for metal analysis as well as all specifics and modifications on the surface were marked, which are related to the production and partition of PCIs such as inclusions, imprints, cracks, plastic deformations and toolmarks. Various outlines drawn around the top side of the PCI finally show whether it has original casting edges or artificial fracture edges with and without toolmarks.

Since the here proposed visual documentation and verbal description is relatively time-consuming, larger quantities of PCIs can also be recorded in lists and presented with selected examples. For closed find complexes, like hoards, statistical evaluations of weight or partition shape should also be carried out.

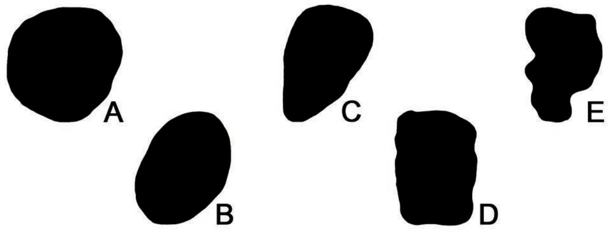

Fig. 6: The primary shape of PCIs: (A) round, (B) ovoid, (C) drop-shaped (triangular), (D) sub-rectangular, (E) irregular (graphic: D. Modl).

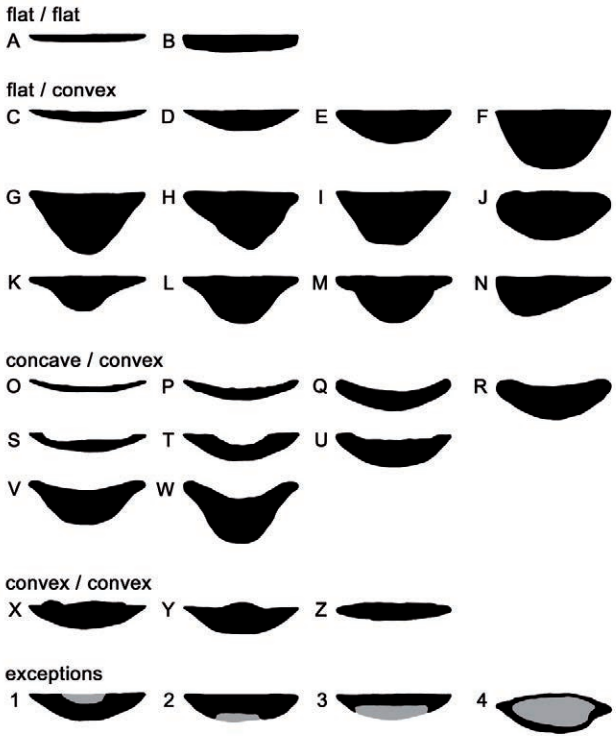

Fig. 7: The primary cross-section of PCIs (not to scale): (A) flat, (B) rectangular, (C-E) plano-convex, (F) hemispherical, (G) catenary, (H) triangular/conical, (I) trapezoid, (J) bun-shaped, (K-L) bell-shaped, (M) bell-shaped/constricted, (N) asymmetrical, (O-R) bowl-shaped/curved, (S-U) shrunken, (V-W) bell-shaped/campanulate, (X-Y) umbonate and (Z) biconvex. Furthermore cross-sections of multi-poured ingots with (1-2) voids at the top or bottom, (3) flat slabs with hook-shaped edges and (4) ingots with very large cavities (graphic: D. Modl).

Form and preservation

To define the form of a PCI, its shape, cross-section and maximum dimensions must be recorded. The primary form and dimensions of a PCI result from the shape, slope and size of the casting mould, which in most cases may have been a simple depression in the ground. In connection with the evaluation of the cross-section, the shape of the original casting edge, where the convex side meets the flatter top, should also be described in detail. In the course of manual partition the PCI is fragmented and receives a secondary form, which makes a conclusive morphological identification without experience usually difficult. The degree of fragmentation of the PCIs in hoards is typically high, so only a few intact specimens are contrasted with a large number of broken pieces, which in most cases can be assigned to the edge, slope or core areas of the ingot by applying the cross-section. As the evaluation of partition patterns and archaeological experiments has shown, most of the PCIs were not broken completely arbitrarily and irregularly, but according to certain rules that can be reconstructed according to the shape of the fragments.

It is not possible to assess the metal composition from the shape or from the surfaces of the PCIs. But to

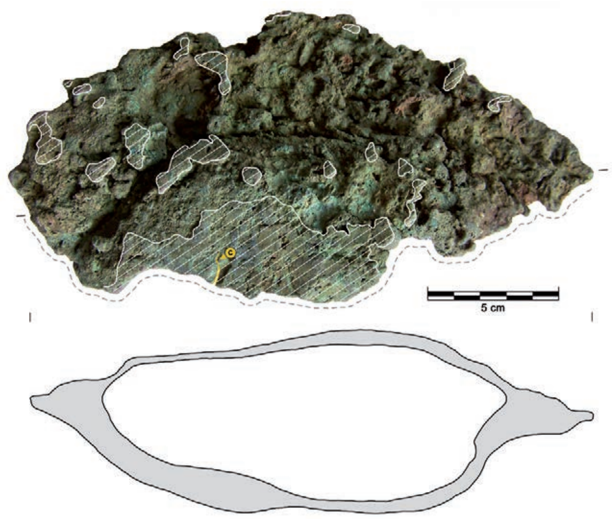

Fig. 8: PCI with a very large cavity and a very smooth inner surface from finding area 'Hallstatt-Seeufer', Upper Austria; unpublished single find (No. 32M07; see Windholz-Konrad, 2018, p.183) (graphic: D. Modl).

get a first idea about the metal composition of a PCI, it is sometimes helpful to inspect the patina and to determine the magnetic properties of the piece. A rust-brown patina and a strong magnetism indicate an increased iron content in the copper, which could be confirmed in following chemical analysis.

Primary shape (after casting)

Complete PCIs usually have a roughly round shape when viewed from above. But there are also more elongated specimens with ovoid, sub-rectangular or drop shape (triangular). Entire ingots that do not correspond to any of the preceding shapes are called irregular (Fig. 6/A-E).

Primary cross-section (after casting)

Intact PCIs are typically flat along the top and convex on the base. In cross-section, they are thickest at or near the center, then incline gradually towards the edges. The inclination of the ingot could possibly be related to the material of the mould, since pits in a loamy soil may have steeper walls than in a sandy ground.

However, the cross-sections of the PCIs are much more diverse and show variable cross-sections consisting of different combinations of the flat, concave or convex top and bottom sides (flat/flat, flat/convex, concave/convex, convex/convex; see Fig. 7). The PCIs can reach extreme manifestations in their cross-section. On the one hand, almost hemispherical and bell-spaped specimens exist - e.g. Czajlik, 1996, p.170, fig.13; Turk, 2000, pp.27-28, tab.22/25) and on the other hand, there are very flat pieces that do not really taper to the edges and look like slabs or 'flat cakes' ('Fladen'; e.g. Höglinger, 1996, p.142, tab.31/542; Bachmann et al., 2002/03, p.79, fig.9/A/2-3, 18/5, 14).

As a result of the faster solidification and shrinkage of the liquid metal around its perimeter during the solidification, a narrow, flat ring evolves often without blisters at the outer edges of the top surface of some PCIs, in which the center arches slightly because of rising gas bubbles (e.g. Pietzsch, 1964, pp.39-40, fig.16) or subsides in a depression due to intense shrinkage. Accordingly, in cross-section the top sides of the PCIs look more or less concave or convex. Secondary use of PCIs can cause their deformation at the edges or at the central base when pieces are used as workaround anvil.

Rarities are well preserved multi-poured ingots with voids on top of theirs bases where individual metal layers were detached because of poor adhesion (e.g. Höglinger, 1996, p.77, 141, tab.29/529; Turk, 2000, p.29, tab.25/37; Tarbay, 2014, p.220, 247, fig.72/85; 2016, p.108, fig.21/121). This group includes also thinner metal disks or fragments with characteristic hook-shaped edges (see Fig. 7/1-3, 9/G, 27), which should not be confused with another type of raw metal, double-flat slabs with very thin cross-sections of approximately 1 cm (e.g. Miske, 1908, p.20, tab.XX/2; Kytlicová, 2007, p.162, 302, 314, tab.56/A/82, 93/249; Tarbay, 2016, p.111, Fig 28/237; Nessel, 2017, p.172, 187, fig.2/c, 20). The different casting layers are sometimes also visible in the cross-section or at the bottom surface of the PCIs with a circular necking or collar (Fig. 7/M; e.g. Viertler, 1973, p.11, fig.2/6, 3/6; Engelmann, 1997, p.30, 74, 113, fig.43, tab.18/1; Weisgerber & Yule, 2003, pp.40-43, 49).

Extremely rare are PCIs with a core consisting of a different material (e.g. lead, slag; see Dörfler et al., 1969, pp.69-77; Weisgerber & Yule, 2003, pp.40-43, 49-51) or showing very large cavities that can not be explained by a simple gas distension (e.g. Mozsolics, 1984, p.37, 57, p.67, tab.16/3, 21/1) and rather seem to be caused by breaking off of such cores (Fig. 7/4, 8).

Casting edge

When describing the periphery of a complete PCI or an edge fragment, it is important to distinguish between the primary casting edge and the secondary fractured surface. The appearance of the casting edge is not only determined by the shape and slope of the mould wall, but also by the surface tension of the liquid metal and the cooling rate. In principle, several edge forms can occur, which can be described as pointed, blunt, edged, steep, round, stepped, hook-shaped ('hakenförmig') and bead-shaped ('wulstförmig') (Fig. 9).

Of particular interest are the two latter types: a hook-shaped edge is a possible indicator for a multi-layered ingot. These edges emerge when the molten metal gets in contact with an already solidified surface and surrounds it at the rounded edge (e.g. Moosleitner, 1982, p.467, fig.9/52; Enăchiuc, 1995, p.291, no. 341, fig.9/15; Teržan, 1995, p.170, tab.68/111; Engelmann,

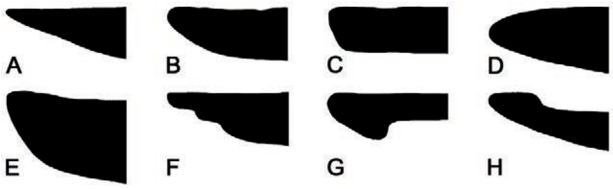

Fig. 9: Common forms of casting edges from PCIs: (A) pointed, (B) rounded, (C) edged, (D) tapered, (E) steep, (F) stepped, (G) hook-shaped, (H) bead-shaped (graphic: D. Modl).

1997, p.31, 74, 113, fig.44-47, tab.19/1-2; Bachmann et al., 2002/03, p.79, fig.9/A/1). Because of a weak bond between the two batches the ingot can break along the contact surface. A bead-shaped edge – sometimes together with cooling cracks on the top surface – is most commonly the result of a much faster cooling and hardening at the periphery of the PCI than in its central region. The outermost edges of the top surface are then marked by a cooling ridge or bulge, where molten metal of an ingot first solidifies (e.g. Krutter, 2015, p.48-49, fig.3). Furthermore it has to be taken into account that edges can be secondarily deformed in the course of partitioning so that they appear, for example, curved upward (e.g. Windholz-Konrad, 2004, p.325, 336, tab.10/11).

Secondary shape (after partition)

Most of the round PCIs may have been partitioned according to the principle of a continuing bisection into halves (e.g. Lauermann & Rammer, 2013, p.192, tab.88/7; Tarbay, 2016, p.99, 108, fig.22/127), quarters (Fig. 10/A-B; e.g. Höglinger, 1996, p.77, 141, tab.31/534; Windholz-Konrad, 2004, p.325, 336, tab.10/8-9) and eighths (e.g. Lauermann & Rammer, 2013, p.8, 23, tab.2/4; Tarbay, 2016, p.99, 109, fig.21/142). The quarter and eighth pieces were partially divided again, resulting in pieces with the shape of a triangle and an isosceles trapezoid (Fig. 11/A). In addition to the halves, there were also narrower circular segments, which were separated towards the edge of the ingot (Fig. 11/B). By splitting them into thirds, middle

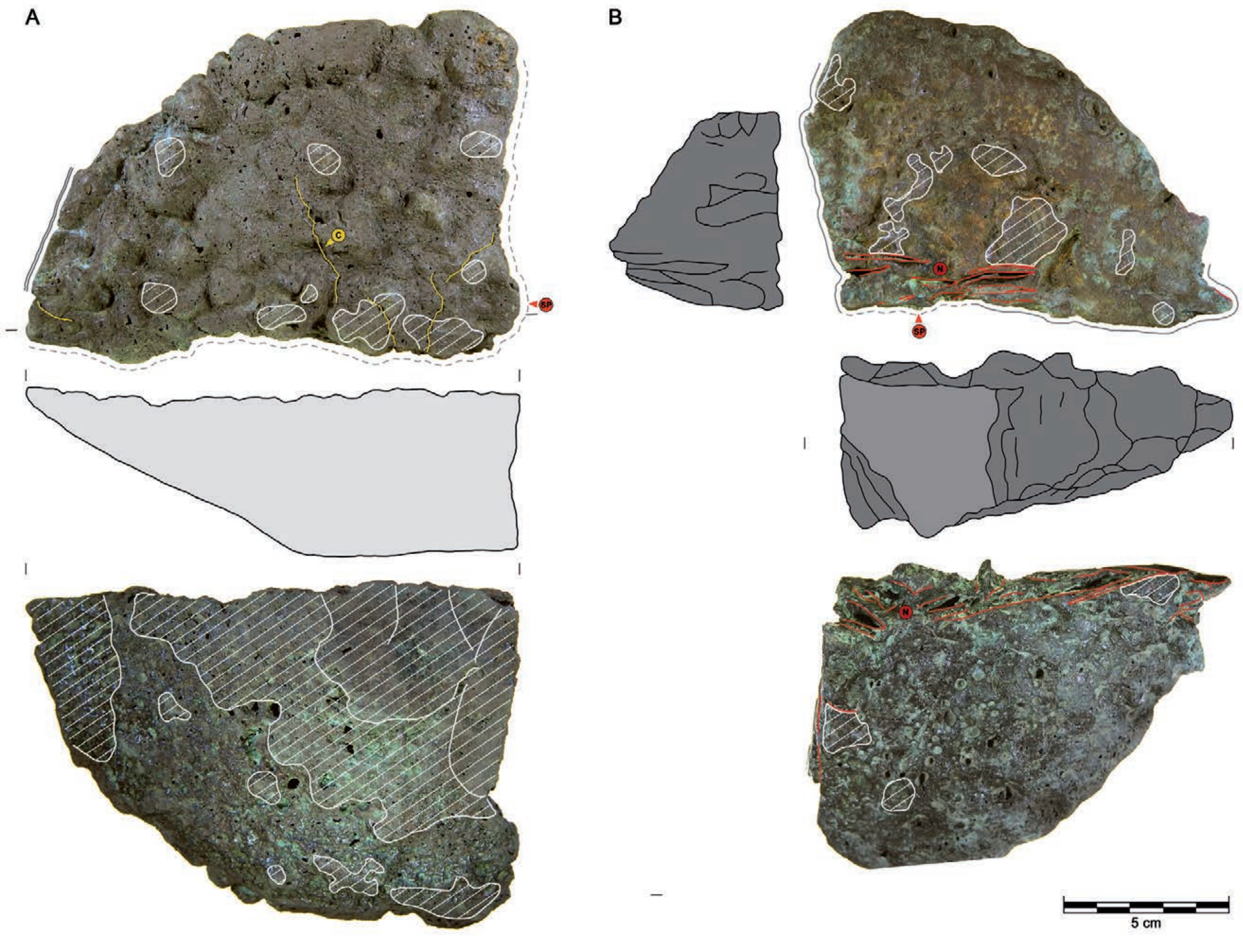

Fig. 10: Quarters of PCIs (A) from hoard III (CNr. 13; Ha A2/Ha B1; see Windholz-Konrad, 2004, p.318, 335, Fig. 33, tab.8/16) at the so-called 'Rabenwand', Styria, and (B) from a hoard near Pichl (CNr. B; Ha A2/Ha B1; see Windholz-Konrad, 2018, p.111, 119, 156-157, Fig. 75-76, tab.2/Cnr. B/3), both close to Bad Aussee, Styria (graphic: D. Modl).

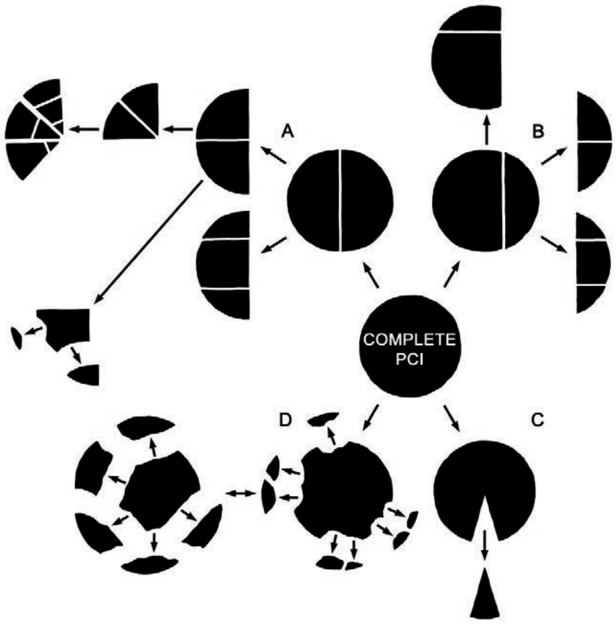

Fig. 11. The most common partition shapes of PCIs: (A) bisection into halves, quarters and eighths, (B) partition of circular segments, (C) separation of wedge-shaped segments and (D) circumferential edge fractions (graphic: D. Modl).

pieces with quadrangular shape were created. In principle, all geometric shapes can arise during partition (see Nessel, 2014, pp.404-405, fig.2; 2017, pp.178-179, fig.8; Tarbay, 2016, pp.99-100, fig.10/1).

The separation of wedge-shaped segments (Fig. 11/C), which approximately correspond to the sixteenth part of a whole ingot, belong to the exceptions (e.g. Mozsolics, 1984, pp.39, 69-70, tab.16/4, 17/2a-b; Czajlik, 1996, p.170, fig.13; Pühringer, 2000, pp.198-200, fig.6; Turk, 2000, p.28, tab.23/31; Ciugudean et al., 2006, pp.96, 98-99, fig.5/1, 9; Nessel, 2014, p.410, 425; 2017, pp.178, 192-193, fig.23). Other recurring partition patterns are isolated or circumferential edge fractions on complete ingots or their quarters (e.g. Windholz-Konrad, 2004, p.305, 334, tab.4/72; Lauermann & Rammer, 2013, p.185, tab.84/2), resulting in small D-shaped edge pieces (Fig. 11/D, 12). These thin edge pieces were probably chipped for a rapid production of minor quantities of copper or as a kind of material testing (see Modl, 2010, p.135, 148; Nessel, 2014, pp.407-408, 410; 2017, pp.187-188, 192). The largest part of the known ingot material is so small and irregularly broken that its emergence can not be reconstructed and must be called amorphous.

Secondary cross-section (after partition)

If fragments have no edge, it seems difficult to match them with a specific part of a PCI. However, by looking at the cross-section of the fragments, it is possible to determine also the inner parts of a PCI and assign them either to the core or to the area between the center and the edge. While the 'edge piece' has a triangular cross-section, the 'core piece' has a rectangular shape with a flat top and plane or slightly convex base and the 'slope piece' is more trapezoid with a significantly inclined base (Fig. 13). The transitions between these three areas are of course fluent and cannot always be clearly defined.

Dimensions

In addition to the major and minor diameter (ma./mi. diam.), the length (l.) and width (w.) of intact PCIs or their partitions and also the thickness (th.) and weight (wt.)

Fig. 12. Nearly complete PCI with circumferential hammer marks and edge fractions from hoard I (CNr. 11; Bz D/Ha A1/A2; see Windholz-Konrad, 2018, p.130, 160, tab.13/72) at the so-called 'Rabenwand' near Bad Aussee, Styria (graphic: D. Modl).

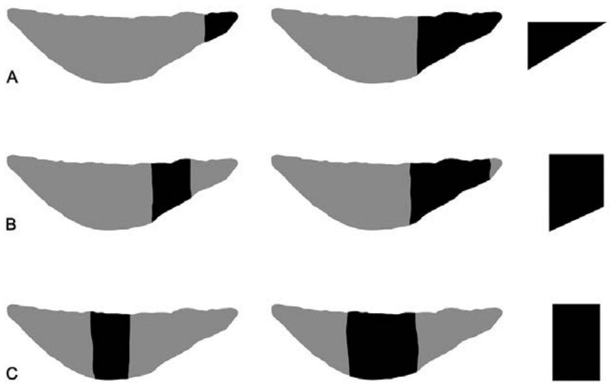

Fig. 13: Identification of different fragments of PCIs according to their cross-section (with the basic geometric form on the right side) in (A) edge pieces, (B) slope pieces or (C) core pieces (graphic: D. Modl).

should be determined (Fig. 14). Due to the fact that PCIs are mostly of a round shape, it is possible to reconstruct the original diameter by using well-preserved edge pieces (>10% from the perimeter) and a circular graph paper. The diameter of complete PCIs mostly varies between 8 and 30 cm, while their thickness ranges frequently between 1 and 10 cm. Some specimens even reach diameters over 45 cm (e.g. Wischenbarth, 1995, p.25). The weight of complete examples is an average between 0.5 and 8 kg, but examples of up to nearly 15 kg are known (e.g. Hild, 1948, p.90). Since PCIs were often poured in several casting batches, the capacity of the crucibles or furnaces cannot be derived from the size of the ingots.

Because of the heterogeneous structure of the PCIs with occasionally numerous gas bubble cavities, the relation between diameter, thickness and weight is not linear and can fluctuate. This will be clarified by the attempt to divide the PCIs with these measured values into different size groups (see Rusu, 1981, p.382; Höglinger, 1996, pp.76-77; Primas & Pernicka, 1998, pp.35-36; Bachmann et al., 2002/03, p.81; Modl, 2010, p.134), which can be roughly defined as large (size class 1: >20 cm diam., > 3 cm th., >4 kg wt.), medium (size class 2: 15-25 cm diam., 2-4 cm th., 2-5 kg wt.) and small (size class 3: <15 cm diam., <3 cm th., <2 kg wt.).

Patina

The patina of PCIs depends primarily on corrosive substances in the soil and secondarily on the chemical composition of the metal. This is why their colour only provides evidence about the metal composition in rare cases. Isolated rust spots, as well as a complete rust-brown coating on PCIs (see Preßlinger, 2004, pp.327-328; Weihs 2004, p.91; Windholz-Konrad, 2004, p.305, 325; Kytlicová, 2007, p.164), are quite reliable evidence of an increased (metallic) iron content above 3 wt%, which can be a result of strongly reducing conditions during primary smelting (see Bachmann, 1982, pp.17-18; Craddock & Meeks, 1987; Trampuž Orel et al., 2002, p.66, 71). But sometimes corrosion and patina can also be adverse because they hide tool marks or cover surface details on the PCIs such as gray-violet oxidation coatings of cuprous oxide, which emerge when the melt was exposed to the oxygen-containig atmosphere during casting or heating.

Magnetism

When the iron content of the copper exceeds 1 wt%, a PCI can show low or high magnetism that can be detected with a strong hand magnet (Fig. 15).

Casting surface and partition features

Depending on the country and research tradition, the definition of the top and base side of a PCI differs. It seems evident to align them according to their orientation during

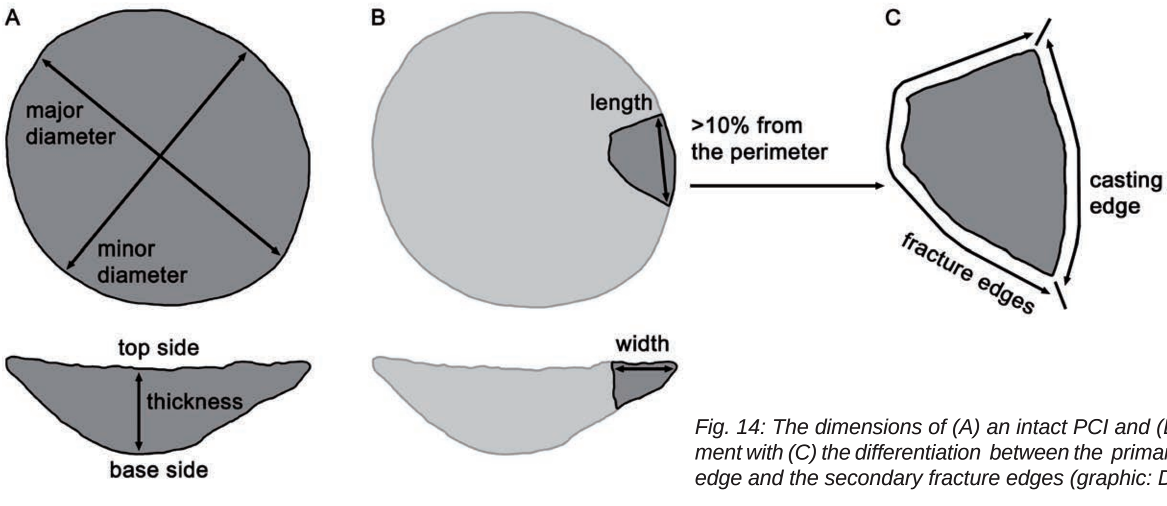

Fig. 14: The dimensions of (A) an intact PCI and (B) a fragment with (C) the differentiation between the primary casting edge and the secondary fracture edges (graphic: D. Modl).

Fig. 15: Ferrous PCI with an adhere neodymium magnet ring (N35) (photo: D. Modl).

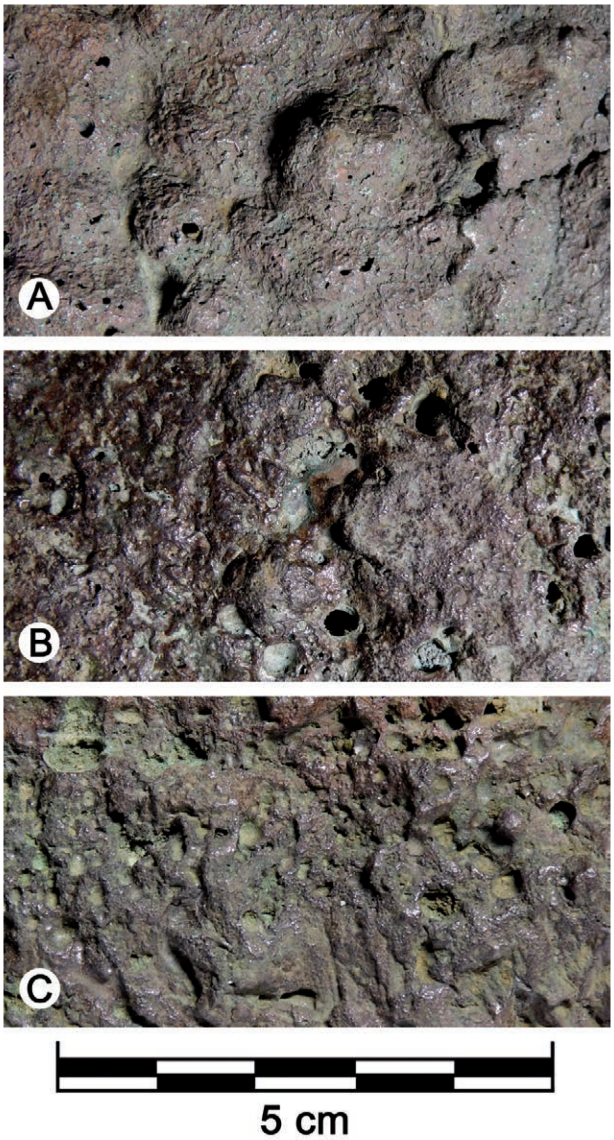

Fig. 16: Detailed views of the (A) top and (B) base as well as the (C) fractured surface of a PCI quarter from hoard III (CNr. 13; Ha A2/Ha B1) at the so-called 'Rabenwand' near Bad Aussee, Styria (see Windholz-Konrad, 2004, p.318, 335, Fig. 33, tab.8/16) (graphic: D. Modl).

casting and solidification. While the flat side at the top is exposed to the air, the convex side at the bottom stands in permanent contact with the mould material. Depending on the enviroment, the surface of the top and base has a distinctly different texture, which is primarily characterised by the formation and escape of gases or by imprints of the mould face and the fuel (Fig. 16). Additionally, the surface of the PCIs shows numerous metallurgical and technological features from pouring and partitioning, like flow structures of the liquid metal, as well as toolmarks or deformations.

Solidification textures and imprints at the top surface (upper side)

One of the distinctive features of PCIs is their blistered and humpy surface on the flat top, which is on the one hand a result of degassing during the solidification of the molten metal, and on the other hand an indicator of pouring into an open mould. Size and density of the blisters depend on the gas saturation, viscosity and the cooling rate of the melt. The violent escape of gas bubbles at the surface – a phenomenon known in metallurgy as crackling ('Spratzen') – shows different stages of development and ranges from slight swellings or spherical bulges over burst and collapsed blisters to more or less deep bubble craters or holes (Fig. 10/A, 16/A, 17/D-F; e.g. Barth & Unterberger, 1983, p.7, fig.2, 4; Mozsolics, 1984, p.36, 63-64, tab.9/2; Windholz-Konrad, 2003, p.66, fig.62; 2018, p.124, 158, tab.7/16). At low gas evolution, the PCIs can also have no blistering on their top and instead show an even surface with a smooth, grainy or wrinkly texture (Fig. 5/A, 17/A-C). Smooth surfaces are the result of well-dried moulds and rapid solidification, but an additional coverage of the melt – possibly by another metal or slag phase or charcoal powder – cannot be excluded. While fine wrinkles can be compared with a 'milk skin', the coarse wrinkles have the appearance of ripples, which can be interpreted as flow structures from the casting. Compared to the bottom side, imprints of charcoals on the top are very rare. The top surface can be considerably compressed and deformed in the course of the secondary partition of the PCI, so that, for example, the protruding blisters are flattened.

Solidification textures and imprints at the base surface (bottom side)

The bottom side of a PCI is also determined by gas evolution, but especially by the material properties or the surface texture of the mould (see Larson, 2009). For example, irregularities or spalling in stone or clay moulds

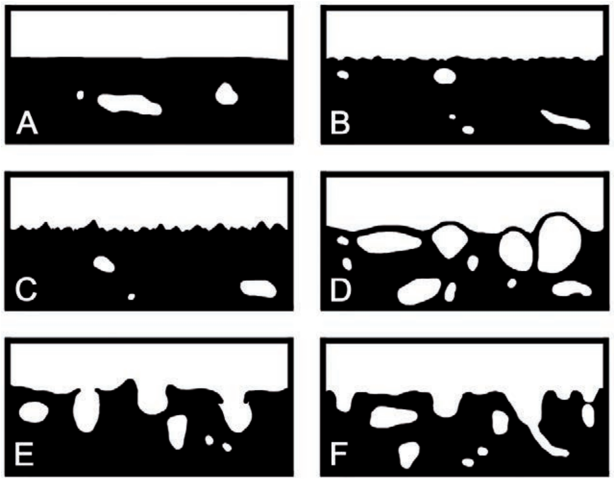

Fig. 17: Textures at the top surface (shown in cross-section): (A) smooth surface, (B) grainy surface, (C) wrinkly surface, (D) slight swellings or spherical bulges, (E) burst and collapsed blisters, (F) deep bubble craters or holes (graphic: D. Modl).

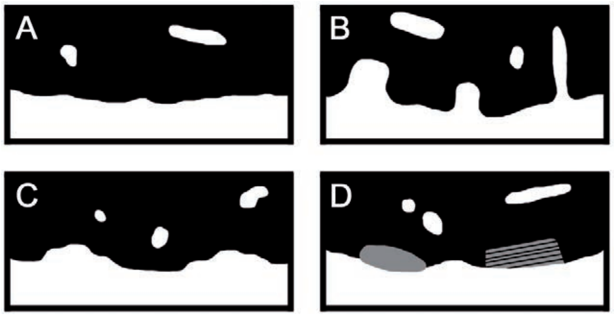

Fig. 18: Textures and imprints at the base surface (shown in cross-section): (A) smooth surface, (B) porous surface, (C) pitted surface, (D) surface with embedded sand/grit or imprints of charcoals (graphic: D. Modl).

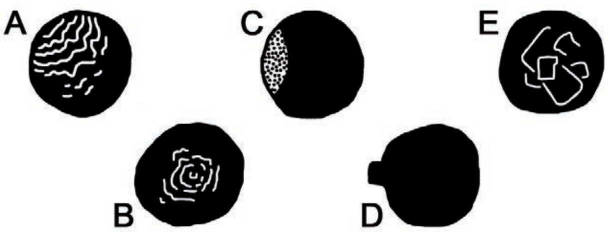

Fig. 19: Pouring characteristics on PCIs: (A) directed flow textures, (B) concentric flow textures, (C) concentration of pores and shrink holes, (D) extensions and (E) half-smelted and protruding objects (graphic: D. Modl).

or deformations in sand moulds with malleable surfaces, which can easily be distorted by the pressure of the molten metal, ensure that no PCI possesses a completely even bottom. Three different surface configurations can be differentiated at the base with smooth, porous and pitted areas (Fig. 16/B, 18/A-C). The round gas pores are either superficial cavities with semi-spherical shape or deep tubular pinholes that are a result of gas exchange between the molten metal and the mould surface, provided that the material of the mould is gas-permeable.

The irregular pits are small, synclinal and interrelated (Fig. 5/A, 12). Their emergence is mainly due to the rough material used to create the mould or because of a sloppily smoothed mould surface. As burnt clay/loam remains or embedded sand/grit on the lower surface shows, the moulds were mostly simple pits in a clayey or sandy/stony ground. Some PCIs also show bulges that could be tree roots (e.g. Viertler, 1973, p.11, fig.2, 3). Sometimes vitreous slag residues can be observed on the base surface which could be a reaction product of the contact between the molten metal and the mould material.

While imprints of small-sized charcoals with relatively sharp edges and unambiguous wood grain are often recognizable (Fig. 18/D), complete charcoal fragments are rarely incorporated in the lower surface (Fig. 1). These charcoals were maybe a temper of the mould material, fuel rests from preheating the mould or impurities that were incorporated into the mould during casting through the liquid melt. However, the well preserved charcoals are an important source for direct dating of PCIs by using the radiocarbon method. The most unusual inclusions on the bottom side of PCIs are ceramic fragments (e.g. Engelmann, 1997, p.30, 73, 113, fig.41-42, tab.18/2).

Pouring characteristics

PCIs are mainly produced by using the open-mould process. This is not only supported by the fact that some PCIs were cast in several batches and consist of two ore more metal layers, but they also display flow textures and features, like a possible ‘sprue’. These casting characteristics are rarely visible on the top, because the surface of the ingots is greatly altered by the rising gas bubbles. The flow textures show a wrinkled or billowy texture that extends in one direction or spreads concentrically (Fig. 19/A-B; e.g. Höglinger, 1996, p.141, tab.27/516, 29/518), sometimes forming a large swelling which can be a sprue from production. These ripples are a result of the movement of the liquid metal under a nearly congealing skin, compressing them in the flow direction. At the edge of some PCIs there are distinct concentrations of pores and shrink holes (Fig. 5/A, 19/C; e.g. Windholz-Konrad, 2003, p.93, 129, fig.128; Modl, 2010, p.130, fig.1; Windholz-Konrad, 2018, p.151, 175, tab.51/8) as well as narrow extensions (Fig. 19/D; e.g. Modl, 2010, p.130, fig.6; Lauermann & Rammer 2013, p.130, tab.44/2; Reiter & Linke, 2016, pp.150-151, fig.48/1), which could indicate a lateral inflow of the metal into the mould. PCIs made from recycled scrap metal sometimes reveal only half-smelted bronze objects on their top surface that protrude slightly (Fig. 19/E; e.g. Mozsolics, 1981; 1984, pp.35-36, tab.5-6; Kacsó, 2013, pp.228-229, fig.5/5; Tarbay, 2014, p. 220, p.247, fig.68/80; Reiter & Linke, 2016, p.150, pp.168-169, fig.45/3, 52/6).

Fig. 20: Complete PCI with hammer marks and shallow notches at the base surface, which possibly originate from the use as primitive anvil; unpublished single find (No. 2MM05) from finding area 'Unteres Koppental', Styria (graphic: D. Modl).

Toolmarks and deformations

On some of the PCIs, a single, round puncture could be observed, presumably from wooden poles stabbed into the viscous copper shortly after the casting, possibly for degassing the melt or to determine the degree of viscosity (e.g. Willvonseder, 1940, p.10, tab.3/1; Drescher, 1976, p.62, fig.15/e; Mozsolics, 1981; Töchterle, 2002, pp.120-122, fig.3/1; Kacsó, 2013, p.228, fig.5). Relatively often, even complete PCIs display superficial scratches or deeper notches that were accrued in the viscous or doughy copper on the top surface to determine where to divide the piece into halves or quarters during a later stage (e.g. Hild 1948, p.90, fig.1/1; De Marinis, 2011, p.93, fig.2; Stöllner, 2015, p.101, fig.7; Nessel, 2017, p.186, fig.13). The further procedure was depending on the porosity and thickness of the PCI and on the intended specific shape of the partitioned section.

If an ingot was rich in gas bubbles and cuprite or copper sulphide inclusions, it could be broken under cold and warm conditions by crashing it with a hammer or a similiarly heavy tool on a massive support (Fig. 2/E-F). The result are pieces with irregular shape and uneven fractures as well as brittle cracks and deformations, like areas with concave and sometimes overlapping imprints caused by blows with a hammer with rounded face (Fig. 5/B, 10/A, 12).

To achieve a definite breaking shape the reheated ingot (over 300°C) was notched on one or both sides and broken or split completely by the use of different wedge-shaped cutting tools (e.g. Drescher, 1976, p.61, fig.15/c-d; Mozsolics, 1984, p.38, 51, 71, tab.10/2, 4; Teržan, 1995, p.203, tab.92/74, 162; Windholz-Konrad, 2004, p.305, 313, 334-335, tab.4/82, 6/18; 2018, p.122, 130, 158, 160, tab.5/2, 13/82; Kytlicová, 2007, pp.162-163, 258, tab.163/2; Nessel, 2014, p.407, fig.7-8; 2017, p.186, fig.14-15). Therefore bronze axes or width chisels ('Abschröter') with a blade lenght of approximately 3-4 cm are used, which typically penetrate 0.5-1 cm into the annealed metal (see Modl, 2010, pp.136-137, 142-144, fig.13, 19, 23, 26). Usually, around the notches single or several imprints of hammers with round and elongated fins are visible (Fig. 5/B). The PCIs broken in this way have surprisingly straight or vertical fracture edges (see Mozsolics, 1984, p.38, 67, tab.21/3; Windholz-Konrad, 2003, p.85, 110, cat.no. 251/1, fig.103; 2018, p.142, 167, tab.39/Cnr. 21/1; Nessel, 2014, p.407, fig.9-10; 2017, p.186, 188, fig.16-17).

Some complete PCIs show flattening of their base with several hammer marks and randomly oriented, shallow notches, which originate from the use as primitive anvils (Fig. 20; e.g. Nessel 2017, p.186, fig.10). The same applies to pieces of PCIs showing a mushroom head (Bartbildung) on one side and a plain face from countless hammer blows from using it as an anvil in a wooden block (see Jockenhövel, 1983; Bachmann et al., 2002/03, p.78, 88, fig.8/B/1; Gogâltan, 2005, p.373, tab. XII/b). The saw marks mentioned by some authors may be misinterpretations (cf. Höglinger, 1996, p.77; contra Modl, 2010, p.144). If the analysed PCIs come from older museum collections, previous cleaning and restoration treatments or metal sampling can obliterate or add tool marks on their surface (see Modl, 2012, p.99, fig.10).

Inner structure and fracture surface

The cooling rate of the molten metal and the solidification conditions in the mould have a big effect on the inner structure of the PCIs. This concerns the development of gas pores and shrinkage cavities, but also the distribution of non-metallic inclusions and the formation of copper

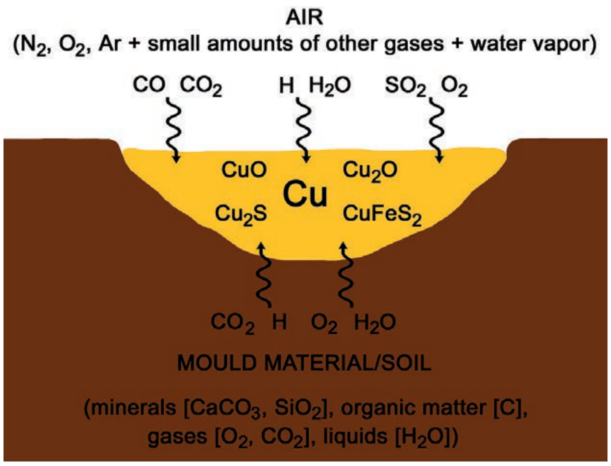

Fig. 21: Simplified representation of the gas apsorption in copper PCIs (graphic: D. Modl).

Fig. 22: Fragmented PCI with a good visible slag grain and a elongated gas cavity on the fracture surface; single find (see Windholz-Konrad, 2003, p.93, 127, cat.no.534, fig.124) from finding area 'Obertraun-Traunweg' near Hallstatt, Upper Austria (photo: D. Modl).

crystals/grains in the solid metal. These characteristics can be macroscopically observed on the fracture edges of PCIs and are important for the evaluation of their general homogeneity. This can also be determined by the fact that numerous PCIs were not poured in a single casting event, but in several batches, which are visible in definable metal layers when broken. In contrast, there exist also numerous very massive PCIs that show an extraordinary density without shrinkage or gas bubbles as well as striations from multiple castings on the fracture surfaces. In addition, the fractured surface provides hints concerning the stress factors and temperature conditions during partition.

Porosity

A characteristic feature of the majority of the PCIs is their high porosity caused by gas evolution and shrinkage that forms numerous pores and cavities inside as well as blisters on the surface during solidification. Liquid copper has the tendency to absorb gases such as oxygen (O_2), hydrogen (H) and water vapour (H_2O), as well as carbon monoxide (CO), carbon dioxide (CO_2) and sulfur dioxide (SO_2). These gases derive, among others, from a combustion reaction between the liquid copper and the mould material, from the burning charcoal, from the evaporation of residual moisture in the mould and charcoal, from the exchange with the humid air and from oxidation of copper sulphide inclusions in the copper (Fig. 21; see Hauptmann, Maddin & Prange, 2002, pp.4-5; Hauptmann & Maddin, 2005, pp.133-136; Bunk & Kuhnen, 2008, pp.310-313; Modl, 2010, pp.129-130, 140-141; Laschimke & Burger, 2012, pp.89-95; Hauptmann et al., 2016, pp.752-759). Because of the transgression of the solubility limit of gases in the melt, the dissolved gases are released while cooling and as a result rapidly increased gas bubbles from greater depth try to escape on the top surface of the ingot. However, slowly growing gas bubbles can easily be trapped in the solid. If the surface is already solidified, it is likely that the gas bubbles will form flat as well as large closed cavities in the upper part of the ingot (Fig. 22).

Accordingly, the size of the cavities ranges from a few micrometres (micropores) up to centimetre scale (macropores). The macropores can be roughly divided into small (<3 mm), medium (3-15 mm) and large pores (>15 mm). Gas pores are generally spherical or ovoid in shape and have a smooth pore boundary. In contrast, shrinkage cavities ('Lunker') created by volume deficits in the solidified molt during cooling have a more or less fissured, irregular shape. Together, gas pores and shrinkage cavities occupy often 15-40% of the volume of a PCI (Fig. 23/C). This high macroporosity was advantageous for breaking the ingots into fragments because the fractures could spread along the pores and cavities through the brittle copper matrix (cf. Hauptmann et al., 2002, p.19; Laschimke & Burger, 2012, p.94; Hauptmann et al., 2016, p.758). For this reason, the porosity of a PCI should not be considered a negative quality characteristic. Often, the PCIs have a much lesser density of pores and cavities in their cross-section, so that a distinction furthermore can be made between a low (<5% of the volume) and medium porosity (5-15% of the volume) (Fig. 16/C; 23/A-B). To characterise the porosity of a PCI, the shape, size, density and distribution of the pores should be described briefly.

Inclusions

Because this manual deals with visible features, microscopic and macroscopic inclusions have to be differentiated. Inclusions of slag, tenorite/cuprite (CuO/Cu_2O) and copper sulphides ($Cu_2S/CuFeS_2$) are usually microscopic in size and can only be clearly seen in metallographic sections (see Tylecote, 1976, pp.159-165; Hauptmann et al., 2002, pp.6-12, 19; Hauptmann & Maddin, 2005, pp.137-139; Hauptmann et al., 2016, pp.753-754; Wang et al., 2018, pp.108-111). While copper sulfides reduce during remelting

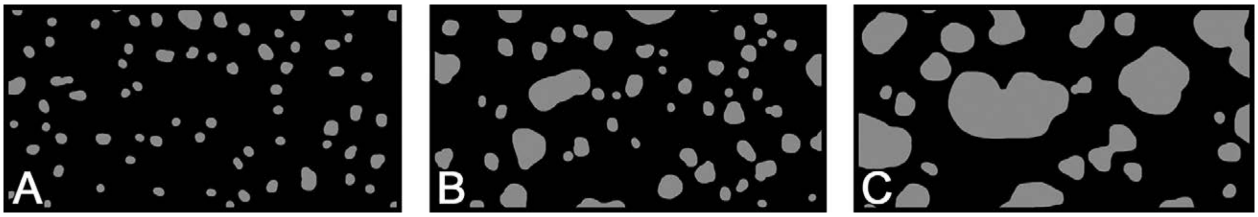

Fig. 23: A comparative standard for the densities of gas pores and shrinkage cavities in the cross-section of PCIs: (A) low porosity with <5 vol%, (B) medium porosity with 5-15 vol% and (C) high porosity with >15 vol% (example with 30 vol%) (graphic: D. Modl).

processes, the metal normally accumulates copper oxides during recasting. Accordingly, both impurities are – together with the chemical composition – important criteria to distinguish copper from primary smelting or from later refining, recasting or recycling operations.

While slag and copper sulphides are relics of the smelting process, especially the cuprite is the result of a reaction between the molten metal and an oxygen-enriched atmosphere during remelting and casting. These oxide droplets are well distributed in the metal and can dramatically deteriorate the mechanical properties of the copper and make it brittle. Due to imperfect refining or sloppy casting, larger slag grains (Fig. 22) well visible to the naked eye and charcoal bits as well as foreign refractory particles from the mould can enter the metal and are sometimes recognizable on the fracture surface (e.g. Modl, 2010, pp.141-142, fig.22; Jansen & Löffler, 2016, pp.129-130). Because of their lower density such inclusions are usually found on the ingot surface (cf. Pietzsch, 1964, p.15, fig.1), however if the solidification happens fast, they can be trapped inside the ingot.

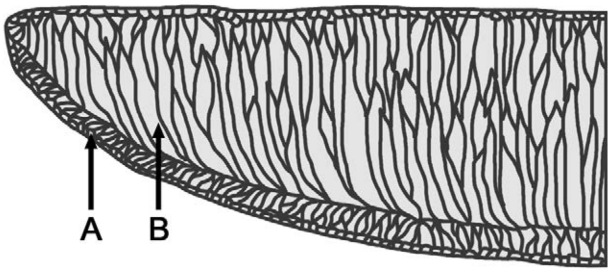

Fig. 24: Grain structure of a PCI: (A) Equiaxed grains and (B) columnar grains. Graphic adapted after a photo with the section of an experimental ingot cast into a drysand mould [see Tylecote, 1976, p.164, Fig. 1.3; University of Oxford, Research Laboratory for Archaeology and History of Art, Tyl_316]; the top surface was exposed to air, while the bottom was at room temperature (graphic: D. Modl).

Fig. 25: Fragmented PCI with good visible columnar grains and hammer marks on the fracture surfaces from a hoard (HaA1) near Lannach, southwest of Graz, Styria (photo: D. Modl).

Crystal/grain structure

When metal begins to solidify, multiple crystals start to grow inside the liquid. In metallurgy, crystals or more precisely the smaller crystallites are preferably termed as grains. The interface formed between grains is called a grain boundary. The size, shape and orientation of the grains depend on several parameters, like cooling rate and direction. While rapid cooling generally results in smaller grains, slow cooling creates larger grains, which can be large enough to be visible to the unaided eye.

There are two major types of grain structures in pure copper: The equiaxed grains have a globular or polygonal shape and extend equally in all directions, while columnar grains are elongated and thin and orientated towards the course of the heat flow. Depending on whether the metal is cast into a cold or preheated mould, two grain structures for uninterrupted single-poured PCIs seem likely. The casting in a cold mould will give a distinctive two-stage cooling structure with an outer layer of many small equiaxed graines reflecting the rapid chilling when it has come into contact with the cold mould wall and an inner layer with columnar grains running in the direction of cooling. The casting into a preheated mould will give the ingot a more columnar structure, whereby the grains grow perpendicularly to the mould in direction of the upper surface, where the heat removal is very high (Fig. 24). These columnar grains are best seen in polished and etched metallographic sections (see Tylecote, 1976, pp.160-165, 170; Scott, 1991, p.6, 97), but can also be

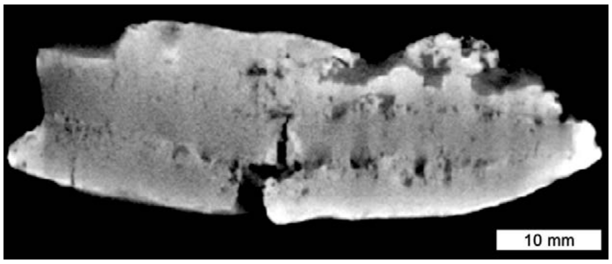

Fig. 26: CT scan of a PCI from a hoard (CNr. A; Ha A2/Ha B1; see Windholz-Konrad, 2018, p.107, 119, Fig. 74, tab.1/8) in Pichl, Styria, with at least three casting layers (photo: Austrian Foundry Research Institute (ÖGI), Leoben).

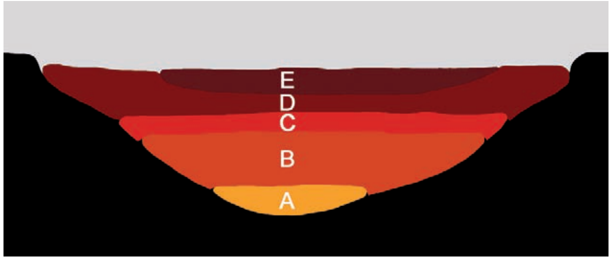

Fig. 27: Highly schematic representation of variants of multi-poured ingots with their characteristic cross-sections and casting edges: (A) small PCI, (B) PCI with a void at the base side, (C) PCI fragment with hook-shaped edges, (A-D) PCI with a void at the top side, (A-E) bell-shaped PCIs with an circumferential necking at the base side and (E) flat PCI (graphic: D. Modl).

relatively frequently observed on fracture surfaces of PCIs (Fig. 25; e.g. Kytlicová, 2007, p.162, tab.28/98, 35/17; Modl, 2010, pp.131-132, fig.7; Le Carlier de Veslud et al., 2014, p.517; Nessel, 2014, p.406, fig.5; 2017, pp.186-187, fig.12). They allow the conclusion that the ingots were cast in a dry and warm environment where they cool relatively quickly because of the open mould. The specific fracture along the columnar grains could be related to cuprite or copper sulphide inclusions along the grain boundaries. How far the primary cast structure of PCIs changes during the partitioning with possibly several heating and dividing episodes has not yet been researched. From a recrystallised structure could be concluded that the PCI comes from a secondary dividing process in which it was alternately reheated and chrushed-up.

Fig. 28: PCI fragment (presumably base-metal speiss with 60,76 wt% Cu, 15,13 wt% As, 0,36 wt% Ni, 13,91 wt% Fe) with an adherent, silvery metallic phase on the top side (80,50 wt% Cu, 0,93 wt% As, 0,03 wt% Ni, 15,44 wt% Fe) from the so-called Brandgraben hoard (CNr. 15; Bz D/Ha A1/A2-Ha B3; see Windholz-Konrad, 2018, p.46, 60, Fig. 34/189) near Bad Aussee, Styria (photo: D. Modl).

Casting Layers

Striations on the fracture surfaces reveal that many of the PCIs consist of two ore more layers and were consequently formed by several casting batches, performed in close succession or separated by a longer interval (e.g. Moosleitner, 1982, p.467, 473, fig.9/49, 51; Engelmann, 1997, p.73, 113; Krauss, 1998/1999, pp.117-118, fig.4/2, 7, 12; Bachmann et al., 2002/03, p.77, fig.7/C/6; Tarbay, 2016, p.99, 110, fig.24/161). Depending on how much time has elapsed between the batches, the result is the complete fusion of the metal layers or the formation of internal cooling rims between them (see Modl, 2010, p.132; Hauptmann et al., 2016, p.754, 756, 759). The rims can be described as sharp cracks, blurred gas bubble horizons or corrosion coating of cuprite among the layers. These interfaces can be clearly seen with the naked eye or in a CT scan (Fig. 26), when the molten metal hits an already cold and solidified surface after an interruption, which makes a complete fusion impossible. The liquid metal of this pour has seeped only into the irregular surface of the previous pour and has created a weak, interlocking, mechanical bond between both batches that could be cracked when the ingot was partitioned.

Accordingly, there exist PCIs with voids on the top or the base, where individual layers have obviously been detached as a consequence of poor adhesion (Fig. 7/1-3, 27). The same applies to thinner metal disks or fragments with hook-shaped edges. As a result of insufficient smelting or refining, also thin layers of slag and other metallic phases (Fig. 28; see Modl, 2011, p.273), like speiss (see Angerbauer, 1985, pp.16-19; Ottaway, 1994, p.103; Trampuž-Orel & Heath, 2001, pp.150-151, 155, 167; Thornton et al., 2009, pp.308-310), can also form layers on PCIs, which lie on top of the copper because of their lower density and specific gravity.

Fracture edges

The fracture behaviour of PCIs and the appearance of their fractured surfaces are determined by the chemical composition, homogeneity (porosity/inclusions) and crystal/grain structure of the metal, as well as the temperature

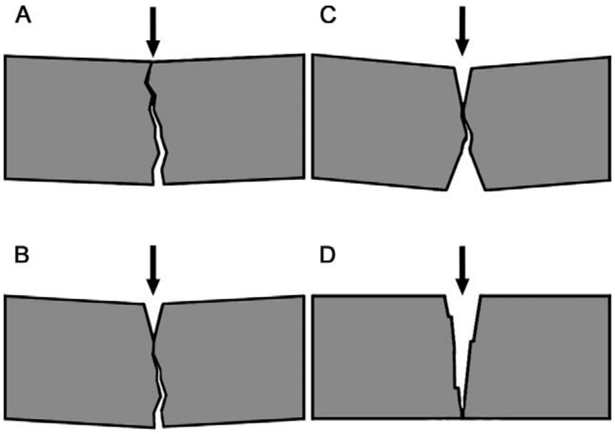

Fig. 29: Fracture types: (A) comminuted fracture, (B) unilateral V-notched fracture, (C) bilateral V-notched fracture, (D) splitting (graphic: D. Modl).

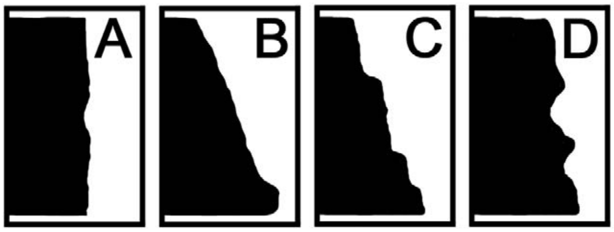

Fig. 30: Fracture behavior: (A) vertical, (B) slanting, (C) stepped, (D) irregular (graphic: D. Modl).

which they were exposed to during partition. Pure copper is very ductile and therefore hard to break under cold conditions. However, a higher content of elements, such as arsenic or iron, as well as impurities along the grain boundaries, like cuprite or copper sulphide inclusions, make it possible to break the metal even in a cold state because of its brittleness, although this is only possible with relatively thin PCIs. This effect is enforced by an increased porosity of the metal, since the fracture can spread out irregularly along the gas pores and shrinkage cavities, which are virtually predetermined breaking points. In this way, even thicker PCIs can be comminuted with a hammer or a similiarly heavy tool ('comminuted fracture'; Fig. 29/A; see Modl, 2010, pp.135-136, fig.11; Nessel, 2014, pp.405-406; 2017, p.182, 186).

At the microstructural level, the cold fracture has frequently run through the individual grains (transgranular fracture) and produced a grainy or spiky surface. When the metal is broken the brittleness increases under hot conditions and a crack propagates mostly along the weakened grain boundaries (intergranular fracture) and the elongated columnar grains often become clearly visible. However, this characteristic grain structure with a splintery surface can disappear in the course of further heating, when the metal is annealing and the sharp-edged surface develops a smooth doughy texture and grain borders or edges begin to round off (e.g. Primas & Pernicka, 1998, p.27, fig.2/1-2, 4; Modl, 2010, p.135, fig.3, 32).

Overall, considerably more – often intergranular – brittle fractures appear on PCIs, while ductile fractures with clear visible plastic deformations are rather rare. The reason for this lies in the multiple notching of many PCIs on one or both sides by axes or chisels ('unilateral or bilateral V-notched fracture'; Fig. 29/B-C), which facilitates the formation of a fracture originating from these structural defects. The surface of the fractures can be vertical, slanting, stepped or irregular (Fig. 30). If the thickness and homogeneity of a PCI did not allow its comminution, the piece was completely split, leaving a vertical cutting edge with a smooth surface and sometimes well visible impressions of the tools ('splitting'; Fig. 10/B, 29/D; e.g. Mozsolics, 1984, p.38, 72, tab.20; Modl, 2010, p.136, 146, fig.32).

Conclusio … or a critical remark

PCIs are amongst the largest cast objects in Bronze Age Europe, as far as the processed amount of metal is concerned. They provide a range of technological information on prehistoric copper metallurgy, given that they are properly described and evaluated, for which this paper offers a first approach. On the basis of the here described parameters and features, future studies will have a basic framework that hopefully simplifies the determination of individual groups of PCIs in the archaeological material trough formal similarities (as well as chemical composition) and allow a better reconstruction of the metallurgical process guidance, the appearance of the casting facilities and the further processing (Fig. 31).

As emerges from the proceeding discussion, the variables that determine the shape and appearance of a PCI are very diverse. The efficiency of the pyrotechnical facilities and the skills representing the experience of the prehistoric smelters as well as their access to the raw metal determined the amount of processible copper and thus the weight of the PCIs. Because of the multilayer structure of many PCIs and their production in several casting batches, their weight is no indication for the size of furnaces. The shape, dimensions and appearance of the PCIs depended on the individual design of the mould, the type of moulding material, the potential preheating of the mould and the external conditions during cooling, whereby external and internal features such as porosity or surface conditions could only be influenced to a limited extent by the prehistoric smelter.

The same applies to the partition of the PCIs. The association of shapes of fragmented PCIs or special geometric fracture forms with certain material qualities, provenances, production areas, distribution networks or weight standards should be done very carefully and with considerable caution.

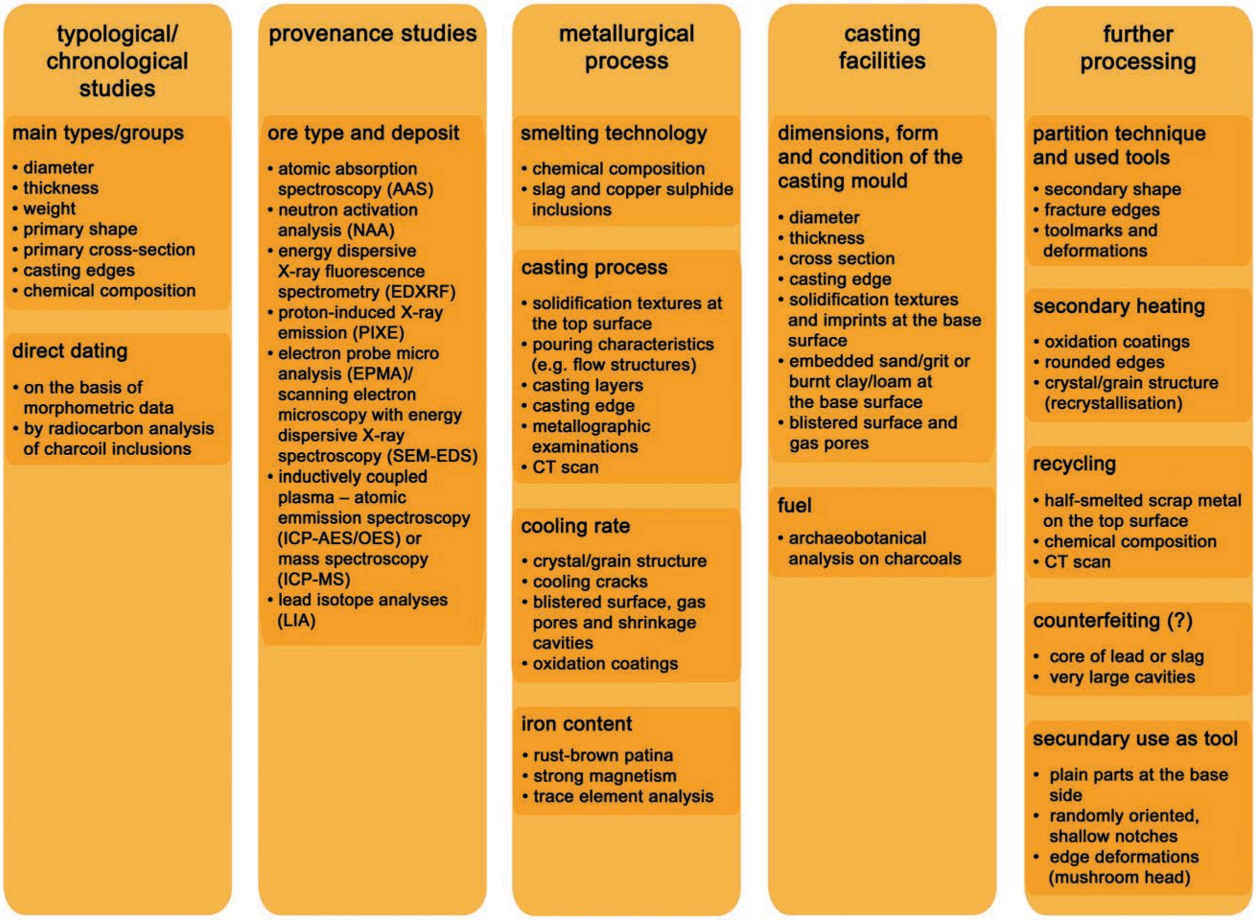

Fig. 31: Parameters and features as well as scientific investigations, which allow typological/chronological and provenance studies on PCIs as well as the reconstruction of the metallurgical process, the appearance of the casting facilities and the procedure of further processing (graphic: D. Modl).

Many characteristics of complete and fragmented PCIs are rather individual or a product of alteration during their processing, which is too often ignored when creating studies and typologies concerned with these artefacts.

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Author

Daniel Modl – Universalmuseum Joanneum, Department Archaeology & Coin Cabinett, Schloss Eggenberg

Correspondence and material requests should be addressed to: daniel.modl@museum-joanneum.at

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Stephan Möslein & Ernst Pernicka

The metal analyses of the SSN-project (with catalogue)

ABSTRACT: *1996-1998 the Volkswagen Foundation funded the metal analysis project "investigations of the metallurgical production chain in the South Bavarian Alpine piedmont, the Salzburg region and in Northern Tyrol from the Middle Bronze Age to the end of the Late Bronze Age " (= SSN). The objective was to gain insights into the distribution of copper from the North Tyrolean Inn Valley, from the Kitzbühel area and from Salzburg (Pongau, Pinzgau) in southern Bavaria, based on the hypothesis that differences between the ores from the main deposits "Mitterberg", "Kitzbühel" and "Schwaz/Brixlegg" should be recognizable in the composition of finished objects found in adjacent areas. The analyses should provide results on the duration of Bronze Age copper production in the individual mining districts, their floruit phases and clues to stability and/or change of Bronze Age alloy compositions.*

Although there is no final publication, the interpretation of the analytical results can be found in broad terms in Sperber (2004). A return towards an increased use of fahlore copper about 1100 BC is evident.

In addition to the general question, the dataset holds great potential for detailed investigations on various issues. The authors intend to supplement this in the near future, but have seized the opportunity to present the original data to the scientific public at this point.

KEYWORDS: METAL ANALYSIS, LATE BRONZE AGE, EAST ALPINE COPPER, FAHLORES, SOUTH GERMANY, CASTING CAKES

It is meanwhile more than 20 years that, in September 1996, the SSN metal analyses project was launched, financed by the Volkswagen Foundation. The acronym SSN is derived from the project title "Untersuchungen zur metallurgischen Produktionskette im Südbayerischen Alpenvorland, im Salzburger Land und in Nordtirol von der mittleren Bronzezeit bis zum Ende der Spätbronzezeit" (investigations of the metallurgical production chain in the South Bavarian Alpine piedmont, the Salzburg region and in Northern Tyrol from the Middle Bronze Age to the end of the Late Bronze Age).

Although the project was in no way comparable to the Copper and Early Bronze Age projects of Otto/Witter and SAM in quantitative terms, we proceeded to uncharted waters dealing with Middle and Late Bronze Age metal analyses in our region. Initiated by Lothar Sperber (Historisches Museum der Pfalz, Speyer), the administrative platform of the project was the Bayerisches Landesamt für Denkmalpflege München (Stefan Winghart), the analyses by energy-dispersive X-ray fluorescence was carried out at the Max-Planck-Institut für Kernphysik in Heidelberg and later at the Technische Universität Bergakademie Freiberg. The analytical method was developed in Heidelberg and published in detail by Lutz and Pernicka (1996). All measurements were performed on drill samples obtained with a 1.0 or 1.5 mm stainless steel drill. In order to avoid any effect from corrosion, the first drill shavings were discarded. For the implementation (sampling etc.) only one job was financed for two years (Stephan Möslein). A comprehensive review of relevant objects resulted in a list of 35 museums and 20 private collections, which detailed documentation and sampling. Additionally, Klaus-Peter Martinek (mineralogy) has collected 116 copper ore samples from the central and eastern Alpine region, part of which were published by Höppner et al. (2005).

The project objectives were rather ambitious, as we wanted to gain insights into the Middle and Late Bronze Age production and distribution of Alpine copper from the North Tyrolean Inn Valley, from the Kitzbühel and the Salzburg regions and from southern Bavaria, based on the hypothesis that differences between the ores from the three main deposits "Mitterberg", "Kitzbühel" and "Schwaz/Brixlegg" should be recognizable in the

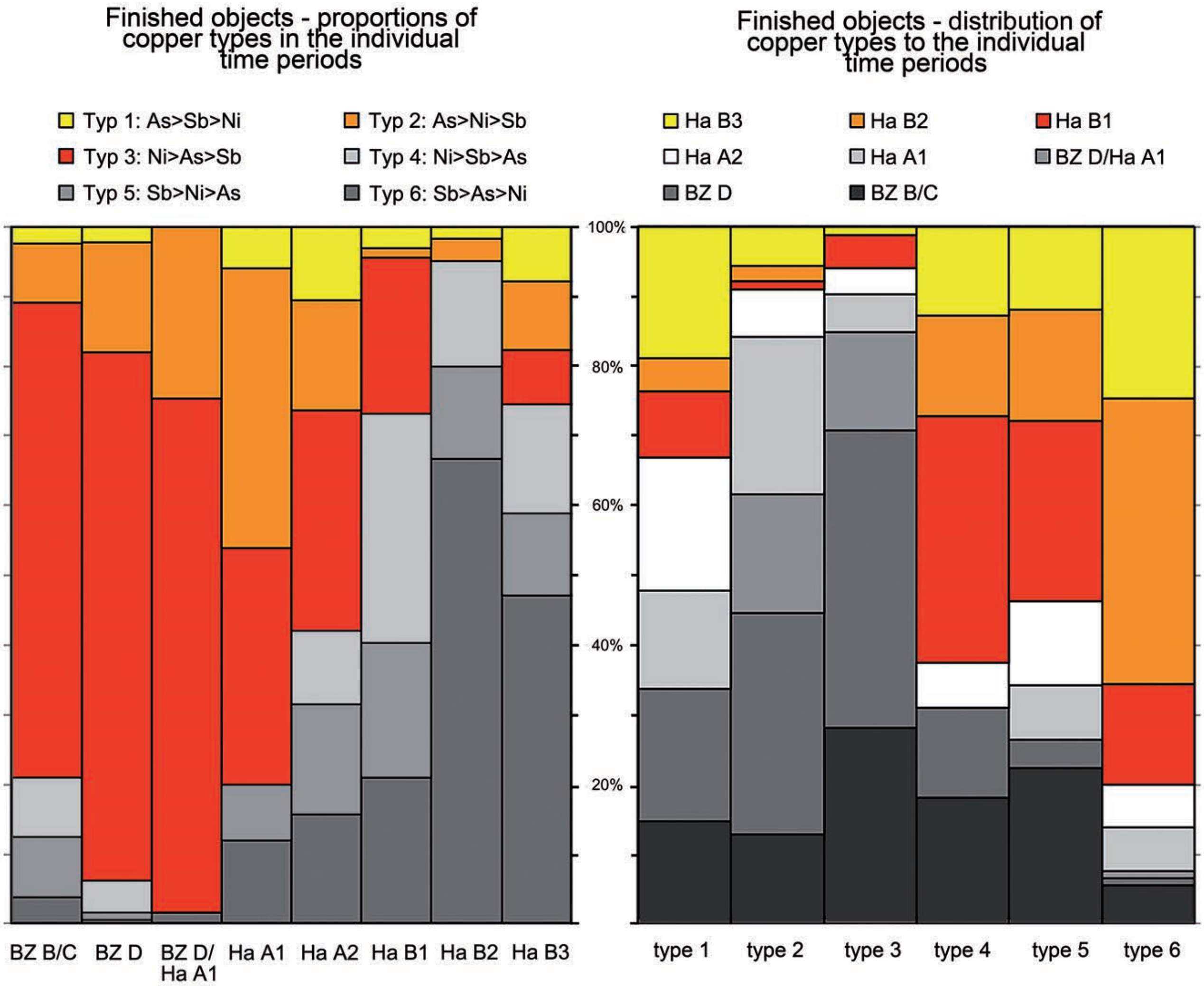

Fig. 1: Analyses of finished objects, classified according to the ranking of the elements As, Sb and Ni (like Rychner & Kläntschi, 1995) (chart: S. Möslein).

composition of finished objects found in adjacent areas. We distinguished six regions (Sperber 2004, Abb. 6), and for each of them we tried to gather a representative number of samples for each time period. The regional and chronological distribution of the respective pieces of evidence should deliver insights into duration of Bronze Age copper production in the individual mining districts, their floruit phases and clues to stability and/or change of Bronze Age alloy compositions. A coherent, but rather naive imagination, as we know today. The problem of provenance determination of metal is far from being solved – except for special cases (see below).

Unfortunately, due to several circumstances, the project was finished without final publication, but at least the interpretation of the analytical results can be found in broad terms in several articles by Sperber (2003; 2004).

What remains to be published now, however, are the analyses of more than 700 artefacts, some of which were sampled more than once, e. g. hilts and blades of swords or different layers recognizable in the broken edges of casting cakes. Therefore, the dataset contains 826 analyses: 641 of finished objects and 185 of casting cakes. Only 79 of the latter can be dated, the remaining 106 casting cakes cannot be fixed exactly within the possible time span between the end of the Early Bronze Age and the Final Bronze Age. According to a rough typological classification by S. Krutter (2015), most of them should belong to the Late Bronze Age. All in all, 613 analyses are chronologically so significant that they can be reasonably compared on a time-scale.

When the first results of the analyses became available, the classification was processed in two ways: Ernst Pernicka performed a classification by cluster analysis, while Lothar Sperber preferred sorting by hand following the method of Rychner and Kläntschi (1995) in a similar project in Switzerland. Since the compositional structure of the data is very clear with two very different compositional types of copper and little overlap between different classes, both approaches yielded similar results.

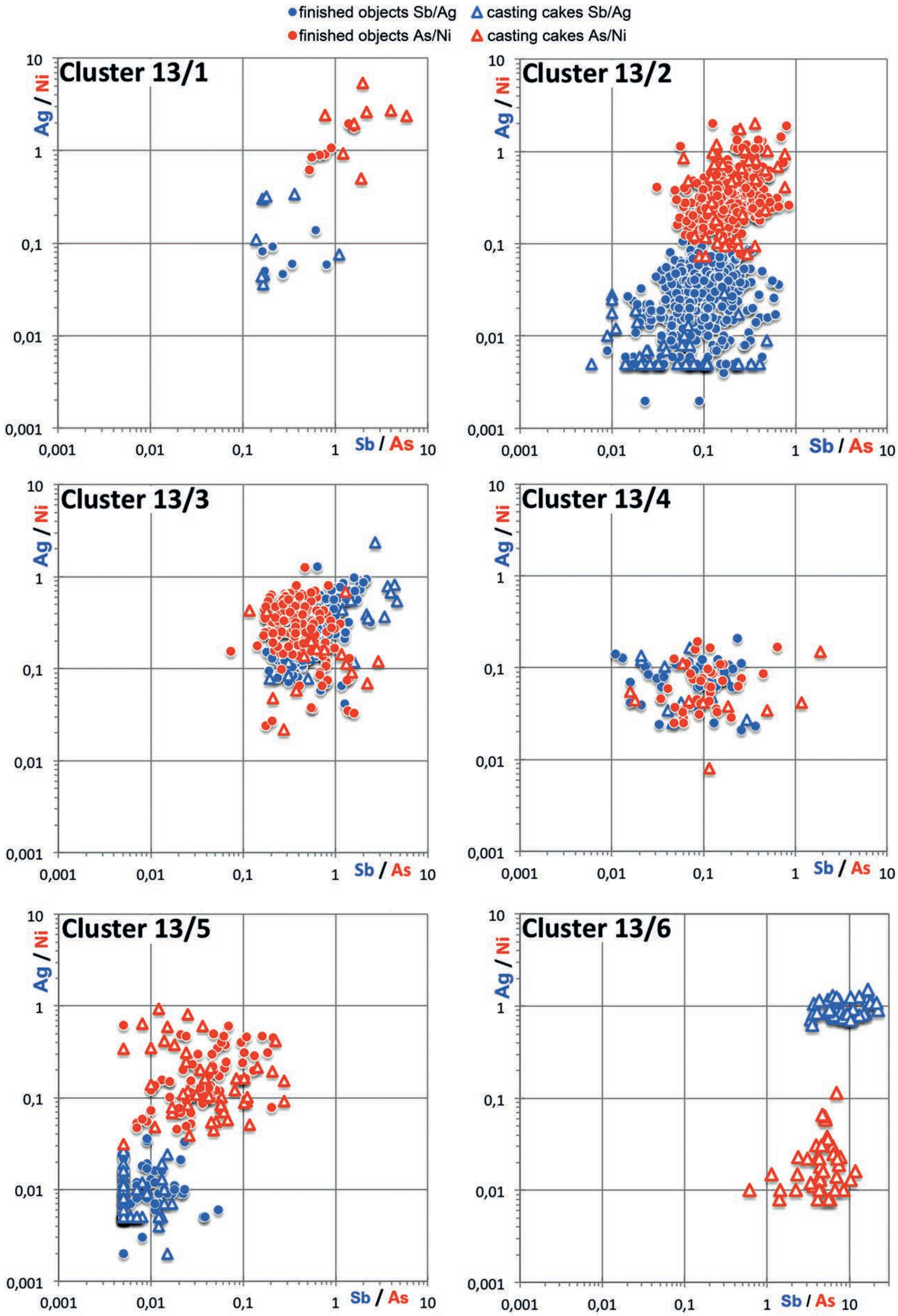

Fig. 2: SSN-dataset, the six largest of 13 clusters (chart: S. Möslein).

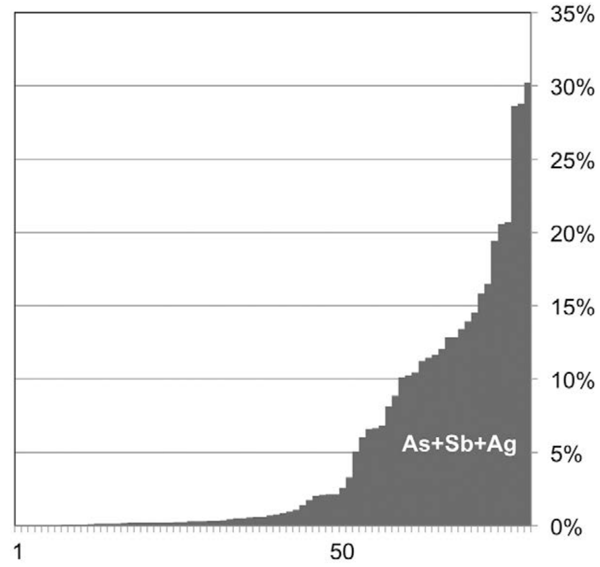

Fig. 3: The summed portions of the elements As, Sb and Ni in casting cakes of the SSN-dataset (chart: S. Möslein).

The hierarchic sorting of the analyses according to the elements As, Sb and Ni shows that the six compositional groups or metal types (cf. Fig. 1, legend of the right diagram) are not randomly distributed over the period under study. In fact, their percentages vary in different time periods. The clear dominance of type 2 (As>Ni>Sb) and especially 3 (Ni>As>Sb) extends from the Middle Bronze Age to the Early/Middle Urnfield Age (Ha A1/2), while the highest frequency of types 5 and 6 are found in the Younger and Late Urnfield Periods (Ha B1-3). With Sb as major impurity and, especially in type 6, with regularly high concentrations of Ag > 0,1%, these compositional types should indicate the processing of fahlores. The phenomenon of re-appearing fahlore-type copper since about 1100 BC can be observed across wide areas of central and north-western Europe (e. g. England, France, Switzerland, Bohemia, Slovenia, Hungary). In our region

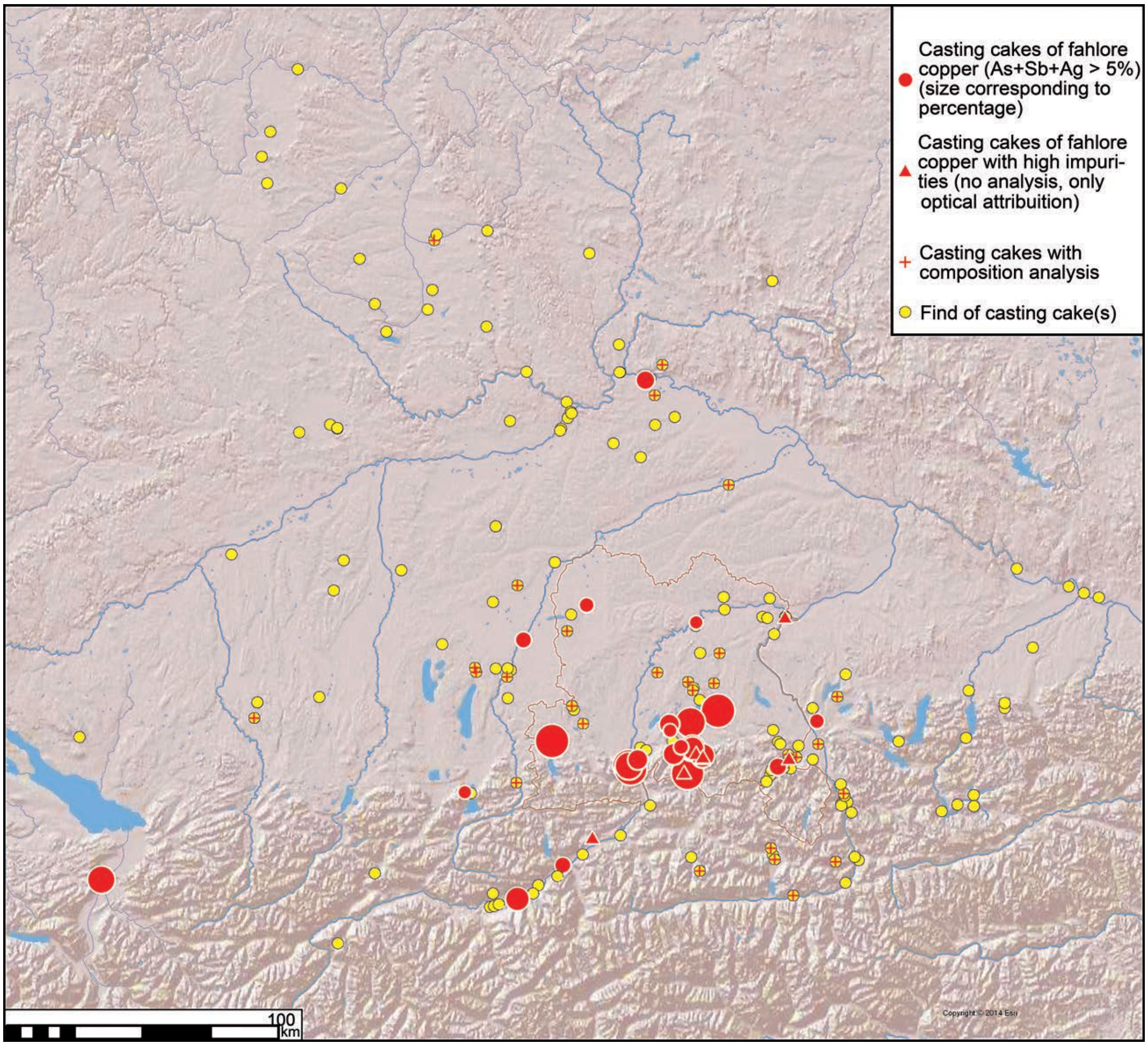

Fig. 4: Distribution of cluster 6 casting cakes and similar objects (map: S. Möslein on ArcGIS basemap).

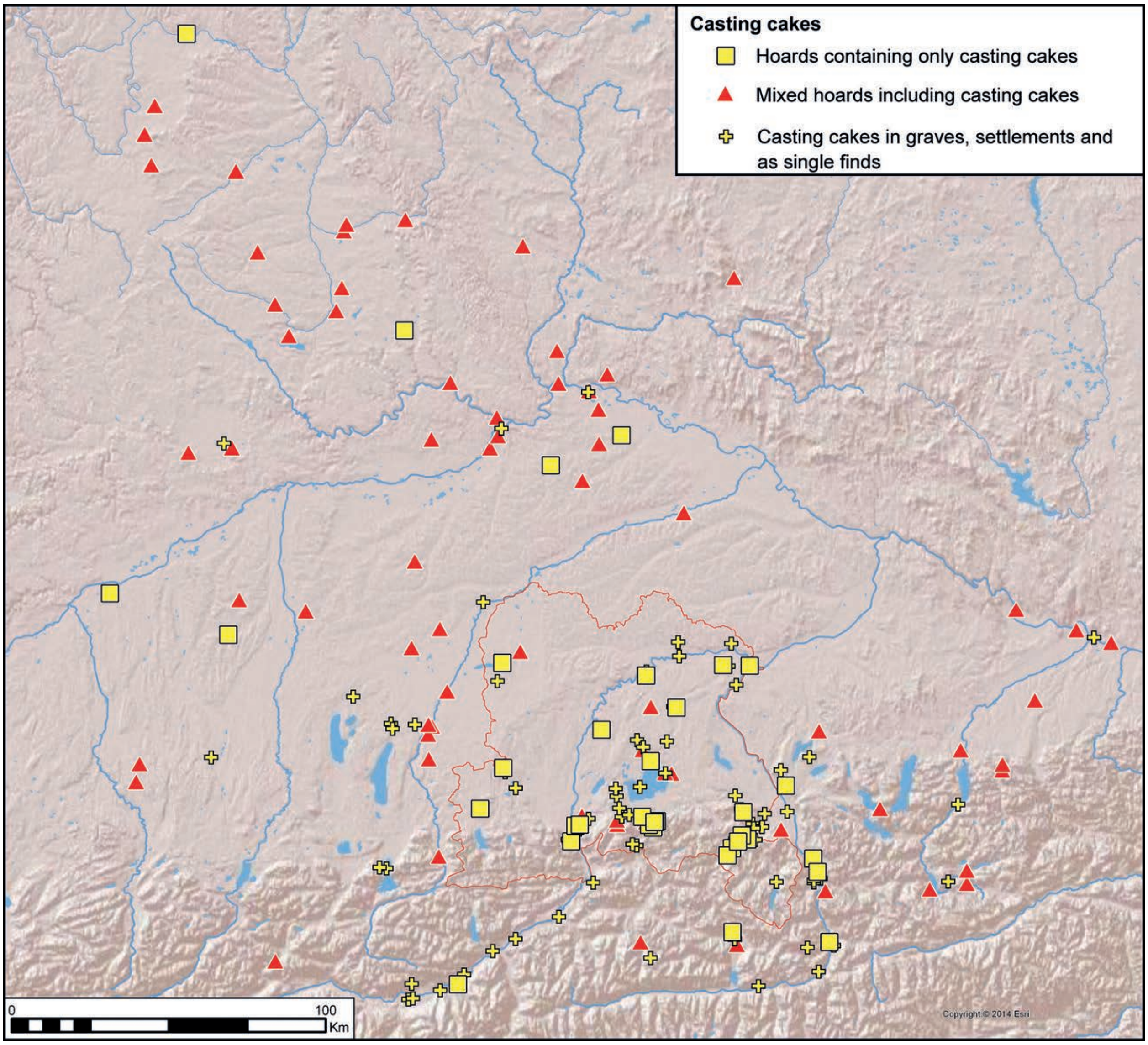

Fig. 5: Distribution of casting cakes in Bavaria and the adjacent eastern alpine regions (bohemian finds are not mapped) (map: S. Möslein on ArcGIS basemap).

it can be linked with fahlore deposits of Northern Tyrol (SSN-data also used by Lutz, 2016, fig.17).

A hierarchical cluster analysis of the complete dataset, calculated for the elements As, Sb, Ag and Ni (logarithmic values) with PASW Statistics 18 (average linkage, squared Euclidian distance) produces compact clusters. The example shows the calculation with 13 clusters, because from this level on additional clusters mostly consist only of single analyses.

The characteristics of the six largest clusters can be seen in the logarithmic Ag/Sb- and As/Ni-diagrams (Fig. 2). The clusters are very homogenous, but in some cases casting cakes and finished objects seem to be distributed in a somewhat different manner (cluster 1-3). This indicates that both categories should be treated separately in further studies. Cluster 6 consists exclusively of casting cakes. The composition of this remarkable material with very high concentrations of As and Sb, with Ag and Bi but without Ni, can be traced back to the typical fahlore deposits of the Schwaz-Brixlegg region in the Lower Inn Valley (Sperber, 2004, p.315, Abb. 9: "*Fahlerzkupfer vom Typ Schwaz/Brixlegg*"; Höppner et al., 2005). The distribution of casting cakes of this type with minor elements summing up to about 30% (Fig. 3) is chronologically restricted to Ha A2/B1, and geographically largely to the Tyrolian Inn Valley and the Alpine piedmont (Fig. 4). Here it was obviously used for mixing with other copper types (pure copper or chalcopyrite copper), for example copper produced from Mitterberg ores, which is characterised by a combination of about equal concentrations of nickel and arsenic as major impurities at variable concentrations combined with relatively low contents of antimony, silver and bismuth (Pernicka, 2014; Pernicka et al., 2016). In our dataset the clusters

2 and 5 match this definition. The result may have been a copper composition as in cluster 3.

From these observations, Sperber (2004, pp.319; pp.330) concluded that copper produced from ores in the north Alpine deposits was processed mostly in the near-by regions and from here distributed in form of finished objects. Only a smaller part of the fresh copper reached the regions far beyond in form of casting cakes, as can be deduced of the distribution of relevant finds (Fig. 5). The analysis data set provides, beyond this outline with regard to the actual project objectives, an extensive potential concerning a variety of research questions, for example

- tin alloying in relation with time and copper type
- comparison of the composition of different object types, for example ornaments vs. tools/weapons
- differentiation of workshops of widespread types. An example of this kind is the comparison of analyses of swords with octogonal metal hilt (*Achtkantschwerter*) of the Middle Bronze Age with two distribution centres in southern Germany/Austria/Bohemia and northern Germany/southern Scandinavia (v. Quillfeldt, 1995, Taf. 112). The identical composition supports the thesis that the northern swords (Bunnefeld & Schwenzer, 2011, p.244) are imports from the South (Fig. 6)
- checking the provenance hypothesis derived from the chemical composition only by additional lead isotope analyses (Pernicka et al., 2016)

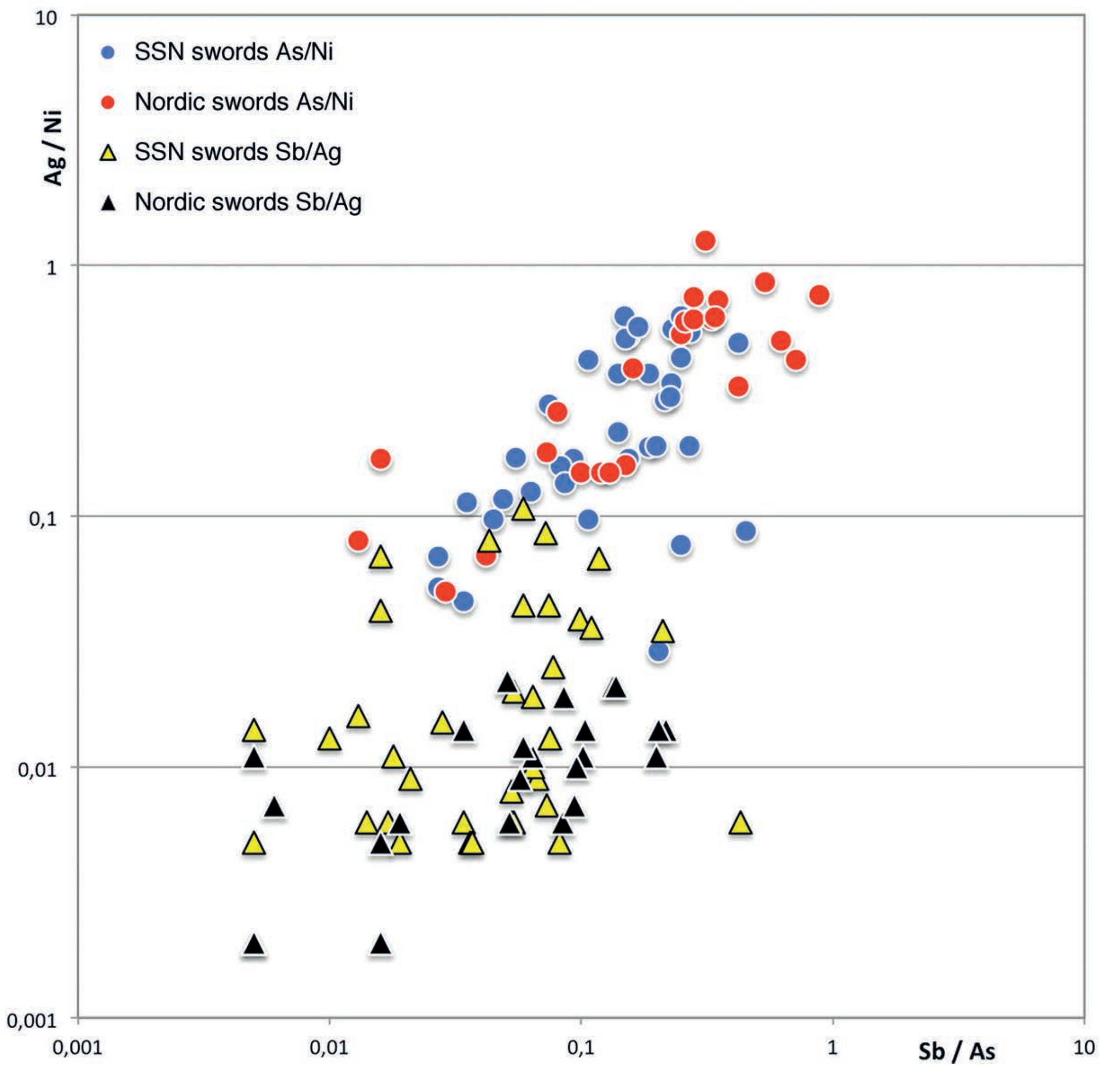

Fig. 6: Swords with octogonal metal hilt (Achtkantschwerter) from southern Germany/Austria and northern Germany: comparison of the analyses (SSN and E. Pernicka, in: Bunnefeld & Schwenzer, 2011) (chart: S. Möslein).

Nr.	Cu	Sn	Pb	As	Sb	Ag	Ni	Bi	Au	Zn	Co	Fe
1	90	7,9	0,02	0,78	0,209	0,091	0,92	< 0,005	< 0,01	< 0,1	0,026	0,08
2	90	9,6	0,03	0,089	0,037	0,016	0,32	< 0,005	< 0,01	< 0,1	0,019	0,08
3	92	6,0	0,09	0,41	1,13	0,42	0,066	0,01	< 0,01	< 0,1	0,008	< 0,05
4	91	8,0	0,33	0,163	0,144	0,124	0,11	0,023	< 0,01	< 0,1	0,029	< 0,05
5	91	8,2	0,19	0,36	0,123	0,05	0,194	0,009	< 0,01	< 0,1	0,136	0,06
6	91	8,0	0,21	0,152	0,071	0,062	0,199	0,013	< 0,01	< 0,1	0,031	0,08
7	89	9,4	0,08	0,39	0,109	0,023	0,45	< 0,005	< 0,01	< 0,1	0,044	0,06
8	93	6,1	0,3	0,129	0,21	0,098	0,087	0,017	< 0,01	< 0,1	0,024	< 0,05
9	89	9,5	0,11	0,37	0,51	0,15	0,5	0,005	< 0,01	< 0,1	0,033	< 0,05
10	92	7,4	0,03	0,055	0,026	0,013	0,192	< 0,005	< 0,01	< 0,1	0,012	0,29
11	96	3,3	0,15	0,162	0,083	0,028	0,38	0,008	< 0,01	< 0,1	0,039	0,13
12	89	10,2	0,1	0,143	0,04	0,036	0,141	0,017	< 0,01	< 0,1	0,046	0,28
13	82	3,8	12,6	0,072	0,091	0,106	0,086	0,127	< 0,01	< 0,1	0,079	1,03
14	92	6,4	0,09	0,43	0,107	0,016	0,69	< 0,005	< 0,01	< 0,1	0,053	0,18
15	92	6,7	0,04	0,35	0,106	0,02	0,81	< 0,005	< 0,01	< 0,1	0,052	0,07
16	93	6,5	0,13	0,115	0,056	0,047	0,201	0,01	< 0,01	< 0,1	0,019	< 0,05
17	93	5,9	0,38	0,285	0,082	0,038	0,216	0,006	< 0,01	< 0,1	0,141	0,2
18	92	6,8	0,14	0,095	0,055	0,036	0,171	0,016	< 0,01	< 0,1	0,033	0,1
19/1	99	0,018	< 0,01	0,044	< 0,005	0,011	0,209	< 0,005	< 0,01	< 0,1	0,006	0,22
19/2	99	0,006	< 0,01	0,034	< 0,005	0,006	0,2	< 0,005	< 0,01	< 0,1	0,015	0,41
20/1	78	< 0,005	0,01	5,1	15,5	0,84	0,059	0,106	< 0,01	0,3	0,015	0,3
20/2	79	< 0,005	0,01	5,0	14,8	0,83	0,064	0,103	< 0,01	0,2	0,01	0,24
21	100	< 0,005	< 0,01	< 0,005	< 0,005	< 0,005	0,031	< 0,005	< 0,01	< 0,1	< 0,005	0,07
22	99	< 0,005	< 0,01	0,017	< 0,005	< 0,005	0,069	< 0,005	< 0,01	< 0,1	0,009	0,29
23	99	< 0,005	< 0,01	0,025	< 0,005	0,007	0,118	< 0,005	< 0,01	< 0,1	0,008	0,5
24	98	0,009	< 0,01	0,01	< 0,005	0,008	0,139	< 0,005	< 0,01	< 0,1	0,028	1,21
25	98	0,007	< 0,01	0,017	0,007	0,01	0,079	< 0,005	< 0,01	< 0,1	0,009	1,93
26/1	84	< 0,005	< 0,01	4,3	10,5	0,74	0,014	0,088	< 0,01	0,2	0,008	0,28
26/2	84	< 0,005	< 0,01	4,5	10,6	0,76	< 0,01	0,09	< 0,01	0,1	0,009	0,23
27	100	0,007	< 0,01	0,101	< 0,005	0,008	0,161	< 0,005	< 0,01	< 0,1	< 0,005	< 0,05
28/1	74	< 0,005	0,1	7,8	16,5	1,17	0,023	0,063	< 0,01	< 0,1	< 0,005	0,24
28/2	72	< 0,005	0,13	8,4	18,1	1,13	< 0,01	0,056	< 0,01	< 0,1	0,01	0,48
29	93	5,8	0,22	0,43	0,241	0,031	0,37	< 0,005	< 0,01	< 0,1	0,049	< 0,05
31	98	1,45	< 0,01	0,022	< 0,005	< 0,005	0,109	< 0,005	< 0,01	< 0,1	0,006	0,6
32	96	0,081	< 0,01	0,249	0,01	0,028	1,75	< 0,005	< 0,01	< 0,1	0,219	1,71
33	87	12,4	0,18	0,145	0,058	0,05	0,101	0,009	< 0,01	< 0,1	0,102	0,07
34	86	12,8	0,13	0,34	0,077	0,069	0,299	0,02	< 0,01	< 0,1	0,033	0,3
35	91	7,8	0,11	0,143	0,34	0,085	0,176	0,007	< 0,01	< 0,1	0,034	0,05
36	89	10,1	0,17	0,234	0,093	0,061	0,275	0,016	< 0,01	< 0,1	0,027	0,13
37	97	0,006	< 0,01	0,37	0,052	< 0,005	0,8	< 0,005	< 0,01	< 0,1	0,026	1,2
38	99	0,016	< 0,01	0,145	0,069	0,005	0,161	< 0,005	< 0,01	< 0,1	0,009	0,8
39	99	< 0,005	< 0,01	0,239	0,062	0,008	0,094	< 0,005	< 0,01	< 0,1	0,011	0,71
40/1	98	< 0,005	0,02	0,148	0,036	0,008	0,127	< 0,005	< 0,01	< 0,1	0,021	1,51
40/2	98	0,008	0,03	0,211	0,068	0,013	0,104	< 0,005	< 0,01	< 0,1	0,019	1,19
41	99	< 0,005	< 0,01	0,113	0,063	0,008	0,237	< 0,005	< 0,01	< 0,1	0,008	0,24
42	99	< 0,005	< 0,01	0,141	0,005	< 0,005	0,213	< 0,005	< 0,01	< 0,1	< 0,005	0,15
43	99	< 0,005	0,01	0,104	0,41	< 0,005	0,117	< 0,005	< 0,01	< 0,1	0,011	0,57
44	99	< 0,005	< 0,01	0,12	0,015	< 0,005	0,52	< 0,005	< 0,01	< 0,1	0,023	0,44

Nr.	Cu	Sn	Pb	As	Sb	Ag	Ni	Bi	Au	Zn	Co	Fe
45	97	0,006	< 0,01	0,37	0,242	< 0,005	0,5	< 0,005	< 0,01	< 0,1	0,056	1,32
46	99	0,006	0,01	0,231	0,025	0,007	0,112	< 0,005	< 0,01	< 0,1	0,015	0,54
47	99	< 0,005	0,01	0,36	0,02	0,006	0,094	< 0,005	< 0,01	< 0,1	< 0,005	0,31
48	98	0,012	< 0,01	0,3	0,011	0,012	0,97	< 0,005	< 0,01	< 0,1	0,029	0,25
49	99	0,007	< 0,01	0,162	0,07	0,008	0,116	< 0,005	< 0,01	< 0,1	< 0,005	0,2
50	100	< 0,005	< 0,01	0,026	0,006	< 0,005	0,039	< 0,005	< 0,01	< 0,1	< 0,005	0,1
51	99	< 0,005	< 0,01	0,3	0,037	0,008	0,078	< 0,005	< 0,01	< 0,1	0,016	0,71
52	96	0,017	< 0,01	0,64	0,49	0,009	0,69	< 0,005	< 0,01	< 0,1	0,099	2,31
53	96	0,013	< 0,01	1,45	0,8	< 0,005	0,4	< 0,005	< 0,01	< 0,1	0,006	1,3
54	98	0,006	< 0,01	0,219	0,023	< 0,005	0,5	< 0,005	< 0,01	< 0,1	0,014	0,91
55	99	< 0,005	< 0,01	0,058	0,008	< 0,005	0,102	< 0,005	< 0,01	< 0,1	0,02	0,57
56	98	< 0,005	< 0,01	0,258	0,026	< 0,005	0,66	< 0,005	< 0,01	< 0,1	0,006	0,69
57	98	< 0,005	< 0,01	0,172	0,058	0,008	0,094	< 0,005	< 0,01	< 0,1	0,019	1,55
58	98	0,006	< 0,01	0,47	0,024	0,007	0,234	< 0,005	< 0,01	< 0,1	0,013	0,7
59	99	< 0,005	< 0,01	0,059	0,012	< 0,005	0,079	< 0,005	< 0,01	< 0,1	0,013	0,86
60	99	< 0,005	< 0,01	0,142	0,014	0,005	0,102	< 0,005	< 0,01	< 0,1	0,006	0,4
61	100	< 0,005	< 0,01	0,048	0,007	< 0,005	0,044	< 0,005	< 0,01	< 0,1	< 0,005	0,14
62	95	< 0,005	< 0,01	1,52	0,71	0,014	2,25	< 0,005	< 0,01	< 0,1	0,012	0,46
63	98	< 0,005	< 0,01	0,09	0,078	< 0,005	0,073	< 0,005	< 0,01	< 0,1	0,007	1,14
64	99	< 0,005	< 0,01	0,05	0,007	< 0,005	0,055	< 0,005	< 0,01	< 0,1	< 0,005	0,46
65	97	0,017	0,02	0,5	0,241	0,017	1,02	< 0,005	< 0,01	< 0,1	0,076	1,39
66	97	< 0,005	< 0,01	0,068	0,019	0,014	0,48	< 0,005	< 0,01	< 0,1	0,069	1,73
67	85	< 0,005	0,03	4,0	8,8	0,62	0,74	0,044	< 0,01	0,1	0,077	0,5
68	88	< 0,005	< 0,01	3,7	7,0	0,94	0,011	0,099	< 0,01	< 0,1	< 0,005	0,06
69	83	< 0,005	< 0,01	5,3	10,4	0,79	0,038	0,064	< 0,01	< 0,1	< 0,005	0,14
70	78	< 0,005	0,25	6,9	13,0	0,79	0,114	0,041	< 0,01	< 0,1	0,014	1,02
71	89	< 0,005	< 0,01	3,4	6,2	0,84	0,012	0,087	< 0,01	< 0,1	< 0,005	< 0,05
72	79	< 0,005	< 0,01	6,2	13,1	1,27	0,03	0,118	< 0,01	< 0,1	0,008	0,16
73	88	0,006	< 0,01	4,4	6,3	0,74	0,018	0,033	< 0,01	< 0,1	< 0,005	0,27
74	85	7,2	0,1	3,0	1,46	0,35	2,75	0,01	< 0,01	< 0,1	0,051	< 0,05
75	88	< 0,005	0,01	2,23	9,0	0,8	< 0,01	0,043	< 0,01	< 0,1	< 0,005	0,06
76	86	< 0,005	0,01	4,1	9,1	0,73	0,023	0,058	< 0,01	< 0,1	< 0,005	0,24
77	88	< 0,005	< 0,01	2,35	6,9	0,87	0,015	0,053	< 0,01	< 0,1	< 0,008	0,06
78	85	< 0,005	< 0,01	4,1	7,9	0,87	< 0,008	0,095	< 0,01	< 0,1	< 0,008	0,19
79/1	87	< 0,005	< 0,01	6,9	5,5	1,17	0,014	0,145	< 0,01	< 0,1	< 0,008	0,08
79/2	74	< 0,005	0,05	11,8	6,1	0,82	0,016	0,097	< 0,01	2,5	0,021	3,5
80	84	< 0,005	< 0,01	5,8	7,4	1,18	< 0,008	0,143	< 0,01	< 0,1	< 0,008	< 0,05
81	100	< 0,005	< 0,01	0,108	0,009	0,01	0,091	< 0,005	< 0,01	< 0,1	< 0,008	< 0,05
82	100	< 0,005	< 0,01	0,102	0,009	0,009	0,088	< 0,005	< 0,01	< 0,1	< 0,008	< 0,05
83	100	< 0,005	< 0,01	0,061	< 0,005	0,009	0,07	< 0,005	< 0,01	< 0,1	< 0,008	< 0,05
84	85	< 0,005	0,2	4,4	6,5	0,8	0,013	0,055	< 0,01	0,2	< 0,008	0,33
85	94	< 0,005	0,01	1,4	3,4	0,72	< 0,008	0,038	< 0,01	< 0,1	< 0,008	< 0,05
86	94	0,052	< 0,01	1,59	0,168	0,045	1,94	< 0,005	< 0,01	< 0,1	0,36	2,11
87	94	0,017	< 0,01	1,14	0,052	< 0,002	1,67	< 0,005	< 0,01	< 0,1	0,027	3
88	98	0,01	< 0,01	0,86	0,041	0,005	0,98	< 0,005	< 0,01	< 0,1	< 0,008	0,26
89	96	0,005	< 0,01	1,42	0,042	0,011	2,22	< 0,005	< 0,01	< 0,1	0,015	0,39
90	94	0,012	< 0,01	1,66	0,069	0,011	2,47	< 0,005	< 0,01	< 0,1	0,078	1,83
91	100	0,006	< 0,01	0,011	< 0,005	0,006	0,048	< 0,005	< 0,01	< 0,1	< 0,008	0,28

Nr.	Cu	Sn	Pb	As	Sb	Ag	Ni	Bi	Au	Zn	Co	Fe
92	89	0,093	0,01	1,98	1,09	0,076	5,4	0,007	< 0,01	0,1	0,57	1,56
93	99	< 0,005	< 0,01	0,039	0,007	0,005	0,099	< 0,005	< 0,01	< 0,1	0,019	0,37
95	98	0,012	< 0,01	0,221	0,105	0,005	0,51	< 0,005	< 0,01	< 0,1	0,059	0,76
96	99	< 0,005	0,22	0,016	0,173	0,076	0,055	< 0,005	< 0,01	< 0,1	< 0,008	< 0,05
97	100	< 0,005	0,02	< 0,005	0,01	0,018	0,013	< 0,005	< 0,01	< 0,1	0,008	0,11
98	97	0,045	0,02	0,278	0,013	0,013	0,091	< 0,005	< 0,01	< 0,1	0,013	2,09
99	96	0,055	0,04	0,184	0,041	0,034	0,038	0,012	< 0,01	< 0,1	0,064	3,7
100	98	0,012	< 0,01	0,06	0,01	0,018	0,85	< 0,005	< 0,01	< 0,1	0,092	0,73
101	84	13,6	0,06	0,246	0,059	0,012	0,46	< 0,005	< 0,01	< 0,1	0,022	0,07
102	90	8,1	0,05	0,253	0,035	0,009	0,66	< 0,005	< 0,01	< 0,1	0,05	0,47
103	90	7,2	0,26	0,36	0,062	0,016	0,71	< 0,005	< 0,01	< 0,1	0,06	0,18
104	90	11,0	0,06	0,25	0,055	0,025	0,46	0,008	< 0,01	< 0,1	0,027	0,16
105	92	5,3	0,11	0,34	0,79	0,253	0,56	0,01	< 0,01	< 0,1	0,022	< 0,05
106	92	6,7	0,27	0,031	0,06	0,027	0,41	< 0,005	< 0,01	< 0,1	0,016	0,15
107	90	5,6	0,05	0,81	1,26	0,72	0,253	0,01	< 0,01	< 0,1	0,022	< 0,05
108	91	9,0	0,15	0,245	0,095	0,04	0,32	0,008	< 0,01	< 0,1	0,039	0,12
109	91	5,9	0,13	0,62	0,82	0,46	0,41	0,014	< 0,01	< 0,1	0,014	< 0,05
110	92	7,5	0,11	0,137	0,088	0,05	0,43	0,008	< 0,01	< 0,1	0,026	0,05
111	88	10,5	0,14	0,194	0,104	0,036	0,32	0,008	< 0,01	< 0,1	0,031	0,15
112	90	7,0	< 0,01	0,074	0,78	0,166	0,156	< 0,005	< 0,01	< 0,1	< 0,008	< 0,05
113	89	10,2	0,07	0,63	0,06	0,04	0,31	0,008	< 0,01	< 0,1	0,034	0,22
114	90	11,3	0,06	0,56	0,07	0,038	0,247	0,005	< 0,01	< 0,1	0,03	0,18
115	89	10,7	0,02	0,51	0,051	0,029	0,53	< 0,005	< 0,01	< 0,1	0,074	0,22
116	88	11,0	0,06	0,5	0,064	0,04	0,32	0,011	< 0,01	< 0,1	0,03	0,24
117	89	10,2	0,07	0,63	0,06	0,04	0,31	0,008	< 0,01	< 0,1	0,034	0,22
118	92	6,2	0,17	0,26	0,064	0,046	0,61	0,006	< 0,01	< 0,1	0,031	< 0,05
119	92	5,9	0,09	0,254	0,06	0,037	0,6	0,007	< 0,01	< 0,1	0,021	0,06
120	91	6,9	0,24	0,204	0,06	0,048	0,38	0,009	< 0,01	< 0,1	0,023	0,07
121	86	11,6	0,15	0,157	0,056	0,056	0,32	0,009	< 0,01	< 0,1	0,026	0,07
122	91	7,1	0,22	0,22	0,058	0,061	0,37	0,011	< 0,01	< 0,1	0,029	0,06
123/G	90	10,0	< 0,01	0,01	0,008	0,003	0,073	< 0,005	< 0,01	< 0,1	0,028	0,21
123/K	87	10,5	< 0,01	0,019	< 0,005	0,006	0,045	< 0,005	< 0,01	< 0,1	0,021	< 0,05
124/G	86	9,5	1,65	0,186	0,211	0,035	0,188	< 0,005	< 0,01	< 0,1	0,031	0,19
124/K	91	6,5	0,24	0,45	0,117	0,068	0,087	0,022	< 0,01	< 0,1	0,084	1,04
125	92	5,3	0,21	0,33	0,193	0,034	0,27	0,007	< 0,01	< 0,1	0,069	< 0,05
126	90	6,6	0,18	0,42	0,212	0,034	0,269	< 0,005	< 0,01	< 0,1	0,049	0,06
127/G	88	10,6	< 0,01	0,02	< 0,005	< 0,002	0,077	< 0,005	< 0,01	< 0,1	< 0,008	< 0,05
127/K	90	9,6	< 0,01	0,024	< 0,005	0,009	0,092	< 0,005	< 0,01	< 0,1	0,014	< 0,05
128	85	11,2	0,05	0,191	0,183	0,019	0,275	< 0,005	< 0,01	< 0,1	0,029	0,37
129	89	9,1	0,12	0,228	0,165	0,004	0,277	< 0,005	< 0,01	< 0,1	0,032	0,14
130	86	10,8	< 0,01	0,277	0,023	< 0,002	0,33	< 0,005	< 0,01	< 0,1	0,032	< 0,05
131	88	13,4	0,03	0,43	0,189	0,019	1,3	< 0,005	0,02	< 0,1	0,042	0,09
132	88	9,3	0,03	0,39	0,136	0,012	1,34	< 0,005	< 0,01	< 0,1	0,042	0,09
133	88	9,5	0,03	0,41	0,148	0,008	1,33	< 0,005	< 0,01	< 0,1	0,038	0,07
134	91	7,3	0,02	0,55	0,272	0,046	0,84	< 0,005	< 0,01	< 0,1	0,049	0,15
135	88	9,2	0,01	0,29	0,089	< 0,002	1,18	< 0,005	< 0,01	< 0,1	0,036	< 0,05
136	86	10,7	< 0,01	0,131	0,278	0,008	0,221	< 0,005	< 0,01	< 0,1	0,009	0,18
137	91	7,6	0,02	0,222	0,272	0,008	0,4	< 0,005	< 0,01	< 0,1	0,029	0,07

Nr.	Cu	Sn	Pb	As	Sb	Ag	Ni	Bi	Au	Zn	Co	Fe
138	95	0,008	0,02	1,04	0,033	0,005	2,27	< 0,005	< 0,01	< 0,1	0,024	1,02
139	96	0,015	< 0,01	0,28	1,44	0,032	0,7	< 0,005	< 0,01	< 0,1	0,084	0,88
140	99	0,103	< 0,01	0,225	< 0,005	0,008	0,42	< 0,005	< 0,01	< 0,1	0,059	0,37
141/G	91	6,3	0,68	0,063	0,043	0,08	0,125	0,008	< 0,01	< 0,1	0,022	< 0,05
141/K	89	7,8	0,15	0,215	0,099	0,039	0,289	0,008	< 0,01	< 0,1	0,022	0,11
142/G	88	8,9	0,04	0,23	0,053	0,008	0,56	< 0,005	< 0,01	< 0,1	0,023	0,09
142/K	86	10,1	< 0,01	0,154	0,017	0,006	0,52	< 0,005	< 0,01	< 0,1	< 0,008	0,06
143/G	95	0,286	0,15	1,59	0,173	0,05	1,77	0,014	< 0,01	< 0,1	0,133	0,48
143/K	94	3,6	0,13	0,47	0,118	0,046	0,59	0,012	< 0,01	< 0,1	0,062	0,46
144	96	2,66	0,25	0,163	0,067	0,046	0,294	0,009	< 0,01	< 0,1	0,024	< 0,05
145	95	3,3	0,09	0,267	0,108	0,043	0,51	0,01	< 0,01	< 0,1	0,041	0,09
146	96	0,015	0,22	< 0,005	0,016	0,042	0,032	< 0,005	< 0,01	0,2	0,048	2,65
147	98	0,56	0,08	0,116	0,021	0,136	< 0,008	0,043	< 0,01	< 0,1	< 0,008	0,7
148	97	0,058	0,52	0,274	0,193	0,078	0,022	0,029	< 0,01	0,3	0,085	1,35
149	99	0,005	< 0,01	0,01	0,134	< 0,005	0,051	< 0,005	< 0,01	< 0,1	0,013	0,85
150	92	5,0	0,25	0,224	0,113	0,046	0,34	0,013	< 0,01	< 0,1	0,044	0,15
151	89	7,7	0,16	0,39	0,15	0,037	0,274	< 0,005	< 0,01	< 0,1	0,053	< 0,05
152	100	< 0,005	< 0,01	0,117	0,015	< 0,002	0,051	< 0,005	< 0,01	< 0,1	< 0,008	0,23
153	99	< 0,005	< 0,01	0,045	0,012	0,004	0,054	< 0,005	< 0,01	< 0,1	< 0,008	0,41
154	98	0,01	< 0,01	0,77	0,228	< 0,005	0,94	< 0,005	< 0,01	< 0,1	< 0,005	0,18
155	100	< 0,005	< 0,01	0,029	0,155	0,004	0,055	< 0,005	< 0,01	< 0,1	< 0,008	0,05
156	80	< 0,005	0,03	4,7	10,4	1,25	0,066	< 0,005	< 0,01	< 0,1	< 0,008	< 0,05
157	92	0,012	0,03	4,0	0,164	0,3	2,73	0,006	< 0,01	< 0,1	0,262	0,68
158	87	9,4	0,39	0,187	0,47	0,134	0,251	< 0,005	< 0,01	< 0,1	0,019	0,08
159	87	9,9	0,02	0,23	0,142	0,031	0,168	< 0,005	< 0,01	< 0,1	0,051	0,07
160	91	9,6	0,02	0,203	0,58	0,026	0,273	< 0,005	< 0,01	< 0,1	0,013	< 0,05
161/K	93	6,0	0,04	0,48	0,55	0,038	0,217	< 0,005	< 0,01	< 0,1	< 0,008	< 0,05
161/N	92	7,0	0,05	0,33	0,56	0,04	0,265	< 0,005	< 0,01	< 0,1	0,017	0,08
162	90	6,9	0,12	0,49	0,97	0,4	0,46	< 0,005	< 0,01	< 0,1	0,061	< 0,05
163	86	< 0,005	< 0,01	5,6	5,5	0,88	< 0,008	0,087	< 0,01	< 0,1	< 0,008	< 0,05
164	99	< 0,005	< 0,01	0,111	0,014	0,01	0,101	< 0,005	< 0,01	< 0,1	0,034	0,92
165	83	11,7	0,02	0,19	0,36	0,206	0,268	< 0,005	< 0,01	< 0,1	0,038	0,09
166	91	5,3	0,19	0,282	0,41	0,148	0,52	< 0,005	< 0,01	< 0,1	0,081	0,13
167	85	11,8	0,23	0,162	0,021	0,039	0,073	0,014	< 0,01	< 0,1	0,036	0,06
168	88	7,1	< 0,01	0,82	1,2	0,86	0,075	0,013	< 0,01	< 0,1	0,008	< 0,05
169/G	86	6,1	1,79	0,67	1,38	0,32	0,146	0,066	< 0,01	< 0,1	0,066	< 0,05
169/K	91	4,8	0,16	0,73	0,81	0,56	0,138	0,02	< 0,01	< 0,1	0,122	< 0,05
170	90	7,5	0,07	0,159	0,078	0,025	0,194	0,005	< 0,01	< 0,1	0,053	0,07
171	93	3,8	0,1	0,9	0,96	0,56	0,277	0,01	< 0,01	< 0,1	0,008	< 0,05
172	93	5,8	< 0,01	0,52	0,084	0,011	0,271	< 0,005	< 0,01	< 0,1	0,044	0,46
173	87	6,0	0,5	0,81	1,57	0,72	0,168	0,026	< 0,01	< 0,1	0,047	< 0,05
174	90	7,9	0,08	0,201	0,239	0,122	0,64	< 0,005	< 0,01	< 0,1	0,044	< 0,05
175	89	7,2	0,61	0,3	0,29	0,249	0,45	0,34	< 0,01	< 0,1	0,046	< 0,05
176/G	87	9,8	0,11	0,41	0,31	0,103	0,61	< 0,005	< 0,01	< 0,1	0,061	0,1
176/K	88	8,4	0,1	0,54	0,51	0,136	0,67	0,007	< 0,01	< 0,1	0,055	0,16
177	87	9,0	0,05	0,7	1,06	0,77	0,165	0,008	< 0,01	< 0,1	0,013	0,1
178	90	8,3	0,03	0,203	0,4	0,028	0,238	< 0,005	< 0,01	< 0,1	0,018	0,07
179	87	9,9	0,23	0,276	0,54	0,197	0,246	0,019	< 0,01	< 0,1	0,03	0,06

Nr.	Cu	Sn	Pb	As	Sb	Ag	Ni	Bi	Au	Zn	Co	Fe
180	87	10,3	0,01	0,39	0,33	0,038	0,31	< 0,005	< 0,01	< 0,1	0,024	0,1
181/G	87	10,7	0,13	0,105	0,087	0,059	0,188	0,024	< 0,01	< 0,1	0,032	0,08
181/K	89	9,4	< 0,01	0,099	< 0,005	0,022	0,239	< 0,005	< 0,01	< 0,1	0,019	0,16
182/G	91	8,4	< 0,01	0,045	0,021	0,009	0,097	< 0,005	< 0,01	< 0,1	0,012	< 0,05
182/K	90	9,2	0,07	0,055	< 0,005	0,014	0,171	< 0,005	< 0,01	< 0,1	0,032	0,06
183/G	90	9,3	0,09	0,093	0,077	0,025	0,169	< 0,005	< 0,01	< 0,1	0,021	< 0,05
183/K	89	9,6	0,4	0,199	0,059	0,107	0,191	0,01	< 0,01	< 0,1	< 0,005	< 0,05
184/G	91	8,1	0,01	0,15	0,014	0,006	0,51	< 0,005	< 0,01	< 0,1	0,021	0,15
184/G	91	7,8	0,09	0,14	0,019	< 0,005	0,37	< 0,005	< 0,01	< 0,1	0,024	0,11
185	92	4,3	0,22	0,63	1,25	0,213	0,6	< 0,005	< 0,01	< 0,1	0,153	0,21
186	92	6,1	< 0,01	0,193	0,49	0,164	0,6	< 0,005	< 0,01	< 0,1	0,012	< 0,05
187	93	5,8	0,11	0,202	0,098	0,041	0,35	0,008	< 0,01	< 0,1	0,027	0,1
188	92	7,1	0,05	0,147	0,053	0,015	0,35	< 0,005	< 0,01	< 0,1	0,045	0,08
189	91	7,1	0,54	0,85	0,276	0,053	0,263	0,014	< 0,01	< 0,1	0,091	0,14
190	91	7,7	0,14	0,177	0,042	0,044	0,45	< 0,005	< 0,01	< 0,1	0,037	0,2
191	94	0,264	0,04	1,52	2,4	0,69	1,35	0,005	< 0,01	< 0,1	0,033	< 0,05
192	91	6,2	0,14	0,41	0,82	0,292	0,59	0,007	0,01	< 0,1	0,102	0,18
193	91	6,9	0,03	0,271	1,16	0,065	0,147	0,02	< 0,01	< 0,1	0,023	0,18
194	91	8,5	0,01	0,21	0,008	0,018	0,45	< 0,005	< 0,01	< 0,1	0,039	0,06
195	88	11,4	0,27	0,085	0,123	0,072	0,045	0,009	< 0,01	< 0,1	0,044	0,08
196	93	6,2	< 0,01	0,19	0,06	0,017	0,23	< 0,005	< 0,01	< 0,1	0,006	< 0,05
197	94	4,7	0,07	0,37	0,097	0,029	0,57	< 0,005	< 0,01	< 0,1	0,023	0,06
198	91	7,6	0,02	0,275	0,155	< 0,005	0,46	< 0,005	< 0,01	< 0,1	0,042	0,12
199	93	5,1	0,11	0,32	0,49	0,135	0,66	0,005	< 0,01	< 0,1	0,029	< 0,05
200/G	90	9,5	< 0,01	0,042	< 0,005	< 0,005	0,175	< 0,005	< 0,01	< 0,1	0,018	0,17
200/K	91	8,7	0,01	0,023	< 0,005	0,007	0,109	< 0,005	< 0,01	< 0,1	0,03	0,16
201	92	6,7	0,02	0,112	0,055	0,006	0,31	0,007	< 0,01	< 0,1	0,053	0,22
202/G	91	7,5	0,11	0,44	0,44	0,122	0,39	0,013	< 0,01	< 0,1	0,042	0,14
202/K	92	5,8	0,08	0,23	0,086	0,043	1,34	0,005	< 0,01	< 0,1	0,07	0,24
203	91	8,6	0,02	0,102	0,047	0,008	0,42	< 0,005	< 0,01	< 0,1	0,008	0,07
204	89	10,6	0,07	0,16	0,039	0,056	0,18	0,009	< 0,01	< 0,1	0,063	0,05
205	91	8,7	0,02	0,162	0,037	< 0,005	0,123	< 0,005	< 0,01	< 0,1	0,024	0,2
206	91	5,3	0,88	0,59	1,09	0,49	0,198	0,017	< 0,01	< 0,1	0,034	0,05
207	91	6,2	0,37	0,78	0,9	0,53	0,191	0,019	< 0,01	< 0,1	0,014	< 0,05
208	92	6,6	0,14	0,179	0,052	0,018	0,34	0,014	< 0,01	< 0,1	0,044	< 0,05
209	91	8,6	0,11	0,143	0,058	0,06	0,142	0,009	< 0,01	< 0,1	0,037	< 0,05
210	91	7,8	0,1	0,32	0,157	0,009	0,69	< 0,005	< 0,01	< 0,1	0,036	0,17
211	93	5,9	0,09	0,231	0,08	0,029	0,234	< 0,005	< 0,01	< 0,1	0,123	0,07
212	89	10,0	0,32	0,117	0,025	0,084	0,054	0,014	< 0,01	< 0,1	0,046	0,05
213	92	6,7	0,06	0,175	0,32	0,164	0,47	< 0,005	< 0,01	< 0,1	0,025	< 0,05
214	91	6,7	0,15	0,6	0,79	0,46	0,234	0,008	< 0,01	< 0,1	0,025	< 0,05
215	89	8,4	0,1	0,47	0,65	0,276	0,47	0,008	0,02	< 0,1	0,026	< 0,05
216	87	10,9	0,08	0,42	0,8	0,34	0,169	< 0,005	< 0,01	< 0,1	0,026	< 0,05
217	95	3,8	0,19	0,32	0,101	0,04	0,35	0,007	< 0,01	< 0,1	0,099	0,05
218	93	5,8	0,22	0,37	0,145	0,044	0,262	0,009	< 0,01	< 0,1	0,056	< 0,05
219	94	4,8	0,27	0,34	0,154	0,035	0,39	0,006	< 0,01	< 0,1	0,044	< 0,05
220	93	5,8	0,16	0,43	0,152	0,06	0,31	0,008	< 0,01	< 0,1	0,077	0,05
221	96	2,47	0,1	0,41	0,05	0,048	0,28	< 0,005	< 0,01	< 0,1	0,193	< 0,05

Nr.	Cu	Sn	Pb	As	Sb	Ag	Ni	Bi	Au	Zn	Co	Fe
222	98	0,111	< 0,01	0,207	0,008	0,012	0,195	< 0,005	< 0,01	< 0,1	0,061	0,93
223	93	< 0,005	< 0,01	0,124	0,021	< 0,005	0,98	< 0,005	< 0,01	< 0,1	0,042	5,4
224/G	90	9,4	< 0,01	0,009	< 0,005	0,007	0,055	< 0,005	< 0,01	< 0,1	< 0,005	0,06
224/K	92	8,0	< 0,01	0,016	< 0,005	0,008	0,102	< 0,005	< 0,01	< 0,1	< 0,005	< 0,05
225/G	90	9,3	0,06	0,141	0,071	0,02	0,39	< 0,005	< 0,01	< 0,1	0,027	0,06
225/K	90	8,9	0,2	0,259	0,12	0,021	0,229	< 0,005	< 0,01	< 0,1	0,035	0,09
226	92	6,6	0,23	0,202	0,125	0,049	0,171	0,016	< 0,01	< 0,1	0,042	0,08
227	95	3,3	0,2	0,193	0,166	0,037	0,44	0,011	< 0,01	< 0,1	0,056	0,08
228	89	< 0,005	0,07	5,5	3,7	1,06	0,036	0,113	< 0,01	< 0,1	< 0,005	< 0,05
229	89	9,6	0,17	0,118	0,234	0,208	0,165	0,012	< 0,01	< 0,1	0,046	0,06
230	92	7,1	0,1	0,111	0,06	0,046	0,228	0,01	< 0,01	< 0,1	0,03	0,11
231	95	1,38	0,18	0,89	1,39	0,7	0,33	0,02	< 0,01	< 0,1	0,021	< 0,05
232	92	6,2	0,27	0,52	0,163	0,082	0,62	0,014	< 0,01	< 0,1	0,058	0,12
233	92	6,4	0,24	0,43	0,161	0,022	0,287	< 0,005	< 0,01	< 0,1	0,072	0,05
234	90	7,4	0,17	0,41	0,095	0,026	1,08	< 0,005	< 0,01	< 0,1	0,064	0,32
235	88	10,9	0,26	0,41	0,157	0,036	0,182	0,008	< 0,01	< 0,1	0,106	0,09
236	88	11,0	0,01	0,064	0,009	0,019	0,38	< 0,005	< 0,01	< 0,1	0,043	0,2
237	91	7,1	0,84	0,274	0,13	0,025	0,177	0,005	< 0,01	< 0,1	0,062	0,06
238	91	7,0	0,52	0,51	0,25	0,038	0,281	0,005	< 0,01	< 0,1	0,042	0,09
239	90	8,7	0,01	0,101	< 0,005	0,021	0,31	< 0,005	< 0,01	< 0,1	0,19	0,16
240	92	5,7	0,61	0,221	0,25	0,09	0,36	0,008	< 0,01	< 0,1	0,164	< 0,05
241	87	9,4	1,16	0,47	0,67	0,207	0,62	0,013	< 0,01	< 0,1	0,151	0,09
242	90	8,5	0,13	0,34	0,11	0,032	0,38	0,015	< 0,01	< 0,1	0,028	0,1
243	89	8,0	0,28	0,287	0,286	0,122	0,62	< 0,005	< 0,01	< 0,1	0,45	0,5
244	91	8,3	0,02	0,176	0,023	0,015	0,174	< 0,005	< 0,01	< 0,1	0,022	0,07
245	91	8,0	0,06	0,186	0,035	0,019	0,186	0,007	< 0,01	< 0,1	0,039	0,35
246	91	8,0	0,11	0,111	0,049	0,023	0,171	0,037	0,01	< 0,1	0,034	0,37
247	88	11,0	0,11	0,145	0,058	0,05	0,162	0,01	< 0,01	< 0,1	0,045	0,06
248	92	6,7	0,15	0,26	0,069	0,053	0,4	0,013	< 0,01	< 0,1	0,034	0,24
249	90	10,0	0,02	0,027	0,009	0,036	0,153	< 0,005	< 0,01	< 0,1	0,016	< 0,05
250	92	7,6	0,14	0,106	0,035	0,051	0,145	0,005	< 0,01	< 0,1	0,042	< 0,05
251	90	9,1	0,14	0,071	0,013	0,129	0,039	0,03	< 0,01	< 0,1	0,018	< 0,05
252	90	9,5	0,13	0,182	0,061	0,053	0,27	0,015	< 0,01	< 0,1	0,03	0,07
253	94	4,8	0,09	0,187	0,103	0,021	0,39	< 0,005	< 0,01	< 0,1	0,025	0,06
254	90	8,8	0,15	0,286	0,074	0,049	0,41	0,01	< 0,01	< 0,1	0,036	0,11
255	92	6,5	0,1	0,173	0,068	0,026	0,267	0,008	< 0,01	< 0,1	0,055	0,48
256	97	2,96	< 0,01	0,056	0,009	0,011	0,119	< 0,005	< 0,01	< 0,1	0,016	< 0,05
257	93	5,9	0,05	0,123	0,051	0,01	0,213	0,006	< 0,01	< 0,1	0,026	0,07
258	96	2,24	0,05	0,129	0,039	0,015	0,249	< 0,005	< 0,01	< 0,1	0,028	1,12
259	92	6,9	0,22	0,182	0,085	0,038	0,31	< 0,005	< 0,01	< 0,1	0,03	0,07
260	95	2,52	0,04	0,297	0,046	0,015	0,53	< 0,005	< 0,01	< 0,1	0,026	1,22
261	98	0,085	0,26	0,059	0,294	0,027	0,111	< 0,005	< 0,01	< 0,1	0,013	1,11
262	97	2,44	< 0,01	0,026	0,023	0,01	0,104	< 0,005	< 0,01	< 0,1	0,025	0,06
263	93	5,8	0,07	0,098	0,045	0,013	0,254	< 0,005	< 0,01	< 0,1	0,044	0,36
264	96	2,87	0,2	0,101	0,098	0,058	0,126	0,047	< 0,01	< 0,1	0,033	0,09
265	90	8,9	0,06	0,086	0,034	0,016	0,189	0,007	< 0,01	< 0,1	0,021	0,25
266	91	8,5	0,05	0,151	0,067	0,035	0,281	0,008	< 0,01	< 0,1	0,02	< 0,05
267	74	2,6	23,4	< 0,005	0,061	0,018	0,111	< 0,005	< 0,01	< 0,1	0,012	0,08

Nr.	Cu	Sn	Pb	As	Sb	Ag	Ni	Bi	Au	Zn	Co	Fe
268	90	8,6	0,06	0,065	0,026	0,018	0,177	0,01	< 0,01	< 0,1	0,024	0,81
269	91	8,4	< 0,01	0,201	< 0,005	0,006	0,079	< 0,005	< 0,01	< 0,1	< 0,005	< 0,05
270	89	8,8	0,36	0,282	0,258	0,035	0,47	0,005	< 0,01	< 0,1	0,038	0,26
271	88	10,7	0,28	0,35	0,278	0,037	0,33	0,005	< 0,01	< 0,1	0,029	0,32
272	91	8,7	0,02	0,028	0,018	0,011	0,104	< 0,005	< 0,01	< 0,1	0,011	< 0,05
273	91	8,0	< 0,01	0,6	< 0,005	0,006	0,237	< 0,005	< 0,01	< 0,1	0,025	0,11
274	91	7,8	0,23	0,153	0,057	0,052	0,279	0,016	< 0,01	< 0,1	0,037	0,16
275	91	8,3	0,08	0,066	0,053	0,021	0,139	< 0,005	< 0,01	< 0,1	0,031	0,07
276	91	8,3	< 0,01	0,027	0,013	0,007	0,114	< 0,005	< 0,01	< 0,1	0,009	0,05
277	91	7,4	< 0,01	0,56	0,01	0,01	0,247	< 0,005	< 0,01	< 0,1	0,036	0,4
278	90	9,2	0,1	0,082	0,053	0,023	0,163	0,006	< 0,01	< 0,1	0,029	0,1
279	89	9,8	0,13	0,139	0,104	0,046	0,212	0,007	< 0,01	< 0,1	0,024	0,08
280/G	90	9,3	0,4	0,239	0,188	0,107	0,063	0,02	< 0,01	< 0,1	0,042	< 0,05
280/K	90	9,4	0,08	0,092	0,113	0,037	0,14	< 0,005	< 0,01	< 0,1	0,037	< 0,05
281/G	87	11,9	< 0,01	0,021	< 0,005	0,016	0,49	0,005	< 0,01	< 0,1	0,027	0,07
281/K	90	9,4	0,02	0,095	0,011	0,012	0,4	< 0,005	< 0,01	< 0,1	0,034	0,12
282/G	90	7,9	0,3	0,257	0,77	0,073	0,147	0,01	< 0,01	< 0,1	0,076	< 0,05
282/K	90	8,5	0,41	0,213	0,168	0,049	0,192	0,017	< 0,01	< 0,1	0,093	< 0,05
283/G	90	8,4	0,63	0,211	0,234	0,08	0,191	< 0,005	0,06	< 0,1	0,035	0,16
283/K	90	9,2	0,62	0,127	0,129	0,044	0,158	0,008	< 0,01	< 0,1	0,055	< 0,05
284/G	90	8,4	0,12	0,31	0,31	0,09	0,174	0,008	< 0,01	< 0,1	0,018	< 0,05
284/K	89	10,3	0,02	0,098	0,133	0,03	0,39	< 0,005	< 0,01	< 0,1	0,021	< 0,05
285/G	90	8,3	0,13	0,37	0,46	0,33	0,241	0,005	< 0,01	< 0,1	0,013	< 0,05
285/K	90	8,0	0,19	0,68	0,79	0,58	0,086	0,01	< 0,01	< 0,1	0,012	< 0,05
286/G	91	7,7	0,32	0,241	0,123	0,022	0,237	< 0,005	< 0,01	< 0,1	0,049	0,11
286/K	91	7,9	0,16	0,17	0,08	0,038	0,215	0,01	< 0,01	< 0,1	0,025	< 0,05
287/G	85	10,2	2,2	0,44	0,68	0,64	0,31	< 0,005	< 0,01	< 0,1	0,007	< 0,05
287/K	90	8,3	< 0,01	0,48	0,55	0,63	0,246	< 0,005	< 0,01	< 0,1	0,008	< 0,05
288/G	91	7,8	0,2	0,176	0,084	0,036	0,094	0,01	< 0,01	< 0,1	0,085	0,07
288/K	89	9,8	0,21	0,158	0,126	0,062	0,213	0,005	< 0,01	< 0,1	0,108	0,21
289/G	89	8,2	0,68	0,58	0,42	0,15	0,31	0,024	< 0,01	< 0,1	0,28	< 0,05
289/K	90	7,8	0,67	0,64	0,05	0,109	0,168	0,032	< 0,01	< 0,1	0,123	< 0,05
290	93	6,1	< 0,01	0,279	0,052	0,038	0,64	< 0,005	< 0,01	< 0,1	0,024	0,12
291/G	90	8,7	0,09	0,149	0,067	0,009	0,63	< 0,005	< 0,01	< 0,1	0,023	0,08
291/K	90	9,6	< 0,01	0,027	0,01	0,013	0,052	< 0,005	< 0,01	< 0,1	0,012	0,12
292/G	91	8,1	< 0,01	0,25	0,085	< 0,005	0,206	< 0,005	< 0,01	< 0,1	0,025	< 0,05
292/K	91	8,5	0,03	0,218	0,137	0,007	0,248	< 0,005	< 0,01	< 0,1	0,022	0,14
293/G	90	9,4	0,02	0,169	0,053	0,006	0,57	< 0,005	< 0,01	< 0,1	0,024	0,08
293/K	92	7,5	< 0,01	0,227	0,034	0,006	0,34	< 0,005	< 0,01	< 0,1	0,028	0,06
294/G	90	9,2	0,14	0,144	0,027	0,019	0,44	< 0,005	< 0,01	< 0,1	0,029	0,05
294/K	89	10,4	0,17	0,104	0,035	0,041	0,244	< 0,005	< 0,01	< 0,1	0,026	0,07
295/G	90	8,0	0,5	0,154	0,072	0,086	0,169	0,027	< 0,01	< 0,1	0,057	0,58
295/K	92	7,0	0,33	0,034	0,016	0,069	0,046	0,016	< 0,01	< 0,1	0,02	0,09
296/G	89	10,4	0,02	0,094	0,02	0,014	0,31	< 0,005	< 0,01	< 0,1	0,022	< 0,05
296/K	93	6,2	0,01	0,065	0,018	0,01	0,246	< 0,005	< 0,01	< 0,1	0,021	0,05
297	91	8,6	< 0,01	0,103	0,069	< 0,005	0,213	< 0,005	< 0,01	< 0,1	0,023	0,22
298	92	7,0	< 0,01	0,06	0,1	< 0,005	0,251	< 0,005	< 0,01	< 0,1	0,038	0,3
299/G	90	9,1	0,06	0,139	0,157	0,044	0,56	< 0,005	< 0,01	< 0,1	0,03	0,08

Nr.	Cu	Sn	Pb	As	Sb	Ag	Ni	Bi	Au	Zn	Co	Fe
299/K	92	6,8	0,06	0,184	0,244	0,075	0,64	< 0,005	< 0,01	< 0,1	0,031	0,06
300	93	5,5	0,01	0,185	0,32	0,02	0,31	< 0,005	< 0,01	< 0,1	0,028	0,52
301/G	91	8,2	0,07	0,202	0,016	0,042	0,029	0,017	< 0,01	< 0,1	0,039	0,1
301/K	91	8,1	0,14	0,27	0,074	0,044	0,191	0,011	< 0,01	< 0,1	0,035	0,13
302/G	91	8,9	< 0,01	0,01	< 0,005	0,009	0,12	< 0,005	< 0,01	< 0,1	0,02	< 0,05
302/K	91	6,4	1,74	< 0,005	< 0,005	0,005	0,62	< 0,005	< 0,01	< 0,1	0,009	< 0,05
303	91	7,4	0,33	0,217	0,181	0,053	0,3	0,011	< 0,01	< 0,1	0,04	0,21
304	90	9,3	0,2	0,048	0,087	0,035	0,126	0,01	< 0,01	< 0,1	0,056	0,21
305	90	9,1	0,02	0,185	< 0,005	0,013	0,31	< 0,005	< 0,01	< 0,1	0,038	0,09
306	89	9,0	0,71	0,134	0,073	0,072	0,32	0,017	< 0,01	< 0,1	0,04	0,64
307	90	8,8	0,17	0,06	0,023	0,102	0,025	0,02	< 0,01	< 0,1	0,026	0,25
308/G	91	8,5	< 0,01	0,008	< 0,005	< 0,005	0,058	< 0,005	< 0,01	< 0,1	0,012	0,06
308/K	90	8,7	< 0,01	0,061	0,007	0,008	0,47	< 0,005	< 0,01	< 0,1	0,046	< 0,05
309/G	91	8,0	0,01	0,229	0,049	0,021	0,218	< 0,005	< 0,01	< 0,1	0,034	0,08
309/K	92	7,3	0,08	0,294	0,178	0,015	0,35	< 0,005	< 0,01	< 0,1	0,015	< 0,05
310	91	8,2	0,02	0,053	0,103	0,011	0,169	< 0,005	< 0,01	< 0,1	0,01	0,06
311	93	6,3	< 0,01	0,084	0,094	0,013	0,167	< 0,005	< 0,01	< 0,1	0,007	0,08
312	91	8,1	0,21	0,061	0,024	0,106	0,028	0,013	< 0,01	< 0,1	< 0,005	< 0,05
313	91	8,0	< 0,01	0,176	0,61	0,251	0,024	< 0,005	< 0,01	< 0,1	< 0,005	< 0,05
314	90	9,1	0,29	0,12	0,076	0,098	0,09	0,02	< 0,01	< 0,1	0,047	< 0,05
315	89	8,7	0,08	0,74	0,75	0,57	0,164	0,013	< 0,01	< 0,1	0,009	< 0,05
316	90	7,6	0,04	0,72	0,9	0,72	0,066	0,011	< 0,01	< 0,1	< 0,005	0,09
317	91	4,9	0,03	1,58	0,64	1,29	0,033	0,009	< 0,01	< 0,1	< 0,005	< 0,05
318	92	5,6	0,1	0,4	0,79	0,213	0,5	< 0,005	< 0,01	< 0,1	0,025	< 0,05
319	91	7,9	0,25	0,125	0,142	0,096	0,086	0,034	< 0,01	< 0,1	0,034	0,14
320	92	7,5	0,3	0,086	0,204	0,062	0,043	0,012	< 0,01	< 0,1	0,044	0,06
321	92	0,026	0,12	2,4	3,6	0,82	0,023	0,023	< 0,01	0,3	0,076	1,14
322	91	< 0,005	0,05	2,9	4,4	0,82	0,12	0,041	< 0,01	< 0,1	0,009	< 0,05
323	91	7,7	0,34	0,093	0,157	0,073	0,073	0,011	< 0,01	< 0,1	0,026	< 0,05
324	92	7,1	0,32	0,094	0,079	0,093	0,041	0,029	< 0,01	< 0,1	0,021	< 0,05
325	90	8,7	0,04	0,37	0,31	0,151	0,286	< 0,005	< 0,01	< 0,1	0,014	0,05
326	92	4,9	< 0,01	0,72	0,147	0,015	0,74	< 0,005	< 0,01	< 0,1	0,043	0,85
327	92	6,6	0,01	0,32	0,124	0,016	0,5	< 0,005	< 0,01	< 0,1	0,015	< 0,05
328	91	8,5	< 0,01	0,044	< 0,005	0,005	0,135	< 0,005	0,03	< 0,1	0,022	0,16
329	93	6,7	< 0,01	0,035	< 0,005	0,015	0,098	< 0,005	< 0,01	< 0,1	0,033	0,09
330	92	7,4	0,01	0,043	0,012	0,009	0,123	< 0,005	< 0,01	< 0,1	0,033	0,19
331	92	7,9	< 0,01	0,036	0,015	0,009	0,111	< 0,005	< 0,01	< 0,1	0,032	0,14
332	92	7,6	< 0,01	0,042	< 0,005	0,008	0,129	< 0,005	< 0,01	< 0,1	0,026	0,11
333	93	5,4	0,25	0,34	0,141	0,035	0,246	0,007	< 0,01	< 0,1	0,08	0,24
334/G	90	9,2	< 0,01	0,024	< 0,005	0,009	0,049	< 0,005	< 0,01	< 0,1	0,01	0,52
334/K	90	9,3	< 0,01	0,024	< 0,005	0,023	0,47	< 0,005	< 0,01	< 0,1	0,02	0,08
335	98	< 0,005	< 0,01	0,31	0,01	0,025	0,8	< 0,005	0,01	< 0,1	0,082	0,46
336	97	0,028	0,07	1,9	0,159	0,044	0,5	< 0,005	< 0,01	< 0,1	0,037	0,58
337	95	0,056	1,71	0,38	0,5	0,078	0,058	0,055	< 0,01	0,7	0,062	1,29
338	95	0,02	1,1	1,16	0,071	0,166	0,042	0,48	< 0,01	< 0,1	0,132	1,73
339	98	0,007	0,48	0,099	0,021	0,12	0,042	0,016	< 0,01	0,1	0,094	1,33
340	93	0,041	3,4	0,211	0,52	0,132	0,048	0,043	< 0,01	0,8	0,072	1,8
341	93	0,007	0,19	1,29	3,4	0,37	0,69	< 0,005	< 0,01	< 0,1	0,068	0,37

Nr.	Cu	Sn	Pb	As	Sb	Ag	Ni	Bi	Au	Zn	Co	Fe
342	79	< 0,005	0,02	0,165	0,03	0,044	0,231	< 0,005	< 0,01	< 0,1	0,071	20
343	89	10,2	0,51	0,059	0,011	0,142	0,033	0,019	< 0,01	< 0,1	0,025	0,09
344	93	6,3	0,11	0,157	0,045	0,051	0,185	0,012	< 0,01	< 0,1	0,055	0,08
345	92	< 0,005	0,73	1,51	4,6	0,54	0,091	0,006	< 0,01	< 0,1	0,046	0,59
346	88	9,7	1,52	0,093	0,223	0,068	0,231	0,02	< 0,01	< 0,1	0,037	0,07
347	90	8,9	0,2	0,096	0,116	0,069	0,076	0,029	< 0,01	< 0,1	0,036	0,07
348	88	9,8	0,12	0,257	0,204	0,021	0,43	< 0,005	< 0,01	< 0,1	0,04	0,69
349	93	6,2	0,04	0,097	0,038	0,025	0,31	0,006	< 0,01	< 0,1	0,022	0,09
350	95	3,9	0,32	0,104	0,1	0,057	0,203	0,011	< 0,01	< 0,1	0,025	< 0,05
351	94	4,7	0,09	0,121	0,063	0,031	0,4	0,005	< 0,01	< 0,1	0,042	0,08
352	88	10,2	0,22	0,267	0,257	0,05	0,37	0,008	< 0,01	< 0,1	0,04	0,18
353	87	11,1	0,18	0,288	0,25	0,045	0,273	0,007	< 0,01	< 0,1	0,028	0,31
354	86	12,0	0,28	0,298	0,32	0,054	0,31	0,013	< 0,01	< 0,1	0,04	0,22
355	90	9,0	0,18	0,088	0,219	0,04	0,149	0,012	< 0,01	< 0,1	0,041	0,12
356	87	12,3	0,06	0,108	0,047	0,009	0,17	0,005	< 0,01	< 0,1	0,017	0,23
357	89	10,3	0,07	0,09	0,073	0,019	0,159	< 0,005	< 0,01	< 0,1	0,012	< 0,05
358	91	8,8	0,07	0,1	0,065	0,016	0,155	< 0,005	< 0,01	< 0,1	0,014	< 0,05
359	90	9,8	0,06	0,052	0,057	0,015	0,161	< 0,005	< 0,01	< 0,1	0,008	0,05
360	91	7,2	0,13	0,211	0,042	0,028	0,59	0,009	< 0,01	< 0,1	0,052	0,44
361	90	8,4	0,23	0,25	0,082	0,055	0,42	0,018	< 0,01	< 0,1	0,039	0,15
362/G	91	7,3	0,16	0,47	0,133	0,043	0,254	0,01	< 0,01	< 0,1	0,019	< 0,05
362/K	91	7,1	0,28	0,66	0,209	0,045	0,253	0,01	< 0,01	< 0,1	0,038	0,12
363/G	91	7,7	0,11	0,37	0,4	0,141	0,298	0,02	< 0,01	< 0,1	0,027	< 0,05
363/K	93	5,6	0,1	0,37	0,6	0,149	0,33	0,013	< 0,01	< 0,1	0,023	< 0,05
364	90	8,6	0,03	0,227	0,169	0,008	0,46	< 0,005	< 0,01	< 0,1	0,026	< 0,05
365	91	6,1	0,01	0,8	0,169	0,014	1,9	< 0,005	< 0,01	< 0,1	0,053	0,2
366	91	8,4	0,08	0,091	0,204	0,078	0,176	< 0,005	< 0,01	< 0,1	0,02	< 0,05
367	89	9,2	< 0,01	0,218	0,289	0,082	1,09	< 0,005	< 0,01	< 0,1	0,031	< 0,05
368	89	8,2	< 0,01	0,125	0,069	0,005	2,02	< 0,005	< 0,01	< 0,1	0,031	0,12
369/G	87	10,8	0,36	0,35	0,62	0,148	0,37	0,016	< 0,01	< 0,1	0,108	0,07
369/G	90	8,4	0,51	0,165	0,38	0,116	0,228	0,007	< 0,01	< 0,1	0,041	0,08
370/G	90	9,9	< 0,01	0,011	< 0,005	0,009	0,135	< 0,005	< 0,01	< 0,1	0,006	< 0,05
370/K	90	9,2	0,02	0,107	0,011	0,007	0,161	< 0,005	< 0,01	< 0,1	0,016	< 0,05
371	90	8,3	0,22	0,221	0,089	0,041	0,64	< 0,005	< 0,01	< 0,1	0,045	0,17
372	90	9,3	0,24	0,16	0,108	0,046	0,31	0,014	< 0,01	< 0,1	0,023	< 0,05
373	90	8,7	0,23	0,149	0,107	0,05	0,297	0,013	< 0,01	< 0,1	0,02	< 0,05
374	87	11,6	0,09	0,293	0,068	0,03	0,74	< 0,005	< 0,01	< 0,1	0,038	0,1
375	88	10,8	0,02	0,38	0,075	0,02	0,65	< 0,005	< 0,01	< 0,1	0,059	0,11
376	93	6,7	0,01	0,146	0,021	0,006	0,097	< 0,005	< 0,01	< 0,1	0,031	0,05
377	91	7,3	0,17	0,213	0,088	0,038	0,59	0,008	< 0,01	< 0,1	0,029	0,06
378/N	91	7,5	0,15	0,21	0,045	0,037	0,61	0,005	< 0,01	< 0,1	0,037	0,29
378/T	87	11,4	0,1	0,267	0,069	0,037	0,72	0,005	< 0,01	< 0,1	0,036	0,11
379	90	8,3	0,28	0,228	0,079	0,054	0,63	< 0,005	< 0,01	< 0,1	0,038	0,16
380	91	7,2	0,17	0,198	0,09	0,043	0,59	0,005	< 0,01	< 0,1	0,034	0,05
381	93	5,7	0,12	0,202	0,083	0,038	0,58	< 0,005	< 0,01	< 0,1	0,03	< 0,05
382	91	7,0	0,04	0,36	0,43	0,14	0,73	0,005	< 0,01	< 0,1	0,017	< 0,05
383	96	3,4	0,19	0,178	0,087	0,041	0,33	0,011	< 0,01	< 0,1	0,027	0,08
384	97	2,11	0,17	0,221	0,139	0,046	0,37	0,013	< 0,01	< 0,1	0,029	0,07

Nr.	Cu	Sn	Pb	As	Sb	Ag	Ni	Bi	Au	Zn	Co	Fe
385	92	5,9	0,47	0,45	0,08	0,038	0,39	0,007	< 0,01	< 0,1	0,035	0,14
386	91	8,0	0,01	0,179	0,082	0,009	0,277	< 0,005	< 0,01	< 0,1	0,04	0,45
387	93	5,4	0,06	0,205	0,077	0,023	0,42	< 0,005	< 0,01	< 0,1	0,036	0,26
388	91	7,8	0,03	0,14	0,125	0,008	0,249	< 0,005	< 0,01	< 0,1	0,036	0,12
389	88	12,0	0,02	0,009	0,032	0,007	0,038	< 0,005	< 0,01	< 0,1	< 0,005	0,11
390/G	89	9,1	< 0,01	0,42	0,028	0,015	0,49	< 0,005	< 0,01	< 0,1	0,03	0,32
390/K	90	9,1	0,05	0,225	0,018	0,011	0,3	< 0,005	< 0,01	< 0,1	0,01	0,11
392	90	8,7	0,13	0,192	0,064	0,019	0,285	< 0,005	< 0,01	< 0,1	0,033	0,18
393	91	7,2	0,07	0,32	0,53	0,222	0,244	0,017	< 0,01	< 0,1	0,076	0,06
394	94	3,5	0,33	0,42	0,83	0,32	0,39	0,012	< 0,01	< 0,1	0,057	0,06
395	98	0,048	0,04	0,47	< 0,005	0,042	0,173	< 0,005	< 0,01	< 0,1	0,51	0,38
396	95	< 0,005	< 0,01	0,87	1,0	0,012	1,06	< 0,005	< 0,01	< 0,1	0,032	1,85
397/G	90	8,4	0,11	0,35	0,279	0,122	0,261	0,01	< 0,01	< 0,1	0,044	0,05
397/K	94	4,9	0,34	0,235	0,205	0,131	0,174	0,027	< 0,01	< 0,1	0,036	0,06
398/G	89	9,6	0,37	0,092	0,137	0,063	0,077	0,019	< 0,01	< 0,1	0,028	0,07
398/K	92	7,4	0,45	0,065	0,086	0,061	0,111	0,015	< 0,01	< 0,1	0,03	0,06
399/G	91	8,2	< 0,01	0,049	0,066	0,017	0,38	< 0,005	< 0,01	< 0,1	0,066	0,14
399/K	91	6,7	0,01	0,264	0,33	0,086	1,1	< 0,005	< 0,01	< 0,1	0,036	0,06
400	91	7,3	< 0,01	0,278	0,216	0,039	0,5	< 0,005	< 0,01	< 0,1	0,022	0,07
401	92	5,5	0,2	0,33	0,62	0,249	0,56	< 0,005	< 0,01	< 0,1	0,193	0,12
402	90	5,9	0,74	0,83	0,48	0,35	0,81	0,007	< 0,01	< 0,1	0,5	0,4
403/G	91	8,3	0,46	0,096	0,162	0,064	0,143	0,007	< 0,01	< 0,1	0,027	< 0,05
403/K	91	7,7	0,21	0,099	0,16	0,071	0,176	0,007	< 0,01	< 0,1	0,049	0,07
404	91	5,8	0,21	0,46	0,65	0,202	0,57	0,009	< 0,01	< 0,1	0,072	1,01
405/G	92	7,3	0,02	0,058	< 0,005	0,011	0,4	< 0,005	< 0,01	< 0,1	0,037	0,15
405/K	90	8,6	0,32	0,205	0,115	0,037	0,35	< 0,005	< 0,01	< 0,1	0,057	0,11
406	91	8,1	0,08	0,185	0,087	0,026	0,71	0,005	< 0,01	< 0,1	0,025	0,06
407	90	< 0,005	< 0,01	0,76	< 0,005	< 0,005	0,288	< 0,005	< 0,01	< 0,1	0,124	9,1
408	99	< 0,005	< 0,01	0,036	< 0,005	0,012	0,61	< 0,005	< 0,01	< 0,1	0,096	0,54
409	99	0,011	0,05	0,021	0,015	0,028	0,039	0,005	< 0,01	< 0,1	0,015	0,77
410	98	< 0,005	< 0,01	0,038	< 0,005	0,01	0,162	< 0,005	< 0,01	< 0,1	0,021	1,72
411	98	0,069	0,2	0,018	0,057	0,042	0,044	0,01	< 0,01	< 0,1	0,05	1,72
412	97	0,49	0,77	0,231	< 0,005	0,35	0,025	0,107	< 0,01	< 0,1	0,188	0,27
413	89	10,0	0,78	0,034	0,023	0,033	0,128	0,006	< 0,01	< 0,1	0,021	0,13
414	91	8,7	0,03	0,09	0,019	0,022	0,142	< 0,005	< 0,01	< 0,1	0,012	0,11
415	95	3,3	0,07	0,086	0,258	0,021	0,192	< 0,005	< 0,01	< 0,1	0,022	0,86
416	92	6,8	0,15	0,094	0,059	0,036	0,159	0,01	< 0,01	< 0,1	0,022	0,25
417/G	93	4,5	0,12	0,37	0,84	0,35	0,48	0,008	< 0,01	< 0,1	0,043	< 0,05
417/K	90	7,4	0,11	0,54	0,99	0,36	0,54	0,01	< 0,01	< 0,1	0,12	0,06
418	91	5,7	0,77	0,46	0,87	0,39	0,218	0,023	< 0,01	< 0,1	0,045	0,09
419/G	91	8,3	0,15	0,127	0,147	0,069	0,283	< 0,005	< 0,01	< 0,1	0,032	< 0,05
419/K	89	8,0	0,19	0,27	0,43	0,168	0,5	0,008	< 0,01	< 0,1	0,188	0,98
420	92	6,2	0,1	0,4	0,77	0,42	0,137	0,007	< 0,01	< 0,1	0,013	0,08
421	91	6,4	0,47	0,48	0,79	0,41	0,229	0,013	< 0,01	< 0,1	0,042	< 0,05
422	89	9,0	0,32	0,274	0,39	0,182	0,33	0,058	< 0,01	< 0,1	0,093	< 0,05
423	94	3,3	0,24	0,77	1,07	0,59	0,156	0,011	< 0,01	< 0,1	0,036	< 0,05
424	93	5,8	0,13	0,233	0,065	0,036	0,194	0,013	< 0,01	< 0,1	0,186	0,12
425	92	6,0	0,02	0,211	0,8	0,07	0,232	< 0,005	< 0,01	< 0,1	0,016	0,07

Nr.	Cu	Sn	Pb	As	Sb	Ag	Ni	Bi	Au	Zn	Co	Fe
426	92	6,1	0,02	0,52	0,41	0,016	0,62	< 0,005	< 0,01	< 0,1	0,034	0,37
427/G	85	14,1	0,02	0,16	0,159	0,054	0,34	< 0,005	0,01	< 0,1	0,023	< 0,05
427/K	89	10,2	0,02	0,108	0,071	0,02	0,34	< 0,005	< 0,01	< 0,1	0,023	< 0,05
428	92	6,8	0,1	0,205	0,44	0,104	0,32	< 0,005	< 0,01	< 0,1	0,019	< 0,05
429	90	6,3	< 0,01	1,35	1,0	0,74	0,035	0,014	< 0,01	< 0,1	< 0,005	0,07
430	91	5,8	0,01	0,79	1,34	0,58	0,12	0,013	< 0,01	< 0,1	0,008	0,06
431	91	5,9	0,02	0,79	1,46	0,61	0,106	0,016	< 0,01	< 0,1	0,007	0,05
432/G	93	3,0	0,1	0,98	1,61	0,7	0,169	0,017	< 0,01	< 0,1	< 0,005	< 0,05
432/K	93	2,11	0,07	1,41	2,18	0,94	0,078	0,014	< 0,01	< 0,1	0,007	< 0,05
433	89	9,4	< 0,01	0,197	0,165	0,01	0,35	< 0,005	< 0,01	< 0,1	0,036	0,38
434	90	7,5	0,02	0,3	0,33	< 0,005	0,57	< 0,005	< 0,01	< 0,1	0,087	0,78
435	93	6,1	0,01	0,35	0,039	0,009	0,51	< 0,005	< 0,01	< 0,1	0,024	0,08
436	88	10,7	0,01	0,52	0,078	0,014	0,53	< 0,005	< 0,01	< 0,1	0,025	0,08
437	92	7,0	< 0,01	0,063	< 0,005	< 0,005	0,46	< 0,005	< 0,01	< 0,1	< 0,005	< 0,05
438	92	6,1	0,07	0,282	0,37	0,146	0,65	0,005	< 0,01	< 0,1	0,027	0,11
439	91	7,4	< 0,01	0,056	0,044	0,011	1,15	< 0,005	< 0,01	< 0,1	0,015	0,18
440	91	7,9	0,05	0,209	0,44	0,144	0,241	< 0,005	< 0,01	< 0,1	0,023	< 0,05
441	91	7,8	0,01	0,077	0,106	0,016	0,48	< 0,005	< 0,01	< 0,1	0,018	0,07
442	92	7,7	0,03	0,024	0,071	0,01	0,095	< 0,005	< 0,01	< 0,1	< 0,005	0,09
443	89	9,6	0,1	0,259	0,32	0,158	0,254	0,008	< 0,01	< 0,1	0,017	< 0,05
444	89	9,5	0,07	0,36	0,31	0,087	0,88	0,005	< 0,01	< 0,1	0,03	0,12
445	92	5,5	0,08	0,42	0,89	0,34	0,269	0,009	< 0,01	< 0,1	0,022	< 0,05
446	89	9,8	0,03	0,186	0,264	0,113	0,54	< 0,005	< 0,01	< 0,1	0,023	< 0,05
447	91	7,1	0,24	0,41	0,84	0,236	0,38	0,009	< 0,01	< 0,1	0,042	0,08
448	91	5,3	0,15	0,97	1,31	0,58	0,271	0,014	< 0,01	< 0,1	0,046	0,17
449	92	3,3	0,1	1,33	2,0	0,87	0,075	0,011	< 0,01	< 0,1	0,007	< 0,05
450	92	6,6	0,5	< 0,005	0,097	0,157	0,214	< 0,005	< 0,01	< 0,1	0,013	0,09
451	98	0,006	0,04	0,13	0,168	0,029	0,73	< 0,005	< 0,01	< 0,1	0,037	0,6
452	99	< 0,005	< 0,01	0,01	0,017	0,007	0,35	< 0,005	< 0,01	< 0,1	< 0,005	0,17
453	89	8,6	0,05	0,57	1,09	0,57	0,037	0,005	< 0,01	< 0,1	0,013	0,33
454	89	8,5	0,05	0,54	1,06	0,54	0,038	0,008	< 0,01	< 0,1	0,017	0,13
455	94	< 0,005	< 0,01	1,12	3,5	0,63	0,015	0,044	< 0,01	< 0,1	< 0,005	0,2
456	92	6,2	0,14	0,36	0,64	0,38	0,273	0,007	< 0,01	< 0,1	0,016	< 0,05
457	91	7,2	0,15	0,258	0,47	0,221	0,098	0,008	< 0,01	< 0,1	0,059	< 0,05
458	91	6,9	0,12	0,48	0,87	0,53	0,21	0,01	< 0,01	< 0,1	0,021	< 0,05
459	90	7,9	0,09	0,65	0,77	0,54	0,15	0,011	< 0,01	< 0,1	0,017	< 0,05
460	91	6,3	0,15	0,54	0,83	0,51	0,154	0,012	< 0,01	< 0,1	0,013	< 0,05
461	92	5,9	0,2	0,49	0,61	0,38	0,202	0,014	< 0,01	< 0,1	0,033	< 0,05
462/G	90	8,9	< 0,01	0,237	0,046	0,006	0,52	< 0,005	< 0,01	< 0,1	0,063	0,1
462/K	89	10,1	< 0,01	0,032	< 0,005	0,006	0,3	< 0,005	< 0,01	< 0,1	0,019	0,13
463	90	9,3	0,12	0,123	0,044	0,026	0,167	0,011	< 0,01	< 0,1	0,04	0,09
464	91	8,1	0,12	0,151	0,109	0,03	0,41	0,007	< 0,01	< 0,1	0,03	0,09
465	93	5,7	0,11	0,32	0,142	0,033	0,42	0,006	0,01	< 0,1	0,086	0,09
466	89	9,4	0,64	0,233	0,168	0,076	0,46	0,011	< 0,01	< 0,1	0,038	< 0,05
467	74	< 0,005	0,02	6,3	18,0	1,08	0,025	0,151	< 0,01	< 0,1	0,01	0,07
468	88	< 0,005	< 0,01	4,3	6,2	1,29	< 0,01	0,142	< 0,01	< 0,1	< 0,005	0,06
469	98	0,015	< 0,01	0,276	0,013	0,019	0,153	< 0,005	< 0,01	< 0,1	0,021	1,01
470	94	0,016	0,03	2,19	0,178	0,32	2,64	< 0,005	< 0,01	< 0,1	0,044	0,1

Nr.	Cu	Sn	Pb	As	Sb	Ag	Ni	Bi	Au	Zn	Co	Fe
471	91	7,9	< 0,01	0,063	0,035	0,01	0,278	< 0,005	< 0,01	< 0,1	0,01	0,1
472	95	4,0	< 0,01	0,111	0,017	0,005	0,41	< 0,005	< 0,01	< 0,1	0,01	0,21
473	93	< 0,005	0,05	2,21	3,7	0,79	0,07	0,049	< 0,01	< 0,1	< 0,005	0,16
474	93	4,2	0,2	0,5	0,99	0,47	0,299	0,014	< 0,01	< 0,1	0,016	< 0,05
475	91	7,9	< 0,01	0,39	< 0,005	0,008	0,174	< 0,005	0,02	< 0,1	0,017	0,16
476	89	10,9	< 0,01	0,028	< 0,005	< 0,005	0,233	< 0,005	< 0,01	< 0,1	0,019	< 0,05
477	100	0,008	0,01	0,057	< 0,005	0,007	0,083	< 0,005	< 0,01	< 0,1	< 0,005	0,08
478	99	0,008	< 0,01	0,76	0,061	0,01	0,41	< 0,005	< 0,01	< 0,1	0,007	< 0,05
479	99	0,01	< 0,01	0,084	< 0,005	0,019	0,161	< 0,005	< 0,01	< 0,1	< 0,005	0,21
480	94	0,006	1,44	0,78	0,165	0,036	2,41	0,014	< 0,01	< 0,1	0,054	1,17
481	100	< 0,005	0,02	0,057	< 0,005	0,016	0,083	< 0,005	< 0,01	< 0,1	0,027	0,13
482	99	0,016	< 0,01	0,031	< 0,005	< 0,005	0,108	< 0,005	< 0,01	< 0,1	0,014	0,97
483	92	3,9	0,66	0,59	1,44	0,6	0,32	0,038	< 0,01	< 0,1	0,022	< 0,05
484	92	5,4	0,18	0,67	0,59	0,48	0,34	0,006	< 0,01	< 0,1	0,008	< 0,05
485/G	92	7,0	0,03	0,076	0,069	0,016	0,201	< 0,005	< 0,01	< 0,1	0,028	< 0,05
485/K	91	8,0	0,03	0,081	0,13	0,025	0,159	0,005	< 0,01	< 0,1	0,03	0,06
486	89	8,5	0,01	0,228	0,16	0,069	1,73	< 0,005	< 0,01	< 0,1	0,074	0,06
487/G	91	8,9	< 0,01	0,016	< 0,005	0,005	0,152	< 0,005	< 0,01	< 0,1	0,019	0,13
487/K	94	5,3	0,1	0,046	0,007	0,012	0,3	< 0,005	< 0,01	< 0,1	0,027	0,05
488	99	0,006	< 0,01	0,024	< 0,005	0,014	0,243	< 0,005	< 0,01	< 0,1	0,035	0,35
489	92	6,3	< 0,01	0,118	0,009	0,007	0,59	< 0,005	< 0,01	< 0,1	0,027	0,61
490	93	6,2	< 0,01	0,062	0,038	< 0,005	0,21	< 0,005	< 0,01	< 0,1	0,012	0,06
491	89	9,6	< 0,01	0,136	0,176	< 0,005	0,36	< 0,005	< 0,01	< 0,1	0,016	0,47
492	93	6,3	< 0,01	0,167	0,061	0,012	0,3	< 0,005	< 0,01	< 0,1	0,011	0,08
493	89	9,9	0,02	0,113	0,178	0,04	0,21	< 0,005	< 0,01	< 0,1	0,026	0,15
494	92	5,1	1,05	0,231	0,163	0,066	1,08	< 0,005	< 0,01	< 0,1	0,047	0,14
495	93	6,0	0,02	0,065	0,024	0,022	0,38	0,008	< 0,01	< 0,1	0,017	< 0,05
496	97	2,39	0,03	0,119	0,026	0,022	0,141	< 0,005	< 0,01	< 0,1	0,017	0,12
497	96	3,4	0,03	0,062	0,023	0,016	0,4	< 0,005	< 0,01	< 0,1	0,028	0,23
498	93	6,1	0,02	0,085	0,027	0,015	0,45	< 0,005	< 0,01	< 0,1	0,029	< 0,05
499	92	6,2	0,06	0,25	0,43	0,149	0,51	< 0,005	< 0,01	< 0,1	0,018	< 0,05
500	95	3,3	0,04	0,248	0,212	0,069	0,59	< 0,005	< 0,01	< 0,1	0,057	0,17
501	92	6,4	1,13	0,231	0,161	0,047	0,215	0,011	< 0,01	< 0,1	0,046	< 0,05
502	90	8,3	0,04	0,206	0,225	0,079	0,31	< 0,005	< 0,01	< 0,1	0,024	0,34
503	94	5,6	0,15	0,157	0,072	0,061	0,229	0,011	< 0,01	< 0,1	0,012	< 0,05
504	90	8,6	0,07	0,154	0,064	0,019	0,27	0,007	< 0,01	< 0,1	0,028	0,38
505	89	8,6	0,08	0,3	0,34	0,02	0,52	0,008	< 0,01	< 0,1	0,039	1,09
506/G	89	10,7	< 0,01	0,022	< 0,005	0,016	0,201	< 0,005	< 0,01	< 0,1	0,022	0,05
506/K	91	8,2	< 0,01	0,016	< 0,005	0,009	0,149	< 0,005	< 0,01	< 0,1	0,017	0,06
507	90	8,7	0,09	0,162	0,076	0,035	0,299	< 0,005	< 0,01	< 0,1	0,023	< 0,05
508	92	6,5	< 0,01	0,285	0,5	0,016	0,51	< 0,005	< 0,01	< 0,1	0,014	0,07
509/G	89	9,7	< 0,01	0,108	< 0,005	0,013	0,46	< 0,005	< 0,01	< 0,1	0,032	0,09
509/K	90	8,8	0,17	0,39	0,203	0,025	0,33	0,006	< 0,01	< 0,1	0,041	< 0,05
510/G	90	9,3	< 0,01	0,095	0,007	0,011	0,159	< 0,005	< 0,01	< 0,1	0,035	0,34
510/K	90	9,9	0,03	0,108	0,034	0,019	0,202	< 0,005	< 0,01	< 0,1	0,016	< 0,05
511	92	6,2	< 0,01	0,4	0,153	< 0,005	1,07	< 0,005	< 0,01	< 0,1	0,016	< 0,05
512	92	5,3	< 0,01	0,9	0,8	0,058	1,07	0,008	< 0,01	< 0,1	0,026	0,09
513	92	5,9	< 0,01	0,36	0,171	0,023	1,08	< 0,005	< 0,01	< 0,1	0,045	0,21

Nr.	Cu	Sn	Pb	As	Sb	Ag	Ni	Bi	Au	Zn	Co	Fe
514	90	8,4	0,02	0,187	0,6	0,017	0,257	< 0,005	< 0,01	< 0,1	< 0,005	0,23
515	99	< 0,005	< 0,01	0,263	0,033	< 0,005	0,207	< 0,005	< 0,01	< 0,1	0,034	0,78
516	96	0,151	< 0,01	0,279	0,032	0,005	1,03	< 0,005	< 0,01	< 0,1	0,095	2,24
517	98	0,013	< 0,01	0,47	0,242	< 0,005	0,63	< 0,005	< 0,01	< 0,1	< 0,005	0,21
518	99	0,015	< 0,01	0,105	0,039	0,007	0,073	< 0,005	< 0,01	< 0,1	0,013	0,28
519	99	< 0,005	< 0,01	0,08	0,112	< 0,005	0,121	< 0,005	< 0,01	< 0,1	0,012	0,42
520	99	< 0,005	< 0,01	0,024	< 0,005	0,011	0,31	< 0,005	< 0,01	< 0,1	0,024	0,28
521	99	< 0,005	< 0,01	0,042	< 0,005	0,008	0,103	< 0,005	< 0,01	< 0,1	0,009	0,28
522	98	< 0,005	< 0,01	1,89	0,038	0,102	0,149	< 0,005	< 0,01	< 0,1	< 0,005	< 0,05
523	90	0,019	0,03	5,9	0,36	0,34	2,4	0,01	< 0,01	< 0,1	0,239	0,22
524	91	< 0,005	< 0,01	0,61	7,0	1,25	< 0,01	0,035	< 0,01	< 0,1	< 0,005	< 0,05
525	90	8,7	0,07	0,149	0,104	0,021	0,4	0,008	< 0,01	< 0,1	0,031	0,07
526	94	4,3	0,05	0,275	0,119	0,018	0,58	< 0,005	< 0,01	< 0,1	0,039	0,25
527	91	7,3	0,06	0,265	0,095	0,018	0,51	< 0,005	< 0,01	< 0,1	0,031	0,09
528	92	7,3	0,15	0,212	0,082	0,019	0,44	< 0,005	< 0,01	< 0,1	0,041	0,15
529	96	2,5	0,12	0,193	0,059	0,051	0,41	0,007	< 0,01	< 0,1	0,02	< 0,05
530	85	14,1	0,4	0,041	0,092	0,063	0,06	0,011	< 0,01	< 0,1	0,038	0,27
531	91	8,8	0,06	0,05	0,017	0,009	0,12	< 0,005	< 0,01	< 0,1	0,025	0,1
532	91	8,0	0,15	0,211	0,07	0,055	0,236	0,008	< 0,01	< 0,1	0,086	0,06
533	89	10,5	< 0,01	0,047	0,012	0,007	0,226	< 0,005	< 0,01	< 0,1	0,012	0,2
534	91	8,4	0,01	0,131	0,009	0,008	0,288	< 0,005	< 0,01	< 0,1	0,029	0,13
535	95	4,8	0,05	0,073	0,039	0,022	0,162	< 0,005	< 0,01	< 0,1	0,007	< 0,05
536	92	6,2	0,02	0,38	0,175	0,032	0,64	< 0,005	< 0,01	< 0,1	0,019	< 0,05
537	99	< 0,005	0,01	0,068	< 0,005	0,027	0,057	< 0,005	< 0,01	< 0,1	0,109	0,82
538	99	< 0,005	< 0,01	0,014	0,006	< 0,005	0,42	< 0,005	< 0,01	< 0,1	0,032	0,61
538	99	< 0,005	< 0,01	0,012	0,014	0,007	0,93	< 0,005	< 0,01	< 0,1	0,022	0,28
540	99	< 0,005	< 0,01	< 0,005	< 0,005	0,006	0,34	< 0,005	< 0,01	< 0,1	< 0,005	< 0,05
541/U	99	< 0,005	< 0,01	0,015	0,013	< 0,005	0,59	< 0,005	< 0,01	< 0,1	< 0,005	< 0,05
541/O	99	< 0,005	< 0,01	0,008	< 0,005	0,006	0,64	< 0,005	< 0,01	< 0,1	0,01	< 0,05
542	92	< 0,005	< 0,01	0,41	0,11	0,008	6,1	< 0,005	< 0,01	0,1	0,177	0,67
543	99	< 0,005	< 0,01	0,018	0,015	0,024	0,38	< 0,005	< 0,01	< 0,1	< 0,005	< 0,05
544/G	90	9,1	0,02	0,083	0,064	0,01	0,158	< 0,005	< 0,01	< 0,1	0,033	0,17
544/K	93	6,6	< 0,01	0,086	0,073	0,007	0,135	< 0,005	< 0,01	< 0,1	< 0,005	0,07
545	91	7,1	0,03	0,269	0,214	< 0,005	0,54	< 0,005	< 0,01	< 0,1	0,044	0,31
546	91	8,0	< 0,01	0,094	0,019	0,019	0,43	< 0,005	< 0,01	< 0,1	0,044	0,18
547	91	7,4	0,17	0,34	0,162	0,04	0,298	0,007	< 0,01	< 0,1	0,061	< 0,05
548	90	8,4	0,21	0,39	0,134	0,053	0,21	0,01	< 0,01	< 0,1	0,086	0,08
549	87	12,0	0,06	0,114	0,038	0,025	0,165	0,007	< 0,01	< 0,1	0,016	0,06
550	90	8,3	0,22	0,4	0,146	0,055	0,214	0,013	< 0,01	< 0,1	0,085	0,06
551	89	10,1	0,09	0,33	0,132	0,038	0,216	0,008	< 0,01	< 0,1	0,054	0,08
552	91	8,0	0,13	0,208	0,074	0,04	0,18	0,008	< 0,01	< 0,1	0,055	< 0,05
553	91	7,9	0,06	0,19	0,038	0,034	0,151	< 0,005	< 0,01	< 0,1	0,084	< 0,05
554	94	5,0	< 0,01	0,37	0,207	0,015	0,7	< 0,005	< 0,01	< 0,1	0,023	0,05
555	91	7,7	0,04	0,194	0,129	0,007	0,237	< 0,005	< 0,01	< 0,1	0,05	0,18
556	89	9,2	0,06	0,34	0,31	0,011	0,295	< 0,005	< 0,01	< 0,1	0,039	0,19
557	89	8,3	< 0,01	0,69	0,112	0,006	1,43	< 0,005	< 0,01	< 0,1	0,02	0,17
558	90	9,1	< 0,01	0,02	0,022	0,009	0,071	< 0,005	< 0,01	< 0,1	0,012	0,24
559	98	< 0,005	< 0,01	0,199	0,33	< 0,005	0,47	< 0,005	< 0,01	< 0,1	0,013	0,38

Nr.	Cu	Sn	Pb	As	Sb	Ag	Ni	Bi	Au	Zn	Co	Fe
560/O	98	< 0,005	< 0,01	0,134	0,101	< 0,005	0,179	< 0,005	< 0,01	< 0,1	0,011	1,8
560/U	99	< 0,005	< 0,01	0,123	0,11	< 0,005	0,282	< 0,005	< 0,01	< 0,1	0,018	0,8
561/G	90	8,6	0,01	0,244	0,08	0,029	0,69	< 0,005	< 0,01	< 0,1	0,024	< 0,05
561/K	90	7,9	0,18	0,31	0,34	0,105	0,57	< 0,005	< 0,01	< 0,1	0,017	< 0,05
562	91	8,8	< 0,01	0,016	0,057	0,006	0,052	< 0,005	< 0,01	< 0,1	0,016	0,17
563	90	8,9	0,06	0,1	0,031	0,005	0,52	< 0,005	< 0,01	< 0,1	0,02	0,06
564/G	91	7,7	0,05	0,273	0,075	0,013	0,54	< 0,005	< 0,01	< 0,1	0,034	0,14
564/K	93	5,7	0,09	0,248	0,064	0,019	0,43	0,009	< 0,01	< 0,1	0,03	0,23
565	87	10,5	0,01	0,73	0,37	0,014	0,76	< 0,005	< 0,01	< 0,1	0,063	< 0,05
566	89	10,1	< 0,01	0,011	0,019	0,005	0,054	< 0,005	< 0,01	< 0,1	< 0,005	0,21
567/G	89	9,2	0,02	0,25	0,082	< 0,005	0,63	< 0,005	< 0,01	< 0,1	0,033	0,19
567/K	92	7,2	< 0,01	0,107	0,036	< 0,005	0,42	< 0,005	< 0,01	< 0,1	0,029	0,15
568	92	6,1	0,04	0,177	0,4	0,137	0,35	< 0,005	< 0,01	< 0,1	0,082	0,28
569	92	3,7	0,2	1,11	1,71	0,56	0,31	0,028	< 0,01	< 0,1	0,066	< 0,05
570	89	9,4	0,22	0,184	0,066	0,035	0,41	0,013	< 0,01	< 0,1	0,03	< 0,05
570	89	9,5	0,21	0,198	0,077	0,052	0,41	0,008	< 0,01	< 0,1	0,03	< 0,05
571	90	9,3	0,02	0,092	0,044	0,012	0,264	< 0,005	< 0,01	< 0,1	0,033	0,23
572	90	7,9	0,11	0,286	0,35	0,085	0,61	0,005	< 0,01	< 0,1	0,034	0,2
573	91	5,7	0,23	0,51	0,78	0,133	0,65	0,008	< 0,01	< 0,1	0,098	0,35
574	93	5,5	0,12	0,34	0,58	0,171	0,48	0,005	< 0,01	< 0,1	0,068	0,08
575	92	5,0	0,24	0,58	1,0	0,24	0,57	0,013	< 0,01	< 0,1	0,064	< 0,05
576	91	6,4	0,27	0,48	0,69	0,197	0,58	0,011	< 0,01	< 0,1	0,09	0,06
577	92	6,4	0,26	0,281	0,42	0,158	0,43	0,014	< 0,01	< 0,1	0,048	< 0,05
578	92	6,4	0,12	0,31	0,47	0,164	0,59	0,007	< 0,01	< 0,1	0,034	0,06
579	91	7,0	0,19	0,44	0,51	0,164	0,65	0,007	< 0,01	< 0,1	0,036	0,06
580	92	6,1	0,39	0,35	0,41	0,33	0,192	0,015	< 0,01	< 0,1	0,023	0,41
581	91	7,3	0,03	0,18	0,221	0,07	0,79	< 0,005	< 0,01	< 0,1	0,018	0,07
582	91	7,4	0,03	0,181	0,22	0,065	0,82	< 0,005	< 0,01	< 0,1	0,024	0,07
583	91	7,5	0,05	0,138	0,15	0,044	0,72	< 0,005	< 0,01	< 0,1	0,029	0,1
584	92	6,9	0,43	0,146	0,053	0,019	0,64	0,005	< 0,01	< 0,1	0,022	0,07
585	87	7,2	0,39	1,4	0,61	0,139	1,96	0,019	< 0,01	< 0,1	0,71	0,35
586	95	4,3	0,07	0,144	0,144	0,059	0,48	< 0,005	< 0,01	< 0,1	0,026	0,07
587	94	4,7	0,07	0,32	0,61	0,193	0,41	0,007	< 0,01	< 0,1	0,018	< 0,05
588	93	5,1	0,17	0,55	0,85	0,32	0,29	0,014	< 0,01	< 0,1	0,036	< 0,05
589	93	5,6	0,38	0,249	0,272	0,115	0,42	0,01	< 0,01	< 0,1	0,031	0,05
590	87	12	0,03	0,141	0,187	0,04	0,33	< 0,005	< 0,01	< 0,1	0,06	0,19
591	91	8,2	0,53	0,051	0,015	0,027	0,3	< 0,005	< 0,01	< 0,1	0,011	< 0,05
592	94	5,7	0,12	0,01	< 0,005	0,038	0,052	< 0,005	< 0,01	< 0,1	0,034	0,15
593	90	7,8	0,27	0,42	0,64	0,233	0,48	0,007	< 0,01	< 0,1	0,065	0,06
594	92	5,6	0,38	0,297	0,49	0,166	0,55	< 0,005	< 0,01	< 0,1	0,082	< 0,05
595	92	4,1	0,17	0,81	2,39	0,32	0,39	0,015	< 0,01	< 0,1	0,027	< 0,05
596	89	7,6	1,29	0,271	0,4	0,131	0,56	0,01	< 0,01	< 0,1	0,152	< 0,05
597	91	8,2	0,04	0,162	0,227	0,047	0,48	< 0,005	< 0,01	< 0,1	0,027	0,13
598	98	< 0,005	< 0,01	0,116	0,31	0,084	0,43	< 0,005	< 0,01	< 0,1	0,034	0,42
599	98	0,015	< 0,01	0,179	0,31	0,118	0,42	< 0,005	< 0,01	< 0,1	0,06	1,06
600	98	< 0,005	0,03	0,138	0,009	0,01	0,93	< 0,005	< 0,01	< 0,1	0,026	1,04
601	96	0,019	0,08	0,55	1,48	0,55	0,228	< 0,005	< 0,01	0,2	0,053	1,19
602	96	0,013	< 0,01	0,76	2,16	0,39	0,162	0,014	< 0,01	< 0,1	0,03	0,4

Nr.	Cu	Sn	Pb	As	Sb	Ag	Ni	Bi	Au	Zn	Co	Fe
603	97	0,048	0,03	0,54	1,18	0,44	0,198	< 0,005	< 0,01	< 0,1	0,044	0,72
604	99	< 0,005	< 0,01	0,163	0,064	< 0,005	0,72	< 0,005	< 0,01	< 0,1	0,008	0,31
605	98	0,006	< 0,01	0,134	0,018	0,019	1,11	< 0,005	< 0,01	< 0,1	0,033	0,73
606	89	9,9	0,12	0,279	0,298	0,019	0,34	< 0,005	< 0,01	< 0,1	0,011	0,23
607	98	< 0,005	< 0,01	0,137	0,006	< 0,005	1,19	< 0,005	< 0,01	< 0,1	< 0,005	< 0,05
608	87	< 0,005	0,05	3,9	8,2	0,75	0,031	0,053	< 0,01	< 0,1	< 0,005	< 0,05
609	99	0,015	< 0,01	0,025	< 0,005	< 0,005	0,084	< 0,005	< 0,01	< 0,1	< 0,005	0,44
610	93	< 0,005	< 0,01	1,43	4,3	1,14	< 0,01	0,112	< 0,01	< 0,1	< 0,005	< 0,05
611	90	6,8	0,11	0,171	0,31	0,072	0,44	0,007	< 0,01	< 0,1	0,056	2,02
612	93	5,2	0,08	0,284	0,4	0,16	0,33	0,014	< 0,01	< 0,1	0,018	< 0,05
613	93	6,1	< 0,01	0,052	0,009	0,017	0,35	< 0,005	< 0,01	< 0,1	0,035	0,16
614	93	< 0,005	0,01	1,32	4,0	0,67	0,113	0,021	< 0,01	< 0,1	0,006	0,38
615	80	< 0,005	0,06	7,5	11,0	0,93	0,019	0,083	< 0,01	< 0,1	0,007	< 0,05
616	85	< 0,005	< 0,01	4,3	9,4	0,82	0,022	0,055	< 0,01	< 0,1	< 0,005	< 0,05
617	100	0,024	< 0,01	0,08	< 0,005	0,006	0,122	< 0,005	0,01	< 0,1	0,031	0,1
618	88	< 0,005	0,67	4,6	5,7	0,91	0,031	0,055	< 0,01	< 0,1	< 0,005	0,14
619	69	< 0,005	0,04	7,1	22,2	0,91	0,022	0,139	< 0,01	< 0,1	0,016	0,34
620	97	0,017	0,03	0,46	1,59	0,118	0,137	0,018	< 0,01	< 0,1	0,098	0,61
621	78	20,8	0,18	0,259	0,034	0,08	0,076	0,026	< 0,01	< 0,1	0,055	0,25
622	91	7,0	0,12	0,49	0,44	0,108	0,62	0,01	< 0,01	< 0,1	0,047	0,07
623	90	8,4	0,12	0,37	0,5	0,126	0,3	0,007	< 0,01	< 0,1	0,046	0,09
624	92	6,6	0,06	0,161	0,166	0,06	0,36	< 0,005	< 0,01	< 0,1	0,023	< 0,05
625	90	9,0	0,13	0,215	0,06	0,031	0,144	0,018	< 0,01	< 0,1	0,042	0,45
626	91	7,7	0,27	0,158	0,073	0,048	0,45	0,014	< 0,01	< 0,1	0,046	0,14
627	89	10,0	0,27	0,211	0,069	0,065	0,43	0,02	< 0,01	< 0,1	0,046	0,05
628	87	10,9	0,15	0,261	0,082	0,04	0,6	< 0,005	0,01	< 0,1	0,039	0,35
629	86	12,8	0,38	0,192	0,095	0,095	0,159	0,023	< 0,01	< 0,1	0,024	0,13
630	96	0,64	< 0,01	0,38	1,12	0,77	0,81	0,007	< 0,01	< 0,1	0,008	< 0,05
631	95	0,149	< 0,01	0,47	1,58	0,98	1,27	< 0,005	< 0,01	< 0,1	0,033	< 0,05
632/G	89	10,2	0,07	0,3	0,118	0,026	0,42	< 0,005	< 0,01	< 0,1	0,013	0,05
632/K		8,7	0,01	0,35	0,159	0,021	0,52	< 0,005	< 0,01	< 0,1	0,017	< 0,05
633/G	90	9,6	0,1	0,248	0,059	0,044	0,077	0,018	< 0,01	< 0,1	0,047	0,05
633/K	89	9,4	0,03	0,074	0,43	0,006	0,278	0,005	< 0,01	< 0,1	0,022	0,19
634/G	91	9,0	< 0,01	0,035	0,054	0,006	0,114	< 0,005	< 0,01	< 0,1	0,017	< 0,05
634/K	92	7,2	< 0,01	0,049	0,037	< 0,005	0,117	< 0,005	< 0,01	< 0,1	0,02	< 0,05
635/G	89	9,8	< 0,01	0,26	0,072	0,01	0,45	< 0,005	< 0,01	< 0,1	0,029	0,16
635/K	93	6,4	0,08	0,192	0,077	0,024	0,35	0,009	< 0,01	< 0,1	0,03	< 0,05
636	92	< 0,005	0,03	3,1	4,0	0,84	0,022	0,059	< 0,01	< 0,1	< 0,005	< 0,05
637	91	8,3	< 0,01	0,102	0,023	< 0,005	0,133	< 0,005	< 0,01	< 0,1	0,015	0,07
638	91	6,9	0,03	0,22	1,26	0,042	0,157	0,005	< 0,01	< 0,1	0,012	0,33
639	89	9,4	0,02	0,33	0,046	0,032	0,57	0,007	< 0,01	< 0,1	0,07	0,31
640	90	8,3	0,06	0,237	0,69	0,058	0,228	< 0,005	< 0,01	< 0,1	0,009	0,08
641	92	6,6	0,27	0,085	0,062	0,049	0,2	0,012	< 0,01	< 0,1	0,021	0,19
642/G	88	11,3	0,33	0,048	0,031	0,076	0,025	0,027	< 0,01	< 0,1	0,032	0,18
642/K	90	9,1	0,36	0,049	0,037	0,08	0,037	0,021	< 0,01	< 0,1	0,039	0,36
643	92	7,3	0,01	0,192	0,236	0,024	0,272	< 0,005	< 0,01	< 0,1	0,035	0,1
644	91	7,0	0,11	0,43	0,142	0,027	1,09	< 0,005	< 0,01	< 0,1	0,055	0,08
645	87	11,2	0,41	0,184	0,094	0,058	0,32	0,016	< 0,01	< 0,1	0,034	0,07

Nr.	Cu	Sn	Pb	As	Sb	Ag	Ni	Bi	Au	Zn	Co	Fe
646	90	8,9	0,28	0,173	0,056	0,065	0,37	0,011	< 0,01	< 0,1	0,03	0,07
647/G	90	9,1	< 0,01	0,069	0,006	0,007	0,61	< 0,005	< 0,01	< 0,1	0,053	0,26
647/K	91	7,0	0,2	0,53	0,203	0,027	0,283	0,006	< 0,01	< 0,1	0,069	0,12
648	88	11,1	0,36	0,188	0,087	0,079	0,238	0,025	< 0,01	< 0,1	0,032	0,19
649	87	11,5	0,61	0,112	0,07	0,116	0,098	0,03	< 0,01	< 0,1	0,026	0,15
650	90	9,1	0,12	0,236	0,049	0,067	0,173	0,016	0,02	< 0,1	0,072	< 0,05
651	88	11,8	0,11	0,113	0,034	0,048	0,063	0,007	< 0,01	< 0,1	0,037	< 0,05
652	90	8,5	0,18	0,227	0,29	0,135	0,267	0,008	< 0,01	< 0,1	0,019	< 0,05
653	91	8,1	0,22	0,179	0,035	0,051	0,112	0,017	< 0,01	< 0,1	0,074	< 0,05
654	89	8,9	0,23	0,39	0,75	0,184	0,183	0,009	< 0,01	< 0,1	0,03	< 0,05
655	89	8,3	0,95	0,278	0,62	0,139	0,33	0,007	< 0,01	< 0,1	0,023	< 0,05
656	89	7,7	0,15	0,75	1,28	0,247	0,43	0,013	< 0,01	< 0,1	0,03	< 0,05
657	89	8,8	0,89	0,209	0,265	0,103	0,31	0,016	< 0,01	< 0,1	0,139	0,2
658	91	6,4	0,52	0,36	0,92	0,37	0,226	0,013	< 0,01	< 0,1	0,028	< 0,05
659	91	5,2	0,08	0,68	1,84	0,73	0,091	0,019	< 0,01	< 0,1	0,019	< 0,05
660	90	9,3	0,01	0,103	0,113	0,013	0,267	< 0,005	< 0,01	< 0,1	0,025	< 0,05
661	91	8,0	< 0,01	0,17	0,07	0,006	0,214	< 0,005	< 0,01	< 0,1	0,039	0,22
662	91	7,8	< 0,01	0,36	0,32	0,009	0,197	< 0,005	< 0,01	< 0,1	0,011	0,54
663	91	7,3	0,06	0,173	0,37	0,143	0,246	< 0,005	< 0,01	< 0,1	0,035	0,09
664/G	90	9,1	0,02	0,047	0,014	0,01	0,22	< 0,005	< 0,01	< 0,1	0,015	< 0,05
664/K	91	8,0	< 0,01	0,048	< 0,005	0,013	0,5	< 0,005	< 0,01	< 0,1	0,023	< 0,05
665	92	6,5	0,2	0,32	0,147	0,033	0,231	< 0,005	< 0,01	< 0,1	0,088	0,08
666/G	92	7,0	< 0,01	0,275	0,102	0,016	0,39	< 0,005	< 0,01	< 0,1	0,008	< 0,05
666/K	91	7,7	0,01	0,285	0,111	0,02	0,4	0,007	< 0,01	< 0,1	0,006	0,09
667	90	7,4	0,16	0,6	0,54	0,149	0,7	0,011	< 0,01	< 0,1	0,043	< 0,05
668	90	7,1	0,17	0,54	1,08	0,47	0,191	0,026	< 0,01	< 0,1	0,042	< 0,05
669	97	1,67	0,04	0,173	0,52	0,297	0,35	0,019	< 0,01	< 0,1	< 0,005	< 0,05
670	89	9,8	0,34	0,152	0,257	0,112	0,11	0,011	< 0,01	< 0,1	0,032	0,08
671	87	11,6	0,03	0,48	0,181	0,153	0,282	< 0,005	< 0,01	< 0,1	0,022	0,19
672	94	3,5	0,21	0,49	1,07	0,47	0,44	0,017	< 0,01	< 0,1	0,027	< 0,05
673	90	8,7	0,33	0,223	0,44	0,131	0,47	0,007	< 0,01	< 0,1	0,018	< 0,05
674	92	5,3	0,35	0,62	1,01	0,46	0,43	0,018	< 0,01	< 0,1	0,077	< 0,05
675	89	10,6	0,1	0,14	0,115	0,035	0,265	0,01	< 0,01	< 0,1	0,024	0,05
676	90	9,3	0,5	0,12	0,097	0,122	0,062	0,031	< 0,01	< 0,1	0,042	< 0,05
677	91	7,7	0,13	0,224	0,193	0,056	0,222	0,009	< 0,01	< 0,1	0,038	0,05
678	91	8,0	0,06	0,101	0,159	0,062	0,143	< 0,005	< 0,01	< 0,1	0,026	< 0,05
679	87	11,9	0,23	0,261	0,062	0,058	0,13	0,013	< 0,01	< 0,1	0,063	0,06
680	88	8,3	0,44	0,68	1,26	0,55	0,4	0,023	< 0,01	< 0,1	0,053	0,06
681	89	10,1	0,24	0,192	0,39	0,081	0,256	0,005	< 0,01	< 0,1	0,055	< 0,05
682	89	8,8	0,22	0,56	0,86	0,176	0,33	0,013	< 0,01	< 0,1	0,022	< 0,05
683	89	9,6	0,08	0,188	0,285	0,085	0,242	0,007	< 0,01	< 0,1	0,038	< 0,05
684	90	8,7	0,47	0,235	0,191	0,095	0,33	0,017	< 0,01	< 0,1	0,104	0,12
685	86	12,8	< 0,01	0,044	0,011	0,006	0,182	< 0,005	< 0,01	< 0,1	0,05	0,32
686	88	10,8	0,05	0,13	0,011	0,016	0,199	0,01	0,02	< 0,1	0,009	0,12
687	88	11,6	0,02	0,021	< 0,005	0,015	0,068	< 0,005	0,01	< 0,1	< 0,005	0,17
688	87	11,9	0,09	0,111	0,088	0,032	0,263	0,005	< 0,01	< 0,1	0,03	0,15
689	90	9,3	0,02	0,013	< 0,005	< 0,005	0,155	< 0,005	< 0,01	< 0,1	0,018	0,11
690	87	13,0	0,06	0,04	0,021	0,021	0,107	< 0,005	< 0,01	< 0,1	0,009	0,13

Nr.	Cu	Sn	Pb	As	Sb	Ag	Ni	Bi	Au	Zn	Co	Fe
691	96	0,016	< 0,01	0,025	< 0,005	0,026	0,82	< 0,005	< 0,01	< 0,1	0,082	2,99
692	97	2,9	< 0,01	0,036	< 0,005	< 0,005	0,086	0,007	< 0,01	< 0,1	0,013	0,05
693	89	10,7	0,06	0,093	0,017	0,024	0,133	0,008	< 0,01	< 0,1	0,008	0,12
694	91	8,1	0,45	0,116	0,117	0,067	0,043	0,025	< 0,01	< 0,1	0,048	< 0,05
695/G	90	9,6	0,03	0,07	0,023	0,02	0,206	< 0,005	< 0,01	< 0,1	0,03	0,11
695/K	90	8,7	0,23	0,13	0,121	0,073	0,262	0,01	< 0,01	< 0,1	0,038	0,06
696/G	90	9,4	< 0,01	0,007	< 0,005	< 0,005	0,053	< 0,005	< 0,01	< 0,1	< 0,005	0,05
696/K	91	8,3	< 0,01	0,007	< 0,005	0,005	0,047	< 0,005	< 0,01	< 0,1	< 0,005	< 0,05
697	84	< 0,005	0,02	4,8	10,3	0,71	0,016	0,136	< 0,01	< 0,1	0,011	0,06
698	94	4,5	0,04	0,265	0,095	0,015	0,42	< 0,005	< 0,01	< 0,1	0,016	0,17
699	97	1,22	0,02	0,33	0,046	0,01	0,85	< 0,005	< 0,01	< 0,1	0,071	0,15
700	93	< 0,005	0,02	1,16	2,7	2,35	0,142	0,038	< 0,01	< 0,1	< 0,005	< 0,05
701	97	0,014	< 0,01	0,36	0,11	0,071	2,0	< 0,005	< 0,01	< 0,1	0,14	0,31
702	98	0,03	0,35	0,07	0,122	0,048	0,043	0,016	< 0,01	0,1	0,054	0,92
703	96	0,005	0,02	1,22	0,139	0,109	0,93	< 0,005	< 0,01	< 0,1	0,074	1,12
704	89	9,6	0,39	0,179	0,064	0,129	0,132	0,024	< 0,01	< 0,1	0,034	0,09
705	92	6,6	0,28	0,215	0,36	0,117	0,196	0,02	< 0,01	< 0,1	0,031	< 0,05
706	95	3,2	0,35	0,37	0,63	0,243	0,32	0,041	< 0,01	< 0,1	0,072	0,21
707	96	2,34	0,64	0,34	0,5	0,189	0,143	0,038	< 0,01	< 0,1	0,048	< 0,05
708	92	7,4	0,07	0,185	0,07	0,015	0,45	< 0,005	< 0,01	< 0,1	0,031	0,08
709	92	6,9	0,56	0,12	0,112	0,01	0,173	0,006	< 0,01	< 0,1	0,008	0,2
710/A	91	6,8	0,45	0,45	0,81	0,41	0,189	0,014	0,03	< 0,1	0,033	0,21
710/B	87	10,1	0,57	0,54	0,96	0,45	0,271	0,02	< 0,01	< 0,1	0,049	< 0,05
711	96,2	< 0,005	< 0,01	0,62	2,26	0,35	0,164	< 0,005	< 0,01	< 0,01	0,011	< 0,05
712	89,9	11,7	0,05	0,147	0,044	0,009	0,282	0,007	< 0,01	< 0,01	0,011	< 0,05
713	86,4	10,8	< 0,01	0,69	< 0,005	< 0,005	0,31	< 0,005	< 0,01	< 0,01	0,017	0,05
714	88,7	10,6	0,21	0,072	0,035	0,048	0,121	0,007	< 0,01	< 0,01	0,016	0,07
715	91,4	10,4	0,22	0,187	0,206	0,026	0,36	0,007	< 0,01	< 0,1	0,025	0,07
716	82,2	20,0	0,54	0,131	0,08	0,048	0,36	0,015	< 0,01	< 0,01	0,025	0,1
717/G	89,3	9,1	0,24	0,47	0,071	0,023	0,257	< 0,005	< 0,01	< 0,01	0,049	0,08
717/K	90,9	9,7	0,05	0,34	0,158	0,034	0,243	0,005	0,01	< 0,01	0,021	< 0,05
718/G	90,6	11,1	0,02	0,027	< 0,005	< 0,005	0,069	< 0,005	< 0,01	< 0,01	0,005	< 0,05
718/K	91,7	11,7	0,03	0,107	0,013	0,016	0,097	< 0,005	0,02	< 0,1	0,017	0,09
719	99,1	< 0,005	0,1	0,49	0,046	0,025	0,034	0,011	< 0,01	< 0,01	0,005	< 0,05
720	90,6	10,9	< 0,01	0,048	< 0,005	0,016	0,197	< 0,005	< 0,01	< 0,01	0,03	0,06
721	91,2	6,6	0,17	0,205	0,83	0,37	0,027	< 0,005	< 0,01	< 0,01	< 0,005	< 0,05
722	70,5	< 0,005	0,14	10,3	16,8	1,5	0,013	0,114	< 0,01	< 0,1	< 0,005	0,6
723	86	9,8	0,02	0,68	0,34	0,06	0,9	0,008	0	0	0,019	0,08
724	88	9,2	0,02	0,22	0,43	0,05	0,26	< 0,01	0	0	0,016	< 0,05
725	90	8,6	0,19	0,39	0,11	0,06	0,23	0,008	0	0	0,082	< 0,05
726	70	< 0,01	< 0,01	6,6	21,1	1,08	< 0,01	0,085	0	0	< 0,005	0,18
727	90,2	7,8	0,02	0,077	0,37	0,023	0,075	< 0,005	0,01	< 0,01	0,009	0,12
728	90,9	3,6	0,23	1,41	1,82	0,86	0,13	0,041	< 0,01	< 0,01	0,018	< 0,05
729	90,4	8,4	< 0,01	0,079	0,192	0,009	0,108	0,016	< 0,01	< 0,01	0,02	0,07
730/G	85,7	10,6	0,04	0,112	0,055	0,017	0,31	< 0,005	< 0,01	< 0,01	0,04	0,4
730/K	84	10,0	0,18	0,272	0,149	0,072	0,208	0,007	< 0,01	< 0,01	0,055	< 0,05
731	90,9	6,5	0,09	0,138	0,035	0,062	0,036	0,017	< 0,01	< 0,01	0,035	0,13
732	95	5,0	0,04	0,089	0,021	0,033	0,232	0,01	< 0,01	< 0,1	0,05	0,15

Nr.	Cu	Sn	Pb	As	Sb	Ag	Ni	Bi	Au	Zn	Co	Fe
733	90,5	13,7	0,08	0,142	0,033	0,024	0,033	< 0,005	< 0,01	< 0,01	0,031	0,12
734	88,5	10,8	0,27	0,09	0,167	0,089	0,031	0,012	< 0,01	< 0,01	0,048	0,1
735	89	7,4	0,09	0,35	0,66	0,036	0,258	< 0,005	< 0,01	< 0,01	0,017	0,38
736/G	89,1	8,2	0,08	0,115	0,074	0,031	0,243	0,005	< 0,01	< 0,01	0,021	0,14
736/K	88,5	8,0	0,15	0,098	0,079	0,041	0,148	0,014	< 0,01	< 0,01	0,032	0,08
737/G	87	8,4	0,23	0,14	0,11	0,036	0,217	0,012	< 0,01	< 0,1	0,015	0,28
737/K	89,3	7,2	0,05	0,185	0,054	0,02	0,37	< 0,005	0,02	< 0,1	0,02	0,14
738/G	85,2	10,5	< 0,01	0,032	0,009	0,034	0,211	0,005	0,01	< 0,01	0,049	< 0,05
738/K	85	10,3	< 0,01	0,16	0,005	0,018	0,47	< 0,005	< 0,01	< 0,01	0,04	< 0,05
739	96,4	0,107	< 0,01	0,35	0,059	0,041	1,05	< 0,005	< 0,01	< 0,1	0,092	1,77
Nicht berücksichtigte Analysen												
30	0,2	99	0,02	0,191	< 0,005	0,011	0,024	0,028	< 0,01	< 0,01	0,008	0,19
94	74	15,8	0,57	0,52	2,3	0,144	0,145	0,036	< 0,01	< 0,1	0,011	0,1
391	0,53	0,78	98	0,022	0,01	0,035	< 0,01	< 0,005	0,04	< 0,01	< 0,005	0,14
467/A	92	5,1	1,27	0,45	0,82	0,28	0,296	0,019	< 0,01	< 0,1	0,076	0,14
467/B	92	4,3	1,33	0,58	0,96	0,37	0,293	0,022	< 0,01	< 0,1	0,054	0,18

Nr.	Fundort	Lkr./Bez.	Fundumstände	Objekt	Datierung	Bemerkung	Literatur
1	Flintsbach a. Inn-“Rachelburg“	RO	Höhensiedlung („Rachelburg“)	Dolch	BZ B		Möslein 1998/99a, 205 Nr. 3 Abb. 1,2.
2	Flintsbach a. Inn-“Rachelburg“	RO	Höhensiedlung („Rachelburg“)	Griffplattenmesser	BZ D2-Ha A1		Möslein 1998/99a, 216 Nr. 93 Abb. 5,7.
3	Flintsbach a. Inn-“Rachelburg“	RO	Höhensiedlung („Rachelburg“)	Griffdornmesser	Ha B2		Möslein 1998/99a, 219 Nr. 102 Abb. 6,6.
4	Flintsbach a. Inn-“Rachelburg“	RO	Höhensiedlung („Rachelburg“)	Griffdornmesser	Ha A1		Möslein 1998/99a, 219 Nr. 100 Abb. 6,4.
5	Flintsbach a. Inn-“Rachelburg“	RO	Höhensiedlung („Rachelburg“)	Griffplattenmesser	BZ D2-Ha A1		Möslein 1998/99a, 216 Nr. 94 Abb. 5,8.
6	Flintsbach a. Inn-“Rachelburg“	RO	Höhensiedlung („Rachelburg“)	Riegseemesser	BZ D		Möslein 1998/99a, 216 Nr. 89 Abb. 5,3.
7	Flintsbach a. Inn-“Rachelburg“	RO	Höhensiedlung („Rachelburg“)	Riegseemesser	BZ D2		Möslein 1998/99a, 216 Nr. 87 Abb. 5,1.
8	Flintsbach a. Inn-“Rachelburg“	RO	Höhensiedlung („Rachelburg“)	Lanzenspitze	Ha B1		Möslein 1998/99a, 206 Nr. 8 Abb. 1,10.
9	Flintsbach a. Inn-“Rachelburg“	RO	Höhensiedlung („Rachelburg“)	Oberständiges Lappenbeil	Ha B1		Möslein 1998/99a, 210 Nr. 52 Abb. 3,2.
10	Flintsbach a. Inn-“Rachelburg“	RO	Höhensiedlung („Rachelburg“)	Mittelständiges Lappenbeil	BZ D-Ha A1		Möslein 1998/99a, 210 Nr. 51 Abb. 3,1.
11	Flintsbach a. Inn-“Rachelburg“	RO	Höhensiedlung („Rachelburg“)	Armring mit Strichgruppenzier	BZ D		Möslein 1998/99a, 225 Nr. 135 Abb. 8,12.
12	Flintsbach a. Inn-“Rachelburg“	RO	Höhensiedlung („Rachelburg“)	Schwertspitze	BZ D		Möslein 1998/99a, 205 Nr. 2 Abb. 1,7.
13	Flintsbach a. Inn-“Rachelburg“	RO	Höhensiedlung („Rachelburg“)	Gusszapfen	?		Möslein 1998/99a, 230 Nr. 152 Abb. 9,6.
14	Flintsbach a. Inn-“Rachelburg“	RO	Höhensiedlung („Rachelburg“)	Schmaler Griffplattendolch	BZ C2		Möslein 1998/99a, 205 Nr. 4 Abb. 1,4.
15	Flintsbach a. Inn-“Rachelburg“	RO	Höhensiedlung („Rachelburg“)	Dolch mit schmaler Griffplatte	BZ D1		Möslein 1998/99a, 205 Nr. 6 Abb. 1,5.
16	Flintsbach a. Inn-“Rachelburg“	RO	Höhensiedlung („Rachelburg“)	Armring-Rohling (?)	BZ D-Ha A2?		Möslein 1998/99a, 230 Nr. 149 Abb. 9,1.
17	Flintsbach a. Inn-“Rachelburg“	RO	Höhensiedlung („Rachelburg“)	Griffdornmesser	BZ D2-Ha A1		Möslein 1998/99a, 219 Nr. 98 Abb. 6,2.
18	Flintsbach a. Inn-“Rachelburg“	RO	Höhensiedlung („Rachelburg“)	Rohling	?		Möslein 1998/99a, 230 Nr. 151 Abb. 9,3.
19/1	Flintsbach a. Inn-“Rachelburg“	RO	Höhensiedlung („Rachelburg“)	Gusskuchenfragm. (Probe 1)	?	2 Proben	Möslein 1998/99a, 230 Nr. 155.
19/2	Flintsbach a. Inn-“Rachelburg“	RO	Höhensiedlung („Rachelburg“)	Gusskuchenfragm. (Probe 2)	?	2 Proben	Möslein 1998/99a, 230 Nr. 155.
20/1	Flintsbach a. Inn-“Rachelburg“	RO	Höhensiedlung („Rachelburg“)	Gusskuchenfragm. (Probe 1)	?	2 Proben, feinpulvrig grau	Möslein 1998/99a, 230 Nr. 154 Abb. 9,11.
20/2	Flintsbach a. Inn-“Rachelburg“	RO	Höhensiedlung („Rachelburg“)	Gusskuchenfragm. (Probe 2)	?	2 Proben, feinpulvrig grau	Möslein 1998/99a, 230 Nr. 154 Abb. 9,11.
21	Flintsbach a. Inn-“Rachelburg“	RO	Höhensiedlung („Rachelburg“)	Gusskuchenfragment	?		Möslein 1998/99a, 230 Nr. 190 Abb. 9,10.
22	Flintsbach a. Inn-“Rachelburg“	RO	Höhensiedlung („Rachelburg“)	Gusskuchenfragment	?		Möslein 1998/99a, 230 Nr. 158.
23	Flintsbach a. Inn-“Rachelburg“	RO	Höhensiedlung („Rachelburg“)	Gusskuchenfragment	?		Möslein 1998/99a, 230 Nr. 159.
24	Flintsbach a. Inn-“Rachelburg“	RO	Höhensiedlung („Rachelburg“)	Gusskuchen	?		Möslein 1998/99a, 230 Nr. 157.
25	Flintsbach a. Inn-“Rachelburg“	RO	Höhensiedlung („Rachelburg“)	Gusskuchenfragment	?		Möslein 1998/99a, 230 Nr. 164-189.
26/1	Flintsbach a. Inn-“Rachelburg“	RO	Höhensiedlung („Rachelburg“)	Gusskuchenfragm. (Probe 1)	?	2 Proben, pulvrig grau	Möslein 1998/99a, 230 Nr. 162.
26/2	Flintsbach a. Inn-“Rachelburg“		Höhensiedlung („Rachelburg“)	Gusskuchenfragm. (Probe 2)	?	2 Proben, pulvrig grau	Möslein 1998/99a, 230 Nr. 162.
27	Flintsbach a. Inn-“Rachelburg“	RO	Höhensiedlung („Rachelburg“)	Gusskuchenfragment	?		Möslein 1998/99a, 230 Nr. 161.

Nr.	Fundort	Lkr./Bez.	Fundumstände	Objekt	Datierung	Bemerkung	Literatur
28/1	Flintsbach a. Inn-“Rachelburg“	RO	Höhensiedlung („Rachelburg“)	Gusskuchenfragm. (Probe 1)	?	2 Proben, pulvrig grau	Möslein 1998/99a, 230 Nr. 163.
28/2	Flintsbach a.Inn-“Rachelburg“		Höhensiedlung („Rachelburg“)	Gusskuchenfragm. (Probe 2)	?		Möslein 1998/99a, 230 Nr. 163.
29	Flintsbach a. Inn-“Rachelburg“	RO	Höhensiedlung („Rachelburg“)	Griffdornmesser	BZ D2-Ha A1		Möslein 1998/99a, 219 Nr. 99 Abb. 6,3.
31	Flintsbach a. Inn-“Rachelburg“	RO	Höhensiedlung („Rachelburg“)	Gusskuchenfragment	?		Möslein 1998/99a, 230 Nr. 156.
32	Flintsbach a. Inn-“Rachelburg“	RO	Höhensiedlung („Rachelburg“)	Gusskuchenfragment	?		Möslein 1998/99a, 230 Nr. 164-189.
33	Flintsbach a. Inn-“Rachelburg“	RO	Höhensiedlung („Rachelburg“)	Riegseemesser	BZ D2-Ha A1		Möslein 1998/99a, 116 Nr. 91 Abb. 5,5.
34	Flintsbach a. Inn-“Rachelburg“	RO	Höhensiedlung („Rachelburg“)	Riegseemesser	BZ D		Möslein 1998/99a, 216 Nr. 88 Abb. 5,2.
35	Flintsbach a. Inn-“Rachelburg“	RO	Höhensiedlung („Rachelburg“)	Griffdornmesser	Ha A1		Möslein 1998/99a, 219 Nr. 101 Abb. 6,5.
36	Flintsbach a. Inn-“Rachelburg“	RO	Höhensiedlung („Rachelburg“)	Schmaler Griffplattendolch	BZ D1		Möslein 1998/99a, 205 Nr. 5 Abb. 1,6.
37	Flintsbach a. Inn-Burgau	RO	Hortfund	Gusskuchenfragment	?		Möslein 1998/99a, 230 Nr. 153.
38	Flintsbach a. Inn-Burgau	RO	Hortfund	Gusskuchenfragment	?		Möslein 1998/99a, 230 Nr. 153.
39	Flintsbach a. Inn-Burgau	RO	Hortfund	Gusskuchenfragment	?		Möslein 1998/99a, 230 Nr. 153.
40/1	Flintsbach a. Inn-Burgau	RO	Hortfund	Gusskuchenfragm. (Unterseite)	?		Möslein 1998/99a, 230 Nr. 153.
40/2	Flintsbach a. Inn-Burgau	RO	Hortfund	Gusskuchenfragm. (Oberseite)	?		Möslein 1998/99a, 230 Nr. 153.
41	Flintsbach a. Inn-Burgau	RO	Hortfund	Gusskuchenfragment	?		Möslein 1998/99a, 230 Nr. 153.
42	Flintsbach a. Inn-Burgau	RO	Hortfund	Gusskuchenfragment	?		Möslein 1998/99a, 230 Nr. 153.
43	Flintsbach a. Inn-Burgau	RO	Hortfund	Gusskuchenfragment	?		Möslein 1998/99a, 230 Nr. 153.
44	Flintsbach a. Inn-Burgau	RO	Hortfund	Gusskuchenfragment	?		Möslein 1998/99a, 230 Nr. 153.
45	Flintsbach a. Inn-Burgau	RO	Hortfund	Gusskuchenfragment	?		Möslein 1998/99a, 230 Nr. 153.
46	Flintsbach a. Inn-Burgau	RO	Hortfund	Gusskuchenfragment	?		Möslein 1998/99a, 230 Nr. 153.
47	Flintsbach a. Inn-Burgau	RO	Hortfund	Gusskuchenfragment	?		Möslein 1998/99a, 230 Nr. 153.
48	Flintsbach a. Inn-Burgau	RO	Hortfund	Gusskuchenfragment	?		Möslein 1998/99a, 230 Nr. 153.
49	Flintsbach a. Inn-Burgau	RO	Hortfund	Gusskuchenfragment	?		Möslein 1998/99a, 230 Nr. 153.
50	Flintsbach a. Inn-Burgau	RO	Hortfund	Gusskuchenfragment	?		Möslein 1998/99a, 230 Nr. 153.
51	Flintsbach a. Inn-Burgau	RO	Hortfund	Gusskuchenfragment	?		Möslein 1998/99a, 230 Nr. 153.
52	Flintsbach a. Inn-Burgau	RO	Hortfund	Gusskuchenfragment	?		Möslein 1998/99a, 230 Nr. 153.
53	Flintsbach a. Inn-Burgau	RO	Hortfund	Gusskuchenfragment	?		Möslein 1998/99a, 230 Nr. 153.
54	Flintsbach a. Inn-Burgau	RO	Hortfund	Gusskuchenfragment	?		Möslein 1998/99a, 230 Nr. 153.
55	Flintsbach a. Inn-Burgau	RO	Hortfund	Gusskuchenfragment	?		Möslein 1998/99a, 230 Nr. 153.
56	Flintsbach a. Inn-Burgau	RO	Hortfund	Gusskuchenfragment	?		Möslein 1998/99a, 230 Nr. 153.

Nr.	Fundort	Lkr./Bez.	Fundumstände	Objekt	Datierung	Bemerkung	Literatur
57	Flintsbach a. Inn-Burgau	RO	Hortfund	Gusskuchenfragment	?		Möslein 1998/99a, 230 Nr. 153.
58	Flintsbach a. Inn-Burgau	RO	Hortfund	Gusskuchenfragment	?		Möslein 1998/99a, 230 Nr. 153.
59	Flintsbach a. Inn-Burgau	RO	Hortfund	Gusskuchenfragment	?		Möslein 1998/99a, 230 Nr. 153.
60	Flintsbach a. Inn-Burgau	RO	Hortfund	Gusskuchenfragment	?		Möslein 1998/99a, 230 Nr. 153.
61	Flintsbach a. Inn-Burgau	RO	Hortfund	Gusskuchenfragment	?		Möslein 1998/99a, 230 Nr. 153.
62	Flintsbach a. Inn-Burgau	RO	Hortfund	Gusskuchenfragment	?	Sehr hart	Möslein 1998/99a, 230 Nr. 153.
63	Flintsbach a. Inn-Burgau	RO	Hortfund	Gusskuchenfragment	?		Möslein 1998/99a, 230 Nr. 153.
64	Flintsbach a. Inn-Burgau	RO	Hortfund	Gusskuchenfragment	?	2 Bohrungen	Möslein 1998/99a, 230 Nr. 153.
65	Flintsbach a. Inn-Burgau	RO	Hortfund	Gusskuchenfragment	?	sehr viele Hohlräume	Möslein 1998/99a, 230 Nr. 153.
66	Flintsbach a. Inn-Burgau	RO	Hortfund	Gusskuchenfragment	?		Möslein 1998/99a, 230 Nr. 153.
67	Flintsbach a. Inn	RO	Hortfund	Gusskuchen	Ha A2-B1	oben metallisch, unten spröde, grau bis rotbraun	Möslein 1998/99b, 341 ff. Abb. 7-9.
68	Flintsbach a. Inn	RO	Hortfund	Gusskuchen	Ha A2-B1	2 Bohrungen	Möslein 1998/99b, 341 ff. Abb. 7-9.
69	Flintsbach a. Inn	RO	Hortfund	Gusskuchen	Ha A2-B1	2 Bohrungen; sehr spröde	Möslein 1998/99b, 341 ff. Abb. 7-9.
70	Flintsbach a. Inn	RO	Hortfund	Gusskuchen	Ha A2-B1	5 ältere Bohrlöcher (Klonk)	Möslein 1998/99b, 341 ff. Abb. 7-9.
71	Flintsbach a. Inn	RO	Hortfund	Gusskuchen	Ha A2-B1	4 ältere Bohrlöcher (Klonk)	Möslein 1998/99b, 341 ff. Abb. 7-9.
72	Flintsbach a. Inn	RO	Hortfund	Gusskuchen	Ha A2-B1	sehr spröde	Möslein 1998/99b, 341 ff. Abb. 7-9.
73	Flintsbach a. Inn	RO	Hortfund	Gusskuchen	Ha A2-B1	2 Bohrungen; sehr spröde	Möslein 1998/99b, 341 ff. Abb. 7-9.
74	Flintsbach a. Inn	RO	Hortfund	Radanhängerfragment	Ha A2-B1(?)		Möslein 1998/99b, 341 ff. Abb. 8.
75	Flintsbach a. Inn	RO	Hortfund	Gusskuchen	Ha A2-B1	5 ältere Bohrungen (Klonk)	Möslein 1998/99b, 341 ff. Abb. 7-9.
76	Flintsbach a. Inn	RO	Hortfund	Gusskuchen	Ha A2-B1		Möslein 1998/99b, 341 ff. Abb. 7-9.
77	Flintsbach a. Inn	RO	Hortfund	Gusskuchen	Ha A2-B1		Möslein 1998/99b, 341 ff. Abb. 7-9.
78	Flintsbach a. Inn	RO	Hortfund	Gusskuchen	Ha A2-B1		Möslein 1998/99b, 341 ff. Abb. 7-9.
79/1	Grassau-Klaus	TS	Sondenfunde (Depot?)	Gusskuchenfragm. (Probe 1)	?	oben metallisch, unten blasig	BVBl. Beih. 10 (München 1997) 88.
79/2	Grassau-Klaus	TS	Sondenfunde (Depot?)	Gusskuchenfragm. (Probe 2)	?	oben metallisch, darunter blasig	BVBl. Beih. 10 (München 1997) 88.
80	Grassau-Klaus	TS	Sondenfunde (Depot?)	Gusskuchenfragment	?	2 Bohrungen	BVBl. Beih. 10 (München 1997) 88.
81	Aschau-Hohenaschau	RO	Hortfund	Gusskuchenfragment	Ha B1	reines Metall, weiches Kupfer	BVBl. Beih. 10 (München 1997) 86.
82	Aschau-Hohenaschau	RO	Hortfund	Gusskuchenfragment	Ha B1	reines Metall, weiches Kupfer	BVBl. Beih. 10 (München 1997) 86.
83	Aschau-Hohenaschau	RO	Hortfund	Gusskuchenfragment	Ha B1		BVBl. Beih. 10 (München 1997) 86.
84	Rimsting-Zacking	RO	Einzelfund (Metallsonde)	Gusskuchenfragment	?	überwiegend pulvrig grau	BVBl. Beih. 9 (München 1996) 113.
85	Prien-Mühltal	RO	Einzelfund	Gusskuchenfragment?	?		Unpubliziert.

Nr.	Fundort	Lkr./Bez.	Fundumstände	Objekt	Datierung	Bemerkung	Literatur
86	Kraiburg a. Inn-Ensdorf	MÜ	Einzelfund	Gusskuchenfragment	?		Unpubliziert.
87	Kraiburg a. Inn-Ensdorf	MÜ	Hortfund?	Gusskuchenfragment	?		Unpubliziert.
88	Kraiburg a. Inn-Ensdorf	MÜ	Hortfund?	Gusskuchenfragment	?	2 Bohrungen	Unpubliziert.
89	Kraiburg a. Inn-Ensdorf	MÜ	Hortfund?	Gusskuchenfragment	?		Unpubliziert.
90	Kraiburg a. Inn	MÜ	Hortfund?	Gusskuchenfragment	?		Unpubliziert.
91	Flintsbach a. Inn-Erlach	RO	Einzelfund	Gusskuchenfragment	?		BVBl. Beih. 10 (München 1997) 87.
92	Aschau-Innerkoy	RO	Einzelfund	Gusskuchenfragment	?		BVBl. Beih. 10 (München 1997) 86.
93	Unterbrunner Forst	STA	Einzelfund	Gusskuchen	?		BVBl. Beih. 11 (München 1998) 208 Abb. 110,7.
95	Altenmarkt a. d. Alz-Baumburg	TS	Einzelfund	Gusskuchenfragment	?		Unpubliziert.
96	Feldkirchen-Westerham - Vagen	RO	Einzelfund	Gusskuchen?	?		Unpubliziert.
97	Grünwalder Forst	M	Hortfund	Gusskuchenfragment	BZ C2		BVBl. Beih. 11 (München 1998) 80 Abb. 50,5.
98	Grünwalder Forst	M	Hortfund	Gusskuchenfragment	BZ C2		BVBl. Beih. 11 (München 1998) 80.
99	Grünwalder Forst	M	Hortfund	Gusskuchenfragment	BZ C2		BVBl. Beih. 11 (München 1998) 80.
100	Grünwalder Forst	M	Hortfund	Gusskuchenfragment	BZ C2		BVBl. Beih. 11 (München 1998) 80.
101	Grünwalder Forst	M	Hortfund	Steckamboß	BZ C2		BVBl. Beih. 11 (München 1998) 80 Abb. 50,3.
102	Grünwalder Forst	M	Hortfund	Meißelfragment	BZ C2		BVBl. Beih. 11 (München 1998) 80 Abb. 50,2.
103	Grünwalder Forst	M	Hortfund	Sichelfragment	BZ C2		BVBl. Beih. 11 (München 1998) 80 Abb. 50,1.
104	Grünwalder Forst	M	Hortfund	Verziertes Blechfragment	BZ C2		BVBl. Beih. 11 (München 1998) 80 Abb. 50,4.
105	Ingolstadt-Zuchering	IN	Grab 70	Griffangelmesser	Ha A2		Schütz 2006, 96 Taf. 39,1.
106	Ingolstadt-Zuchering	IN	Grab 106	Felgenniet	Ha B3		Schütz 2006, 107 f. Taf. 51,12.
107	Ingolstadt-Zuchering	IN	Grab 106	Griffdornmesser	Ha B3		Schütz 2006, 107 f. Taf. 51,9.
108	Ingolstadt-Zuchering	IN	Grab 136	Griffplattenmesser	BZ D		Schütz 2006, 119 ff. Taf. 67,2.
109	Ingolstadt-Zuchering	IN	Grab 24	Griffdornmesser	Ha A2	verbrannt	Schütz 2006, 75 ff. Taf. 12,6.
110	Ingolstadt-Zuchering	IN	„Grab" 63A (Grabdepot)	Muffe	BZ D		Schütz 2006, 90 f. Taf. 33,3.
111	Ingolstadt-Zuchering	IN	Grab 192	Griffplattenmesser	BZ D	verbrannt	Schütz 2006, 157 ff. Taf. 107,6.
112	Manching	PAF	Grabfund 1995	Griffdornmesser	Ha A2		Unpubliziert.
113	Münchsmünster	PAF	Wagengrab	Trensenknebel	BZ D2		Schütz-Tillmann 1997, Abb. 3,3.
114	Münchsmünster	PAF	Wagengrab	Trensenknebel	BZ D2	überwiegend pulvrig rotbraun	Schütz-Tillmann 1997, Abb. 3,2.
115	Münchsmünster	PAF	Wagengrab	Trensenknebel	BZ D2		Schütz-Tillmann 1997, Abb. 3,4.
116	Münchsmünster	PAF	Wagengrab	Trensenknebel	BZ D2	Endknopf abgebrochen	Schütz-Tillmann 1997, Abb. 3,5.

Nr.	Fundort	Lkr./Bez.	Fundumstände	Objekt	Datierung	Bemerkung	Literatur
117	Münchsmünster	PAF	Wagengrab	Lanzenspitze	BZ D2		Schütz-Tillmann 1997, Abb. 3,1.
118	Münchsmünster	PAF	Wagengrab	Aufsatzstange	BZ D2		Schütz-Tillmann 1997, Abb. 5,6.
119	Münchsmünster	PAF	Wagengrab	Aufsatzstange	BZ D2		Schütz-Tillmann 1997, Abb. 5,4.
120	Münchsmünster	PAF	Wagengrab	Nagel	BZ D2		Schütz-Tillmann 1997, Abb. 7,8.
121	Münchsmünster	PAF	Wagengrab	Tüllenhorn mit Aufsatz	BZ D2		Schütz-Tillmann 1997, Abb. 5,1.
122	Münchsmünster	PAF	Wagengrab	Kräftiger Bügel	BZ D2		Schütz-Tillmann 1997, Abb. 7,7.
123/G	Aufhausen-Gansbach	R		Vollgriffschwert Typ Riegsee	BZ D	Griff	v. Quillfeldt 1995, 117 Nr. 115 Taf. 39,115.
123/K	Aufhausen-Gansbach	R		Vollgriffschwert Typ Riegsee	BZ D	Klinge	v. Quillfeldt 1995, 117 Nr. 115 Taf. 39,115.
124/G	Forstmühler Forst	R	Hortfund	Achtkantschwert	BZ C2	Griff	v. Quillfeldt 1995, 48 Nr. 22 Taf. 8,22.
124/K	Forstmühler Forst	R	Hortfund	Achtkantschwert	BZ C2	Klinge	v. Quillfeldt 1995, 48 Nr. 22 Taf. 8,22.
125	Mintraching	R	Hortfund	Beil	BZ D2		Torbrügge 1959a, 205 Nr. 321 Taf. 69,*.
126	Mintraching	R	Hortfund	Beilfragment	BZ D2		Torbrügge 1959a, 205 Nr. 321 Taf. 69,*.
127/G	Barbing	R	Flußfund	Vollgriffschwert Typ Riegsee	BZ D	Griff	v. Quillfeldt 1995, 115 Nr. 107 Taf. 36,107.
127/K	Barbing	R	Flußfund	Vollgriffschwert Typ Riegsee	BZ D	Klinge	v. Quillfeldt 1995, 115 Nr. 107 Taf. 36,107.
128	Wenzenbach-Abbachhof	R	Grabhügel 2	Beil	BZ C		Torbrügge 1959a, 193 Nr. 269 Taf. 55,13.
129	Wenzenbach-Abbachhof	R	Grabhügel 2	Dolch	BZ C		Torbrügge 1959a, 193 Nr. 269 Taf. 55,14.
130	Regenstauf-Hagenau	R	Grabhügel („Häuptlingsgrab“)	Beil	BZ C2		Stary 1980, 78 Taf. 3,3.
131	Regenstauf-Hagenau	R	Grabhügel („Häuptlingsgrab“)	Kleines meißelartiges Gerät	BZ C2		Stary 1980, 78 Taf. 3,7.
132	Regenstauf-Hagenau	R	Grabhügel („Häuptlingsgrab“)	Kleines punzenartiges Gerät	BZ C2		Stary 1980, 78 Taf. 3,5.
133	Regenstauf-Hagenau	R	Grabhügel („Häuptlingsgrab“)	Kleines meißelartiges Gerät	BZ C2		Stary 1980, 78 Taf. 3,6.
134	Regenstauf-Hagenau	R	Grabhügel („Häuptlingsgrab“)	Nadel	BZ C2		Stary 1980, 77 Taf. 2,1.
135	Regenstauf-Hagenau	R	Grabhügel („Häuptlingsgrab“)	Dolch	BZ C2		Stary 1980, 76 Taf. 1,5.
136	Regenstauf-Hagenau	R	Grabhügel („Häuptlingsgrab“)	Kurzschwert	BZ C2		Stary 1980, 76 Taf. 1,4.
137	Regenstauf-Hagenau	R	Grabhügel („Häuptlingsgrab“)	Griffzungenschwert T. Asenkofen	BZ C2		Stary 1980, 76 Taf. 1,1.
138	Forstmühler Forst	R	Hortfund	Gusskuchenfragment	BZ C2		Torbrügge 1959a, 191 Nr. 261.
139	Forstmühler Forst	R	Hortfund	Gusskuchenfragment	BZ C2		Torbrügge 1959a, 191 Nr. 261.
140	Forstmühler Forst	R	Hortfund	Gusskuchenfragment	BZ C2		Torbrügge 1959a, 191 Nr. 261.
141/G	Regensburg	R	Flußfund	Achtkantschwert	BZ C2	Griff	v. Quillfeldt 1995, 74 Nr. 71 Taf. 23,71.
141/K	Regensburg	R	Flußfund	Achtkantschwert	BZ C2	Klinge	v. Quillfeldt 1995, 74 Nr. 71 Taf. 23,71.
142/G	Regensburg	R	Flußfund	Achtkantschwert	BZ C2	Griff	v. Quillfeldt 1995, 64 Nr. 57 Taf. 19,57.

Nr.	Fundort	Lkr./Bez.	Fundumstände	Objekt	Datierung	Bemerkung	Literatur
142/K	Regensburg	R	Flußfund	Achtkantschwert	BZ C2	Klinge	v. Quillfeldt 1995, 64 Nr. 57 Taf. 19,57.
143/G	Barbing („Sarching“)	R	Hortfund	Vollgriffschwert	BZ D1	Griff	v. Quillfeldt 1995, 97 Nr. 75 Taf. 24,75.
143/K	Barbing („Sarching“)	R	Hortfund	Vollgriffschwert	BZ D1	Klinge	v. Quillfeldt 1995, 97 Nr. 75 Taf. 24,75.
144	Barbing („Sarching“)	R	Hortfund	Beilfragment	BZ D1		Torbrügge 1959a, 207 Nr. 333 Taf. 70,4.
145	Barbing („Sarching“)	R	Hortfund	Sichel	BZ D1		Torbrügge 1959a, 207 Nr. 333 Taf. 70,11
146	Barbing („Sarching“)	R	Hortfund	Gusskuchenfragment	BZ D1		Torbrügge 1959a, 207 Nr. 333).
147	Barbing („Sarching“)	R	Hortfund	Gusskuchenfragment	BZ D1		Torbrügge 1959a, 207 Nr. 333).
148	Barbing („Sarching“)	R	Hortfund	Gusskuchenfragment	BZ D1		Torbrügge 1959a, 207 Nr. 333).
149	Barbing („Sarching“)	R	Hortfund	Gusskuchenfragment	BZ D1		Torbrügge 1959a, 207 Nr. 333).
150	Mintraching	R	Grabfund (Grab 1)	Griffzungenschwert T. Riedheim	BZ D		Hennig 1993, Nr. 16 Taf. 48,8.
151	Marquartstein-Piesenhausen	TS	Höhensiedlung (?) „Aggbichel“	Griffzungenmesser	Ha A2		BVBl. Beih. 12 (München 1999) 85.
152	Marquartstein-Piesenhausen	TS	Hortfund auf dem „Aggbichel“	Gusskuchenfragment	?		BVBl. Beih. 12 (München 1999) 85.
153	Marquartstein-Piesenhausen	TS	Hortfund auf dem „Aggbichel“	Gusskuchenfragment	?		BVBl. Beih. 12 (München 1999) 85.
154	Marquartstein-Piesenhausen	TS	Hortfund auf dem „Aggbichel“	Gusskuchenfragment	?		BVBl. Beih. 12 (München 1999) 85.
155	Marquartstein-Piesenhausen	TS	Höhensiedlung (?) „Aggbichel“	Gusskuchenfragment	?		OA BLfD München.
156	Marquartstein-Piesenhausen	TS	Höhensiedlung (?) „Aggbichel“	Gusskuchenfragment	?	sehr spröde, silbrig-grau	OA BLfD München.
157	Marquartstein-Piesenhausen	TS	Höhensiedlung (?) „Aggbichel“	Gusskuchenfragment	?		OA BLfD München.
158	Marquartstein-Wuhrbichl	TS	Streufund auf dem „Wuhrbichl“	Oberst. Lappenbeil mit Öse	Ha B3		BVBl. Beih. 12 (München 1999) 85.
159	Marquartstein-Wuhrbichl	TS	Streufund auf dem „Wuhrbichl“	Mittelständiges Lappenbeil	Ha A2		BVBl. Beih. 12 (München 1999) 85.
160	Marquartstein-Wuhrbichl	TS	Streufund auf dem „Wuhrbichl“	Griffplattendolch	BZ C		BVBl. Beih. 12 (München 1999) 85.
161/K	Bad Reichenhall-Nonn	BGL	Einzelfund	Griffplattendolch	BZ B	Klinge	BVBl. Beih. 12 (München 1999) 67.
161/N	Bad Reichenhall-Nonn	BGL	Einzelfund	Griffplattendolch	BZ B	Niet	BVBl. Beih. 12 (München 1999) 67.
162	Marquartstein-Nock	TS	Einzelfund	Griffdornmesser	Ha B2		Hohlbein 2016, 345 Nr. 1280 Taf. 111,1280.
163	Grassau-Klaus	TS	Sondenfunde (Depot?)	Gusskuchenfragment	?	2 Bohrungen	BVBl. 10 (München 1997) 88.
164	Grassau-Fahrnpoint	TS	Einzelfund (Metallsonde)	Gusskuchenfragment	?		BVBl. Beih. 12 (München 1999) 69.
165	Schleching-Streichen	TS	Hortfund	Meißel	Ha B2		BVBl. Beih. 11 (München 1998) 98.
166	Schleching-Streichen	TS	Hortfund	Sichel	Ha B2		BVBl. Beih. 11 (München 1998) 98.
167	Moosburg a. d. Isar-Aich	FS	Aus zerstörten Gräbern	Schwertklingenfragment	Ha B3		BVBl. Beih. 2 (München 1988) 86 Abb. 62,3.
168	Bergkirchen-Feldgeding	DAH	Grab 4 (Urnengrab)	Messer	Ha B3		Müller-Karpe 1957, Taf. 49,E 2.
169/G	Bergkirchen-Feldgeding	DAH	Grab 4 (Urnengrab)	Vollgriffschwert Typ Mörigen	Ha B3	Griff	v. Quillfeldt 1995, 240 Nr. 278 Taf. 99,278.

Nr.	Fundort	Lkr./Bez.	Fundumstände	Objekt	Datierung	Bemerkung	Literatur
169/K	Bergkirchen-Feldgeding	DAH	Grab 4 (Urnengrab)	Vollgriffschwert Typ Mörigen	Ha B3	Klinge	v. Quillfeldt 1995, 240 Nr. 278 Taf. 99,278.
170	Edling-Allmannsberg	RO	Grabfund	Griffzungenmesser Typ Mühlau	BZ D2-Ha A1		Hohlbein 2016, 159 Nr. 352 Taf. 31,352.
171	Bergkirchen-Feldgeding	DAH	Grabfund (Urnengrab)	Zwiebelkopfnadel	Ha B2		Müller-Karpe 1957, Taf. 49,D 1.
172	Garching-Dirnismaning	M	Körpergrab	Griffplattendolch	BZ B		Koschik 1981a, 168 Nr. 74 Taf. 32,3
173	Feldafing-Wörth	STA	Roseninsel	Messer	Ha B2		Müller-Karpe 1959, Taf. 192,B 11.
174	Feldafing-Wörth	STA	Roseninsel	Messer	Ha B2		Müller-Karpe 1959, Taf. 192,B 13.
175	Grünwald	M	Grab 16 (Urnengrab)	Messer	Ha A1		Müller-Karpe 1957, Taf. 9,A 2.
176/G	Pliening	EBE	Einzelfund	Vollgriffschwert Typ Högl	Ha A2	Griff	v. Quillfeldt 1995, 174 Nr. 168 Taf. 58,168.
176/K	Pliening	EBE	Einzelfund	Vollgriffschwert Typ Högl	Ha A2	Klinge	v. Quillfeldt 1995, 174 Nr. 168 Taf. 58,168.
177	München-Obermenzing	M	Grab 7 (Urnengrab)	Armringfragment	Ha B2		Müller-Karpe 1957, Taf. 4,E 3.
178	Riegsee-Leibersberg I	GAP	Grabhügel 37	Randleistenbeil	BZ C1		Koschik 1981a, 214 ff. Nr. 204 Taf. 109,7.
179	Unterhaching	M	Grab 78 (Urnengrab)	Griffdornmesser	Ha A2		Müller-Karpe 1957, Taf. 29,A 2.
180	Reichersbeuern	TÖL	Einzelfund (Fundort unsicher)	Absatzbeil	BZ C		Koschik 1981a, 148 Nr. 8 Taf. 2,8.
181/G	Rohrdorf-Geiging	RO	Fund 1979	Vollgriffschwert Typ Gundelsheim	Ha A1	Griff	v. Quillfeldt 1995, 150 Nr. 145 Taf. 49,145.
181/K	Rohrdorf-Geiging	RO	Fund 1979	Vollgriffschwert Typ Gundelsheim	Ha A1	Klinge	v. Quillfeldt 1995, 150 Nr. 145 Taf. 49,145.
182/G	München-Englschalking	M	Einzelfund	Achtkantschwert	BZ C2	Griff	v. Quillfeldt 1995, 61 Nr. 53 Taf. 17,53.
182/K	München-Englschalking	M	Einzelfund	Achtkantschwert	BZ C2	Klinge	v. Quillfeldt 1995, 61 Nr. 53 Taf. 17,53.
183/G	Tutzing-Traubing	STA	Hügel 1 (Brandgrab)	Achtkantschwert	BZ C2	Griff	v. Quillfeldt 1995, 72 Nr. 62 Taf. 21,62.
183/K	Tutzing-Traubing	STA	Hügel 1 (Brandgrab)	Achtkantschwert	BZ C2	Klinge	v. Quillfeldt 1995, 72 Nr. 62 Taf. 21,62.
184/G	Vilgertshofen-Pflugdorf	LL	Moor- oder Feuchtbodenfund	Achtkantschwert	BZ C2	Griff	v. Quillfeldt 1995, 53 Nr. 34 Taf. 12,34.
184/G	Vilgertshofen-Pflugdorf	LL	Moor- oder Feuchtbodenfund	Achtkantschwert	BZ C2	Klinge	v. Quillfeldt 1995, 53 Nr. 34 Taf. 12,34.
185	Bayerisch-Gmain	BGL	Aus zerstörten Gräbern	Messer	Ha B2		Hohlbein 2016, 334 Nr. 1229 Taf. 105,1229.
186	Bayerisch-Gmain	BGL	Aus zerstörten Gräbern	Messer	Ha B3		Hohlbein 2016, 330 Nr. 1191 Taf. 101,1191.
187	Burgkirchen a. d. Alz-Höhlen	AÖ	Grabhügel	Mittelständiges Lappenbeil	BZ C2		Pászthory/Mayer 1998, 120 Nr. 686 Taf. 47,686.
188	Bad Reichenhall-Eisenbichler	BGL	Einzeldeponierung	Griffzungendolch	BZ C2		Chlingensperg 1904, 69 Taf. 7,19.
189	Bad Reichenhall-Marzoll	BGL	Grab 1 (Brandgrab)	Griffdornmesser	Ha A1		Hell 1948, 28 Abb. 5a, 5.
190	Ainring-Au	BGL	Einzelfund von feuchtem Grund	Vollgriffmesser	BZ D		Hohlbein 2016, 42 Nr. 21 Taf. 3,21.
191	Bad Reichenhall-Karlstein	BGL	Hortfund in HW XIX	Sichelfragment	Ha B2		Möslein 1996, Kat. 59 ff. Nr. 90 Taf. 158,19.
192	Bad Reichenhall-Karlstein	BGL	Hortfund in HW XIX	Sichel	Ha B2		Möslein 1996, Kat. 59 ff. Nr. 90 Taf. 158,20.
193	Bad Reichenhall-Karlstein	BGL	Hortfund in HW XIX	Stabförmiger Meißel	Ha B2		Möslein 1996, Kat. 59 ff. Nr. 90 Taf. 158,18.

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194	Saaldorf-Brünnthal	BGL	Einzelfund aus zerstörtem Grab	Schwer gerippter Armring	BZ D		Möslein 1996, Kat. 114 Nr. 140 Taf. 222,3.
195	Manching	PAF	Grabfund	Rasiermesserfragment	Ha A1		Müller-Karpe 1959, Taf. 197,D.
196	Hienheimer Forst	KEH	Hortfund	Randleistenbeil	BZ B-C1		Hochstetter 1980, 130 Nr. 104 Taf. 38,7.
197	Hienheimer Forst	KEH	Hortfund	Randleistenbeil	BZ B-C1		Hochstetter 1980, 130 Nr. 104 Taf. 38,6.
198	Hienheimer Forst	KEH	Brandgrab?	Dolch	BZ C2		Hochstetter 1980, 130 Nr. 105 Taf. 39,2.
199	Kastl-Trenkermühle	AÖ	Flußfund	Griffzungenschwert ähnl. T. Traun	BZ C2-D		Schauer 1971, 123 Nr. 378 Taf. 55,378.
200/G	Aschau a. Inn-Klugham	MÜ	Flußfund	Vollgriffschwert Typ Riegsee	MBZ	Griff	v. Quillfeldt 1995, 114 Nr. 104 Taf. 35,104.
200/K	Aschau a. Inn-Klugham	MÜ	Flußfund	Vollgriffschwert Typ Riegsee	BZ D	Klinge	v. Quillfeldt 1995, 114 Nr. 104 Taf. 35,104.
201	Polling-Ehring	MÜ	Flußfund	Griffzungenschwert Typ Traun	BZ D	sehr kleine Ausführung	Schauer 1971, 120 Nr. 359 Taf. 53,359.
202/G	Bad Reichenhall-Langacker	BGL	Grabfund	Vollgriffschwert Einzelform	Ha A2	Griff	v. Quillfeldt 1995, 173 Nr. 167 Taf. 58,167.
202/K	Bad Reichenhall-Langacker	BGL	Grabfund	Vollgriffschwert Einzelform	Ha A2	Klinge	v. Quillfeldt 1995, 173 Nr. 167 Taf. 58,167.
203	Eggstätt	RO	Moorfund?	Griffzungenschwert T. Asenkofen	BZ C2		BVBl. Beih. 4 (München 1991) 62 Abb. 36,2.
204	Chieming	TS	Einzelfund (Moorfund?)	Tüllenmesser	Ha A2		Hohlbein 2016, 51 Nr. 33 Taf. 5,33.
205	Altenmarkt a. d. Alz	TS	Einzelfund	Vasenkopfnadel m.Winkelfurchen	BZ D2-Ha A1		Maier o. J., 29 Taf. 6.
206	Tacherting	TS	Flußfund, Depot mit Beil?	Armring Typ Homburg	Ha B3		Maier o. J. m. Abb.
207	Tacherting	TS	Flußfund, Depot mit Ring?	Oberst. Lappenbeil mit Öse	Ha B3		Pászthory/Mayer 1998, 138 Nr. 856 Taf.60,856.
208	Trostberg-Getzing	TS	Brandgrab 1	Tüllenbeil	BZ D2		Pászthory/Mayer 1998, 152 Nr. 1022 Taf. 69,1022.
209	Trostberg-Getzing	TS	Brandgrab 1	Griffzungenmesser	BZ D2		Hohlbein 2016, 158 Nr. 347 Taf. 30,347.
210	Prien a. Chiemsee	RO	Grab- oder Hortfund	Lanzenspitze	Ha A1		Torbrügge 1959b, Nr. 107, Taf. 10,2.
211	Prien a. Chiemsee	RO	Grab- oder Hortfund	Griffzungenschwert	Ha A1		Schauer 1971, 165 Nr. 491 Taf. 73,491.
212	Prien a. Chiemsee	RO	Grab- oder Hortfund?	Lanzenspitze	Ha A1		Müller-Karpe 1959, Taf. 197,L 1.
213	Fridolfing	TS	Hortfund	Tüllenmeißel	Ha B2		Koschik 1981b, Abb. 4,1.
214	Fridolfing	TS	Hortfund	Griffdornmesser	Ha B2		Koschik 1981b, Abb. 4,4.
215	Fridolfing	TS	Hortfund	Posamenteriefibel	Ha B2	Manschette	Koschik 1981b, Abb. 1,2.
216	Chiemsee-Herrenchiemsee	RO	Einzelfund	Armring mit Strichgruppenzier	Ha B2		Müller-Karpe 1959, Taf. 141,B.
217	Aschau-Weidachwies	RO	Hortfund	Zungensichel	BZ D2-Ha A1		Nagler-Zanier 2010, 36 Nr. 18 Abb. 5,18.
218	Aschau-Weidachwies	RO	Hortfund	Zungensichel	BZ D2-Ha A1		Nagler-Zanier 2010, 36 Nr. 21 Abb. 5,21.
219	Aschau-Weidachwies	RO	Hortfund	Vasenkopfnadel	BZ D2-Ha A1		Nagler-Zanier 2010, 33 Nr. 1 Abb. 3,1.
220	Aschau-Weidachwies	RO	Hortfund	Zungensichel	BZ D2-Ha A1		Nagler-Zanier 2010, 36 Nr. 22 Abb. 6,22.
221	Aschau-Weidachwies	RO	Hortfund	Zungensichel	BZ D2-Ha A1		Nagler-Zanier 2010, 36 Nr. 19 Abb. 5,19.

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222	Aschau-Weidachwies	RO	Hortfund	Gusskuchen	BZ D2-Ha A1		Nagler-Zanier 2010, 38 Nr. 30 Abb. 7,30.
223	Aschau-Weidachwies	RO	Hortfund	Gusskuchenfragment	BZ D2-Ha A1		Nagler-Zanier 2010, 38 Nr. 31 Abb. 7,31.
224/G	Fridolfing	TS	Brandgrab	Vollgriffschwert Typ Riegsee	BZ D	Griff	v. Quillfeldt 1995, 117 f. Nr. 117 Taf. 39,117.
224/K	Fridolfing	TS	Brandgrab	Vollgriffschwert Typ Riegsee	BZ D	Klinge	v. Quillfeldt 1995, 117 f. Nr. 117 Taf. 39,117.
225/G	Rohrdorf-Geiging	RO	Urnengrab 1922	Vollgriffschwert Typ Illertissen	Ha A1	Griff	v. Quillfeldt 1995, 160 f. Nr. 155 Taf. 53,155.
225/K	Rohrdorf-Geiging	RO	Urnengrab 1922	Vollgriffschwert Typ Illertissen	Ha A1	Klinge	v. Quillfeldt 1995, 160 f. Nr. 155 Taf. 53,155.
226	Otzing-Arndorf	DEG	Grabfund	Messer	Ha B3		Schmotz 1989,142 Taf. 5,E 3 („Haunersdorf“).
227	Wallersdorf-Moosfürth	DGF	Einzelfund	Messer	BZ D		Hochstetter 1980, 125 Nr. 87 Taf. 24,1.
228	Barbing	R	Grab 63	Gusskuchenfragment	Ha A2	oben metallisch, unten pulvrig grau	Hennig 1993, 84 Taf. 45,20.21.
229	Riekofen-Taimering	R	Grab 28	Messer	Ha A1		Hennig 1993, Nr. 29 Taf. 85,1.
230	Moos-Langenisarhofen	DEG	Siedlungsfund?	Messer	BZ D		Hochstetter 1980, 115 Nr. 30 Taf. 12,7.
231	Pfatter-Geisling/ Leiterkofen	R	Grab 10	Messer	Ha B2		Hennig 1993, Nr. 25 Taf. 64,4.
232	Bad Reichenhall-Nonn	BGL	Einzelfund	Riegseemesser	BZ D		Hohlbein 2016, 105 Nr. 189 Taf. 20,189.
233	Staudach-Egerndach	TS	Einzelfund	Griffdornmesser	Ha A1		Hohlbein 2016, 208 Nr. 526 Taf. 46,526.
234	Flintsbach a. Inn-“Rachelburg“	RO	Höhensiedlung („Rachelburg“)	Gewicht (?)	BZ D		Möslein 1998/99a, 229 Nr. 148 Abb. 9,7.
235	Flintsbach a. Inn-“Rachelburg“	RO	Höhensiedlung („Rachelburg“)	Nadel	BZ D2	rotbraun, pulvrig	Möslein 1998/99a, 222 Nr. 121 Abb. 7,7.
236	Flintsbach a. Inn-“Rachelburg“	RO	Höhensiedlung („Rachelburg“)	Nadel	BZ D2		Möslein 1998/99a, 222 Nr. 120 Abb. 7,8.
237	Flintsbach a. Inn-“Rachelburg“	RO	Höhensiedlung („Rachelburg“)	Nadel	BZ D2-Ha A1	Nadelkopf	Möslein 1998/99a, 222 Nr. 122 Abb. 7,5.
238	Flintsbach a. Inn-“Rachelburg“	RO	Höhensiedlung („Rachelburg“)	Nadel	BZ D2-Ha A1	Nadelkopf	Möslein 1998/99a, 222 Nr. 124 Abb. 7,1.
239	Flintsbach a. Inn-“Rachelburg“	RO	Höhensiedlung („Rachelburg“)	Nadel	BZ D2-Ha A1	Nadelkopf	Möslein 1998/99a, 222 Nr. 123 Abb. 7,4.
240	Flintsbach a. Inn-“Rachelburg“	RO	Höhensiedlung („Rachelburg“)	Nadel	Ha B1		Möslein 1998/99a, 222 Nr. 127 Abb. 7,10.
241	Flintsbach a. Inn-“Rachelburg“	RO	Höhensiedlung („Rachelburg“)	Nadel	Ha B1		Möslein 1998/99a, 222 Nr. 130 Abb. 7,16.
242	Flintsbach a. Inn-“Rachelburg“	RO	Höhensiedlung („Rachelburg“)	Nadel	BZ D1		Möslein 1998/99a, 222 Nr. 118 Abb. 7,9.
243	Flintsbach a. Inn-“Rachelburg“	RO	Höhensiedlung („Rachelburg“)	Nadel	Ha B1		Möslein 1998/99a, 222 Nr. 128 Abb. 7,11.
244	Waging	TS	Grab 7 (FZ Nr. B 220856)	Riegseemesser	BZ D2		Hohlbein 2016, 89 Nr. 94 Taf. 13,94.
245	Waging	TS	Grab 11 (FZ Nr. B 223532)	Turbankopfnadel	BZ D2		Irlinger 1988.
246	Waging	TS	Grab 11 (FZ Nr. B 223531)	Turbankopfnadel	BZ D2		Irlinger 1988.
247	Poing	EBE	Urnengrab B5	Vasenkopfnadel	BZ D2-Ha A1		Unpubliziert.
248	Poing	EBE	Obj. 10001 (Brandgrab)	Nadel	BZ D1	z. T. spröde, rotbraun, pulvrig	Unpubliziert (Winghart 1999).
249	Poing	EBE	Urnengrab B4	Griffplattenmesser	Ha A1		Hohlbein 2016, 119 Nr. 280 Taf. 25,280.

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250	Poing	EBE	Urnengrab B6	Griffzungenmesser	Ha A1		Unpubliziert (Winghart 1999).
251	Poing	EBE	Urnengrab B6	Kugelkopfnadel	Ha A1		Unpubliziert (Winghart 1999).
252	Poing	EBE	Obj. 10001 (Brandgrab)	Nadelfragment	BZ D1		Unpubliziert (Winghart 1999).
253	Poing	EBE	Obj. 10001 (Brandgrab)	Stabförmiges Gewicht (?)	BZ D1		Pare 1999, Abb. 19,2.
254	Poing	EBE	Obj. 2002 (Brandgrab)	Gewicht, flachkugelig	BZ D2		Pare 1999, 446 Nr. 20 Abb. 19,11.
255	Poing	EBE	Obj. 2002 (Brandgrab)	Felgenniet	BZ D2		Winghart 1993a, Abb. 10-11.
256	Poing	EBE	Obj. 2002 (Brandgrab)	Felgenniet	BZ D2		Winghart 1993a, Abb. 10-11.
257	Poing	EBE	Obj. 2002 (Brandgrab)	Felgenniet	BZ D2		Winghart 1993a, Abb. 10-11.
258	Poing	EBE	Obj. 2002 (Brandgrab)	Felgenniet	BZ D2		Winghart 1993a, Abb. 10-11.
259	Poing	EBE	Obj. 2002 (Brandgrab)	Felgenniet	BZ D2		Winghart 1993a, Abb. 10-11.
260	Poing	EBE	Obj. 2002 (Brandgrab)	Felgenniet	BZ D2		Winghart 1993a, Abb. 10-11.
261	Poing	EBE	Obj. 2002 (Brandgrab)	Gusskuchenfragment	BZ D2		Unpubliziert (Winghart 1999).
262	Poing	EBE	Obj. 2002 (Brandgrab)	Sichelfragment	BZ D2		Unpubliziert (Winghart 1999).
263	Poing	EBE	Obj. 2002 (Brandgrab)	Sichelfragment	BZ D2		Unpubliziert (Winghart 1999).
264	Poing	EBE	Obj. 2002 (Brandgrab)	Sichelfragment	BZ D2		Unpubliziert (Winghart 1999).
265	Poing	EBE	Obj. 2002 (Brandgrab)	Tragebügel	BZ D2		Unpubliziert (Winghart 1999).
266	Poing	EBE	Obj. 2002 (Brandgrab)	Tragebügel	BZ D2		Unpubliziert (Winghart 1999).
267	Poing	EBE	Obj. 2002 (Brandgrab)	Barrenfragment	BZ A2b-c?		Unpubliziert (Winghart 1999).
268	Poing	EBE	Obj. 2002 (Brandgrab)	Vasenkopfnadel	BZ D2		Unpubliziert (Winghart 1999).
269	Poing	EBE	Obj. 2002 (Brandgrab)	Schwertklinge	BZ D2	rotbraunes, pulvriges Material	Unpubliziert (Winghart 1999).
270	Poing	EBE	Obj. 2002 (Brandgrab)	Kappe mit Niet	BZ D2		Unpubliziert (Winghart 1999).
271	Poing	EBE	Obj. 2002 (Brandgrab)	Kappe mit Niet	BZ D2		Unpubliziert (Winghart 1999).
272	Poing	EBE	Obj. 2002 (Brandgrab)	Achskappe	BZ D2		Winghart 1999, Abb. 2 links.
273	Poing	EBE	Obj. 2002 (Brandgrab)	Achskappe	BZ D2		Winghart 1999, Abb. 2 rechts.
274	Poing	EBE	Obj. 2002 (Brandgrab)	Achsnagel	BZ D2		Winghart 1999, Abb. 2 rechts (Achsnagel)
275	Poing	EBE	Obj. 2002 (Brandgrab)	Achsnagel	BZ D2		Winghart 1999, Abb. 2 links (Achsnagel)
276	Poing	EBE	Obj. 2002 (Brandgrab)	Achskappe	BZ D2		Winghart 1999, Abb. 2 links.
277	Poing	EBE	Obj. 2002 (Brandgrab)	Achskappe	BZ D2		Winghart 1999, Abb. 2 rechts.
278	Poing	EBE	Obj. 2002 (Brandgrab)	Achsnagel	BZ D2		Winghart 1999, Abb. 2 links (Achsnagel)
279	Poing	EBE	Obj. 2002 (Brandgrab)	Achsnagel	BZ D2		Winghart 1999, Abb. 2 rechts (Achsnagel)

Nr.	Fundort	Lkr./Bez.	Fundumstände	Objekt	Datierung	Bemerkung	Literatur
280/G	Polling-Ehring	MÜ	Flußfund	Dreiwulstschwert Typ München	Ha A2	Griff	v. Quillfeldt 1995, 171 Nr. 166 A Taf. 57,166 A.
280/K	Polling-Ehring	MÜ	Flußfund	Dreiwulstschwert Typ München	Ha A2	Klinge	v. Quillfeldt 1995, 171 Nr. 166 A Taf. 57,166 A.
281/G	Germering	FFB	Einzelfund	Vollgriffschwert Typ Erding	BZ D2-Ha A1	Griff	v. Quillfeldt 1995, 143 f. Nr. 133 Taf. 44,133.
281/K	Germering	FFB	Einzelfund	Vollgriffschwert Typ Erding	BZ D2-Ha A1	Klinge	v. Quillfeldt 1995, 143 f. Nr. 133 Taf. 44,133.
282/G	München-Theresienstraße	M	Einzelfund?	Spiralknaufschwert	Ha B3	Griff	v. Quillfeldt 1995, 208 Nr. 219 Taf. 75,219.
282/K	München-Theresienstraße	M	Einzelfund?	Spiralknaufschwert	Ha B3	Klinge	v. Quillfeldt 1995, 208 Nr. 219 Taf. 75,219.
283/G	Pöcking-Aschering	STA	Grabhügel 8 (Körpergrab) Ha C	Vollgriffschwert Typ Riedlingen	Ha B3-C1	Griff	v. Quillfeldt 1995, 212 Nr. 222 Taf. 76,222.
283/K	Pöcking-Aschering	STA	Grabhügel 8 (Körpergrab) Ha C	Vollgriffschwert Typ Riedlingen	Ha B3-C1	Klinge	v. Quillfeldt 1995, 212 Nr. 222 Taf. 76,222.
284/G	Töging	AÖ	Flußfund	Vollgriffschwert Typ Mörigen	Ha B3	Griff	v. Quillfeldt 1995, 230 Nr. 247 Taf. 86,247.
284/K	Töging	AÖ	Flußfund	Vollgriffschwert Typ Mörigen	Ha B3	Klinge	v. Quillfeldt 1995, 230 Nr. 247 Taf. 86,247.
285/G	Feichten a. d. Alz-Wiesmühl	AÖ	Flußfund	Vollgriffschwert Typ Mörigen	Ha B3	Griff	v. Quillfeldt 1995, 234 Nr. 259 Taf. 91,259.
285/K	Feichten a. d. Alz-Wiesmühl	AÖ	Flußfund	Vollgriffschwert Typ Mörigen	Ha B3	Klinge	v. Quillfeldt 1995, 234 Nr. 259 Taf. 91,259.
286/G	Neustadt a. d. Donau-Schwaig	KEH	Einzelfund von feuchtem Grund	Dreiwulstschwert Typ Schwaig	Ha A1	Griff	v. Quillfeldt 1995, 156 Nr. 151 Taf. 52,151.
286/K	Neustadt a. d. Donau-Schwaig	KEH	Einzelfund von feuchtem Grund	Dreiwulstschwert Typ Schwaig	Ha A1	Klinge	v. Quillfeldt 1995, 156 Nr. 151 Taf. 52,151.
287/G	Gstadt a. Chiemsee-Preinersdorf	RO	Hortfund in Tongefäß im Moor	Rundknaufschwert	Ha B3	Griff	v. Quillfeldt 1995, 214 Nr. 224 Taf. 77,224.
287/K	Gstadt a. Chiemsee-Preinersdorf	RO	Hortfund in Tongefäß im Moor	Rundknaufschwert	Ha B3	Klinge	v. Quillfeldt 1995, 214 Nr. 224 Taf. 77,224.
288/G	Gstadt a. Chiemsee-Preinersdorf	RO	Hortfund in Tongefäß im Moor	Vollgriffschwert Typ Auvernier	Ha B3	Griff	v. Quillfeldt 1995218 Nr. 235 Taf. 81,235.
288/K	Gstadt a. Chiemsee-Preinersdorf	RO	Hortfund in Tongefäß im Moor	Vollgriffschwert Typ Auvernier	Ha B3	Klinge	v. Quillfeldt 1995218 Nr. 235 Taf. 81,235.
289/G	Gstadt a. Chiemsee-Preinersdorf	RO	Hortfund in Tongefäß im Moor	Vollgriffschwert Typ Mörigen	Ha B3	Griff	v. Quillfeldt 1995, 235 Nr. 266 Taf. 94,266.
289/K	Gstadt a. Chiemsee-Preinersdorf	RO	Hortfund in Tongefäß im Moor	Vollgriffschwert Typ Mörigen	Ha B3	Klinge	v. Quillfeldt 1995, 235 Nr. 266 Taf. 94,266.
290	München-Obermenzing	M	Einzelfund	Griffplattenschwert	BZ C1		Koschik 1981a, 188 Nr. 119 Taf. 56,13.
291/G	Unterföhring	M	Flußfund	Achtkantschwert	BZ C2	Griff	v. Quillfeldt 1995, 53 Nr. 31 Taf. 11,31.
291/K	Unterföhring	M	Flußfund	Achtkantschwert	BZ C2	Klinge	v. Quillfeldt 1995, 53 Nr. 31 Taf. 11,31.
292/G	Berg-Bachhausen/Höhenrain	TÖL	Grab?	Vollgriffschwert	BZ C2	Griff	v. Quillfeldt 1995, 39 Nr. 10 Taf. 4,10.
292/K	Berg-Bachhausen/Höhenrain	TÖL	Grab?	Vollgriffschwert	BZ C2	Klinge	v. Quillfeldt 1995, 39 Nr. 10 Taf. 4,10.
293/G	Marktl-Leonberg	AÖ	Grabhügel	Achtkantschwert	BZ C2	Griff	v. Quillfeldt 1995, 61 Nr. 52 Taf. 17,52.
293/K	Marktl-Leonberg	AÖ	Grabhügel	Achtkantschwert	BZ C2	Klinge	v. Quillfeldt 1995, 61 Nr. 52 Taf. 17,52.
294/G	Eiselfing-Alteiselfing	RO	Vermutlich Grabhügel	Vollgriffschwert Sonderform	BZ D1	Griff	v. Quillfeldt 1995, 98 Nr. 82 Taf. 27,82.
294/K	Eiselfing-Alteiselfing	RO	Vermutlich Grabhügel	Vollgriffschwert Sonderform	BZ D1	Klinge	v. Quillfeldt 1995, 98 Nr. 82 Taf. 27,82.
295/G	Ainring-Hausmoning	BGL	Einzelfund wohl von feuchtem Grund	Achtkantschwert	BZ C2	Griff	v. Quillfeldt 1995, 54 Nr. 33 Taf. 11,33.

Nr.	Fundort	Lkr./Bez.	Fundumstände	Objekt	Datierung	Bemerkung	Literatur
295/K	Ainring-Hausmoning	BGL	Einzelfund wohl von feuchtem Grund	Achtkantschwert	BZ C2	Klinge	v. Quillfeldt 1995, 54 Nr. 33 Taf. 11,33.
296/G	Kraiburg a. Inn	MÜ	Flußfund	Vollgriffschwert Typ Riegsee	BZ D	Griff	v. Quillfeldt 1995, 115 Nr. 109 Taf. 37,109.
296/K	Kraiburg a. Inn	MÜ	Flußfund	Vollgriffschwert Typ Riegsee	BZ D	Klinge	v. Quillfeldt 1995, 115 Nr. 109 Taf. 37,109.
297	Fürstenfeldbruck-Buchenau	FFB	Grabfund (dazu SSN-298)	Mittelständiges Lappenbeil	BZ C2		Pászthory/Mayer 1998, 100 Nr. 540 Taf. 36,540.
298	Fürstenfeldbruck-Buchenau	FFB	Grabfund (dazu SSN-297)	Griffplattenschwert	BZ C2		Schauer 1971, 56 Nr. 71. Taf. 8,71.
299/G	Waginger See	TS	Gewässerfund	Vollgriffschwert Typ Königsdorf	Ha B1	Griff	v. Quillfeldt 1995, 189 Nr. 198 Taf. 66,198.
299/K	Waginger See	TS	Gewässerfund	Vollgriffschwert Typ Königsdorf	Ha B1	Klinge	v. Quillfeldt 1995, 189 Nr. 198 Taf. 66,198.
300	Forstbezirk Königswieser Forst	STA	Hügel 20	Absatzbeil	BZ C		Pászthory/Mayer 1998, 87 Nr. 451 Taf. 50,451.
301/G	Bad Tölz-Kirchbichl	TÖL	Einzelfund	Achtkantschwert Typ Kirchbichl	BZ C	Griff	v. Quillfeldt 1995, 47 Nr. 18 Taf. 6,18.
301/K	Bad Tölz-Kirchbichl	TÖL	Einzelfund	Achtkantschwert Typ Kirchbichl	BZ C	Klinge	v. Quillfeldt 1995, 47 Nr. 18 Taf. 6,18.
302/G	Garching a. d. Alz-Wimm	AÖ	Vermutlich Grabhügel	Vollgriffschwert Typ Riegsee	BZ D	Griff	v. Quillfeldt 1995, 112 Nr. 95 Taf. 32,95.
302/K	Garching a. d. Alz-Wimm	AÖ	Vermutlich Grabhügel	Vollgriffschwert Typ Riegsee	BZ D	Klinge	v. Quillfeldt 1995, 112 Nr. 95 Taf. 32,95.
303	Riegsee	GAP	Hügel 8 Brandgrab 1	Riegseemesser	BZ D1		Koschik 1981a, 244 ff. Nr. 234 Taf. 130,3
304	Riegsee	GAP	Hügel 8 Brandgrab 1	Stollenarmring Typ Allendorf	BZ D1		Koschik 1981a, 244 ff. Nr. 234 Taf. 128,2.
305	Riegsee	GAP	Hügel 8 Brandgrab 1	Schwer gerippter Armring	BZ D1		Koschik 1981a, 244 ff. Nr. 234 Taf. 128,6.
306	Uffing a. Staffelsee	GAP	Hügel 1 (Brandgrab)	Armring Typ Leibersberg	BZ D1		Koschik 1981a, 250 f. Nr. 241 Taf. 139,4.
307	Riegsee	GAP	Hügel 23 (Brandgrab)	Griffzungenschwert T. Reutlingen	BZ D1		Schauer 1971, 141 Nr. 424 Taf. 62,424.
308/G	Riegsee	GAP	Hügel 9 (vermutlich Brandgrab)	Vollgriffschwert Typ Riegsee	BZ D	Griff	v. Quillfeldt 1995, 117 Nr. 114 Taf. 38,114.
308/K	Riegsee	GAP	Hügel 9 (vermutlich Brandgrab)	Vollgriffschwert Typ Riegsee	BZ D	Klinge	v. Quillfeldt 1995, 117 Nr. 114 Taf. 38,114.
309/G	Spatzenhausen	GAP	Einzelfund	Vollgriffschwert T. Spatzenhausen	BZ B-C1	Griff	v. Quillfeldt 1995, 31 Nr. 2 Taf. 1,2.
309/K	Spatzenhausen	GAP	Einzelfund	Vollgriffschwert T. Spatzenhausen	BZ B-C1	Klinge	v. Quillfeldt 1995, 31 Nr. 2 Taf. 1,2.
310	Regenstauf-Medersbach	R	Grabhügel 1	Dolch	BZ C		Torbrügge 1959a, 195 f. Nr. 280 Taf. 57,18.
311	Regenstauf-Medersbach	R	Grabhügel 1	Griffplattenschwert	BZ C		Torbrügge 1959a, 195 f. Nr. 280 Taf. 57,14.
312	Unterhaching	M	Grab 68 (Urnengrab)	Griffzungenmesser Typ Matrei	Ha A2	rotbraunes, pulvriges Material	Müller-Karpe 1957, Taf. 22,A 2.
313	Unterhaching	M	Grab 91 (Urnengrab)	Messer	Ha B2		Müller-Karpe 1957, Taf. 25,A 1.
314	Unterhaching	M	Grab 52 (Urnengrab)	Messer	Ha A2 [früh]		Müller-Karpe 1957, Taf. 19,B 18.
315	München-Pullach i. Isartal	M	Hortfund	Oberständiges Lappenbeil	Ha B2		Pászthory/Mayer 1998, 131 Nr. 783 Taf. 54,783.
316	München-Pullach i. Isartal	M	Hortfund	Tüllenmeißel	Ha B2		Pászthory/Mayer 1989,165 Nr.1099 Taf. 74,1099.
317	München-Pullach i. Isartal	M	Hortfund	Oberständiges Lappenbeil	Ha B2		Pászthory/Mayer 1998, 131 Nr. 784 Taf. 54,784.
318	München-Widenmayerstraße	M	Hortfund in der Flußaue	Oberständiges Lappenbeil	Ha B1		Pászthory/Mayer 1998, 135 f. Nr.830 Taf. 58,830.

Nr.	Fundort	Lkr./Bez.	Fundumstände	Objekt	Datierung	Bemerkung	Literatur
319	München-Widenmayerstraße	M	Hortfund in der Flußaue	Lanzenspitze	Ha B1		Pászthory/Mayer 1998, Taf. 107,8.
320	München-Widenmayerstraße	M	Hortfund in der Flußaue	Lanzenspitze	Ha B1		Pászthory/Mayer 1998, Taf. 107,10.
321	München-Widenmayerstraße	M	Hortfund in der Flußaue	Gusskuchenfragment	Ha B1	pulvriges Material	Pásthory/Mayer 1998, Taf. 107,30.
322	München-Widenmayerstraße	M	Hortfund in der Flußaue	Gusskuchen	Ha B1		Stein 1979, 154 ff. Nr. 352.
323	München-Widenmayerstraße	M	Hortfund in der Flußaue	Vollgriffschwert (Griff)	Ha B1		v. Quillfeldt 1995, 170 f. Nr. 166 Taf. 57,166.
324	München-Widenmayerstraße	M	Hortfund in der Flußaue	Schwertklingenfragment	Ha B1		v. Quillfeldt 1995, 170 f. Nr. 166 Taf. 57,166.
325	München-Widenmayerstraße	M	Hortfund in der Flußaue	Vollgriffschwert (Griff)	Ha B1		v. Quillfeldt 1995, 187 Nr. 190 Taf. 64,190.
326	Abensberg	KEH	Einzelfund	Absatzbeil	BZ C		Pászthory/Mayer 1998, 79 Nr. 398 Taf. 27,398.
327	Abensberg-Sandharlanden	KEH	Grabhügel	Dolch/Kurzschwert	BZ B-C1		Schauer 1971, 25 Nr. 25 Taf. 3,25.
328	Langquaid-Niederleierndorf	KEH	Hortfund	Nadel Typ Winklsaß	BZ D2-Ha A1		Engelhardt 1980, Abb. 55.
329	Langquaid-Niederleierndorf	KEH	Hortfund	Nadel Typ Winklsaß	BZ D2-Ha A1		Engelhardt 1980, Abb. 55.
330	Langquaid-Niederleierndorf	KEH	Hortfund	Nadel Typ Winklsaß	BZ D2-Ha A1		Engelhardt 1980, Abb. 55.
331	Langquaid-Niederleierndorf	KEH	Hortfund	Nadel Typ Winklsaß	BZ D2-Ha A1		Engelhardt 1980, Abb. 55.
332	Langquaid-Niederleierndorf	KEH	Hortfund	Nadel Typ Winklsaß	BZ D2-Ha A1		Engelhardt 1980, Abb. 55.
333	Langquaid-Niederleierndorf	KEH	Hortfund	Nadel Typ Gemeinlebarn	BZ D2-Ha A1		Engelhardt 1980.
334/G	Erding	ED	Brandgrab	Vollgriffschwert Typ Erding	BZ D2-Ha A1	Griff	v. Quillfeldt 1995, 144 Nr. 135 Taf. 45,135.
334/K	Erding	ED	Brandgrab	Vollgriffschwert Typ Erding	BZ D2-Ha A1	Klinge	v. Quillfeldt 1995, 144 Nr. 135 Taf. 45,135.
335	Wörth-Niederwörth	ED	Hortfund	Gusskuchenfragment	Ha B1		BVBl. 37, 1972, 161.
336	Wörth-Niederwörth	ED	Hortfund	Gusskuchenfragment	Ha B1		BVBl. 37, 1972, 161.
337	Wörth-Niederwörth	ED	Hortfund	Gusskuchen	Ha B1		BVBl. 37, 1972, 161 Abb. 51,3.
338	Wörth-Niederwörth	ED	Hortfund	Gusskuchen	Ha B1		BVBl. 37, 1972, 161 Abb. 52,1.
339	Wörth-Niederwörth	ED	Hortfund	Gusskuchen	Ha B1		BVBl. 37, 1972, 161 Abb. 52,2.
340	Wörth-Niederwörth	ED	Hortfund	Gusskuchen	Ha B1		BVBl. 37, 1972, 161 Abb. 51,2.
341	Wörth-Niederwörth	ED	Hortfund	Gusskuchenfragment	Ha B1		BVBl. 37, 1972, 161 Abb. 53,3.
342	Wörth-Niederwörth	ED	Hortfund	Zapfenartig, m. Hohlraum	Ha B1	oben metallisch, unten schwarz, pulvrig	BVBl. 37, 1972, 161 Abb. 50,2.
343	Wörth-Niederwörth	ED	Hortfund	Quaderförmiges Bruchstück	Ha B1		BVBl. 37, 1972, 161 Abb. 50,3.
344	Wörth-Niederwörth	ED	Hortfund	Armring	Ha B1		BVBl. 37, 1972, 161 Abb. 50,1.
345	Wörth-Niederwörth	ED	Hortfund	Gusskuchenfragment	Ha B1		BVBl. 37, 1972, 161. - Stein 1979, 169 f. Nr. 383.
346	Poing	EBE	Obj. 2002 (Brandgrab)	Trensenknebel	BZ D2		Winghart 1999, Abb. 9,oben rechts.
347	Poing	EBE	Obj. 2002 (Brandgrab)	Trensenknebel	BZ D2		Winghart 1999, Abb. 9,oben links.

Nr.	Fundort	Lkr./Bez.	Fundumstände	Objekt	Datierung	Bemerkung	Literatur
348	Poing	EBE	Obj. 2002 (Brandgrab)	Riemendurchzug	BZ D2		Unpublziert, wie Winghart 1999, Abb. 9, u. re.
349	Poing	EBE	Obj. 2002 (Brandgrab)	Trense	BZ D2		Winghart 1999, Abb. 9, oben Mitte.
350	Poing	EBE	Obj. 2002 (Brandgrab)	Kräftiger Nietnagel	BZ D2		Unpubliziert. Zur Fund-stelle Winghart 1999.
351	Poing	EBE	Obj. 2002 (Brandgrab)	Nagel, vierkantig	BZ D2		Unpubliziert. Zur Fund-stelle Winghart 1999.
352	Poing	EBE	Obj. 2002 (Brandgrab)	Aufgebogener Endbeschlag	BZ D2		Unpubliziert (wie Winghart 1999, Abb. 5,C).
353	Poing	EBE	Obj. 2002 (Brandgrab)	Aufgebogener Endbeschlag	BZ D2	rotbraun, pulvrig	Winghart 1999, Abb. 5,C.
354	Poing	EBE	Obj. 2002 (Brandgrab)	Aufgebogener Endbeschlag	BZ D2		Unpubliziert (wie Winghart 1999, Abb 5,C).
355	Poing	EBE	Obj. 2002 (Brandgrab)	Gezackter Endbeschlag	BZ D2		Winghart 1999, Abb. 7,A.
356	Poing	EBE	Obj. 2002 (Brandgrab)	Aufsteckvögelchen	BZ D2		Unpubliziert (Winghart 1999).
357	Poing	EBE	Obj. 2002 (Brandgrab)	Aufsteckvögelchen	BZ D2		Unpubliziert (Winghart 1999).
358	Poing	EBE	Obj. 2002 (Brandgrab)	Lanzettanhänger	BZ D2		Unpubliziert (Winghart 1999).
359	Poing	EBE	Obj. 2002 (Brandgrab)	Lanzettanhänger	BZ D2		Unpubliziert (Winghart 1999).
360	Poing	EBE	Obj. 10002 (Brandgrab)	Kugelkopfnadel	BZ D1		Unpubliziert (Winghart 1999).
361	Poing	EBE	Obj. 10002 (Brandgrab)	Nadel	BZ D1		Unpubliziert (Winghart 1999).
362/G	Bogen-Grubhöh	SR	Grab?	Vollgriffschwert Typ Schwaig	BZ D2-Ha A1	Griff	v. Quillfeldt 1995, 156 Nr. 153 Taf. 52,153.
362/K	Bogen-Grubhöh	SR	Grab?	Vollgriffschwert Typ Schwaig	BZ D2-Ha A1	Klinge	v. Quillfeldt 1995, 156 Nr. 153 Taf. 52,153.
363/G	Salching-Piering	SR	Urnengrab	Messer	Ha A2	Griff	Hundt 1964, 88 Taf. 83,9.
363/K	Salching-Piering	SR	Urnengrab	Messer	Ha A2	Klinge	Hundt 1964, 88 Taf. 83,9.
364	Bogen-Muckenwinkling	SR	Grabhügel 11	Dolch	BZ C		Hundt 1964, Taf. 7,3.
365	Bogen-Muckenwinkling	SR	Grabhügel 11	Mittelständiges Lappenbeil	BZ C		Hundt 1964, Taf. 7,2.
366	Straubing-Sand	SR	Grab 213	Messer	Ha B3		Schopper 1996, Abb. 51.
367	Straubing-Sand	SR	Grab 213	Lanzenspitze	Ha B3		Schopper 1996, Abb. 51.
368	Straubing-Sand	SR	Grab 65	Schaukelring	Ha B3		Unpubliziert (Schopper 1996).
369/G	Burgkirchen a. d. Alz-Bruck a. d. Alz	AÖ	Grabhügel 34 (Brandgrab)	Rundknaufschwert	Ha B3	Griff	v. Quillfeldt 1995, 213 Nr. 223 Taf. 77,223.
369/G	Burgkirchen a. d. Alz-Bruck a. d. Alz	AÖ	Grabhügel 34 (Brandgrab)	Rundknaufschwert	Ha B3	Klinge	v. Quillfeldt 1995, 213 Nr. 223 Taf. 77,223.
370/G	„Neuburg a. Inn“	PA	Unbekannt	Vollgriffschwert Typ Riegsee	BZ D	Griff	v. Quillfeldt 1995, 113 Nr. 98 Taf. 33,98.
370/K	„Neuburg a. Inn“	PA	Unbekannt	Vollgriffschwert Typ Riegsee	BZ D	Klinge	v. Quillfeldt 1995, 113 Nr. 98 Taf. 33,98.
371	Ruhstorf a. d. Rott-Hader	PA	Brandgrab	Tordierter Stab	BZ D2		Pätzold/Uenze 1963, 65 ff. Nr. 24 Taf. 30,4.
372	Ruhstorf a. d. Rott-Hader	PA	Brandgrab	Tordierter Stab	BZ D2		Pätzold/Uenze 1963, 65 ff. Nr. 24 Taf. 30,7.
373	Ruhstorf a. d. Rott-Hader	PA	Brandgrab	Tordierter Stab	BZ D2		Pätzold/Uenze 1963, 65 ff. Nr. 24 ohne Abb.

Nr.	Fundort	Lkr./Bez.	Fundumstände	Objekt	Datierung	Bemerkung	Literatur
374	Ruhstorf a. d. Rott-Hader	PA	Brandgrab	Tüllenhorn	BZ D2		Pätzold/Uenze 1963, 65 ff. Nr. 24 Taf. 28,1.
375	Ruhstorf a. d. Rott-Hader	PA	Brandgrab	Sichelfragment	BZ D2		Pätzold/Uenze 1963, 65 ff. Nr. 24 Taf. 30,6.
376	Ruhstorf a. d. Rott-Hader	PA	Brandgrab	Lanzenspitzenfragment	BZ D2	rotbraun, pulvrig	Pätzold/Uenze 1963, 65 ff. Nr. 24 Taf. 29,5.
377	Ruhstorf a. d. Rott-Hader	PA	Brandgrab	Stangenaufsatz kurz	BZ D2		Pätzold/Uenze 1963, 65 ff. Nr. 24 Taf. 29,7.
378/N	Ruhstorf a. d. Rott-Hader	PA	Brandgrab	Tüllenhorn	BZ D2	Tülle	Pätzold/Uenze 1963, 65 ff. Nr. 24 Taf. 29,1.
378/T	Ruhstorf a. d. Rott-Hader	PA	Brandgrab	Tüllenhorn	BZ D2	Nagel	Pätzold/Uenze 1963, 65 ff. Nr. 24 Taf. 29,1.
379	Ruhstorf a. d. Rott-Hader	PA	Brandgrab	Bügel	BZ D2		Pätzold/Uenze 1963, 65 ff. Nr. 24 Taf. 31,9.
380	Ruhstorf a. d. Rott-Hader	PA	Brandgrab	Stangenaufsatz	BZ D2		Pätzold/Uenze 1963, 65 ff. Nr. 24 Taf. 28,5.
381	Ruhstorf a. d. Rott-Hader	PA	Brandgrab	Tüllenhorn	BZ D2		Pätzold/Uenze 1963, 65 ff. Nr. 24 Taf. 28,2.
382	Vilshofen-Pleinting	PA	Einzelfund	Absatzbeil	BZ A2b		Hochstetter 1980, 156 Nr. 212 Taf. 98,1.
383	Abensberg-Offenstetten	KEH	Einzelfund	Mittelständiges Lappenbeil	BZ D-Ha A1		Pászthory/Mayer 1998, 120 Nr. 684 Taf. 47,684.
384	Hienheim	KEH	Grabhügel	Dolch	BZ C2		Hochstetter 1980, 130 Nr. 103 Taf. 37,10.
385	Hienheim	KEH	Grabhügel	Nadel	BZ C2		Hochstetter 1980, 130 Nr. 103 Taf. 37,7.
386	Hienheim	KEH	Grabhügel	Längs gerippter Armring	BZ C2		Hochstetter 1980, 130 Nr. 103 Taf. 37,11.
387	Hienheim	KEH	Grabhügel	Vierkantiger Armring	BZ C2		Hochstetter 1980, 130 Nr. 103 Taf. 37,14.
388	Ihrlerstein	KEH	Grabhügel	Dolch	BZ C		Hochstetter 1980, 131 Nr. 110 Taf. 40,11.
389	Otzing-Arndorf	DEG	Brandgrab	Beinreif	Ha B2		Schmotz 1989, Taf. 1, D 10.
390/G	Mengkofen-Hüttenkofen	DGF	Einzelfund	Achtkantschwert Typ Kirchbichl	BZ C2	Griff	v. Quillfeldt 1995, 48 Nr. 21 Taf. 7,21.
390/K	Mengkofen-Hüttenkofen	DGF	Einzelfund	Achtkantschwert Typ Kirchbichl	BZ C2	Klinge	v. Quillfeldt 1995, 48 Nr. 21 Taf. 7,21.
392	Griesstätt-Kettenham	RO	Grabfund	Schwertklinge	BZ D		BVBl. Beih. 5 (München 1992) 57 Abb. 34.
393	Eiselfing-Spielberg	RO	Hortfund im Moor	Lanzenspitze	Ha B1		Müller-Karpe 1959, Taf. 170,D 2.
394	Eiselfing-Spielberg	RO	Hortfund im Moor	Oberständiges Lappenbeil	Ha B1		Müller-Karpe 1959, Taf. 170,D 1.
395	Eiselfing	RO	Depot	Gusskuchenfragment	?		Steffan/Uenze 2003, 159 Nr. 202 Taf. 37,4.
396	Eiselfing	RO	Depot	Gusskuchenfragment	?		Steffan/Uenze 2003, 159 Nr. 202 Taf. 37,3.
397/G	Oberneukirchen-Zehethof	MÜ	Grab?	Vollgriffschwert	Ha A2	Griff	v. Quillfeldt 1995, 187 Nr. 191 Taf. 64,191.
397/K	Oberneukirchen-Zehethof	MÜ	Grab?	Vollgriffschwert	Ha A2	Klinge	v. Quillfeldt 1995, 187 Nr. 191 Taf. 64,191.
398/G	Polling-Ehring	MÜ	Flußfund	Dreiwulstschwert Typ Erding	BZ D2-Ha A1	Griff	v. Quillfeldt 1995, 144 Nr. 134 Taf. 45,134.
398/K	Polling-Ehring	MÜ	Flußfund	Dreiwulstschwert Typ Erding	BZ D2-Ha A1	Klinge	v. Quillfeldt 1995, 144 Nr. 134 Taf. 45,134.
399/G	Raubling-Pfraundorf	RO	Flußfund	Schalenknaufschwert	Ha B1	Griff	v. Quillfeldt 1995, 191 Nr. 201 Taf. 68,201.
399/K	Raubling-Pfraundorf	RO	Flußfund	Schalenknaufschwert	Ha B1	Klinge	v. Quillfeldt 1995, 191 Nr. 201 Taf. 68,201.

Nr.	Fundort	Lkr./Bez.	Fundumstände	Objekt	Datierung	Bemerkung	Literatur
400	Langenbach-Asenkofen	FS	Grabhügel, Körpergrab	Griffzungenschwert Asenkofen	BZ C2		Schauer 1971, 105 Nr. 329 Taf. 48,329.
401	Gauting-Reismühl	STA	Hortfund	Messer	Ha B1		Müller-Karpe 1959, Taf. 166,C 5.
402	Feldafing-Roseninsel	STA	Seeufersiedlung	Messer	Ha B2 [früh]		Müller-Karpe 1959, Taf. 192,B 8.
403/G	Valley-Mitterdarching	MB	Einzelfund	Vollgriffschwert Typ Högl/Liptau	Ha A2	Griff	v. Quillfeldt 1995, 175 Nr. 174 Taf. 60,174.
403/K	Valley-Mitterdarching	MB	Einzelfund	Vollgriffschwert Typ Högl/Liptau	Ha A2	Klinge	v. Quillfeldt 1995, 175 Nr. 174 Taf. 60,174.
404	Waldkraiburg-Pürten	MÜ	Flußfund	Griffzungenschwert Großaueim	Ha B1		Schauer 1971, 180 Nr. 534 Taf. 80,534; 83,534.
405/G	Passau-Hals	PA	Flußfund?	Vollgriffschwert Typ Illertissen	BZ D2-Ha A1	Griff	v. Quillfeldt 1995, 150 Nr. 144 Taf. 49,144.
405/K	Passau-Hals	PA	Flußfund?	Vollgriffschwert Typ Illertissen	BZ D2-Ha A1	Klinge	v. Quillfeldt 1995, 150 Nr. 144 Taf. 49,144.
406	Straubing	SR	Grab?	Griffzungenschwert Reutlingen	BZ D-Ha A1		Schauer 1971, 133 Nr. 405 Taf. 59,405.
407	Nürnberg-Mögeldorf	N	Hortfund	Gusskuchenfragment	BZ D2-Ha A1	vorläufige Nr. 47	Nadler 1994; ders. 1998
408	Nürnberg-Mögeldorf	N	Hortfund	Gusskuchenfragment	BZ D2-Ha A1	vorläufige Nr. 16	Nadler 1994; ders. 1998.
409	Nürnberg-Mögeldorf	N	Hortfund	Gusskuchenfragment	BZ D2-Ha A1	vorläufige Nr. 15	Nadler 1994; ders. 1998.
410	Nürnberg-Mögeldorf	N	Hortfund	Gusskuchenfragment	BZ D2-Ha A1	vorläufige Nr. 14	Nadler 1994; ders. 1998.
411	Nürnberg-Mögeldorf	N	Hortfund	Gusskuchenfragment	BZ D2-Ha A1	vorläufige Nr. 13	Nadler 1994; ders. 1998.
412	Nürnberg-Mögeldorf	N	Hortfund	Gusskuchenfragment	BZ D2-Ha A1	vorläufige Nr. 55	Nadler 1994; ders. 1998.
413	Nürnberg-Mögeldorf	N	Hortfund	Stempel	BZ D2-Ha A1	vorläufige Nr. 61	Nadler 1994; ders. 1998, Abb. 18.
414	Nürnberg-Mögeldorf	N	Hortfund	Vasenkopfnadel	BZ D2-Ha A1	vorläufige Nr. 25	Nadler 1994; ders. 1998, Abb. 15.
415	Nürnberg-Mögeldorf	N	Hortfund	Zungensichel	BZ D2-Ha A1	vorläufige Nr. 30	Nadler 1994; ders. 1998, Abb. 14.
416	Nürnberg-Mögeldorf	N	Hortfund	Mittelständiges Lappenbeil	BZ D2-Ha A1	vorläufige Nr. 7	Nadler 1994; ders. 1998, Abb. 12.
417/G	Augsburg-Haunstetten	A	Brandgrab	Phantasiegriff-Messer	Ha B2	Griff	Wirth 1998, 178 f. Grab 1 Taf. Haunstetten VI,17.
417/K	Augsburg-Haunstetten	A	Brandgrab	Phantasiegriff-Messer	Ha B2	Klinge	Wirth 1998, 178 f. Grab 1 Taf. Haunstetten VI,17.
418	Garching a. d. Alz	AÖ	Brandgrab 16	Griffdornmesser	Ha B2		Hohlbein 2016, 300 Nr. 1034 Taf. 85,1034.
419/G	Garching a. d. Alz	AÖ	Brandgrab 16	Spiralknauf- o. Antennenschw.	Ha B2	Griff	v. Quillfeldt 1995, 246 f. Nr. 286A Taf. 103,286A.
419/K	Garching a. d. Alz	AÖ	Brandgrab 16	Spiralknauf- o. Antennenschw.	Ha B2	Klinge	v. Quillfeldt 1995, 246 f. Nr. 286A Taf. 103,286A.
420	Waging-Gastag	TS	Hortfund	Oberständiges Lappenbeil	Ha B2		BVBl. Beih. 3 (München 1990) 49 f. Abb. 36,10.
421	Waging-Gastag	TS	Hortfund	Oberständiges Lappenbeil	Ha B2		BVBl. Beih. 1 (München 1987) 104 Abb. 67,1.
422	Waging-Gastag	TS	Hortfund	Zungensichel	Ha B2		BVBl. Beih. 3 (München 1990) 49 f. Abb. 36,8.
423	Waging-Gastag	TS	Hortfund	Zungensichel	Ha B2		BVBl. Beih. 3 (München 1990) 49 f. Abb. 36,9.
424	Seeon-Seebruck-Truchtlaching	TS	Flußfund	Griffzungenschw. Hemigkofen	Ha A2		Uenze 1992.
425	Tacherting-Unterbrunnham	TS	Hügel 13	Randleistenbeil	BZ C1		Mayer/Pászthory 1998, 65 Nr. 296 Taf. 20,296.

Nr.	Fundort	Lkr./Bez.	Fundumstände	Objekt	Datierung	Bemerkung	Literatur
426	Tacherting-Unterbrunnham	TS	Hügel 13	Griffplattendolch	BZ C1		Maier 1970, Abb.S. 16 oben (oberer Dolch).
427/G	Trostberg	TS	Flußfund	Dreiwulstschwert Typ Aldrans?	Ha A2	Griff	v. Quillfeldt 1995, 188 Nr. 196 Taf. 66,196.
427/K	Trostberg	TS	Flußfund	Dreiwulstschwert Typ Aldrans?	Ha A2	Klinge	v. Quillfeldt 1995, 188 Nr. 196 Taf. 66,196.
428	Eching (Frühlingstraße)	FS	Grab 205	Messer	Ha A2		Unpubliziert (Schefzik 2001, 283 Nr. 223/4).
429	Eching (Frühlingstraße)	FS	Bef. 100	Armring	Ha B3		Unpubliziert (Schefzik 2001, 283 Nr. 223/4).
430	Eching (Frühlingstraße)	FS	Bef. 148	Armring	Ha B3	Verzierung kaum erkennbar	Unpubliziert (Schefzik 2001, 283 Nr. 223/4).
431	Eching (Frühlingstraße)	FS	Bef. 148	Armring	Ha B3	Verzierung kaum erkennbar	Unpubliziert (Schefzik 2001, 283 Nr. 223/4).
432/G	Eching (Frühlingstraße)	FS	Bef. 148	Ringgehänge	Ha B3	großer Ring	Unpubliziert (Schefzik 2001, 283 Nr. 223/4).
432/K	Eching (Frühlingstraße)	FS	Bef. 148	Ringgehänge	Ha B3	kleiner Ring	Unpubliziert (Schefzik 2001, 283 Nr. 223/4).
433	Deggendorf-Fischerdorf	DEG	Grabhügel 3/3	Griffzungenschwert	BZ C2		Schmotz 1984, 49 Abb. 8,1.
434	Deggendorf-Fischerdorf	DEG	Grabhügel 3/3	Beil	BZ C2		Schmotz 1984, 49 Abb. 8,3.
435	Stephansposching-Uttenhofen	DEG	Hortfund	Randleistenbeil	BZ B		Hochstetter 1980, 118 Nr. 46 Taf. 15,1.
436	Stephansposching-Uttenhofen	DEG	Hortfund	Lanzenspitze	BZ B		Hochstetter 1980, 118 Nr. 46 Taf. 15,2.
437	Stephansposching-Uttenhofen	DEG	Hortfund	Dolch	BZ B		Hochstetter 1980, 118 Nr. 46 Taf. 15,3.
438	Künzing	DEG	Brandgrab 143	Messer	Ha B3		Schopper 1995, 267 Taf. 104,8.
439	Künzing	DEG	Brandgrab 143	Lanzenspitze	Ha B3		Schopper 1995, 267 Taf. 104,1.
440	Künzing	DEG	Brandgrab 27	Schaukelring	Ha B2		Schopper 1995, 207 Taf. 23,6.
441	Künzing	DEG	Brandgrab 96	Messer	Ha B3		Schopper 1995, 241 Taf. 66,3.
442	Künzing	DEG	Brandgrab 129	Tüllenbeil	Ha B2-3		Schopper 1995, 259 Taf. 94,B 7.
443	Künzing	DEG	Brandgrab 126	Messer	Ha B3		Schopper 1995, 258 Taf. 91,A 5.
444	Künzing	DEG	Brandgrab 45	Messer	Ha B3		Schopper 1995, 214 Taf. 32,5.
445	Künzing	DEG	Brandgrab 141	Messer	Ha B3		Schopper 1995, 266 Taf. 103,12.
446	Künzing	DEG	Brandgrab 57	Messer	Ha B3		Schopper 1995, 220 Taf. 39,7.
447	Bad Reichenhall-Karlstein	BGL	Siedlungsfund (aus HW III)	Oberständiges Lappenbeil	Ha B2		Pásthory/Mayer 1998, 130 Nr. 755 Taf. 52,755.
448	Bad Reichenhall-Karlstein	BGL	Hortfund Haiderburgstein	Zungensichel	Ha B2		Müller-Karpe 1959, Taf. 167,A 29.
449	Bad Reichenhall-Karlstein	BGL	Hortfund Haiderburgstein	Zungensichel	Ha B2		Müller-Karpe 1959, Taf. 167,A 28.
450	Bad Reichenhall-Karlstein	BGL	Hortfund Haiderburgstein	Oberständiges Lappenbeil	Ha B2		Müller-Karpe 1959, Taf. 167,A 27.
451	Bad Reichenhall-Karlstein	BGL	Hortfund Haiderburgstein	Gusskuchenfragment	Ha B2		Unpubliziert (Reinecke 1903-11).
452	Bad Reichenhall-Karlstein	BGL	Hortfund Haiderburgstein	Gusskuchenfragment	Ha B2		Reinecke 1903-11, 395 Nr. 1275 Taf. 68,1275.
453	Eching (Frühlingstraße)	FS	Grab Bef. 249	Armring	Ha B3		Unpubliziert (Schefzik 2001, 283 Nr. 223/4).

Nr.	Fundort	Lkr./Bez.	Fundumstände	Objekt	Datierung	Bemerkung	Literatur
454	Eching (Frühlingstraße)	FS	Grab Bef. 249	Armring	Ha B3		Unpubliziert (Schefzik 2001, 283 Nr. 223/4).
455	Waldkraiburg-Pürten	MÜ	Flußfund	Gusskuchen	?		Torbrügge 1960, 52 Nr. 19 B.
456	Margarethenberg	AÖ	Hortfund auf dem Wallkörper	Oberständiges Lappenbeil	Ha B2		Pászthory/Mayer 1998, 131 Nr. 772 Taf. 53,772.
457	Margarethenberg	AÖ	Hortfund auf dem Wallkörper	Oberständiges Lappenbeil	Ha B2		Pászthory/Mayer 1998, 131 Nr. 770 Taf. 53,770.
458	Margarethenberg	AÖ	Hortfund auf dem Wallkörper	Oberständiges Lappenbeil	Ha B2		Pászthory/Mayer 1998, 131 Nr. 771 Taf. 53,771.
459	Margarethenberg	AÖ	Hortfund auf dem Wallkörper	Oberständiges Lappenbeil	Ha B2		Pászthory/Mayer 1998, 131 Nr. 773 Taf. 54,773.
460	Margarethenberg	AÖ	Hortfund auf dem Wallkörper	Oberständiges Lappenbeil	Ha B2		Pászthory/Mayer 1998, 131 Nr. 774 Taf. 54,774.
461	Margarethenberg	AÖ	Hortfund auf dem Wallkörper	Oberständiges Lappenbeil	Ha B2		Pászthory/Mayer 1998, 142 Nr. 921 Taf. 64,921.
462/G	Haiming-Holzhausen	AÖ	Flußfund	Vollgriffschwert Typ Riegsee	BZ D	Griff	v. Quillfeldt 1995, 115 Nr. 108 Taf. 36,108.
462/K	Haiming-Holzhausen	AÖ	Flußfund	Vollgriffschwert Typ Riegsee	BZ D	Klinge	v. Quillfeldt 1995, 115 Nr. 108 Taf. 36,108.
463	Töging	AÖ	Flußfund	Griffzungenschw. Hemigkofen	Ha A2		Schauer 1971, 163 Nr. 483 Taf. 71,483.
464	Töging	AÖ	Flußfund	Griffzungenschw. Typ Traun (?)	BZ C2		Schauer 1971, 123 Nr. 377 Taf. 55,377.
465	Töging	AÖ	Flußfund	Griffzungenschwert	Ha A2		Schauer 1971, 165 Nr. 492 Taf. 73,492.
466	Altötting	AÖ	Aus zerstörten Brandgräbern	Griffdornmesser	Ha A1		Hohlbein 2016, 211 Nr. 561 Taf. 48,561.
467	Chiemsee-Krautinsel	RO	Einzelfund	Gusskuchenfragment	?	sehr spröde, grau, pulvrig	Steffan/Uenze 2003, 144 ff. Nr. 169.
468	Nußdorf a. Inn	RO	Einzelfund	Gusskuchen	?		BVBl. Beih. 12 (München 1999) 86.
469	Salzburg-Rainberg	Salzburg	Höhensiedlung	Gusskuchenfragment	?		Unpubliziert?
470	Salzburg-Rainberg	Salzburg	Höhensiedlung	Gusskuchenfragment	?		Unpubliziert?
471	Bischofshofen-Mitterberg	Salzburg	Einzelfund aus dem Bergbaugebiet	Tüllenpickel	BZ D-Ha A1		Klose 1918, Abb. 29,1.
472	Bischofshofen-Mitterberg	Salzburg	Einzelfund aus dem Bergbaugebiet	Tüllenpickel	BZ D-Ha A1		Klose 1918, Abb. 29,2.
473	Unterragging	Salzburg	Hortfund	Gusskuchen	?		Klose 1918, Abb. 42,6.
474	Salzburg-Maxglan	Salzburg	Grab 143	Griffdornmesser	Ha B2		Unpubliziert.
475	Salzburg-Maxglan	Salzburg	Grab 36	Schwer gerippter Armring	BZ D		Unpubliziert (Moosleitner 1993).
476	Salzburg-Maxglan	Salzburg	Streufund Gräberfeldbereich	Turbankopfnadel	BZ D2		Unpubliziert (Moosleitner 1993).
477	Bischofshofen-Mitterberg	Salzburg	Einzelfund Bergbaugebiet	Gusskuchen	?		Unpubliziert.
478	Bischofshofen-Mitterberg	Salzburg	Einzelfund Bergbaugebiet	Gusskuchen	?		Unpubliziert.
479	Bischofshofen-Mitterberg	Salzburg	Einzelfund Bergbaugebiet	Gusskuchen	?		Unpubliziert.
480	Bischofshofen-Mitterberg	Salzburg	Einzelfund Bergbaugebiet	Gusskuchen (?)	?		Klose 1918, Abb. 42,11.
481	Nußdorf-Rottstätt	Salzburg	Einzel- oder Hortfund	Gusskuchenfragment	?		Fundber. Österreich 22, 1983, 247.
482	St. Georgen b. Bruck (Pinzgau)	Salzburg	Einzel(Gewässer-?) fund?	Gusskuchen	?		Klose 1918, Abb. 42,7.

Nr.	Fundort	Lkr./Bez.	Fundumstände	Objekt	Datierung	Bemerkung	Literatur
483	Lamprechtshausen	Salzburg	Moorfund	Oberst. Lappenbeil m. Öse	Ha B3		Mayer 1977, 166 Nr.789 Taf. 58,789.
484	Wals-Siezenheim	Salzburg	Flußfund aus der Salzach	Oberst. Lappenbeil m. Öse	Ha B3		Mayer 1977, 166 Nr. 792 Taf. 58,792.
485/G	St. Martin b. Lofer	Salzburg	Brandgrab	Vollgriffschwert Typ Rankweil	Ha A2	Griff	Krämer 1985, 31 Nr. 89 Taf. 15,89.
485/K	St. Martin b. Lofer	Salzburg	Brandgrab	Vollgriffschwert Typ Rankweil	Ha A2	Klinge	Krämer 1985, 31 Nr. 89 Taf. 15,89.
486	Bischofshofen	Salzburg	Gewässerfund (Mühlbach)	Oberständiges Lappenbeil	Ha B1		Mayer 1977, 160 Nr. 735 Taf. 54,735.
487/G	Salzburg	Salzburg	Flußfund (Salzachschotter)	Vollgriffschwert	BZ C2	Griff	Krämer 1985, 12 Nr. 7 Taf. 2,7.
487/K	Salzburg	Salzburg	Flußfund (Salzachschotter)	Vollgriffschwert	BZ C2	Klinge	Krämer 1985, 12 Nr. 7 Taf. 2,7.
488	Edt b. Schleedorf	Salzburg	Einzelfund	Gusskuchen	?		Fundber. Österreich 2, 1935-38, 169.
489	Mühlbach-Mitterberg	Salzburg	Einzelfund (1908)	Mittelständiges Lappenbeil	BZ D-Ha A1		Mayer 1977, 137 Nr. 580 Taf. 41,580.
490	Mühlbach-Mitterberg	Salzburg	Einzelfund (1908)	Mittelständiges Lappenbeil	BZ D-Ha A1		Mayer 1977, 136 Nr. 566 Taf. 40,566.
491	Mühlbach-Mitterberg	Salzburg	Einzelfund 1908	Mittelständiges Lappenbeil	BZ D-Ha A1		Mayer 1977, 135 Nr. 558 Taf. 39,558.
492	Schwarzach	Salzburg	Einzelfund	Randleistenbeil	BZ C		Fundber. Österreich 27, 1988, 274.
493	Lofer	Salzburg	Einzelfund 1927	Oberständiges Lappenbeil	Ha B1		Mayer 1977, 162 Nr. 763 Taf. 56,763.
494	Lofer-Paß Strub	Salzburg	Einzelfund	Oberständiges Lappenbeil	Ha B1		Mayer 1977, 162 Nr. 762 Taf. 56,762.
495	Flintsbach a. Inn-“Rachelburg“	RO	Höhensiedlung („Rachelburg“)	Sichelfragment	BZ D-Ha A1		Möslein 1998/99a, 214 Nr. 65 Abb. 4,3.
496	Flintsbach a. Inn-“Rachelburg“	RO	Höhensiedlung („Rachelburg“)	Sichelfragment	BZ D-Ha A1		Möslein 1998/99a, 214 Nr. 67 Abb. 4,1.
497	Flintsbach a. Inn-“Rachelburg“	RO	Höhensiedlung („Rachelburg“)	Sichelfragment	BZ D-Ha A1		Möslein 1998/99a, 214 Nr. 66 Abb. 4,2.
498	Flintsbach a. Inn-“Rachelburg“	RO	Höhensiedlung („Rachelburg“)	Sichelfragment	BZ D-Ha A1		Möslein 1998/99a, 214 Nr. 74 Abb. 4,12.
499	Lenggries-Untermurbach	TÖL	Siedlungsfund?	Griffdornmesser	Ha B1		Unpubliziert (wie SSN-698-699).
500	Lenggries-Untermurbach	TÖL	Siedlungsfund?	Meißel	Ha A2/B1		Unpubliziert (wie SSN-698-699).
501	Flintsbach a. Inn-“Rachelburg“	RO	Höhensiedlung („Rachelburg“)	Griffplattenmesser	BZ D-Ha A1		Möslein 1998/99a, 216 Nr. 95 Abb. 5,9.
502	Flintsbach a. Inn-“Rachelburg“	RO	Höhensiedlung („Rachelburg“)	Armringfragment	Ha B1		Möslein 1998/99a, 225 Nr. 138 Abb. 8,10.
503	Flintsbach a. Inn-“Rachelburg“	RO	Höhensiedlung („Rachelburg“)	Griffplattendolch	BZ D1		Möslein 1998/99a, 205 Nr. 7 Abb. 1,3.
504	Flintsbach a. Inn-“Rachelburg“	RO	Höhensiedlung („Rachelburg“)	Fragment einer Berge (?)	BZ D?		Möslein 1998/99a, 225 Nr. 139 Abb. 8,9.
505	Polling-Etting	WM	Hügel 22 (Brandgrab)	Vasenkopfnadel	BZ D2		Koschik 1981a, 225 ff Nr. 210 B Taf. 118,8.
506/G	Polling-Etting	WM	Hügel 22 (Brandgrab)	Vollgriffschwert Typ Riegsee	BZ D2	Griff	Koschik 1981a, 225 ff Nr. 210 B Taf. 118,6.
506/K	Polling-Etting	WM	Hügel 22 (Brandgrab)	Vollgriffschwert Typ Riegsee	BZ D2	Klinge	Koschik 1981a, 225 ff Nr. 210 B Taf. 118,6.
507	Polling-Etting	WM	Hügel 22 (Brandgrab)	Riegseemesser	BZ D2		Koschik 1981a, 225 ff Nr. 210 B Taf. 118,7.
508	München-Bogenhausen	M	Flußfund	Griffplattenschwert	BZ B-C1		Koschik 1981a, 194 Nr. 139 Taf. 65,2.
509/G	Rott a. Inn-Lengdorf	RO	Flußfund	Vollgriffschwert Typ Illertissen	Ha A1	Griff	v. Quillfeldt 1995, 160 Nr. 154 Taf. 53,154.

Nr.	Fundort	Lkr./Bez.	Fundumstände	Objekt	Datierung	Bemerkung	Literatur
509/K	Rott a. Inn-Lengdorf	RO	Flußfund	Vollgriffschwert Typ Illertissen	Ha A1	Klinge	v. Quillfeldt 1995, 160 Nr. 154 Taf. 53,154.
510/G	Forstinning	EBE	Brandgrab	Vollgriffschwert, Sonderform	BZ D1	Griff	v. Quillfeldt 1995, 97 f. Nr. 81 Taf. 27,81.
510/K	Forstinning	EBE	Brandgrab	Vollgriffschwert, Sonderform	BZ D1	Klinge	v. Quillfeldt 1995, 97 f. Nr. 81 Taf. 27,81.
511	Bad Reichenhall-Eisenbichler	BGL	Hortfund	Knopfsichel mit Knopfpaar	BZ C2		v. Chlingensperg auf Berg 1904, Taf. 7,16.
512	Bad Reichenhall-Eisenbichler	BGL	Hortfund	Knopfsichelfragment	BZ C2		v. Chlingensperg auf Berg 1904, Taf. 7,18.
513	Bad Reichenhall-Eisenbichler	BGL	Hortfund	Sichelfragment	BZ C2		v. Chlingensperg auf Berg 1904, Taf. 7,17.
514	Andechs-Frieding	STA	Angeblich Grabhügel	Griffplattenschwert	BZ C		Koschik 1981a, 204 Nr. 175 Taf. 80,9.
515	Bad Reichenhall-Karlstein	BGL	„Hallstatt-Wohnstätte XIX“	Gusskuchenfragment	Ha B2		Unpubliziert (Reinecke 1903-11).
516	Bad Reichenhall-Karlstein	BGL	„Hallstatt-Wohnstätte XIX“	Gusskuchenfragment	Ha B2		Unpubliziert (Reinecke 1903-11).
517	Bad Reichenhall-Karlstein	BGL	Siedlungsfund („Wohnstätte XIX“)	Gusskuchenfragment	Ha B2		Unpubliziert (Reinecke 1903-11).
518	Bad Reichenhall-Karlstein	BGL	Siedlungsfund („Wohnstätte XIX“)	Gusskuchenfragment	Ha B2		Unpubliziert (Reinecke 1903-11).
519	Bad Reichenhall-Karlstein	BGL	Siedlungsfund („Wohnstätte XIX“)	Gusskuchenfragment	Ha B2		Unpubliziert (Reinecke 1903-11).
520	Bad Reichenhall-Karlstein	BGL	Siedlungsfund („Wohnstätte XIX“)	Gusskuchenfragment	Ha B2		Unpubliziert (Reinecke 1903-11).
521	Bad Reichenhall-Karlstein	BGL	Siedlungsfund („Wohnstätte XVIII“)	Gusskuchenfragment	Ha B2		Unpubliziert (Reinecke 1903-11).
522	Bad Reichenhall-Karlstein	BGL	Siedlungsfund („Wohnstätte XVIII“)	Gusskuchenfragment	Ha B2		Unpubliziert (Reinecke 1903-11).
523	Bad Reichenhall-Karlstein	BGL	Siedlungsfund („Wohnstätte XVIII“)	Gusskuchenfragment	Ha B2		Unpubliziert (Reinecke 1903-11).
524	Bad Reichenhall-Karlstein	BGL	Siedlungsfund („Wohnstätte XVIII“)	Gusskuchenfragment	Ha B2		Unpubliziert (Reinecke 1903-11).
525	Lappersdorf-Hainsacker	R	Hortfund	Vollgriffmesser	BZ C2		Torbrügge 1959a, 194 Nr. 273 Taf. 59,4.
526	Lappersdorf-Hainsacker	R	Hortfund	Beil	BZ C2		Torbrügge 1959a, 194 Nr. 273 Taf. 59,7.
527	Lappersdorf-Hainsacker	R	Hortfund	Beil	BZ C2		Torbrügge 1959a, 194 Nr. 273 Taf. 59,9.
528	Lappersdorf-Hainsacker	R	Hortfund	Beilfragment	BZ C2		Torbrügge 1959a, 194 Nr. 273 Taf. 59,8.
529	Lappersdorf-Hainsacker	R	Hortfund	Sichel	BZ C2		Torbrügge 1959a, 194 Nr. 273 Taf. 59,2.
530	Lappersdorf-Hainsacker	R	Hortfund	Lanzenspitze	BZ C2		Torbrügge 1959a, 194 Nr. 273 Taf. 59,5.
531	München-Bogenhausen	M	Brandgrab?	Mittelständiges Lappenbeil	BZ D2-Ha A1		Koschik 1981a, 193 Nr. 138 Taf. 64,2.
532	München-Bogenhausen	M	Brandgrab?	Schwertklingen-fragment	BZ D2-Ha A1		Koschik 1981a, 193 Nr. 138 Taf. 64,1.
533	München-Bogenhausen	M	Brandgrab?	Beilfragment	BZ D2-Ha A1		Koschik 1981a, 193 Nr. 138 Taf. 64,3.
534	München-Bogenhausen	M	Brandgrab?	Nagel	BZ D2-Ha A1		Koschik 1981a, 193 Nr. 138 Taf. 64,6.
535	München-Bogenhausen	M	Brandgrab?	Sichelfragment	BZ D2-Ha A1		Koschik 1981a, 193 Nr. 138 Taf. 64,4.
536	München-Bogenhausen	M	Brandgrab?	Nagel mit großer Kopfplatte	BZ D2-Ha A1		Koschik 1981a, 193 Nr. 138 Taf. 64,7.
537	Obing	TS	Einzelfund	Gusskuchen	?		Menke 1978/79, Abb. 116,1.

Nr.	Fundort	Lkr./Bez.	Fundumstände	Objekt	Datierung	Bemerkung	Literatur
538	Bad Reichenhall-Kirchberg	BGL	Hortfund	Gusskuchen	?		Menke 1978/79, 291 Nr. 115 Abb. 20.
539	Bad Reichenhall-Kirchberg	BGL	Hortfund	Gusskuchen	?		Menke 1978/79, 291 Nr. 115 Abb. 20.
540	Bad Reichenhall-Kirchberg	BGL	Hortfund	Gusskuchen	?		Menke 1978/79, 291 Nr. 115 Abb. 20.
541/O	Bad Reichenhall-Kirchberg	BGL	Hortfund	Gusskuchen	?	obere Schicht	Menke 1978/79, 291 Nr. 115 Abb. 20.
541/U	Bad Reichenhall-Kirchberg	BGL	Hortfund	Gusskuchen	?	untere Schicht	Menke 1978/79, 291 Nr. 115 Abb. 20.
542	Bad Reichenhall-Kirchberg	BGL	Hortfund	Gusskuchen	?		Menke 1978/79, 291 Nr. 115 Abb. 20.
543	Bad Reichenhall-Kirchberg	BGL	Hortfund	Gusskuchenfragment	?		Menke 1978/79, 291 Nr. 115 Abb. 20.
544/G	Regensburg	R	Flußfund	Achtkantschwert	BZ C2	Griff	v. Quillfeldt 1995, 74 Nr. 72 Taf. 24,72.
544/K	Regensburg	R	Flußfund	Achtkantschwert	BZ C2	Klinge	v. Quillfeldt 1995, 74 Nr. 72 Taf. 24,72.
545	Eggstätt	RO	Moorfund	Griffzungenschwert Asenkofen	BZ C2		Schauer 1971, 105 Nr. 330 Taf. 48,330.
546	Garching a. d. Alz-Hart a. d. Alz	AÖ	Brandgrab	Dreiwulstschwert Typ Erding	Ha A1	Griff	v. Quillfeldt 1995, 145 Nr. 141 Taf. 47,141.
547	Garching a. d. Alz-Hart a. d. Alz	AÖ	Brandgrab	Achskappe	Ha A1		Müller-Karpe 1956, 66 q Abb. 6,3 Taf. 6,8.
548	Garching a. d. Alz-Hart a. d. Alz	AÖ	Brandgrab	Tordierter Stab	Ha A1		Müller-Karpe 1956, 66 k.
549	Garching a. d. Alz-Hart a. d. Alz	AÖ	Brandgrab	Tüllenhorn	Ha A1		Müller-Karpe 1956, 65 e Taf. 7,2.
550	Garching a. d. Alz-Hart a. d. Alz	AÖ	Brandgrab	Tordierter Stabaufsatz	Ha A1		Müller-Karpe 1956, 66 k Abb. 5,14 Taf. 6,24.
551	Garching a. d. Alz-Hart a. d. Alz	AÖ	Brandgrab	Fragment v. tordiertem Stab	Ha A1		Müller-Karpe 1956, 66 k Abb. 5,13 Taf. 6,9.
552	Garching a. d. Alz-Hart a. d. Alz	AÖ	Brandgrab	Vogelkopfförmiges Endstück	Ha A1		Müller-Karpe 1956, 66 g Taf. 6,15.
553	Garching a. d. Alz-Hart a. d. Alz	AÖ	Brandgrab	Tüllenförmiger Beschlag	Ha A1		Müller-Karpe 1956, 66 g Taf. 6,6.
554	Haimhausen	DAH	Hortfund	Sichelfragment	BZ D		BVBl. Beih. 11 (München 1998) 80 Abb. 50,10.
555	Haimhausen	DAH	Hortfund	Sichelfragment	BZ D		BVBl. Beih. 11 (München 1998) 80 Abb. 50,9.
556	Haimhausen	DAH	Hortfund	Beilfragment	BZ D		BVBl. Beih. 11 (München 1998) 80 Abb. 50,11.
557	Haimhausen	DAH	Hortfund	Beilfragment	BZ D		BVBl. Beih. 11 (München 1998) 80 Abb. 50,6.
558	Haimhausen	DAH	Hortfund	Beilfragment	BZ D		BVBl. Beih. 11 (München 1998) 80 Abb. 50,7.
559	Haimhausen	DAH	Hortfund	Gusskuchenfragment	BZ D		Moosauer/Bachmaier 2005, Abb. 100.
560/O	Haimhausen	DAH	Hortfund	Gusskuchenfragment	BZ D	obere Schicht	Moosauer/Bachmaier 2005, Abb. 100.
560/U	Haimhausen	DAH	Hortfund	Gusskuchenfragment	BZ D	untere Schicht	Moosauer/Bachmaier 2005, Abb. 100.
561/G	Nußdorf a. d. Oichten	Salzburg	Einzelfund	Vollgriffschwert Typ Wörschach	Ha B1	Griff	Krämer 1985, 33 Nr. 100 Taf. 16,100.
561/K	Nußdorf a. d. Oichten	Salzburg	Einzelfund	Vollgriffschwert Typ Wörschach	Ha B1	Klinge	Krämer 1985, 33 Nr. 100 Taf. 16,100.
562	Lamprechtshausen-Nopping	Salzburg	Grabfund	Schwert	BZ C2		Mayer 1977, Taf. 122,A 1.
563	Lamprechtshausen-Nopping	Salzburg	Grabfund	Beil	BZ C2		Mayer 1977, 143 Nr. 616 Taf. 44,616.

Nr.	Fundort	Lkr./Bez.	Fundumstände	Objekt	Datierung	Bemerkung	Literatur
564/G	Freilassing	BGL	Einzelfund	Achtkantschwert	BZ C2	Griff	v. Quillfeldt 1995, 73 Nr. 65 Taf. 22,65.
564/K	Freilassing	BGL	Einzelfund	Achtkantschwert	BZ C2	Klinge	v. Quillfeldt 1995, 73 Nr. 65 Taf. 22,65.
565	Waging	TS	Grab	Griffplattenmesser	BZ D2		Hohlbein 2016, 94 Nr. 117 Taf. 15,117.
566	Waging	TS	Grab	Nadel Typ Gemeinlebarn	BZ D2		Irlinger 1988.
567/G	Maishofen-Atzing	Salzburg	Einzelfund	Achtkantschwert	BZ C2	Griff	Moosleitner 1991, 89 Nr. 8,1 Abb. 64,1.
567/K	Maishofen-Atzing	Salzburg	Einzelfund	Achtkantschwert	BZ C2	Klinge	Moosleitner 1991, 89 Nr. 8,1 Abb. 64,1.
568	Saalfelden-Magnesitfeld	Salzburg	Hortfund	Griffzungenmesser	Ha B1		Moosleitner 1991, 62 ff. Nr. 2,4 Taf. 20,19.
569	Saalfelden-Magnesitfeld	Salzburg	Hortfund	Messer	Ha B1		Moosleitner 1991, 62 ff. Nr. 2,4 Taf. 20,17.
570	Saalfelden-Magnesitfeld	Salzburg	Hortfund	Riegseemesser	BZ D	2 Analysen	Moosleitner 1991, 62 ff. Nr. 2,4 Taf. 20,18.
570	Saalfelden-Magnesitfeld	Salzburg	Hortfund	Riegseemesser	BZ D	2 Analysen	Moosleitner 1991, 62 ff. Nr. 2,4 Taf. 20,18.
571	Saalfelden-Magnesitfeld	Salzburg	Hortfund	Oberständiges Lappenbeil	Ha B1		Moosleitner 1991, 62 ff. Nr. 2,4 Taf. 18,8.
572	Saalfelden-Magnesitfeld	Salzburg	Hortfund	Oberständiges Lappenbeil	Ha B1		Moosleitner 1991, 62 ff. Nr. 2,4 Taf. 18,6.
573	Saalfelden-Magnesitfeld	Salzburg	Hortfund	Beil	Ha B1		Moosleitner 1991, 62 ff. Nr. 2,4 Taf. 18,7.
574	Saalfelden-Magnesitfeld	Salzburg	Hortfund	Oberständiges Lappenbeil	Ha B1		Moosleitner 1991, 62 ff. Nr. 2,4 Taf. 18,5.
575	Saalfelden-Magnesitfeld	Salzburg	Hortfund	Beil	Ha B1		Moosleitner 1991, 62 ff. Nr. 2,4 Taf. 18,2.
576	Saalfelden-Magnesitfeld	Salzburg	Hortfund	Beilfragment	Ha B1		Moosleitner 1991, 62 ff. Nr. 2,4 Taf. 18,4.
577	Saalfelden-Magnesitfeld	Salzburg	Hortfund	Ring	Ha B1		Moosleitner 1991, 62 ff. Nr. 2,4 Taf. 21,30.
578	Saalfelden-Magnesitfeld	Salzburg	Hortfund	Armringfragment	Ha B1		Moosleitner 1991, 62 ff. Nr. 2,4 Taf. 22,42.
579	Saalfelden-Magnesitfeld	Salzburg	Hortfund	Armring	Ha B1		Moosleitner 1991, 62 ff. Nr. 2,4 Taf. 22,35.
580	Saalfelden-Magnesitfeld	Salzburg	Hortfund	Armring	Ha B1		Moosleitner 1991, 62 ff. Nr. 2,4 Taf. 21,28.
581	Saalfelden-Magnesitfeld	Salzburg	Hortfund	Armring	Ha B1		Moosleitner 1991, 62 ff. Nr. 2,4 Taf. 21,29
582	Saalfelden-Magnesitfeld	Salzburg	Hortfund	Armring	Ha B1		Moosleitner 1991, 62 ff. Nr. 2,4 Taf. 21,31
583	Saalfelden-Magnesitfeld	Salzburg	Hortfund	Armring	Ha B1		Moosleitner 1991, 62 ff. Nr. 2,4 Taf. 21,32
584	Saalfelden-Magnesitfeld	Salzburg	Hortfund	Armring	Ha B1		Moosleitner 1991, 62 ff. Nr. 2,4 Taf. 21,27
585	Saalfelden-Magnesitfeld	Salzburg	Hortfund	Armring	Ha B1	hohl gegossen	Moosleitner 1991, 62 ff. Nr. 2,4 Taf. 20,26.
586	Saalfelden-Magnesitfeld	Salzburg	Hortfund	Sichel	Ha B1		Moosleitner 1991, 62 ff. Nr. 2,4 Taf. 19,9
587	Saalfelden-Magnesitfeld	Salzburg	Hortfund	Sichel	Ha B1		Moosleitner 1991, 62 ff. Nr. 2,4 Taf. 19,10
588	Saalfelden-Magnesitfeld	Salzburg	Hortfund	Sichel	Ha B1		Moosleitner 1991, 62 ff. Nr. 2,4 Taf. 19,11
589	Saalfelden-Magnesitfeld	Salzburg	Hortfund	Felgenniet	Ha B1		Moosleitner 1991, 62 ff. Nr. 2,4 Taf. 23,48.
590	Saalfelden-Magnesitfeld	Salzburg	Hortfund	Wagenteil	Ha B1		Moosleitner 1991, 62 ff. Nr. 2,4 Taf. 23,45.

Nr.	Fundort	Lkr./Bez.	Fundumstände	Objekt	Datierung	Bemerkung	Literatur
591	Saalfelden-Magnesitfeld	Salzburg	Hortfund	Wagenbeschlag	Ha B1		Moosleitner 1991, 62 ff. Nr. 2,4 Taf. 23,46.
592	Saalfelden-Magnesitfeld	Salzburg	Hortfund	Wagenteil	Ha B1		Moosleitner 1991, 62 ff. Nr. 2,4 Taf. 23,44.
593	Saalfelden-Magnesitfeld	Salzburg	Hortfund	Lanzenspitze	Ha B1		Moosleitner 1991, 62 ff. Nr. 2,4 Taf. 20,22.
594	Saalfelden-Magnesitfeld	Salzburg	Hortfund	Lanzenspitze	Ha B1		Moosleitner 1991, 62 ff. Nr. 2,4 Taf. 20,20.
595	Saalfelden-Magnesitfeld	Salzburg	Hortfund	Lanzenspitze	Ha B1		Moosleitner 1991, 62 ff. Nr. 2,4 Taf. 20,21.
596	Saalfelden-Magnesitfeld	Salzburg	Hortfund	Schwertklingen-fragment	Ha B1		Moosleitner 1991, 62 ff. Nr. 2,4 Taf. 20,24.
597	Saalfelden-Magnesitfeld	Salzburg	Hortfund	Tüllenmeißel	Ha B1		Moosleitner 1991, 62 ff. Nr. 2,4 Taf. 18,1.
598	Saalfelden-Magnesitfeld	Salzburg	Hortfund	Gusskuchen	Ha B1		Moosleitner 1991, 62 ff. Nr. 2,4 Taf. 24,50.
599	Saalfelden-Magnesitfeld	Salzburg	Hortfund	Gusskuchen	Ha B1	2 Bohrungen	Moosleitner 1991, 62 ff. Nr. 2,4 Taf. 24,51.
600	Saalfelden-Magnesitfeld	Salzburg	Hortfund	Gusskuchen	Ha B1	ältere Materialprobe	Moosleitner 1991, 62 ff. Nr. 2,4 Taf. 24,49.
601	Saalfelden-Magnesitfeld	Salzburg	Hortfund	Gusskuchenfragment	Ha B1		Moosleitner 1991, 62 ff. Nr. 2,4 Taf. 24,53.
602	Saalfelden-Magnesitfeld	Salzburg	Hortfund	Gusskuchenfragment	Ha B1		Moosleitner 1991, 62 ff. Nr. 2,4 Taf. 24,54.
603	Saalfelden-Magnesitfeld	Salzburg	Hortfund	Gusskuchenfragment	Ha B1		Moosleitner 1991, 62 ff. Nr. 2,4 Taf. 24,55.
604	Saalfelden-Magnesitfeld	Salzburg	Hortfund	Gusskuchenfragment	Ha B1		Moosleitner 1991, 62 ff. Nr. 2,4 Taf. 24,52.
605	Lenzing-Wiesersberg	Salzburg	Einzelfund	Gusskuchen	?		Krauß 1998/99, 118 Nr. 16 Abb. 4,16.
606	München-Oberföhring	M	Flußfund	Randleistenbeil	BZ C	Probe entnommen in Aachen	Koschik 1981a, 196 Nr. 152 Taf. 67,7.
607	Kuchl-Georgenberg	Salzburg	Höhensiedlung (Sondengängerfund)	Gusskuchenfragment	?		Unpubliziert.
608	Aschau-Hohenaschau	RO	Hortfund	Gusskuchenfragment	Ha B1		BVBl. Beih. 10 (München 1997) 86.
609	Marquartstein	TS	Einzelfund	Gusskuchenfragment	?		Unpubliziert.
610	Bernau a. Chiemsee-Schleipfen	RO	Einzelfund	Gusskuchenfragment	?		BVBl. Beih. 13 (München 2000) 53.
611	Nußdorf-Sondermoning	TS	Hortfund	Armringfragment	Ha A2-B1		BVBl. Beih. 7 (München 1994) 91.
612	Nußdorf-Sondermoning	TS	Hortfund	Sichelfragment	Ha A2-B1		BVBl. Beih. 7 (München 1994) 91.
613	Nußdorf-Sondermoning	TS	Hortfund	Sichel	Ha A2-B1		BVBl. Beih. 7 (München 1994) 91.
614	Nußdorf-Sondermoning	TS	Hortfund	Gusskuchenfragment	Ha A2-B1		BVBl. Beih. 7 (München 1994) 91.
615	Nußdorf-Sondermoning	TS	Hortfund	Gusskuchen (Hohlform)	Ha A2-B1	spröde, silbrig-grau	BVBl. Beih. 7 (München 1994) 91.
616	Nußdorf-Sondermoning	TS	Hortfund	Gusskuchenfragment	Ha A2-B1	spröde, pulvrig grau	BVBl. Beih. 7 (München 1994) 91.
617	Nußdorf-Sondermoning	TS	Hortfund	Gusskuchenfragment	Ha A2-B1		BVBl. Beih. 7 (München 1994) 91.
618	Nußdorf-Sondermoning	TS	Hortfund	Gusskuchenfragment	Ha A2-B1		BVBl. Beih. 7 (München 1994) 91.
619	Nußdorf-Sondermoning	TS	Hortfund	Gusskuchenfragment	Ha A2-B1	sehr spröde, pulvrig grau	BVBl. Beih. 7 (München 1994) 91.
620	Nußdorf-Sondermoning	TS	Hortfund	Gusskuchenfragment	Ha A2-B1		BVBl. Beih. 7 (München 1994) 91.

Nr.	Fundort	Lkr./Bez.	Fundumstände	Objekt	Datierung	Bemerkung	Literatur
621	Hurlach	LL	Brandgrab B	Bronzetasse	Ha A2	kleines Blechfragment	Unpubliziert (Winghart 1996).
622	Hurlach	LL	Brandgrab B	Messer	Ha A2		Hohlbein 2016, 238 Nr. 715 Taf. 58,715.
623	Hurlach	LL	Lesefund Gräberfeldbereich	Messer	Ha A1		Hohlbein 2016, 203 Nr. 482 Taf. 42,482.
624	Hurlach	LL	Brandgrab A	Rasiermesser	Ha A2		Unpubliziert (Winghart 1996).
625	Hurlach	LL	Brandgrab Bef. 1578	Messer	BZ D2		Hohlbein 2016, 139 Nr. 309 Taf. 26,309.
626	Hurlach	LL	Brandgrab Bef. 1578	Gewicht (?)	BZ D2		Winghart 1996, Abb. 43,3.
627	Hurlach	LL	Brandgrab 1578	Gewicht (?)	BZ D2		Winghart 1996, Abb. 43,1.
628	Hurlach	LL	Brandgrab 1578	Gewicht (?)	BZ D2		Winghart 1996, Abb. 43,2.
629	Hurlach	LL	Brandgrab Bef. 1578	Gewicht (?)	BZ D2		Winghart 1996, Abb. 43,3.
630	Hopfgarten	Tirol	Einzelfund	Randleistenbeil	BZ A2		Zemmer-Plank 1968, 107 Abb. 2.
631	Innsbruck-Berg Isel	Tirol	Einzelfund	Randleistenbeil	BZ A2		Mayer 1977, 102 Nr. 308 Taf. 21,308.
632/G	Absam	Tirol	Einzelfund	Vollgriffschwert Typ Spatzenhausen	BZ B-C1	Griff	Krämer 1985, 11 Nr. 4 Taf. 1,4.
632/K	Absam	Tirol	Einzelfund	Vollgriffschwert Typ Spatzenhausen	BZ B-C1	Klinge	Krämer 1985, 11 Nr. 4 Taf. 1,4.
633/G	Kramsach-Achenrain	Tirol	Einzelfund	Achtkantschwert	BZ C2	Griff	Krämer 1985, 13 Nr. 10 Taf. 2,10.
633/K	Kramsach-Achenrain	Tirol	Einzelfund	Achtkantschwert	BZ C2	Klinge	Krämer 1985, 13 Nr. 10 Taf. 2,10.
634/G	Vermutlich Rattenberg	Tirol	Einzelfund	Achtkantschwert	BZ C2	Griff	Huijsmans 1994, Nr. 77 Taf. 17,2.
634/K	Vermutlich Rattenberg	Tirol	Einzelfund	Achtkantschwert	BZ C2	Klinge	Huijsmans 1994, Nr. 77 Taf. 17,2.
635/G	Kufstein	Tirol	Einzelfund	Vollgriffschwert	BZ D	Griff	Huijsmans 1994, Nr. 88 Taf. 17,3.
635/K	Kufstein	Tirol	Einzelfund	Vollgriffschwert	BZ D	Klinge	Huijsmans 1994, Nr. 88 Taf. 17,3.
636	Wiesing-Buchberg	Tirol	Unbekannt	Gusskuchen	?		Otto/Witter 1952, 204 Nr. Z 1276. - Ausstellungskat. Kufstein 1993 I, 81 Nr. 1.57 b.
637	Eben	Tirol		Griffplattendolch	BZ B		Huijsmans 1994, Nr. 70 Taf. 12,4.
638	Rum	Tirol		Griffplattendolch	BZ C		Huijsmans 1994, Nr. 42 Taf. 12,5.
639	Zirl	Tirol		Griffplattendolch	BZ C		Huijsmans 1994, Nr. 20 Taf. 13,1.
640	Natters-Sonnenburger Hügel	Tirol		Griffplattendolch	BZ C		Huijsmans 1994, Nr. 28 Taf. 13,2.
641	Ampaß	Tirol		Griffplattendolch	BZ C		Huijsmans 1994, Nr. 45 Taf. 13,3.
642/G	Innsbruck-Wilten	Tirol		Vollgriffschwert (Sonderform)	BZ D	Griff	Krämer 1985, 19 Nr. 41 Taf. 8,41.
642/K	Innsbruck-Wilten	Tirol		Vollgriffschwert (Sonderform)	BZ D	Klinge	Krämer 1985, 19 Nr. 41 Taf. 8,41.
647/G	Innsbruck-Wilten	Tirol		Vollgriffschwert Typ Gundelsheim	BZ C	Griff	Krämer 1985, 25 Nr. 67 Taf. 12,67.
643	Alpach-Steinbergalpe	Tirol	Höhenfund, ca. 1000 m	Mittelständiges Lappenbeil	BZ D1		Mayer 1977, 144 Nr. 624 Taf. 45,624.
644	Sistrans	Tirol	Grab	Armring	BZ D1		Sperber 1977, Taf. 74,8.

Nr.	Fundort	Lkr./Bez.	Fundumstände	Objekt	Datierung	Bemerkung	Literatur
645	Sistrans	Tirol	Grab	Mohnkopfnadel	BZ D1		Sperber 1977, Taf. 74,11.
646	Innsbruck-Wilten	Tirol	Grab 16	Dolch	BZ D2-Ha A1		Wagner 1943, 123 Nr. 6 Taf. 37,15.
647/K	Innsbruck-Wilten	Tirol		Vollgriffschwert Typ Gundelsheim	BZ D2-Ha A1	Klinge	Krämer 1985, 25 Nr. 67 Taf. 12,67.
648	Innsbruck-Wilten	Tirol	Grab 15	Messer	BZ D1		Wagner 1943, 123 Nr. 4 Taf. 37,20.
649	Innsbruck-Wilten	Tirol	Grab 88	Messer	BZ D1		Wagner 1943, 132 Nr. 11 Taf. 37,14.
650	Innsbruck-Wilten	Tirol	Grab 70	Griffdornmesser	BZ D2		Wagner 1943, 129 Nr. 5 Taf. 31,11.
651	Innsbruck-Wilten	Tirol	Grab 68	Griffzungenmesser Typ Matrei	BZ D2		Wagner 1943, 129 Nr. 4 Taf. 30,19.
652	Innsbruck-Mühlau	Tirol	Grab 54b	Griffdornmesser	Ha A1		Wagner 1943, 99 Gr.54b Nr. 5 Taf. 14,8.
653	Innsbruck-Mühlau	Tirol	Grab 35	Griffzungenmesser Typ Mühlau	Ha A1		Wagner 1943, 93 f. Gr. 35 Nr. 7 Taf. 15,6.
654	Innsbruck-Mühlau	Tirol	Grab 5	Messer	Ha A1		Wagner 1943, 87 Gr. 5 Nr. 4 Taf. 11,25.
655	Innsbruck-Wilten	Tirol	Grab 72	Messer	Ha B1		Wagner 1943, 130 Gr. 72 Nr. 3 Taf. 27,13.
656	Innsbruck-Mühlau	Tirol	Grab 30	Messer	Ha B1		Wagner 1943, 93 Gr. 30 Nr. 4 Taf. 12,22.
657	Innsbruck-Mühlau	Tirol	Grab 53	Griffdornmesser	Ha B1		Wagner 1943, 98 Gr. 53 Nr. 8; Sperber 1977, Taf. 206,8.
658	Innsbruck-Berg Isel	Tirol		Messer	Ha B2		Tomedi/Appler/Putzer 2001, Abb. 1,4.
659	Jerzens („Ritzenried, Pitztal“)	Tirol		Oberständiges Lappenbeil	Ha B2		Mayer 1977, 181 Nr. 921 Taf. 68,921.
660	Rimsting-Hörzing	RO	Grabhügel	Petschaftkopfnadel	BZ C1		BVBl. Beih. 10 (München 1997) 91 Abb. 62,7.
661	Rimsting-Hörzing	RO	Grabhügel	Mittelständiges Lappenbeil	BZ C1		BVBl. Beih. 10 (München 1997) 91 Abb. 62,8.
662	Rimsting-Hörzing	RO	Grabhügel	Griffplattendolch	BZ C1		BVBl. Beih. 10 (München 1997) 91 Abb. 62,6.
663	Gars a. Inn-Winterberg	MÜ	Einzelfund	Oberständiges Lappenbeil mit Öse	Ha B3		BVBl. Beih. 12 (München 1999) 69.
664/G	Volders	Tirol	Grab 18	Vollgriffschwert Typ Gundelsheim	BZ D2	Griff	Krämer 1985, 25 Nr. 58 Taf. 11,58.
664/K	Volders	Tirol	Grab 18	Vollgriffschwert Typ Gundelsheim	BZ D2	Klinge	Krämer 1985, 25 Nr. 58 Taf. 11,58.
665	Volders	Tirol	Grab 18	Griffzungenmesser Typ Matrei	BZ D2		Kasseroler 1959, 34 ff. Abb. S. 210/18.
666/G	Wattenberg	Tirol		Vollgriffdolch	BZ B	Griff	Huijsmans 1994, Nr. 58 Taf. 15,1.
666/K	Wattenberg	Tirol		Vollgriffdolch	BZ B	Klinge	Huijsmans 1994, Nr. 58 Taf. 15,1.
667	Volders	Tirol	Grab 202	Messer	Ha A2		Kasseroler 1959, 88; Sperber 2003, Abb. 7,6.
668	Volders	Tirol	Grab 244	Messer	Ha B2		Kasseroler 1959, 105; Sperber 2003, Abb. 6,8.
669	Volders	Tirol	Grab 349	Messer	Ha B1		Kasseroler 1959, 139 f.; Sperber 2011, Abb. 6,1.
670	Volders	Tirol	Grab 331	Griffzungenmesser Typ Pfatten	Ha B1		Kasseroler 1959, 134 Taf. 32/331.
671	Volders	Tirol	Grab 329	Armring	Ha B2		Kasseroler 1959, 133 f. Taf. 36/329.
672	Volders	Tirol	Grab 328	Fragment Griffdornmesser	Ha B2		Kasseroler 1959, 132 f.; Sperber 2003, Abb.6,7.

Nr.	Fundort	Lkr./Bez.	Fundumstände	Objekt	Datierung	Bemerkung	Literatur
673	Volders	Tirol	Grab 266	Messer	Ha B2		Kasseroler 1959, 114 Taf. 33/266.
674	Volders	Tirol	Grab 358	Messer	Ha B2		Kasseroler 1959, 142 f.; Sperber 2003, Abb. 6,9.
675	Volders	Tirol	Grab 144	Messer	BZ D1		Kasseroler 1959, 70 Taf. 31/144.
676	Volders	Tirol	Grab 86	Messer Typ Mühlau	BZ D2		Kasseroler 1959, 56.
677	Volders	Tirol	Grab 99	Messer	Ha A1		Kasseroler 1959, 59 Taf. 31/99.
678	Volders	Tirol	Grab 110	Messer	Ha A1		Kasseroler 1959, 62.; Sperber 1977, Taf. 92,4.
679	Volders	Tirol	Grab 28	Griffzungenmesser Typ Mühlau	Ha A1		Kasseroler 1959, 37 f.; Sperber 1977, Taf. 86,2.
680	Volders	Tirol	Grab 296	Messer	Ha B2		Kasseroler 1959, 122 f. Taf. 33/296.
681	Volders	Tirol	Grab 215	Messer	Ha A2		Kasseroler 1959, 93 f.
682	Volders	Tirol	Grab 398	Messer	Ha A2		Kasseroler 1959, 155 f. Taf. 32/398.
683	Volders	Tirol	Grab 176	Messer	Ha A2		Kasseroler 1959, 79 Taf. 33/176.
684	Volders	Tirol	Grab 256	Messer	Ha B1		Kasseroler 1959, 109 f. Taf. 32/256.
685	Jochberg-Kelchalm	Tirol	Scheidehalde	Nadel Typ Gemeinlebarn	BZ D2		Pittioni 1968, Abb. 16, 2. Nadel v. links.
686	Jochberg-Kelchalm	Tirol	Scheidehalde	Nadel Typ Gemeinlebarn	BZ D2		Pittioni 1968.
687	Jochberg-Kelchalm	Tirol	Scheidehalde	Nadel	BZ D2		Pittioni 1968, Abb. 16, 3. Nadel v. rechts.
688	Jochberg-Kelchalm	Tirol	Scheidehalde	Nadel Typ Gemeinlebarn	BZ D2		Pittioni 1968.
689	Jochberg-Kelchalm	Tirol	Scheidehalde	Nadel m. Kugelkopf	BZ D2		Pittioni 1968, Abb. 16, 1. Nadel v. rechts.
690	Jochberg-Kelchalm	Tirol	Scheidehalde	Messer	BZ D		Pittioni 1968, Abb. 16, oberes Messer.
691	Jochberg-Kelchalm	Tirol	Scheidehalde, Abfallgrube 47	Gusskuchenfragment	?		Preuschen/Pittion 1954, 28 Abb. 27,7.
692	Jochberg-Kelchalm	Tirol	Scheidehalde, Abfallgrube 47	Sichel	BZ D		Preuschen/Pittioni 1954, 28 Abb. 27,5.
693	Kitzbühel-Lebenberg	Tirol	Brandgrab 5	Messer	BZ D1		Zemmer-Plank 1968, 127 f. Abb. 32.
694	Kitzbühel-Lebenberg	Tirol	Brandgrab 16	Lanzenspitze	Ha B1		Zemmer-Plank 1968, 133 Abb. 45.
695/G	Kitzbühel-Lebenberg	Tirol	Brandgrab 16	Dreiwulstschwert m. Pilzknauf	Ha B1	Griff	Krämer 1985, 31 Nr. 92 Taf. 16,92.
695/K	Kitzbühel-Lebenberg	Tirol	Brandgrab 16	Dreiwulstschwert m. Pilzknauf	Ha B1	Klinge	Krämer 1985, 31 Nr. 92 Taf. 16,92.
696/G	Kitzbühel-Kirchberg	Tirol	Einzelfund	Dreiwulstschwert Erding/Gundelsheim	BZ D2-Ha A1	Griff	Krämer 1985, 28 Nr. 75 Taf. 13,75.
696/K	Kitzbühel-Kirchberg	Tirol	Einzelfund	Dreiwulstschwert Erding/Gundelsheim	BZ D2-Ha A1	Klinge	Krämer 1985, 28 Nr. 75 Taf. 13,75.
697	Volders	Tirol	Grab 256	Gusskuchenfragment	Ha B1	Stück für Schliff abgetrennt	Kasseroler 1959, 109 f.
698	Lenggries-Untermurbach	TÖL	Hortfund (?)	Randleistenbeil	BZ B		Lenggrieser Museumsschr. 1 (2008) Abb. S. 6, ob. Beil.

Nr.	Fundort	Lkr./Bez.	Fundumstände	Objekt	Datierung	Bemerkung	Literatur
699	Lenggries-Untermurbach	TÖL	Hortfund (?)	Sichelfragment	BZ B		Lenggrieser Museumsschr. 1 (2008) Abb. S. 6, links.
700	Schlehdorf-Schlehdorfer Joch	TÖL	Höhensiedlung?	Gusskuchenfragment	?		Unpubliziert.
701	Schlehdorf-Schlehdorfer Joch	TÖL	Höhensiedlung?	Gusskuchenfragment	?		Unpubliziert.
702	Schlehdorf-Schlehdorfer Joch	TÖL	Höhensiedlung?	Gusskuchenfragment	?		Unpubliziert.
703	Schlehdorf-Schlehdorfer Joch	TÖL	Höhensiedlung?	Gusskuchenfragment	?		Unpubliziert.
704	Schlehdorf-Schlehdorfer Joch	TÖL	Höhensiedlung?	Messer	Ha A1		Unpubliziert.
705	Schlehdorf-Schlehdorfer Joch	TÖL	Höhensiedlung?	Lappenbeil	Ha A		Unpubliziert.
706	Schlehdorf-Schlehdorfer Joch	TÖL	Höhensiedlung?	Sichel	Ha A1	gussgleich mit SSN-Nr. 707?	Unpubliziert.
707	Schlehdorf-Schlehdorfer Joch	TÖL	Höhensiedlung?	Sichel	Ha A1-2	gussgleich mit SSN-Nr. 706?	Unpubliziert.
708	Schlehdorf-Schlehdorfer Joch	TÖL	Höhensiedlung?	Sichel	Ha A		Unpubliziert.
709	Mühldorf a. Inn	MÜ	Flußfund	Randleistenbeil	BZ C		Unpubliziert.
710/A	Neuburg a. Inn-Dommelstadl	PA	Angeblich aus einem Grabhügel	Vollgriffschwert Typ Mörigen	Ha B3	2 Proben (Griff und Klinge, jedoch nicht zuweisbar); Proben entnommen vom Mus. Karlsruhe	v. Quillfeldt 1995, 237 Nr. 272 Taf. 96,272.
710/B	Neuburg a. Inn-Dommelstadl	PA	Angeblich aus einem Grabhügel	Vollgriffschwert Typ Mörigen	Ha B3	2 Proben (Griff und Klinge, jedoch nicht zuweisbar); Proben entnommen vom Mus. Karlsruhe	v. Quillfeldt 1995, 237 Nr. 272 Taf. 96,272.
711	Schlehdorf-Schlehdorfer Joch	TÖL	Höhensiedlung?	Gusskuchenfragment	?		Unpubliziert.
712	Nußdorf a. Inn	RO	Zerstörte Brandgräber (8/95)	Vasenkopfnadel	BZ D2-Ha A1		BVBl. Beih. 11 (München 1998) 82.
713	Nußdorf a. Inn	RO	Zerstörte Brandgräber (9/93)	Gerippter Stollenarmring	BZ D		BVBl. Beih. 9 (München 1996) 111.
714	Nußdorf a. Inn	RO	Zerstörte Brandgräber (10/93)	Gerippter Stollenarmring	BZ D		BVBl. Beih. 9 (München 1996) 111.
715	Nußdorf a. Inn	RO	Aus zerstörten Brandgräbern	Griffplattendolch	BZ D		BVBl. Beih. 11 (München 1998) 82.
716	Aschau	RO	Einzelfund	Tüllenhammer oder Amboß	?	sehr sprödes Material	Zanier 2001, 50; 143 Nr. B9; 135 Abb. 13,B9.
717/G	Völs	Tirol	Wahrscheinlich Körpergrab	Vollgriffschwert Derivat Spatzenhausen	BZ B-C1	Griff	Krämer 1985, 11 Nr. 5 Taf. 1,5.
717/K	Völs	Tirol	Wahrscheinlich Körpergrab	Vollgriffschwert Derivat Spatzenhausen	BZ B-C1	Klinge	Krämer 1985, 11 Nr. 5 Taf. 1,5.
718/G	Breitenbach	Tirol	Einzelfund	Achtkantschwert	BZ C2	Griff	Krämer 1985, 15 Nr. 13A Taf. 3,13A.
718/K	Breitenbach	Tirol	Einzelfund	Achtkantschwert	BZ C2	Klinge	Krämer 1985, 15 Nr. 13A Taf. 3,13A.
719	Starnberg-Mühlthal	STA	Einzelfund von der „Karlsburg“	Gusskuchenfragment	?		OA BLfD München (FZ-Nr. 15832 D).
720	Nußdorf a. Inn	RO	Lesefund v. Gräberfeld (1/97)	Turbankopfnadel	BZ D2		BVBl. Beih. 13 (München 2000) 70.
721	Kiefersfelden-Ried	RO	Einzelfund	Oberst. Lappenbeil mit Öse	Ha B3		BVBl. Beih. 11 (München 1998) 95.

Nr.	Fundort	Lkr./Bez.	Fundumstände	Objekt	Datierung	Bemerkung	Literatur
722	Flintsbach a. Inn	RO	Siedlungsfund (evtl. ehem. Depot)	Gusskuchenfragment (?)	Ha A2-B1	grüngrau, pulvrig	Möslein 1998/99b, 346 Abb. 12,7.
723	Bad Füssing(?)-Würding	PA	Flußfund	Fragm. Schwert	Ha A2		Schauer 1971, 189 Nr. 587 Taf. 90,587.
724	Vilshofen	PA	Einzelfund	Griffzungenschwert T. Reutlingen	BZ D-Ha A1		Schauer 1971, 136 Nr. 409 Taf. 60,409.
725	Bad Füssing-Würding (?)	PA	Flußfund	Griffzungenmesser Typ Matrei	Ha A1		Pätzold/Uenze 1963, 149 Nr. 135 Taf. 25,1.
726	Schleching-Streichen	TS	Höhensiedlung. Zum Hortfund?	Gusskuchenfragment	?	spröde, pulvrig schwarzgrau	OA BLfD München. - BVBl. Beih. 11 (München 1998) 98.
727	Petting-Ammerberg	TS	Grabfund	Großköpfige Vasenkopfnadel	Ha B2		Unpubliziert.
728	Petting-Ammerberg	TS	Grabfund	Messer	Ha B2		Unpubliziert.
729	Petting-Ammerberg	TS	Grabfund	Armringfragment	Ha B2		Unpubliziert.
730/G	Nußdorf a. Inn	RO	Grabfund	Dreiwulstschwert T. Gundelsheim	Ha A1	Griff	Möslein 1997, Abb. 40; 41,1.
730/K	Nußdorf a. Inn	RO	Grabfund	Dreiwulstschwert T. Gundelsheim	Ha A1	Klinge	Möslein 1997, Abb. 40; 41,1.
731	Nußdorf a. Inn	RO	Grabfund	Messer	Ha A1		Möslein 1997, Abb. 41,4.
732	Nußdorf a. Inn	RO	Grabfund	Nadel	Ha A1		Möslein 1997, Abb. 40,3.
733	Nußdorf a. Inn	RO	Grabfund	Rasiermesser	Ha A1		Möslein 1997, Abb. 40,2.
734	Schleching-Streichen	TS	Hortfund	Stabförmiges Fragment	Ha B2		BVBl. Beih. 15 (München 2002) 98.
735	Walpertskirchen-Ringelsdorf	ED	Einzelfund	Absatzbeil	BZ C		Unpubliziert.
736/G	Wartenberg-Thenn	ED	Einzelfund	Dreiwulstschwert Typ Erding	BZ D2-Ha A1	Griff	Schefzik 2001, 272 Nr. 208.
736/K	Wartenberg-Thenn	ED	Einzelfund	Dreiwulstschwert Typ Erding	BZ D2-Ha A1	Klinge	Schefzik 2001, 272 Nr. 208.
737/G	Fahrenzhausen-Weng	FS	Einzelfund, wohl von feuchtem Grund	Achtkantschwert	BZ C2	Griff	v. Quillfeldt 1998.
737/K	Fahrenzhausen-Weng	FS	Einzelfund, wohl von feuchtem Grund	Achtkantschwert	BZ C2	Klinge	v. Quillfeldt 1998.
738/G	Tacherting-Unterbrunnham	TS	Grabfund	Dreiwulstschwert Typ Illertissen	Ha A1	Griff	Unpubliziert.
738/K	Tacherting-Unterbrunnham	TS	Grabfund	Dreiwulstschwert Typ Illertissen	Ha A1	Klinge	Unpubliziert.
739	Tacherting-Unterbrunnham	TS	Grabfund	Kleiner Gusskuchen	Ha A1		Unpubliziert.
Nicht berücksichtigte Analysen							
30	Flintsbach-“Rachelburg“ RO	RO	Höhensiedlung „Rachelburg“	Zinnplättchen	?		Unpubliziert.
94	Irschenberg-Wilparting MB	MB	Einzelfund	Gußkuchen	?		Unpubliziert.
391	Flintsbach-“Rachelburg“ RO	RO	Höhensiedlung „Rachelburg“	Bleibatzen	?		Unpubliziert.
467A	Bullenheimer Berg		Hortfund von Höhensiedlung	Gußform für Lappenbeil	Ha B3		Braun 1998, Abb. 1.
467B	Bullenheimer Berg		Hortfund von Höhensiedlung	Gußform für Lappenbeil	Ha B3		Braun 1998, Abb. 1.

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Authors

Ernst Pernicka – Curt Engelhorn Centre of Archaeometry, Mannheim, ernst.pernicka@cez-archaeometrie.de
Stephan Möslein, Austraße 30, D-83646 Bad Tölz, stephan.moeslein@t-online.de

Correspondence and material requests should be addressed to: stephan.moeslein@t-online.de

Peer-reviewers of this volume

Univ.-Prof. Dr. Martin Bartelheim
Institut für Ur- und Frühgeschichte und Archäologie des Mittelalters
Eberhard Karls University of Tübingen
Schloss Hohentübingen, D-72070 Tübingen
martin.bartelheim@uni-tuebingen.de

Mirco Brunner M.A.
University of Bern, Institute of Archaeological Science, Prehistory Department
& Oeschger Centre for Climate Change Research (OCCR)
Research Group, Prehistory Archeology
Mittelstrasse 43, CH-3012 Bern
mirco.brunner@iaw.unibe.ch

Univ.-Prof. Dr. Philippe Della Casa
University of Zürich, Institut für Archäologie
Fachbereich Prähistorische Archäologie
Karl-Schmid-Str. 4, CH - 8006 Zürich
philippe.dellacasa@uzh.ch

Dr. Jennifer Garner
Deutsches Bergbau-Museum Bochum
Research Department, Mining Archaeology
Haus der Archäologien
Am Bergbaumuseum 31, D-44791 Bochum
Jennifer.Garner@bergbaumuseum.de

Dr. Guntram Gassmann
Landesamt für Denkmalpflege
Berliner Straße 12, D-73728 Esslingen
guntram.gassmann@rps.bwl.de

Ao. Univ.-Prof. Dr. Gert Goldenberg
University of Innsbruck
Institut für Archäologien
Forschungszentrum HiMAT
Langer Weg 11, A-6020 Innsbruck
gert.goldenberg@uibk.ac.at

Mag. Caroline Grutsch
University of Innsbruck
Institut für Archäologien
Forschungszentrum HiMAT
Langer Weg 11, A-6020 Innsbruck
Caroline.Grutsch@student.uibk.ac.at

Ao. Univ.-Prof. Dr. Roland Haubner
TU Vienna, Institute of Chemical Technologies and Analytics.
Division Chemical Technologies, Research Group Chemical Vapour Deposition
Getreidemarkt 9/164-CT, A-1060 Wien
roland.haubner@tuwien.ac.at

Dr. Stefan Heuberger
ETH Zürich, Dep. of Earth Sciences
Fachgruppe Georessourcen Schweiz
Sonneggstrasse 5, CH-8092 Zürich
stefan.heuberger@erdw.ethz.ch

Dr. Martin Hinz
University of Bern Institute of Archaeological Science, Prehistory Department
Research Group, Prehistory Archaeology
Mittelstrasse 43, CH-3012 Bern
martin.hinz@iaw.unibe.ch

Dr. Vera Hubert
Wiss. Mitarbeiterin Konservierungsforschung
Schweizerisches Nationalmuseum, Sammlungszentrum
Lindenmoosstrasse 1, CH-8910 Affoltern a. Albis
vera.hubert@snm.admin.ch

Univ.-Prof. Dr. Christoph Huth
Institut für Archäologische Wissenschaften,
Abteilung für Urgeschichtliche Archäologie
Belfortstraße 27, D-79085 Freiburg
christoph.huth@archaeologie.uni-freiburg.de

PD Dr. Reinhard Jung
Österreichische Akademie der Wissenschaften
Institut für Orientalische und Europäische Archäologie (OREA)
Hollandstr. 11-13, A-1020 Wien
Reinhard.Jung@oeaw.ac.at

Apl. Univ.-Prof. Dr. Sabine Klein
Research Department, Archaeometallurgy
Deutsches Bergbau-Museum Bochum
Haus der Archäologien
Am Bergbaumuseum 31, D-44791 Bochum
Sabine.Klein@bergbaumuseum.de

Univ.-Prof. Dr. Rüdiger Krause
Institut für Archäologische Wissenschaften.
Vor- und Frühgeschichte
Campus Westend Norbert-Wollheim-Platz 1
D-60629 Frankfurt (Main)
R.Krause@em.uni-frankfurt.de

Dr. Joachim Lutz
Curt-Engelhorn-Zentrum Archäometrie gGmbH
D6, 3, D-68159 Mannheim
joachim.lutz@cez-archaeometrie.de

Dipl. min. Klaus-Peter Martinek
Unabhängiger Forscher, Mineraloge, München
kpmartinek@t-online.de

Ao. Univ.-Prof. Dr. Kurt Nicolussi
AG Alpine Dendrochronologie/Alpine Tree-ring group
Institut für Geographie, University of Innsbruck
Innrain 52, A-6020 Innsbruck
kurt.nicolussi@uibk.ac.at

Univ.-Prof. Dr. Paolo Nimis
Dipartimento di Geoscienze. Università di Padova
Via G. Gradenigo 6, I-35131 Padova
paolo.nimis@unipd.it

Dr. Klaus Powroznik
Archäologe, Osiris Imaging
Mozartstraße 12, D-79761 Waldshut-Tiengen
powroznik@osiris-imaging.de

Dr. Vanessa Py-Saragaglia
GEODE - UMR 5602 CNRS
5, all. Antonio Machado,
F-31058 Toulouse cedex 9
vanessa.py@univ-tlse2.fr

Univ.-Prof. Dr. Thilo Rehren
Science and Technology in Archaeology and Culture
Research Center (STARC)
The Cyprus Institute, CyI Athalassa Campus
20 Constantinou Kavafi Street,
CY-2121 Nicosia
th.rehren@cyi.ac.cy

Dr. Thomas Reitmaier
Kantonsarchäologe/Archeolog chantunal/
Archeologo cantonale
Archäologischer Dienst Graubünden/Amt für Kultur/
Servetsch archeologic dal Grischun/Uffizi da cultura/
Servizio archeologico dei Grigioni/Ufficio della cultura
Loëstrasse 26, CH-7001 Chur/Cuira/Coira
thomas.reitmaier@adg.gr.ch

Dr. Leandra Reitmaier-Naef
University of Zürich, Institut für Archäologie
Fachbereich Prähistorische Archäologie
Karl-Schmid-Str. 4, CH - 8006 Zürich
leandra.reitmaier@gmx.ch

Ass. Univ.-Prof. Dr. Benjamin W. Roberts
Durham University, Dept. Archaeology
South Road. Durham, GB, DH1 3LE
benjamin.roberts@durham.ac.uk

Dr. Marianne Senn
Eidgenössische Materialprüfungs- und
Forschungsanstalt (EMPA)
Leiterin Empa-Archiv
Ueberlandstrasse 129,
CH-8600 Dübendorf
marianne.senn@empa.ch

Univ.-Prof. Dr. Vincent Serneels
Université de Fribourg, Department of Geosciences
PER 07 bu. 3.313. Ch. du Musée 6
CH-1700 Fribourg
vincent.serneels@unifr.ch

Mag. Markus Staudt
University of Innsbruck, Institut für Archäologien
Forschungszentrum HiMAT
Langer Weg 11, A-6020 Innsbruck
Markus.Staudt@uibk.ac.at

Univ.-Prof. Dr. Thomas Stöllner
Ruhr-University Bochum
Institute of Archaeological Studies,
Pre- and Protohistory
and
Deutsches Bergbau-Museum Bochum
Research Department, Mining Archaeology
Haus der Archäologien
Am Bergbaumuseum 31, D-44791 Bochum
thomas.stoellner@bergbaumuseum.de; thomas.
stoellner@rub.de

Dr. Willy Tegel
Institute of Forest Sciences/Forest Growth
and Dendroecology
University of Freiburg, Tennenbacher Str. 4.
D-79106 Freiburg
tegel@dendro.de

Dr. Peter Thomas
Deutsches Bergbau-Museum Bochum
Research Department, Mining Archaeology
Haus der Archäologien, Am Bergbaumuseum 31,
D-44791 Bochum
Peter.Thomas@bergbaumuseum.de

Dr. Ulrike Töchterle
University of Innsbruck, Institut für Archäologien
Fachbereich Klassische und Provinzialrömische
Archäologie, Restaurierung
Templstr. 22, A-6020 Innsbruck
Ulrike.Toechterle@uibk.ac.at

Univ.-Prof. Dr. Peter Trebsche
University of Innsbruck, Institut für Archäologien
Forschungszentrum HiMAT
Langer Weg 11, A-6020 Innsbruck
Peter.Trebsche@uibk.ac.at

Dr. Rouven Turck
University of Zürich, Institut für Archäologie
Fachbereich Prähistorische Archäologie
Karl-Schmid-Str. 4, CH - 8006 Zürich
turck@archaeologie.uzh.ch

Dr. Samuel van Willigen
Musée national suisse/Landesmuseum Zürich.
Museumstrasse 2, Postfach, CH-8021 Zurich
samuel.vanwilligen@nationalmuseum.ch

Dr. Philipp Wiemann
Archäologischer Dienst Graubünden/Amt für Kultur
Archäologischer Dienst Graubünden/Amt für Kultur/
Servetsch archeologic dal Grischun/Uffizi da cultura/
Servizio archeologico dei Grigioni/Ufficio della cultura
Loëstrasse 26, CH-7001
Philipp.Wiemann@adg.gr.ch