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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, DENDRO-CHRONOLOGY, 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;

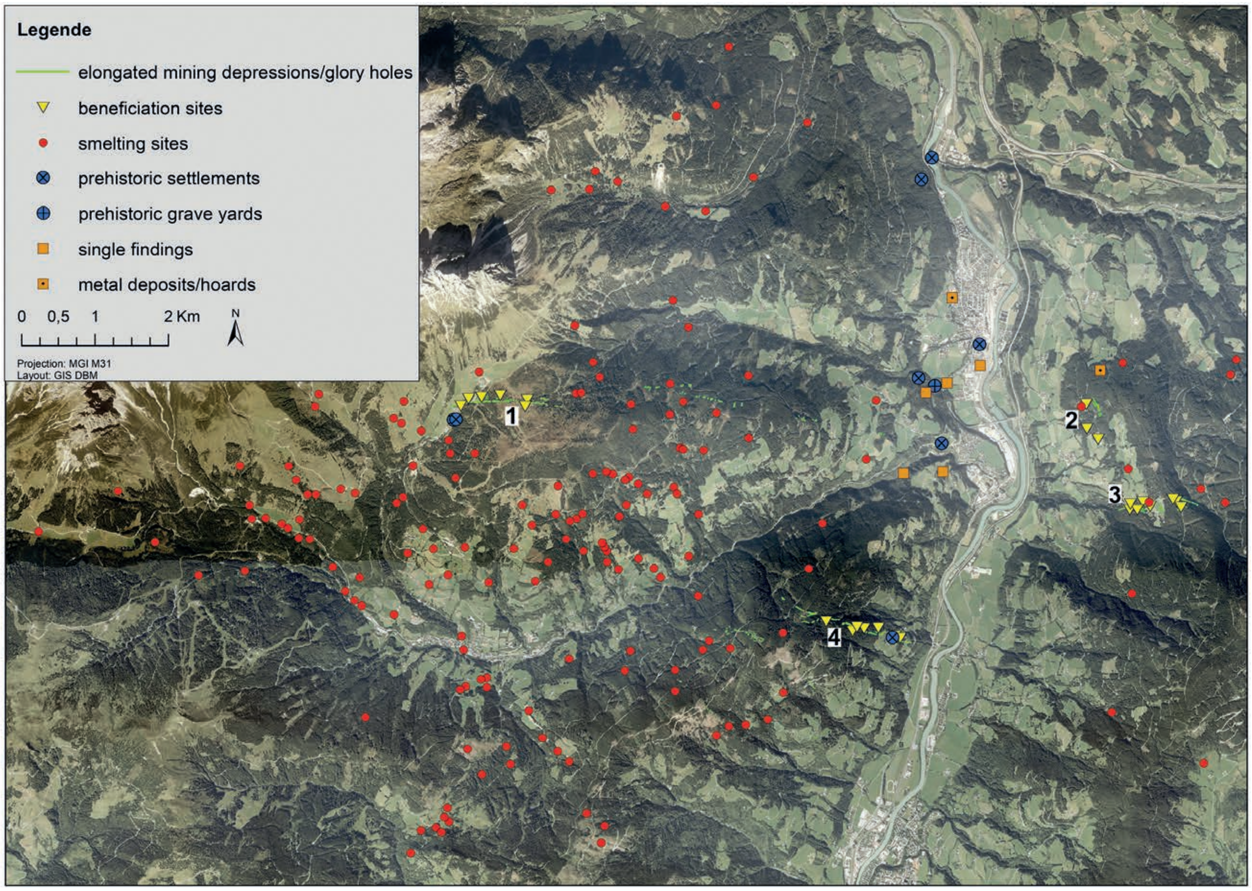

Fig. 1: The "Mitterberg" mining district (the mining field of Mühlbach-Bischofshofen) at the centre of the Salzach-Pongau region as displayed by mining lodes (and their surface depressions), beneficiation and smelting sites as well as settlements, single finds and graves; 1: Main Lode beneficiation sites; 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

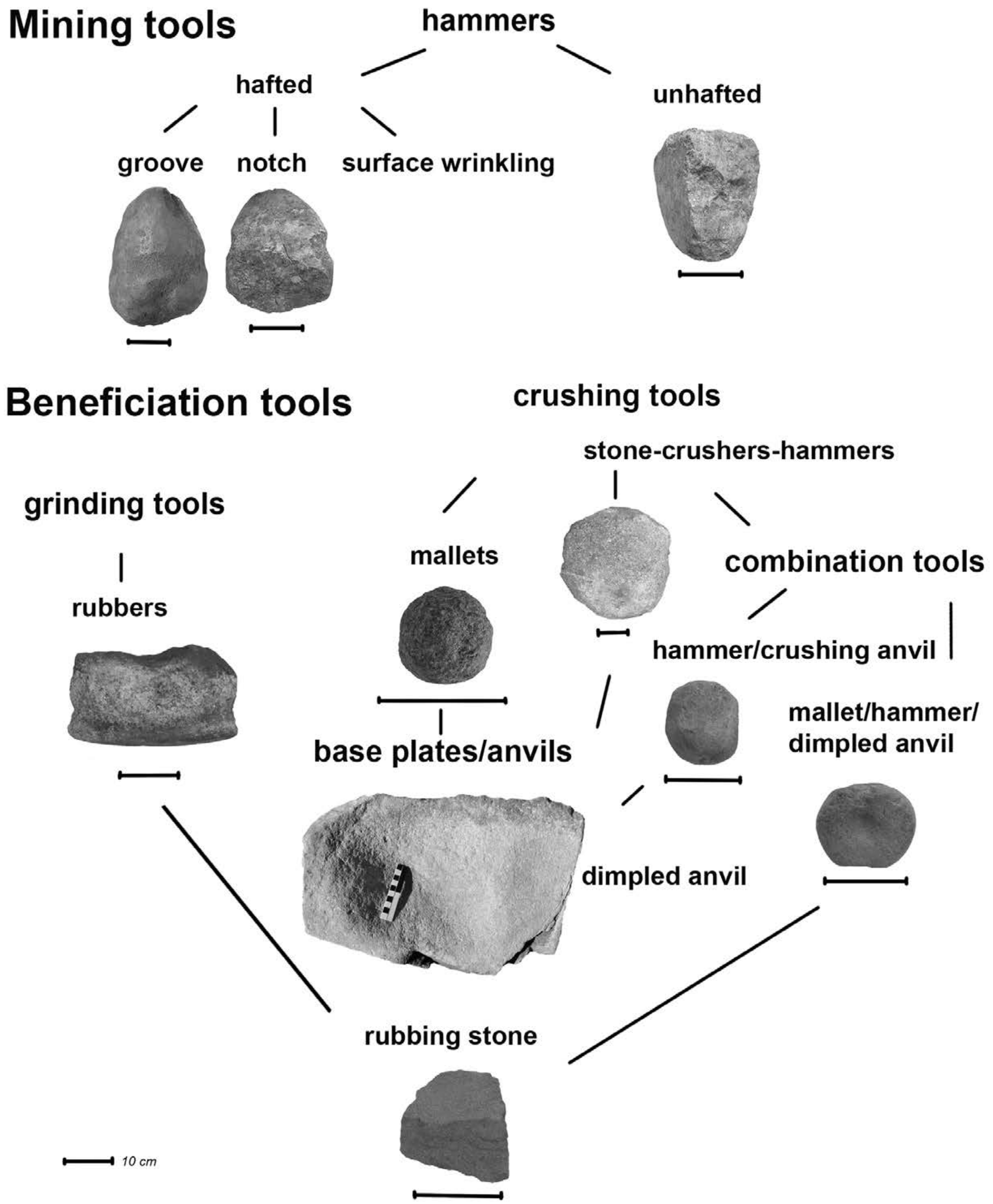

Fig. 2: Bronze Age stone tools at the Mitterberg district according to their usage in mining and beneficiation, modified after A. Maass, in: Stöllner et al., 2009, p.151 Fig. 50.

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,

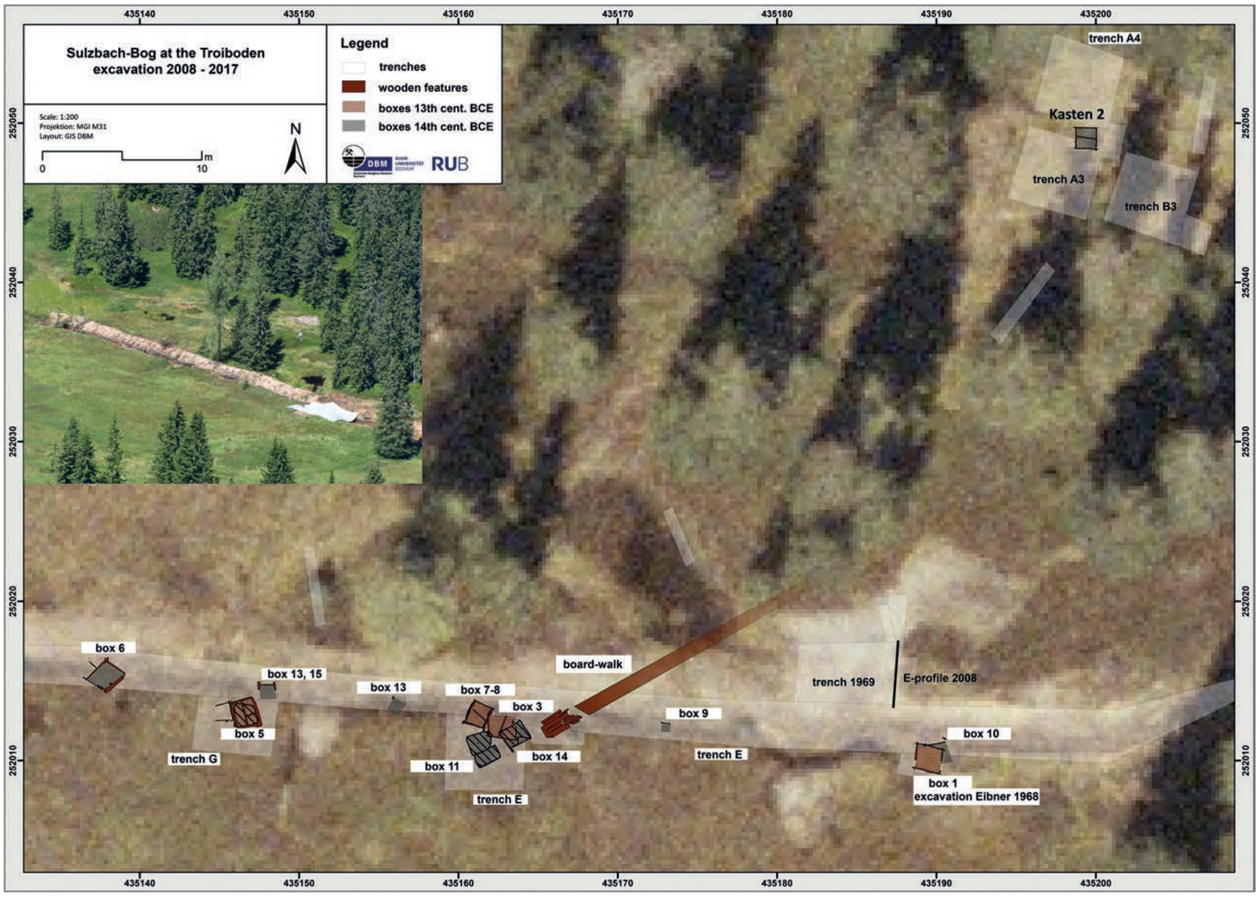

Fig. 5: Sulzbach bog excavation 2008-2017, overview of the excavation trenches and the boxes 1-15 (map/graphics: DBM/RUB, J. Schröder, Th. Stöllner).

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.

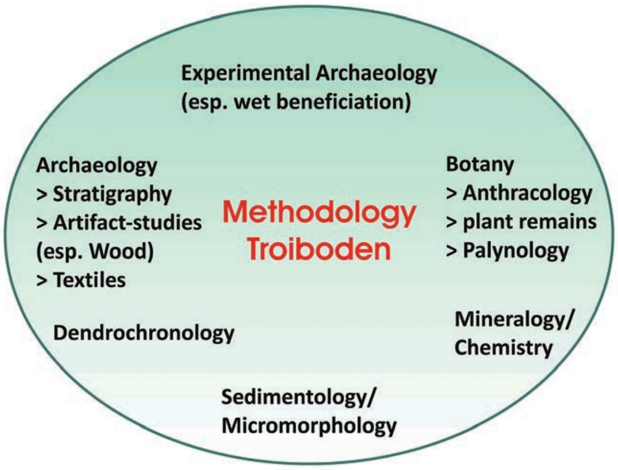

Fig. 6: Scheme of the methodological concept of interdisciplinary work of the Troiboden research (graphics: DBM/RUB, Th. Stöllner).

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 multi-disciplinary 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

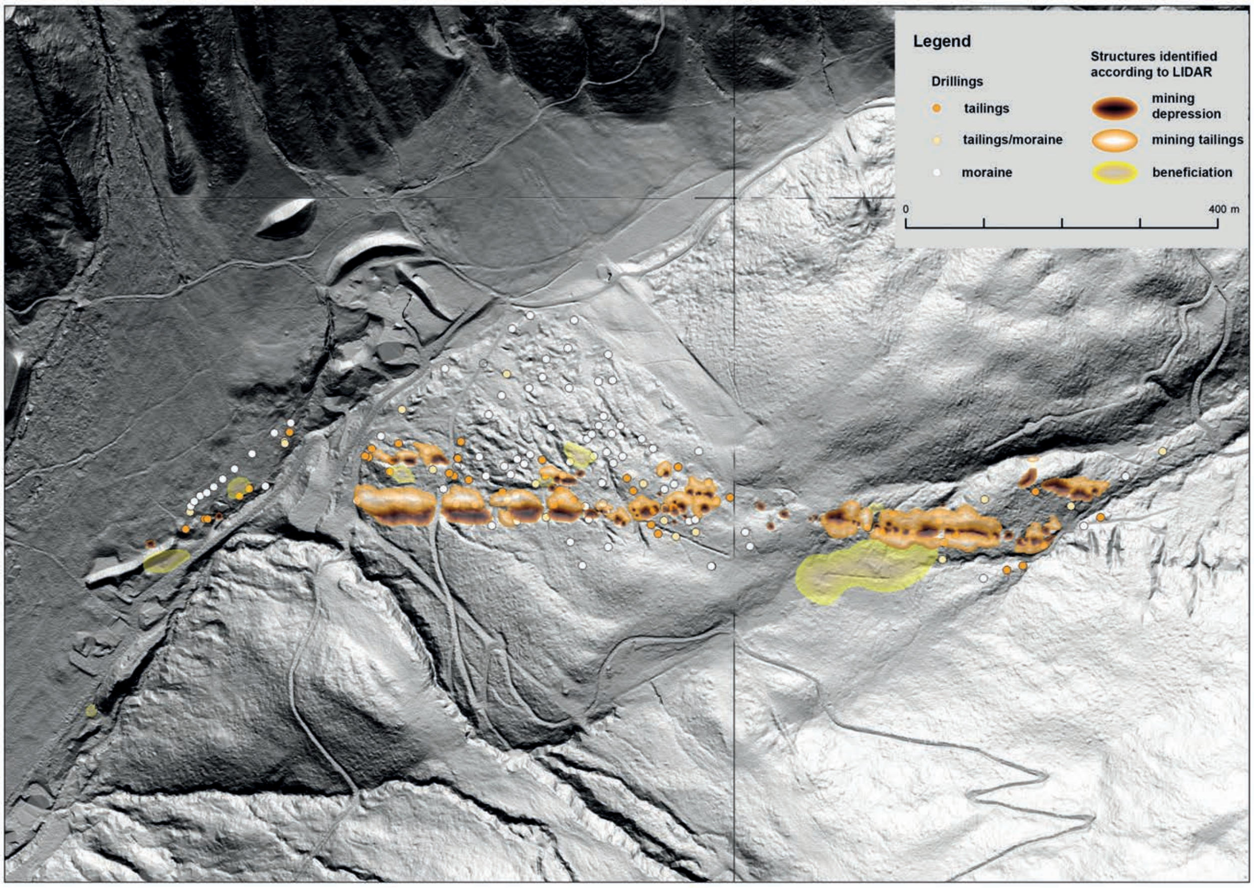

Fig 7: Mitterberg, Main Lode, the mining area according to mining structures and geological based soils, according to a drilling survey in 2009/2010 (map/graphics: DBM, A. Hornschuch).

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

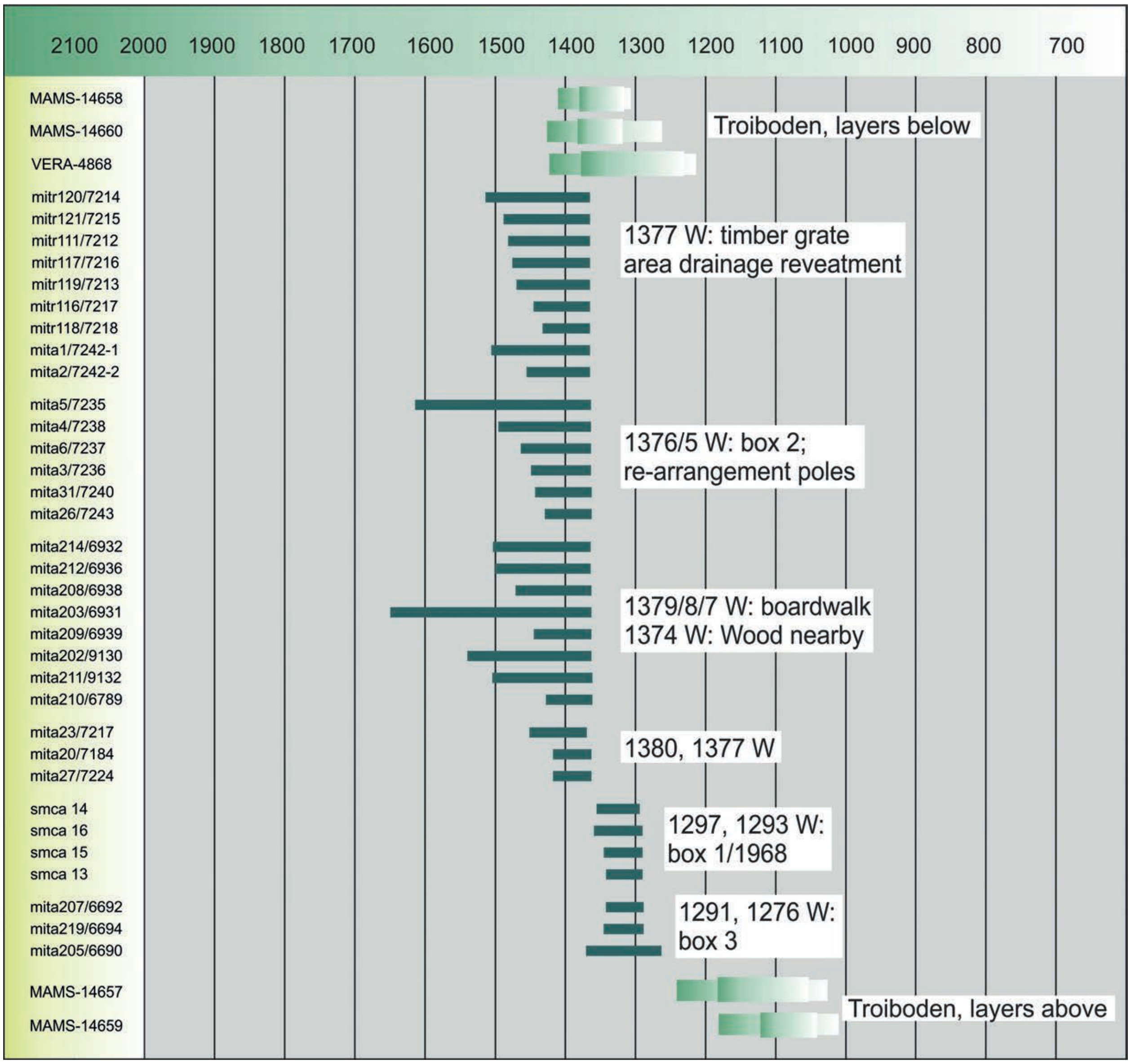

Fig. 8: ^{14}C-dating and dendro-dates from various features indicate a 200 to 250 years operation period; dendro dates after K. Nicolussi, T. Pichler, Univ. Innsbruck, data: Pichler et al., 2018 and Table 1 (graphics: DBM/RUB, Th. Stöllner).

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)

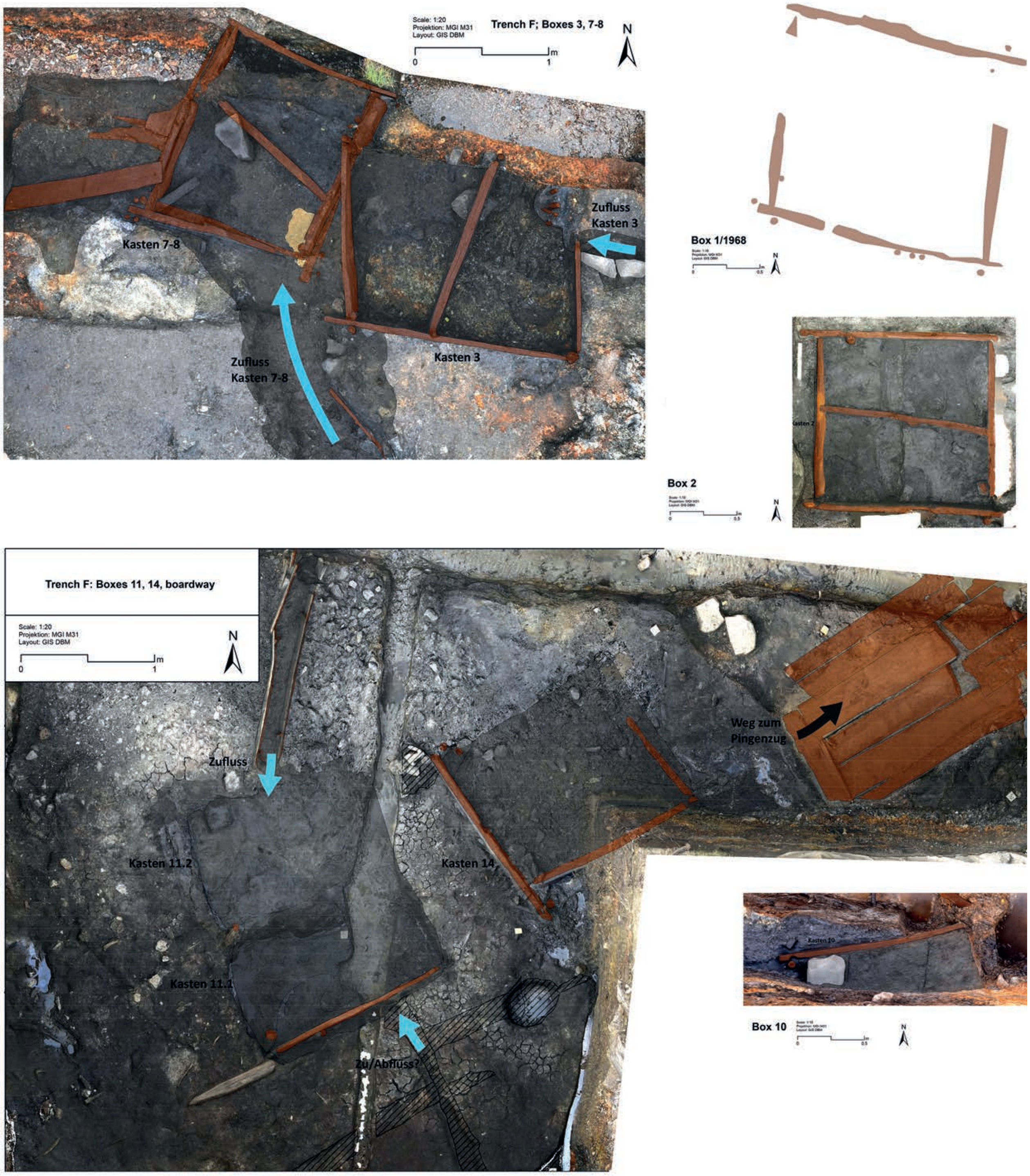

Fig. 9.1: Wet beneficiation boxes 1-3, 7-8, 10 from the eastern part of the Sulzbach-bog excavations (graphics/photo: DBM/RUB, J. Schröder).

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

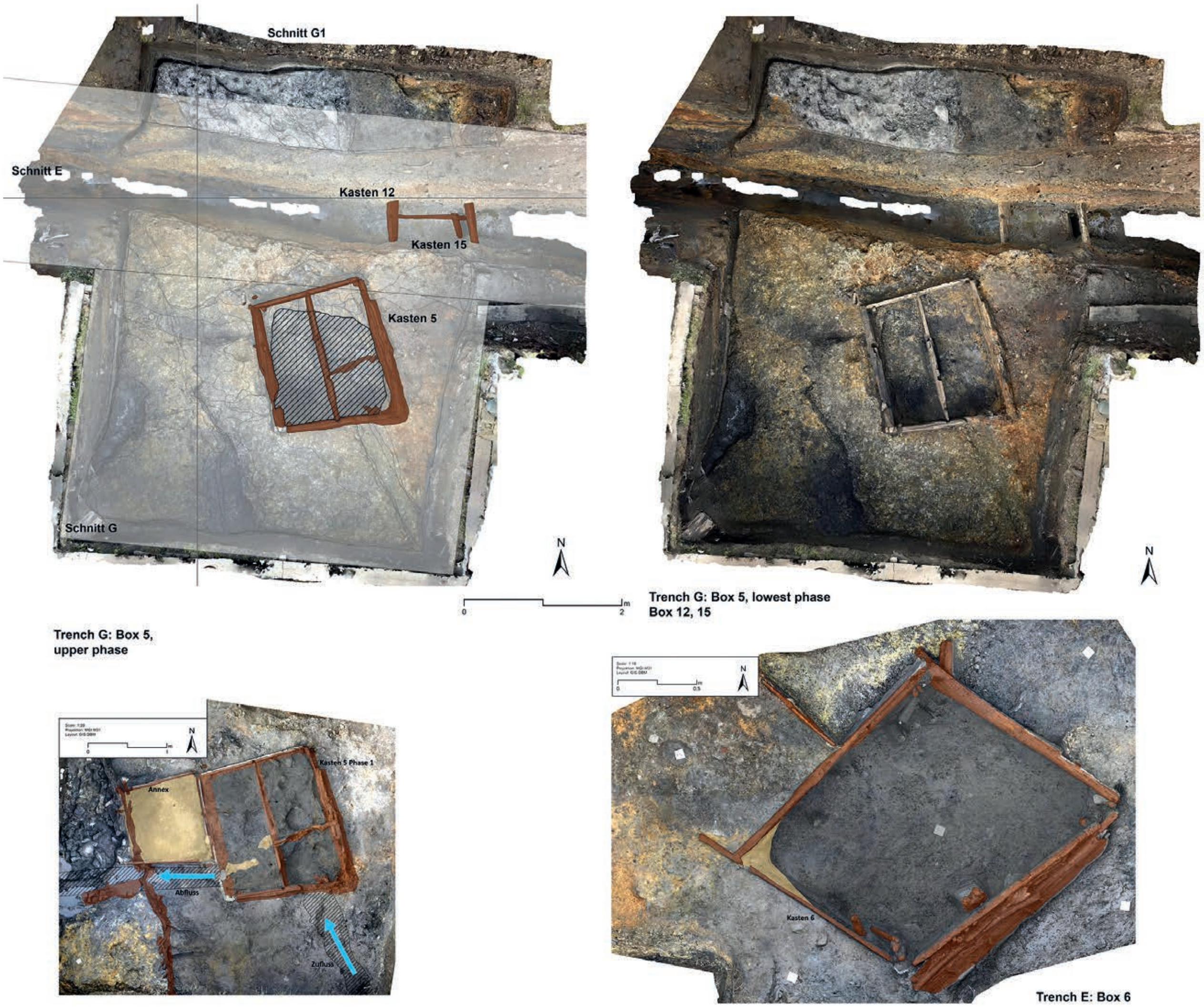

Fig. 9.2: Wet beneficiation boxes 5-6, 12, 15 from the western part of the Sulzbach-bog excavations (graphics/photos: DBM/RUB, J. Schröder).

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

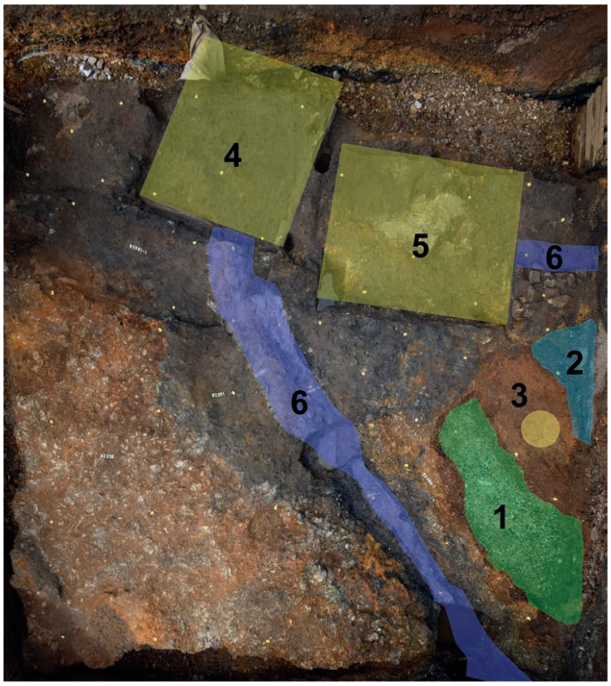

Fig. 11: Vertical photo plan with a crushing site in trench F south of boxes 3 and 7/8, east with coarser siderites (grade II) (1) and west with quartz mixed with siderites (grade III) (2) and the presumed location of a crusher when working and separating the grades (3); 4-5: boxes 3, 7/8, 6: water channels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

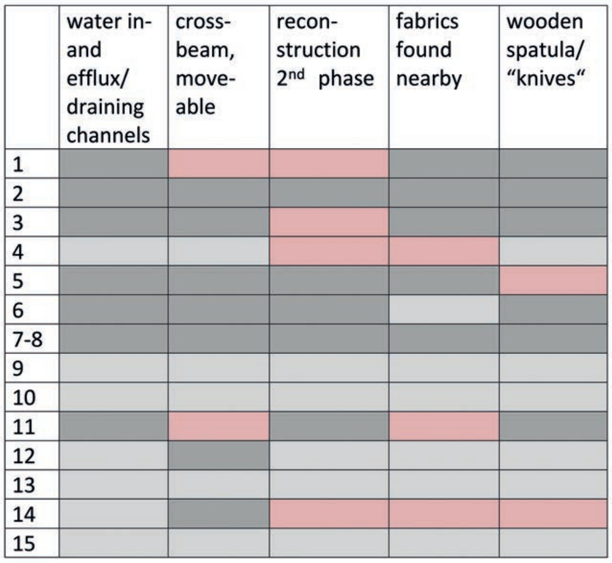

Fig. 12: Characteristics of operation and construction as observed or not observed with boxes 1-15, dark grey: evidenced, light grey: unknown, red: not evidenced (graphics: DBM/RUB, Th. Stöllner).

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

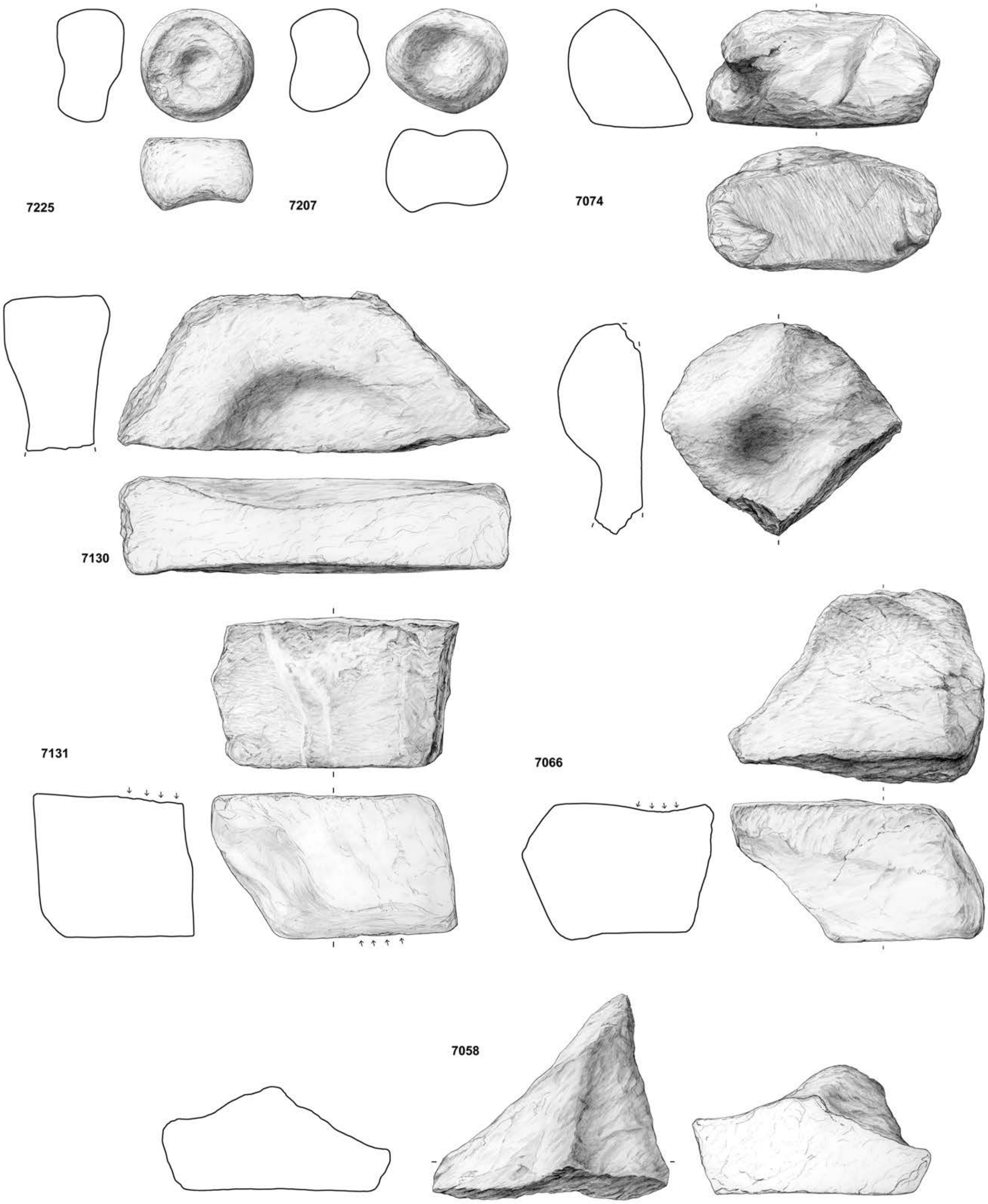

Fig. 13: Crushing and grinding stones found in or nearby box 2 in 2009, after Stöllner et al., 2012a, Fig. 14 (drawing: DBM/RUB, A. Kuczminski).

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

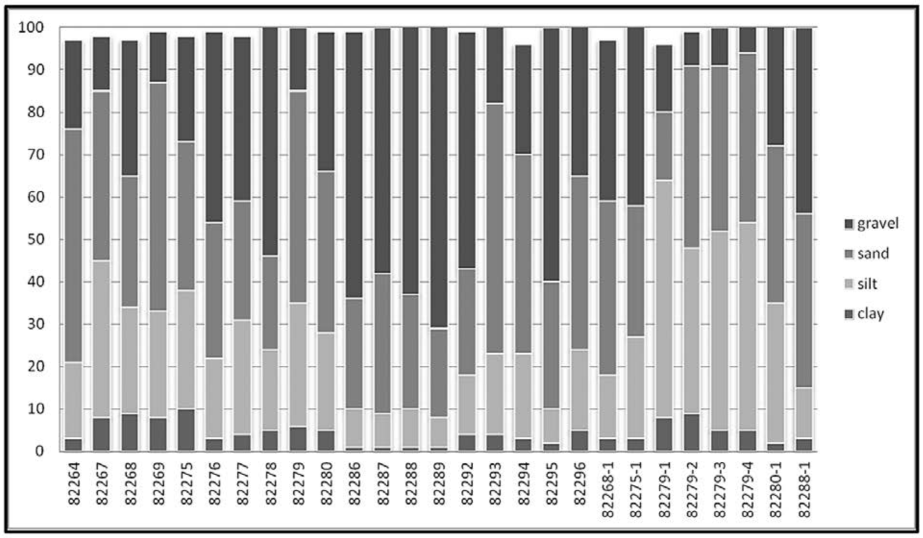

Fig. 16: Layers and their grade according to their weight of the sampled material; due to losses not always corrected to 100%, after Rashidian, 2016 (report).

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.

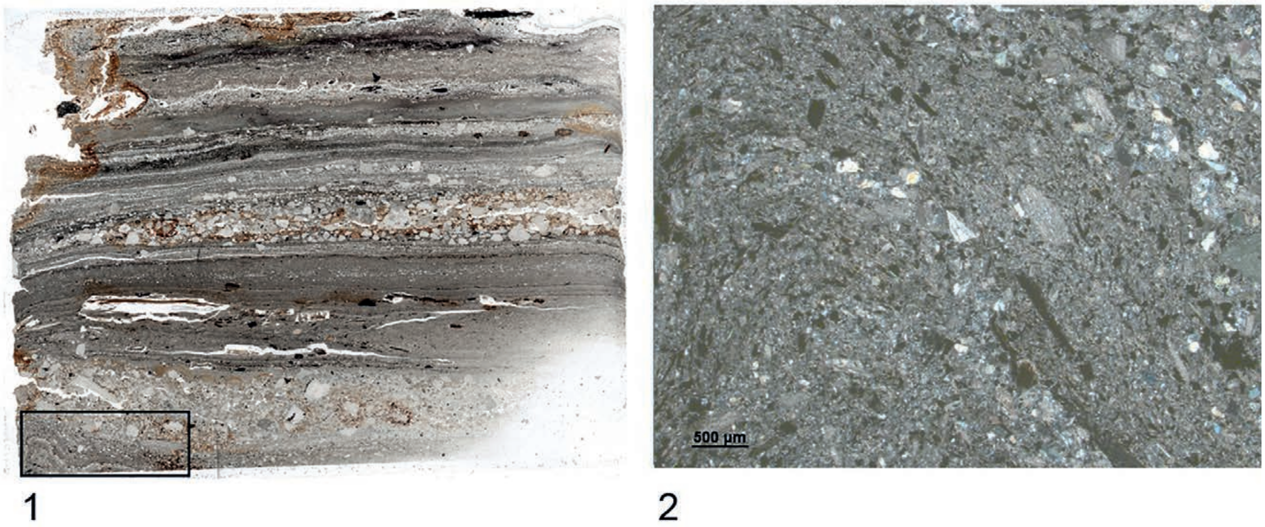

Fig. 17: Micromorphology of sediments of box 2, after D. Fritzsch and H. Thiemeyer in: Stöllner et al., 2012a, pp.25-26 Fig. 18 and report, 1: overview of the upper part, 2: Layer 16, with swirled sediments.

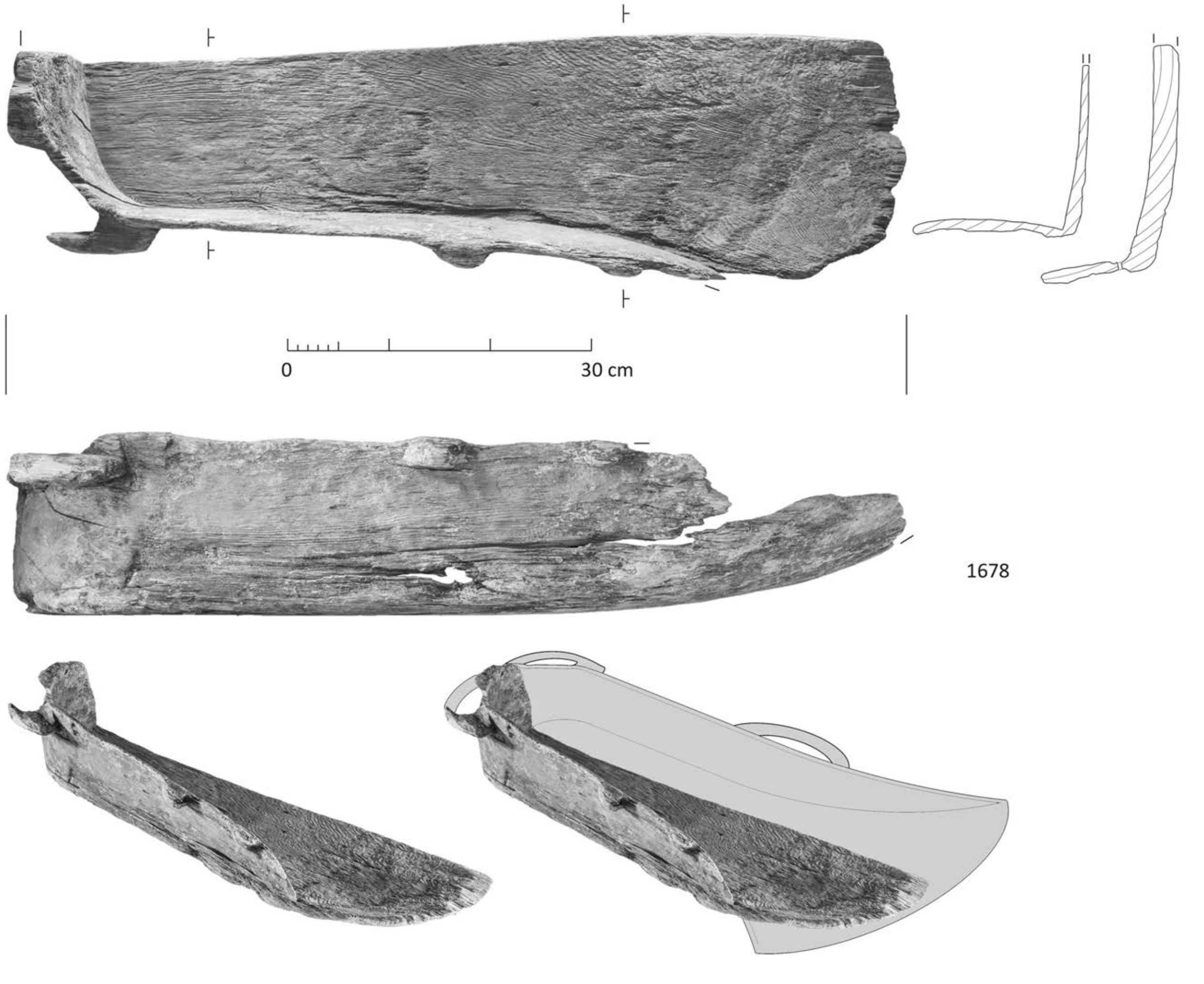

Fig. 18: Trough 1678 found in the open western mine cavern of 1867 after Thomas, 2018, p.357-358 Fig. 329-330.

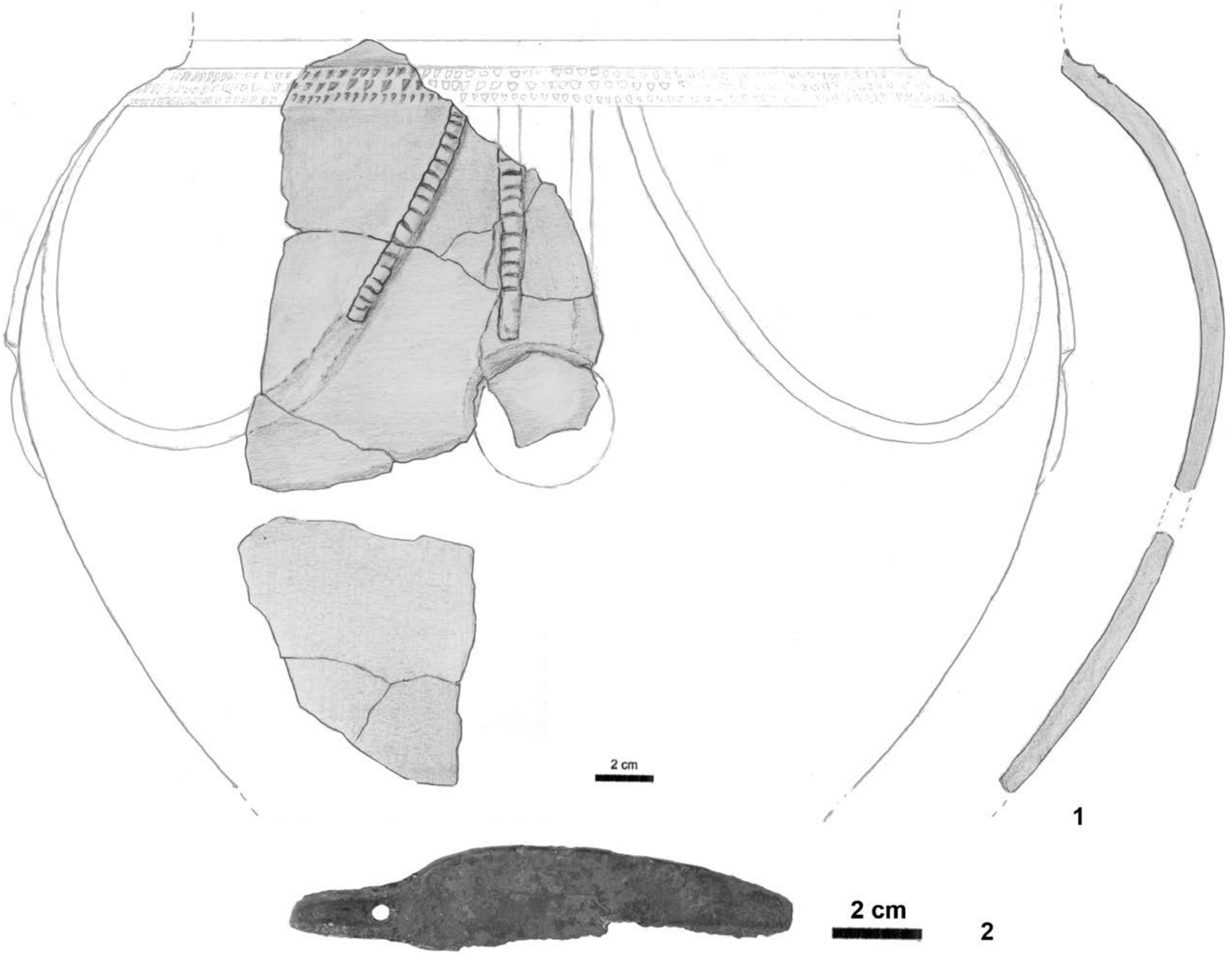

Fig 19: Troiboden, Sulzbach-bog, excavation 2013, large container with distinct decoration found nearby a hearth (1), Riegsee-knife (2), found nearby the boxes 3, 7-8 (drawing/photo: RUB, H.J. Lauffer).

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

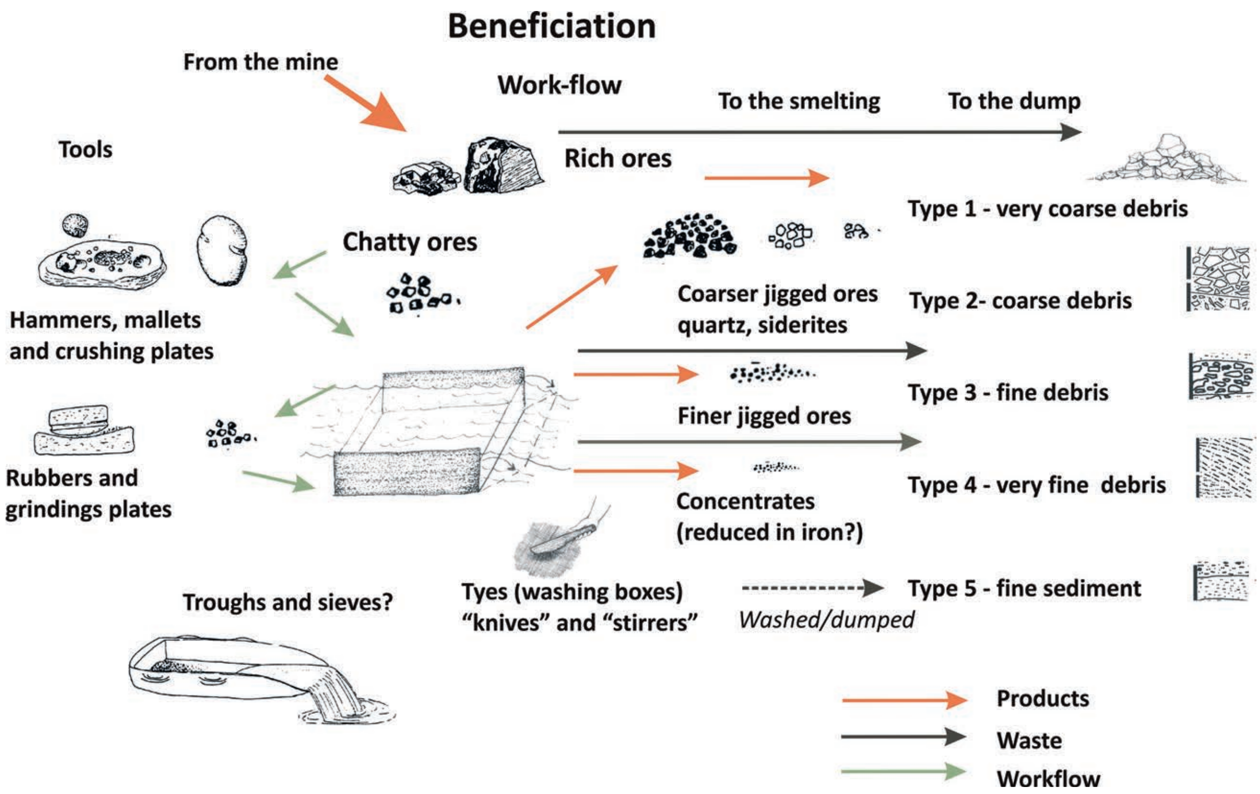

Fig. 20: Reconstruction of the beneficiation processes at the Mitterberg Main Lode area on basis of the features of the Sulzbach-Bog beneficiation site, graphics on the basis of Eibner 1979 and Rashidian 2016 (graphics: DBM/RUB, Th. Stöllner).

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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