Medieval lead-silver smelting in the Siegerland, West Germany

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Abstract

Excavations at a Medieval mining settlement in north-west Germany produced a series of metallurgy-related finds, including ore, slag, lead bullion and silver coins. These were analysed by various methods to establish their relationship to one another, in order to reconstruct the lead smelting process. The mineralogical analysis of ores and slags, and particularly of inclusions of matte, speiss and metal trapped in the slag, led to an estimate of roasting and smelting conditions. The analysis of lead isotope ratios of several of the finds further revealed two distinct strands of smelting, indicating the treatment of silver-rich ores separately from the bulk lead ore. This evidence underpins current historic research on the organisation of medieval metal mining and extraction in Central Europe in general, and illustrates the benefits of interdisciplinary research integrating archaeological, scientific and historical approaches alike.

Introduction

The Siegerland in Westphalia, Germany, has a continuous history of mining, mainly for iron, but also for various base metals and silver from the high Middle Ages to well into this century. Mining ceased only some 30 years ago, due to overall economic reasons rather than exhausted ore resources (Schawacht 1991). With a total of at least 220 million tons of siderite ore, it represents the world's largest hydrothermal vein-type siderite deposit. Despite this, the Siegerland never really achieved the reputation of, say, the Saxon-Bohemian Erzgebirge, the Harz Mountains or other famous mining regions.

During the 1970s, a medieval mining settlement on the Altenberg near the modern town of Müsen (Fig 1) was investigated by a group from the Deutsches Bergbau-Museum, Bochum. The team excavated several houses with cellars and mining shafts (Dahm *et al* 1998). The whole settlement was rather short-lived, and is securely dated by ceramics and dendrochronology from about 1210 to 1290 AD (Lobbedey 1998, Weisgerber 1998). Among the finds from the settlement were several pieces of ore, apparently stored in the basement of one of the houses; others were stray finds within the medieval horizon. Beside these 'archaeological' ores, many more 'geological' ore samples were taken from mineralizations in the walls of the medieval shafts. At the foot of the Altenberg on the banks of a local rivulet, two heaps of tap slag were found (place names 'In der Wilden Wiese' and 'Alte Allee') which are probably contemporaneous with the mining activity of the Altenberg (see Dahm *et al* 1998 for a full discussion of the archaeology and history of the Altenberg mining complex).

The excavations of the settlement and mines at the

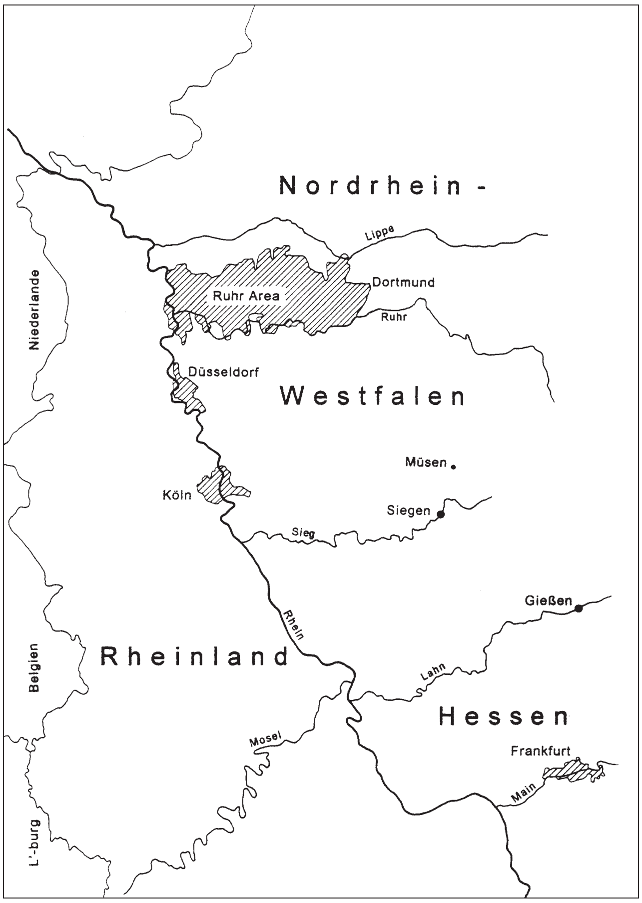


Figure 1: Map of west Germany, showing Müsen in Westfalen

Altenberg, directed by U Lobbedey and G Weisgerber, respectively, provided the opportunity for a detailed study of a well-dated medieval mining and lead smelting activity. Of particular interest were the smelting technology used and the relation between the local ores, the slags found nearby, and the contemporaneous silver currency. For this, 'archaeological' and 'geological' ore samples, tap slags and furnace material from the slag heap 'In der Wilden Wiese', a sample of lead, and several contemporaneous silver coins from a hoard at the Altenberg were analysed. This paper summarises the results of chemical, mineralogical and lead isotope work on these samples, and interprets them for their relevance to medieval lead and silver smelting and silver production in general.

Ore samples

The vein-type hydrothermal mineralizations of the Siegerland area contain quartz and siderite as the main constituents, with late subordinate base metal sulphides and a wide range of complex sulphosalts (Fenchel *et al* 1985). Locally, these base metal sulphides were mined for lead, zinc, copper and silver. The antimony sulphosalt mineralizations carried most of the silver, either as massive lumps of rich ore or finely interspersed in the galena. As elsewhere, the rich silver ores were mined preferentially in the Middle Ages (see Schneider 1998 for more geological detail, and literature).

Three 'geological' ore samples, taken from outcrops in the medieval mining shafts during the excavation and selected macroscopically for their richness in galena, were subjected to chemical and mineralogical investigation. They yielded 50-80wt% lead, 5-20wt% zinc, 0.2-0.3wt% antimony and 0.01wt% silver. Recalculated to 100wt% metallic lead, this equals only 130-200ppm silver in the lead smelted from this ore. By contrast, one sample of the 'archaeological' ore, *ie* ore found within the medieval layers in the settlement surrounding the shafts, also contained about 50wt% lead and 20wt% zinc, but roughly 6wt% antimony and 0.1wt% silver. Assuming a total recovery of both lead and silver during smelting, this would result in about 2000ppm silver in the metal smelted, *ie* about ten times the amount found in the geological ore samples.

Microscopic analyses proved that the ores were dominated by galena and sphalerite, with antimony and silver being bound mostly to the antimonial fahlore tetrahedrite ($Cu_{12}Sb_4S_{13}$), with some of the copper being replaced by silver, iron and zinc. According to EDS-SEM analyses, this fahlore typically contained around 2wt% silver, occasionally amounting to 5wt%. Another major source of antimony and copper in the ore was bournonite, $PbCuSbS_3$. Other mineral phases include chalcopyrite, pyrite and the gangue minerals quartz, manganiferous siderite, and barite. The texture of the ores clearly reflects a two-phase mineralization, which is in good agreement with the general interpretation of the genesis of the Siegerland deposits (Schneider 1998).

Tap slags

Two major slag heaps were discovered close to the Altenberg, consisting of huge, though unmeasured, amounts of macroscopically very homogeneous tap slag. It is a dense black material with only a few large vesicles. It is roughly broken, with most pieces still showing either top or lower flow surfaces, or both. Pieces weighing more than one kilogram are quite frequent, as are samples preserving the V-shaped form of small channels through which the liquid slag was tapped. Except for their surface characteristics (top and bottom surfaces and flow directions), the slags yielded no other macroscopically accessible information. There were no inclusions of unreacted raw materials visible nor other metallurgical by-products present, such as matte (metal sulphides), speiss (arsenides, antimonides or phosphides) or metal. Five of these slags were mounted for petrographic and SEM analysis, and two of them were also subjected to AAS analysis. All these samples stem from the 'Wilde Wiese', and in view of the apparent homogeneity of the material from this slag heap, the relative small sample was considered acceptable for this kind of study. The second slag heap, from the 'Alte Allee', was not included in the sampling, but is thought to be very similar to the material investigated.

Slag composition

The slags were basically iron silicates (about 35wt% each SiO_2 and FeO), containing significant amounts of manganese and lead oxides (about 7.5wt% each MnO and PbO). Al_2O_3 and ZnO were present at below 5wt% each, and MgO and CaO at below 2wt% each. Antimony and copper were found in concentrations just below half a percent (Table 1). This bulk chemical composition is reflected in a rather simple mineralogy, being dominated by fayalite crystals in a glassy matrix. Thus far, the slags are similar to with the vast majority of prehistoric to early modern period fayalitic smelting slags. The relatively high level of lead in these slags, present mostly as lead silicate glass, strongly links them to the extractive metallurgy of lead metal. This was confirmed by the identification and microanalysis of opaque inclusions, which occured in most samples and consisted of either base metal sulphides (matte) or antimonides (speiss), or mixtures of both, along with some metallic lead. The mineralogy and chemistry of these slags is thus in perfect accordance with the smelting of a lead-rich sulphidic ore, containing significant amounts of both antimony and zinc, and a manganiferous gangue rich in iron and silica. This interpretation matches the typical ores of the Siegerland in general, and the Altenberg in particular.

Table 1: AAS analyses of slag samples from the 'Wilde Wiese'

Sample No	82/1	82/3
Oxide or metal (wt%)		
SiO_2	35.5	31.9
Al_2O_3	4.5	4.6
FeO	35.4	35.9
MnO	7.5	7.1
MgO	1.8	1.7
CaO	1.8	1.6
ZnO	3.1	2.5
K_2O	1.2	1.3
PbO	6.9	8.8
Sb	0.24	0.34
Cu	0.38	0.52
Na_2O	*c*0.5	*c*0.5
TiO_2	0.2	0.2
BaO	0.2	0.2
Trace element (ppm)		
Co	150	150
Ni	80	80
Ag	30	30

Despite the macroscopic homogeneity of the slags, they were more inhomogeneous at a microscopic level. The basic composition was dominated by fayalite crystals in a glassy matrix (Fig 2). Differences occured mostly in the amount and nature of opaque phases present. One section for example (82/7) was characterized by the marked presence of various iron oxides. These were wüstite-rich islands, externally transforming into magnetite and locally forming areas rich in iscorite, a complex iron silicate with both ferric and ferrous iron. Apart from these, this particular sample was free of opaque inclusions. The opaque fraction of the other four slag samples studied was dominated by different proportions of inclusions of matte and speiss (see below). The differences in inclusion mineralogy coincided with some differences in the chemical composition of the glass matrix. Viewed in the back-scattered mode of the SEM, the glass showed different shades of grey indicating different levels of heavy elements, mostly lead and antimony. In order to determine the composition of these glasses, 5 to 10 spot analyses were done for each sample, selecting the brightest areas, *ie* those richest in lead. Individual points generally displayed little variation, and therefore only the averages of the results are given (Table 2). The widest scatter between samples was found for lead and antimony, ranging from 9-25wt% PbO and from 1-8wt% Sb_2O_3 in the glass.

An exception to the apparent homogeneity within each sample was found, however, in samples 82/1 and 82/3, with antimony being drastically enriched close to speiss inclusions, reaching up to 16wt% Sb_2O_3 (Fig 3). These extreme data are given separately in the table. It is noteworthy that the increased antimony content is not simply balanced by a proportional reduction of all the other elements, but is mostly compensated for by lower concentrations of lead and lime. This indicates that the antimony enrichment is a real chemical gradient, and not an analytical artefact or contamination by the neighbouring speiss inclusion.

Compared with the bulk composition of the two samples analysed by AAS, the glass matrix is significantly enriched in silica, alumina, lime, lead and antimony, and contains accordingly less iron and manganese. This simply reflects the enrichment of these two elements in fayalite, relative to the surrounding matrix. Only in sample 82/3, lead

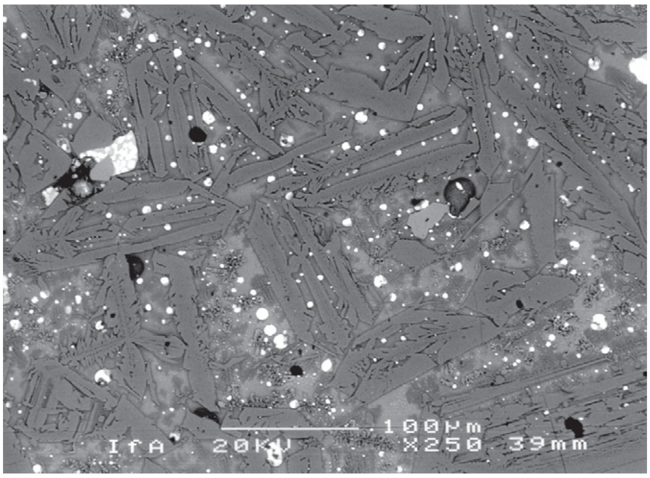


Figure 2: Fayalite crystals (grey, skeletal growth in two generations) in a glassy matrix containing numerous matte inclusions (white). Sample 82/3, BSE image.

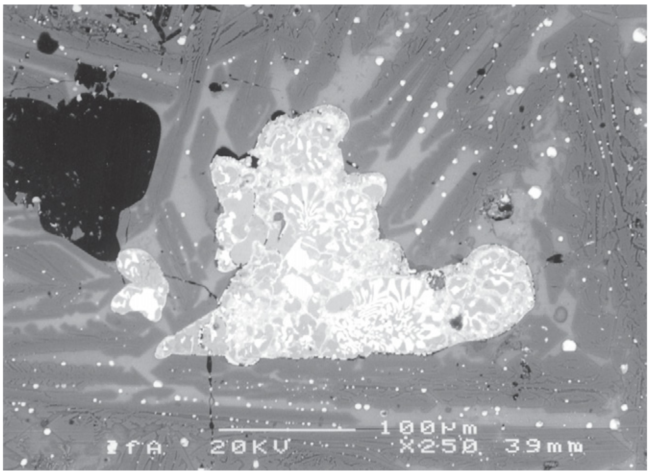


Figure 3: Large matte/speiss inclusion in sample 82/1. The increased brightness of the surrounding glass phase directly reflects the increased amount of antimony of this glass. BSE image.

Table 2: Averages of several spot analyses of glass matrix in fayalite slag from the 'Wilde Wiese'

Sample No	82/1	82/1+	82/2	82/3	82/3+	82/5
Oxide (wt%)						
SiO_2	46	43	35	53	25	45
Al_2O_3	8	8	5	12	1	8
FeO	12	11	13	15	57	17
MnO	3	2	1	2.5	1	3.5
CaO	6	3.5	3	4	-	7
ZnO	3	1.3	6	1.5	1	3
K_2O	1.5	1.5	1.5	3	-	1
PbO	17	13	25	9	3.5	13
Sb_2O_3	1.5	16	8	<1	10	1

Note: Beam current about 1nA, accelerating potential 20kV. Analysis 82/1+ represents the immediate vicinity (*c*5-10 µm) of a matte/speiss inclusion (Fig 3). Analysis 82/3+ is an oxidic rim between a metal/speiss inclusion and its matte surrounding. Absence of matte/speiss inclusions in the analysed area was checked by the absence of the S K_α peak from the spectra.

appears not enriched in the glass as compared with the bulk analysis; this is due to numerous lead-rich inclusions which were analysed with the bulk, but not with the glass analyses.

In summary, the SEM-EDS analyses of glass and crystalline phases demonstrated some variability within the compositional pattern as described above. With the exception of sample 82/7, all samples are similar enough to indicate that they are all related to the same process of lead smelting, using a complex antimoniferous sulphidic lead ore with a manganiferous iron-rich siliceous gangue.

Having established the nature of these samples as lead smelting slags, we focused our further research onto the spherical inclusions and their relationship to the surrounding glassy matrix. This was in order to learn as much as possible about the smelting processes which led to the production of these slags, and the nature of the other products of the furnaces, not preserved in the archaeological record. Beside an assessment of the smelting regime(s) prevailing in the furnaces and possible conclusions concerning the pre-smelting treatment of the ore, it was of major importance to discuss the extent to which silver played a role in the metallurgy of the Altenberg.

Matte and speiss inclusions in the slag

The total amount of opaque inclusions present in the slags is rather low, indicating a good fluidity of the molten slag, and hence easy density-controlled separation of melts and components immiscible in the silicate slag. There are, however, small globules or spheres up to several microns in diameter which, following Stokes' law, did not settle before the slag solidified, and so remained in the slag. Some others, being bigger, remained in the slag due to adhering gas bubbles whose buoyancy kept them in balance. These opaque inclusions are predominantly matte, made up of mixed lead and copper sulphide in a typical eutectic intergrowth pattern. In particular several of the larger inclusions are composed of this matte, together with antimony-based speiss, and finally metallic lead, antimony, and silver. The occurrence of this range of phase families, matte, speiss and metal, and their separation into subsequent layers according to their densities and mutual (im)miscibilities is well known in lead smelting of complex sulphidic ores which contain significant amounts of elements of the fifth group of the periodic table, in particular phosphorus, arsenic and antimony (Tylecote 1987, Bachmann 1993, Keesmann 1993 and 1999, Craddock 1995). Detailed investigations of their phase relationships, and interpretations as to the conditions under which they do or do not form are rarely found for archaeological material (Craddock *et al* 1987, Keesmann 1993 and 1999, Eckstein *et al* 1996, Kassianidou 1998). Due to their importance in 19th and 20th century metallurgy, however, a considerable body of modern technical literature exists for them.

Matte inclusions make up the vast majority of inclusions in the Altenberg slags. They are mostly composed of lead sulphide and the lead-sulphide–copper-sulphide eutectic with minor amounts of iron and zinc (see Figs 2 and 3). The size of these inclusions goes down to sub-micron levels, without significant changes in their composition or the ratio of lead to copper sulphide. The composition of the surrounding glass matrix is not noticeably affected by the presence or absence of these inclusions. It is concluded that they are in chemical equilibrium with the slag matrix.

The case is different for the speiss inclusions. Speiss is usually found only in bigger droplets, and is often surrounded by a protective cover of matte. When in direct contact with the glass, however, a marked increase in the antimony concentration in the glass is observed. Here, the content of Sb_2O_3 in the glass can reach as much as 10-16wt%, compared with an average concentration in the glass of about 1wt% only (see Table 2 and Fig 3). Considering an almost complete absence of smaller speiss inclusions in direct contact with the glass, this is strong evidence for non-equilibrium between the speiss inclusions and the slag melt. The melt is apparently not saturated in Sb_2O_3 component, and still absorbs the speiss inclusions. Therefore, the smaller ones with their high surface contact area relative to their volume had already gone, and only those protected by an outer layer of matte or by a relatively great volume were still preserved.

Sample 82/3 contained several coarse-grained speiss inclusions sufficiently large to allow a detailed phase analysis. This determination was deemed necessary in order to test the suggested link between the mineralization present in the various ore samples (see above) and the material smelted which produced these slags. The dominant phases in this inclusion (Fig 4a-f) are metallic lead, copper antimonide, and metallic antimony. Other phases regularly present, though on a much lesser scale, include copper nickel antimonide, copper arsenide and silver antimonide. The X-ray maps demonstrate the clear-cut separation of these phases and their sometimes well-developed crystal faces. It must be noted, though, that there is some mutual substitution of elements within these phases. The metallic lead contains, according to EDS analyses, about 3% antimony, while the metallic antimony contains 4% each arsenic and lead, and some copper. Copper antimonide contains regularly up to 1% nickel and 0.5% silver substituting copper, and 2-4% arsenic instead of antimony. The copper nickel antimonide has a rather wide range of copper to nickel ratios, but only 1% of arsenic, *ie* significantly less than the immediately surrounding copper antimonide.

The control over speiss formation

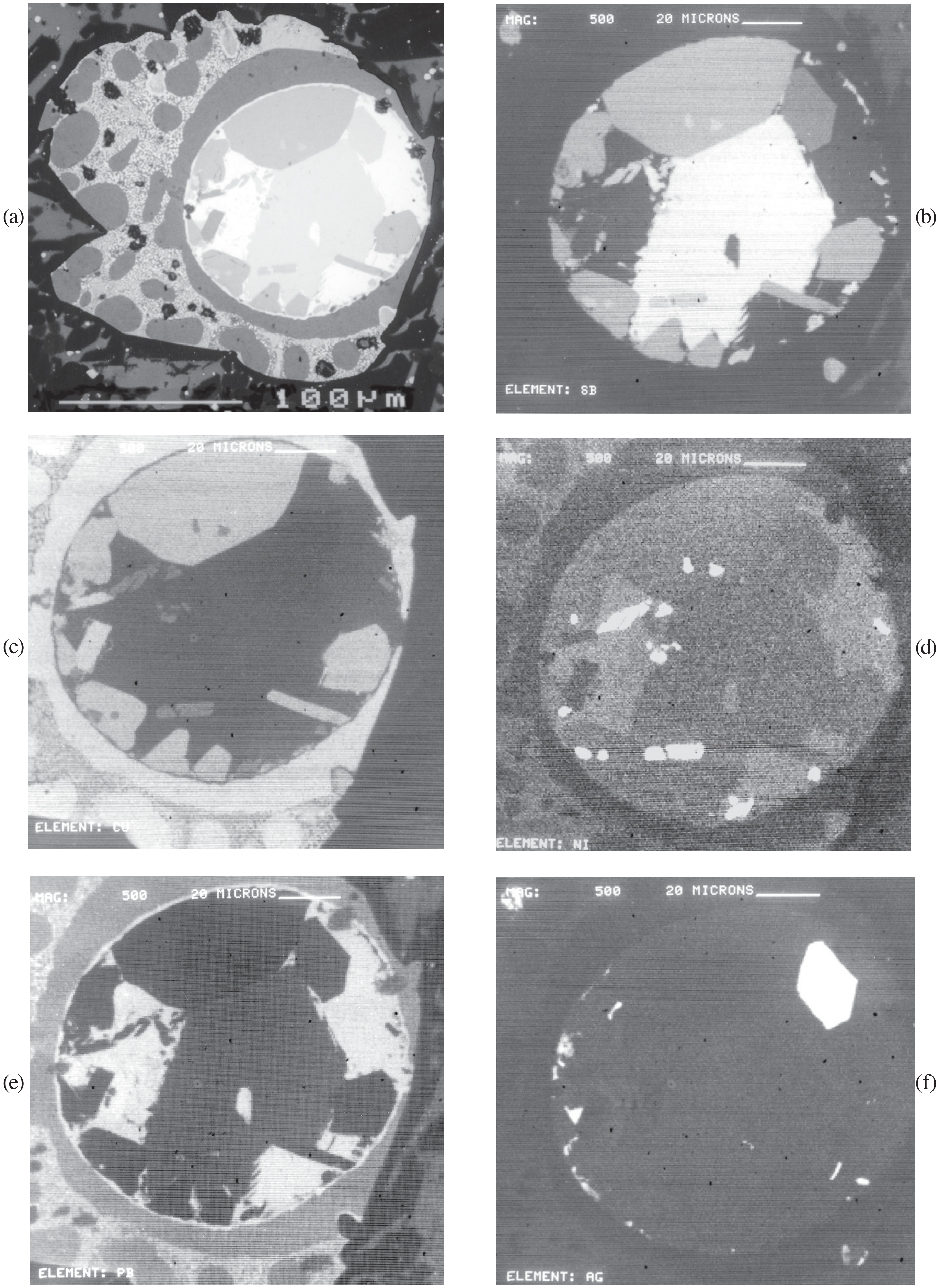
The formation of speiss has long been known to be unfavourable to silver recovery, due to high losses of silver into the speiss. This phenomenon is very obvious in the present case, with silver being incorporated not only as a minor component into the copper antimonide, reaching up to 0.5%, but forming a separate phase, silver antimonide. This silver, together with that trapped mechanically in the speiss via argentiferous lead, was lost for the medieval craftsmen. The reworking of argentiferous speiss in antiquity, suggested by Craddock *et al* (1987), was only recently rebutted by Kassianidou (1998) who re-investigated the very same material from Rio Tinto that led to the initial interpretation. Thus, all the silver bound or trapped in the speiss has to be considered a loss for the ancient metallurgist, and the production of speiss was therefore unwelcome.

The formation of speiss is determined by several factors, of which only a few were controllable by the ancient craftsmen. Firstly, the ore needs to have significant amounts of antimony, arsenic or phosphorus. These elements are usually chemically bound to the lead-silver bearing mineral, and cannot be kept away from the smelting operations. Secondly, elements like iron, copper, nickel, and silver need to be available, again elements typical of the ore mineral. Given the physical presence of the elements mentioned, redox and temperature conditions govern the formation of the speiss phases. These are about the same as those necessary for the smelting of lead, apparently leaving little room to avoid the formation of speiss. However, the formation of speiss phases is reduced by several factors. Under less reducing conditions, for instance, and given a typical pre-modern slag regime, iron will preferably enter into fayalite. Similarly, in the presence of active sulphur, the copper, iron and to some extent nickel will preferentially form sulphides (matte) rather than speiss. Finally, antimony, arsenic and phosphorus may enter the slag glass phase once they are oxidized. It must be stated here that this is a rather simplistic description of a much more complex reality, leaving plenty of room for further research and interpretations.

In the case of the slags under discussion here, we argue that despite a significant amount of antimony in the ore, only little speiss was produced during smelting. Evidence for this is the low content of antimony in the average glass as compared to the amount which it could incorporate. Very obviously, the slag reacts with the antimony component of the speiss phases, which is oxidized into the glass phase (see Table 2). The sulphur activity, on the other hand, seems to be high enough to act as a strong competitor for the limited amounts of copper and nickel that are present in the charge, resulting in the frequent formation of matte as a stable phase in the slag melt. From this, one may infer that the ore charged into the furnace was neither completely sulphidic nor completely roasted. Apparently, enough sulphur was left in the ore to allow the formation of matte, which is not adverse in silver smelting, but also conditions were sufficiently oxidizing to force most of the antimony into the slag. Though this inevitably meant to slag some of the lead also, this was not necessarily a negative side effect. It would rather reduce the melting point and enhance the fluidity of the slag, allowing a better separation of the metal, and also result in the production of less lead metal, but with a higher silver content. Consequently, the relatively high lead content of the slags simply indicates that the medieval metallurgists aimed for the silver and not for the lead. Allowing a higher loss of lead as lead silicate into the slag would enhance the recovery of silver, due to less metallic (argentiferous) lead being trapped in the slag, and suppression of speiss formation resulting from the almost complete oxidation of antimony. Even the cupellation process would have benefited from this, by working less, but richer, bullion.

The relation of ores, slag and metal

Beside the ores and slags, a lump of lead bullion and a hoard of local 13th century silver coins were found at the Altenberg (Ilisch 1998). It was possible to sample five of the coins (which contained a little lead as almost all such coins do), the lead lump and several pieces of ore and slag for lead isotope ratio determinations. These were undertaken at the Institut für Geowissenschaften und Lithosphärenforschung, University of Giessen, using a


(a)
100µm
(b)
MAG: 500 20 MICRONS
ELEMENT: SB
(c)
MAG: 500 20 MICRONS
ELEMENT: CU
(d)
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ELEMENT: NI
(e)
MAG: 500 20 MICRONS
ELEMENT: PB
(f)
MAG: 500 20 MICRONS
ELEMENT: AG

TIMS Finnigan Mat 261. Details of sample preparation, analysis and data correction are given in Schneider (1994). Isotopic data for local lead and silver mineralizations were taken from Schneider (1998) and Brauns (1995). According to these, most ores of the Siegerland area fall within two populations of different geological age, labelled 'A' and 'B', respectively. Poor ores are found in both populations, while only the geologically younger field 'B' contains silver-rich ores as well. Very often, ore samples from a single occurrence plot into both fields (Fig 5). The four ore samples taken from the Altenberg mine shaft walls all plot into field 'A', while the one 'archaeological' ore sample, *ie* the rich ore excavated from a storage area of one of the medieval houses, plots into field 'B.' Among the artefacts analysed, we find the same division. The slag samples and the lead bullion plot into field 'A', together with the 'poor' geological ores, while the lead extracted from the silver coins all put them into field 'B' close to the rich ore sample (Fig 6). While this generally confirms the correlation of ores, slags and metals related to the Altenberg, it also clearly separates the lead slags and the lead lump from the silver metal. This separation, a surprise only at first sight, ties in with current historical research on medieval silver mining, and opens up new possibilities for the reconstruction of medieval lead and silver smelting.

Figure 4: Large matte/speiss inclusion in sample 82/2.
(a) BSE image, showing inclusion surrounded by fayalite crystals (black) in a glassy matrix (grey). The central sphere consists of metallic lead (bright white, left and right) and antimony (white, centre) intergrown with various antimonides (speiss, cf (b)-(f)). The outer layer of matte consists of copper sulphide (grey) and lead sulphide (white).
(b)-(f) X-ray maps showing distribution of elements in the core region of the inclusion. (b) Antimony: metallic antimony in the centre, surrounded by antimonides (dark grey); (c) Copper: the outer layer of copper sulphide appears light grey; copper antimonide is clearly visible in the centre; (d) Nickel: enriched in a few isolated crystals only, together with antimony (cf (b)); (e) Lead: present as metal inclusions in the central sphere (left, right and bottom), and as a sulphide in the surrounding matte layer; (f) Silver: Like nickel, silver is mostly concentrated in a few isolated crystals, together with antimony (cf (b)).

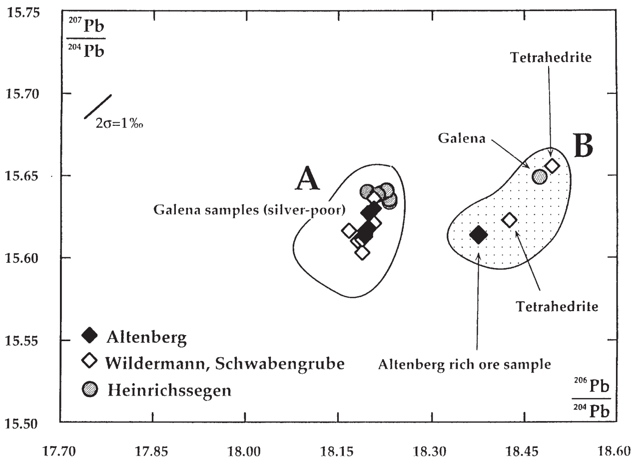

Figure 5: Lead isotope ratio plot of ore samples from the Altenberg and neighbouring mines. The fields labelled 'A' and 'B' define two different mineralizations from the region, with silver-rich ores occurring only in field B, but silver-poor galena in both fields.

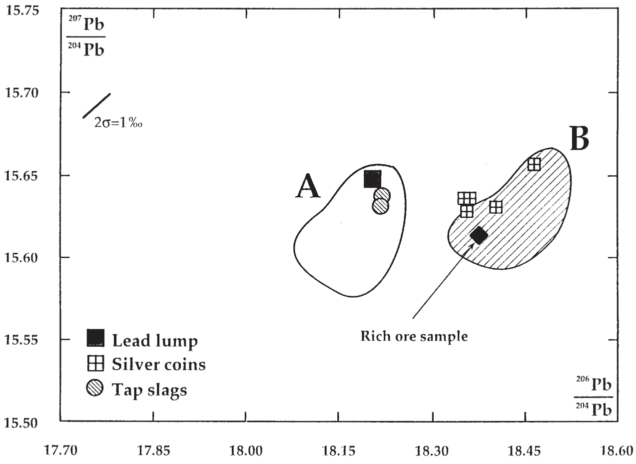

Figure 6: Lead isotope ratio plot of archaeological samples from the Altenberg region. The lead lump and tap slags from the Wilde Wiese all fall in the 'poor' field 'A', while the local silver coins and the silver-rich ore sample fall in field 'B', indicating a processing of silver-rich ore to silver metal separate from the bulk lead smelted at the Wilde Wiese.

Discussion

If the lead isotope evidence is neglected, the petrological and chemical investigation of the ores and slags points to a simple, though well controlled, smelting process. The ore was mined, probably roasted, fluxed with sideritic gangue mineral, and smelted to a reasonably rich lead bullion which eventually went to cupellation to extract the silver (Gassmann and Rehren 1998). The isotopic data, however, produces a radical change in this model and allows us to construct a much more interesting picture. Obviously, the mineralization of the Müsen region falls into two discrete isotopic fields, of which the geologically older populations 'A' contains only silver-poor, but lead-rich ores, while field 'B' comprises rich silver minerals as well as silver-poor lead sulphides. It has to be stressed here that very often ores of both mineralization types 'A' and 'B' are present in a single occurrence (Fig 5) and form geochemical mixtures, due to tectonic reactivation of the vein structures and repeated hydrothermal activity. The formation of silver-rich minerals, however, was restricted to the mineralization period expressed by field 'B.'

Figure 7a: Detail of the Kuttenberger Kanzionale, dated to the late 15th century (Haas and Kurzel-Runtscheiner 1929, Fritzsch 1967), depicting medieval miners at work. Note the closed chests at the bottom which hold the silver-rich ore, while the low-grade ore is hauled in open trays (right). Photo Deutsches Bergbau-Museum, Bochum.

Although the database available from archaeological objects from the Altenberg region is still relatively small, some conclusions may already be drawn from it. Isotopically, the silver coins match the rich ores, while the large-scale lead smelting indicated by the slag heaps at the foot of the Altenberg relates to the smelting of poor ores. It is apparent from this that poor and rich ores were not smelted together, but separately. This is in good agreement with results of historical research at several medieval mining regions. Ongoing research by Christoph Bartels (1992: 132-142, 149ff; 1997: 32f) indicates that medieval mining typically aimed selectively at the silver-rich ores, which were carefully collected and stored separately from the poor ores already in the mine. From the smelter's point of view, it also makes sense to treat rich ore separately from the poor ore, using a different furnace. Somewhat later, in the early modern period, Agricola writes:

> 'Experienced miners, when they dig the ore, sort the metalliferous material from earth, stones, and solidified juices before it is taken from the shafts and tunnels, and they put the valuable metal in trays and the waste into buckets.' (Hoover and Hoover 1950: 268)

and he continues:

> 'The metal which is dug out in a pure or crude state, to which class belong native silver, silver glance, and gray silver, is placed on a stone by the mine foreman and flattened out by pounding with heavy square hammers. ... ... These pieces of metal are afterwards heated in iron basins and smelted in the cupellation furnace by the smelters.' (Hoover and Hoover 1950: 269-270).

The rich ore, that is, was not smelted in a typical slag-tapping furnace, but went straight to the cupellation furnace, together with the necessary addition of metallic lead (see below).

Figure 7b: Detail from Figure 7a, showing miners with a closed chest.

For the Altenberg, the joint analytical evidence, together with analogies drawn from other medieval mining sites, tentatively combines to form a picture in which the rich ores were smelted directly to silver metal, while the mass of poor ore was smelted to lead bullion. While the silver was obviously used for coin making, we do not know whether the lead was subjected to cupellation and silver-making near the Altenberg, or whether it was sold and used as such. The production of lead and silver thus appear as two separate strands of metallurgy, beginning in the same mine but following two different production chains.

The Central European context

Mining and smelting at the Altenberg was relatively short-lived, and the medieval use of this deposit was a single episode of less then 100 years (Lobbedey 1998). Nevertheless, it can be understood only within the contextual framework of contemporary European mining and metallurgy. In general, this field of production was closely bound to institutions and structures of enormous influence on European economic and political developments within the century under discussion, as, *eg*, the order of the Cistercians (Bartels 1998). The knowledge and manpower of the important monastic orders of the time not only formed a network including intensive exchange-processes all over Europe, but are closely related to mining and metal production in general. In fact, we know their relevance to the Altenberg and its settlement (Johanek 1998). We have to assume that miners and smelters of the Altenberg settlement were in contact with the mainstream of medieval developments in metallurgy. To find two (or more) lines of metal production based on one deposit at the same time (or closely following one another, which seems less likely) is far from being a surprise in 13th century mining and metallurgy. Such combinations are visible in texts on mining, metallurgy and mineralogy of the time, as in Theophilus Presbyter's (*ie* Ruger von Helmarshausen, *c*1070-1125) *Schedula* (Hawthorne and Smith 1979), or the work of Albertus Magnus (*c*1200-1280), *de mineralibus* (Wyckoff 1967).

The production of silver during the middle ages was primarily based on rich silver-ores (Stromer 1995). Very often they formed part of sulphidic ore bodies of high complexity, as known from the Altenberg. The zones near the surface (but in some cases reaching depths of more than 100m, Bartels 1997), with considerable contents of secondary (oxidation-induced) concentrations of precious metals, intergrown with primary ores, were subject to medieval mining. Many deposits, *eg* of the Harz region, the Schwarzwald in southern Germany, or the Saxonian and Bohemian ore-mountains (Erzgebirge) are similar mineralogically to those of the Altenberg, and were subject to mining during the same time. There is both historical and archaeological evidence for at least three related metal production lines in the Harz region: silver, copper and lead were produced (Klappauf and Linke 1997; Bartels 1996). These metals can be traced throughout a series of historical documents of the 13th/14th centuries, being items of a widespread trade. Silver from the Harz mountains reached Cologne. Merchants providing Harz copper for the brass production of the Dinant area enjoyed privileges in that town (Bartels 1997). The delivery of large quantities of lead from the Harz mountains (and sites in the UK and Poland, Blanchard 1995) to the centre of silver production around Freiberg, Saxony, during the medieval and post-medieval production periods, is of particular interest for our study (see below).

Multi-metal metallurgy

The two lines of silver production based on rich ore, and extracting lead (or other non-precious metals) from poorer ores, can be traced to the primary source of minerals, the mines. In many cases the zone of medieval mining activity contained both rich and poor ores in varying composition, and we know that these components have been separated in the mine before being hauled to the surface. Mining laws as well as iconographical sources of the late Middle Ages show that the rich ores were kept in special, armoured cases, separately from the ordinary ore (Fig 7).

Rich silver ore continued to be the most important source of this precious metal (besides silver-containing copper) up to the first half of the 16th century. This is demonstrated by the development of St Joachimsthal in Bohemia between 1515 and 1580 (Bartels 1997). Even during the early 17th century, rich silver minerals could be of regional importance, thus providing documentation both of the nature of these minerals (mostly fahlores) and the separate treatment of rich and poor ores, respectively, before silver production became generally based on mining masses of galena with a low content of silver minerals (Bartels 1992 and 1997).

We find very different methodes of using poor ores, governed by local developments or changes of trade. Sometimes they were not used at all, but deposited on the surface or left as waste in the mines. Such earlier waste often became then subject of metal production later on, using more elaborate methods of ore-processing and smelting. Sometimes, at least parts of the poor ores formed sidelines to silver production. But also, the precious metal itself could result from sideline production, as it did supposedly during the medieval use of the famous Rammelsberg near Goslar/Harz. From early medieval times until the beginning of the 14th century, copper was its central product. Together with other problems, the exhaustion of the copper-rich minerals caused a crisis, followed by collapse of production at the Rammelsberg around 1360. Some 150 years later a new boom was based on combined lead and silver production, mining and smelting those ores previously left behind (Bartels 1997).

In a word, medieval metallurgy was not a closed and fixed system, but underwent considerable development, responding to complex changes in the bulk of minerals available by developing parallel and interacting lines of metallurgy. Thus the different lines of metal production as revealed by mineralogical and archaeometallurgical evidence from the Altenberg correspond with a more general context.

The Altenberg case

How about the archaeological evidence for the separate smelting of ores, and particularly for the smelting of rich ores? Smelting of poor ore produces large quantities of poor slag, of which we have ample evidence near the Altenberg. By contrast, it is reasonable to assume that the smelting of rich ores produced relatively rich slags (Tafel and Wagenmann 1953), which were immediately recycled and thus are absent from the archaeological record. In the absence of a contemporary treatise, we have to go back again to Agricola:

> ‘Some people smelt lumps of native silver not sufficiently pure, in pots or triangular crucibles, whose lids are sealed with lute. They do not place these pots in the blast furnace, but arrange them in the assay furnace ... To one part of the native silver they add three parts of powdered litharge, as many parts of hearth-lead, half a part of galena, and a small quantity of salt and iron-scales. The alloy which settles at the bottom of the other substances in the pot is carried to the cupellation furnace, and the slags are re-melted with the other silver slags. They crush under the stamps and wash the pots or crucibles to which silver-lead alloy or slags adhere, and having collected the concentrates they smelt them together with the slags.’ (Hoover and Hoover 1950: 400).

Clearly, the absence of evidence for smelting rich silver ores is no evidence of its absence from the Altenberg, while the isotopic evidence strongly suggests a treatment of the silver-rich material separately from the process which produced the lead slag.

We do not know what the lead produced at the Altenberg was used for, but any medieval town had a tremendous need for lead metal, mostly for constructional purposes, but also in warfare, metal working, medicine and other arts and crafts. The absence of cupellation debris from the archaeological record at the Altenberg and the surrounding smelting sites indicates that lead was not desilvered locally. Instead, it may have been traded for use elsewhere. There is increasing evidence for an extensive trade of lead bullion across medieval Europe (Blanchard 1995) as a metallurgical commodity for silver smelting in areas which were short of lead, like the Mansfeld region. Also the Erzgebirge imported substantial quantities of lead metal (ten thousand hundredweights per year) to assist in smelting its own rich ores. The imported lead bullion, not being rich enough to justify cupellation on its own, was needed to collect silver from silver ores that did not yield enough lead in themselves. Only then the enriched bullion was cupelled, and the silver originally contained in the lead together with the silver from the rich ores was eventually obtained.

This medieval trade in large quantities of lead bullion throughout Europe has several implications which should be stressed briefly, although they are beyond the aim of this paper. Firstly, the price paid for the lead bullion took into account its silver content as soon as a certain threshold in silver was exceeded. Thus, reliable silver analyses were clearly required, and had to be accurate even at low levels (Rehren 1997). Secondly, it should be noted that this long-distance trade in lead metal, as well as the co-smelting of ores from neighbouring mining districts, is a regular feature in the Middle Ages. Therefore, the lead isotope and trace element signature of a medieval or early modern gold, silver or copper object may in fact reflect the origin of the lead bullion added in its metallurgical treatment rather than the original signature of the gold, silver or copper ore.

Conclusions

The chemical, mineralogical and isotopic investigation of ores, slags and metals from the context of a medieval mining town in the Siegerland allows us to reconstruct with some certainty the medieval smelting technology for lead ores poor in silver. Although the ore contains considerable amounts of antimony, the smelting practice effectively suppressed speiss formation. The combination of lead isotopic data with the archaeological evidence and current historical research further indicates that rich ores were kept and treated separately from the poor ones, resulting in two separate lines of metal production for silver and lead. For the time being, it is impossible to decide whether rich and poor ores were mined and smelted contemporaneously, or whether the slags studied relate to a somewhat later period, when the rich ores were already exhausted. The absence of any evidence for the smelting of rich ores, except for the presence of silver which isotopically matches the rich ore, is no surprise, as any residues from this operation were probably reworked to keep silver losses low. This model of a more complex metallurgy than visible through mineralogical analyses alone corresponds with ideas currently emerging from historical research in major parts of Central Europe. Furthermore, it underlines the necessity to employ various different lines of investigation even in the study of apparently simple and straightforward archaeological situations.

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