Agricola and Zwickau: theory and practice of Renaissance brass production in SE Germany

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ABSTRACT: The technology of brass production in the Renaissance has received only little attention so far. This paper concentrates on late 15th-century brass production by studying crucibles recovered in Zwickau (SE Germany). Their scientific analysis by optical microscopy, ED-XRF and SEM-EDX is presented in conjunction with a little known text on brass making written by Agricola in the mid 16th century. As a result, two main crucible types are defined: one big lidded pot used for brass making via cementation, and one smaller triangular vessel used for the melting and casting of the fresh brass produced in the former type. The particular compositional characteristics and slag remains identified in each type of ceramic (big crucibles, lids, and small crucibles) are discussed in the light of their specific function and the diverse technical requirements that they had to meet. All in all, the archaeological picture almost exactly matches Agricola's account, while it adds further information as to the technical details of the brass making process.

Introduction

The history of brass is relatively well known in its origins, spread and uses. The early stages of brass up to the Roman period have been intensively studied by using both literary information and analytical data (Forbes 1950, Caley 1967, Craddock 1978, Bayley 1984 and 1988, Dutrizac and O'Reilly 1989, Picon *et al* 1995, Rehren 1999a). After a peak in the use of brass during the 1st century AD and a subsequent decline (Caley 1967, Dungworth 1996), the production of brass in Europe experienced a sudden resumption during the Middle Ages, possibly as a result of Eastern influences rather than a continuation of the Roman tradition (Rehren 1999b). Soon it was to become the most common copper alloy, used for architectural and luxurious items, for lay and ecclesiastical furniture and for technical and domestic implements. This is true up to the present day, with the main areas of brass production throughout the Middle Ages and the Renaissance being in Central Europe (de Ruette 1996, Day 1998).

The composition and manufacture of medieval and later brass artefacts are reasonably well studied (Cameron 1974, Craddock 1985, Mortimer *et al* 1986, Caple 1995, Bayley 1996, de Ruette 1996, Pollard and Heron 1996: 196–238, Eniosova 1999). Others have concentrated on the production of brass chiefly based on contemporary treatises (Zacharias 1989, Day 1998). However, archaeological evidence of brass production during the late Middle Ages and particularly the Renaissance is still scarce (but see Rehren *et al* 1993 and Rehren 1999b for examples of medieval brass-making remains).

The present paper aims at contributing to fill this gap. The study focuses on metallurgical debris attributed to brass production from late 15th-century Zwickau in SE Germany in conjunction with a little known, roughly contemporary, treatise on brass making by Agricola.

The metallurgical remains from Zwickau

The Zwickau material comes from a rescue excavation directed by J Beutmann, carried out within the medieval area of the city during 1998 (Fig 1). A comprehensive presentation of the results of the recent excavations in Zwickau is given in Beutmann *et al* 2000; here we concentrate on the brass making residues. In a 7x7x1m pit, some 3000 fragments of technical ceramic were

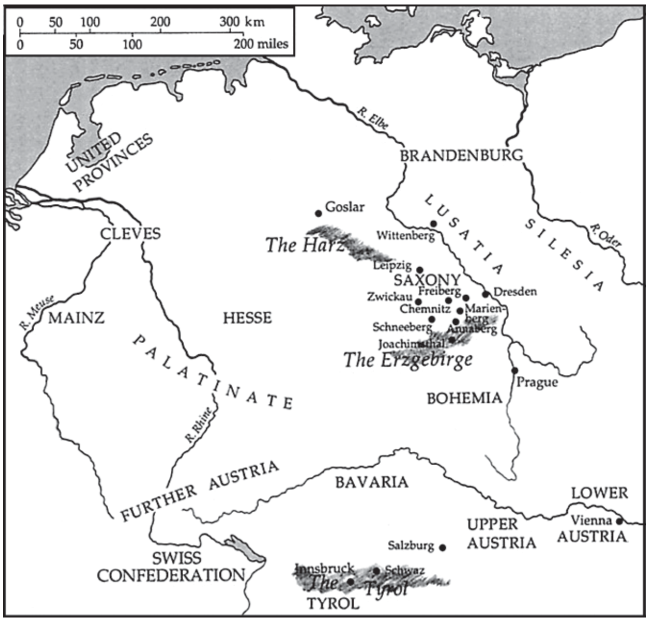

Figure 1: Map of Central Europe about 1600. Note the location of Zwickau near some of the main mining regions (shadowed areas); adapted from Roberts 1991, 149.

found, together with some slag, clay moulds and furnace lining. Although the latter did not seem to be *in situ*, they are very consistent in their fabrics, shapes and associated debris. The deposition of the finds was dated stratigraphically and by dendrochronology to AD 1465–1491.

The preliminary assessment of the assemblage by J Beutmann led to the definition of three different types of crucible fragments (here labelled A to C)[1]. The first two were tentatively identified as coming from brass-making vessels, while the third derives from vessels used for the melting and casting of brass (J Beutmann, pers comm 1999). For an independent assessment of this interpretation, selected samples were submitted for scientific examination. A number were analysed non-destructively by energy-dispersive X-ray fluorescence (ED-XRF) using an instrument and software Spectro XLab 2000. The comparative analyses of relatively large areas of the inner and outer surfaces of crucible sherds aimed to screen the used crucibles for metallic contamination. In addition, cut sections of crucible bodies were analysed for the bulk chemical composition of the fabrics. For a more detailed study, several polished cross-sections were mounted for optical and scanning electron microscopy (SEM), using a Philips XL 30 ESEM with an INCA Oxford energy-dispersive spectrometer package (EDX), following established protocols (cf Tite *et al* 1985, Freestone and Tite 1986, Freestone 1989, Bayley *et al* 1991). The compositions of ceramic fabrics and slags is given as averages normalized to 100wt%, of about ten measurements of areas ~100 by ~70µm taken on two or three specimens of each fabric, avoiding large inclusions such as sand grains and metal prills. Precision and accuracy were tested via the analysis of mounted pellets of standard reference materials. Variation was normally within 0-0.5% for major and 0-0.2% for minor element oxides, in both precision and accuracy tests. Lower confidence limits were established at 0.5wt%, but lower values are also given as indicative where considered relevant. The peak overlap between As K and Pb L lines was routinely addressed by checking alternative lines in the spectra. Only sodium was neglected in all analyses, as both Na Kα and Na Kβ peaks overlap with the Zn Lα peak.

Type A

The first type of crucible fragments defined archaeologically comes from the biggest vessels. These were quite tall (at least 400mm), with a thick flat bottom (35mm thick, 180mm in diameter), and a bulbous body with a maximum diameter of up to 280mm. The average thickness of the walls is 25mm. The majority of type A fragments studied were coated with an outer layer of less refractory ceramic, *c*5mm thick, which appears more vitrified (Fig 2).

The ceramic fabric is grey-dark violet, well kneaded and tempered with very abundant quartz grains, amounting to around 40vol%, mostly still angular and measuring up to 1mm across. The orientation of clay minerals parallel to the surfaces is still noticeable; however the pores tend to be subcircular with developing mid-coarse voids throughout, indicating long exposure to high temperatures. In spite of this, due to its thickness and density, the paste appears firm and far from collapsing (Fig 3). The type A body is characterized by an alumina to silica ratio of around 1:4, and a high iron oxide content

Figure 2: Fragments of base and rim of the large type A crucibles. Scale bar 100mm. (photo: J Beutmann)

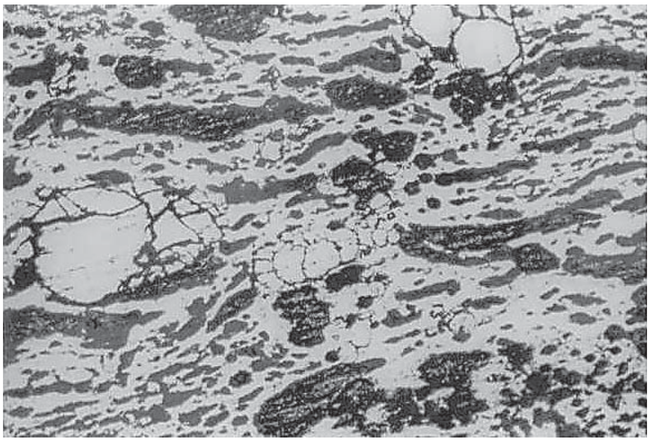

Figure 3: Backscattered electron image of the ceramic fabric of a type A crucible, with fine to coarse voids (dark) developing within a dense matrix. Note the abundance of (mid-grey) quartz grains. Width of image c3mm.

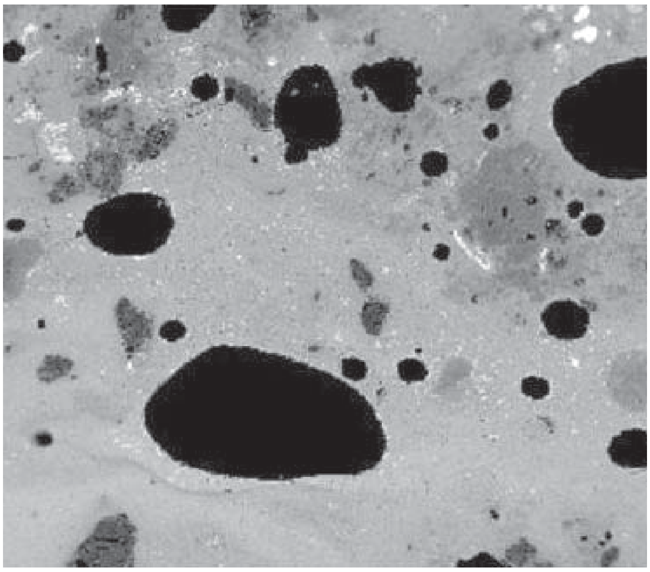

Figure 4: Backscattered electron image of the external ceramic wrap of a type A crucible, highly vitrified with a few quartz grains in the matrix. The bright areas (top and top left) are titanium minerals and the white spots (top right) are droplets of copper with Zn, Fe and Ni. Width of image c3mm.

(Table 1). The main metallurgical contamination is by about 7wt% zinc oxide on average (Table 1, Body), reaching up to 40wt% in some areas, together with copper oxide in lower concentrations. The added external ceramic layer is less refractory, heavily vitrified with coarse round bloating pores and ochre to brown-red colours. Only a few sand grains are embedded in the glassy matrix, some areas contain abundant titanium minerals and also tiny droplets of copper containing iron, nickel and zinc up to 3wt% each (Fig 4). The chemical composition of the ceramic reflects the low refractoriness, with high potash and lime concentrations (Table 1, Wrap). The thermal gradient denotes an exterior source of heat, though a vitrified layer can also be seen on the inner surface of the crucibles.

Two types of metallurgical remains were identified inside the crucibles: a thin (≤ 5mm) layer of slag, and remains of corroded metal. The slag is dense and grey, very rich in zinc oxide (average 42wt%, but up to 80wt% in some areas) and iron oxide (18wt%) (Table 2, A slag and Fig 5). It appears to penetrate up to 2mm into the

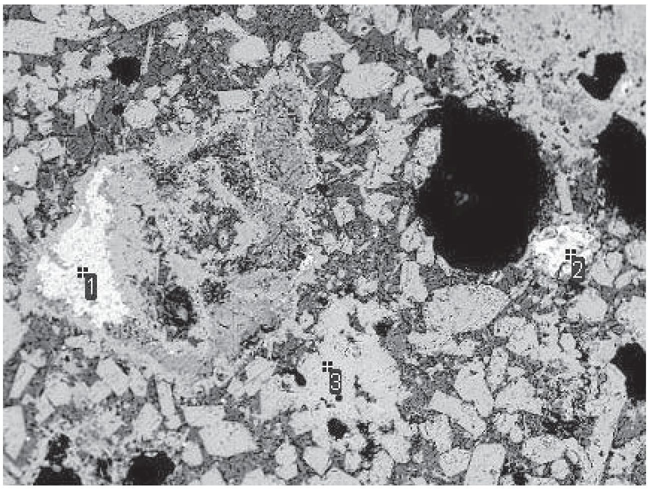

Figure 5: Backscattered electron image of slag layer within a type A crucible. Bright area 1 is metallic zinc, area 2 is a copper droplet, white crystals 3 are richer in zinc oxide, within a matrix containing more FeO and Al_2O_3. Width of image c600µm.

Table 1: Average compositions (wt%) of the ceramic body and outer layer (wrap) of type A crucibles.

Source	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	MnO	FeO	CuO	ZnO	PbO
Body∞	0.7	16.5	61.8	0.4	1.9	0.8	2.7	0.1	7.3	0.2	7.3	<0.1
Wrap∞	1.5	16.2	61.1	0.8	5.8	3.3	3.6	0.4	3.2	1.5	2.1	nd
Body*	0.8	17.9	67.0	0.4	2.1	0.9	2.9	0.1	7.9	-	-	-
Wrap*	1.6	16.9	63.7	0.8	6.0	3.4	3.8	0.4	3.3	-	-	-

Note: ∞ represents SEM/EDX analyses normalized to 100wt% for all elements; * same but re-normalized omitting CuO, ZnO and PbO. Traces of NiO, As_2O_5 and SnO_2 were detected in both matrices, all at 0.1wt% except 0.5wt% SnO_2 in the wrap.

Table 2: Average compositions (wt%) of the slag layers within types A and C crucibles.

Source	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	MnO	FeO	NiO	CuO	ZnO	As_2O_5	SnO_2	PbO
A slag	2.1	6.1	26.7	0.9	0.8	0.8	0.4	1.1	18.7	0.1	0.1	42.0	0.1	0.1	<0.1
B slag	2.0	7.9	36.9	1.6	2.1	4.9	1.1	1.1	15.1	0.1	0.6	26.5	0.2	0.2	nd

Note: SEM/EDX analyses normalized to 100wt%.

ceramic, probably due to its high concentration of zinc oxide. It contains droplets of metal of up to 2mm diameter, some of them copper but mostly brass (up to 15wt% zinc) with iron (~7wt%), nickel (~7wt%), arsenic (~1wt%) and tin (<1wt%).

The metal remains form subcircular corroded areas a few centimetres across, greenish or orange in colour, scattered over the inner surfaces. ED-XRF surface analyses of one of these features revealed a high content of copper and iron, together with minor amounts of zinc. In cross-section, these crusts appear as glassy slags holding together particles of brass (8–12wt% Zn) with small amounts of iron (*c*2.5wt%) and traces of arsenic and nickel (*c*1wt% each). The exact composition of the metal varies significantly, even between different spot analyses of the same area. The glassy slag is very rich in alumina (18wt%) and contains some silica grains and minute droplets of metallic iron alloyed with copper (≤ 8wt%), nickel (≤6wt%), arsenic (≤2wt%) and tin (≤1wt%).

Type B

Pieces of crucible lids are the second type of fragments. They are bell-shaped, with a rim approximately 200mm in diameter and walls about 7mm thick. The top of the lid has a knob 55mm in diameter, with a central hole about 27mm across. At some point this hole was blocked with a clay plug. A third kind of ceramic paste covers the outer surface of these lids, from the edges of the hole almost to the rim (Fig 6).

The ceramic matrix of the main body is at first sight similar to that of the type A crucibles, dark violet and tempered with abundant crushed quartz. However, it is far less vitrified. In these samples, the porosity is still angular and elongated, and the matrix looks 'drier'. Expansion voids surround the quartz grains, together with long open cracks along the fabric. The quartz grains are still angular or subangular, indicating that they did not react with the surrounding matrix during the high-temperature processes (Fig 7). This is probably due to the much more refractory nature of the ceramic, as indicated by the much higher ratio of alumina to silica, and a far lower iron oxide content (Table 3, Body) when compared to the type A ceramic. The only vitrification consists of an even glaze on the inner surface of this lid, which is very rich in zinc oxide. Covering this siliceous glaze, certain thin white-yellow crusts were found, which both ED-XRF and SEM-EDX analyses proved to be more or less pure zinc oxide.

Figure 6: Section of the top of a bell-shaped (type B) crucible lid. Note the ceramic wrap covering the outer surface and the different ceramic blocking the perforation. Scale bar 50mm.

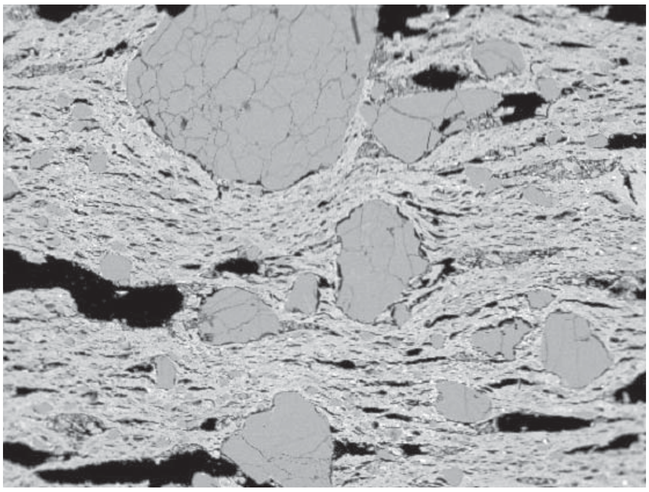

Figure 7: Backscattered electron image of ceramic fabric of a type B crucible, showing abundant unreacted quartz grains of various sizes surrounded by expansion voids, and elongated cracks parallel to the surface of the sherd. The matrix is not very vitrifed. Width of image c30mm.

Table 3: Average compositions (wt%) of the three ceramic fabrics of the type B crucible lids.

Source	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	MnO	FeO	CuO	ZnO	PbO
Body$^{\infty}$	0.4	22.4	60.7	0.4	1.4	0.3	3.7	<0.1	2.6	<0.1	7.8	<0.1
Wrap$^{\infty}$	0.8	22.9	64.4	0.5	4.3	0.3	1.4	0.1	2.9	0.1	2.5	<0.1
Plug$^{\infty}$	1.1	12.9	71.1	0.5	2.9	0.6	0.8	0.1	4.7	0.2	4.9	<0.1
Body*	0.4	24.4	66.1	0.4	1.5	0.3	4.0	<0.1	2.8	-	-	-
Wrap*	0.8	23.5	66.0	0.5	4.4	0.3	1.5	0.1	3.0	-	-	-
Plug*	1.2	13.6	75.1	0.5	3.1	0.6	0.8	0.1	5.0	-	-	-

Note: $^{\infty}$ represents SEM/EDX analyses normalized to 100wt% for all elements; * same but re-normalized omitting CuO, ZnO and PbO. Traces of NiO, As_2O_5 and SnO_2 were detected in all the matrices, all at ≤ 0.2wt% except 0.8wt% SnO_2 in the wrap.

The outer layer is a different, finer, ceramic, less porous and with only scarce quartz grains. It appears ochre-red in colour, and is vitrified only at the lower end, where it was obviously more exposed to the fire than higher up. Chemically, this outer ceramic is similar to the main matrix, albeit with a much higher concentration of potash and lower titania, which makes the wrap significantly less refractory (Table 3, Wrap). In the samples studied here, this ceramic wrap tapers smoothly and does not reach the rim of the lid, where it would have come into contact with the crucible. According to J Beutmann (pers comm), however, this outer layer often appears broken near the rim of the lids, indicating that it was routinely used to lute these lids to the body of the vessels.

The plug is made of a pumice-like clay, now dark grey in colour, characterized by an abundance of round voids. It is far less refractory than the other ceramics, as revealed by its heavily bloated appearance and chemical analysis — much lower alumina and titania, and high in potash and iron oxide (Table 3, Plug). The only noteworthy inclusions in this matrix are some titanium-rich particles and iron prills. Judging by its shape, thicker in the lower part, and the significant cleft on the bottom of these plugs, it seems that it was inserted from the inside of the lid by pressing with a finger or round-ended tool.

All three ceramic elements — body, wrap and plug — contain significant amounts of zinc oxide, but only traces of copper (Table 3).

Type C

The last type of crucible fragments is identified by its triangular shape at the rim and its flat round bottom and a considerably smaller overall size. The standard vessel is 150mm high and has a maximum width of about 130mm. The walls are 15mm thick, tapering to 10mm towards the rim, which is bent slightly inwards. Again there is an added outer layer of less refractory ceramic, about 8mm thick, which is fully vitrified. Both the inner and outer surfaces exhibit a substantial layer of glaze or slag up to 0.5mm thick (Fig 8).

The ceramic fabric is nearly identical in its original chemical composition to the lids, only with slightly higher iron oxide values, while the zinc contamination is less than half a percent, not even a tenth of that of types A and B (Table 4, Body; cf Table 3). It shows an open porosity, with many fine bloating pores alternating with some scattered coarse voids (upper part Fig 9). The colour of the fabric generally is grey-violet to black,

Table 4: Average compositions (wt%) of the ceramic body and two outer ceramic layers on the type C crucibles.

Source	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	MnO	FeO	CuO	ZnO	PbO
Body$^{\infty}$	0.4	23.9	63.9	0.4	1.8	0.5	4.1	<0.1	4.3	0.1	0.4	<0.1
Wrap 1$^{\infty}$	1.2	16.0	67.7	0.7	6.1	2.0	1.6	0.3	4.0	0.1	0.1	<0.1
Wrap 2$^{\infty}$	0.4	13.3	55.9	0.3	0.6	0.6	5.1	0.1	1.6	11.4	7.9	nd
Body*	0.4	24.1	64.4	0.4	1.8	0.5	4.1	<0.1	4.3	-	-	-
Wrap 1*	1.2	16.1	68.0	0.7	6.1	2.0	1.6	0.3	4.0	-	-	-
Wrap 2*	0.5	16.6	70.0	0.4	3.3	0.8	6.4	0.1	2.0	-	-	-

Note: $^{\infty}$ represents SEM/EDX analyses normalized to 100wt% for all elements; * same but re-normalized omitting CuO, ZnO and PbO. Traces of NiO, As_2O_5 and SnO_2 were detected in all the matrices, all at 0.1wt% except 0.4wt% NiO and 0.3wt% As_2O_5 in wrap 2.

Table 5: Average compositions (wt%) of the ceramic bodies and outer ceramic layers of the three crucible types.

Source	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	MnO	FeO
Body A*	0.8	17.9	67.0	0.4	2.1	0.9	2.9	0.1	7.9
Body B*	0.4	24.4	66.1	0.4	1.5	0.3	4.0	<0.1	2.8
Body C*	0.4	24.1	64.4	0.4	1.8	0.5	4.1	<0.1	4.3
Wrap A*	1.6	16.9	63.7	0.8	6.0	3.4	3.8	0.4	3.3
Wrap B*	0.8	23.5	66.0	0.5	4.4	0.3	1.5	0.1	3.0
Plug B*	1.2	13.6	75.1	0.5	3.1	0.6	0.8	0.1	5.0
Wrap C1*	1.2	16.1	68.0	0.7	6.1	2.0	1.6	0.3	4.0
Wrap C2*	0.5	16.6	70.0	0.4	3.3	0.8	1.4	0.1	2.0

Note: SEM/EDX analyses normalized to 100wt% omitting CuO, ZnO and PbO (data from Tables 1, 3 and 4).

Figure 8: Triangular type C crucibles. Scale bar 100mm. (Photo J Beutmann).

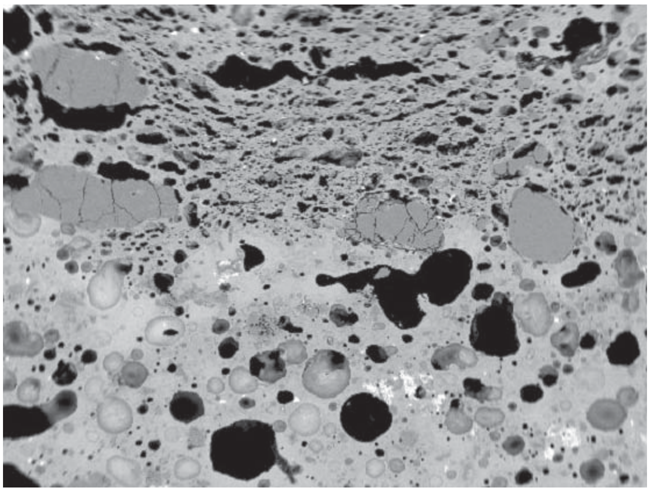

Figure 9: Backscattered electron image of the interface between the ceramic fabric of a type C crucible (top) and the external ceramic wrap (bottom). Note the increased number of round voids and more vitrified quality of the less-refractory wrap, in contrast to the the fine pores of the quartz-tempered body. Width of image c3mm.

although there are less vitrified examples with an ochre tone. Crusts of zinc oxide are the most significant metallic or submetallic feature identifiable by SEM-EDX. In addition, a small lump of glaze was detected on the inner surface of one specimen, which contained small prills of iron with several weight percent of copper, nickel, arsenic and zinc, and a large inclusion of brass with a few percent of iron.

The added outer layer on type C crucibles appears in all cases as a dense and bloated layer, made of a finer clay with scarce inclusions and now heavily vitrified (lower part Fig 9). However, the chemical analyses allowed us to distinguish two different varieties of clay used for these wraps, one richer in magnesia, potash, lime and iron oxide, the other richer in titania. In the former type, there are minute brass droplets trapped in the outermost glaze (probably simply mechanical contamination), whereas the bulk composition of this fabric reveals a generally low impregnation by metallic elements. The titania-rich ceramic wrap does not show any metallic prills but contains high concentrations of zinc oxide (11wt%) and copper oxide (8wt%) (Table 4, Wraps).

The slag layer present within the type C crucibles is mostly grey and heterogeneous. It appears thicker near the rim than towards the bottom, apparently due to it floating and accumulating on the molten metal (Fig 10). Its microstructure is dense and glassy, with scarce, round pores and newly-grown zinc-rich crystals (Fig 11). The average composition is shown in Table 2. When compared to the slag in the type A crucibles, it is less rich in zinc and iron oxides, but has higher concentrations of alumina, silica, potash, lime and copper oxide. In addition, the slag contains several metal prills, up to 1mm across, all of them being copper with

Figure 10: Inner surface of a type C crucible. Note the line of a thick later of slag parallel to the rim, probably floating on the molten brass. Scale bar 50mm.

zinc (≤4wt%), nickel (≤3.5wt%), arsenic (≤2wt%) and iron (≤0.3wt%).

Summary

The combination of evidence for long and intense firing in the type A ceramics, and the consistently high level of zinc oxide contamination in the type A and B crucibles confirms the initial identification of these fragments as remains from brass cementation vessels. In contrast, the type C crucibles, although clearly contaminated inside with brass, is far less heavily impregnated with zinc oxide, indicating that in these vessels brass was indeed melted and cast, but not produced from its raw materials. Thus far, the initial interpretation by J Beutmann could be confirmed, and certain details such as the manufacture of the ceramic vessels from different clay types emerged. The spatial and temporal proximity of these fragments to a little-known, detailed account by Georgius Agricola of brass cementation prompted us to compare it to the archaeological evidence before attempting a comprehensive interpretation of the evidence.[2]

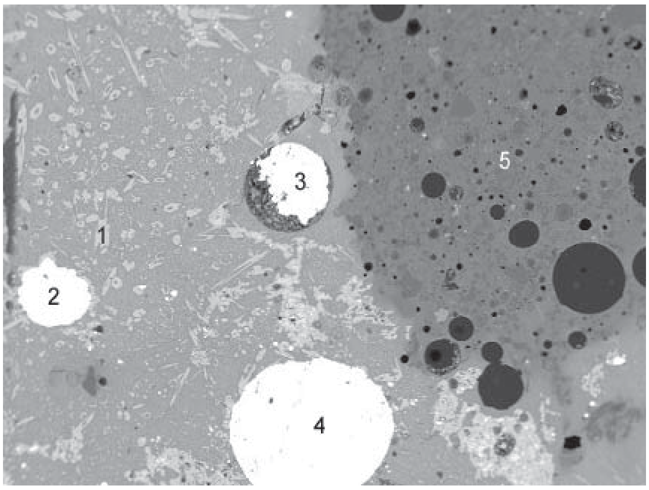

Figure 11: Backscattered electron image of the slag layer within a type C crucible. (1) zinc-rich crystals within the matrix, (2-4) circular droplets of copper with Zn, Ni, As and Fe, (5) large siliceous inclusion. Width of image c3mm.

The theory: brass production according to Agricola

The Zwickau remains precede, by less than a century, a surge in the technical literature devoted to mining and metallurgy, which led to well-known sources such as Biringuccio's *De la Pirotechnia* (1540, English trans Smith and Gnudi 1990); Ercker's *Probierbücher* (1574, English trans Sisco and Smith 1951) and last but not least Agricola's monumental opus of all aspects of mining and metallurgy, *De re metallica* (first edition 1556, English trans Hoover and Hoover 1912). While the first two of these texts do cover brass making, the latter surprisingly does not. However, the first edition of Agricola's *De natura fossilium* (German trans Fraustadt 1958), published in 1546, incorporated a description of brass production. This description was further extended in the second edition of this work, which appeared twelve years later (Agricola 1558), and which detailed two variants of the cementation processes current in Renaissance Germany. As far as we are aware, only the first edition of *De natura fossilium* has ever been translated into English (Bandy and Bandy 1955, cited in Beretta 1997), and there is apparently no English translation of the second edition. Due to its significance for the Zwickau material, and considering the lack of attention hitherto paid to this text, a translation of the relevant section has been attempted. Our English translation is included here, while the transcript of the Latin version from 1558 is given in the appendix:

> 'Nature dyes metals in an alien colour. For, while copper is reddish in its proper state, sometimes,

> though rarely, it becomes golden on its own — what the Greeks call *ορειχαλκον*, and from time to time it appears white — they call it *ψευδαργυρον*[3]. The latter exhibits the appearance of silver, the former of gold. The golden copper achieved singular pureness and admiration for a long time, Pliny writes; the white one was produced in Teuthrania, near Andera, and in Lydia, near Mount Tmolo, Strabo [writes].
>
> Art imitates nature and dyes copper in both colours. In fact, absorbing *cadmiam fossilem* it becomes brass. Once, *Livian* copper [from Livia], asserts Pliny, absorbed best cadmia, and after that, Marian. And this happens this way.
>
> Artisans arrange small fragments of the best, soft copper and fossil *cadmia*, calcined and ground to flour, in alternate layers in six or eight oblong pots, each of which holds more or less fifty *librae* [= 17kg]. There are some who add glass to the copper and the *cadmia*, so that it liquefies more easily. There are some who in place of *cadmiae fossilis* [mineral cadmia] substitute *cadmiam fornacum* [cadmia from furnaces].
>
> And they place the crucibles, filled this way with copper and cadmia, in big furnaces excavated underneath the ground, on iron rods that are approximately in the middle of these furnaces. And fire is set afterwards in some kind of short underground passages. On the top of each furnace, which just barely protrudes from the ground, there is a round hole and a baked clay lid, with which the fire is controlled. For sometimes they open it almost completely, sometimes they shut it up almost completely, in other moments they adjust a part of it, as each situation requires.
>
> And when it has cooked in a strong fire for eight or nine hours, and is gone liquid, the copper, though it does not yet seem to have been dyed in golden colour, nevertheless, has been transformed into brass, and has become much heavier. They remove the crucibles, once it [the brass] has cooled down, from the furnaces, and while the brass is still glowing like ash, and is porous like pumice, it is again liquefied and poured in a receptacle which is placed in the middle between two thick coatings of baked clay. These coatings are faced in such a way that from the brass, which now already is of the colour and shine of gold, thick or thin sheets can be obtained. They finish these sheets after they have been placed on an anvil and beaten with a hammer. This way of producing brass is common.
>
> Some others, on the contrary, put thin copper leaves, about one finger thick, into a jar[4], in which silver is normally melted, so that it can be poured, and the outside of which they smear with clay which has been mixed with *ferri squama* [hammer scale], but the inner side, instead, they smear with very pure honey. Similarly, they smear the individual small copper leaves with honey, and sprinkle them with very fine powder which they make from *cadmia fossilis*, dried wine dregs — which they call *tartarum* — and linden charcoal in equal proportions.
>
> The jar is afterwards covered with a ceramic lid. This has a hole, where a rod is placed, with which the liquid is stirred. But also the lid, there where it is in contact with the crucible, is smeared with the above mentioned clay. Then the jar is placed in a furnace like those used by the artisans who manufacture coins. When the cadmia is mixed with the copper, firstly it emits red smoke; later on, partly red and partly blue; lastly, golden, which indicates that the mixture has been made. And then the jar is removed from the furnace. From brass many things can be made, but mainly basins, candelabra, lamps and tubes. They are more appreciated than copper ones, since they have the hardness of copper and the pleasant colour of gold.' (Agricola 1558, 133–134).

The first method described by Agricola coincides, in essence, with the cementation process as detailed previously by Biringuccio and later by Ercker. Large crucibles were used, and crushed glass was added as an optional flux. In the same way as Biringuccio, Agricola does not refer to the charcoal in the charge, an essential requirement to render the conditions reducing within the vessels. The main peculiarity of this method is the arrangement of calamine and copper in alternate layers. This organization of the charge had already been advised by Biringuccio for the cementation of gold (Smith and Gnudi 1990, 203) but it had not, however, been suggested by him for brass making. The furnaces for this process are only vaguely characterized, yet they seem to bear a resemblance to those described by Biringuccio. This is particularly clear in the need for a substructure, where the crucibles are placed while the draught is let in, as well as in the use of a lid on the top of the furnace in order to adequately control the fire. With regard to the zinc ores, Agricola acknowledges the use of both natural zinc carbonate (*cadmiam fossilem*) and artificial zinc oxide (*cadmiam fornacum*, also called *tutty*), condensed in the upper parts of lead and silver smelting furnaces. However, the former seems to be more common. The charged crucibles would be strongly fired for a long time, apparently until the metal liquefied, and were only removed from the furnaces when they had cooled. Hence the alloy, having become noticeably heavier, would have to be re-melted before casting.

The second cementation process described is slightly different. In this case, the crucibles utilized are described as similar to those 'in which silver is normally melted', lidded but with a hole to allow a stirring rod. As indicated by Agricola, these crucibles were externally coated with clay tempered with *ferri squama*, and internally smeared with honey. The charge consisted of copper leaves, coated with honey and sprinkled with a powder of calamine and linden charcoal. A different type of furnace was also used, this being 'like those used by the artisans who manufacture coins'.

This paragraph is of importance, since it documents a significantly different way of making brass and therefore evidences the availability of at least two 'technological choices' which could achieve essentially the same result (cf Sillar and Tite 2000). However, the exact identification of the previously mentioned silver melting crucibles and furnaces for making coins is difficult. But when analysed in the light of the archaeological evidence, a hypothetical picture of the practice may be inferred (see below). In addition, the honey would add carbon to the charge, thus helping to reduce the zinc, and ensure a close contact between the raw materials. As for the temper of *ferri squama*, this expression can be translated as 'hammer scale' with some confidence. The use of metallurgical debris in the manufacture of crucibles has been documented in archaeological samples (*eg* Freestone 1989), and further underlines the existence of contacts among different spheres of technology. The function of this addition to the clay, however, remains uncertain at present. Iron oxide acts as a flux for siliceous ceramics, and would thus have had a detrimental influence on the refractoriness of the clay. In the archaeological samples, however, this outer layer of clay which was to be mixed with the hammer scale, was already less refractory than the main crucible matrix, as demonstrated for all the crucible types (and see Table 5), and thus apparently not selected for its thermal stability. Furthermore, the fact that at least four different types of clay were used for these wraps, all of them barely tempered and less refractory than the main ceramic bodies, seems to indicate that any clay available would be used for this, with little previous preparation. Quite possibly, it was indeed intended to vitrify during the operation, either to provide a viscous wrapping to counteract the effect of any cracks in the main ceramic, and/or to distribute the heat from the furnace more evenly to the main ceramic in order to prevent the formation of steep thermal gradients and subsequent cracking in the first place (Bayley and Barclay 1990; Bayley *et al* 1991). The first point is illustrated by one of the samples analysed here: in this case, the crucible actually cracked right through, but the pieces were kept together by this highly vitrified and very viscous outer layer.

The practice: discussion of the analytical results and the textual evidence

Returning to the Zwickau remains, there is very little doubt that all three types of crucible fragments can be linked to the metallurgy of brass. Their impregnation with copper and zinc, both as metal phases and as oxides, demands this interpretation. Specific features are discussed below.

Types A and B: Crucibles for brass making

As noted above, some small bits of metal appear attached to the inner surfaces of these vessels, possibly remains of the pieces of copper used for the cementation process. As they had been in contact with the vitrified and hence sticky surface of the hot vessels, it is feasible that some pieces of the metal could adhere to the inner surface. The zinc vapour would still have diffused into the copper; hence they appear now as brass. The variability in the chemical composition between different metallic pieces (and even within the same bits), suggests an irregular diffusion of the zinc, as though the cementation had not been completed and the alloy never fully liquefied.

The slaggy matter that binds together these inner metal particles, rich in iron and zinc oxides, is likely to have formed from the remains of a dirty zinc ore. Calamine ore is very difficult to refine completely (Morgan 1985). Unless it was thoroughly refined, most of the base metal impurities such as lead and copper would go into the alloy. Others, such as iron, might stay bound in a silicate and remain as a slag, which seems to have been the case here. Similarly, the slag layer covering other parts of the inner surfaces, again rich in iron and reaching an average of 42wt% ZnO (Table 2), may have originated from the highly reactive zinc vapour rising from the calamine and interacting with the crucible fabric. The presence of metallic iron may also be explained by this hypothesis: originally included either in the unrefined copper or, more probably, in the zinc ore, the iron would have been reduced to the metallic state during the cementation. Iron and zinc require similar reducing conditions to form from their oxides; thus, the presence of metallic iron is consistent with the cementation process. In contrast, it is unlikely that the iron- and zinc-rich slag comes from the refining of raw copper within these crucibles. Their closed shape is in itself strong evidence against their use for a necessarily oxidizing refining operation.

The relatively open mouths of these vessels apparently contradict the interpretation of being used for brass cementation. However, the ceramic lids described above as type B fragments fit well on the type A crucible bodies, as identified by J Beutmann. The image of these big crucibles covered by dome-shaped lids with a single hole is tempting. If this reconstruction is correct, then we have an archaeological picture that almost exactly matches Agricola's second account (Fig 12).

We suggest the following interpretation of the perforated lids: Initially, the charge in the crucible would develop a large amount of expanding gas which needed to escape, with some inevitable zinc losses. At some point during the process — probably towards the end — the lid would momentarily be lifted, the hole in it blocked with soft clay, and the crucible then covered to finish the process. Any zinc vapour still forming would be absorbed by the metal or the ceramic fabric, resulting in only limited pressure build-up. In fact, the zinc oxide contamination and the vitrification of the inner surface in the area of the knob, now covered by the clay plug, are similar to those of the rest of the lid, which indicates that the lid was used without the plug for almost the entire duration of the process.

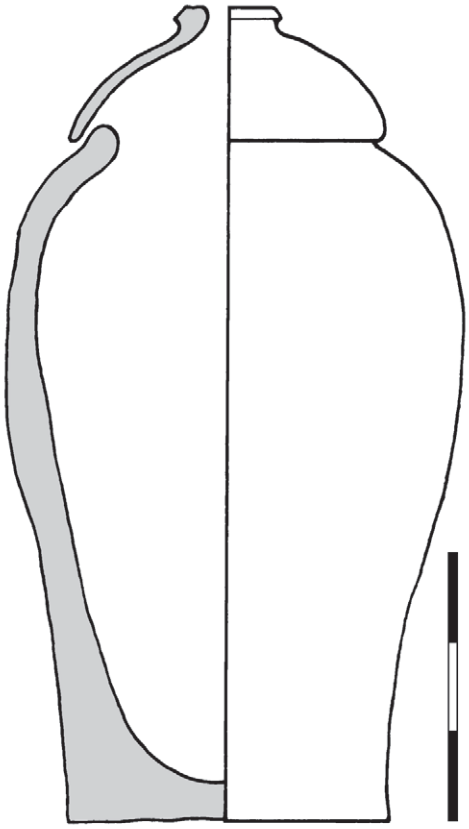

Figure 12: Reconstruction of the lidded cementation crucibles. Type A vessels with type B lids. Scale bar 150mm. (Drawing J Beutmann).

Arguments against the use of these crucibles and lids together, are that the thinness of the lids contrasts with the thick walls of the crucible bodies. Furthermore, different clays were used for making the two parts of the vessels. However, this disparity is explained when the technical requirements of each of the parts are explored. On the one hand, as mentioned before, the lids' fabric is relatively light and contains quartz grains, which still appear subangular or angular, and are surrounded by open voids and elongated cracks. Freestone (1989) and Bayley *et al* (1991: 402) relate these voids to the increase in the volume of quartz when it is heated through 573°C, during the initial firing of the vessels. Afterwards, when the crucible cools down, the quartz shrinks back, leaving the elongated voids along the fabric and the round ones around the quartz itself (Fig 7). Subsequently, during the crucible's use, as the grains expand again, the elongated cracks open up to accommodate such expansion. Accordingly, the effect of this temper would be that of a 'dimensional stabilizer' (Freestone 1989: 159), rather than improving the chemical refractoriness. The increase in thermal shock resistance caused by quartz temper in ranges at or above 20vol% has been further demonstrated by Kilikoglou *et al* (1998, see also Tite *et al* 2001). The side effect of this might be a decrease in the tensile strength of the fabric. However, given that this is not the crucible itself but the lid, strength would not be a prime requirement. Instead, the lid would be expected to be light, and to withstand long exposure to high temperatures and thermal shock without cracking.

On the other hand, the crucibles themselves would have to face different problems, such as direct contact with an unevenly distributed fire and supporting considerable weights of metal while hot. The higher compression of the body fabric and the subsequent lower abundance of cracks and pores (Fig 3) would increase the tensile strength (cf Tite *et al* 2001). In addition, its thickness would be adequate to withstand the corrosion by the reactive zinc vapour. The zinc oxide impregnation of the fabric (see Table 5) and the presence of a zinc-rich even glaze on the inner surfaces of the lids appear to be the result of zinc vapour rising from the interior of the vessels. The differences in design between pots and lids are responses to the differing physical and chemical stresses involved. Thus, there is no reason why the use of such different crucibles and lids together cannot be accepted. The initial categorization of the fragments into three types may be revised, assigning them to two crucible types only, a large lidded one with two different fabrics used, and a small open triangular one.

There are more clues that confirm the interpretation of these crucibles as cementation vessels. When Agricola refers to the lidded brass cementation crucibles or 'jars', he indicates that vessels 'in which silver is normally melted' may be used, fired in furnaces like those used 'by the artisans who manufacture coins'. Without any further reference to such furnaces, we may suggest — of course cautiously — that they could resemble the furnaces used for parting gold and silver, which were, indeed, used primarily by coin minters. This hypothesis is based on the fact that these furnaces were used for a similar solid state metallurgical process, where the temperature had to be carefully adjusted by controlling the air draught. If we look at the depiction of this type of workshop provided by Agricola in *De re metallica* (Fig 13) and as modified by Libavius (Fig 14), the similarities between the lidded vessels illustrated and those reconstructed in Figure 12 are striking.

Figure 13: Agricola's illustration of a gold-silver parting workshop. Note the use of large lidded crucibles for cementation, similar to Fig 12. (Illustration from Hoover and Hoover 1912, 455).

Figure 14: Reinterpretation of Fig 13 by Libavius in which the crucible lid appears perforated as Agricola advised, although Fig 13 does not show this detail. (Illustration from Rex 1964, 74).

Mass-balance calculation of the charge

From the similarity in crucible shape, and the evidence for lids with a central hole, it appears that the Zwickau remains relate to a workshop following the second variant of brass cementation as described by Agricola in 1558. But how do the size of the Zwickau vessels and the scarce information concerning the make-up of the charge provided by Agricola match?

The volume of the Zwickau vessels is estimated to be about 12.5 litres, based on the reconstruction and measurements provided by J Beutmann (pers comm), and calculating for a vessel with an average internal diameter of 200mm and a height of 400mm. Agricola and Biringuccio report that the cementation vessels hold between 50 and 60 pounds of metal (around 17 to 20kg), but do not specify the quantities of calamine or charcoal used. In an attempt to relate the volume as reconstructed from the archaeological finds and the weight provided in the texts, we have to look at the make-up of the charge. Unfortunately, the sources are not very detailed; the omission of charcoal in several of the recipes has already been noted, and no quantities or ratios are given for copper and calamine. Thus, we have to work from a theoretical basis, and translate weights into volumes. We assume that the brass produced had about 25 to 30wt% zinc, following Ercker's observation that the metal gained one third in weight during the cementation (equivalent to a brass with 25wt% zinc), and the generally accepted upper level of about 30wt% zinc for cementation brass. Allowing for some loss of zinc as vapour and into the slag and ceramic, we use the upper value of 30wt% zinc and 70wt% copper as a starting point of our discussion. Using a nominal 100kg brass yield, we thus need to add 70kg copper, 30kg zinc as zinc oxide, and enough carbon to reduce the zinc oxide to zinc metal. 30kg zinc metal equal about 40kg zinc oxide; the resulting 10kg oxygen in turn require another 10kg carbon to form carbon monoxide for the cementation to proceed. In effect, we have a ratio by weight of copper to zinc oxide to charcoal of 7:4:1. Using specific gravities of 7 for (porous) copper, 4 for calamine, and 0.5 for charcoal, this translates into a volume ratio of 1:1:2, which indicates that half of the charge consisted of charcoal, and only about a quarter each of copper and calamine. A volume of 3 litres of copper (equivalent to a quarter of a crucible volume of 12 litres), with a specific gravity of about 7, equals 21kg, or almost exactly 60 *librae*. This indicates that the weight information provided by Agricola and Biringuccio probably refers to the amount of copper metal treated in these crucibles; a sensible assumption given that they would probably not record the gross weight of the crucible charge, and that it is only Lazarus Ercker in the late-16th century who quantifies and discusses the increase in weight of the brass made during the cementation; an increase which Agricola just reports qualitatively and without further comment ('the copper … has been transformed into brass, and has become much heavier'). This argument gains further support from the traditional habit of measuring metals by weight, while ores and fuels such as charcoal were typically measured by volume. It can then be deduced that the capacity of a cementation vessel of a certain volume was expressed as the weight of copper it could hold together with the necessary nonmetallic ingredients for the process, and not as the weight it could hold if filled entirely with the metal.

It should be noted that the densities are extremely difficult to assess, since we have very little information concerning the size and shape of the various raw materials when measured or prepared for the crucible charge. The copper metal may have been provided in rectangular ingots or sheets such as those found on board a late medieval/early modern ship wreck from Hamburg (Rehren 1995), and hence a density relatively close to the true density is assumed here. The density of calamine is more problematic since we do not have any details of the precise nature of this material; calamine as an ore is a rather loosely defined material, in contrast to the pure mineral of this name. As discussed elsewhere, the specific gravity of charcoal is probably even less than 0.5; however, for some of the other carbonaceous materials mentioned, such as dried wine dregs or honey, it is closer to 1; hence, we kept the value of 0.5. Due to these inherent limitations, it is felt justifiable to use rounded-up figures, while emphasising the necessarily approximate nature of the calculation. In spite of these uncertainties, however, the match between the archaeologically determined volume of the vessels and the weights mentioned by the Renaissance authors is reassuringly good.

The type of calamine used

The generally low lead content of the remains from Zwickau, and in particular in the crucible slag (see Table 2), points to the use of natural calamine ore rather than furnace calamine. The latter typically forms during smelting complex lead-zinc ores to produce argentiferous lead bullion (Sisco and Smith 1951), and is expected to be severely contaminated by lead oxide particles. The few published analyses of furnace calamine (Hezarkhani-Zolgharnian *et al* 1994, Eckstein *et al* 1996) confirm this, showing lead oxide levels from ten to fifty weight percent in the calamine crusts. This would inevitably result in lead-rich slags forming during the cementation process; the virtual absence of lead oxide in the slags from Zwickau is thus interpreted as evidence for the use of natural calamine. This is further corroborated by the high levels of iron oxide in these slags (see Table 2), a component far less likely to be present in furnace calamine in any significant concentrations, but a typical contaminant of oxidized zinc ores.

Type C: Crucibles for brass melting

Finally, the discussion must address the crucibles of Type C. These triangular open vessels are interpreted as melting vessels, rather than as brass-making crucibles. First, the much lower levels of zinc oxide in the ceramic fabric indicates a lower vapour pressure, such as one would expect in an open melting vessel. The slightly higher zinc contamination of the external ceramic wrap could be the result of a furnace full of zinc-rich fumes evaporated from the melting metal. Ironically, the direct contact with the molten metal on the inside of the vessels apparently led to less contamination of the ceramic than the contact with zinc oxide-rich fumes on the outside. Second, the limited volume of the crucibles also indicates that they were probably used for melting purposes. The large size could be seen as an advantage in cementation vessels, since the larger crucibles allowed bigger yields, in addition to the fact that a smaller surface relative to volume would decrease the zinc losses into and through the walls[5]. Instead, in melting processes brassmakers would only melt down the amounts of metal required for each cast, based on their awareness of the 'colour', *ie* the zinc content, fading with each melting. Biringuccio states that the founders would use crucibles 'singly, or in pairs, or several at a time, according to the number of moulds' (Smith and Gnudi 1990: 74), hence the appropriateness of small-sized crucibles. Third, their open shape would also be very detrimental for cementation processes. It is worthwhile mentioning that Biringuccio refers to a specific melting process used by brass founders, which involved the use of brick structures with a diameter of a *palmo* [291mm], *ie* not much bigger than these crucibles, heated from underneath and covered by a heap of charcoal (Smith and Gnudi 1990, 292). The crucibles represented in his woodcuts are triangular, like those from Zwickau.

Agricola (1558) describes the casting of the freshly made brass into sheets of varying thickness; at Zwickau, fragments of clay moulds for thin long rectangular bars with a maximum width of around 10mm were found (Beutmann *et al* 2000, 299 and pers comm). These may have been used for wire making, rather than being hammered into sheet as suggested by Agricola's text, but no evidence for the further manufacturing of the Zwickau brass is known at present.

One argument against this interpretation might be the presence of cementation-like slags within these crucibles (see Table 2). However, these are interpreted as resulting from contamination of the primary cementation product by residual slag, which would only fully separate from the metal during re-melting for casting. Agricola (1558, 133–134) mentions how the brass still looks porous and dirty once the cementation is finished, and only after being re-melted 'is of the colour and shine of gold'. As mentioned above, the layer of slag in some type C crucibles is thickest at about 2/3 of their height, probably originating from the impurities floating on the molten metal (see Fig 8). In terms of composition, the slag layer in the triangular crucibles appears to be a mixture of the slag found in the type A vessels, which were extraordinarily rich in zinc and iron oxide, with ceramic material (increased alumina and silica) and charcoal ash (increased potash and lime, see Table 2). Therefore we can assume that the final refining of the brass would not take place until the melting prior to casting, and that the charge in the cementation vessels probably did not melt completely, but remained at least partially as a semi-fused mixture of brass fragments, non-reacted remains of the calamine and charcoal ash.

The choice of ceramic material

A few comments have been made already regarding the chemical composition of the fabrics used for the crucibles. When looking at the likely original composition of the ceramic material, *ie* omitting the contamination by copper and zinc oxide (Table 5), as a function of the use of this ceramic material, several interesting patterns emerge. One is the almost identical composition of the fabrics (within analytical accuracy) for the lids (type B) and the small triangular crucibles (type C) which, according to their shapes, clearly do not belong to the same vessel types. This material is characterized by the very favourable ratio of alumina to silica of more than 1:3, contrasting to a ratio of around 1:4 for the main vessel fabric (type A). As discussed above, the technical requirements were highest for types B and C which were to be moved and handled while hot. One may assume that the very alumina-rich clay used for types B and C was more difficult to obtain than other clays, and hence used sparingly. Type A, in contrast, was only under static pressure from the weight of the charge. Thus, a sturdy, more massive build from a less refractory clay was still sufficient for the latter, indicating a design solution to the operational requirements rather than a material-specific one. The exceptionally high iron oxide content of this fabric does not necessarily diminish its refractory nature. The strongly reducing conditions within the vessels had reduced much of this to metallic iron, which, unlike iron oxide, does not act as a flux (see Freestone and Tite 1986 for a similar example, concerning steel-making crucibles from India).

Thus, the key oxides, which under these circumstances differentiate more refractory compositions from less refractory ones, are soda, potash, magnesia and lime. We could not analyse for soda due to the peak overlap between the Zn Lα and the Na Kα lines, given the generally high levels of zinc in the fabrics studied. However, the potash content very clearly differentiates the ceramic material used for the crucible fabrics from the outer wraps, which were supposed to vitrify to fulfil their function (see above). Similarly, the levels of magnesia and lime are typically higher in the wraps than in the crucibles. Some of this may be due to contamination from fuel ash dust in the furnaces; however, no compositional gradients were observed for these oxides, and we believe that contamination is only a minor factor in the overall composition of the vitrified ceramics. The rather wide compositional variability of the wraps indicates an opportunistic procurement strategy for these, in contrast to the specialized ceramics of the crucibles.

A final comment concerns the exceptionally high level of titania found in most of the fabrics, of up to six percent, and often exceeding the level of iron oxide present. Although titania should enhance the refractoriness of ceramic, it is assumed that it is merely a chance component reflecting the local geology in the hinterland of Zwickau. A large granitic intrusion near Zwickau (the Kirchberg), is known to be rich in titanium minerals (K Eckstein, pers comm), and may have contributed to this chemical signature. Similarly, the tin occasionally found in some of the fabrics (see notes to Tables 1 and 3), is likely to reflect the geological background scatter of cassiterite in the lowlands near the Erzgebirge (see Fig 1), once a major tin producer in Central Europe with an abundance of placer deposits in its foothills.

Summary and conclusion

The detailed analysis of both archaeological and written information allows a reconstruction of Renaissance brass production in SE Germany. In late 15th-century Zwickau, brass was made on a considerable scale by the cementation of metallic copper with zinc ore mixed with charcoal, in big, thick and reasonably refractory lidded crucibles. The ratio by volume of copper, calamine and charcoal is estimated to have been about 1:1:2, based on textual and archaeological evidence. The charged crucibles were fired in furnaces that allowed an appropriate control of the fire, apparently using the colour of the fumes emanating from the vessels as a guide to the progress of the operation.

Both the vessels and the lids were well designed to meet different thermal and chemical demands. The clays used for the lids and small crucibles were different from those used for the large cementation vessels, because of the need to handle the former two items while hot, which required greater strength. In addition, they all were externally coated with a second, less refractory outer ceramic layer, which improved their strength and prevented accidental breakages of the crucibles. The choice of clay was opportunistic for the wraps and the plugs closing the lids, while the crucibles proper were made using a specific clay with good refractory properties. The titania signature indicates that regional clay deposits were exploited for both purposes, although further research to identify the clay deposits is still necessary.

Both natural and artificial calamine of the time would have contained considerable quantities of impurities. The nature of the impurities found in the crucible slag indicates the use of natural calamine rather than furnace calamine, resulting in a high-quality brass with little if any lead, and hence suitable for both gilding and wire drawing. Fragments of clay moulds for long thin bars found in Zwickau could indicate the latter. We assume that no complete liquefaction of the charge occurred during the cementation, and that the metal produced may have remained in a solid state. This is indicated by the remains of cementation slag found inside the open triangular crucibles, thought to be used for melting and refining of the metal prior to casting, as this slag only separated completely from the metal during melting. Furthermore, the subsequent melting and casting in smaller units would have been much more difficult if the entire metal charge, of around 20kg, had solidified as one lump.

This study provides another demonstration of the relevance of archaeological research even for those periods where written sources are available. Texts and archaeology supply the clues necessary for full understanding and, at the same time, illustrate the relationship between the theories and practices of past societies and their approach to materials. Each of the sources is valuable on its own merit—their combination, fully worthwhile.

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Appendix: Transcript of the original Latin text on brass making from Agricola 1558

Natura tingit metalla alieno colore. Cum enim æs suo modo rubeat, id, etsi raro, interdum gignitur fuluum, quod Græci ὀρείχαλκον appellant. Interdu candidum, quod ψευδάργυρον. Hoc argēti speciem exprimit, illud auri. Æs fuluum pręcipuam bonitatem admiratiōemque diu obtinuisse Plinius scribit, candidum factum fuisse in Teuthrania circa Anderam, & in Lydia iuxta Tmolum montem Strabo.

Naturam ars imitata ęs utroque colore tingit. Etenim cadmiam fossilem combibens fit orichalcum. Quondam æs Liuianum, ut autor est Plinius, maxime forbebat cadmiam, & post ipsum Marianum. Hac autem ratione fit.

Parua æris optimi fragmenta & cadmiæ fossilis ustæ & molitæ farinam artifices alterna imponunt in oblongas ollas sex uel octo, quaru singulæ libras plus minus quinquaginta capiunt. Sunt qui ad æs & cadmiam adijciunt uitrum, ut illud facilius liquescat. Sunt qui in cadmiæ fossilis locum cadmiam fornacum substituunt.

Ollas autem sic ære & cadmia repletas in fornaces sub excavata terra concameratas demitut in ferrea bacilla, quę in cuiusque fornace ferme medio sunt: Ignisque accenditur in breuibus quibusdam quasi cuniculis. Cuique uero fornaci parte suprema, quæ modice extat à solo, rotundum foramen est, & faxeum operculum, quo moderantur ignem. Nam modo totum aperiunt, modo ferè totum claudunt, nunc uero aliquam eius partem regunt, prout res hoc postulat.

Itaque cum hæc ad horas octo uel nouem simul in acri igne cocta & liquefacta fuerint, æs, quāquam nondum auri colore videtur tinctum, tamē in orichalcum mutatum multo grauius factum est. Ollas, postquam id ipsum fuerit refrigeratum, ex fornace eximunt, & orichalcum fauilæ modo candicans, & pumi cis instar cauernulis refertum denuo liquatum infundunt in receptaculum, quod est inter duas latas crustas faxeas medium. Hæ enim cru stæ sic committuntur, ut ex orichalco, cui iam auri color & splendor est, laminae crassae uel tenues effici passint. Quas laminas postea incudi impositas & malleo percussas perficiunt. Quae ratio orichalci conficiendi vulgaris est.

At alij tenues æris bracteas circiter digitum latas, inijciunt in catinum, in quo argentum liquari solet, ut fundi possit, eiusque exteriorem partem oblinunt argilla, cum qua mista sit ferri squama, interiorem uero melle mundissimo. Similiter singulas æris bracteolas oblinunt melle, eisque inspergunt puluerem subtilissimum, qui fit ex cadmiæ fossilis, fecis uini ficci, quam tartarum vocant, carbonum tiliae æquis portionibus.

Catinis autem tegitur oper culo fictili. Cui est foramen, in quod immittitus stilus, quo liquefactu ęs cōmouetur. Sed operculum quoque, qua parte cum catino coit, argilla supradicta oblinitur. Catinus autem imponitur in fornacem talem, quali utuntur fabri monetales.

Cu igitur cadmia cōmiscetur cum ære, primo emittitur ruber fumus: deinde partim ruber, partim cæruleus: postremo luteus, qui significat mistionem esse factam. Atque tum catinus ex fornace eximitur. Ex orichalco autem aria siunt opera, sed inprimis pelves, candelabra, lichnuchi, siphones. Ea pluris æstimantur, quàm ærea, quòd cum ęris habeant duriciam, aureo placeant colore.

Notes

1. Our types A, B and C respectively correspond to the types 3, 2 and 1 defined by J Beutmann in his preliminary study. They have been re-ordered in accordance with the logic of our discourse.
2. Agricola spent several years of his early career as a teacher for ancient languages in Zwickau (*c*1517 to 1520), and his later academic interest in mining and smelting technology certainly benefitted from this early years in a town with close and important connections to the mining industry (Slotta and Bartels 1990: 155). However, no direct links between these early years and the later works are apparent in his writings.
3. For a recent discussion of the terms ὀρείχαλκος and ψευδάργυρος as used by Strabo see Rehren 1999c.
4. The original Latin text consistently uses *olla* for crucible in the first part, and *catinus* (here translated as jar) in this second recipe. We do not know whether this reflects a subtle difference in the meaning of the two terms, thus offering additional evidence to the diversity of the two variants, or whether this simply reflects the use of a synonymous term by the informant from whom Agricola took the second text, obviously some time after the publication of the first edition in 1546 and before his death in 1555.
5. But note the opposite argument used elsewhere for Roman brass making vessels (Rehren 1999a), stating that a large surface area relative to the volume, *ie* smaller vessels, is beneficial for the thermal balance of the process. The increase in cementation vessel sizes throughout the middle ages (Rehren and Martinón-Torres, in prep) is understood as a consequence of combined technical developments in refractory materials and furnace design.

References

Agricola G 1558, *De natura fossilium libri X* (2nd rev edn) (Basilea).

Bandy M C and Bandy J 1955 (transl), *Agricola: De natura fossilium* (New York).

Bayley J 1984, 'Roman brass making in Britain', *Historical Metallurgy* 18, 42–43.

Bayley J 1996, 'Innovation in later medieval urban metalworking', *Historical Metallurgy* 30, 67–71.

Bayley J 1998, 'The production of brass in antiquity with particular reference to Roman Britain', in P T Craddock (ed), *2000 years of zinc and brass* (rev edn, 1st edn 1990) (London: British Museum Occasional Paper 50), 7–26.

Bayley J and Barclay K 1990, 'The crucibles, heating trays, parting sherds, and related material', in M Biddle (ed) *Object and Economy in Medieval Winchester* (Oxford: Winchester Studies 7.2i), 175–197.

Bayley J, Freestone I, Jenner A and Vince A G 1991, 'Aspects of Saxon and Norman London: Metallurgy', in A G Vince (ed), *Aspects of Saxon and Norman London 2: Finds and Environmental Evidence* (London and Middlesex Archaeological Society Special Paper 12), 389–405.

Beretta M 1997, 'Humanism and chemistry: the spread of Georgius Agricola's metallurgical writings', *Nuncius. Annali di Storia della Scienza* 12, 17–47.

Beutmann J, Kenzler H and Zeischka A 2000, 'Die Entwicklung der Stadt Zwickau im Mittelalter', *Sächsische Heimatblätter* 46, 293–301.

Caley E R 1967, *Orichalcum and related ancient alloys: Origin, composition and manufacture with special reference to the coinage of the Roman Empire* (rep edn, 1st edn 1964) (New York).

Cameron H K 1974, 'Technical aspects of medieval monumental brasses', *Archaeological Journal* 131, 215–236.

Caple C 1995, 'Factors in the production of medieval and post-medieval brass pins', in D R Hook and D R M Gaimster (eds), *Trade and discovery: The scientific study of artefacts from post-medieval Europe and beyond* (London: British Museum Occasional Paper 109), 221-234.

Craddock P T (ed) 1998, *2000 years of zinc and brass* (rev edn, 1st edn 1990) (London: British Museum Occasional Paper 50).

Craddock P T 1978, 'The composition of the copper alloys used by the Greek, Etruscan and Roman Civilizations, 3: The origins and early use of brass', *Journal of Archaeological Science* 5, 1–16.

Craddock P T 1985, 'Medieval copper alloy production and West African bronze analyses', *Archaeometry* 27, 17–41.

Day J 1998, 'Brass and zinc in Europe from the middle ages until the nineteenth century', in P T Craddock (ed), *2000 years of zinc and brass* (rev edn, 1st edn 1990) (London: British Museum Occasional Paper 50), 133–158.

de Ruette M 1996, 'Brass foundry workshops of the southern Low Countries and the Principality of Liége. A Technical Approach', *Historical Metallurgy* 30, 116–120.

Dungworth D 1996, 'Caley's "zinc decline" reconsidered', *Numismatic Chronicle* 156, 228–234.

Dutrizac J E and O'Reilly J B 1989, 'The origins of zinc and brass', in M L Wayman (ed), *All That Glitters: Readings in Historical Metallurgy* (Montreal), 26–30.

Eckstein K, Craddock P and Freestone I 1996, 'Silber, Blei oder Zink? Frühe Bergbau- und Verhüttungsaktivitäten in Zawar, Dariba und Agucha (Nordwestindien)', *Metalla (Bochum)* 3, 11–26.

Eniosova N 1999, 'Manufacturing techniques of belt and harness fittings of the 10th century AD', *Journal of Archaeological Science* 26, 1093-1100.

Forbes R J 1950, *Metallurgy in antiquity: a notebook for archaeologists and technologists* (Leiden).

Fraustad G (transl) 1958, *Georgius Agricola: De natura fossilium libri X* (Berlin).

Freestone I C 1989, 'Refractory materials and their procurement', in A Hauptmann, E Pernicka, and G A Wagner (eds), *Old World Archaeometallurgy, Proceedings of the International Symposium, Heiderberg 1987* (Bochum), 155–162.

Freestone I C and Tite M S 1986, 'Refractories in the ancient and preindustrial world', in W D Kingery (ed), *High-Technology Ceramics: Past, Present and Future* (Westerville, OH: Ceramics and Civilization 3), 35–63.

Hezarkhani-Zolgharnian Z, Keesmann I, Kronz A and Maier P 1994, 'Zink in alten Schlacken und technischen Produkten', *Berichte der Deutschen Mineralogischen Gesellschaft, Beihefte zum European Journal of Mineralogy* 6, 1, 107.

Hoover H and Hoover L (trans) 1912, *Georgius Agricola: De Re Metallica. Translated from the first Latin edition 1556* (London).

Kilikoglou V, Vekinis G, Maniatis Y and Day P M 1998, 'Mechanical performance of quartz-tempered ceramics. Part 1: strength and toughness', *Archaeometry* 40, 261–79.

Morgan S W K 1985, *Zinc and its alloys and compounds* (New York, Chichester, Brisbane and Toronto).

Mortimer C, Pollard A M and Scull C 1986, 'XRF analyses of some Anglo-Saxon copper alloy finds from Watchfield, Oxfordshire', *Historical Metallurgy* 20, 36–42.

Picon M, Le Nezet-Celestin M and Desbat A 1995, 'Un type particulier de grands récipients en terre réfractaire utilisés pour la fabrication du laiton par cémentation' *Actes du Congrès de Rouen, Société Francaise d'Étude de la Céramique Antique en Gaule*, 207–215.

Pollard A M and Heron C 1996, *Archaeological chemistry*. (Cambridge).

Rehren Th 1995, 'Kupfer vom Tor zur Welt', in S Lux and R Althoff (eds), *Kissipenny und Manilla. Begleitband zur Ausstellung im Kultur- und Stadthistorischen Museum der Stadt Duisburg, 20. Mai bis 13. August 1995* (Duisburg), 59–64.

Rehren Th 1999a, 'Small size, large scale: Roman brass production in Germania Inferior', *Journal of Archaeological Science* 26, 1083-1087.

Rehren Th 1999b, '"The same… but different": A juxtaposition of Roman and medieval brass making in central Europe', in S M M Young, A M Pollard, P Budd and R A Ixer (eds), *Metals in Antiquity* (Oxford: BAR IS 792), 252–257.

Rehren Th 1999c, 'Quellen und Funde zum frühen Zink in Europa', in R Fellmann, Das Zink-Täfelchen vom Thormebodenwald auf der Engehalbinsel bei Bern und seine keltische Inschrift, *Archaeologie im Kanton Bern* 4B, 169–172.

Rehren Th, Lietz E, Hauptmann A and Deutmann K H 1993, 'Schlacken und Tiegel aus dem Adlerturm in Dortmund: Zeugen einer mittelalterlichen Messingproduktion', in H Steuer and U Zimmermann (eds), *Montanarchäologie in Europa* (Sigmaringen), 303–314.

Rex F 1964 *Die Alchemie des Andreas Libavius Ein Lehrbuch der Chemie aus dem Jahre 1597* (Illustrations compiled from the *Commentarii 1* which was attached to the second edition of 1606 are reproduced in the translation following the text with their own pagination as pp 3–74).

Roberts G K 1991 'Science from the Earth in Central Europe', in D Goodman and C A Russell (eds), *The Rise of Scientific Europe* (Sevenoaks Kent), 145–70.

Sillar B and Tite M S 2000, 'The challenge of the "technological choices" for materials science approaches in archaeology', *Archaeometry* 42, 2-20.

Sisco A G and Smith C S (trans) 1951, *Lazarus Ercker's treatise on ores and assaying. Translated from the German edition of 1580* (Chicago).

Slotta R and Bartels Chr (eds) 1990, *Meisterwerke bergbaulicher Kunst vom 13. bis 19. Jahrhundert* (Bochum).

Smith C S and Gnudi M T (trans) 1990, *The Pirotechnia of Vannoccio Biringuccio. The classic sixteenth-century treatise on metals and metallurgy* (rev edn, 1st edn 1942) (New York).

Tite M S, Freestone I C, Meeks N D and Craddock P T 1985, 'The examination of refractory ceramics from metal-production and metalworking sites', in *The archaeologist and the laboratory* (Council for British Archaeology Research Report 58), 50–55.

Tite M S, Kilikoglou V and Vekinis G 2001, 'Strength, toughness and thermal shock resistance of ancient ceramics, and their influence on technological choice', *Archaeometry* 43, 301–324.

Zacharias S 1989, 'Brass making in medieval western Europe', in M L Wayman (ed), *All That Glitters: Readings in Historical Metallurgy* (Montreal), 35–40.

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