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POST-MEDIEVAL CRUCIBLE PRODUCTION AND DISTRIBUTION: A STUDY OF MATERIALS AND MATERIALITIES*

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This paper is concerned with the manufacture and trade of post-medieval crucibles (14th–19th centuries). The analytical study of crucibles from different contexts in Europe and America employed optical microscopy and SEM–EDS, coupled with archaeological and historical data. We identified two major producers of crucibles, both of them in Central Europe, whose products appear widely distributed internationally. The analytical data allow an explanation of the technical reasons behind their superior reputation, as both crucible types shared comparable material properties, such as thermal, chemical and mechanical stability. Conversely, the two crucible types were radically different in their manufacture and appearance. We argue that, besides technical considerations, sensorial aspects such as texture and colour may have played an important role in the perception and choice of materials.

KEYWORDS: CRUCIBLES, GRAPHITE, MULLITE, HESSE, OBERNZELL, POST-MEDIEVAL, SEM–EDS, MATERIALITY, TECHNOLOGICAL CHOICE, PERFORMANCE CHARACTERISTICS, COLOUR

INTRODUCTION

Technical ceramics such as furnaces, crucibles and moulds are an intrinsic requirement for most pyrotechnological processes, and as such their use is attested in past metallurgical workshops, glassworks, mints and al/chemical laboratories. Crucibles are free-standing vessels, used for high-temperature operations. This paper is concerned with the production and consumption of crucibles since the late Middle Ages, when their use is reported in a wide range of contexts in Europe and America. Notwithstanding some valuable studies (e.g., Tite *et al.* 1985; Freestone and Tite 1986; Freestone 1989; Bayley *et al.* 1991; Cotter 1992; Stephan 1995; Rehren 2003), no attempt has hitherto been made at obtaining a broader understanding of the technology and distribution of crucibles across the post-medieval world.

Here, we present the results of a project combining archaeometric, archaeological and historical approaches to crucibles from Europe and America, covering a chronological range from the 14th to the 19th centuries AD (cf., Martinón-Torres 2005; Martinón-Torres and Rehren 2006). This paper centres around two main issues:

- Identification of the main crucible producers, the geographical distribution of their products and the possible reasons for their success in the market.
- Reconstruction of crucible manufacturing processes and their resulting formal and material properties.

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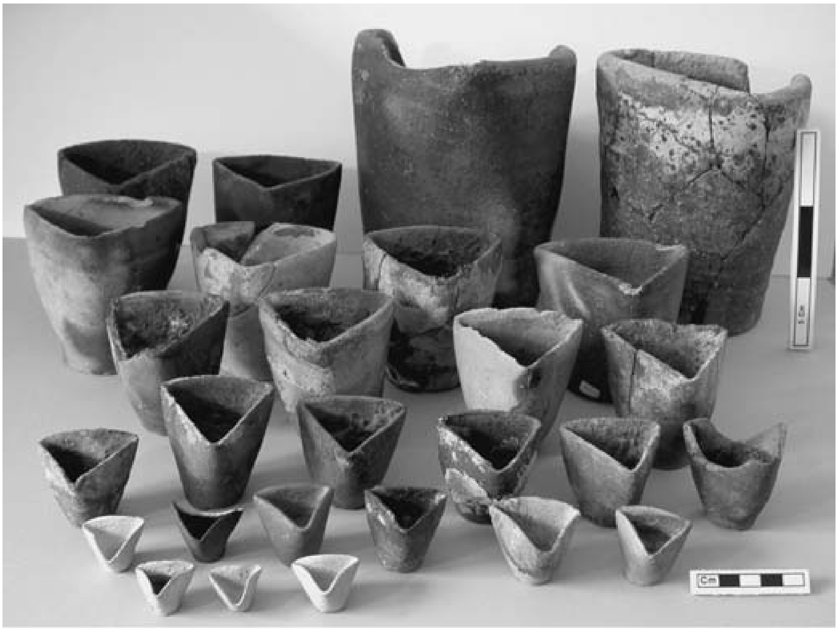

Figure 1 *A selection of triangular crucibles recovered in Oberstockstall (Austria). The scale bars are 5 cm and 15 cm.*

In addition, we briefly address the relationships between crucible production and consumption, with a special focus on the consumers' choice, thus discussing some wider implications of this work for scholars with general interests in past materials and materiality.

BACKGROUND AND SAMPLE SELECTION

The so-called triangular crucible is easily recognizable due to its peculiar shape and its frequent depiction in popular representations of al/chemical laboratories (Principe and De Witt 2002). Its characteristic shape was achieved by pushing inwards the rim of a vessel prior to firing, thus creating three convenient pouring spouts. Their heights range from approximately 2 to 20 cm, and they were often sold stacked in 'nests' of decreasing sizes (Fig. 1). Although some formal variations are noticeable (e.g., in the vessel profile or the height to width ratio), triangular crucibles have been identified at a large number of post-medieval sites (see below). It should be noted, however, that these crucibles coexisted with other crucible forms. Many craftspeople used crucibles, including bronze and brass casters, minters, al/chemists, ore assayers, jewellers and glassworkers. In fact, prior to the 18th century, the boundaries among some of these specialities were very permeable or non-existent, as they largely involved the same tools, techniques and ideas (Martinón-Torres and Rehren 2005a).

We selected a stratified sample of crucibles, including both unused and used, triangular and non-triangular vessels, from a variety of contexts and assumed producers. Geographically, special emphasis was placed on the area of the Holy Roman Empire in the 16th century, as this was the region housing the best-known producers of crucibles and witnessing the most important developments in chemistry and metallurgy. However, samples from as far as Britain, Portugal or America were also studied.

We attempted to cover a large range of utilization contexts, including crucible production sites, remains from al/chemical laboratories, goldsmiths' workshops, ore assaying, bronze and brass metallurgy, and a mint. Additional references will be made to published studies. Details of the sites and materials analysed are summarized in Table 1.

METHODOLOGIES

The typical specimen for analysis was a crucible cross-section mounted in epoxy resin and polished to 1 μm grain size. These specimens were first examined under a Leica DM LM reflected light optical microscope, and subsequently carbon coated for analysis on a scanning electron microscope with an energy-dispersive spectrometer (SEM–EDS).

SEM–EDS employed a Philips XL30 instrument with an INCA Oxford spectrometer package, at a working distance of 10 mm, with an accelerating voltage of 20 kV; a spot size of 4.7 to 5.3 (INCA conventional units) and process time 5, corresponding to a detector deadtime of 25–40%; and an acquisition time of 75 s.

Accuracy and precision were routinely tested via the analysis of pellets of siliceous certified reference materials. Accuracy tests typically showed relative errors below 10% for major element oxides, with the error increasing for elements in minor concentrations, although it usually remained below 20%. Coefficients of variation in precision tests were typically below 5% for major, and up to 15% for minor, element oxides.

The compositions of ceramic matrices reported are averages normalized to 100% by weight (wt%) of 5–10 measurements of relatively homogeneous areas of ~70–100 by 100–150 μm per crucible section. These analyses avoided large mineral inclusions, which were probed separately. The possibility of chemical alteration of these ceramics during burial is generally negligible, primarily due to their low microporosity (resulting from high firing temperatures) and their typically high alumina (which makes them less prone to corrosion). More significant is the contamination of crucible fabrics during use, particularly when alkali fluxes were used, which is partly responsible for the compositional variation shown by the crucibles from Oberstockstall (see Table 3 below).

RESULTS: CRUCIBLES IN THE POST-MEDIEVAL WORLD

The study allowed the identification of two major producers of crucibles, whose products appear distributed across large regions. Smaller productions, possibly local or *ad hoc* manufactures, were also identified. These groups will be addressed in turn, before presenting a broader discussion.

The 'bright' crucibles from Hesse

Introduction The Hessian crucible retains such a historical reputation that the term 'Hessian' is often used for any triangular vessel, even though not all triangular crucibles are from Hesse; nor are all Hessian crucibles triangular. Archaeological evidence proves the production of technical ceramics in the villages of Epterode and Almerode (later merged into 'Großalmerode'), in the German region of Hesse, as early as the 12th century. From the 17th century, legal disputes emerge for the exploitation of specific clay deposits (Stephan 1995).

Most relevant historical sources date to relatively late periods. Particularly famous is the line by Robert Plot, who referred to 'the mystery of the Hessian wares' (Plot 1677, 250). Several

Table 1 *A summary of the main crucible assemblages discussed in the paper, and relevant bibliographical references*

Site	*Dates (centuries AD)*	*Context*	*Type*	*Attribution*	*Reference(s)*
Casa da Moeda (Porto, Portugal)	14th–18th	Mint	Triangular	Hesse	Dordio *et al*. (1997)
La Isabela (Dominican Republic)	Late 15th	First European town in America; ore assaying?	Triangular	Bavaria (Obernzell?)	Deagan and Cruxent (2002)
Trondheim (Norway)	15th	Mint, with crucibles exhibiting star-like stamps typical from Hesse	Triangular	Hesse	Saunders (2001)
Zwickau (Saxony, Germany)	Late 15th	Brass-making and -casting workshop	Triangular, globular and lids	Other	Martinón-Torres and Rehren (2002)
Weyerstraße, Cologne (North Rhine – Westphalia, Germany)	16th	Goldsmith's workshop involving noble metal refining; triangular crucibles present, but analysed sherd uncertain shape	Triangular	Other	Rehren (1996)
Oberstockstall (Austria)	Late 16th	Laboratory in the sacristy of a church, where crucibles were used for testing ores	Triangular	Austria? (graphitic and non-graphitic)	von Osten (1998), Martinón-Torres *et al*. (2003), Martinón-Torres and Rehren (2005b), Martinón-Torres (2005)
Obernzell (Bavaria, Germany)	16th–17th (?)	Crucible production site	Triangular and beaker	Obernzell	Bauer (1983), Martinón-Torres (2005)
Großalmerode (Hesse, Germany)	16th–18th	Crucible production site	Triangular and beaker	Hesse	Stephan (1995), Martinón-Torres (2005), Martinón-Torres *et al*. (2006)

Jamestown (Virginia, USA)	Early 17th	First British colony in North America; crucibles associated with ore assaying and bronze metallurgy	Triangular and beaker	Hesse	Kelso and Straube (2004), Hudgins (2005)
Cripplegate Buildings (London, UK)	Early 17th	Goldsmiths' workshops remains	Triangular and beaker	Hesse and other	Bayley (2003), Martinón-Torres (2005)
Kapfenberg (Austria)	17th–18th	Laboratory concealed under a fortification wall	Triangular	Obernzell and other	Friedl (2006)
Burgsteinfurt (North Rhine – Westphalia, Germany)	17th–18th (?)	Bronze and brass casting workshop	Triangular	Hesse	Martinón-Torres (2005)
Old Ashmolean Laboratory (Oxford, UK)	Late 18th	Chemical laboratory; crucibles used for experiments involving manganese, zinc and lead crystal	Triangular and beaker	Hesse, Obernzell and other	Hull (2003), Martinón-Torres (2005), Maraun (2006)
Morat-Combettes (Fribourg, Switzerland)	Unknown	Intrusive on a Roman site, with an Obernzell stamp	Beaker?	Obernzell	Unpublished
Museum of London (UK)	Unknown	Crucibles found in London (MoL 24859 and MoL A730), with Obernzell stamps	Beaker?	Obernzell	Cotter (1992), Martinón-Torres (2005)
Royal Museum of Canterbury (Kent, UK)	19th	Crucibles recovered in Canterbury (Acc. Nos. 4247 and 6795), with Obernzell stamps	Triangular	Obernzell	Cotter (1992), Martinón-Torres (2005)
Imperial Mint (Rio de Janeiro, Brazil)	18th–19th	Mint; crucibles with Obernzell stamps	Triangular	Obernzell	Lima and da Silva (2003)

failed attempts at replicating the quality of Hessian crucibles are known, notably that by John Dwight (Freestone 1991; Cotter 1992, 265; Freestone *et al*. forthcoming). It is estimated that millions of crucibles were imported from Hesse into Britain in the post-medieval period (Cotter 1992). From the 18th century we have references to the export of Hessian wares to England, Scandinavia, Russia, America, India and China, via the harbours of Bremen, Amsterdam and Danzig (Stephan 1995, 32).

Manufacture and formal properties The analyses of Hessian crucible fabrics reveal a very standardized manufacturing process. All the samples show the use of a very alumina-rich kaolinitic clay, tempered with almost pure quartz sand, wheel-thrown and subsequently fired to very high temperatures.

The peculiar appearance of the crucibles is noteworthy. When unused, they always show a bright orange colour and a sandy, pimply texture. In cross-section, the ceramic matrix typically shows alternating patches of grey and orange colours (Fig. 2). Given that the lighter shades appear to be associated with pores and surfaces, we hypothesize that the scarce free iron oxide in the matrix (≤2% FeO on average) is here in the more oxidized Fe_2O_3 form—which has a characteristic red colour—whereas in the more vitrified and denser matrix areas there was probably less oxygenation and iron would be present as black Fe_3O_4. In any case, most of the Hessian crucibles identified as such had lost this diagnostic appearance during high-temperature use.

The compositions of Hessian ceramic matrices fall within a tight cluster (Table 2), characterized by an exceptionally high alumina concentration (36.9% on average for unused vessels) and relatively low levels of alkali and earth alkali oxides (their sum just around 2%). This clay composition would have conferred upon the crucibles an extraordinary thermal refractoriness.

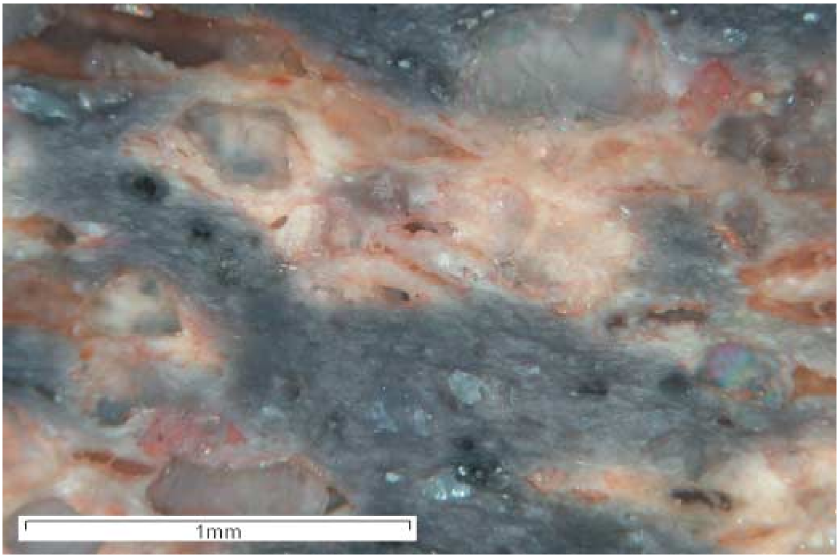

Figure 2 *A cross-section of the fabric of a Hessian crucible found in Cripplegate, London (WFG 18/129/s2), under cross-polarized light (×50), showing the characteristic appearance of unused Hessian crucibles; that is, alternating grey and orange areas. A few spheroidal iron-rich minerals (dark) and molten feldspars are the only notable inclusions in addition to the quartz temper.*

Table 2 *Chemical compositions of ceramic matrices of Hessian crucibles*

	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	FeO	CuO	ZnO
Großalmerode 52205Z	0.1	0.5	37.5	56.5	0.4	1.2	0.3	1.9	1.7	–	–
Std dev.	0.10	0.10	0.46	0.43	0.14	0.16	0.05	0.04	0.09	–	–
Max.	0.2	0.7	38.2	57.1	0.6	1.4	0.4	1.9	1.9	–	–
Min.	0.0	0.4	37.0	55.8	0.2	1.0	0.2	1.8	1.6	–	–
Großalmerode 52207V	0.1	0.5	36.9	56.8	0.2	1.5	0.3	1.9	1.9	–	–
Std dev.	0.09	0.12	0.21	0.24	0.11	0.51	0.08	0.12	0.15	–	–
Max.	0.2	0.6	37.2	57.1	0.4	2.4	0.4	2.1	2.1	–	–
Min.	0.0	0.3	36.7	56.5	0.2	1.2	0.2	1.8	1.7	–	–
Oxford 1413	0.4	0.2	36.4	58.0	0.2	1.9	0.2	1.6	1.2	–	–
Std. dev.	0.09	0.09	0.42	0.42	0.15	0.04	0.06	0.35	0.13	–	–
Max.	0.5	0.3	36.9	58.6	0.3	2.0	0.3	2.1	1.3	–	–
Min.	0.3	0.1	35.8	57.5	0.0	1.9	0.1	1.2	1.0	–	–
Oxford n001	0.2	0.5	36.5	57.1	0.2	1.4	0.2	2.0	2.0	–	–
Std dev.	0.04	0.07	0.47	0.52	0.14	0.08	0.10	0.18	0.11	–	–
Max.	0.2	0.6	37.0	58.0	0.4	1.5	0.4	2.2	2.1	–	–
Min.	0.2	0.5	36.0	56.6	0.1	1.3	0.1	1.7	1.9	–	–
Cripplegate WFG 18/116	0.5	0.5	36.6	57.0	0.3	1.2	0.2	1.8	2.0	–	–
Std dev.	0.15	0.05	0.38	0.50	0.05	0.29	0.08	0.07	0.31	–	–
Max.	0.6	0.5	37.2	57.6	0.4	1.7	0.3	1.9	2.4	–	–
Min.	0.3	0.4	36.3	56.4	0.3	1.0	0.1	1.7	1.7	–	–
Cripplegate WFG 18/129	0.1	0.5	36.9	56.8	0.3	1.2	0.2	1.8	2.2	–	–
Std dev.	0.04	0.08	0.40	0.34	0.12	0.23	0.11	0.07	0.25	–	–
Max.	0.2	0.6	37.4	57.3	0.4	1.5	0.3	1.9	2.6	–	–
Min.	0.1	0.4	36.3	56.3	0.1	0.9	0.0	1.7	1.9	–	–
Jamestown A631/CC2	0.1	0.5	35.6	57.8	0.4	1.2	0.4	2.2	1.7	–	–
Std dev.	0.03	0.03	0.68	0.76	0.03	0.14	0.05	0.11	0.08	–	–
Max.	0.2	0.6	36.0	58.9	0.4	1.4	0.5	2.3	1.8	–	–
Min.	0.1	0.5	34.6	57.2	0.3	1.1	0.4	2.1	1.7	–	–
Jamestown JR 1024/CC3	0.2	0.4	36.8	56.4	0.3	1.5	0.2	1.9	2.3	–	–
Std dev.	0.04	0.14	0.28	0.43	0.08	0.51	0.04	0.06	0.77	–	–
Max.	0.2	0.5	37.0	56.9	0.4	1.9	0.2	1.9	3.2	–	–
Min.	0.1	0.3	36.5	56.1	0.3	0.9	0.2	1.8	1.8	–	–
Jamestown JR 124F/C1	0.2	0.5	36.8	57.1	0.2	1.1	0.4	2.0	1.8	–	–
Std dev.	0.05	0.06	0.18	0.35	0.14	0.08	0.06	0.08	0.19	–	–
Max.	0.2	0.6	37.0	57.5	0.4	1.2	0.4	2.1	1.9	–	–
Min.	0.1	0.5	36.7	56.8	0.1	1.1	0.3	1.9	1.5	–	–
Porto CI/91/3032/60	0.2	0.7	36.6	56.9	0.1	1.4	0.3	1.8	2.0	–	–
Std dev.	0.05	0.15	0.35	0.55	0.08	0.15	0.09	0.20	0.14	–	–
Max.	0.2	0.9	36.8	57.5	0.2	1.6	0.4	2.0	2.2	–	–
Min.	0.1	0.5	36.1	56.2	0.0	1.3	0.2	1.6	1.8	–	–
Burgsteinfurt 01	0.2	0.5	36.7	56.3	0.1	1.4	0.5	2.0	1.9	≤0.1	0.3
Std dev.	0.09	0.10	0.20	0.30	0.13	0.26	0.02	0.06	0.17	0.08	0.22
Max.	0.3	0.6	36.9	56.8	0.3	1.8	0.5	2.1	2.2	0.1	0.7
Min.	0.1	0.4	36.4	56.0	0.0	1.1	0.5	2.0	1.8	0.0	0.2
Burgsteinfurt 02	0.1	0.5	36.3	57.0	0.3	1.7	0.4	2.0	1.6	–	0.3
Std dev.	0.04	0.03	0.47	0.37	0.08	0.17	0.02	0.13	0.14	–	0.3
Max.	0.2	0.5	36.7	57.5	0.4	1.9	0.4	2.1	1.8	–	0.7
Min.	0.1	0.4	35.6	56.6	0.2	1.5	0.4	1.8	1.4	–	0.0
Burgsteinfurt 03	0.2	0.5	37.6	56.0	0.3	1.6	0.4	1.8	1.5	–	0.1
Std dev.	0.11	0.04	0.11	0.33	0.09	0.28	0.08	0.07	0.11	–	0.07
Max.	0.3	0.5	37.7	56.3	0.4	2.1	0.6	1.9	1.7	–	0.3
Min.	0.1	0.4	37.5	55.5	0.2	1.4	0.3	1.8	1.4	–	0.0

The scarcity of mineral inclusions other than the added temper suggests that clays were levigated. Leaving the sand temper aside, the only notable inclusions are concentric ferruginous concretions, together with rare ilmenite, humboldtine, rutile and zircon (Fig. 2). The manufacture with such lean clay would minimize the risk of crucible failure during use due to inclusions of unpredictable thermal or mechanical behaviour. Conversely, the addition of quartz sand was beneficial to the material properties of the vessel.

The temper typically consists of 20–40 vol% of subrounded or spheroidal quartz grains, moderately well sorted in the medium to coarse sand range (diameter 0.25–1.0 mm; Fig. 3). Some partly molten potassium feldspars are also identified in much lower abundance. Non-plastic inclusions in concentrations above 20 vol% can significantly increase the toughness and thermal shock resistance of ceramics (Freestone 1989; Kilikoglou *et al.* 1998; Tite *et al.* 2001). Quartz is particularly suitable for this purpose, given its high melting point (~1700°C) and especially its increase in size accompanying the lattice inversion of α- to β-quartz during the original firing of the crucible. This expansion, followed by contraction as the fabric cools, creates open voids around the quartz grains and elongate cracks parallel to the wall surfaces. Upon subsequent firings, these voids and cracks accommodate further expansions of the quartz grains, thus functioning as dimensional stabilizers for the vessel. Furthermore, this network of microcracks and hard inclusions arrests and dissipates the propagation of fractures created by thermal or mechanical shock, requiring more energy for them to catastrophically expand through the ceramic bodies. As a result, a Hessian crucible would be less prone to breaking

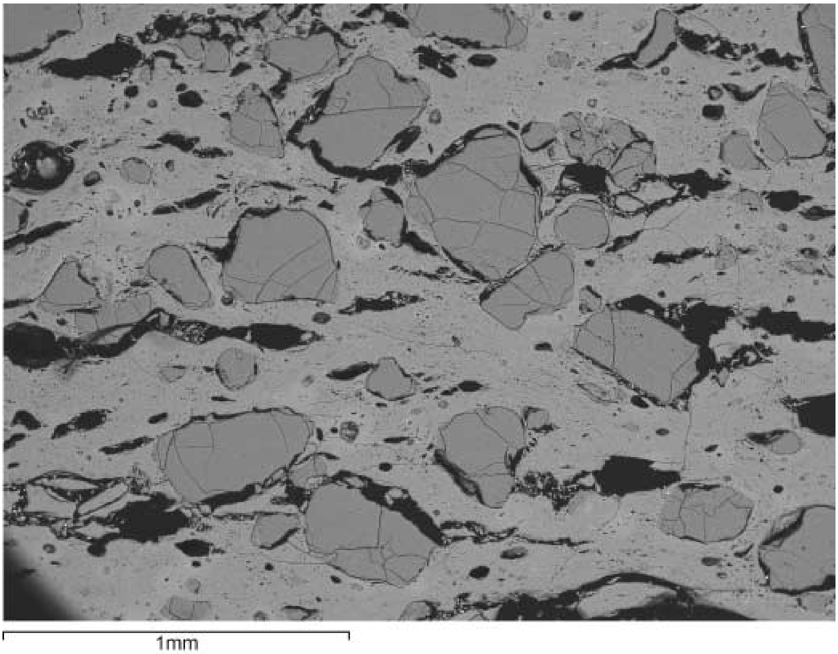

Figure 3 *An SEM backscattered electron image of the fabric of an unused Hessian crucible found in Großalmerode (52207v/s1), Hesse. Note the presence of quartz grains (dark grey) shattered due to thermal stress and surrounded by shrinkage voids, as well as the elongated cracks (black). Some of the open pores may be due to quartz grains being plucked out during sample polishing, but most of the porosity is original.*

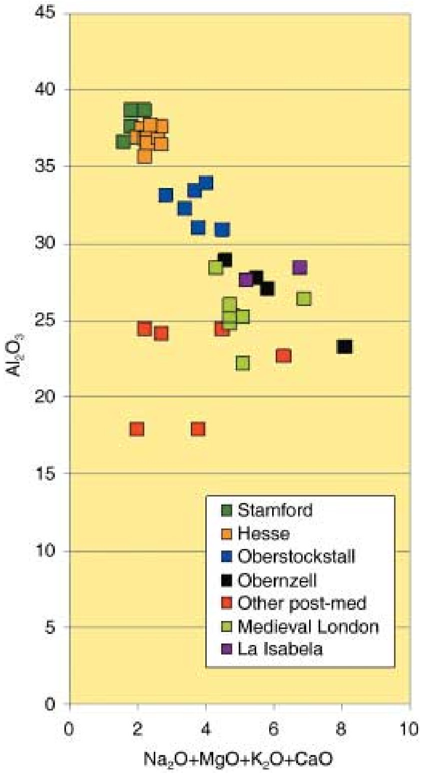

Figure 4 *A comparative graph of the thermal refractoriness of the ceramic matrices of different medieval and post-medieval crucibles, based on their chemical compositions. Heat resistance increases with higher alumina concentrations (y-axis) and decreases with higher levels of alkali and earth alkali oxides (x-axis). Note that medieval crucibles from Stamford, UK, plot very close to the Hessian ones. For the Obernzell, La Isabela and Oberstockstall crucibles, thermal refractoriness would be further increased by the presence of graphite inclusions in the fabric, not reflected in these chemical compositions. Data are from Tables 2–4, except for the Stamford and London medieval crucibles (data from Freestone and Tite 1986).*

when removed from a hot furnace—or if inserted from the cool environment—or when struck while stirring or by accidental mishandling.

Despite the expedient material properties mentioned, the use of sand-tempered kaolinitic clays alone is not sufficient to explain the technical supremacy of the Hessian wares. Indeed, medieval crucible-makers in the English town of Stamford used some clays with very similar compositions to those from Hesse (Freestone and Tite 1986; Bayley *et al*. 1991), but the English industry never achieved the success of its famous German counterpart (Kilmurry 1980) (Fig. 4). We believe that a key stage in the manufacture of Hessian crucibles was a high-temperature prefiring in the potter's kiln. Despite their high refractoriness, Hessian crucibles are the only ones showing continuous vitrification of the ceramic matrix in unused specimens. Furthermore, quartz grains have started buckling and fusing with the surrounding ceramic, and subsequently shattered upon cooling (Figs 2 and 3), which suggests firing temperatures above 1200°C (Ohya *et al*. 1999). XRD spectra obtained for a typical Hessian crucible show the presence of cristobalite and mullite, most likely crystallized from the decomposition of kaolinite at high temperatures (Martinón-Torres *et al.* 2006). SEM examination of HF-etched sections shows the ceramic matrices now to be composed largely of interlocking cuboid, primary mullite crystals, with some networks of highly acicular, secondary mullite in alkali-rich areas caused by molten feldspars. These observations indicate a sustained firing temperature range between 1300 and 1400°C (Lee *et al.* 1999; Iqbal and Lee 2000; Lee and Iqbal 2001; Chen and Tuan 2002)—in agreement with a recent, independent estimate by Freestone *et al.* (forthcoming). Such high temperatures were unusual for the firing of ordinary pottery in post-medieval Europe, even for German stoneware, although a link between both technologies remains plausible.

A long, high-temperature manufacturing firing meant that the crucibles would have undergone a thermal stability test before reaching the user. More importantly, this firing led to the formation of synthetic mullite, which we understand as a crucial secret behind the excellent material properties of the ceramic (Martinón-Torres *et al.* 2006). Mullite ($Al_6Si_2O_{13}$) is deliberately developed in a wide range of modern ceramics, including building materials, refractories, optical materials, and ceramic matrix composites such as thermal protection systems for aircraft engines. Some relevant properties of mullite are low thermal expansion—and the associated excellent thermal shock resistance—high creep resistance, high temperature strength and an outstanding stability in aggressive chemical environments (Aksay *et al.* 1991; Schneider and Komarneni 2005).

Distribution Hessian crucibles were identified in a range of contexts, besides the production area of Großalmerode (Fig. 5, Table 1). Still within Germany, the bronze and brass casting crucibles recovered in an urban excavation in Burgsteinfurt (North Rhine – Westphalia), tentatively dated to the 17th or 18th centuries, were proved to be of Hessian origin. Also, several assemblages from Britain contain Hessian wares: on the one hand, crucibles related to goldsmithing and copper-alloy melting activities found in Cripplegate (London), from a deposit filled in the early 17th century; and, on the other hand, some of the crucibles used in the late 18th century Old Ashmolean Laboratory (Oxford), where chemistry was first taught experimentally.

Crucibles manufactured in Hesse were documented further afield. The only crucible sample hitherto analysed from the large assemblage recovered at the Porto Mint (Portugal) was also a Hessian vessel. Unfortunately, this was an unstratified find; therefore the presence of Hessian crucibles in Portugal cannot be dated precisely within the long lifespan of this mint (14th–18th centuries). Hessian crucibles were also used in early 17th century Jamestown (Virginia, USA), the first British colony in America, for ore assays and bronze casting.

On the basis of their fabric appearance and makers' stamps, some archaeological crucibles may be tentatively ascribed to Hesse. As far as we are aware, the earliest examples of Hessian crucibles known outside Central Europe were those excavated at the Trondheim Mint (Norway), dated to 1500–37. Besides their appearance and texture (Saunders 2001, 27–8 and 85), the three star-like stamps found on the base of one of them are identical to the two on a crucible found in Großalmerode (Stephan 1995, 47). This finding establishes the presence of Hessian crucibles in Scandinavia over 200 years before the first written record of this trade.

Other examples of Hessian crucibles have been published by Cotter (1992), who reports two nearly identical nests found in Colchester and Norfolk (UK). In both cases, the biggest vessel is stamped in the base with the letters 'CG' inside an oval cartouche (Cotter 1992, 267–9)—a stamp bearing a close resemblance to one known from Hessian examples (Stephan 1995, 36, fig. 24).

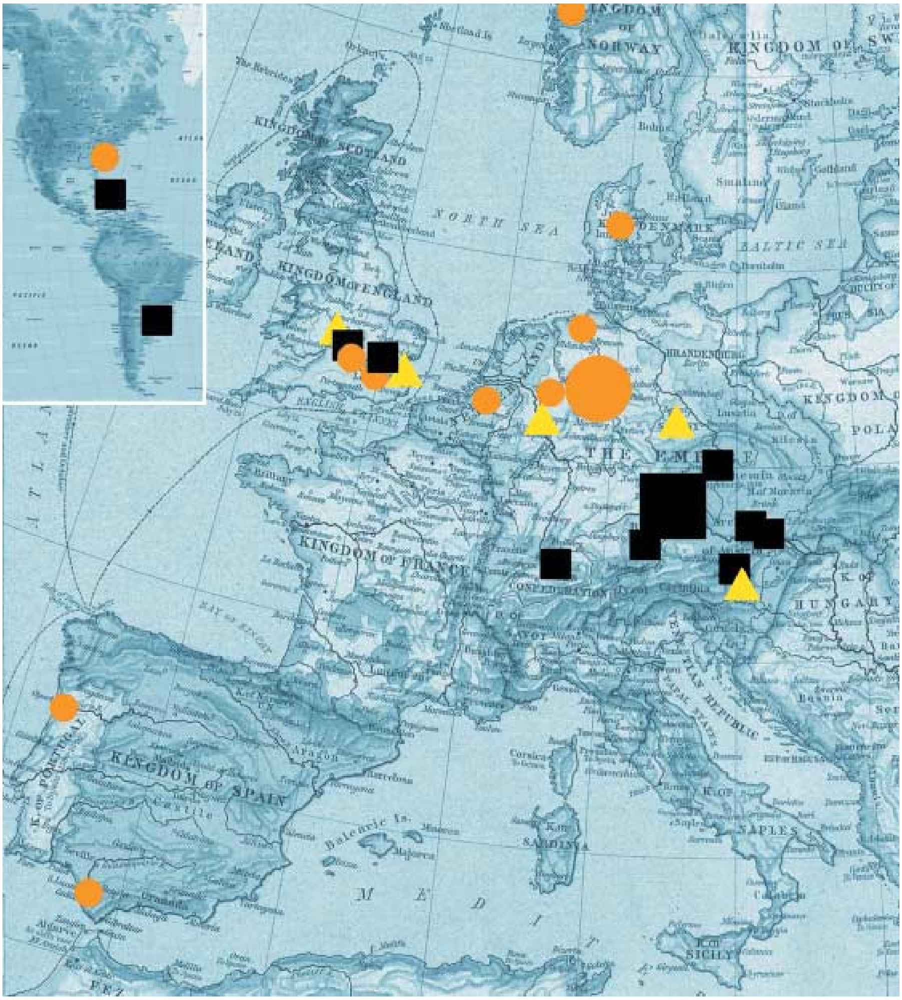

Figure 5 *A distribution map of post-medieval crucibles, based on archaeological and contrasted written sources. Circles represent bright Hessian crucibles, squares represent dark, normally graphitic, crucibles and triangles represent other productions. Larger icons indicate the main production centres.*

Another crucible published by Cotter was found in London and dated *ante quem* to 1647 (Museum of London No. BRO 90 [205] (353); cf., Cotter 1992, 259). He tentatively read the stamp as a circumference containing the letters ‘PIV’ and ‘GHK’ (the last two letters as a ligature). Most likely, the actual reading of the stamp is ‘PTV GER’, making it identical to those in contemporary crucibles found in Hesse (Stephan 1995, 26–37, figs 24 and 25) and Jamestown (see above).

The inventory of possible Hessian crucibles concludes with a group of 10 unused vessels found at the mouth of the Guadalquivir river in southern Spain (Amores Carredano and Lloret Marín 1995). The description of the crucibles, the illustrations and the context of the finds, in combination support a Hessian origin. These crucibles may have been swept ashore from a ship wrecked at this difficult point on the Atlantic route to Seville. Amores Carredano and

Lloret Marín (1995, 266) note that Seville held a commercial monopoly for trade with the Indies between the 16th and the 18th centuries, and thus even German goods would have had to stop over in Seville prior to shipping to the Americas. Nevertheless, it is worth noting that archaeological excavations at La Isabela (Dominican Republic), the first Spanish colony in America, have not uncovered bright Hessian crucibles, but black, probably Bavarian, ones (see below).

The 'dark' crucibles from Bavaria and surrounding regions

Introduction A somewhat surprising discovery of this study was the existence of another region where high-quality crucibles were produced in large quantities. With some notable exceptions (see below), these crucible manufacturers were startlingly overlooked in Renaissance treatises, just as in present-day studies.

Local historical documents from southern Germany and western Austria document the keen interest of medieval potters in the exploitation and use of graphitic clays, as also demonstrated by archaeological materials (Schultheiß 1956; Bauer 1976; Holl 1976; Pittioni 1976, 1977; Steininger 1980; Endres 1982; Bauer 1983; Kainz and Ratsuny 2000; Hammel 2002). A small village played a central role: Obernzell, in the archdiocese of Passau, located on the right bank of the River Danube in Upper Bavaria (southeastern Germany), and lying in the heart of the largest graphite deposits in Europe.

A variety of wares manufactured in Obernzell were traded widely along the Danube. In 1509, trade regulations in nearby Regensburg banned the commerce of any non-local pottery, with the only exception being the black ceramics from Obernzell (Bauer 1983, 29). This indicates that Obernzell wares were established and recognized as special. It is not clear when the large-scale production of crucibles started. Written documents prove that Obernzeller crucibles were used at the Linz Mint (Austria) in 1549 (Marktarchiv Obernzell, transcr. R. Hammel 2002). By the early 17th century, we see them delivered to the Royal Mints in Vienna, Munich and Prague (Bauer 1983, 30). The crucible industry appears as a prosperous trade, with increasing numbers of apprentices in the many workshops scattered across the region.

Even though Obernzell potters had the legal prerogative to exploit the local graphitic clays (Bauer 1983, 29), smaller occurrences were probably exploited elsewhere, and there is evidence of clays being both exported from, and imported into, Obernzell (Kainz and Ratsuny 2000; Hammel 2002). This creates a rather confusing picture for provenancing studies. Crucibles were produced primarily in Obernzell, but also in other villages scattered within Bohemia, Bavaria and Upper Austria. For example, a 1548 document mentions crucible makers in Heroldsberg, Nüremberg (Schultheiß 1956, 27–8). Black crucibles were also produced in Ips, another town by the Danube, closer to Vienna. These have become historically more famous than those from Obernzell, despite the remarkable fact that, at least in the 18th century, Ipsian crucible-makers had to import clay from Passau and Bavaria (Gaspari 1797, 591). In addition, 'Vienna crucibles' are known to several 16th century writers (Sisco and Smith 1949, 110; Smith and Gnudi 1990, 72), although these may have been simply traded from there. Overall, a number of crucible-makers seem to have operated in the region, but all of their products share one attribute: their black colour (Bauer 1976, 14–15; Stephan 1995, 31).

Manufacture and material properties Obernzell produced both beaker-shaped and triangular crucibles. These are consistently wheel-thrown and exhibit very smooth surfaces, which were sooted dark grey or black in a smoky kiln. Again, a high variability is noticed in used samples, ranging in colour from brown through purple to orange. New crucibles were fired to relatively high temperatures, in the range 950–1050°C, as evidenced by the initial to intermediate degree of vitrification, together with the unaltered state of potassium feldspar inclusions in unused vessels.

The ceramic matrices are rich in alumina (28.3% on average for unused vessels), although they also show moderately high iron oxide levels (≥7%) (Table 3). Thus, the chemical data do not indicate such a high refractoriness as noted for the Hessian wares (Fig. 4). Resistance to heat, however, would also be heightened by the typical abundance of graphite flakes within the paste.

Most dark crucibles analysed contain graphite speckles, in volume concentrations ranging from 20 to 70%, but usually above 40%. These sometimes appear intergrown with silicates (Fig. 6). The presence of graphite enhanced most of the material properties of the crucibles. Being extremely stable at high temperatures, graphite would have contributed to the vessels' thermal refractoriness. Furthermore, due to its chemical inertness, these crucibles would be more resistant to chemical attack by the potentially corrosive charge and the forming slag. If graphite did react—as seen in some of the used vessels—it would also behave favourably, in this case to inhibit oxidation or favour reduction, since graphite is pure carbon. Although the mechanical behaviour of graphite as ceramic temper remains uninvestigated, we may assume that its platy shape and flaky fracture, together with the toughness of graphite speckles along the long axis, could make it ideal for preventing the propagation of potentially fatal cracks across the body of the fabric, as is the case with mica (Tite *et al*. 2001), which has a very

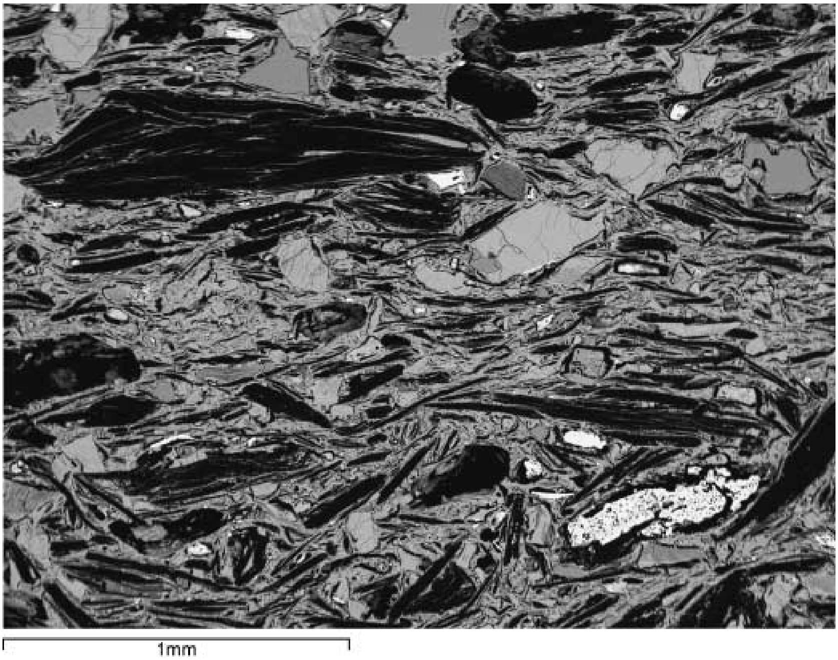

Figure 6 *An SEM backscattered electron image of the fabric of a stamped Obernzell crucible found in Oxford (1422/s1), UK. Note the abundance of relatively large graphite flakes (black), together with potassium feldspars (mid-grey) and other mineral inclusions (bright).*

Table 3 *Chemical compositions of ceramic matrices of dark crucibles from Bavaria and surrounding regions. All of them are graphitic, except for Oberstockstall 394 and 560*

	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_2	Cl	K_2O	CaO	TiO_2	FeO	ZnO	Sb_2O_3	PbO
Obernzell 01	1.1	1.0	27.7	58.3	0.4	–	–	2.5	0.9	1.2	6.9	–	–	–
Std dev.	0.32	0.75	0.51	2.10	0.17	–	–	0.46	0.29	0.32	1.28	–	–	–
Max.	1.5	2.2	28.4	61.3	0.5	–	–	3.1	1.4	1.6	8.2	–	–	–
Min.	0.8	0.3	27.1	55.6	0.1	–	–	2.1	0.7	0.8	4.9	–	–	–
Oxford 1422	0.3	0.8	28.9	55.5	0.2	–	–	2.6	0.9	1.4	9.3	–	–	–
Std dev.	0.13	0.24	1.11	1.04	0.11	–	–	0.41	0.13	0.16	0.60	–	–	–
Max.	0.5	1.1	29.9	57.1	0.4	–	–	3.1	1.0	1.6	9.9	–	–	–
Min.	0.1	0.4	26.8	54.1	0.1	–	–	2.0	0.7	1.2	8.2	–	–	–
Kapfenberg 163	0.8	1.2	23.2	59.0	0.5	0.5	–	4.6	1.5	1.5	7.3	–	–	–
Std dev.	0.20	0.44	1.03	2.45	0.21	0.33	–	0.27	0.13	0.29	1.50	–	–	–
Max.	1.1	1.8	24.6	61.4	0.7	0.8	–	4.9	1.7	1.7	9.5	–	–	–
Min.	0.6	0.8	22.2	56.0	0.2	0.2	–	4.3	1.4	1.1	6.3	–	–	–
Morat-Combettes B217/508/15	0.3	0.7	27.1	57.0	0.7	0.3	–	3.8	0.9	1.7	7.5	–	–	–
Std dev.	0.08	0.06	1.08	1.23	0.03	0.13	–	0.24	0.41	0.29	1.18	–	–	–
Max.	0.4	0.8	28.4	58.3	0.7	0.4	–	4.2	1.6	2.1	9.4	–	–	–
Min.	0.2	0.7	26.0	55.4	0.6	0.1	–	3.5	0.7	1.3	6.1	–	–	–
La Isabela FS 5751 19	1.0	0.8	27.6	60.4	0.4	–	0.1	2.4	1.0	1.2	5.2	–	–	–
Std dev.	0.28	0.26	0.78	1.07	0.21	–	0.02	0.17	0.24	0.30	1.07	–	–	–
Max.	1.3	1.3	28.5	61.8	0.5	–	0.1	2.6	1.3	1.4	6.9	–	–	–
Min.	0.8	0.6	26.6	59.3	0.0	–	0.1	2.1	0.7	0.7	4.3	–	–	–
La Isabela 6231 24	1.2	1.0	28.4	56.4	0.5	–	0.1	2.8	1.8	1.1	7.0	–	–	–
Std dev.	0.36	0.16	0.87	0.56	0.15	–	0.06	0.24	0.24	0.24	0.91	–	–	–
Max.	1.9	1.2	29.2	57.1	0.3	–	0.2	3.1	2.0	1.4	8.5	–	–	–
Min.	1.0	0.7	27.2	55.9	0.0	–	0.1	2.5	1.4	0.8	6.1	–	–	–
Oberstockstall 286	0.5	1.1	28.5	55.6	0.2	3.0	–	2.3	3.0	1.4	4.5	–	–	–
Std dev.	0.32	0.61	1.73	1.97	0.14	1.81	–	0.55	1.07	0.33	0.54	–	–	–
Max.	1.2	2.5	30.7	58.3	0.4	6.0	–	3.2	4.7	2.0	5.5	–	–	–
Min.	0.2	0.8	25.7	53.7	0.0	0.8	–	1.6	1.6	1.0	3.8	–	–	–
Oberstockstall 288	0.1	0.6	33.1	58.7	0.4	–	–	1.5	0.6	1.1	3.9	–	–	–
Std dev.	0.07	0.09	0.34	0.34	0.12	–	–	0.14	0.08	0.06	0.38	–	–	–
Max.	0.2	0.7	33.6	59.2	0.5	–	–	1.6	0.7	1.2	4.3	–	–	–
Min.	0.0	0.5	32.9	58.5	0.3	–	–	1.3	0.5	1.1	3.6	–	–	–
Oberstockstall 290	0.2	0.7	32.2	57.5	0.2	–	–	1.9	0.6	1.2	5.3	–	–	–
Std dev.	0.06	0.21	0.92	0.77	0.11	–	–	0.29	0.16	0.09	0.34	–	–	–
Max.	0.2	1.0	33.5	58.3	0.3	–	–	2.2	0.9	1.3	5.8	–	–	–
Min.	0.1	0.5	31.2	56.3	0.1	–	–	1.5	0.5	1.1	5.0	–	–	–
Oberstockstall 307	2.5	0.8	31.2	55.0	0.2	–	0.7	5.5	0.6	1.2	2.4	–	–	–
Std dev.	0.54	0.13	0.40	1.09	0.03	–	0.03	0.34	0.18	0.18	0.14	–	–	–
Max.	3.3	0.9	31.8	56.0	0.2	–	0.7	5.9	0.9	1.3	2.6	–	–	–
Min.	2.1	0.6	30.8	54.0	0.2	–	0.6	5.1	0.4	1.0	2.2	–	–	–
Oberstockstall 345	0.4	0.5	30.4	57.4	0.3	3.3	–	2.1	0.6	1.3	3.6	–	–	–
Std dev.	0.06	0.13	1.62	2.63	0.19	1.35	–	0.08	0.07	0.15	0.84	–	–	–
Max.	0.4	0.7	31.5	59.4	0.4	4.8	–	2.2	0.7	1.4	4.5	–	–	–
Min.	0.3	0.4	28.5	54.4	0.1	2.2	–	2.0	0.5	1.1	2.8	–	–	–
Oberstockstall 394	0.1	0.8	30.9	58.5	0.2	–	–	2.3	0.6	1.3	5.3	–	–	–
Std dev.	0.14	0.14	1.08	1.75	0.28	–	–	0.27	0.15	0.40	0.56	–	–	–
Max.	0.3	1.0	32.3	61.1	0.6	–	–	2.7	0.8	1.8	6.0	–	–	–
Min.	0.0	0.5	29.1	55.8	0.0	–	–	1.9	0.4	0.7	4.2	–	–	–

Table 3 *(Continued)*

	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_2	Cl	K_2O	CaO	TiO_2	FeO	ZnO	Sb_2O_3	PbO
Oberstockstall 395	0.3	0.7	33.4	56.2	0.3	–	0.2	2.1	0.6	1.3	5.1	–	–	–
Std dev.	0.12	0.30	1.23	0.94	0.17	–	0.13	0.23	0.22	0.22	0.46	–	–	–
Max.	0.5	1.2	35.2	57.4	0.4	–	0.3	2.4	0.8	1.7	6.0	–	–	–
Min.	0.1	0.4	32.3	55.2	0.0	–	0.0	1.9	0.3	1.1	4.7	–	–	–
Oberstockstall 466	0.5	0.5	32.0	56.3	0.2	0.2	0.1	2.5	0.7	1.4	5.6	–	–	–
Std dev.	0.06	0.10	1.08	0.68	0.09	0.09	0.07	0.31	0.23	0.31	0.59	–	–	–
Max.	0.6	0.6	33.5	57.0	0.3	0.3	0.2	3.0	1.0	1.9	6.7	–	–	–
Min.	0.4	0.4	30.5	55.1	0.1	0.1	0.0	2.1	0.5	1.0	4.9	–	–	–
Oberstockstall 494	2.5	1.2	29.3	55.4	0.3	–	1.2	7.2	0.6	1.2	1.3	–	–	–
Std dev.	0.11	0.30	3.56	3.95	0.13	–	0.65	0.29	0.05	0.15	0.18	–	–	–
Max.	2.6	1.5	32.5	59.6	0.5	–	1.9	7.4	0.6	1.3	1.4	–	–	–
Min.	2.4	0.9	25.4	51.8	0.2	–	0.6	6.9	0.6	1.0	1.1	–	–	–
Oberstockstall 495	0.2	0.4	32.7	53.9	0.4	–	–	1.8	0.6	1.4	7.9	–	–	0.7
Std dev.	0.07	0.16	2.04	2.49	0.19	–	–	0.18	0.05	0.29	3.45	–	–	0.42
Max.	0.3	0.6	34.6	56.2	0.6	–	–	1.9	0.7	1.7	11.9	–	–	1.2
Min.	0.2	0.3	30.5	51.3	0.2	–	–	1.6	0.6	1.1	5.8	–	–	0.3
Oberstockstall 515	0.5	0.7	34.0	57.3	0.5	0.2	0.2	2.5	0.5	1.4	2.5	–	–	–
Std dev.	0.07	0.09	1.92	1.56	0.15	0.17	0.06	0.08	0.14	0.16	0.95	–	–	–
Max.	0.6	0.8	36.5	59.2	0.7	0.2	0.3	2.6	0.6	1.5	3.9	–	–	–
Min.	0.4	0.5	32.4	55.4	0.4	0.0	0.2	2.5	0.4	1.1	1.7	–	–	–
Oberstockstall 519F	0.3	0.7	33.9	56.2	0.4	–	–	2.0	1.0	1.1	4.5	–	–	–
Std dev.	0.11	0.41	1.39	1.60	0.06	–	–	0.37	0.27	0.26	0.32	–	–	–
Max.	0.4	1.5	34.8	59.4	0.5	–	–	2.7	1.4	1.4	5.1	–	–	–
Min.	0.1	0.4	31.1	55.0	0.3	–	–	1.6	0.7	0.7	4.1	–	–	–
Oberstockstall 520	1.9	0.7	32.8	54.7	0.4	–	0.8	2.8	0.4	1.3	4.0	–	–	–
Std dev.	0.71	0.11	0.87	0.51	0.16	–	0.30	0.35	0.10	0.42	0.86	–	–	–
Max.	2.6	0.9	33.7	55.1	0.5	–	1.3	3.1	0.5	1.9	5.2	–	–	–
Min	1.0	0.6	32.0	54.0	0.2	–	0.6	2.3	0.2	1.0	3.2	–	–	–
Oberstockstall 560	0.2	0.7	30.8	56.9	0.2	–	–	2.8	0.8	1.6	6.1	–	–	–
Std dev.	0.14	0.14	1.07	1.78	0.33	–	–	0.64	0.20	0.30	0.63	–	–	–
Max.	0.4	0.8	32.2	58.8	0.5	–	–	3.6	1.0	2.1	7.2	–	–	–
Min.	0.0	0.5	29.2	54.0	0.0	–	–	1.8	0.6	1.2	5.5	–	–	–
Oberstockstall 569	0.3	0.5	34.4	56.0	0.3	0.6	≤0.1	1.5	1.6	1.5	3.3	–	–	–
Std dev.	0.04	0.06	0.35	0.67	0.10	0.17	0.02	0.19	0.27	0.13	0.12	–	–	–
Max.	0.3	0.6	34.9	56.7	0.4	0.9	0.1	1.8	2.0	1.6	3.4	–	–	–
Min.	0.2	0.5	33.9	54.9	0.2	0.5	0.0	1.4	1.3	1.3	3.2	–	–	–
Oberstockstall n001	0.4	0.8	30.1	55.1	0.2	–	–	2.5	1.2	1.5	7.1	0.2	1.0	–
Std dev.	0.08	0.20	1.26	1.73	0.17	–	–	0.43	0.36	0.23	1.18	0.28	0.15	–
Max.	0.5	1.0	31.9	57.1	0.3	–	–	3.1	1.7	1.9	8.2	0.5	1.2	–
Min.	0.3	0.5	28.5	53.4	0.0	–	–	2.1	0.9	1.3	5.2	0.0	0.9	–

similar crystallographic structure. This would increase both toughness and thermal shock resistance. The critical expansion and contraction with changing temperatures would also be significantly lower in graphitic fabrics (Duma and Ravasz 1976). Furthermore, given the flexibility of graphite flakes, these inclusions may have enhanced the tensile strength of the vessels (i.e., the resistance to fracture due to sustained pressure), which tends to be the main weakness of ceramics heavily tempered with aplastics (Kilikoglou *et al*. 1998; Tite *et al*. 2001). Finally, as an excellent heat conductor, graphite would improve the thermal conductivity of the vessel, hence allowing steeper heating rates and savings on time and fuel. The down side would be the quicker cooling rate of the crucibles, if the content had to be poured. Only repeated firings in oxidizing conditions would progressively lead to the burning away of graphite and the subsequent weakening of the vessels—a phenomenon observed in some of the used crucibles.

In addition to graphite, Obernzell crucibles contain 10–15 vol% of other mineral inclusions, sub-angular and up to 1 mm in size (Fig. 6). These are mostly quartz grains and potassium feldspars, and a few plagioclase, iron oxides, apatite, amphibole, mica, rutile and zircon particles. Some of these inclusions have melted during high-temperature use, thus locally fluxing some parts of the ceramic body. However, this rarely reaches catastrophic levels and, indeed, upon fusing some of those grains may have added consistency to the ceramic paste.

Distribution Further research is needed to characterize this crucible production region, given the likely existence of several guilds in different localities and periods, probably competing with each other. Still, Bavarian crucibles have been identified in sites across Europe and beyond (Fig. 5, Table 1), by comparison with Obernzell reference samples and, in some cases, through their stamps. The best-known maker's stamp from this producer shows variations of a number '4' crossed by a second horizontal dash, with two initials on either sides of the vertical stem, and often framed by a niche-shaped cartouche (Fig. 7). However, this stamp was probably not in use until the 17th century, and crucibles without stamps have been recovered in the village.

In Europe, we have at least two examples of Obernzell crucibles in the recently discovered site of Kapfenberg (Austria), a laboratory concealed within a 17th–18th century fortification wall. An Obernzell vessel was identified in the 18th century assemblage from the Old Ashmolean laboratory in Oxford (UK). In both of these sites, Bavarian crucibles appear mixed with non-Bavarian ones. We have also analysed a clearly intrusive find from the Roman site of Morat-Combettes in Fribourg, Switzerland, which is also incontestably Bavarian. Based on the stamp, we also identified crucibles of this type in London (crucibles 24859 and A730 in the Museum of London) and Kent (UK) (Cotter 1992), as well as in Austria (Pittioni 1977). Finally, the stamps exhibited by a large number of crucibles found in the Rio de Janeiro Mint (Brazil), and dated to the late 18th or early 19th century, are also indicative of the Obernzell manufacturer.

A remarkable instance of dark crucibles is that of La Isabela (Dominican Republic), the first European town in America, a short-lived settlement founded by Christopher Columbus' second expedition in 1494. The fact that Bavarian crucibles were taken to the colony demonstrates the reputation and long distance trade of these vessels already at an early date, despite the near absence of relevant written evidence, and the fact that no other Bavarian pottery was exported during this period (Gaimster 1997). While the fabrics and compositions of these crucibles are rather similar to those produced in Obernzell, there are some slight differences. Notably, the abundant graphite flakes often appear intergrown with plagioclase feldspars and, less frequently,

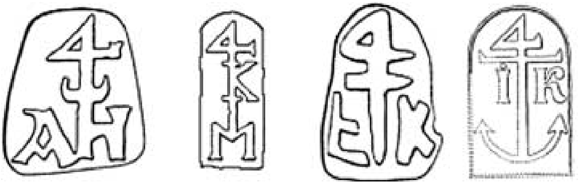

Figure 7 *Stamps imprinted on the bases of graphitic crucibles (drawings after Cotter 1992), which can be attributed to Obernzell makers (Bauer 1983).*

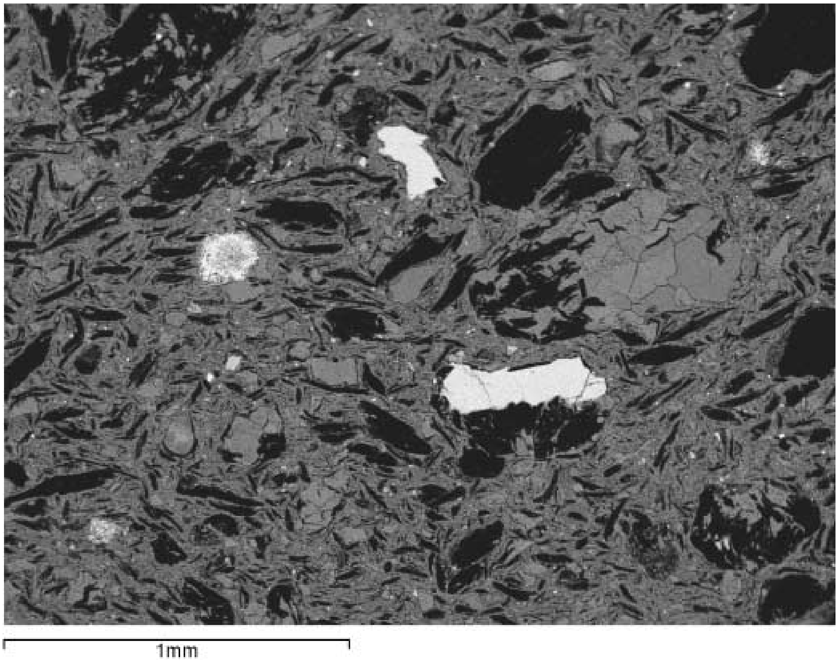

Figure 8 *An SEM backscattered electron image of the fabric of a graphitic crucible found in La Isabela (FS 5751 19). Note the abundance of graphite flakes (black), often intergrown with sodium feldspars (mid-grey) or iron minerals (bright). Compare with Figure 6, where graphite flakes appear longer and the mineral inclusions are different.*

with rutile, quartz and iron oxides and sulphides, forming relatively large (diameter ≤ 2 mm) rock inclusions (Fig. 8). These minerals appear also as discrete inclusions within the ceramic. In contrast, potassium feldspars are much rarer than in the dark crucibles characterized above. This suggests a different source of graphitic clay within the Bavarian region, which might be simply a reflection of the earlier date or of a different producer.

The case of Oberstockstall Paradoxically, the largest assemblage of dark triangular crucibles ever found cannot be easily ascribed to the Obernzell producer. In the late 16th century laboratory of Oberstockstall (Austria), about 300 crucibles were recovered, and those unused still exhibit smooth, dark grey or black surfaces (Fig. 1). However, some features set them apart.

The large majority of these crucibles contain graphite inclusions, but these appear generally smaller in size, and in lower concentrations, than in those vessels unquestionably made in Obernzell. Their matrix chemical compositions are also slightly different, notably in the higher alumina and lower iron oxide levels (Table 3). Furthermore, most of the crucibles with heights above 6.5 cm have one or two letters ‘T’ stamped on their base, depending on their size. Similar stamps appear in contemporaneous pottery of the region along the Danube from Bavaria to Hungary, with a special concentration around Vienna (Holl 1976), and it has been suggested that the T might stand for Tulln, a nearby village of pottery producers (Wiesinger 1937; Holl 1976; Pittioni 1976).

The assemblage from Oberstockstall adds even more complexity. A few crucibles (Table 3, specimens 394 and 560) do not contain graphite but had, however, been deliberately blackened

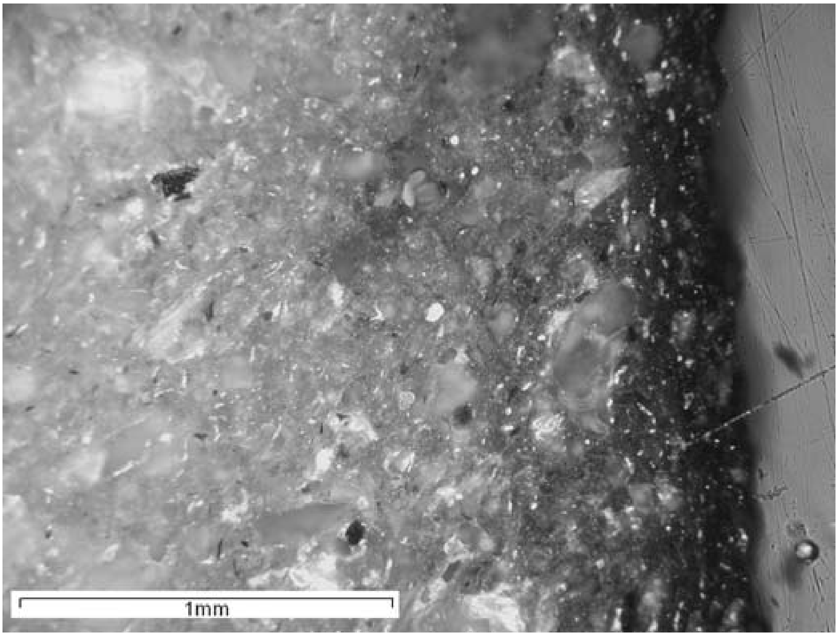

Figure 9 *A cross-polarized light micrograph of a black crucible from Oberstockstall (OB394, ×50). Note that the surface (right) has been blackened, in spite of the absence of graphite inclusions.*

in a smoky potter's kiln (Fig. 9). Although their matrix chemical composition, and the nature of their mineral inclusions, are very similar to those of the graphitic vessels, some slight differences in the alumina and potash concentrations can be noted. Comparison of graphitic and non-graphitic fabrics by cathodoluminescence also showed some mineralogical differences (Lonné *et al*. 2004) and it was noticed that none of the non-graphitic crucibles identified was stamped. Altogether, this suggests that graphitic and non-graphitic crucibles may have been made in the same area, but probably not as a part of the same batch, or even by the same producer.

Why were the crucibles blackened? For the graphitic ones, the black colour might be interpreted as a side-effect of firing the vessels in reducing kilns, in order to prevent the oxidation of graphite. For non-graphitic ones, however, we cannot find any technical explanation. The outer black layer is too thin (~0.5 mm) to have any effects on the performance of the vessel, and in fact it disappears as soon as the crucible is used in a hot furnace. It would be tempting to see the blackening as a deliberate attempt at deception, by making crucibles that were presumably cheaper but looked like the graphitic ones. However, another explanation may be proposed.

Graphite and colour Traditionally, it has been assumed that graphitic clays were chosen for reasons akin to present-day ones, such as their thermal refractoriness, conductivity or impermeability (e.g., Kappel 1969; Duma and Ravasz 1976; Bauer 1983). Nevertheless, there is no clear evidence to support this claim for early modern times. Firstly, none of the numerous 16th century and earlier written sources reviewed mention the addition of graphite temper to clay (cf., Martinón-Torres 2005). This is surprising if we bear in mind, for example, Biringuccio's, Agricola's and Ercker's familiarity with Central European chymistry and metallurgy, their references to 'Vienna' crucibles, and their explicit and detailed descriptions of other temper types such as sand, grog or crushed fired bricks. When describing crucible-making clays, the main features used to discern them are colour, texture, plasticity, taste and smell (Fraustadt and Prescher 1958, 44–5); in other words, sensorial rather than compositional or microstructural aspects. In this context we can understand the eagerness—involving legal disputes—that Bavarian potters had for the exploitation of *Eisentachen* ('iron clay'), a term that may well originate from the dark lustre of the naturally graphite-bearing clay deposits (Schultheiß 1956; Bauer 1976; Pittioni 1977; Bauer 1983). In stark contrast, no reference is made to the much more abundant graphite deposits, which could be easily processed to artificially make graphitic clays. Thus, it appears reasonable to assume that early producers of graphitic crucibles only exploited naturally graphitic clays.

Only from the late 18th century do we find explicit allusions to the artificial mixture of clay and graphite during paste preparation for crucible manufacture. In these sources, the term used for the temper is *Wasserbley* ('liquid lead', or 'lead water'—Beckmann 1780, as cited in Stephan 1995, 31; Beckmann 1787, as cited in Bauer 1976, 15). Again, the expression highlights the greasy and metallic appearance of the mineral, and also that some confusion may have existed in its identification or categorization. The longer and more abundant graphite flakes in the 18th century fabrics (Fig. 8), compared to the smaller, and more rounded inclusions of the earlier ones (Fig. 6), also indicate their different technological histories.

Overall, it seems that some potters were particularly interested in the use of 'iron clay' for the production of crucibles and other black wares, but their products were only perceived and known by customers as 'black pottery'. At some point, the link between this 'iron clay' (dark, greasy clay) and the 'liquid lead' (graphite) must have been realized, and artificial mixtures began to be made. Before this, perhaps some potters and consumers were happy enough with black, lustrous pots—including crucibles—regardless of the exact nature of that blackness. This would explain the presence of black, non-graphitic crucibles in Oberstockstall, as well as the lack of historical evidence for the conscious addition of graphite temper prior to the 18th century.

This tentative explanation seems to fit the evidence available, as well as the widespread medieval and Renaissance understanding of matter. Before the 17th century Scientific Revolution, alchemists and laypersons believed that matter had only one intrinsic nature, although it could show different outward qualities—this being one of the main arguments supporting the belief in metallic transmutation. Since what really counted was the sensorial quality of matter, rather than matter itself, perhaps 16th century people were making crucibles that looked alike in the belief that they would perform alike.

Whatever the case, the peculiar black and lustrous appearance would have conferred Bavarian crucibles with a coherent appearance, all of them readily identifiable as 'one of a kind'. In this sense, the perceived materiality of the vessels, much more than their structure or composition, may have been at stake when choosing and using a particular type. We shall return to this point later.

Neither bright nor dark: other crucible productions

It is notable that the vast majority of the crucibles analysed were found to be either Hessian or Bavarian, especially considering that the selection of samples was not guided by their assumed provenance. This hints at a considerable dominance of these major productions at the expense of smaller or local producers, although much more archaeological data are still needed.

Interestingly, a review of relevant written sources would portray a completely different picture: notwithstanding the relatively abundant references to Hessian wares, different authors detail a variety of clay banks, temper types and manufacturing recipes, which probably reflect the reality best known to them, but not necessarily the most widespread practices. For example, as opposed to wheel and sand, they often talk about moulds and grog—which might be better suited for small scale, *ad hoc* productions by the users—but so far these have little archaeological presence (cf., Martinón-Torres 2005).

In any case, the existence of a few technical ceramics outside the two major groups should be noted. We shall not detail the various wares identified in this broad category of 'other crucible productions'. In general, there are greatly variable size and shape ranges, whilst the most frequent temper is sand—in various concentrations and grain sizes. There are also fragments of ordinary pottery such as stoneware that appear to have been reused for metallurgical operations. Post-medieval crucibles in this category are, among others, the 15th century brass production vessels from Zwickau (Germany); 16th century triangular vessels associated with goldsmithing in Cologne (or Köln, Germany); some of the 17th century crucibles from Cripplegate (UK), associated with Hessian wares; and, most likely (although awaiting analytical confirmation), some of the crucibles found in Kapfenberg (Austria) and the Old Ashmolean Laboratory (UK), where they appeared mixed with some of their more famous counterparts.

What all of the 'other crucibles' have in common is, on the one hand, a generally lower alumina concentration (Table 4 and Fig. 4)—denoting a lower thermal refractoriness—and, on the other hand, an absence of ceramic vitrification in unused specimens—indicating lower prefiring temperatures. These general aspects suffice as background for the broader picture attempted in the next section.

MATERIALS AND MATERIALITIES

The information gathered does not reveal any great difference between the material properties of Hessian and Bavarian crucibles, in spite of their different raw materials and *chaîne opératoires*. They represent different technological traditions, embedded in their particular environmental

Table 4 *Chemical compositions of ceramic matrices of other post-medieval crucible productions*

	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	Cl	K_2O	CaO	TiO_2	FeO	ZnO
Cripplegate WFG 118/107	0.2	0.2	17.8	77.3	0.1	–	1.2	0.4	1.2	1.0	0.7
Std dev.	0.14	0.09	1.91	2.47	0.13	–	0.19	0.08	0.15	0.12	0.54
Max.	0.4	0.3	21.2	79.6	0.2	–	1.5	0.5	1.5	1.1	1.5
Min.	0.0	0.1	15.8	73.4	0.0	–	1.0	0.3	1.1	0.8	0.1
Cripplegate WFG 118/114	0.7	0.8	23.9	68.5	0.3	–	2.1	0.7	1.3	1.7	–
Std dev.	0.16	0.12	1.08	1.88	0.17	–	0.13	0.08	0.21	0.20	–
Max.	0.9	1.0	24.9	71.7	0.5	–	2.2	0.8	1.6	1.9	–
Min.	0.5	0.7	22.1	66.9	0.0	–	1.9	0.6	1.0	1.5	–
Cripplegate WFG 118/121	0.3	1.2	22.6	66.1	0.1	–	4.3	0.5	1.0	3.8	–
Std dev.	0.13	0.08	1.39	1.56	0.11	–	0.39	0.04	0.34	0.42	–
Max.	0.5	1.3	24.2	68.2	0.2	–	4.7	0.6	1.4	4.3	–
Min.	0.2	1.1	20.9	64.4	0.0	–	4.0	0.5	0.6	3.3	–
Weyerstraße D-94/4/s1	0.5	0.5	25.2	65.3	0.5	0.5	3.0	0.8	1.7	2.1	–
Std dev.	0.13	0.18	0.34	0.54	0.06	0.05	0.14	0.22	0.11	0.16	–
Max.	0.6	0.8	25.6	65.9	0.5	0.6	3.2	1.0	1.8	2.3	–
Min.	0.3	0.4	24.8	64.8	0.4	0.5	2.9	0.6	1.6	1.9	–

and social contexts, but aimed at solving similar problems (Sillar and Tite 2000). Some minor differences do exist (e.g., dark crucibles would perform better in reducing reactions), but even the opinions given by 18th century and later authors reinforce that, in general terms, both types were of exceptional quality and either of them was well suited for most high-temperature operations (cf., Martinón-Torres 2005). When compared to a wider spectrum of earlier and contemporary vessels, the more successful crucibles jointly stand out on two main features: on the one hand, the combined thermal and chemical refractoriness; on the other, their standardization. In this sense, their success may be partly explained by the changing demand, as the growth of these industries was intertwined with the expansion and modification of pyrotechnological practices in Europe.

Previous studies of medieval crucibles have shown that their material properties were generally sufficient for their applications and, notably, that 'corrosion resistance was not a major concern' (Freestone and Tite 1986, 55). The 16th century, however, saw a surge in the investigation of matter, with great developments in fire assay techniques, and increasing experimentation, including the quest for the philosopher's stone (cf., e.g., Smith and Forbes 1969; Principe 2000; Martinón-Torres and Rehren 2005a). The centre of the Holy Roman Empire was also the core of this process. These are strands of a wider cultural and economic atmosphere, all of them recurrently necessitating high-temperature, small-scale, carefully controlled, reproducible experiments such as fire assays, calcinations and other reactions using newly discovered acids and fluxes. Spagyric chymistry, concerned with the decomposition of substances into their 'Essentials' by means of chemical attack and extreme temperature, may have played a special role here. Just as these reactions would attack the sample processed, so would they corrode the container. Only thermally *and* chemically refractory crucibles could serve these new needs and, insofar as these crucible-making industries developed thanks to existing demand, we can also assert that the Renaissance developments in analytical chemistry were only possible because these technical ceramics existed. On a related point, only standardized vessels would allow reproducibility, a crucial requirement of these experiments and indeed a leading factor behind the development of modern science.

In any case, it is reasonable to assume that crucible users would have to face the choice between alternative crucible productions. And here, on a routine basis, materiality may have been much more relevant than material properties.

It was noted above that crucible-makers selected their clay on the basis of the reputation of certain clay deposits, and by checking sensorial aspects such as colour and texture. In a comparable way, a finished crucible would probably be assessed by looking at it, perhaps handling it, touching and inspecting its surface, listening to its ring and perhaps turning it over to glance at a stamp (Sillar 1997). This apprehension would be subjective and influenced by previous knowledge and experience, habit, reputation, the need of replication and so on—expectations that could only be confronted with the external formal properties of the vessel. It is in this sense that we use the term 'materiality', to encompass the immediately perceptive aspects of an object *together with* the subjective connotations that it may entail (cf., e.g., Miller 1987; Jones 2002, 168–82; Gosden 2004; Jones 2004; Meskell 2005). The concept of materiality acknowledges that the physical components of materials, and their related cultural perceptions, symbolizations and uses, are analytically indivisible, and that 'material qualities of material culture are central to how they are used and made meaningful' (Jones 2004, 330).

Returning to the crucibles, the strikingly different appearance between Hessian and Bavarian vessels may have been particularly important. One can picture the situation in Renaissance and later Europe, when two major producers compete in the market of technical ceramics. The crucibles from both sources are technically fit: in general terms, either type would serve any common utilitarian purpose with more or less equivalent efficiency (i.e., similar material properties). However, they look radically different, and may well inspire different expectations (i.e., dissimilar materialities): one region produces crucibles that are invariably dark and smooth; the other one offers bright, pimply vessels. In this picture, the peculiar appearance not only strengthens the ties amongst the constituents of the same group, but also accentuates their disparity with regard to the others. When confronted in the market, appearance and texture would be the most conspicuous factors telling a user that *this, and not that*, is the desired vessel.

The very existence of a contrasting opposite would make it easier for the consumer to identify the 'reputable pot', whichever this may have been (Sillar 1997, 79–80; Sillar 2000). This 'reputable materiality' might convey different meanings in each case: it could mean provenance, quality, tradition, technical performance, adherence to an authoritative recipe or any other combination of incentives. On most occasions, however, this causal relationship between materiality and material properties would not even operate; non-verbal, learned, apprehended, ritualized factors would lead the choice (Pfaffenberger 1992). People would choose a bright, pimply crucible because they 'needed' a bright, pimply crucible, because that was the way things were done or, perhaps, because that was the way things had *always* been done (Lemonnier 1986, 165).

From an analytical standpoint, it is useful to separate out the formal properties, material properties and performance characteristics of technical ceramics (*sensu* Schiffer *et al*. 2001; Skibo and Schiffer 2001; Schiffer 2003—see also Sillar 2003). On this basis, however, it would be tempting to construct a model of consumption whereby the crucible user would assess the formal properties of a vessel, infer from them its material properties and, on this basis, visualize its performance characteristics. However, such an explanatory model involves some bold assumptions. Most notably, it surmises a cause–effect logic leading to the decision: from what one sees—for example, triangular and smooth—through what one understands—for example, good for pouring and corrosion resistant—to what one expects—for example, an efficient service in assaying silver ores. In actual fact, consumption may have worked as a much more complicated network of factors, moved by perceptive stimuli that cannot be explained in a logical sentence because they are neither logical nor can they be verbalized. As put by Pfaffenberger (1992, 508), 'the portion of technical knowledge that people can verbalize represents only the tip of the iceberg'. This makes it clear that ancient technology studies cannot rely on written sources alone. Moreover, it highlights the importance that materialities may have had in the choice of materials, even in practice-oriented fields such as pyrotechnologies.

CONCLUSION

The availability of high-quality crucibles was a major requirement for conducting specialized high-temperature reactions. Without them, several developments in metallurgy and analytical chemistry would not have been possible. This study has demonstrated the existence of a large-scale international trade of crucibles since the Renaissance. Two main crucible types were identified and mapped: on the one hand, the bright, pimply, sand-tempered kaolinitic crucibles from Hesse; and, on the other hand, the dark, smooth, usually graphitic crucibles from Bavaria and surrounding regions. More work will be needed to investigate the social and cultural ramifications of this trade, its internal variability, and its spatial and chronological developments. In general, both crucible types showed similarly expedient material properties, which differentiated them from earlier and smaller-scale productions: most notably, their combined thermal and chemical refractoriness, and their standardization. Both types were used in a variety of pyrotechnological contexts, including copper metallurgy, ore assaying, coin minting and al/chemical experimentation. Conversely, Hessian and Bavarian crucibles were different in their raw materials, their manufacture and, importantly, their appearance. It seems sensible that their different appearances may have facilitated their recognition in the market, and also that they raised different connotations and expectations for the users. Thus, in spite of the similar material properties of both crucible types, a study of consumption should consider their different materialities.

The study of crucibles—like any other study of material culture—should assess their performance in the widest sense; in other words, not only in the furnace but also in the social contexts where they were manufactured, acquired and used. Moreover, sophisticated analytical studies should not forget the readily perceptive aspects of the objects analysed, as they are also relevant to past technologies and understanding of materials. In the early modern world, sensorial aspects of the material world were often more important than compositions and microstructures, and thus, whilst investigating material properties, we should give more regard to materialities.

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