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Some provisional results of experiments undertaken using a reconstructed sluice box: an attempt to try and reproduce the methods of washing and concentrating chalcopyrite at the Middle Bronze Age ore processing site of Troiboden, Mitterberg, Austria

ABSTRACT: *On-going experiments carried out by the author in 2012 and 2016 on the Mitterberg have attempted to reconstruct the use of the wooden sluice boxes found by the RUB/DBM team during excavations carried out on the Troiboden MBA processing site. A number of different hypotheses for their function and also means of operation have been tested, including as a simple washing box, as a buddle, as a tye, a simple form of jig used with sieves, and as a panning box. Several possibilities, some more probable than others, have been suggested, but no firm conclusions drawn. In addition, some useful general observations have been made, alongside recommendations for procedure in the case of future experiments*

KEYWORDS: ORE WASHING, CHALCOPYRITE, WATER FLOW, SLUICE BOX, BUDDLE, TYE, JIG SIEVE; PANNING, CONCENTRATE

Introduction

The archaeological context and interpretation of the wooden sluice boxes found at the ore processing site of the Troiboden is discussed elsewhere in this volume, and in the already published literature on this site (see Stöllner et al., 2012; Rashidian, 2016; see Stöllner 2019, this volume). However, the current series of experiments conducted during the DBM and RUB excavation campaigns of 2012 and 2016 were designed specifically to establish what exactly it was possible to achieve using just these boxes, a controllable water flow, and credible materials such as wooden spatulas and scoops (similar to those found at the Troiboden in 1972 and in 2009: See Stöllner et al. *ibid.* 21 + Abb.15 and Eibner, 1972, Abb. 7) and a range of coarsely-woven textiles and stick-mesh frames or sieves and containers. By no means all the latter types of objects have been identified from the Troiboden, yet some of these (or similar examples) have previously been reported from the mining area of Brixlegg at Radfeld, Mauk A (Goldenberg & Rieser 2004) from the Mitterberg and Kelchalm (Pittioni & Preuschen 1954) mining areas, and all of them would have been available to the Alpine cultures of the Middle Bronze Age and also the late Bronze Age at Kitzbühel and Radfeld. In this respect, given that a number of stated hypotheses were being tested, and that the procedures being attempted were to be repeated and also verified, the practice of these experiments conforms well with the procedural guidelines for the science of experimental archaeology first established by John Coles in 1973. Furthermore we should remember that such experiments can also be used to *predict* the sorts of archaeological traces formed by the processes investigated – a phenomenon which may prove useful during future archaeological work (Timberlake, 2015, pp.145-146). In fact the latter approach is a very valuable tool and an acceptable practice to follow when undertaking experimental mining archaeology.

The main hypothesis being tested here by experiment was that this box (and the other 8-9 similar-looking variants of these boxes) found embedded these now dendrochronological and radiocarbon-dated 14th-13th century BCE working floors of the processing site was being used to wash and concentrate (by means of gravity separation and water flow) the crushed chalcopyrite ore from the adjacent Main Lode mine. However, included within this were a series of other practical hypotheses which could be tested experimentally, none of which were necessarily mutually exclusive. First perhaps is that these boxes were primarily used just for 'washing' the ore.

Ore washing is a process first referred to (in technical detail) by Agricola in *De Re Metallica* (1556), and before that by Pliny (AD 77), whilst interpretations of processing features at Classical period mining sites such as Laurium in Greece as well as at Bronze Age mining sites (Timberlake, 2014, p.48) suggests that cleaning the ore is an important first stage of its preparation for the smelter, and in fact precedes the stage of concentration. In this respect it has been very interesting to note the importance attached to the washing (but not the gravity separation or concentration) of chalcopyrite within the 2015 film of the Nepalese tribal copper smelters *Tama Gaun* (see Anfinset in his lecture during the conference, see also: Anfinset, 2011). This appears to have been an indigenously – developed mining and smelting tradition, yet one which shares certain similarities perhaps with the sorts of processes which *could* have been taking place in the Eastern Alps during the prehistoric period (Goldenberg et al., 2012). There are inherent dangers in making these archaeo-ethnographic parallels, particularly in respect of theories concerning archaeological experiment, yet there is still a valid point to be made here I think. Washing the ore is a natural and spontaneously-developed stage of the ore preparation process which becomes visible once we are looking at furnace charges beyond the easy capability of hand-sorting and cleaning (i.e. above 5-8 kg in weight). For this purpose square or rectangular structures (made of either stone or wood) will be built, and the ore washed within a flow of water to remove both organics, clay, silt and sand and even the light particles of rock brought in from the mine and crushing floors. Apart from removing the fine waste material, this aids visibility in the subsequent selection and concentration process of the ore. On the Troiboden the pre-sorted and broken-up ore from the mine would have arrived in baskets, most likely mixed with clay, flakes of mica, charcoal and possibly wood. Of course the washing of the ore may well have been carried out twice; first on its arrival from the mine, and secondly following crushing of this to the grade size required for smelting. A set of experiments therefore were designed to test the effectiveness of this using the boxes.

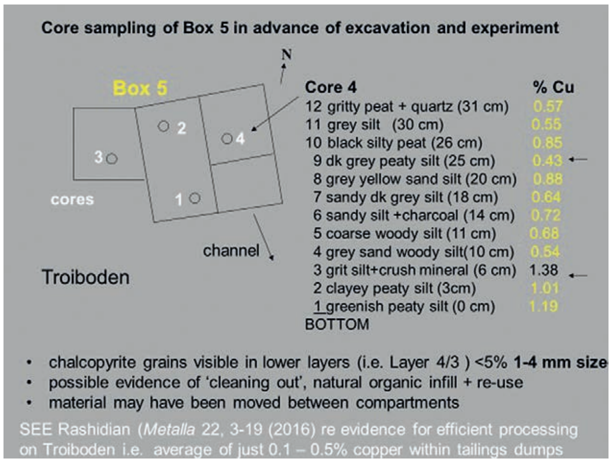
Much thought also went into planning experiments to test the possible use of this box for the gravity separation of ore from the lighter gangue minerals, in effect the concentration of the chalcopyrite. Likewise this included attempts at separating the finely-crushed chalcopyrite from the pyrite and other heavy minerals.

The **first** hypothesis to be tested was the use of a controlled water flow into the box to try and separate out piles of mixed gangue and chalcopyrite composed of different ore grades and grain sizes. In effect this was using the box as a tye or strake – a process which is described and illustrated in Agricola (ibid., pp.306-308). Here it is shown as involving a series of interconnected boxes, usually set into a slope, in which the ore minerals and gangue become separated into layers as a result of a fast, turbulent or variable water flow. Whether this is comparable to the water flow regime achievable within a single box is an interesting question, as might be the separation of the mineral into vertical/ horizontal layers, and following that the effective recovery from the box of selected enriched fractions.

The **second** hypothesis was to test its possible use as a buddle. In this scenario the tank would be filled with water and the finely ground ore rapidly mixed into it and agitated, the water then perhaps being rotated, allowing the heavier minerals to settle out first at the base. Possible examples of these are described in Agricola (ibid., p.300), some off which just consisted of wood-lined boxes set into the ground. Yet others, including simple stone-lined boxes without any planks or openings have been recorded from the hand-dressing floors of a number of Medieval – Postmedieval metal mines (see Craddock 1995, p.166 Fig. 5.9).

A **third** hypothesis was that the box was used in combination with a sieve as a jig. Jigging is another technique used for ore separation and concentration, and is likewise described and first illustrated in Agricola (ibid., pp.310-11), thereafter becoming one of the principal ore-dressing techniques employed within Postmedieval mines (latterly as manual or automated jigging frames). In terms of primitive ore dressing, it is suggested that a container bottomed with a sieve and filled with finely crushed ore and gangue of similar grain size might be pushed down gently, but repeatedly, into a still water-filled tank in order so as to saltate the mineral grains and thus allow for gravity separation. This may occur within the container, or else may be divided between the container (which retains the lighter gangue fraction that can be discarded) and the heavier sulphide-rich fraction which passes through this and settles upon the floor of the tank. The crucial skills to master here are the techniques of saltation (such that the separation of minerals divide accurately between the gangue and the sulphides collecting in the tank), and the control of grain size. Without competence in both, the process as a whole becomes inefficient.

The **fourth** hypothesis was to examine the possible use of this box to assist in the panning (therefore the gravity separation) of chalcopyrite from the other sulphide and gangue minerals using a simple scoop, ladle or trough, perhaps even suspended from a rope hanging to a frame or tripod. Agricola does not mention this specifically as a concentration technique suitable for sulphide ores, yet there are examples of its use in gold recovery. In particular we find shallow wooden troughs with handles (*Sichertrog*) being used for the panning of gold out the rivers in Transylvania (Apuseni Mountains, Roumania). Although there is no evidence for the use of these pans



Core sampling of Box 5 in advance of excavation and experiment

Core 4	% Cu
12 gritty peat + quartz (31 cm)	0.57
11 grey silt (30 cm)	0.55
10 black silty peat (26 cm)	0.85
9 dk grey peaty silt (25 cm)	0.43 ←
8 grey yellow sand silt (20 cm)	0.88
7 sandy dk grey silt (18 cm)	0.64
6 sandy silt +charcoal (14 cm)	0.72
5 coarse woody silt (11 cm)	0.68
4 grey sand woody silt(10 cm)	0.54
3 grit silt+crush mineral (6 cm)	1.38 ←
2 clayey peaty silt (3cm)	1.01
1 greenish peaty silt (0 cm)	1.19
BOTTOM	

- chalcopyrite grains visible in lower layers (i.e. Layer 4/3) <5% **1-4 mm size**
- possible evidence of ‘cleaning out’, natural organic infill + re-use
- material may have been moved between compartments

SEE Rashidian (*Metalla* 22, 3-19 (2016) re evidence for efficient processing on Troiboden i.e. average of just 0.1 – 0.5% copper within tailings dumps

Fig. 1: Core sampling in 2016 of Box 5 in advance of excavation and experiment, with Core 4 copper values (diagram: S. Timberlake).

in water-filled sluice boxes, there are some examples described as having been used for panning *above* water-filled wooden tanks during the 19th century (Pošepny 1868). The use of similar troughs or pans during the Middle Bronze Age for gravity separation of chalcopyrite continues to be a possibility – and such a hypothesis is worthy of testing by experimentation. In fact there are a number of wooden artefacts from the Bronze Age mines of the Mitterberg, from Brixlegg (Mauk F) and Kelchalm some of which could have been used for the panning of sulphide ores.

The *modus operandi* of the tank itself also needs to be addressed. For example, do we know whether the tank required one or more people to operate it? Was it always water-filled? Was the cross-bar used for sitting on, or for leaning against? Might this bar also have helped deflect the water current, and for what purpose? What was the working depth of the tank i.e. were the sides dug into the sediment (as has been suggested), and if so was the tank then dug out in the middle? Finally, how quickly and easily could the tank have been emptied of water (assuming that it was important function to recover the waste or ore fraction from the tank with the minimum of disruption)? Answers to all or most of the above questions can be addressed by experiment, and following this a range of possible scenarios examined.

The analysis of a sediment core from Sluice Box 5 (September 2016) – crushed ore, grain size and copper concentration

Prior to the planning of the 2016 experiments an opportunity arose to core the *in situ* sediment fills present within the compartments of a recently excavated sluice box (Box 5) from the Troiboden. In September 2016 four cores were taken from three of the interconnected boxed compartments. These were examined sedimentologically, which included visual particle size analysis and mineral grain identification undertaken using a binocular microscope, and semi-quantitative elemental analysis (% Cu) with a Niton pXRF. The results for Core 4 from the sediment-filled compartment closest to the northern inflow channel to the box were compared with those from Core 3, an annexe to the box on its western side (see Fig. 1). In Core 4 grains of crushed vein mineral and rock appeared to be enhanced within the lower layers 3 and 4 at a depth of 21-26 cm, from a level just above what was presumed to be the original peat-cut floor of the box. Just under 5% of these grains were recognisable as the sulphides chalcopyrite or pyrite, with all of the visible ore grains being in the range of 1-4 mm. The slightly higher pXRF reading of 1.38% copper for layer 3 reflects the very small increase in the number of ore grains within this layer which remained upon the box floor after concentration – a value which probably accurately reflects the presence of c. 5% chalcopyrite within the sediment with a copper content of around 20-25%. The results for Core 3 on the other hand show a slightly different pattern. Here considerable numbers of grains of crushed vein rock consisting mostly of the gangue minerals quartz, ankerite and goethite (with slightly elevated copper values of between 0.57 and 0.82%) remained within layers 4-6 and 8 in the upper half of this infilled compartment, evidence perhaps for the use of these multi-compartment boxes for the dumping or storing of the already separated fractions of ore concentrate and waste. Whilst it is difficult to be certain of this as a true function of the box, the evidence obtained so far from this coring study has provided a useful database for this on-going programme of experimental work.

To some extent the results of the copper analyses of the sediments recovered from Box 5 supports the general conclusion of Rashidian (2016, pp.3-16) concerning the efficiency of the ore processing on Troiboden; i.e. that a high rate of recovery of chalcopyrite from the middling ores which exceeded 95% has resulted in a loss to the spoil (tailings) averaging just 0.1-0.5% of detectable copper. Not surprisingly some of this copper will have been lost to solution within the oxidising conditions of the tips, and in some cases we are may be finding this copper re-deposited (i.e. ‘fixed’) within the organic peat horizons underlying the tailings and the boxes themselves (N.B. Layer 1 within Cores 3 + 4 contained 1.08 and 1.19% Cu respectively).

In September 2016 some of the archaeological sections within the vicinity of Box 5 were likewise sampled for copper. Thus layer [82246] just outside of Box 5 was found to contain 0.68% Cu, the fill [86041] of the drainage channel on the south side of this box 0.91% Cu, the upper tailings debris sampled within the east profile of Trench G 0.54% Cu, the lower tailings debris within the same profile 1.26% Cu, and the tailings debris of the north profile of Trench E (Rösche) 0.01% Cu. These results were slightly higher than those obtained by Rashidian, yet were from samples taken in the field only using pXRF, so in actual fact these may well be comparable.

August 2012: The reproduction of Box 1 – its manufacture and installation within the riverbed site below the Athurhaus: the controlled waterflow ore-separation experiments

Box manufacture

The reproduction of Box 1 excavated on the Troiboden in 2008-2009 was undertaken in August 2012 by the prehistoric wood technologist Wolfgang Lobisser (Vienna Institute of Archaeological Science) to the dimensions of the original pieces recorded in Stöllner et al. 2012, Abb.11 (see Stöllner 2019, this volume). Consisting of four morticed plank uprights and a crossbar the facsimile was manufactured from the same wood species (*Picea abies*) using reproduced Middle Bronze Age bronze carpentry tools which included an adze, axe and gouges (Fig. 2).

Fig. 2: Construction of Box 1 facsimile in advance of experiments in August 2012 (photo: S. Timberlake).

Box installation

The four sides of the box were slotted together and this was then placed in a suitable position to the side and downslope of the active stream course within the stone-covered riverbed (Fig. 3) The box was dug into the dry gravel riverbed to about half its depth, and the original gravel and stones emptied out from the middle. Fine gravel was now collected and the base of the box re-filled to a height of 10-15cm from the base, and levelled. On top of this was added a layer of clay gathered from the stream bank to a depth of c. 26 cm from the base. This was again levelled and then 'puddled' to make a reasonably flat surface, then left overnight to dry. The depth of placed sediment within the experimental box thus corresponded to the approximate depth of sterile sediment found within the archaeological example.

A small reservoir with a clay lining was then constructed in front of the inflow to the box, and the box was

Fig. 3: 2012 river bed experimental ore-washing and processing site, Mitterberg (photo: S. Timberlake).

Fig. 4: Water-filled reconstructed box ready for experiments, showing lay-out of leat, diversionary channel and drain (photo: DBM).

Fig. 5: Rock slabs collected from river bed for use as mortar stones and anvils, along with crushed chalcopyrite. The stones show working faces/hollows from 6-8 hours of use (photo: S. Timberlake).

then tested to ensure that it was watertight and could maintain the same level of water fill. A small channel was then dug into the riverbed on a suitable gentle gradient up to the main course of the active stream. At this point, close to the junction with the stream, was built a small clay plug dam with a stone core. The centre of this dam would form part of an easy to break and repair sluice designed to control water flow along this inflow channel to the box. This set-up was tested and the box filled with water, the channel remaining slightly open in order to maintain a slow but steady and continuous flow of water into and across the box (Fig. 4).

Following the first buddling experiment (1A) the floor level of the box was raised up (using a mixture of fine river gravel and clay/silt) to the level of the bottom of the outflow hole at its rear, leaving a very slight slope towards this from the inflow. A plank was also placed across the top of the box at its rear for use as a seat. The outflow channel outside of the box (i.e. to its rear) was then deepened to ensure that a fairly rapid and constant flow of water spread across the inside floor of the box. This was for the purpose of using the box as a tye or strake to separate out piles of ore simply by controlling the flow of water.

Ore preparation

Approximately 50 kg of chalcopyrite ore associated with vein quartz and ankerite was mined using sledge hammers and picks from an exposed vein outcrop close to the Arthurhaus. In addition to this a number of boulders rich in chalcopyrite were collected from the floor of the

Mineral	Specific gravity (gm/cc)	Comments
microcline feldspar	2.56	gangue minerals
calcite	2.71	
quartz	2.72	
muscovite	2.76	
ankerite	3.05	
epidote	3.4	
siderite	3.96	
chalcopyrite	4.2	ore concentrate
pyrite	5	included
hematite	5	

Tab. 1: A table of specific gravities of minerals common to the Mitterberg ore veins.

Fig. 6: Using the box as a buddle with a facsimile wooden shovel. August 2012 (photo: DBM).

riverbed upstream of the experimental site. In total some 75 kg of ore was available.

Most of the ore crushing was attempted using just stone tools. These were selected from a range of water-worn rock slabs along the river bed and were collected for use as anvils or mortar stones. Naturally-indented boulders were chosen wherever possible for making mortar stones, and as the use of these progressed the development of deeper mortar hollows as a result of the continuous pounding and crushing of the ore was closely monitored and recorded (Fig. 5). Suitable cobbles for use as hand-held crushing stones were also gathered from the riverbed, and wherever possible these were chosen from harder rock types, such as quartzites, gabbros or ultrabasic rocks, the latter lithologies being quite rare but still present in small amounts within fluvial assemblage. The use of such mortar stones, stone anvils, and occasionally grind stones in this process is supported by the archaeological evidence from the Troiboden, although stones of exactly the same size, shape and composition were difficult to come by within walking distance of the experimental site.

In 2012 the ore crushing was carried out on the dry riverbed next to the experimental site by five or six RUB - Archaeological Institute students (see Fig. 3). All of this work was fully documented, and from the initial processing some 7 buckets consisting of several different grades of crushed ore and gangue were obtained permitting 11 separate washing experiments to be undertaken. The categories included hand-picked lumps which made up a *'high-grade' ore* (perhaps 60-80% pure chalcopyrite), a *'middle-grade' ore* (40-60% chalcopyrite) and a *'poor-grade' ore* (perhaps 20-40% chalcopyrite in quartz). The three grades were then crushed and 'milled' to approximately three different grain sizes within the following size ranges: *coarse* (<10 mm >5 mm), *medium* (<5 mm >3 mm) and *fine* (<3 mm). However, an extra finely-milled high-grade ore sample of < 2 mm was also prepared using a grindstone in an attempt to separate the pyrite from the chalcopyrite.

As a general rule, the sieves were only used as a guide in the business of grain size separation, so much of this work was carried out instead by eye and by guesswork, much as it probably would have been done during the Middle Bronze Age at the Troiboden site.

In brief, the following experiments were carried out using the reconstructed box in 2012, the results (data) of which are shown in Table 2 [N.B. unless otherwise stated the weight of each of the fractions was recorded when wet. They should not be regarded therefore as being composed of 'pure' sulphide or gangue but simply as 'enriched' samples]. Table 1 provides an indication of the specific gravities of some of the commonly occurring minerals within the Mitterberg ore veins, in particular at the Troiboden.

Using the box as a buddle (Experiment 1A)

The first experiment was undertaken to try and buddle a bucket sample of coarse poor-grade quatz-rich chalcopyrite within the waterfilled box. Using a facsimile of the wooden paddle found at the Troiboden (see Fig. 6), the water was stirred in a clockwise direction in order to agitate and suspend the grains for the purposes a gravity separation. This was not particularly successful, although a slightly richer chalcopyrite concentrate of 0.613 kg (out of 1.75 kg of sample) was removed from the floor of the box.

Using the box as a 'tye' to concentrate a poor-middling ore (Experiments 1C + 1D, 2, 4.1 + 4.3 and 5)

In these experiments small piles of crushed ore were placed directly in front of the inflow hole upon the raised floor of the box, and the controlled flow of water from this then used to separate out the coarse from the fine-crushed

Experi-ment	Hypothesis	Procedure	Ore	Chalcopyrite	Comments
1A	use of the box as a **buddle** for gravity separation	closed water-filled box agitated and allowed to settle	**1.72** kg 20-40% ch @ <10 mm	**0.613** kg sulphide	
1C	use of the box as a **tye or strake**	separation of a pile raked back and forth under continuous water from the inflow	**4** kg – same –	138 g (from 450 g)	method separated out fine-grained fraction (0.503 kg) from coarse (3.514 kg) = returned for re-milling
1D	– same –	washed the same but sieved (<3 mm) to improve gravity separation	**7 kg** – same –		2.146 kg (>3mm) returned for re-milling – from finer grained 3 fractions incl sulphide separated from semi-circular spread
2	– same –	fine milling to try and improve the degree of separation	225 g 20-40% ch @ 4 mm	108 g	partial collection of gangue (98 g +)
4.1	the use of the box as a **tye** to test the separation + recovery of known composition	the washing of a fine-milled synthetically composed ore	250 g sulphide + 250 g ankerite + 100 g quartz	250 g	sulphide-rich concentration scooped up with spatula and squeeze to remove water (incl. 25% gangue)
4.3	– same –	The same – but put through a sieve to remove >3 mm fraction	100 g each of quartz, ankerite, crushed rock + sulphides	101 g sulphides (wet)	229 g gangue left in <3 mm fraction
6.1	use as **tye** with slow-water pulsed washing for better recovery?	first passed through 2 mm sieve	511 g of high grade fine-milled ore	293 g of sulphide	65 g of gangue (incomplete collection)
6.2	better recovery through finer milling + repeated washing?	2 mm sieved and washed x4 times	1.117 kg of high grade ore	833 g of sulphide -rich fraction	
4.2	**separation of the chalcopyrite from pyrite**	fine-milled high-grade ore pulse-washed + separated with a spatula	208 g of high grade ore	not recorded – but different samples taken for analysis	no visible gravity separation was evident

Table 2: 2012 buddle and tye box experiments – using water flow to separate out ore and gangue and to concentrate chalcopyrite.

grains, and the heavier (sulphide) minerals from the lighter (gangue) minerals. The results from Experiments 1C and 1D suggest the re-deposition and partial separation of the mixture in the water flow, the finer grained material (consisting both of sulphides and gangue – but with an enrichment in chalcopyrite) reporting to the base and to the edges of the pile (Fig. 7). It was not really possible to recover a concentrate from this. However, after collecting the now-separated coarse (<10 mm >3 mm) and fine (<3 mm) fractions with a wooden spatula these were dried and re-milled down to a finer grain size (<3 mm). The sample was then re-washed and a better recovery of sulphides obtained. So, after a somewhat lengthy process it was possible to raise the chalcopyrite % from a poor to a middling-grade ore.

In Experiment 2 the same poor grade ore was milled to a standard size (<4 mm). The ore was washed in the same way, but this time the gangue and sulphide-rich

Fig. 7: Washed and partly separated chalcopyrite and gangue within the 'tye box' [Experiment 1d] (photo: S. Timberlake).

fractions were carefully separated, dried and weighed. Thus 225 g of a slightly richer middling grade chalcopyrite concentrate was obtained just in one step from 275 g of ore.

Experiment 5 involved the attempted separation of 1.6 kg of finely milled ore by means of a more skilful use of water flow through the repeated opening and closing of the inflow hole into the box using a fabric bung. This enabled a much better grain density separation under gentle water flow conditions. Another effect of this was the flotation of the finest chalcopyrite dust upon the water surface, much of which accumulated on the far side of the box to the rear of the wooden bar (Fig. 8). An attempt was made to collect this using the wooden spatulas, but it proved difficult to recover. Almost 50% of the processed and partly separated sample was recovered from the floor of the box. This was a good result showing that there was very little loss from the box, yet the improvement in grade from 'digging' the sediment out was probably little more than 20-30%.

A better result was obtained in Experiments 4.1 and 4.3 using finely-milled synthetically composed ores made up of 250 g of pure chalcopyrite, 250 g of ankerite, and 100 g of quartz (in the case of Experiment 4.1) and exactly 100 g portions each of quartz, ankerite, sulphide and rock (within Experiment 4.3). These minerals were separated out in the water flow, the sulphide fraction being collected more or less in its entirety in Experiment 4.1, but just as a 50% concentrate within Experiment 4.3. This seems to suggest that a complete separation is theoretically possible this way, but that it is practically difficult and time-consuming to achieve, and probably only effective when using just small amounts of carefully milled, simple, and moderately-rich ores.

Using the box as a 'tye' to concentrate a rich sulphide ore (Experiments 4.2 and 6)

Finely-milled high-grade ore was washed in a similar way, but then passed through a 2 mm sieve in order to try and eliminate the grain size from the gravity separation effect of washing. It was also hoped that a much cleaner and richer concentrate might be obtained if the mix was better prepared and already enriched by careful sorting. The first experiment (6.1) yielded a c. 60+% concentrate of chalcopyrite, which may in fact be the same as the ore treated. However, the second experiment (6.2) yielded a c. 75% concentrate, but only after four separate washes followed by collection.

The final experiment (Experiment 4.2) was designed to see if it was possible to separate chalcopyrite (specific gravity 4.2 gm/cc) from pyrite (SG 5 gm/cc) in its finely-milled form by means of skilfully controlled pulsed washings at the inflow to the box. Unfortunately very little visible separation could be seen, and given the number of attempts trying to do this it seemed unlikely that this procedure could ever have been successfully achieved. Nevertheless, samples from both the bottom and top layers were returned to the DBM for analysis.

Fig. 8: Flotation of fine chalcopyrite bubbles upon the water surface. August 2012 experiment (photo: S. Timberlake).

August 2016: Further experiments carried out using the reconstructed box – including ore preparation, ore-washing, gravity-separation, ore flotation, jigging and panning

These experiments were conducted by the author, and the RUB students Eva Neuber and Tim Teufel between the 4th and the 16th August at the same riverbed site.

Re-assembly and experiments with water flow and the sealing/ emptying of the box

The box was once again assembled and dug into the dry riverbed. The level of the river was considerably higher at this point, therefore there were difficulties in digging a leat to the box, and also in controlling the water flow. Because of this a much better sluice and also a system of release channels became necessary, and on several occasions during the experiments the box became inundated by water and silt after nights of heavy rain.

One of the experimental modifications made to the box following the leakage of water from its joints and base was the use of sphagnum moss as 'caulking material' to seal around the inside edges. This proved to be a very effective method of stopping water leaks, as well as a method of closing-down the water inflow and outflow to the tank. Indeed, moss was much preferable to clay or sand in this respect, and it would be worthwhile therefore to search for the use of this same material within the excavated box(es) upon the Troiboden. The necessity of digging high waterflow release channels around the box as well as other channels adjacent to the box sides to drain water away from the surrounding sediments when emptying the box raise important questions about the practical issues of using these, as it does about the actual environment in which these were used. Certainly as regards water flow rate and the maintenance of clear still-water conditions which may or may not be necessary for washing and separation the environments of the peat-covered plateau of the Troiboden and that of the experimental site are barely, if at all, comparable.

One final experiment to do with construction and use was carried out to try and solve the issue of how to rapidly and completely drain the box (and thus remove its contents) without completely dismantling it. An earlier attempt to do this by removing the back board proved problematic, for even the slightest sediment flow or movement made it difficult, if not impossible to replace. This was an unanticipated problem. Removal of the back board had been suggested as an operating feature, but experimentation now suggests this to be highly unlikely. Instead experiments have shown that the box, so long as the level of its working floor lies above the base of the drainage cut issuing from its outflow, can simply and effectively be emptied of water by digging a sump beneath the board into the drain (see Fig. 15). Once emptied of water the accumulated ore or gangue sediments may then be removed using a wooden shovel or series of large spatulas. The sump hole may then be blocked up again with clay or moss before re-filling with water

Ore preparation

Some 58 kg of ore remained for the experiments carried out in 2016. This consisted of 7.963 kg of high-grade (>60%) ore, 20.95 kg of medium-grade (40-60%) ore, and 29.152 kg of low-grade (<40%) ore).

Following the coring exercise carried out on Box 5 at the Troiboden site a simple experiment was devised with the goal of crushing a medium-grade ore using just stone hammers and a mortar stone to a size believed to have been the standard equivalent for wet processing during the Middle Bronze Age (i.e. around 4 mm). The necessity for skill in this task soon became apparent, such that by Experiment 3 just one person undertook the crushing and milling of an ore in preparation for its separation by jigging. This reduced any variability in assessing the efficiency of the process.

Interestingly the scale of loss from ‘prehistoric’ ore processing compares well with more modern methods, although the time required to process just a few kilograms of ore to the required size for concentration and for smelting provides us with a clue as to the labour-intensiveness of the ore preparation process carried out on the Troiboden. Even assuming a much-improved and more consistent work rate, 1.5-2 hours may have been required to reduce 5 kg of ore to a size suitable for processing. What it was also possible to show was the difficulty in reducing this to a standard size without the use of sieves or screens. Chalcopyrite and pyrite in particular are brittle, resulting in a much higher than expected report of material to the finer grain fractions (i.e. < 0.5 mm). Even so, the greater proportion of this ore (i.e. > 50%) remained within 1-4 mm fraction. Continued milling of the ore upon a grindstone (or mortar) produced a more consistent grain size (0.5-2 mm) suitable for separation, although not of course necessarily the size desirable for smelting.

Fig. 9: Using the water-filled box with a woven wattle frame and sacking for the washing of the crushed ore in August 2016 (photo: S. Timberlake).

Use of the box for washing ore

This simplest use of the box for was addressed by a couple of experiments involving the construction of a square frame made out of woven hazel (*Corylus* sp.) branches gathered from the banks of the river. The frame did not function a sieve, but rather as a rigid grate on which a loose fabric could be laid and upon which copper ore might be placed in order to rapidly wash within the water-filled box (Fig. 9). The experiments were carried out using several fabrics, including a synthetic fleece (mimicking a tightly woven fabric) and also hessian (as a coarsely woven fabric; see also Grömer et al., 2018). Freshly crushed but not size-graded ore was experimented with alongside ore intentionally mixed with clay, soil and vegetation, and charcoal – much as it might have arrived at the Troiboden washing floors from the Main Lode workings.

The most effective washing out of the lighter rock (mica schist particles) and clay was achieved by immersing (dipping and agitating) the frame into a fairly fast stream of water passing through the box, although this could also be achieved within the still water-filled box through more intensive agitation and the stirring of the spread-out ore upon the hessian bed. The use of smaller open-weave baskets for washing were also experimented with, and in some ways the use of these seem much more likely, and probably more efficient.

In conclusion it can be said that upwards of 20% of the dirt and lighter rock waste accompanying the ore (alongside the organics) could have been removed by washing this within boxes, or perhaps inside of baskets in a stream of flowing water. The advantages of using a box includes the control of water flow, the provision of a silt trap, and the possibility also of collecting and re-working the waste.

Washing and cleaning the ore was probably an essential pre-requisite to assessing its grade and grain size following crushing.

Further 'tye' box experiments to try and improve the gravity-separation of sulphides and capture chalcopyrite by flotation

A short series of experiments were undertaken to try and refine the 'tye' box water flow-assisted gravity separation of ore achieved in 2012. None of the samples used and recovered here were measured, as this was primarily an attempt to see whether the technique worked under the higher water flow conditions present.

In the second experiment the box was first emptied of water, and a shallow clay cone constructed upon the inside rising towards the intake, the highest point lying only a few centimetres short of the inflow. The surface of the clay was then moulded into riffles by means of semi-circular grooves. Crushed ore was added to the top of the cone, but the power of the water flow scoured much of the ore and the clay away, though a small concentration of chalcopyrite (sulphides) did remain within the highest riffle with some of the lighter gangue minerals below. Most of the ore was lost to the water current, which proved difficult to control, even with the use of fabric and moss 'bungs' to slow the rate of inflow (Fig. 10). Whatever remained upon the clay likewise proved difficult to collect.

Fig. 10: Tye box experiment in August 2016 using the clay cone and sphagnum moss as a 'bung' to control water inflow (photo: DBM).

It seems unlikely that a more complex use of the tye box for the gravity separation of sulphides would have been any more effective than the 'rough and ready' results achieved in 2012.

Experiments in ore concentration using the 'jigging method'

Jigging is a method of ore concentration based upon a very simple principle[1]. Basically this is a form of gravity separation of ore and gangue minerals which is assisted manually or mechanically through the vertical agitation of the grains inside of a sieve container suspended in water. The heavier metallic fraction (the ore) will also partition within the sieve itself, if the sieve is fine enough,

Crushing experi-ment	Ore grade %	Process	Weight before crush-ing (kg)	Weight after crush-ing (kg)	Loss (kg)	>4 mm (kg)	4-1 mm (kg)	1-0.5 mm (kg)	<0.5 mm (kg)	Time pe-riod (hrs)	Rationale
1	40-60	crushed	4.838	4.679	0.159	1.486	2.005	0.445	0.757	3.5	crush to c. 4 mm
2	40-60	crushed	5.236	5.019	0.217	0.590	2.419	0.882	1.192	2.21	same
3a	40-60	crushed	3.466	3.275	0.191						
3b	40-60	no further crushing		1.091							sieve into 3 equal portions
3c		crushed again	1.104				1.05			1	to try and improve upon yield for jigging
3d		milled upon grindstone	1.104					1.066		1.5	milling takes more time but gives more even grain size (0.5-2 mm)

Table 3: 2016 experiments – some data on ore preparation

Experiment	Sieve type	Procedure	Question/ hypothesis	Weight + of ore added (g)	Grade and size of ore	Duration and number of motions	Weight remains sieve (g)	Weight concentr (g)	% chalcop through sieve	Comments
Bucket 1.1	4 mm	sieve bucket in 19 cm water	possible? is even grain size better?	835 g	25% 1-4mm	1 minute (24x)	90 g		30% ?	insufficient separation
1.2	4 mm	same	increase speed?	835 g	25%	1 minute (69x)	5 g		25%?	insufficient separation
1.3	4 mm	same	speed + rotation?	835 g	25%	1 minute (75x)	<5 g		25%	motion is difficult
1.4	4 mm	same	shorter time?	835 g	25%	25 secs (7x)	205 g		40%+?	slower more effective
1.4.1	4 mm	same	ore spread over sieve?	835 g	25%	25 secs (7x)	85 g		50%	separation in bucket
1.5	2 mm	similar w hessian	use of fabric sieve?	835 g	25%	2 minute (135x)	745 g	90 g	75%?	enriched but low recovery
1.6	2 mm	same	slower	835 g	25%	2 minute (10x)	c. 800 g			separates out on sieve
1.7	2 mm	larger bucket 10 cm water	stretched fabric + water vibration?	835 g	25%	2 minute (10x)	c. 800 g			no clear separation
‘Mini-jig’ 2.0	4 mm	plastic bottle sieve base	use of a jig container	1091 g	25% >4 mm – 0.5 mm	4 minute	1060 g		low	coarser fractions retained in jig container
2.1	4 mm	same	fine fraction of 2.0 added	1091 g	25%	4 minute	370 g		c. 50%	quartz retain in container
2.2	4 mm	same	residue of 2.1 re-sieved	370 g	25%	4 minute	231 g		50%	all <5 mm ch separates
2.3	4 mm	same	with grain size control	370 g	25% <4 mm	15 secs	53 g		60%?	
Withy sieve 3.1	5 mm	‘authentic’ use in Box	attempt in flowing water	639 g	25%?	45 secs (10x)				separation is on size only
3.2	5 mm	same	placed whilst under water	639 g	25%?	30 secs (3x)			30-40%?	chalcop on bottom
3.3	5 mm	same	under water flow	639 g		30 secs			>50%	concentrate below sieve
3.4	5 mm	same	with control of water flow	639 g		30 secs				zoned concentrate
‘**Mini-jig’** 3.5	4 mm	use still within box	quick vs slow submerganc	480 g	25% 1-4 mm	10 minutes	282g	192g	75%	25% chalcop remaining in jig
3.5.1	4 mm	same	residue of 3.5 re-sieved	282 g	25% 1-4 mm	3 secs			60%	just 15% of jig residue is ch
3.6	4 mm	same	re-sieve 3.5 add finer frac	600 g	0.5- 4 mm	56 secs			75%	<30% of jig residue is ch
3.6.1	4 mm	same	re-sieve 3.6 enriched frac						75%	25% of jig residue is ch
3.6.2	4 mm	same	re-sieve 3.6 jig residue						40%	minimal enrichment
3.6.3	5 mm	same	re-sieve 3.6.2 jig res						40%	30% of jig residue is ch
3.7	2 mm	same	hessian over sieve	504 g	2-3 mm	48 secs			75%	45% jig residue is ch
Basket 3.8	1-2 mm	same	ore washed in water flow	600 g		6 minute			60%?	most washed out
3.9	1-2 mm	same	ore washed over hessian	600 g		1.2 minutes			60%	grain size separation
3.9.1	1-2 mm	same	repeat of 3.9 using finer gr	968	<2 mm	1.5 minute			50%	20% of jig residue is ch

Table 4: 2016 experiments using various different types of jigging sieves – within and outside of the reconstructed box.

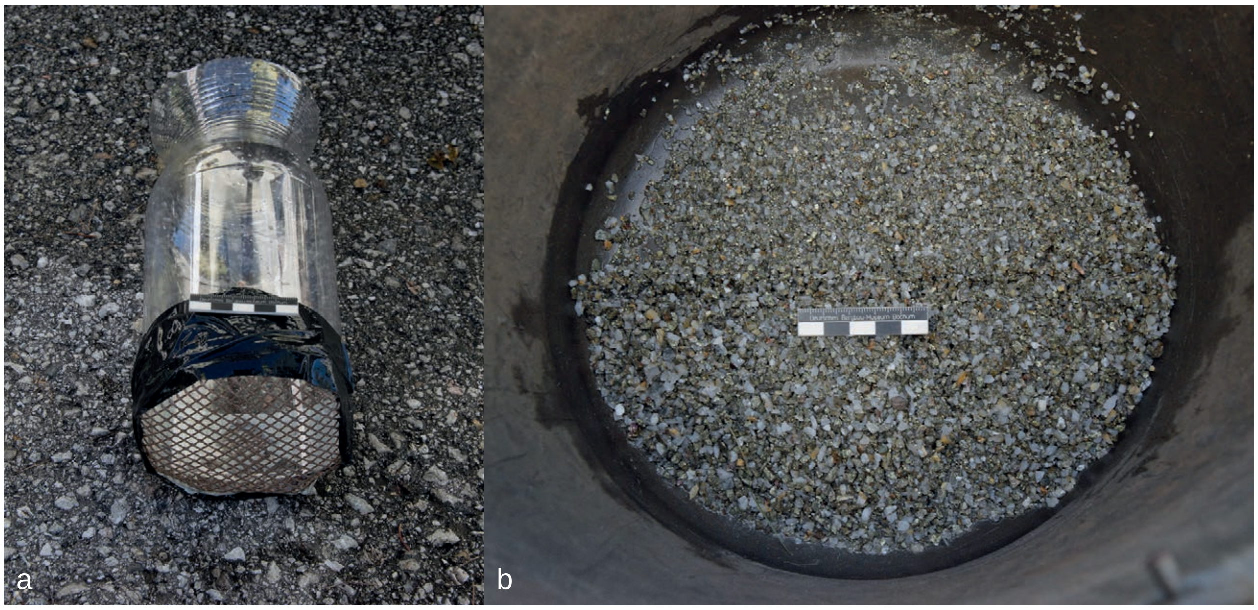


Fig. 11a + b: The 'mini-jig' sieve container used to test the principle of jig separation of the chalcopyrite (sulphide fraction) from the lighter quartz-rich gangue. Figure 11b shows this gangue fraction in the sieve with about 25% of the chalcopyrite remaining (photo: DBM).

with the lighter gangue minerals forming the layer on top. This can be skimmed off using a rake or spatula, and the concentrate beneath collected.

At least 26 experiments were conducted within the box, and on a smaller scale in buckets of water, using reduced-size improvised sieves and sieve containers to investigate the jigging method applied to the concentration of the Mitterberg ores. Given what was available at the time, or could easily be made on the spot (which included materials credible to the period), most of the sieves used by the experimenters were coarse meshed (4 mm). This allowed the passage of much of the crushed mineral, yet retained a relatively higher proportion of the lighter fraction(s) when used correctly. Most experiments therefore were simply limited to seeing whether the principle worked, and if so whether this held out promise for further investigation. As such, the collected data (Tab. 4) provides a good guide to its potential, but not to the efficiency of the process.

Almost all of the experiments showed jigging to be a relatively quick and effective method of separating out gangue and enhancing the percentage of ore minerals; the lighter material remaining in the sieve and the enriched ore deposited upon the floor of the box (or into a pan placed beneath the sieve ready for further processing). The experimental results were quite variable, though typically an average recoverable enrichment of between 20-30% (chalcopyrite/pyrite) could be achieved just through the skilled use of a jigging sieve, the best results being achieved using the flask-like 'mini-jig' (Fig. 11 a+b). Some success was also achieved using a woven withy (*Corylus* sp) sieve – equivalent perhaps to the use of a basket (Experiments 3.1-3.4; Fig. 12). The form of the former suggests what might have been used in association with these wash boxes; a wooden container possessing a perforated sieve-plate bottom upon which the ore may be concentrated and separated from the gangue. There are few contenders at present moment from these Alpine copper ore processing sites, one of them being the wooden 'Wasserkübel' described by Klose (1918) from the Mitterberg. However, this seems more likely to be domestic in purpose rather than proto-industrial.

The use of a pan to concentrate ore

The final series of experiments with the water-filled box involved the use of an improvised pan to try and enrich a low-medium grade chalcopyrite ore.

The particular technique of panning used was based upon the long-handled vanning shovel (traditionally used in Cornwall for assaying tin) and the light wooden Transylvanian gold pan from the Apuseni Mountains (Roumania). Such a wooden trough was described from Verespataker, Roumania where it was used above a water-filled box for the pan concentration of gold (Pošepny 1868). More relevant perhaps are the remains of another similar four-handled wooden trough found underground within the Western part of the St. Josefi Main Lode mine which was described by Klose (1918, Fig. 53; see also Thomas 2018, pp. 357-358) (Fig. 13). The function of this trough may have been to process chalcopyrite, as suggested by Modl (2015, 223) and it has been referred to as a *Sichertrog*. In the current experiment it was decided to test the hypothesis that this could have been used with the wash box to enrich a poor-quality ore to a sufficient degree to successfully smelt it.

It was found that a small hand shovel (Fig. 14) or a short metal pan with a handle and a 200 mm long x

Fig. 12: Experiment 3.1 or 3.2 in August 2016 Using an open weave withy sieve (Corylus or Salix) in an attempt to jig separate good ore from gangue within the water-filled tank (photo: DBM).

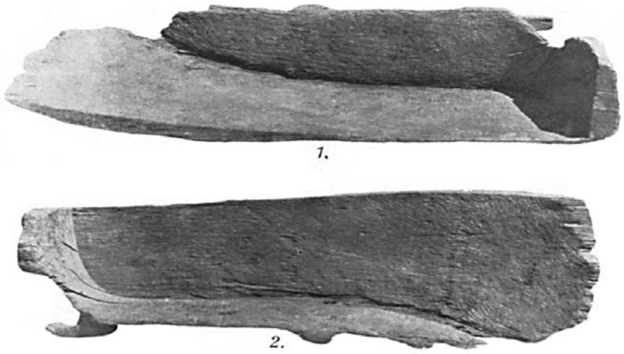


Fig. 13: The broken Bronze Age sichertrog found within a mine on the Mitterberg. Illustrated by O. Klose (1918), now in the Salzburg Museum.

Fig. 14: A reciprocating 'pan' separation of chalcopyrite from gangue within the water-filled box using just a flat-tipped hand shovel. Note the good retention of sulphide (photo: DBM).

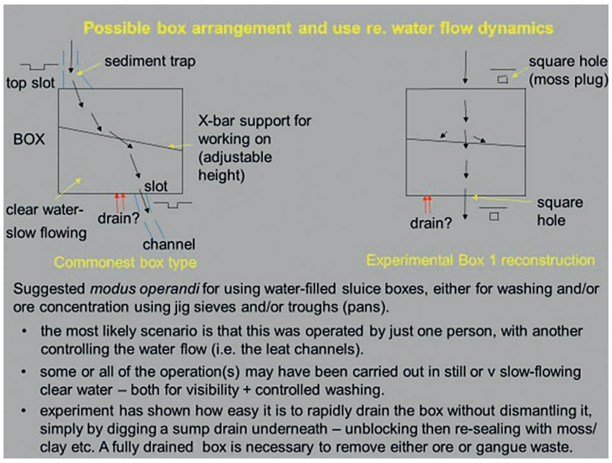
150 mm deep opening at the front could be filled with between 0.5 to 1 kilogramme of ore (consisting of 25-40% chalcopyrite) and be panned to a concentrate of c. 95% chalcopyrite. This could be achieved by means of a gentle forward and backwards 'rolling' motion of the filled pan upon the surface of a slow-flowing current of water. Bit by bit this motion saltated the lighter rock and mineral grains across the lip of the pan onto the floor of the box. After several hours of practice using this technique it was possible to clean and enrich a kilogramme of ore in just 20-25 minutes. The use of the cross-bar for resting the pan against was ideal in this respect. Over the course of one afternoon some 4 kilogrammes of ore were processed this way – the product being the equivalent of a high-grade hand-picked ore.

Needless to say, we are making a big assumption in assuming that a 95% chalcopyrite concentrate was either a necessary or desirable ore grade to smelt with in these MBA Alpine furnaces, yet the point we should be making here is that this is a *viable* way in which a pure standardised product might be obtained.

Conclusions

What we know about the use of these boxes and the processing of the ore

1. It seems possible that Box 2 could have been operated by one person, with another in assistance to control the water inflow into the box, the leat, and the drain. The rate for washing/ore separation would probably have been one 'basket' at a time (i.e. probably not more than 5-10 kg per hour).
2. Most of the operations may have been carried out within still or slow-flowing water. It may have been desirable to control water flow where this was necessary for washing, though it was probably never designed for 'fast water' use. The environment of the Troiboden is very different from that of the experimental site.
3. We would expect to see these boxes associated with a feeder leat, a release or diversionary channel, a drain, and perhaps also a silt trap located at the front.



Suggested *modus operandi* for using water-filled sluice boxes, either for washing and/or ore concentration using jig sieves and/or troughs (pans).

- the most likely scenario is that this was operated by just one person, with another controlling the water flow (i.e. the leat channels).
- some or all of the operation(s) may have been carried out in still or v slow-flowing clear water – both for visibility + controlled washing.
- experiment has shown how easy it is to rapidly drain the box without dismantling it, simply by digging a sump drain underneath – unblocking then re-sealing with moss/ clay etc. A fully drained box is necessary to remove either ore or gangue waste.

Fig. 15: A diagram showing the suggested modus operandi of the two different types of box (diagram: S. Timberlake).

4. It seems likely that the box was emptied of water by digging a sump beneath the drain, rather than by removing the back board. The drained sediments might then have been dug out.
5. It seems unlikely that these boxes were ever used as buddles.
6. I remain un-convinced that any of the boxes were designed for the *in situ* collection of ore concentrate from the sediments within their base. Experimentation suggests that the concentrated ore will have settled into lenses in between and surrounded by the gangue minerals from the washings – for which the subsequent draining and recovery would have been a difficult and time-consuming process. Traditionally tye boxes or strakes tend to be longer structures with sloping floors associated with faster flowing water.
7. Not all of the boxes found upon the Troiboden were used for the same thing. Box 2 constructed with holes both for inflowing and outflowing water is an oddity in this respect. More common are the boxes with slots (or no slots) in the top and some evidence for a diagonal water flow (Fig. 15). The wooden cross-bars may have been used for deflecting the current, but more likely were used for support.
8. Quite possibly all of the boxes could have been used for the washing of the mined and crushed ore. This may have been their main function. It has been shown that up to 20% of the accompanying clay, silt and light rock particles can be removed using just a gentle-moderate stream of water.
9. With a mortar or anvil stone the greater part of the ore can be crushed to a grain size of between 1-4 mm suitable for the purposes of gravity separation and concentration – the ideal being around 4 mm. This is supported by the sedimentological evidence from the Troiboden archaeological site.
10. Experiments have shown that it would have been possible to separate up to 60-70% of the sulphides (chalcopyrite and pyrite) from the gangue minerals (mica, rock, quartz, ankerite, feldspar etc.) through the skilled use of sieves within the water-filled boxes. However, it would not have been possible to separate pyrite from chalcopyrite.
11. Although partial flotation of the finely-milled chalcopyrite was observed within the tank, it probably would never have been possible to recover this.
12. Woven basket or container-like jigging sieves could have been used to enrich the poorer (20-40% chalcopyrite) ores. A 'moderate' enrichment could have been achieved using this method once the ability to make suitable sieves had been mastered.
13. Better control in achieving a standard grain size, an improved grade, recovery and a more efficient use of the ore could have been achieved by repeatedly re-processing and re-working the rejected material.
14. Waste mineral fractions (such as quartz) may have been collected for use as a flux.
15. The panning of the crushed ore using tight-weave baskets or wooden troughs may have been carried out to produce a high-grade chalcopyrite concentrate from. 'middling' ores.

Recommendations for future work

- The current experiments using jigging sieves and pans should be continued, but the equipment for these should be constructed in advance of this, be made out of credible materials, and be built to a suitable scale.
- The experimental site should move to the same environment and setting as the objects being studied (i.e. the Troiboden may be a better location)
- A proper means of sampling the products of these experiments is required (i.e. full chemical/mineralogical analysis of the processed ores and washed concentrates will be necessary rather than just calculated guesswork)
- It may be better to experiment with a 'more typical' box from the Troiboden (in concern of the construction of effluxes and influxes) and to use this facsimile within a series of repeat experiments
- Careful excavation/re-excavation of one or more of the smelting sites on the Mitterberg is required to properly understand the nature of the prepared ore charge and fluxes used. This way we might obtain a better idea of the grade of ore concentrate they were trying to achieve at the Troiboden.

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Note

1 Simple hand-jigging techniques involving water-filled wooden tubs or boxes and sieves are described and illustrated in Georgius Agricola's *De Re Metallica* (1556, Book VIII, 310-311), and subsequently in most Postmedieval texts on the arts of mining and processing ores. In fact mechanical jigging was a standard method of ore concentration used in 19th-20th century industrial metal mining (see Earl 1968, 79), which continues in some parts of the world today.

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