Mitt. Österr. Miner. Ges. 163 (2017)

RECENT AND ANCIENT COPPER PRODUCTION IN THE LOWER INN VALLEY. AN OVERVIEW OF PREHISTORIC MINING AND PRIMARY COPPER METALLURGY IN THE BRIXLEGG MINING DIRSTRICT

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Introduction

In the Eastern Alps there is widespread evidence for a long tradition of metal ore mining and smelting (HÖPPNER et al., 2005). The first smelting activities or more probably a first "experimental phase" has been documented at the Mariahilfbergl in the Lower Inn Valley near Brixlegg in North Tyrol (BARTELHEIM et al., 2002). This Neolithic phase is otherwise characterized by only little archaeometallurgical evidence however local Fe-Zn tetrahedrite-tennantite heating and possible smelting (?) could be shown. The second metallurgical phase during the Chalcolithic and Early Bronze Age is characterized by a small-scale Fe-Zn tetrahedrite-tennantite based copper metallurgy. This metallurgy occurred outside the immediate ore districts in settlements. The Buchberg near Jenbach in Tyrol (MARTINEK, 1996; MARTINEK & SYDOW, 2004), the Tischofer Höhle near Kufstein (HARB, 2002) and the Kiechlberg near Innsbruck (KRISMER et al., 2010; TÖCHTERLE et al., 2012; TÖCHTERLE, 2015) are well-documented examples of this second phase, where the copper metallurgy suggests the smelting of fahlores from the local mining sites of Schwaz-Brixlegg (KRISMER et al., 2010). However, the archaeological confirmation of the related fahlore mining in the field is still a desideratum. Referring to geochemical analyses performed on copper and bronze artefacts this period of prosperity was interrupted in the late Early Bronze Age and only regained importance in the Late Bronze Age (LUTZ & PERNICKA, 2013). The late Early Bronze Age and Middle Bronze Age copper and bronze artefacts found in the Eastern Alps and in their northern periphery are characterized by a more chalcopyrite-pronounced copper composition (LUTZ, 2016). During this time period the Mitterberg mining area in Salzburg near Bischofshofen rose to become the largest mining district in the Eastern Alps (STÖLLNER et al., 2006). Large scale mining and smelting was carried out within the mining districts where specialised workshop settlements and smelting sites were established. In the Kitzbühel-Jochberg-Kelchalm region (chalcopyrite + pyrite occurrences) Middle to early Late Bronze Age chalcopyrite smelting is also evident (GOLDENBERG, 2004; KOCH-WALDNER & KLAUNZER 2015). During the Late Bronze Age and till the Early Iron Age (1200 – 700

BC) fahlore-copper based artefacts - more or less mixed with chalcopyrite copper - become evident again (MÖSLEIN & WINGHART, 2002; SPERBER, 2004; LUTZ, 2016). In this context intense mining and smelting has been archaeologically documented in the Schwaz-Brixlegg region, where highly specialized mining and smelting workshop settlements were established within the ore districts. For this period the complete operation chain for the copper production (mining, beneficiation, smelting) could be investigated and documented in the mining district of Brixlegg-Zimmermoos (Moosschrofen, Schwarzenberg Moos) and Radfeld (Mauken Valley) (GOLDENBERG et al., 2012; GOLDENBERG, 2013; GOLDENBERG 2015).

The easternmost part of the fahlore district Schwaz-Brixlegg namely the Moosschrofen, the Schwarzenbergmoos and the Mauken region in the municipal area of Brixlegg and Radfeld (Fig. 1) shows excellent archaeological evidence for Late Bronze Age to Early Iron Age mining and smelting activities (GOLDENBERG & RIESER, 2004; GOLDENBERG et al. 2012). The area has only little been over-

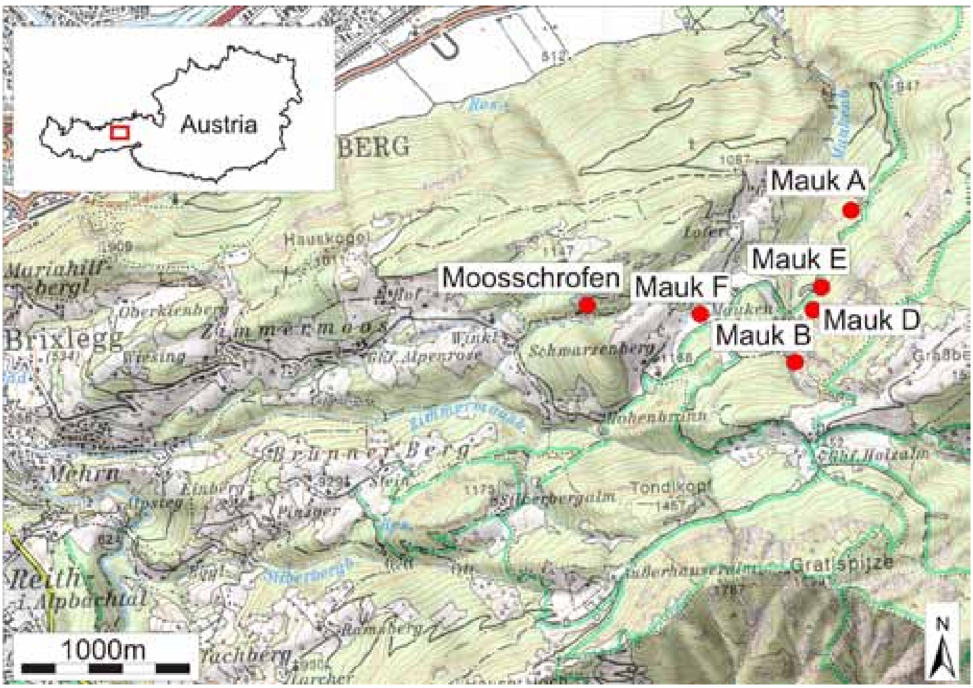

Figure 1: This figure shows the morphology of the Mauken area, which is positioned in the easternmost part of the mining complex Schwaz-Brixlegg in the North Tyrolean Lower Inn Valley. The red dots mark selected prehistoric mining, ore beneficiation and smelting sites. Mauk B, Mauk D and Mauk E are underground mines, which date in the Late Bronze Age / Early Iron Age. They all were mined by fire setting. The Moosschrofen is an outstanding example of such surface near fire-setted mines dating in the same period. Mauk F is an ore beneficiation site in the area of a former peat bog where wooden troughs and installations for the wet mechanical separation and concentration of the nearby mined ores could be excavated and documented. Mauk A is a smelting site with a multiphase roasting hearth, two excavated smelting furnaces and an extensive dump of slag sand including a washing and separation installation. (Map source: ÖK 50, Blatt 120, Bundesamt für Eich- und Vermessungswesen, Wien).

printed by medieval and modern mining activities and thus contains archaeological evidence for the whole chaîne opératoire namely fahlore mining by fire setting, ore beneficiation and smelting (Fig. 2). Even though ^{14}C and dendrochronological dating do not prove a time-related continuity of single mining, beneficiation and smelting sites, the long lasting intensive metal production from about 1200 to 700 BC is evident by the age data (GOLDENBERG, 2013, 2015).

On the southern side of the Lower Inn Valley (North Tyrol) an important historic mining area for copper and silver ores extends from Schwaz in the west to Brixlegg/Radfeld in the east, well known since the Early Modern Age as the famous mining region of Schwaz. Based on the exploitation of copper and silver from rich fahlore deposits, this part of Tyrol developed to a leading mining area in Central Europe during the 15th and 16th century AD. In the course of its important economic success technological innovations and social acquirements influenced to a certain extent the societal development of the European Renaissance. Referring to the current state of research a comparable situation can be expected for the same area more than 2000 years earlier, during the Late Bronze Age/Early Iron Age. This prehistoric era of prosperous fahlore mining and copper production is not recorded in written sources and is therefore accessible only by archaeological and archaeometrical investigations. Within the framework of the Special Research Program HiMAT (The History of Mining Activities in the Tyrol and Adjacent Areas – Impact on Environment and Human Societies), established at the University of Innsbruck and supported by the Austrian Science Fund (FWF) from 2007 to 2012, a number of prehistoric mining sites in the area of Brixlegg-Zimmermoos and the Mauken Valley (Radfeld) have been studied and documented by interdisciplinary investigations.

The aim of this excursion is to bring together aspects of modern Cu-smelting and prehistoric Cu-mining and smelting. The following stops are planned during the excursion: Montanwerke Brixlegg, Moosschrofen, Holzalm.

Geology

The Mauken Area is located in the easternmost part of the prehistoric and historic silver and copper mining area of Schwaz-Brixlegg in the lower Inn Valley. 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 Paleozoic Greywacke Zone (Fig. 2).

Mining activities related to these ores can be dated back to the Late Bronze Age. 2.) The second ore type is hosted in the Anisian carbonates of the Schwaz Triassic. Latter ore type shows a complex mineralogy with tennantite-rich fahlore-group minerals (in part Ag-rich) as primary copper phase in association with Fe, Co, Ni and Pb minerals. The complex mineral assemblage consists of Fe-Zn tennantite + pyrite/bravoite + enargite/luzonite-famatinite ± chalcopyrite ± thiospinel ± gersdorffite-cobaltite-arsenopyrite ± galena ± sphalerite ± marcasite ± pearceite ± barite. The mineralogical/chemical composition of these ores is highly variable and changes on a local scale. Geochemical bulk analyses of some slag, copper, bronze samples as well as “fahlore copper” artefacts from the Chalcolithic to Early Bronze Age

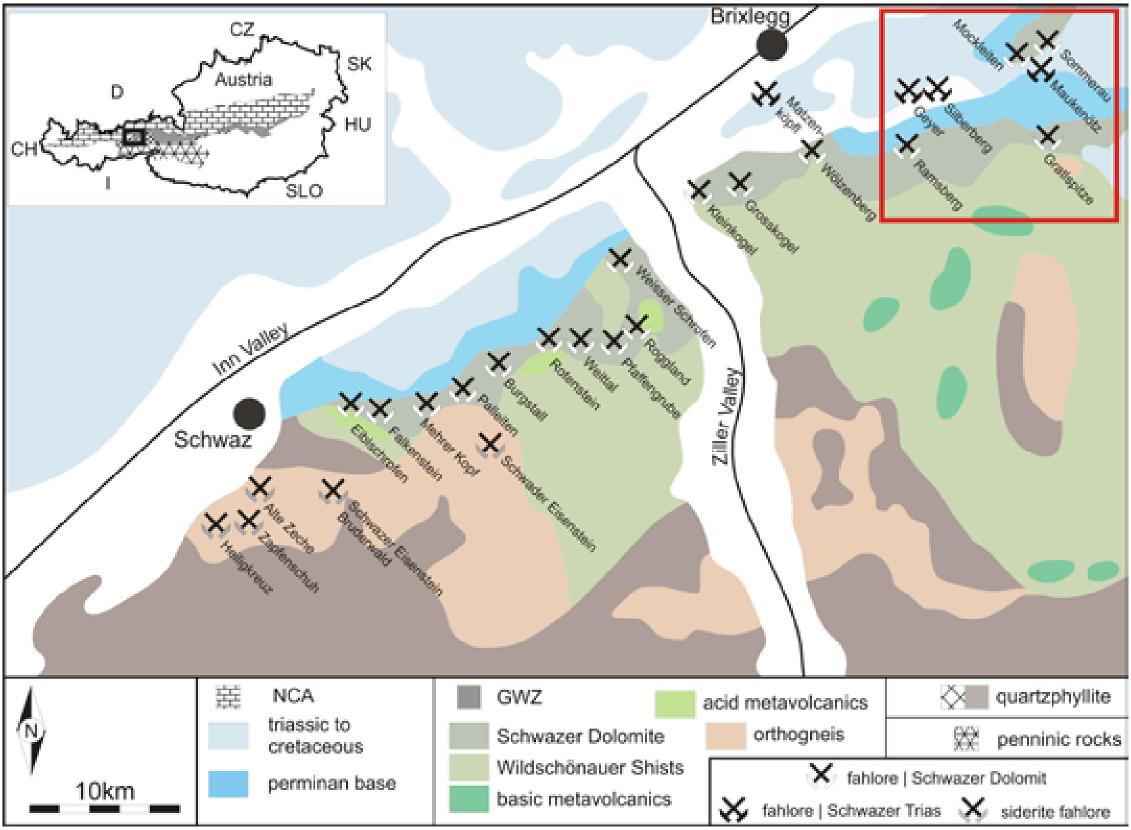

Figure 2: Simplified geological map of the Lower Inn Valley between Schwaz and Brixlegg. The geology is based on the metallogenetic map of Austria of WEBER et al. (1997). The most important mining sites of the Schwaz-Brixlegg mining province are indicated by mining symbols. The square designates the Mauken Area.

Kiechlberg hilltop settlement near Thaur (Innsbruck, Tyrol) show besides Sb and/or As in addition considerable impurities of Fe, Co, Ni and Pb, which are absent in artefacts when only fahlore from the Schwaz Dolomite is used. Geochemical analysis of bulk samples indicate that also these ores might indeed have played a role in prehistoric metal production in the Lower Inn valley.

The Pb-Zn-fahlore district "Anis-North Tyrolean Calcareous Alps" is an east-west striking ore belt extending north of the Inn Valley from the Mieming Kette to the Innsbruck Nordkette (SCHULZ & SCHROLL, 1997). Thirty kilometres eastwards of Innsbruck on the south side of the Inn Valley the Schwaz Triassic (ST) contains similar ores in the same stratigraphic level (SCHULZ & SCHROLL, 1997). While the ores of the Mieming Kette and the Innsbruck Nordkette are mostly Pb-Zn dominated with minor amounts of tennantite-rich fahlore, the ores of the ST are dominated by tennantite-rich fahlore and Pb-Zn phases as minor constituents (SCHULZ & SCHROLL, 1997). The copper mineralizations of the ST described in this study are situated south 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" and stratigraphically it occurs in the Triassic Anisian to Carnian/Norian rocks of the Northern Calcareous Alps. The host rocks consist mainly of limestones, dolomites, cellular dolomites and breccias.

Stratigraphy of the Mauken Area

The mining district of the "Mauken Valley" is situated to the southeast of Brixlegg and Radfeld in the lower Inn Valley in Tyrol and is part of the large Schwaz-Brixlegg mining district. A simplified map of the geological situation is presented in Figure 1. The region studied is characterized by rocks of the Greywacke Zone (GWZ) and the overlying ST (Figure 1). The Wildschönau Schists and the stratigraphically higher Schwaz Dolomite are the major lithologies of the GWZ south of the Inn Valley. The Wildschönau Schists consist of greenschist-facies Palaeozoic shales and sandstones. The Schwaz Dolomite represents a greenschist-facies Devonian platform carbonate sequence. These two rock types are dominant in the southernmost part of the Mauken Area. The Schwaz Dolomite is overlain by the Permo-Triassic sediments of the ST. The ST represents a few kilometres wide tectonic slice between the Inn Valley Fault and the Northern Calcareous Alps in the North and the Schwaz Dolomite and the Wildschönau Schists of the GWZ in the south (Figure 1). These rocks crop out on the south side of the Inn Valley (Figure 1). The ST consists of a Triassic rock sequence similar to the sedimentation sequence of the Northern Calcareous Alps. The contact between the ST and the underlying Schwaz Dolomite is an erosional unconformity, which is in many cases tectonically overprinted. The basement of the ST consists of the basal breccia and the Gröden Formation. The Basal Breccia consists of limestone-dolomite breccias and dolomite-phyllite breccias of the Lower Permian. The Gröden Formation consists of red quartz-sandstones, conglomerates and mica-rich schists. These basal strata are followed by the Skythian sediments of the Alpine Buntsandstein and the Werfen Formation. The rocks consist mainly of quartz-sandstones, conglomerates, argillites and arkoses. This succession is followed by the Reichenhall Formation (cellular dolomites, dolomite and gypsum, Skyth-Anis) and the group of the Alpiner Muschelkalk (Anis-Ladin). The rocks of the Alpine Muschelkalk consist mainly of bedded dolomites and limestones. The Reifling Formation (limestones; Ladin) contain interlayers of greenish tuff (pietra verde). These Anisian rocks are followed by clay shales, marls and limestones of the Partnach Formation. The Partnach Formation is followed by the stratigraphically higher Wettersteindolomite (Anis-Ladin), which is the main rock type of the northern part of the Mauken Area. The Raibl Formation and the Hauptdolomit Formation are the uppermost stratigraphic members outcropping in the ST between Brixlegg and Radfeld. The Raibl Formation (Karn) consists mainly of shales and marls, sandstones and dolomites. In the Mauken Area the Hauptdolomit Formation is the uppermost stratigraphic member, which crops out in the ST of the Mauken Area.

Copper ores in the Mauken Area

The tetrahedrite-tennantite ores of the historic and prehistoric copper and silver mines of Schwaz-Brixlegg are hosted in the Devonian Schwaz Dolomite (GWZ)

Figure 3: Fahlore veins hosted in dolomite, which were mined by fire-setting in surface near and underground mines.

and occur as thin veins with azurite and malachite alterations at their rims (Fig. 3).

Exceptions are the siderite-rich veins in the Kellerjochgneis to the southwest of Schwaz and the polymetallic copper mineralizations in the ST to the southeast of Brixlegg (Mauken Area). As shown by ARLT & DIAMOND (1998) and KRISMER et al. (2011) the chemical composition of these monomineralic Fe-Zn-Hg tetrahedrite-tennantite ores is characterized by a Sb/As ratio near 1 with a slight Sb-predominance, variable Fe:Zn:Hg ratios and low Ag concentrations with a mean value of approximately 0.5 wt.%. A geographic zoning trend was not recognized but compared to fahlore-group minerals from Schwaz KRISMER et al. (2011) reported slightly higher overall Zn/Fe ratios and lower Hg-concentrations in the samples from Brixlegg. The ore composition and the dolomitic host rock (Ca- and Mg-rich) nicely fit these observed chemical composition and mineral chemistry of slag and copper finds from Chalcolithic and Late Bronze Age settlements in the Inn Valley (MARTINEK & SYDOW, 2004; KRISMER et al., 2012). In the Mauken Area both, the common tetrahedrite-tennantite mineralizations of the Schwaz Dolomite (Fig. 3) and the polymetallic copper ores of the ST occur in the immediate vicinity. Although fahlore-group minerals represent always the major copper phase, the ores hosted in the Triassic rocks of the ST show a very different ore mineral assemblage, which can be described in the complex chemical system Cu-Ag-Sb-As-Fe-Co-Ni-Pb-Zn-S (±Bi ±Ba). Only few samples contain barite associated with the sulfide assemblage. The following description of the mining sites refers to the excellent contribution of PIRKL (1961). The two major mining districts in the ST are Geyer Silberberg and Maukenötz. One of the most outstanding examples of an ore district in the ST is the Geyer-Silberberg mining district (Figure 4). This mining area is located to the north of the Gratlspitze-Hauser Joch ridge (Figure 4). The northern part of the mining area is characterized by the occurrence of mineralized Partnach Layers, which are separated by a fault zone from the Wettersteindolomite (PIRKL, 1961; Ramsaudolomite). The ores occur adjacent to the fault zone in the hanging wall of the Wettersteindolomit. Further to the south the ore-bearing zones are located in the footwall of the Wettersteindolomit. The southernmost ore zone of the Geyer-Silberberg district is the Geyerköpfl. The ores are hosted within the Anisian limestones and dolomites of the Alpine Muschelkalk. The second important mining area in Triassic rocks in the Mauken Area is Maukenötz (Figure 4). These ores occur in the Norian Hauptdolomit (PIRKL, 1961; Oberer Dolomit).

The metallogenetic processes of ore formation are still controversially discussed. GSTREIN (1979) favours at least for some fahlore-group minerals mineralizations hosted in the Schwaz Dolomite (GWZ) a syngenetic mineralization process in

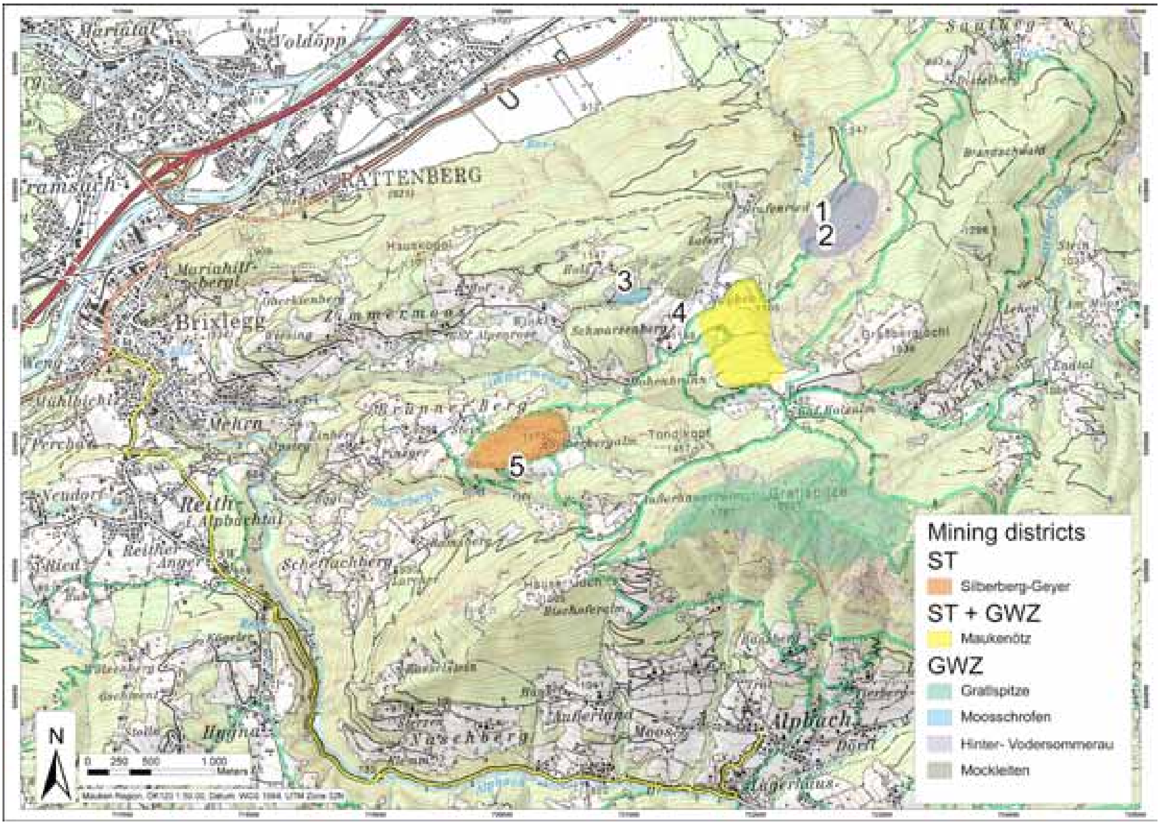

Fig. 4 One of the most outstanding examples of an ore district in the ST is the Geyer-Silberberg mining district. This mining area is located to the north of the Gratlspitze-Hauser Joch ridge. The southernmost ore zone of the Geyer-Silberberg district is the Geyerköpfl. The second important mining area in Triassic rocks in the Mauken Area is Maukenötz.

the Devonian sedimentation environment. On the other hand stable isotope studies of fahlore-group mineral-barite mineralizations from the Großkogel-Kleinkogel mining district (GWZ) indicate an epigenetic event in the Variscan Belt/Foreland (FRIMMEL, 1991). The ores in the ST are interpreted to represent at least partly Eo-Alpine remobilizations of the deeper seating copper ores of the Schwaz Dolomite since GSTREIN (1979) described decreasing Sb/As ratios in fahlore-group minerals hosted in the Triassic carbonates of the ST.

Mining

In the Schwaz/Brixlegg district remains of prehistoric fahlore mining are widespread (PIRKL 1961; RIESER & SCHRATTENTHALER 2000, 2004; GOLDENBERG & RIESER 2004; GOLDENBERG et al. 2012; GOLDENBERG, 2013; GOLDENBERG, 2015). Some of these near surface mining cavities are known as "heathen mines" since the 16th century AD (Schwazer Bergbuch, WINKELMANN, 1956). An outstanding monument of Late Bronze Age/Early Iron Age fahlore mining is represented by the Moosschrofen (Fig. 5).

The easily accessible site shows typical structures of exploitation in the form of surface near cupola shaped cavities resulting from fire setting. This special driving

Figure 5: Photographs of the fire-set cuppolas at the Moosschrofen. Left: overview, right: close-up of a cuppola.

technic used wood fires to break down the hard dolomitic rock (WEISGERBER & WILLIES, 2001). Radiocarbon data and finds of pottery fragments date the local mining activities at the Moosschrofen into the $9^{th}/8^{th}$ century BC. Other remarkable examples for Late Bronze Age/Early Iron Age fahlore mines exploited with fire setting are represented by the mines Mauk B and Mauk E in the Mauken Valley (difficult accessibility). Extended archaeological excavations could be realised in the mine Mauk E. This mine is driven about 25 meters deep into the dolomitic host rock. The ore exploited was antimony-rich fahlore, from which thin veinlets (millimeter to centimeter thick) are still recognizable on fresh rock surfaces (Fig. 3). After the first investigation it became clear that the mine is primarily of prehistoric origin, but reworked during Early Modern Times. Fortunately and due to the minor ore content left in the dolomite, the younger works did not go beyond a prospecting of the remaining ore so that for the most part of the mine the prehistoric structures were preserved. The prehistoric work is characterized by carbon black covered rock surfaces and the traces of fire setting as the principal driving technic. These are the typical cupola like cavities formed as a result of the heating effect to the dense and solid structure of the dolomitic host rock. The Early Modern works show bright surfaces with the cut marks from iron tools (hammer and chisel). Parts of the Early Iron Age cavities were 3 D laser scanned in order to enable the calculation of exploitation volumes (HANKE et al., 2012). The application of fire setting left behind fillings in the mine, which are rich in charcoal (Fig. 6a).

Beneficiation

In the former peat bog Schwarzenberg-Moos (Brixlegg-Zimmermoos) traces of a Late Bronze Age ore beneficiation site were discovered in 2000 in a drainage channel and could be investigated in the frame of the SFB HiMAT program. Two excavations in 2007 and 2008 furnished excellent materials for the reconstruction of the site as well as for the dating by dendrochronological analysis (GOLDENBERG et al., 2012). Here, after local forest clearing, a small workshop was installed in order

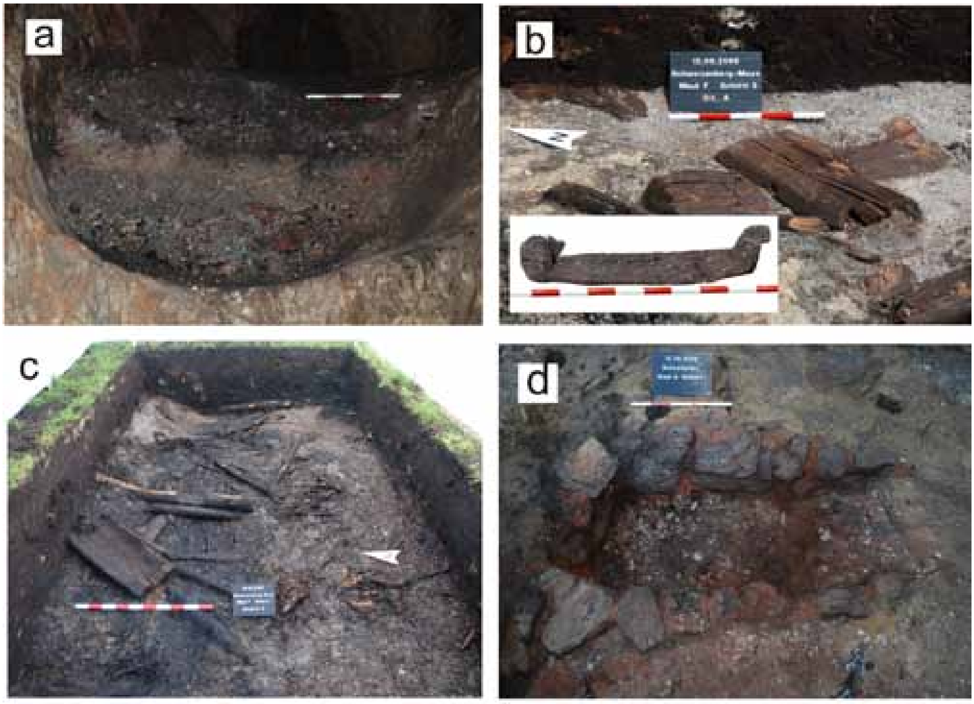

Figure 6: Images a) to e) show the metallurgical chaîne opératoire in the Mauken region: a) the stratified debris in the underground mine Mauk E, b) and c) details of the ore beneficiation installations at the site Mauk F with the wooden washing structure and the wooden trough, d) one of the two smelting furnaces of the site Mauk A, e) the two-phase roasting bed of the site Mauk A.

to use the outflow of the bog water for the beneficiation process (Fig. 6b). Fahlore was exploited in a mine only a few hundred meters distant. A kind of a washing basin with a rectangular wooden structure was set up, from which the basic beams could be excavated in their in situ position (Fig. 6b). In connection to this basin, two wooden troughs were uncovered and interpreted as parts of the ore washing equipment (Fig. 6c). Furthermore, a waste dump connected with the crushing of ore could be documented, containing a mortar stone in situ, fragments of hammer stones, a few wooden tools and ceramic. By the systematic dendrochronological analysis of the wooden remains an accurate dating could be achieved, which shows an occupation of the site between 900 and 870 BC (NICOLUSSI et al., 2012 a, b). Several soil samples from the prehistoric strata as well as pollen profiles from the surrounding peat bog were collected and analysed to reconstruct the palaeo-environment (BREITENLECHNER & OEGGL, 2012). An excavation on the mining field Mauk D (2000) revealed a number of stone tools (hammer stones), which are also related to the mechanical treatment of the ore bearing rock (first crushing and sorting). These finds provide an insight into the tool set in use, referring to stone material, typology and use marks. The mineralogical determination shows that high metamorphic greenstones (amphibolite, garnet amphibolite and eclogite) were the preferred material for hammer stones. These stones (well rounded pebble stones) were collected from the gravel banks of the Inn River or from glacial moraine deposits.

Smelting

In the Mauken Valley a Late Bronze Age smelting site could be discovered in the 1990's during archaeological prospection and excavated in the frame of several campaigns between 1994 and 2009. A main emphasis was placed on the slag-heap (mainly "slag sand"), on the metallurgical installations (furnaces, roasting hearths) and on the reconstruction of the metallurgical process (GOLDENBERG et al., 2012; GOLDENBERG, 2013; KRISMER et al., 2011; KRISMER & TROPPER, 2013). The topographic record of the site, geomagnetic measurements and drillings helped to quantify the volume of the slag-heap (about 100 tonnes) and to localize the former metallurgical plant. Two smelting furnaces (Fig. 6d), a multiphase roasting bed (Fig. 6e) and a washing plant (for crushed slags, with wooden remains) could be uncovered and documented during the excavations. The collected archaeometallurgical material from the smelting site (ores, slags, roasting products) were analysed in order to work out the raw materials and the process parameters. A section of the slag heap, consisting mainly of crushed slag ("slag sand") was selected for a special excavation with the aim to collect animal bones for archaeozoological analysis. The remarkable preservation of organic materials (HEISS & OEGGL, 2008), especially bones, is mainly due to the antibacterial effect of the remaining copper salts in the slag sediments. The recovered animal bones were suitable for the reconstruction of the meet supply of the local miners/smelters community (SCHIBLER et al., 2011).

Metallurgical remains

Besides huge masses of finely crushed slag sand numerous fragments of platy slags and slag cakes, thermally altered and partly slagged rock (furnace wall), partly slagged furnace lining and a few roasting products as well as some fragments of technical ceramic (tuyères) were also recovered. The slag can be clearly attributed to primary copper metallurgy. There are two distinct slag types, namely slag cakes and platy slag. Slag cakes are only present as small fragments mostly without any reference to the initial size and shape. Highly porous slag cakes contain not molten irregularly distributed quartz fragments, which are also visible with the naked eye (Fig. 7a). Platy slag fragments can be attributed to a circular, disc-shaped, thin slag with low porosity and are more or less absent of any molten quartz fragments (Fig. 7b). The surface of platy slag is smooth with "skin on the milk"-like unevenness's and a "pizza crust"-like rim (Fig. 7b). Both slag types have a dark grey colour without any macroscopic visible minerals. The weathered rind of the slag cakes is of brownish and crumbly appearance. In contrast the platy slag shows an unaltered,

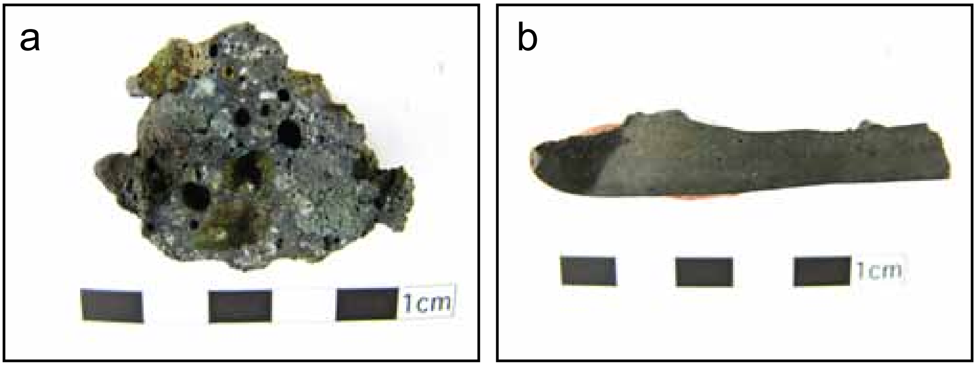

Figure 7: a) cross section through a slag cake, the white patches are not molten quartz relicts. b) typical shape of a platy slag.

glossy surface. Besides these slag remains huge quantities of crushed slag sand were encountered at the smelting site. Slag relicts can also be found in the clay lining of the furnaces.

Both slag types are composed of a fine-grained silicate matrix, containing crystals, glass and sulfide-metal inclusions/droplets. Un-melted quartz relicts are only evident in the slag cakes. The sulfide-metal droplets can be regarded as physically separated S-rich domains, within a silicate-rich melt. The distribution of crystals, un-melted fragments and droplets in the slag cakes is inhomogeneous. Large fully molten patches composed of silicates crystallized from the silicate-rich melt and silicate-glass alternate with spinel-rich agglomerates and a high density of sulfide-metal inclusions. This reflects local compositional variations within the silicate rich melt. Especially the spinel agglomerates reflect a more oxide-rich and silica-poor compositional domain. Spinel grains are idiomorphic and crystallized from the silica-poor domains. The degree of crystallinity in this area is much higher compared to the silicate-rich regions of the slag and in the transition zone between spinel-rich and silicate-rich regions silicate crystals nucleate around spinel grains. The platy slag is texturally more or less homogeneous with large dendritic silicate laths, fine dispersed spinel dendrites, silicate glass and fine sulfide- and metal inclusions. There is no evidence for larger spinel- and sulfide agglomerates and unmelted quartz fragments. These two slag types can be distinguished macroscopically by their shape and inclusion mineralogy. Slag cakes are fragments of large slag blocks showing high porosity. As the name implies platy slag is represented by thin fragments of a larger circular slag disc with a pizza-crust-like rim, a dense inner structure without larger pores and without macroscopically visible inclusions. The chemical differences are in the variations of the SiO_2 content, which is much higher in slag cakes containing macroscopic quartz relicts. Platy slag is enriched in Fe_3O_4. The mineralogy in both slag types is characterized by Ca-Fe-Mg olivine, Fe-Mg orthopyroxene, Ca-Fe-Mg-Al clinopyroxene, Fe-Mg spinel and silicate glass. The chemical composition of silicate glass is complex and major components are SiO_2, CaO, MgO, Fe_3O_4 and Al_2O_3, minor components are K_2O, Na_2O, ZnO, in some cases BaO and up to 3 wt.% Sb_2O_3 and As_2O_3, suggesting oxidizing conditions above the Sb(As)-$Sb(As)_2O_3$ reaction since Sb and As were not incorporated into crystalline silicate- and oxide phases.

Metallurgical implications

In both slag types Cu occurs in delafossite-rims surrounding spinel. This texture suggests oxidizing conditions crossing the magnetite-delafossite reaction during cooling. One slag cake contains idiomorphic Sb_2O_3 crystals and a Cu-Sb bearing spinel. Both phases crystallized from the Cu_2O and Sb_2O_3 bearing melt. All other samples do not contain Cu_2O in the silicate matrix suggesting log*f*O_2 conditions below the Cu-Cu_2O reaction. The more oxidizing sample probably represents the product of an unsuccessful smelting operation where no metal segregation occurred. Estimated log*f*O_2 conditions of -6 to -8 favour partial depletion of Sb in the metal thus producing a relative Sb-poor (and As-poor) metallic copper segregate. Metal and sulfide droplets are present in both slag types. The metal composition is Cu-rich with notable Sb and As and minor Ag concentrations. Even if Sb and As were partially depleted during the smelting process, the fahlore signature is always evident. Due to the similar compositions of metal and sulfide inclusions and similar *T*-log*f*O_2 conditions both slag types are considered to have formed in the same environment during the same process.

The size of the metal droplets in the silicate matrix range from >100 µm down to <1 µm. The larger droplets have a typical two-phase eutectic texture in the Cu-Sb(As) system. Dendritic CuSb(As) compounds separate from Sb- and As-poor copper in the Cu-rich portion of the system. Modally predominant are Sb- and As-poor and Cu-rich domains. Cu-rich metal phases contain 90-95 wt.% Cu. Sb- and As-rich domains contain up to 30 wt.% Sb+As. All metal analyses of the platy slag reveal 1-2 wt.% Fe. Small galenite (PbS) inclusions are enclosed in the metal. Most of the metal droplets are surrounded by a digenit rim containing small CuSb(As) inclusions. The contact zone (~ 10 microns) between the sulfide rim and the metal droplet is inclusion-free. Small sphalerite aggregates are commonly observed within chalcocite. Most slag samples contain besides Cu and CuSb(As) droplets variable concentrations of Sb in oxide- and silicate phases which crystallized from the molten charge. The most common Sb_2O_3 is stored in silicate glass with concentrations up to 3 wt.% and the same analyses also yield As_2O_3 concentrations near 1 wt.%. The occurrence of Sb-oxides indicates oxygen fugacities above the following reaction (Fig. 8):

$$2Sb + 1½O_2 \rightarrow Sb_2O_3$$

One sample contains Sb_2O_3 and Cu_2O in silicate glass. Large amounts of idiomorphic Sb_2O_3 grains crystallized from the silicate melt. The same sample also contains Cu-and Sb-bearing spinels. Cu-bearing spinel and silicate glass indicating oxygen fugacities above the following reaction:

$$2Cu + ½O_2 \rightarrow Cu_2O$$

Most other samples contain minor delafossite ($Cu^{1+}Fe^{3+}O_2$), which occurs as small rims surrounding spinel aggregates suggesting the following oxidation reaction:

$$Cu_{Metal} + ⅓Fe_3O_4 + ⅓O_2 \rightarrow Cu^{1+}Fe^{3+}O_2$$

In a *T*-log*f*O_2 diagram this reactions lies above the Cu-Cu_2O reaction at temperatures >1000°C (Fig. 8). Below 1000°C this reaction lies below the Cu-Cu_2O reaction. Most slag samples show mineralogical and chemical evidence for fairly high oxygen fugacity during slag formation so that Cu was at least partially stored in oxide and silicate phases. On the other hand side these T-logfO_2 conditions also favour the removal of Sb and As from the metal phase.

Age constraints on prehistoric mining in the Mauken area

By systematic sampling and subsequent ^{14}C dating and dendrochronological analysis of charcoal it was possible to get an accurate dating of the mining activities, which in the case of the mine Mauk E falls in the last two decades of the 8^{th} century BC (Fig. 9, cutting dates from 715 to 706 BC, NICOLUSSI et al., 2013; PICHLER et al., 2012, 2013). The Early Modern prospecting activities in the mine Mauk E

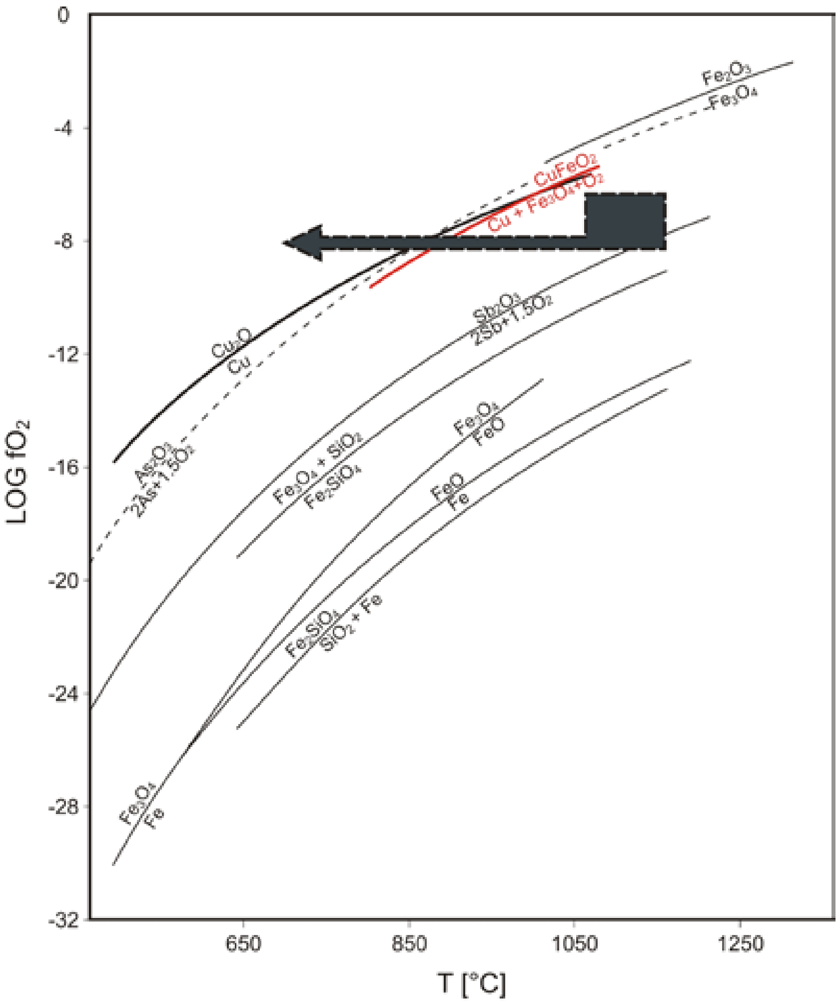

Figure 8: The T-logfO_2 diagram shows the most important oxidation reactions in the relevant Cu-Sb-As-Fe-Si-O system. The dashed field marks the approximate oxygen fugacity estimated from slag samples, slightly below the Cu-Cu_2O reaction and near the Sb-Sb_2O_3 reaction. The arrow marks the possible cooling path, overstepping the magnetite-delafossite reaction and resulting in delafossite rims surrounding magnetite.

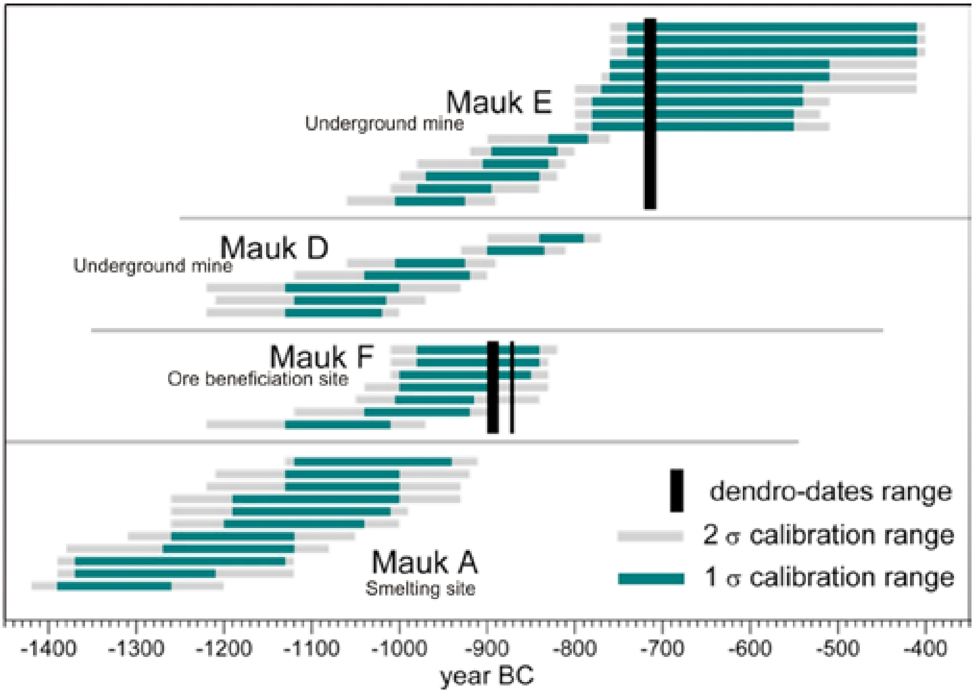

Figure 9: Radiocarbon- and dendrochronological table of the Mauken A, D, E, F sites. Especially the fire-setted mines contain large charcoal fragments which could be dated using dendrochronology and which yielded more precise data of the felling of the wood.

could also be dated by the same method to the 16th century AD (using wooden remains).

Discussion

The vicinity of the smelting site Mauk A to the Fe-Zn tetrahedrite-tennantite occurrences of the Brixlegg mining district suggests that local fahlore was indeed smelted. Chemical bulk analyses from this study also confirm this assumption. The metal inclusions in all slag samples show a typical fahlore signature, containing notable Sb and As concentrations and traces of Ag. The commonly observed Pb inclusions probably stem from remobilized fahlore veins from the Schwaz Trias. CaO and MgO are besides SiO_2 and Fe_3O_4 the major components of the slag reflecting the dolomitic host rocks of the fahlore deposits. The high BaO concentrations reflect the occasional use of fahlore + barite ores from Brixlegg. Extensive Late Bronze Age ore-mining (near surface and underground fire setting) as well as the ore beneficiation installations in the vicinity of the smelting site Mauk A yield evidence for a highly specialized and organized copper production. The smelting site contained two furnaces wherein copper was produced. Another important intermediate step in the metallurgical treatment of the ores is roasting. A two-phase roasting bed was found near the furnaces. However, it is not clear if the ores were first roasted and then smelted or if the ores were first smelted, then roasted and then smelted again to produce a more refined copper. The produced slag was subsequently crushed and washed out to remove any metallic copper/copper matte trapped in the slag by gravity separation. The crushed slag sand was then dumped on the slope down to the Mauken creek. Platy slag and slag cakes have a different macroscopic appearance. Slag cakes are fragments of a not further recognizable slag mass. Platy slag is part of a thin disc-shaped slag with a pizza-crust like rim. The shape as well as the smooth surface indicates floating of the molten slag on a heavier metal or sulfide melt. Whether both slag types are the product of one smelting action or two separated steps is still a matter of discussion. Chemical, mineralogical and petrological similarities indicate one production step so far. The chemical composition of the metal and sulfide droplets and the similar oxygen fugacities confirm this scenario. Any differences between the slags can be explained by the fact that both slag types did not cool in the same position in the furnace.

Spinel agglomerates including sulfide and metal droplets and periclase reflect decomposed, partly homogenized and recrystallized charge fragments. The outlines of the agglomerates still indicate the initially sharp-edged shape of the former fragments. Periclase (MgO) crystals represent the decomposed Mg-component of dolomite, which probably had not enough time to react with SiO_2 to form Ca-Mg-Fe silicates or silicate glass. The origin of the quartz fragments is still unclear since the ores are hosted within dolomites. Although the gangue is basically composed of quartz, such high SiO_2 concentrations in the slag cannot be produced by smelting fahlore + gangue minerals + surrounding rock fragments (dolomite). Quartz therefore seems to be added as a flux material. The oxygen fugacity seems to be high in all slag samples, resulting in the formation of Sb-bearing silicate glass. Commonly observed delafossite rims surrounding magnetite indicate oxygen fugacities slightly below the Cu-Cu_2O reaction (Fig. 8). The delafossite rims can also be explained as a cooling product at constant oxygen fugacity. In this environment Cu was trapped only to some extend in the slag. Since the Sb-Sb_2O_3 reaction was overstepped this element was at least in part removed from the metal. The result was a depleted fahlore copper signature. One sample shows much higher oxygen fugacities resulting in the formation of Cu- and Sb- oxides (spinel and Sb_2O_3). This sample probably reflects an unsuccessful smelting procedure.

In the Schwaz/Brixlegg mining district, all steps of a complete operation chain (mining, ore beneficiation, smelting) could be documented in the area between the Moosschrofen, the Schwarzenberg Moos and the Mauken Valley (GOLDENBERG et al., 2012; GOLDENBERG, 2013; 2015). Small scale Late Bronze Age "workshop settlements" are to be expected in the immediate vicinity of the mines and the smelting site Mauk A. This is indicated by huge amounts of domestic pottery and animal bones in the waste heaps. Whereas it is not yet clarified if these complexes were occupied seasonally or year-round, valuable results have been obtained concerning the food supply: Archaeobotanical analyses show that food plants and specifically cereals were not cultivated in the vicinity of the mining area. The food supply is characterized by the import of foodstuffs like bread or cleaned cereal, choice cuts of meat and preserved ham (SCHIBLER et al., 2011), complemented by milk and dairy products. Close to the mining area in the Mauken Valley a small cemetery (St. Leonhard) and a settlement area (Kundl Wimpissinger) are considered to be directly linked to the miners'/smelters' community (TOMEDI et al., 2013; STAUDT & TOMEDI, 2015). This is reflected in the presence of ceramic tempered with crushed slag from extractive copper metallurgy.

Copper metallurgy in Brixlegg today

Today the Montanwerke Brixlegg, founded in 1463, are Austria's only copper producer. Until the 20th century copper and silver ore was extracted in Tyrol and refined into pure metal in Brixlegg. Today the Montanwerke Brixlegg is a 100% recycling business. Pure copper is extracted from secondary materials like copper containing scraps and alloys. For metal extraction pyrometallurgical and hydrometallurgical refining processes are being employed in the production of high purity copper and the recycling of economically important metals (Au, Ag, Pt, Ni) from the secondary raw materials. The final product copper is known for its high level of purity since the copper content is more than 99.99 %!

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received: 12.07.2017
accepted: 14.07.2017