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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

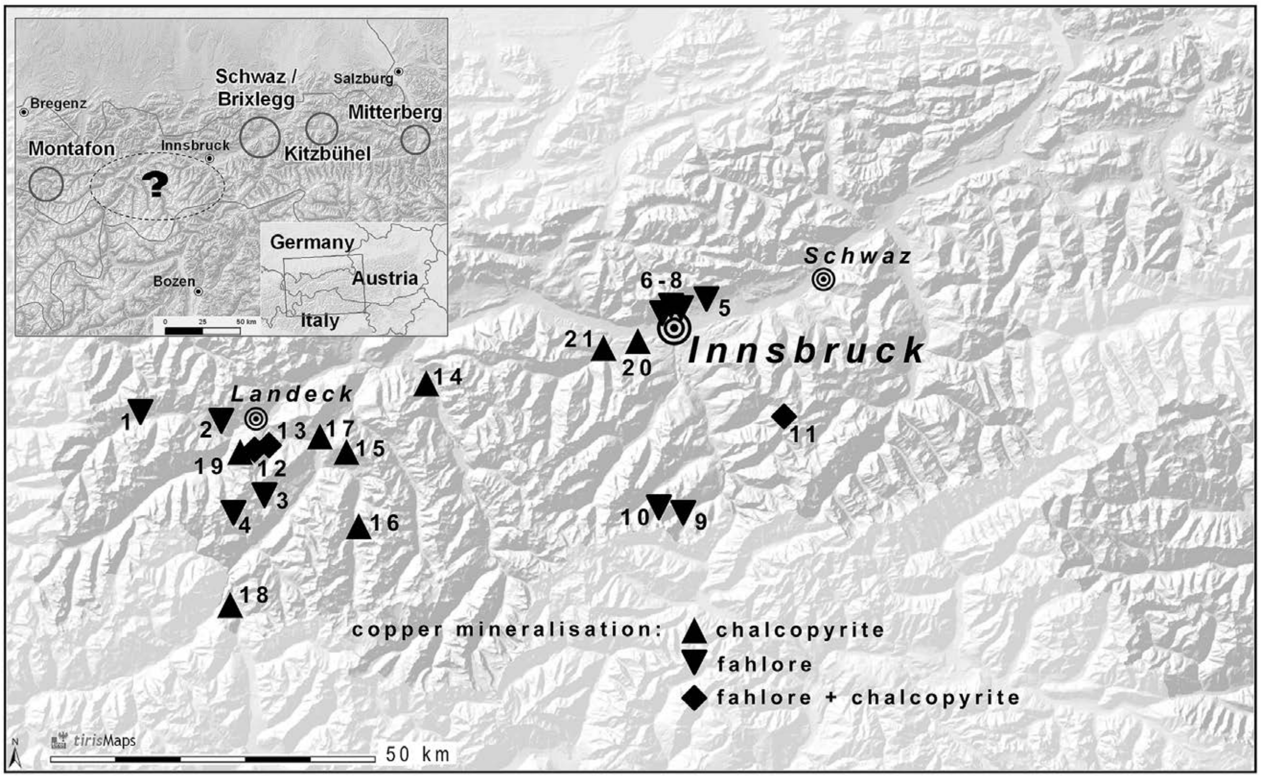

Fig. 1: Within the project "Prähistorische Kupferproduktion im Nordtiroler Oberland" surveyed and sampled copper mineralizations and mining sites. For corresponding site names see Table 1. Insert top left: mining archaeological research gap in the western part of North Tyrol in contrast to the key areas 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

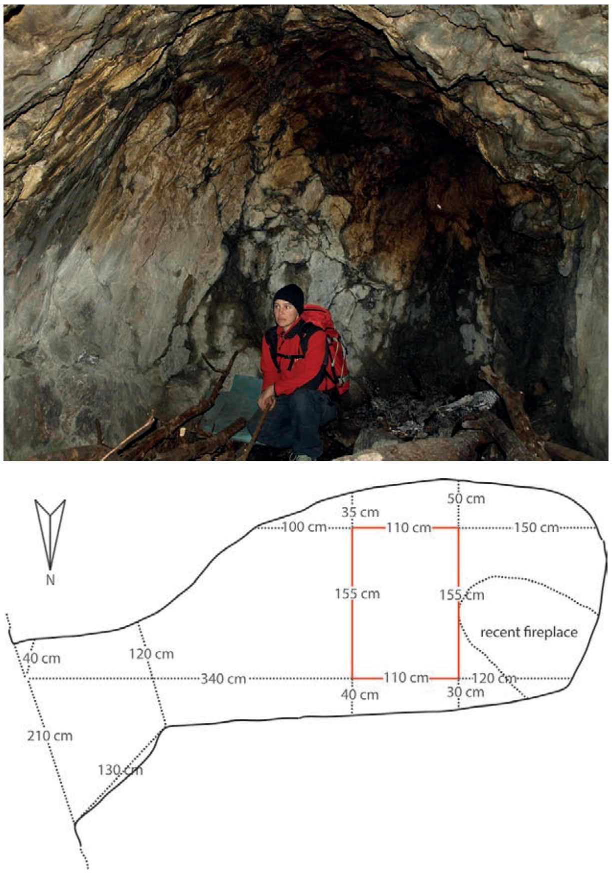

Fig. 6: Top: The fire-set pit in the Höttinger Graben (Knappenlöcher/ Innsbruck-Hötting). Bottom: The ground plan with the position of the sondage (red). No evidence for prehistoric copper mining was found.

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).

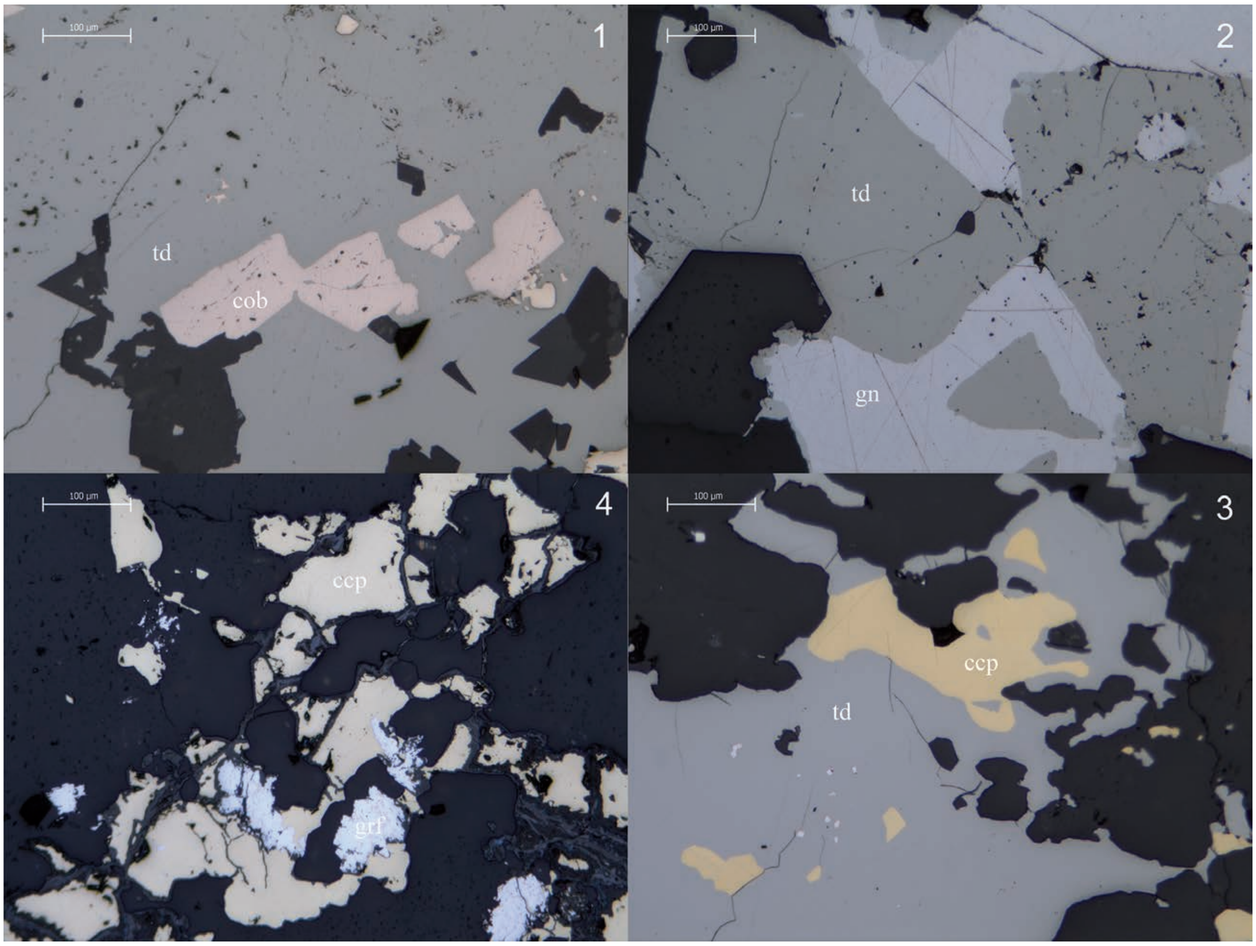

Fig. 7: Polished sections of ore samples. (1) Tetrahedrite (td) and cobaltite (cob), Rotenstein/Serfaus. (2) Tetrahedrite and galena (gn), Wildgrube/Obernberg. (3) Tetrahedrite and chalcopyrite (ccp), Knappenhäusl/Landeck. (4) Chalcopyrite and gersdorffite (grf), Großmutzkopf/Nauders.

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.

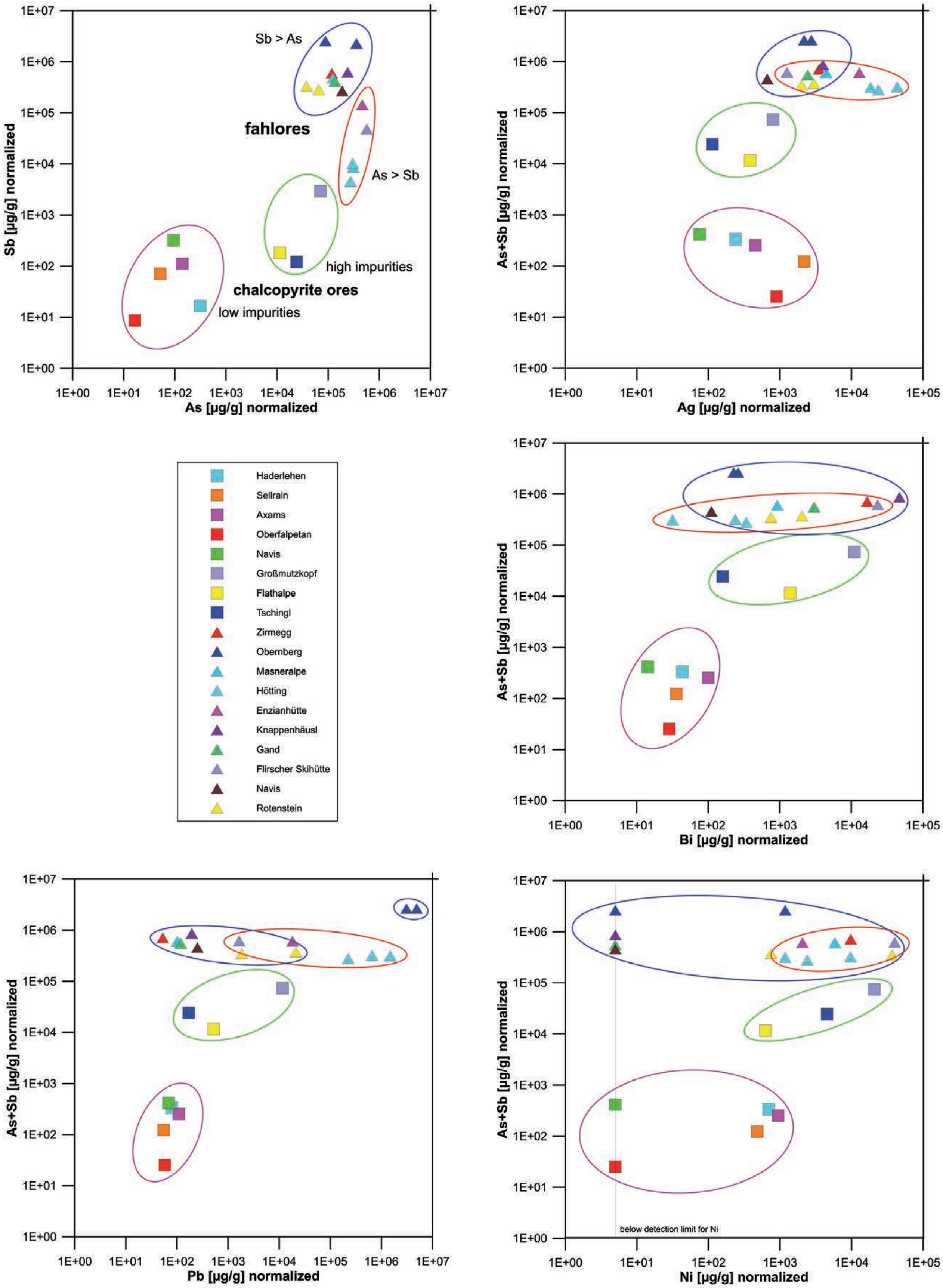

Fig. 8: Logarithmic plotting of normalized element concentrations selected from Table 2. Four copper ore types become apparent which are marked with circles.

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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