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Slag heap quantification: re-evaluating the Mitterberg smelting sites

ABSTRACT: *The Mitterberg Mining District near St. Johann i. Pongau, Salzburg, Austria belongs to one of the most intensively investigated Bronze Age copper production landscapes in the eastern Alpine region. Starting 2006, a new series of prospection and excavation campaigns were initiated, which included, among others, a program of intensified prospection and sampling of the smelting sites.*

The combination of geomagnetic surveys, systematic coring and sampling of the slag heaps proved to be an effective way to quantify smelting sites, allowing the efficient investigation of a larger area and creating a more detailed view of a complex copper production landscape, without the need of a full excavation of the archaeological site. The study has also highlighted the importance of taking the depositional context into account, in order to gauge the amount of metallurgical debris actually present. When morphology and depositional characteristics of the slag heap were not taken into consideration, there can be a substantial overestimation of slag at the smelting site, which would in turn lead to a gross overestimation of the theoretical metal production output.

KEYWORDS: BRONZE AGE, METALLURGY, COPPER SMELTING, SLAG, GEOMAGNETIC PROSPECTION, MITTERBERG

Location and Dating of the Smelting Sites

The Mitterberg Mining District near St. Johann i. Pongau, Salzburg, Austria belongs to one of the most intensively investigated Bronze Age copper production landscapes in the eastern Alpine region. In 2006, the Deutsches Bergbau-Museum Bochum, in conjunction with the SFB HiMAT (History of Mining Activities in the Tyrol and adjacent areas, University of Innsbruck) initiated a new series of prospection and excavation campaigns in order to continue the over 180 years of archaeological investigation of the mining landscape (see Stöllner, 2009; 2015; Stöllner et al., 2011). As part of this work, a series of prospection campaigns were carried out in order to investigate the smelting sites, which are recognizable by their slag heaps and are scattered throughout the Mitterberg Mining District and its hinterland. Over 200 smelting sites are known from the literature (Zschocke & Preuschen, 1932; Preuschen & Pittioni, 1955, 1956; Pausweg, 1976; Krauß, 2004, 2001, 1991; Eibner, 1993; Günther et al., 1993; Günther, 2007, Neuniger et al., 1969) and prospection surveys in this greater area, 190 of which fall within the area mapped out by Zschocke and Preuschen in the early 20th century (Fig. 1, area outlined in grey). At least 45 of the known smelting sites have been classified in the literature as iron smelting, and belong to a later period of iron mining and production that began most likely during the Medieval Period[1]. The remaining sites are assumed to belong to prehistoric copper production.

The smelting sites are scattered throughout the landscape between the different ore veins, sometimes at great distance from the nearest known ore source, most likely in order to take advantage of the surrounding forests for the fuel-intensive smelting process. Moreover, they are almost always near a source of water, such as a stream or spring, often with several sites situated along a single watercourse (see for example Fig. 2, No 12, 13, 14, 15).

Especially during the Middle to Late Bronze Age, the layout and construction of the smelting sites, as well as the external appearance of the slags show a surprising level of conformity, pointing to certain amount of standardization of the sulfide copper smelting process across the eastern Alpine region. A “typical” Middle to

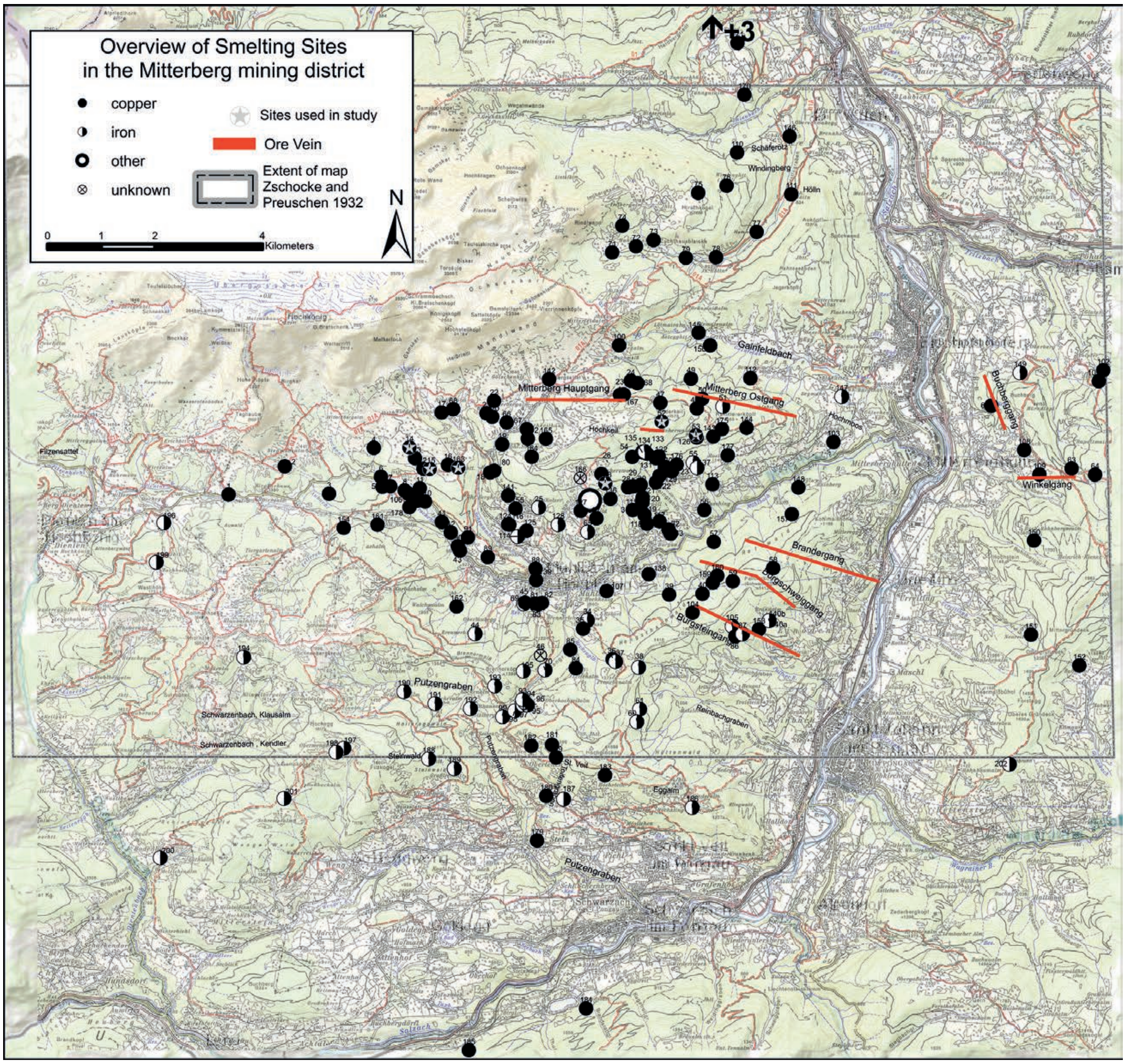

Fig 1: Overview of Mitterberg Mining District and surrounding regions. The area mapped out by Zschocke and Preuschen (1932) is outlined in grey (graphics: E. Hanning, DBM).

Late Bronze Age eastern Alpine smelting site is usually located near a source of water and is comprised of three general elements: roasting beds, furnaces and slag heaps. The roasting beds (Fig. 3a) were carefully leveled with a clay coated floor and often delimited by stones. The furnaces (Fig. 3b) were usually located below the roasting beds, often in pairs, or sometimes as batteries of several furnaces in a row. They were typically dug into the slope, with stone-and-clay walls on at least three sides, a low clay threshold is usually all that has been preserved of the front wall, which was presumably destroyed in order to extract the smelting products. Slag heaps were usually situated below the furnaces where the product of the smelt was separated and the waste (slag) was discarded.

To date, circa 20 smelting sites have been dated via ^{14}C. The majority of the ^{14}C dates fall into the Middle Bronze Age, with three outliers dating to the end of the Early Bronze Age and two into the Late Bronze Age (Fig. 4) (Stöllner, 2009; 2015; Stöllner et al., 2010; Pernicka, et al. 2016). Moreover, the smelting sites can also have several phases of use over a long time-span. For example, excavations at the smelting site “Brennerwald” (Fig. 2, No 162) revealed at least four different phases of furnaces, while the two radiocarbon dates from the site span roughly two centuries (Herdits, 1997, Herdits & Löcker, 2004); a similar spread of about 200 years can be seen from ^{14}C samples taken from different depths at Site 14 (Fig. 4, No 14), and those from Site 15 (Fig. 4, No 15). At this time, it is not known if smelting was continuous over several centuries

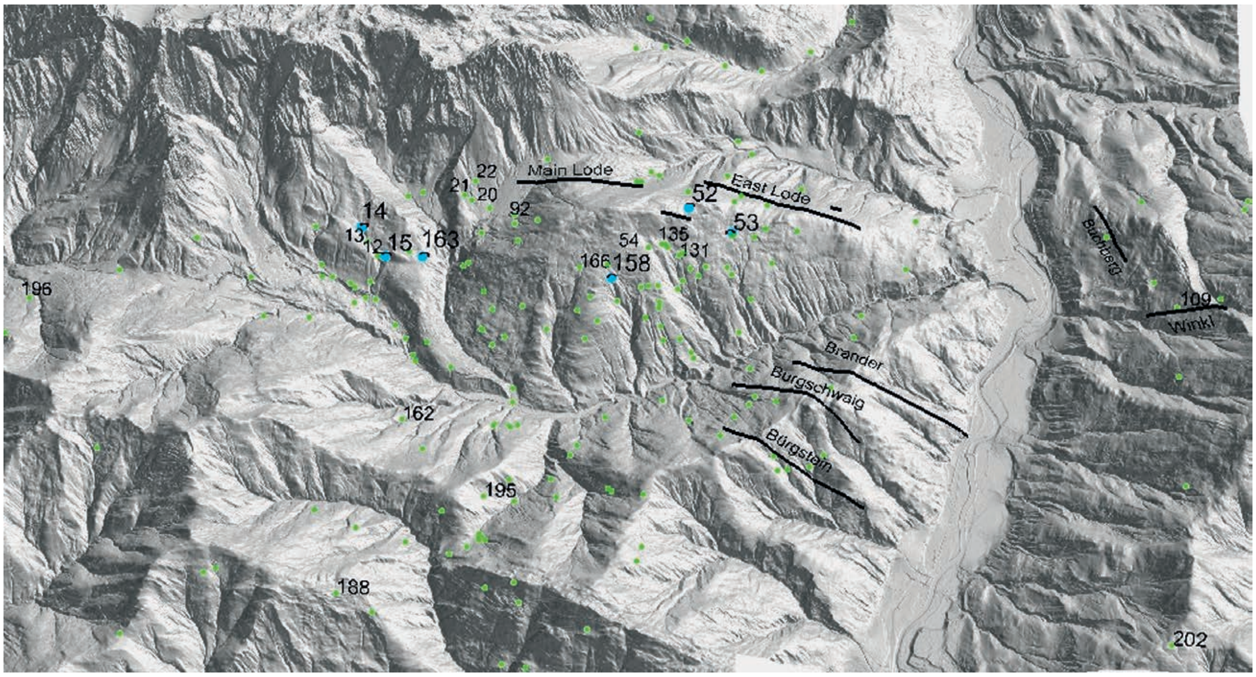

Fig 2: Close-up of the Main Lode area, with the position of the smelting sites and ore veins mentioned in the text (graphics: E. Hanning).

or if the sites went through cycles of abandonment und subsequent revitalization. However, the longevity of the smelting sites hints at a transference of knowledge over many generations - not only about the location of the site, but also the construction of the metallurgical installations and the operational sequence of smelting the ore (Stöllner et al., 2016, pp.80-83).

Intensive prospection of the smelting sites and calculation of slag heap volume

Between 2007 and 2009 (Stöllner et al., 2009; Hanning, 2013, DBM, 2015), four prospection campaigns were carried out where circa 30 smelting sites mentioned in the literature were relocated, while 6 previously unpublished sites were also recorded. 6 smelting sites (Fig. 1 and 2, No 14, 15, 52, 53, 158, 163) were then chosen around the area of the Main Lode for an intensified prospection program[2].

Calculation of the amount of slag can give information about the productivity of each individual site. Quantification can be done, for example, by extensive excavation of the site and by measuring all pieces of slag present (ex. Herdits, 1997, Klemm, 2015). This method is however, expensive, time consuming and leads to the ultimate destruction of the site. Other less or non-invasive methods that have been used on smelting sites include coring and/or subsampling via smaller sondages, GIS-based surface modeling, magnetometry and magnetic susceptibility surveys, induced polarization, electrical resistivity tomography and ground penetrating radar, and/or a combination thereof (ex. Rothenberg & Palmero, 1986; Perret & Serneels, 2009; Humphris & Carey 2016; Powell, et al 2002; Florsch, et al. 2011; Günther & Martin, 2016; Qi et al., 2018, Ullrich et al., 2007; 2015). Like the work carried out by Humphris and Carey (2016), a variety of methods including field surveys, geophysical prospection, coring and small sondages for sample collection were used in the current study to gain more information about the overall state of preservation, size and amount of slag present at the smelting sites.

Gradiometer survey

Although slag remains eroded out onto the surface point to the general location of the smelting sites, their full extent and location of the metallurgical installations (i.e. furnaces, roasting beds and slag heaps) is usually obscured by varying amount of sediment and flora. However, the strong magnetic anomalies created by the metallurgical remains make them ideal candidates for geomagnetic prospection: both the roasting beds and smelting furnaces are subjected to relatively high temperatures and the baked clay linings and/or natural clay of the soil surrounding the structures have acquired a high thermoremanent magnetization (TRM) during their firing. Likewise, other metallurgical material, in particular the slag, is also characterized by a higher magnetic susceptibility than its surroundings, which show up as positive magnetic anomalies on the gradiometer survey. All of the six smelting sites were measured using a single

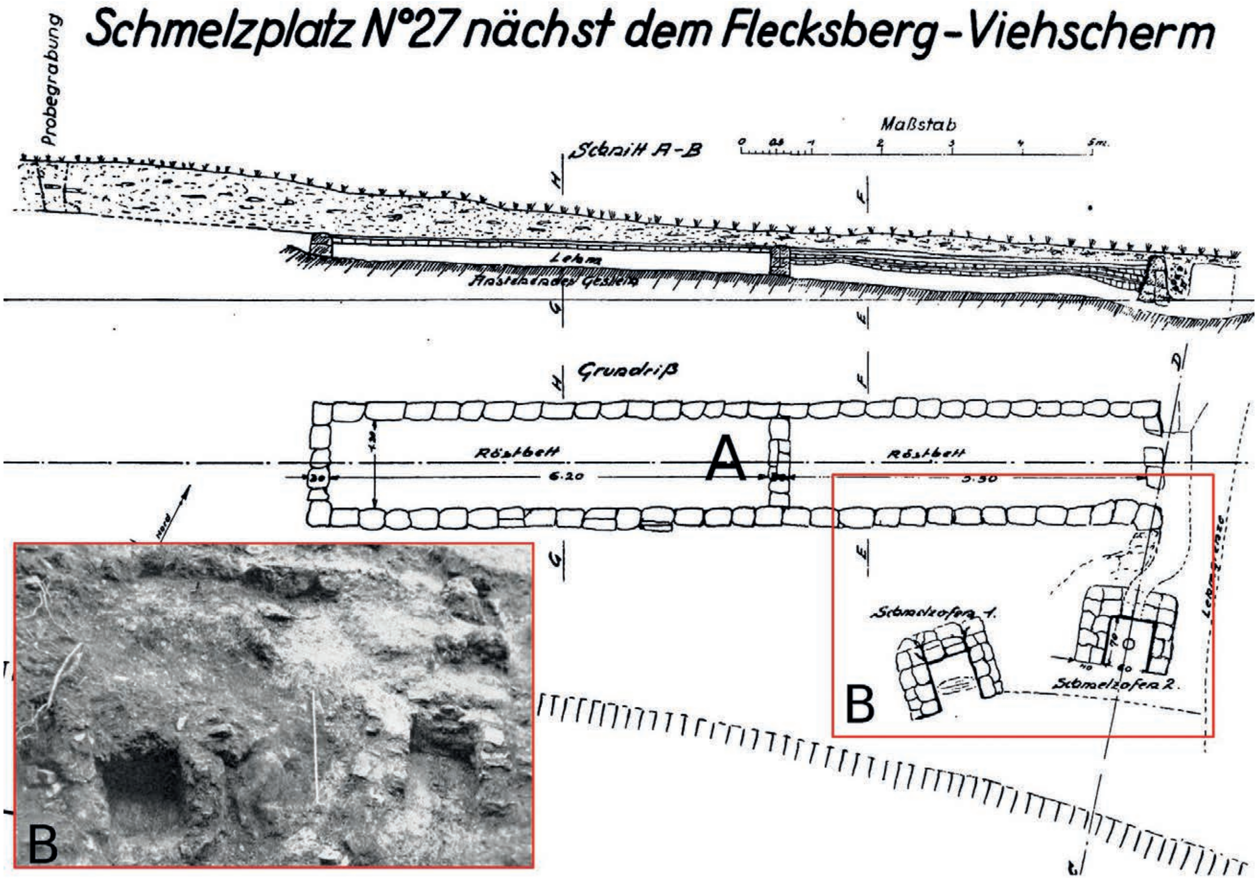

Fig 3: Drawing and photograph of a "typical" smelting site with roasting bed (A) and smelting furnaces (B and photo insert). Modified after Zschocke & Preuschen, 1932, pl. III and V.

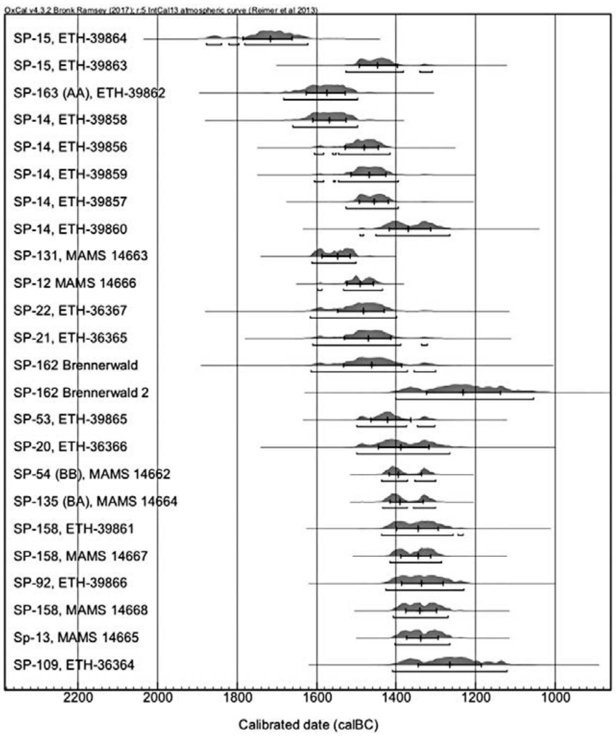

Fig 4: C^{14} dates from the smelting sites. Modified after Stöllner, 2009; Pernicka et al., 2016. Generated using OxCal v4.3.2.

channel handheld fluxgate gradiometer (B. Sikorski, B. Song, Ruhr Universität Bochum); additionally, one site (Fig. 3, No 52) was also remeasured using a 6-channel Foerster FEREX gradiometer mounted on a hand pulled cart (Eastern Atlas GmbH, B. Ullrich).

In many cases, it is possible to interpret the position of the roasting beds, furnaces and slag heaps from the geomagnetic anomalies (for example Smelting Site 52, Fig. 5 left). This is mainly due to the fact that many the Middle to Late Bronze Age smelting sites have an extremely similar organizational plan (see above). The long rectangular roasting beds present as a linear positive magnetic anomaly; the smelting furnaces were positioned just below these, usually grouped in pairs or several in a row, and appear as a series of round to ovoid magnetic anomalies; the slag heaps are located downslope from the furnaces, and – due to their heterogeneous composition – take the form of an irregularly shaped mass with a magnetic signature that varies greatly within the heap. In other cases, the overlapping of several different phases of furnaces and slag heaps, as well as destruction of the site through subsequent land use make it impossible to discern the position of the furnace batteries and roasting beds from the geomagnetic anomalies alone (Smelting Site 53, Fig. 5 right). In such cases, further investigation

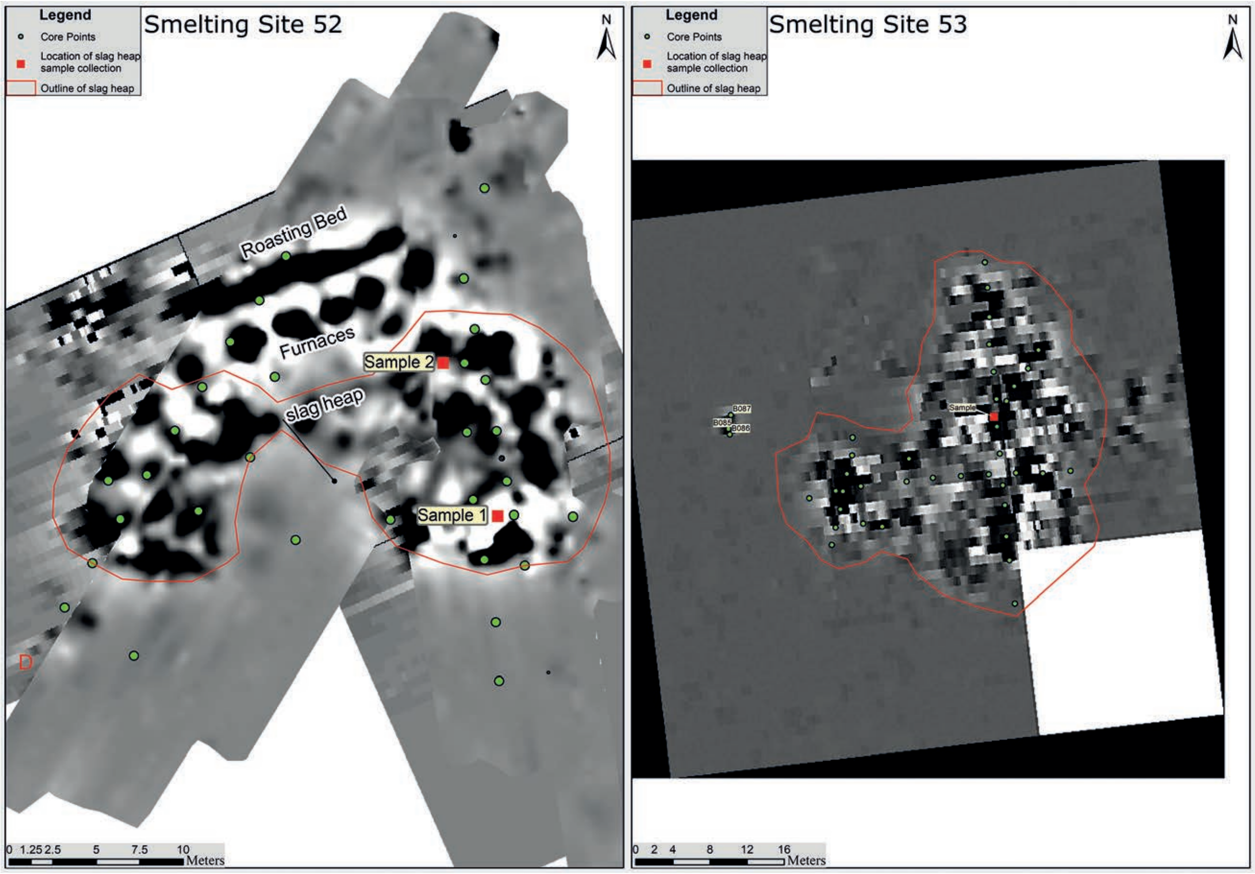

Fig 5: Two examples of geomagnetic surveys from the smelting sites. The position of the cores are marked in green, the circumferences of the slag heap are outlined in red and the location of the sample collection is marked with a square. Left: Smelting Site 52. The position of the roasting beds, furnaces and slag heaps can be clearly interpreted from the geomagnetic anomalies. Right: Smelting Site 53: overlapping of the different archaeological features makes it difficult to properly identify the metallurgical installations without further coring or sondages (graphics: E. Hanning, DBM).

in the form of coring or sondages are necessary in order to interpret the composition and function of the anomalies seen on the magnetogram.

Coring and calculation of the slag heap volume

Systematic coring was also done at the 6 sites in order to calculate the volume of the slag heaps, as well as to confirm the type and position of the pyrometallurgical installations interpreted from the geomagnetic surveys. Two types of corers were used: a hand driven slit corer (= Pürkhauer corer) and a motor driven percussion corer (= Cobra corer). The Pürkhauer corer has the advantage of being relatively light, easily taken into the field. The fine stratigraphy is also preserved without a large amount of compression of the individual layers. It does not do well, however, with coarse material such as large pieces of slag or stone, which are frequent in mining tips and slag heaps and inhibit the passage of the corer. For this reason, the larger Cobra corer was also used, which can literally punch through most material and retain coarse sediment in the sampling chamber. Using alternating Pürkhauer and Cobra coring points, it was possible to gain information about the coarse material in the slag dumps, while correcting the depth and position of the finer stratigraphy.

In this way, information about the depth and thickness of the archaeological layers could be obtained from the core profiles, while the boundaries of the slagheap could be interpreted by marking the edges of the strong magnetic anomalies created by the slag in the geomagnetic survey (Fig. 5, red outline). By combining this information - the circumference of the slagheap estimated from the magnetometer survey and its thickness from the core profiles - it was possible to give an approximation of the volume of the slag heap with minimal impact to the site. A 3-dimensional model was then generated using the x and y coordinates taken from the core positions and from points placed around the magnetic anomaly marking the position of the slag heap (Fig. 6). The z coordinates were calculated by taking the thickness

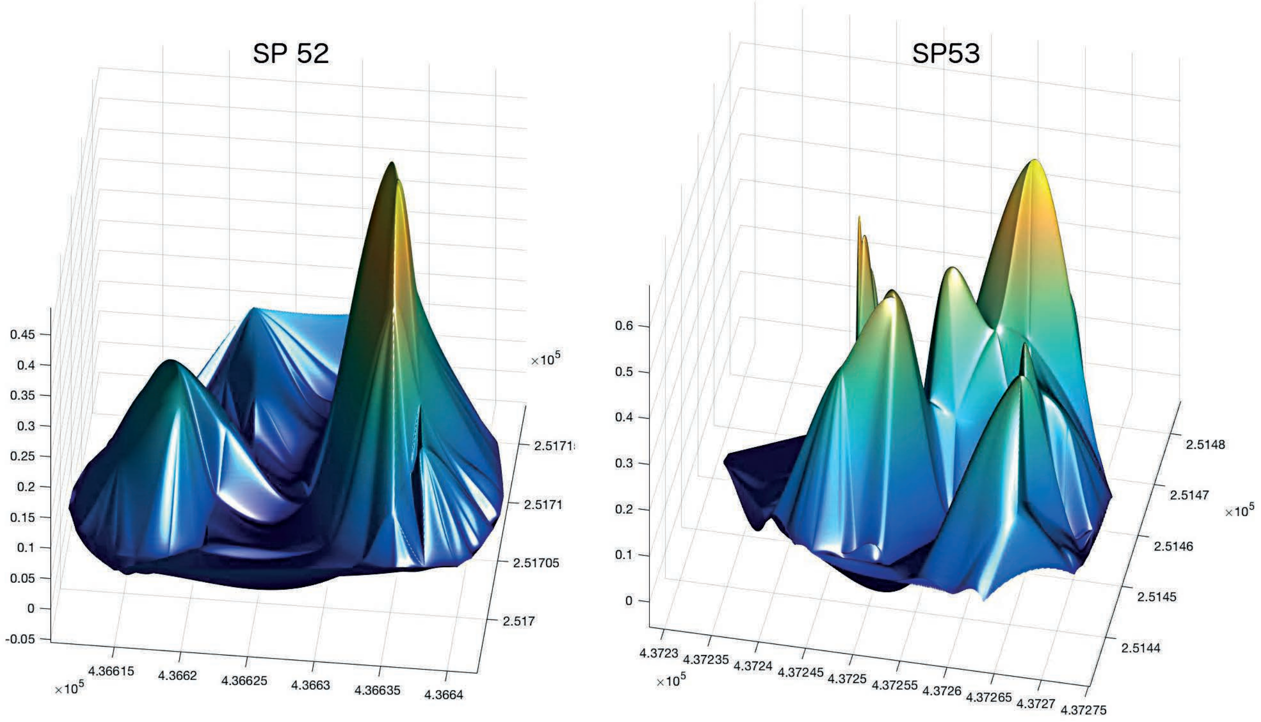

Fig 6: Examples of the 3-dimensional model of the slag heap used for the calculation of their volume. X and Y axes give the coordinates of the slag heap while the z axis presents its thickness in meters. The model is not a reconstruction of the actual 3D shape of the slag heap, but rather its thickness. The model was generated in MatLAB using a cubic interpolation (graphics: E. Hanning).

of the archaeological layers from the core profile. This does not, however, generate a model of the actual 3-dimensional shape of the slagheap, but is instead a model of its thickness. This was done due to the fact that at most points along the perimeter of the slagheap, (as seen by low or absent geomagnetic anomalies) do not have a depth – only an x and y coordinate taken from the magnetometer survey. Trying to recreate a 3D model of the true shape of the slagheap from this information would create a body in which the edges would be pulled unnaturally upwards towards the surface, skewing the model. When using the thickness instead of the actual depth of the archaeological layers, the points along the perimeter and outside the slagheap have a z-value of 0, and thus do not contribute to the volume calculation. The information was then graphed using a mesh plot in MatLAB with a bounding box sufficiently large enough to encompass the entire area. The surface between the points was interpolated using 4 different types of triangulation-based interpolation methods[3]; the resulting plots are comprised of a series of peaks and valleys which correspond to the thickness of the slag heap at a given x-y coordinate (Fig. 6). The area under the resulting mesh surface was then "filled" with virtual cubes measuring 5x5x5cm in order to estimate its volume and thus the volume of the slag heap. A table of the calculated surface areas and volumes can be seen in Table 1. As the different interpolation methods generated different mesh surfaces, the resulting calculated volumes also varied (between ca. 2-4m^3). As a result, an average of the four calculated volumes for each slagheap was also taken; the average value is given in Table 1, b.

Calculation of amount of slag and slag typology

However, due to the fact that the slag heap is composed of a mixture of slag, and non-slag material (such as stone, sediment, organics, ceramic, and water), estimation of the heap volume does not necessarily directly correspond to the amount of slag at the site. Thus, in order to gain a better estimate of the amount of slag in comparison to other material, a vertical sample was taken from the center of the dump, taking ca. 0.01m^3 of material for every 10cm of depth[4]. Each stratified 10cm sub-sample was placed in a separate sack and evaluated individually. The total volume[5] of the sample was recorded using the water displacement method and was then wet sieved using standardized mesh sizes ranging from 0.25mm up to 22.5mm. All pieces of slag above 22mm were individually recorded in a database, recording their characteristics such as external appearance, size, weight, density, porosity, number of original surfaces, type and size of inclusions, color, and magnetism (Fig. 7). For

Fig 7. Left: selection of slag pieces in the slag heap sample. Right: Section through a larger piece of slag. Unmelted pieces of ore and gangue material are clearly visible as white inclusions in the slag.

	A	B	C	D	E
Site	Slag Heap Surface Area m^2	Slag Heap Volume m^3	Average Slag Density t/m^3	Packing Factor (Slag vs other Material)	Amount of Slag (B xC x D) tonne
14	507	40	2.61	0.31	32
15	424	53	2.91	0.47	72
52	310	38	2.87	0.44	48
53	845	140	2.3	0.66	213
158	330	74	2.21	0.45	74
163	441	79	2.68	0.51	108

Tab. 1: Estimation of the amount of slag present at the smelting sites.

	Slag vs Other Material from Slag Heap Sample (Vol %)			
Site	Water and Sediment <0,25 mm	Mixed Material >0,25 <2 mm	Non-Slag Components >2 mm	Slag >2 mm
14	35	18	16	31
15	18	28	7	47
52	15	21	20	44
53	15	10	9	66
158	6	35	14	45
163	17	18	14	51

Tab. 2: Slag vs. other Material in the slag heap samples, by Vol%.

the smaller sieve fractions, the slag was also sorted out by hand[6]; the weight and volume of the pieces of slag were recorded in bulk. Additionally, both XRD and XRF analysis (D. Kirchner, DBM) were done on powdered samples taken from the different sorted sieve fractions to give information of the bulk mineral and chemical content from the different sites.

The weight, volume and average density of the slag in the sample can then be used to estimate the amount of slag in that heap as a whole.

The determination of the amount of slag vs. other material is analogous to the "packing factor", found in an equation put forward by Bachmann (1982, p.5) for the calculation of the amount of slag found at a site: *Slag-covered area* x *depth* x *specific gravity of the slag*[7] x *packing factor* = *amount of slag* (*metric tons*). When the slag density and packing factor are unknown, Bachmann puts forward an average value of 3.5g/cm^3 for the slag and a packing factor of 0.8 (i.e. 80% of the slag dump is comprised of slag). However, the average of the apparent particle densities[8] of the slag varied from 2.2 to 2.9 g cm^3 (Tab. 1, C), much lower than the value put forward by Bachmann, mainly due to the bulk of the slag at the sites being quite porous.

This very detailed recording of the samples led to some interesting results. In particular, it becomes apparent that the slag heaps have a large quantity of non-slag components, including ground moisture, sediment, stones, and organic material. As a result, the packing factor (Tab. 1, D), which was calculated by taking the bulk volume of all slag above 2mm in diameter and dividing it by the total soil volume - i.e. the combined volume of the solids, liquids, pores and inter-particle voids present in the sample through the slag heap (for terminology, see Webb, 2001; Hanning, in prep.) - was also much lower than what was put forward by Bachman. This was due to the fact that non-slag components made up ca. 30 to 60 % of the volume of the samples, depending on the site (Tab. 2). The packing factors and estimation of the total amount slag at each site can be seen in Table 1, D.

Thus, the calculation of the amount of slag at each site is well below what it would have been when using the above-mentioned average density (3.5) and packing factor (0.8) put forward by Bachmann. For example, at smelting Site 15, only 47 vol% of the slag heap sample was comprised of slag, with an average density of 2.91 t/m^3. Using the information gained from the cores and geomagnetic surveys, the slag heap volume was calculated to be ca. 53 m^3. Thus, the calculated amount of slag at the site would be 72 tons. If the generic packing factor (0.8) and slag density (3.5) put forward by Bachmann are used, then there would be an estimated 148 tons of slag at the site - over twice the amount.

These numbers must of course also be viewed as an approximation, as the slag heaps are far from homogenous and some material would have been transported away from the site, either by erosion or subsequent use of the land for agriculture or other activities. Ideally the method should be double checked by fully excavating the site and weighing the full amount of slag and sediment present, which is not only extremely time consuming and labor intensive, but would also lead to the complete destruction of the archaeological deposit.

Estimation of copper production – possibilities and limitations

Previous estimations of prehistoric copper production in the Mitterberg area have been calculated using the theoretical amount of copper present in the exploited ore minus copper loss during mining, beneficiation and smelting (see Stöllner et al., 2011; Pernicka et al., 2016, 27), as well as trying to calculate the amount of metal produced via a copper:slag ratio (Kyrle, 1918, p.46-47). One of the motives for the estimation of the amount of slag found at each smelting site is in part to try to estimate the amount of metal being produced there through calculation of the copper to slag ratio. However, this is not as straight forward as it seems. The metal:slag ratio is dependent on several variables, including the composition of the charge, the operational sequence and efficiency of the smelting process. Kyrle's estimation of a slag to copper ratio of 4:1 (Kyrle, 1918, pp.46-47) should be met with some skepticism, as he estimated that one conglomerate of furnace slag equated to one plano-convex ingot, ignoring the theory that the process most likely had multiple steps, each producing a certain amount of waste product in the form of slag. From the archaeological remains, the use of a multi-step roast-reduction process can be surmised, though the exact allocation to a specific slag type to a specific step in the process has long been debated (ex. Eibner, 1982; Metten, 2003; Hanning et al., 2015, Silvestri et al., 2015; Zschocke & Preuschen, 1932, p.73-95; Czedik-Eysenberg, 1958; Preßlinger et al., 1988).

The use of a mass balance equation is one possible way to approximate the copper to slag ratio, and has been used for production estimations for both copper and iron metallurgy (ex. Kronz, 2000, Maldonado & Rehren, 2009). Based on the principle of mass conservation, a simple mass balance equation for a smelting process can be written as furnace charge + fuel ash + furnace clay = matte (and/or) metal + slag + unreacted furnace charge. However, the furnace charge would not have contained pure copper ore. It is known that the main copper-bearing ore in the Mitterberg area was chalcopyrite ($CuFeS_2$), associated with Pyrite (FeS_2) and a host of other accessory minerals in a gangue of quartz (SiO_2), dolomite ($CaMg(CO_3)_2$), siderite ($FeCO_3$) and ankerite ($Ca(Fe,Mg,Mn)(CO_3)_2$) (Pernicka et al., 2016, p.22; Günther et al., 1993 p.44; Weber et al., 1972). Analysis of slag pieces from the smelting sites often show slag conglomerates containing large pieces of partially melted gangue material (mainly quartz and Fe/Mg oxides) encapsulated in a fayalitic matrix (Fig. 7 right) (ex. Metten, 2003, p.77-81; Viertler, 2011; Zschocke & Preuschen, 1932). Evidence of large Bronze Age ore beneficiation sites in the Mitterberg area (Stöllner et al., 2010) point to an ore enrichment process that would have a positive effect on the metal to slag ratio. However, the smelting charge did not contain pure chalcopyrite - a host of associated minerals from the ore vein, as well as a certain amount gangue material from an incomplete separation of the ore was also intentionally or unintentionally introduced into the smelt. Silica-bearing minerals (such as quartz from the gangue) are an essential part of the smelting process as they are needed to remove the iron from smelt in the form of slag. Ash from the fuel, as well as parts of the furnace lining will also contribute to the smelting remains. Additionally, slag from previous smelts can be added to help recuperate copper loss and act as a flux (see Hanning et al., 2015; Herdits, 1997; Silvestri et al., 2015). For each step in the process, a new mass balance equation would have to be calculated, and the slag from all processes totalized. Mass balance calculations for the Mitterberg slag have not yet been carried out in detail and remain a desideratum for future work.

Maldonado and Rehren (2009) calculated the copper to slag ratio of about 1:3.75 for the copper smelting in Itziparátzico Mexico by assuming that the iron content of the slag originated almost exclusively from the chalcopyrite

($CuFeS_2$) in the ore (Maldonado & Rehren, 2009, pp.2004-2006). This is not completely viable for the Mitterberg ore due to the introduction of additional iron from pyrite (FeS) and siderite ($FeCO_3$) which are naturally associated with the ore and gangue (Weber et al., 1972, Pernicka et al., 2016; Günther et al., 1993, Günther, 2007).

Attempts have also been made to recreate the alpine copper smelting process through experimental archaeology (Hanning, in prep.; Herdits, 1997; Rose et al., 2018). Comparison of the experimental slag to the original can help by creating comparable slag where charge composition is known. However, it must be considered that the copper to slag ratio and metal output from such experiments is probably much worse than what an experienced smelter could produce. This is mainly due to the fact that the ore available today is usually of a much poorer quality and the process was most likely much less efficient due to lack of smelting experience on the part of the investigators running the experiments.

Another option is to look at written accounts of pre-industrial era copper smelting. However, emphasis is often put onto the description of the process and little empirical data is given to the amount of slag produced. One exception to this is a study on the traditional chalcopyrite smelting in a small-scale bowl-type furnace in Nepal (Anfinset, 2011). Although the process cannot be compared exactly to the Bronze Age smelting remains, it can give a point of comparison. The measured slag to copper ratio was quite high, ranging from1:15.2 to 1:10.1, depending on the smelt (Anfinset, 2011 p.58).

As can be seen the copper to slag ratio from the ethnographic account from Nepal is markedly higher than the theoretical calculations listed above. At the moment the spread between the lowest theoretical copper to slag ratio of ca. 1:4 and the highest known values from ethnographic examples of ca. 15:1 creates too great of a margin of error. For example, the calculated tonnage of slag at smelting site 14 was calculated to be 32 tons. This would equate to a copper output at the site between 8 tons (copper:slag ratio of 1:4) and 2.1 tons (copper:slag ration of 1:15) of metal depending on which copper to slag ratio is taken. Considering that the stratified radiocarbon dates for Site 14 span roughly 180 years, this would equate to only 44 to 11 kg of metal per season, if the site was actually used on a yearly basis. Combining the calculation from the 6 sites from the study equates to 547 tons of slag, which would be the equivalent of between 137 and 36 tons of copper, depending on the ratio used. Roughly 154 copper smelting sites are known form the greater Mitterberg mining area to date (DBM 2015; Hanning, in prep). Taking the mean volume of ca. 90 tons of slag from the 6 investigated sites and multiplying by 154 smelting sites gives a total of 13,860 t of slag, which could equate to between ca. 3,500 and 925 tons of copper metal produced at the known smelting sites. Zschocke and Preuschen calculated an output for the Mitterberg Main Lode ore vein to be ca 11,000 t (Zschocke & Preuschen, 1932, pp.100-103), while Stöllner et al. (2011, p.125) put the output for the Main Lode to be ca. 14,700, and a total prehistoric copper production of the Mitterberg mining district at 23,000 t. (Pernicka et al., 2016, 27).

The discrepancy in the numbers can be accounted for in several ways. First of all, one must consider that most likely not all of the copper smelting sites are known; even smelting sites documented in the 1930’s are not always relocatable today due to destruction from subsequent land use (road building, etc.), erosion or reburial through natural sedimentation processes. Likewise, it is very likely that only a portion of the metallurgical debris is still in situ: there is considerable erosion on the steep alpine slopes, as well as deliberate extraction of material (for example for use as road fillers, or to even out the land for better pasturage) from the sites over the millenia have taken their toll. Furthermore, the above study has also shown that the investigated smelting sites have a large variability in both their size and amount of slag present; the amount of slag at the sites from this study can be seen as a conservative estimation, full excavation could lead to a larger volume of slag and thus a larger production output. Also, as stated above, the slag to copper ratio is at the moment not well known, which again brings error into such calculations.

Conclusion

The combination of geomagnetic surveys, systematic coring and sampling of the slag heaps has proved to be an effective way to quantify smelting sites, allowing the efficient investigation of a larger area and creating a more detailed view of a complex copper production landscape. The study has also highlighted the importance of taking the depositional context into account, in order to gauge the amount of metallurgical debris actually present at the site. When morphology and depositional characteristics of the slag heap were not taken into consideration, there was a substantial overestimation of slag at the smelting site. Moreover, before the hypothetical copper production at the sites can be calculated, more work has to be done on calculating a viable copper:slag ratio through further investigation of slag composition, mass balance calculations and experimental archaeological reconstructions.

Notes

1 The first written documentation of iron mining in Dienten am Hochkönig, just to the west of the Miterberger mining district, date to the second half of the 12th century AD (Günther & Krauß, 2004, 134). However, 5 iron smelting sites have been dated via ^{14}C analysis from the late Early Medieval to early High Medieval periods (Hanning, in prep. cat No 166; DBM 2015, cat. No 100; Krauß, 2004, pp.11-13).

2 The results of the survey are being studied as part of the author’s PhD thesis (Hanning, in prep.).

3 The interpolation methods used were nearest neighbor, natural neighbor, linear and cubic. For documentation of Interpolate Scatted Data in MatLAB, see https://www.mathworks.com/help/matlab/ref/griddata.html and https://www.mathworks.com/help/matlab/math/interpolating- gridded-data.html.

4 Due to the problem that large pieces of slag and stone in the heaps made it impossible to create a straight-sided test pit through the slag heap, a test pit with a larger dimension as the sample was dug down, taking a 32x32cm sample every 10 cm of depth.

5 The total volume in this case refers to the combined volume of solids, closed pores, and inter-particle voids, which may contain air or water or both http://www.soilquality.org.au/factsheets/bulk-density-measurement

6 For sieve fraction below 8mm, a smaller representative sample was taken and the slag fragments were separated by hand. The mass fraction of slag in the representative sample was then used to estimate the total amount of slag in the sieve fraction. The presence of slag in the sieve fractions below 2 mm was checked using XRD analyses by looking for fayalite-like phases, which are almost always present in the Bronze Age copper slag from Mitterberg (ex. Viertler, 2011), but not present as naturally occurring mineral in the local rocks. Quantification of slag in the sieve fractions below 2 mm was not possible that this time. However, examination of a sample of the sieve fraction under the microscope showed that the slag particles did not make up a significant amount of the sediment and thus were not included in the calculations.

7 Bachmann mistakenly refers to the specific gravity of the slag, which is a ratio and is a unitless value. For the calculation of the weight of the slag present at the site, one needs to take into account the density of the slag, which is the amount of mass per volume.

8 Since most pieces of slag are of irregular shape and tend to have both open and closed pores, the apparent particle density of the slag was used – i.e. the dry weight of the piece of slag divided by the exterior volume, including pores (Webb, 2001 p.4). This was calculated using a variance of the standard test method for bulk density of refractory brick and insulating firebrick (ASTM C20-00, 2015).

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