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LEGGE'S MOUNT, THE TOWER OF LONDON, LONDON
SCIENTIFIC ANALYSIS OF THE CRUCIBLES

TECHNOLOGY REPORT

Harriet White and Thérèse Kearns

ARCHAEOLOGICAL SCIENCE

ENGLISH HERITAGE

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SUMMARY
A number of used and unused crucibles were recovered from the vicinity of a 16th-century furnace located at Legge's Mount, the Tower of London. A crucible typology based upon form was established for the assemblage that illustrates the range of crucibles in use at the site. The crucible fabrics were examined using a combination of macroscopic, chemical and petrographic analyses, the results of which demonstrate the crucibles were manufactured from different clays that were either grog-tempered or quartz-tempered. Crucible use was investigated using a combination of X-ray fluorescence and energy dispersive-scanning electron microscopy. The results show that they were used for processing base metals and precious metals, while some unusual alloy types were detected.

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ARCHIVE LOCATION
Mounted samples are archived at Fort Cumberland, Fort Cumberland Road, Eastney, Portsmouth, PO4 9LD

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INTRODUCTION

Excavations carried out in 1976 in the north-west bastion of the Tower of London, known as Legge's Mount, revealed a furnace which incorporated two key-hole shaped hearths and an attached ash pit. Archaeomagnetic dating of the furnace indicates it was in use during the 16th century (Parnell 1993). Investigations of the ash pit and surrounding areas uncovered an assemblage of material which included both used and unused crucibles, several bone ash cupels and fragments of long-necked, globular ceramic flasks, as well as other ceramic vessels and various vitrified residues. The variety of remains suggests that a number of metallurgical processes were carried out at the site, and some finds such as the bone ash cupels used for silver assaying are particularly diagnostic (White 2010). The most likely scenario is that the material recovered relates to operations of the Royal Mint which was housed in the buildings near Legge's Mount until about 1560 (Barter 1978). This report presents results of an in-depth study of the Legge's Mount crucibles which focuses on form, fabric and use.

BACKGROUND

Crucibles are free-standing vessels used for a number of high temperature operations and as such have been used in the past by metal casters, minters, al/chemists, assayers, jewellers and glassworkers (Martinón-Torres and Rehren 2009). The diversity of their use is reflected in the variety of shapes and sizes which have been uncovered from archaeological contexts in Europe and beyond. Throughout the late medieval period in particular, their use was widespread and it is during this time that descriptions of various techniques used for their manufacture begin to appear in metallurgical treatises (for example Lazarus Ercker's *Treatise on Ores and Assaying* (Sisco and Smith 1951), Agricola's *De Re Metallica* (Hoover and Hoover 1950) and Biringuccio's *Pirotechnia* (Smith and Gnudi 1959)).

Crucibles are generally classified using a number of criteria. One approach is based on functional requirements which are technically determined by physical and chemical properties. In general, crucibles must have a high thermal shock resistance, be strong enough to hold the weight of the metal they contain, be sufficiently refractory to withstand high temperatures and sufficiently inert so as not to react with the crucible contents (Bayley and Rehren 2007). More basically they must be of a suitable size and form so that they are easily manipulated during use. Studies by Bayley (1992; 2003) have shown that there is often an association between particular types of crucibles and specific metals and alloys. It has been observed, for example, that precious metals are often melted in crucibles with superior refractory qualities to ensure that no metal is lost through failure of the crucible (Bayley *et al* 1991). Previous studies have greatly enhanced our understanding of crucibles from a variety of contexts (for example Bayley 1992, Rehren 2003, Martinón-Torres and Rehren 2005a, Bayley and Rehren 2007, Martinón-

Torres and Rehren 2009). Remains from minting contexts are, however, still relatively scarce, and where material has been recovered it has been little studied (for example McLees 1994 and Dordio *et al* 1997). Because the Legge's Mount crucible assemblage comprises many complete vessels (or fragments that have complete profiles preserved), and in a number of cases with both used and unused examples surviving, it provides a rare opportunity to clarify correlations between crucible type, fabric and use in a minting context in general, and more specifically, to further our understanding of the metallurgical operations carried out at Legge's Mount. The overall aims of the study were to:

1. establish a typology for the forms of the Legge's Mount crucibles
2. classify the crucible fabrics using a combination of macroscopic and microscopic analyses
3. determine the range of metals that were processed at Legge's Mount, and hence
4. investigate correlations between crucible type, fabric and use

METHODOLOGY

Crucible typology

The Legge's Mount crucible assemblage comprises 73 pieces, 21 of which are complete vessels or have complete profiles preserved. These were used to establish the typology. Crucibles were assigned 'Types' based on form (profile and dimensions). Terminology used to describe features such as rims, bases and spouts follows the standard set out in the Medieval Pottery Research Group's guide to the classification of medieval ceramic forms (MPRG 1998). Dimensions of all crucibles, and where possible fragments, were recorded (Appendix I). In cases where crucibles are elliptical in plan the minor and major exterior rim diameters are given. Where crucibles are circular in plan the exterior rim diameter is noted as the major diameter. In a number of cases diagnostic sherds (rims/bases) could be assigned as 'Type Associated' based on curvature, wall thickness, rim type and so on. Of the 73 pieces 24 were too fragmentary to assign to type with any certainty and so remain unclassified.

Fabric analysis

Ceramic fabric type was a further criterion used to investigate the crucibles. Initially, freshly fractured surfaces were examined using a low-powered microscope at x10 and x30 magnifications to identify inclusion type and distribution, and nature of fracture, while fabric colour was assessed using a Munsell Soil Colour Chart (1994). Fabric hardness (cohesiveness) was determined using the standard scratch test method: very soft – fingernail scratches easily, soft – fingernail scratches, medium hard – penknife scratches, hard – penknife just scratches and very hard – penknife will not scratch.

It was immediately apparent that the crucible fabrics divided into two broad types: those whose main inclusions were quartz, and those with quartz and other inclusion types present. The variation within the two broad groups was often obscured by the wide range in firing temperatures and atmospheres which the unused and used crucibles had been exposed to. Firing temperature and atmosphere affect the colour of both the ceramic matrix and inclusions, and also the level of vitrification. The latter influences the nature of fracture and hardness. As a result the same fabric may appear radically different depending on use. The macroscopic analysis was supplemented by petrographic and chemical analyses of 12 samples which were selected to cover the variation observed in the assemblage. The purpose of the petrographic and chemical analyses was to characterise the crucible fabrics in a more objective manner than provided by visual criteria alone, and to establish details of production technologies of the Legge's Mount crucibles which contribute to the broader understanding of crucible use at the site. Several of the unclassified sherds were included in the petrographic and chemical analyses to help determine how they fit into the assemblage as a whole.

Thin sections of the 12 samples were prepared according to the standard method of mounting a section onto a glass slide and polishing down to a thickness of 30µm. They were examined using an Olympus polarising light microscope at magnifications of x40 and x100 under plane-polarised light (pp) and crossed polars (xp). The samples were characterised following Whitbread's (1989; 1995, 379-388) thin section descriptive system. Definitions of the descriptive terms used are presented in Appendix II. The principal criteria for fabric grouping following Whitbread's system are:

1. colour and optical activity of the micromass (fired clay matrix and fine silt)
2. void type and orientation
3. mineral and rock types comprising the non-plastic inclusions
4. quantity, shape, size and grain-size distribution of the non-plastic inclusions, and
5. textural concentration features (such as clay pellets)

A hierarchy of classification is used to order the fabrics. A 'Fabric Class' brings together Fabric Groups that are related by general geological or technological characteristics. A 'Fabric Group' contains related samples that are made from the same raw materials and use the same paste preparation techniques. Individual samples within a group may show variation in terms of frequency and/or size of the main inclusions, colour difference due to firing atmosphere, and extent of optical activity resulting from firing temperature. A 'Fabric Sub-Group' is a well defined variant of a Fabric Group. It may represent the use of the same raw materials, but reflect a slightly different and definable paste recipe such as a finer or coarser version. Finally, a 'Fabric' is a lone sample representing a discrete fabric type. Summary fabric descriptions are presented in the results section while the full thin section descriptions, which can be used for comparative purposes, are given in Appendix III.

Chemical analysis of the crucible fabrics

Compositional analysis of the selected sherds was carried out using a scanning electron microscope with an attached energy dispersive spectrometer (SEM-EDS). Sample preparation followed the standard protocol of mounting the section in epoxy resin and polishing the surface to a 1µm finish. The SEM used was a FEI Inspect F which was operated at 25kV with a beam current of approximately 1.2nA. The X-ray spectra were detected using an Oxford Instruments X-act SDD detector, the elements quantified using the Oxford Instruments INCA software and a cobalt standard was used to calibrate the spectra. Since ED X-ray spectrometry provides no direct information on the valence states of the elements present in the analysed material, appropriate valence states were selected and the oxide weight percents were calculated stoichiometrically. Areas in the order of 2mm across were scanned and their mean composition is given (n=4 to 10).

Crucible use

Determining crucible use through surface analysis (or the analysis of metallic droplets trapped within crucible fabrics) is fraught with difficulties, and some comment must be made to justify the methodology selected for this aspect of the research. Crucibles are customarily analysed using energy dispersive-X-ray fluorescence (EDXRF) and/or SEM-EDS to determine use (for example Bayley 1989, Bayley *et al* 1991). Nevertheless, work has shown that the metallic elements detected do not always reflect the original composition of the metal processed in the crucible (for example Dungworth 2000). This is due, in part, to the variation in volatility of the different metallic elements during heating at high temperatures. For example, lead and zinc are more volatile than copper and tin, will be more easily lost during melting in an oxidising atmosphere, and so may be more enriched within the crucible fabric in comparison to the original alloy composition (Dungworth 2000, 85). Moreover, the metallic residues trapped within the fabric may be exposed to successive reheating (effectively fire-refining) should the crucible be reused. The situation becomes even more complex if a crucible has been reused to melt separate alloys of different compositions. In such circumstances a range of different metals will be detected within a single crucible which does not correspond to a single alloy. Contamination of surfaces due to burial environments presents a further problem. A number of Legge's Mount crucibles or crucible sherds do not appear to have been used

(Appendix I). Their fabrics are oxidised, their surfaces show no vitrification and no metallic residues are present. Despite this, qualitative EDXRF of these sherds detected traces of copper and lead in four cases (LM 19, 20, 21 and 63), and traces of copper and silver in one case (LM 31). In the case of one sherd (LM 63) a quantity of soil stained green from copper corrosion salts remains attached to the surface, and the sherd itself also shows green staining. Moreover, unused cupels excavated from Legge's Mount show surface lead enrichment, presumably due to post-burial contamination. These results indicate surface contamination of copper and lead due to mobility of these metals in the burial environment is likely to be encountered more widely across the crucible assemblage. Metals such as gold or silver are more stable and so would be less likely to present contamination problems. To further test the appropriateness of surface analysis of the Legge's mount crucible assemblage a number of sherds were analysed using both quantitative SEM-EDS (metallic droplets contained within the sherds) and qualitative EDXRF (crucible surfaces) and the results compared. In ten out of fourteen cases, the two datasets were inconsistent (Appendix IV). This disparity between EDXRF and SEM-EDS has previously been reported in the case of crucibles from Housesteads (Dungworth 2001, 14). It was therefore felt that reliance upon EDXRF analysis of the crucible surfaces alone has the potential to produce misleading results.

With these points in mind an analytical methodology was selected which aimed at reducing these problems as much as possible. Metal droplets attached to crucible surfaces (LM 2, 5, 6, 75 and 76) were sampled and any corrosion products present were cleaned away to expose the underlying metal. These samples were analysed by EDXRF. In one case (LM 54) metal droplets trapped within the vitrified surface layer were noted in the pouring spout area of the crucible. These were isolated and analysed by EDXRF. The EDXRF system used was an EDAX Eagle II which was operated at 40kV with a current of 1mA.

Where metallic droplets were not present on the crucible surfaces or could not easily be removed, metal trapped within the crucible fabrics were instead analysed using SEM-EDS on polished sections (see above for methodology). While the majority of crucible types were represented, no metal droplets could be isolated from any of the crucibles belonging to Types 5, 6 and 8.

RESULTS

Crucible typology

Nine crucible types were identified. Of these, eight are described in full. Three are considered large (height = 150mm and above) and five are considered small (height = 110mm and below) (Figure 1). It was apparent from the assessment that further crucible

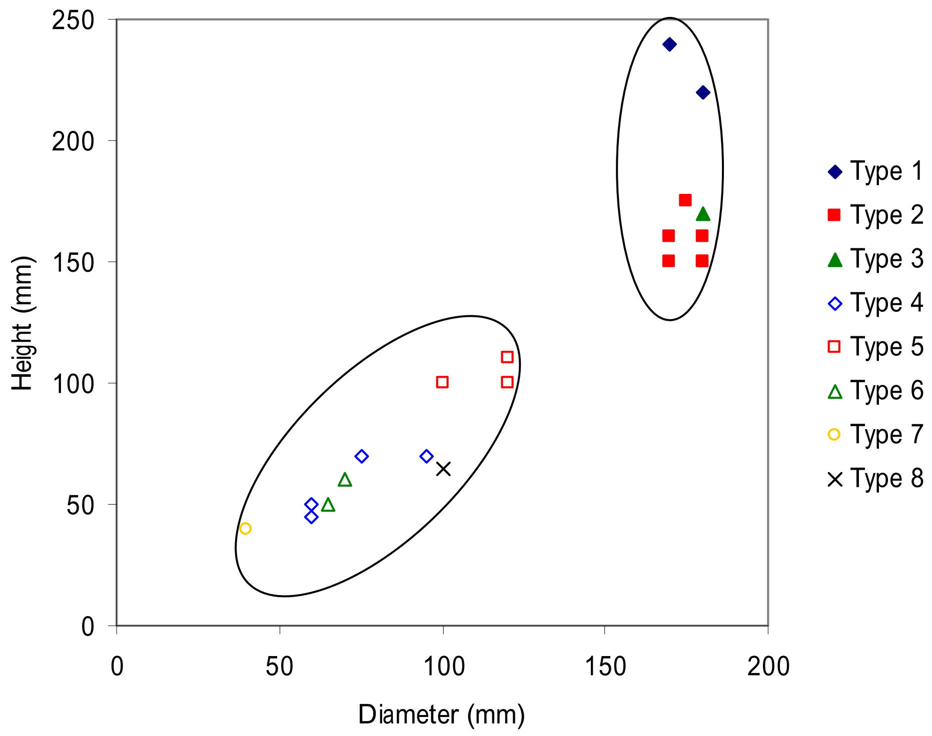


Figure 1. Scatter plot showing the crucible size ranges by Type. By plotting crucible rim diameter against height it can be seen the crucibles fall into two groups based on their dimensions.

Figure 2. Type I crucible, showing elliptical form, and pinched and pulled pouring lip (LM 1).

Figure 3. Type 2 Crucible has walls flaring outwards from the base (LM 9).

types were in use at Legge's Mount but the pieces preserved are not complete enough in order to classify them in full. The types identified are discussed in detail below:

Type 1

Type I crucibles are tall (220 and 240mm in height) with relatively vertical walls and are elliptical in plan (Figure 2). The pouring spouts, which are situated on the minor curve where the crucible rim is thinnest (approximately 11.0 and 12.5mm), occur as pinched and pulled lips. The rim is thickest on the opposite curve (approximately 15.0 to 18.5mm). The minor rim diameter of the Type 1 crucible measures between 140 and 150mm. The major rim diameter measures between 170 and 180mm (Appendix I). The rims are upright, simple and squared in profile, or slightly externally bevelled (LM 31, Appendix V(a)). Two variants of the Type 1 crucible are present. Type 1A has a flat base (for example LM 1) and Type 1B has a rounded base (LM 2). No surface features such as rilling are apparent which indicate method of manufacture.

Type 2

Type 2 crucibles are shorter than Type 1 crucibles, with heights in the range of 150 to 160mm (Figure 3 and Appendix I). They are slightly elliptical in plan (the minor rim diameter ranges between 130mm and 160mm, and the major rim diameter between 170 and 180mm), and the vessel walls flare outwards from the base. The rims are upright, simple and squared in profile (Appendix V(b)). The walls are thinner at the top (between 10 and 12mm) and broaden significantly (up to 20mm) towards a thick base that is slightly concave on the external surface (for example LM 6). Crucible LM 3 shares the same features, though stands taller at 175mm (see Appendix I). None of the six almost complete examples show evidence of a pouring spout. Like Type 1, there are no features which might indicate manufacturing method. Three examples (LM 3, 4 and 9) have fragments of brick or tile attached to the base, which are presumably remnants of a furnace structure.

Type 3

The assemblage contains one half crucible with a complete profile surviving (LM 5) and one large rim/body fragment. The form of Type 3 is intermediate between Types 1 and 2. Crucible LM 5 is 170mm in height; the walls have an obtuse angle from the base but show constant thickness through the profile. The rim is elliptical in plan (minor diameter is 160mm and major diameter is 180mm), is between 15 and 16mm in thickness and is upright, simple and squared in profile (Appendices I and IV(c)). The base of the Type 3 crucible is flat (Figure 4). The 'Type 3 Associated' fragment (LM 30) has what appears to be a band of decoration extending 20 mm from the top, comprising incised diagonal lines (Figure 5).

Figure 4. Type 3 crucible, showing the oblique angle of the walls (LM 5).

Figure 5. Showing the band of incised diagonal line decoration circling the rim of crucible LM 30.

Figure 6. Type 4 crucible group, showing size range (LM 11, 13 and15).

Type 4

Type 4 crucibles range from 45 to 100mm in height, are circular in plan, and have straight to very slightly curved walls that join the base at an obtuse angle (Figure 6 and Appendix I). Where measurable, the rim diameters range from 60 to 95mm and have a rim thickness of about 6.0 to 9.0mm. The rims are upright, simple and squared in profile (Appendix V(d)). The Type 4 crucible has a pinched and pulled pouring lip. No surface marks which might indicate forming method are apparent.

Type 5

Type 5 crucibles are 100 to 110mm in height. They are circular to very slightly elliptical in plan, and have rim diameters of 100 to 120mm and rim thicknesses of about 7.5 to 8.0mm (Figure 7 and Appendix I). The pouring spouts occur as pulled lips. Two variants of Type 5 are present. They are Type 5A, which has a rim that is upright, simple and squared in profile (Appendix V(e)), and straight vessel walls that join the base at an obtuse angle (for example LM 17), and Type 5B which has an upright, simple rim that is rounded in profile (Appendix V(f)), and slightly curved vessel walls that join the base at an obtuse angle (for example LM 18). Both variants possess sagged bases and the vessel walls are knife-trimmed around the bottom. Rilling is visible on the inner surfaces demonstrating that Type 5 crucibles were wheel-thrown.

Figure 7. Examples of Type 5 crucibles. The crucible on the left is a Type 5A variant, showing the squared rim profile and straight vessel walls. It is unused. The crucible on the right is a Type 5B variant, showing the rounded rim profile and slightly curved walls. It has been used. The rilling (on the inner surface) and knife-trimmed base is more apparent on the unused example (LM 17 and 18).

Type 6

Type 6 crucibles are small (50 to 60mm in height) and are elliptical in plan. The minor rim diameter is 40 to 50mm and the major rim diameter is 70mm (Appendix I). They are thin-walled (rim thickness is 3.5 to 4.5mm), the walls meet the base at an obtuse angle and the bases are flat (Figure 8). Two variants of the Type 6 crucible are present. Type 6A has a slightly splayed base and an upright, simple and rounded rim profile, and Type 6B has a knife trimmed base and an upturned, simple rim that is squared in profile (Appendix V(g and h)). Rilling is visible on the internal walls demonstrating Type 6 was wheel-thrown.

Type 7

There is one complete example of the Type 7 crucible (Figure 9). It is small (41mm in height), circular in plan with a pulled pouring lip, and has a rim diameter of 40mm (Appendix I). The rim is upright, simple and has a rounded profile, and is 4.5mm thick (Appendix V(i)). It has relatively parallel walls and the walls meet the base at a right-angle. The base is flat. Traces of rilling are present on the external surface demonstrating this crucible type was wheel-thrown. Remnants of a band of clay applied to the upper wall/rim survive. It is possible that it represents the remains of luting used to seal on a crucible lid.

Figure 8. Example of Type 6 crucibles. Type 6A (left) has a slightly splayed base and Type 6B (right) has a knife-trimmed base (LM 20 and 21).

Figure 9. Type 7 crucible. Note the remnants of the applied clay band circling the upper wall/rim of the crucible (LM 22).

Figure 10. Showing the curved profile of the Type 8 crucible (LM 23).

Type 8

One large fragment (about 15% of the vessel, rim to base) of a Type 8 crucible survives (Figure 10 and Appendix I). It is open bowl-shaped and is 65mm in height. The rim diameter is approximately 100mm and rim thickness 10.5mm. The rim type is upright, simple and is internally bevelled in profile (Appendix V(j)). What remains of the pouring spout suggests it is a pinched and pulled lip. The walls join the base at an obtuse angle, and the base is flat. No rilling is visible on the surfaces.

Type 9

Two small rim fragments and one body sherd (possibly belonging to a single vessel) survive of a further crucible type. There is not enough of the profile preserved to describe it in full. What does remain suggests that it is similar in form to Type 8 (open bowl-shaped), although much smaller in size; the wall thickness is 3.0mm in contrast to 10.5mm. The rim is upright, simple, and like Type 8 is internally bevelled in profile (Appendix V(k)). What survives of the pouring spout on one fragment (LM 58) indicates it is of the pulled lip type.

Unclassified Sherds

A further 24 sherds (rim, base, and body pieces) could not be classified because they were too fragmentary, or suffered distortion and bloating from overheating. The majority of the unclassified rims were of the upright, simple and squared type, though two rims flared outwards in profile (LM 28 and LM 59, Appendix V(l and m)), indicating variation on the types identified.

Fabric analysis

As noted previously, the initial macroscopic assessment of the crucible assemblage revealed the samples can be divided into two broad fabric types; those in which the main inclusion type is quartz (17 samples), and those with quartz and other inclusion types present (56 samples). The petrographic analysis revealed that the inclusions mixed with quartz in the second group are grog (crushed ceramic material). It proved difficult to classify the grog-containing fabrics any further on a macroscopic level given the wide range in firing temperatures and atmospheres the crucibles had been exposed to. The petrographic analysis, however, revealed the presence of two distinct groups within the grog-containing fabric class, with one group containing a further sub-group. The chemical analysis supported these findings. Variations present within the quartz-containing fabrics were easier to discern in hand specimen, and those observations were supported by the petrographic analysis. Hand specimen descriptions are thus given for the Grog-Tempered Fabric Class as a whole, which records the macroscopic variations present within the class, while the petrographic and chemical characteristics for the groups and sub-groups highlight the differences on a more detailed level. Since the differences between the quartz-containing fabrics are more apparent, each group within the Quartz-Tempered Class are described on macroscopic and microscopic levels.

Crucible fabrics

Grog-Tempered Fabric Class

Samples: LM 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49, 52, 54, 55, 57, 59, 60, 62, 64, 65, 66, 67, 68, 69, 70, 72

Hand Specimen Analysis

Colour: this fabric has a wide colour range in hand specimen which includes very dark grey (1 Gley 3/N), dark grey (1 Gley 4/N), grey (2.5Y 5/1 to 6/1) dark reddish grey (10R 4/1 and 2.5YR 4/1) to dusky red (10R 3/2) very dusky red (10R 2.5/2) pink (7.5YR 7/4) light reddish brown (2.5YR 6/4 and 5YR 6/4), light yellowish brown (10YR 6/4), brown (10YR 5/3) and light brownish grey (10YR 6/2). The single unused example (LM 31) is very pale brown (10YR 7/4).

Hardness: hard to very hard.
Fracture: hackly to concoidal.

Inclusions: abundant, well sorted, sub-rounded quartz, and poorly to moderately sorted sub-angular to sub-rounded grey to black inclusions (Figure 11).

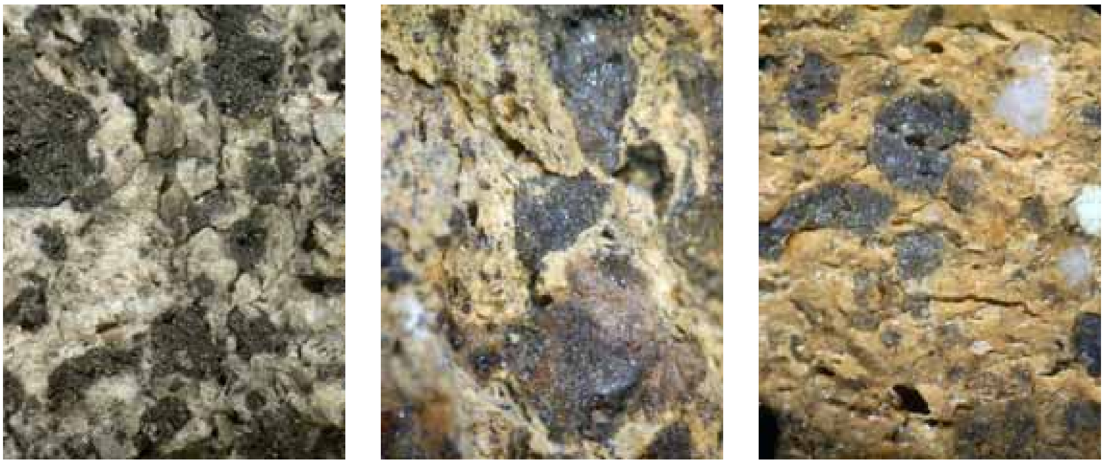


Figure 11. Showing the variation present in the Grog-Tempered Fabric Class. The coarse grey to black pieces are grog fragments, and the white inclusions (right image) are quartz grains. The left image is crucible LM 47, the middle image is crucible LM 24 and the right image is crucible LM 31. The width of each image is 3.3mm.

Petrographic Analysis

The petrographic analysis shows that three versions of the grog-tempered fabric type are present within this class. These are:

1. Grog-Tempered Fabric Group A1

Samples: LM 27, 37, 47, 49, 59, 64

This fabric is characterised by its quartz inclusions and fragments of grog temper. In thin section the micromass is optically inactive to optically slightly active and its colour ranges from yellow brown to pale grey brown (pp x40) and red brown to grey brown and black (xp x40). Voids occupy between 5 and 10% of the total field and are moderately to strongly aligned with the vessel walls. They occur as dominant macroplanar voids, frequent macrovughs, common mesovughs and absent to rare mesovesicles. Overall, the non-plastic inclusions show a bimodal grain-size frequency distribution. The mineral content occupies about 15 to 25% of the total field and comprises predominant sub-rounded to sub-angular monocrystalline quartz in the silt to very fine sand size range, which shows a unimodal grain-size distribution frequency. Sub-rounded to sub-angular medium sand-sized chert is absent to very rare. Textural concentration features occupy about 40 to 50% of the total field and occur as rounded to angular grog inclusions. The grog inclusions range in size from 0.2mm (fine sand-sized) to 2.5mm (granule-sized). They have sharp to clear boundaries and are commonly surrounded by voids. They may have a high optical density where the grog is black in a matrix of grey in xp (for example LM 47, Figure 12(a)), a neutral optical density where the grog is difficult to distinguish from the surrounding matrix in pp and xp (for example LM 27, Figure 12(b)) and a low optical density where the grog is grey in a black matrix (xp) (for example LM 49, Figure 12(c)). The fabric of the grog has the same composition and grain-size frequency distribution as the surrounding matrix, indicating the grog was prepared from vessels belonging to the same fabric group.

2. Grog-Tempered Fabric A2

Sample: LM 24

This fabric is characterised by its quartz and coarse grog inclusions (Figure 13). It is optically active and is orange brown (pp and xp). Voids occupy about 15% of the total field and occur as frequent macroplanar voids, few mesoplanar voids and few mesovughs. The non-plastic inclusions have a bimodal grain-size frequency distribution. The mineral content occupies about 15% of the total field. They comprise predominant silt to very fine sand-sized quartz. Textural concentration features occupy about 50% of the total view and occur as poorly sorted sub-rounded to angular fragments of grog that range in size from 0.2 (fine sand-sized) to 3.5mm (granule-sized). They have sharp to clear boundaries, can be surrounded by voids and have a high optical density. They are grey brown (pp) and dark grey brown to black (xp). The grog fabric has the same composition and grain-

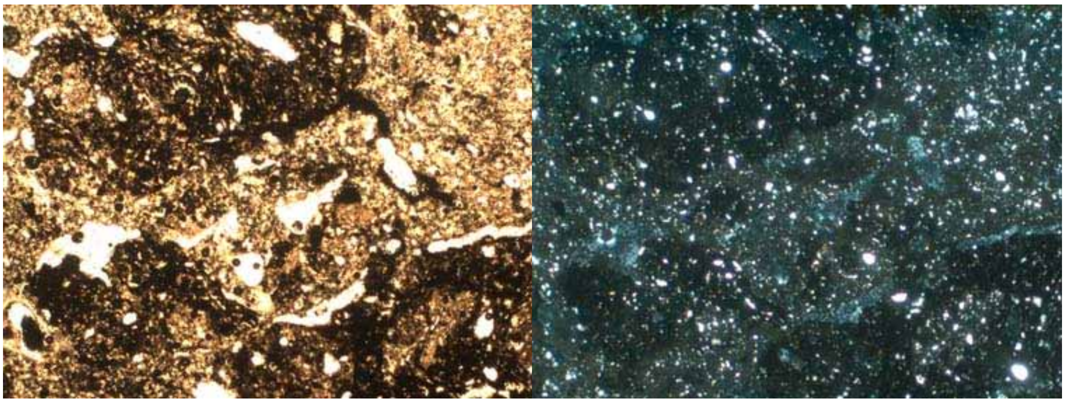


Figure 12(a). Thin section micrograph of crucible LM 47 (left pp, right xp). Showing black grog inclusions in a dark grey matrix (xp). Voids occasionally surround the grog as can be seen by the white outline around the bottom right grog inclusion (pp). Width of image is 2.5mm.

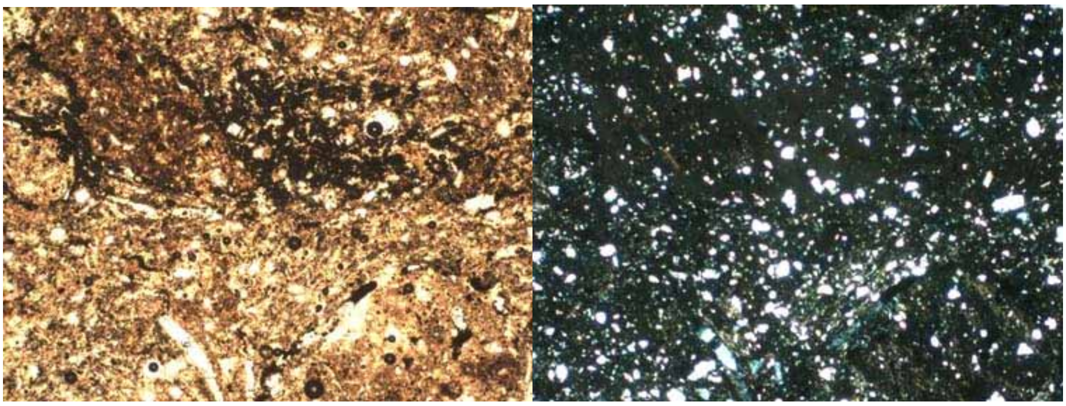


Figure 12(b). Thin section micrograph of crucible LM 27 (left pp, right xp). The grog inclusions are hard to discern from the surrounding matrix in xp. Width of image is 2.5mm.

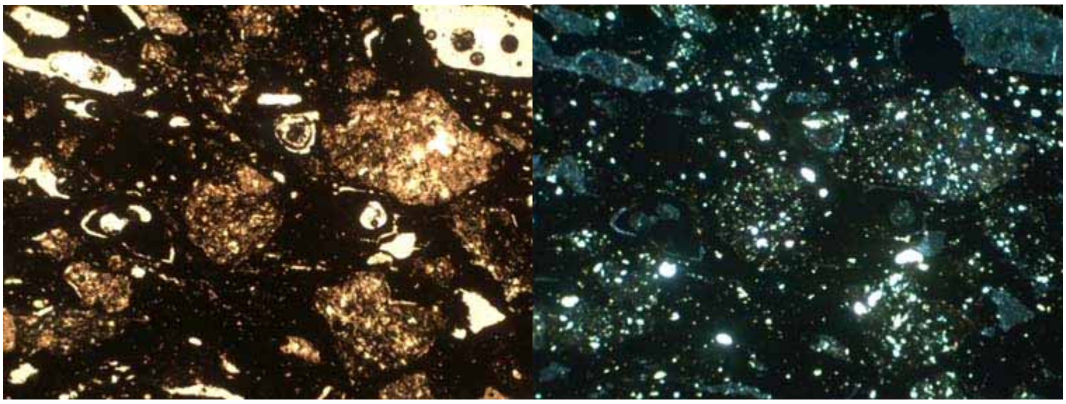


Figure 12(c). Thin section micrograph of crucible LM 49 (left pp, right xp). Showing grey grog inclusions in a black matrix (xp). Width of image is 2.5mm.

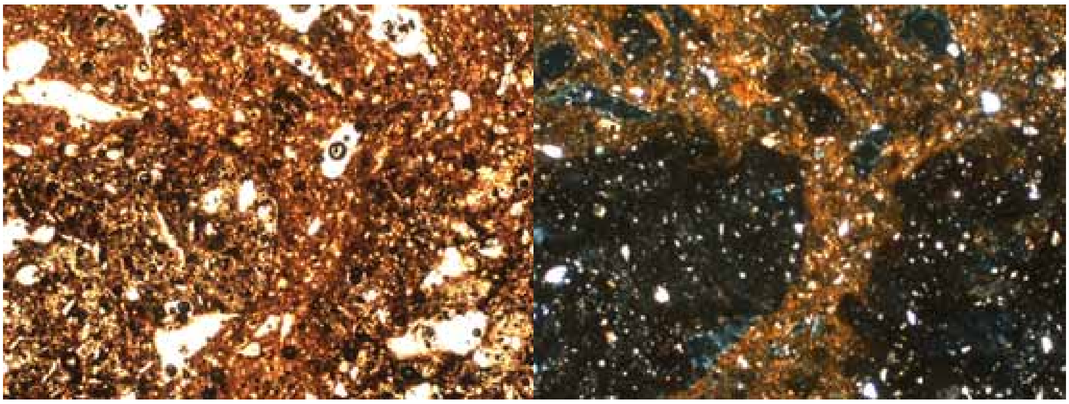


Figure 13. Thin section micrograph of crucible LM 24 (left pp, right xp). The grog inclusions in the sub-group Grog-Tempered Fabric A2 are significantly coarser than those observed in the Grog-Tempered Fabric A1. Width of image is 2.5mm.

size frequency distribution as the surrounding matrix, and as seen in Grog-Tempered Fabric A1. Bloated pores may be present, usually within the grog, and the larger pieces may contain grog inclusions themselves. This is a coarser variant of Grog-Tempered Fabric A1.

3. Grog-Tempered Fabric B

Sample: LM 31

This fabric is characterised by its quartz and grog inclusions (Figure 14). In thin section it is optically active and is grey to dark brown (pp) and grey brown (xp). Voids occupy about 20% of the total field and occur as frequent macroplanar voids, common mesoplanar voids and common mesovughs. Overall, the fabric has a bimodal grain-size frequency distribution. The fine fraction (mineral inclusions) occupies about 15% of the total field. They occur as predominant monocrystalline quartz in the coarse silt to medium sand-sized range. The coarse fraction occupies about 40% of the total field and occurs as rounded to sub-angular fragments of grog which range in size from 0.25mm to 1.50mm (fine to very coarse sand-size). They have high optical density, are optically inactive and have sharp to clear boundaries. The colour is brown-black (pp) and very dark brown (xp). The grog inclusions contain absent to rare monocrystalline quartz in the very fine sand size range, and bloated pores can be present. The fabric of the grog differs from that of the surrounding matrix, and of the grog and matrix identified in the Grog-Tempered Fabric A variants.

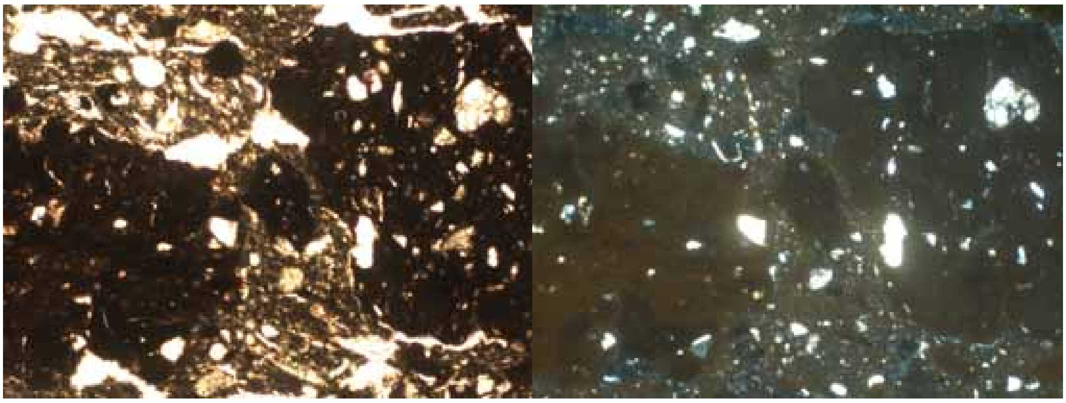


Figure 14. Thin section micrograph of the Grog-Tempered B fabric (crucible LM 31) (left pp, right xp). The difference in size range and distribution of the quartz inclusions both within the grog and surrounding matrix indicate the use an alternate source for raw materials. Width of image is 2.5mm.

The chemical compositions of the grog-tempered crucible fabrics support the petrographic divisions, suggesting they are 'real' in terms of the raw materials used in their manufacture. For example, Figures 15 shows magnesia concentrations plotted against silica and titanium oxide concentrations. In both plots the Grog-Tempered A2 Fabric clusters with samples belonging to the Grog-Tempered A1 group, demonstrating that they are indeed made from the same raw materials, and the only real difference is in the coarseness of grog pieces added as the temper. The Grog-Tempered B fabric sits as an outlier to the Grog-Tempered A cluster in both plots, and in comparison to the Grog-Tempered A fabrics has lower magnesia, calcium oxide and iron oxide, and higher silica and titanium oxide (Figure 15 and Table 1). This lends strength to the notion that the B fabric is manufactured using different raw materials, both in terms of the clay used, and of the source ceramic material used as grog.

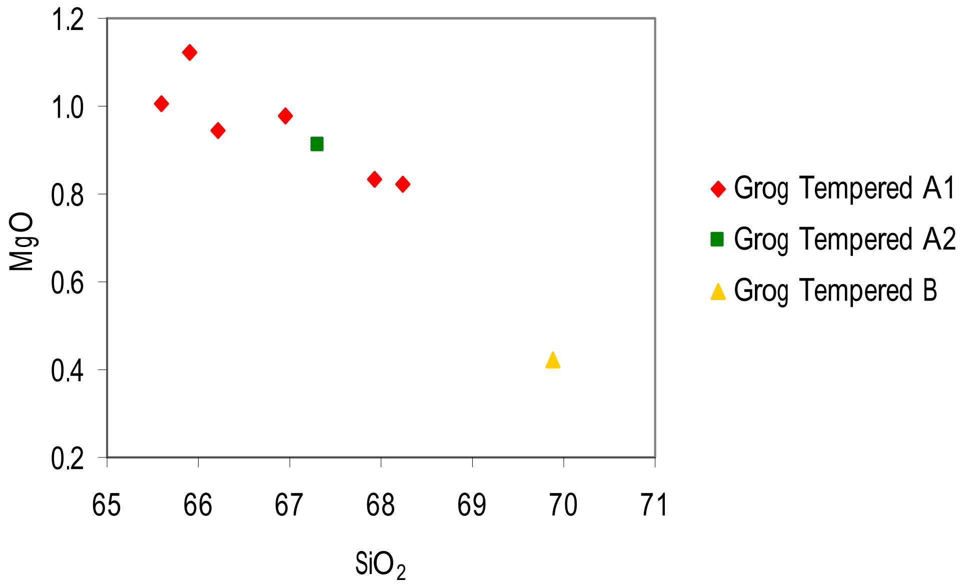
Quartz-Tempered Fabric Class

Quartz-Tempered Fabric Group A

Samples: LM 17, 19, 20, 21, 50, 63, 73

Hand Specimen Analysis

Colour: when unused the fabric is pink (7.5YR 7/4 to 8/4) to very pale brown (10YR 8/3), and pale yellow (2.5Y 8/3). The used crucible fabric is greyish brown (10YR 5/2).



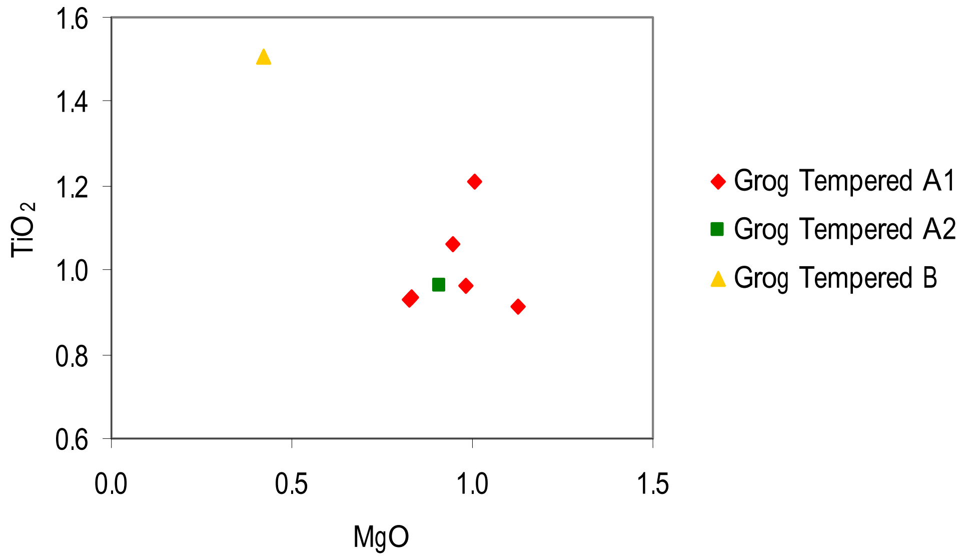


Figure 15. Biplots comparing MgO and SiO_2 concentrations (top) and MgO and TiO_2 concentrations (bottom) of the grog-tempered fabric variants.

Table 1. Showing the major and minor element oxide concentrations of the different crucible fabrics, determined by SEM-EDS.

Crucible LM	Fabric	Na_2O_3	MgO	Al_2O_3	SiO_2	K_2O	CaO	TiO_2	Fe_2O_3
27	Grog-Tempered A1	0.6	0.9	23.4	66.2	3.1	1.5	1.1	3.2
37	Grog-Tempered A1	0.4	1.0	23.9	67.0	2.6	1.0	1.0	3.2
47	Grog-Tempered A1	0.4	1.0	24.9	65.6	2.7	0.7	1.2	3.5
49	Grog-Tempered A1	0.3	0.8	23.8	68.2	2.4	0.9	0.9	2.7
59	Grog-Tempered A1	0.4	0.8	24.4	67.9	2.5	0.8	0.9	2.3
64	Grog-Tempered A1	0.4	1.1	23.8	65.9	2.6	1.3	0.9	4.0
24	Grog-Tempered A2	0.3	0.9	23.5	67.3	2.5	1.1	1.0	3.4
31	Grog-Tempered B	0.3	0.4	24.4	69.9	2.0	0.4	1.5	1.3
19	Quartz-Tempered A	0.2	0.7	13.4	79.8	2.3	1.2	0.6	1.8
18	Quartz-Tempered B	0.2	0.6	16.4	76.8	1.9	1.6	0.7	1.8
56	Quartz-Tempered C	0.3	0.5	13.7	80.5	2.0	0.4	0.9	1.8

Figure 16. Comparing the different fabric variants within the Quartz-Tempered Fabric Class. Top left is Quartz-Tempered Fabric A, top right is Quartz-Tempered Fabric B, Bottom Left is Quartz-Tempered Fabric C and bottom right is Quartz-Tempered Fabric D. The width of each image is 4.5mm

Hardness: medium hard.
Fracture: granular.

Inclusions: predominant, well sorted, sub-rounded quartz, and few powdery red-orange and black inclusions (Figure 16, top left).

Petrographic Analysis

Crucibles LM 19 and 20 were sampled for thin section analysis. In thin section the fabric is characterised by its bimodal grain-size frequency distribution, quartz inclusions and textural concentration features (Figure 17). It is optically active to optically slightly active and has a yellow (pp) and yellow brown (xp) micromass. Inclusions are very well sorted and occupy about 20% of the total field. Voids occupy about 5% of the total field and show strongly preferred orientation; they are parallel with the vessel walls. They occur predominantly as mesovughs (LM 20) and macro-vughs (LM 19). The coarse fraction (>0.06mm) consists of predominant sub-rounded to sub-angular, very fine sand-sized monocrystalline quartz, rare sub-rounded to sub-angular, very fine sand-sized chert and very rare sub-rounded to sub-angular, very fine sand-sized plagioclase. The fine inclusions (<0.06mm) comprise predominant monocrystalline quartz silt, rare white (muscovite)

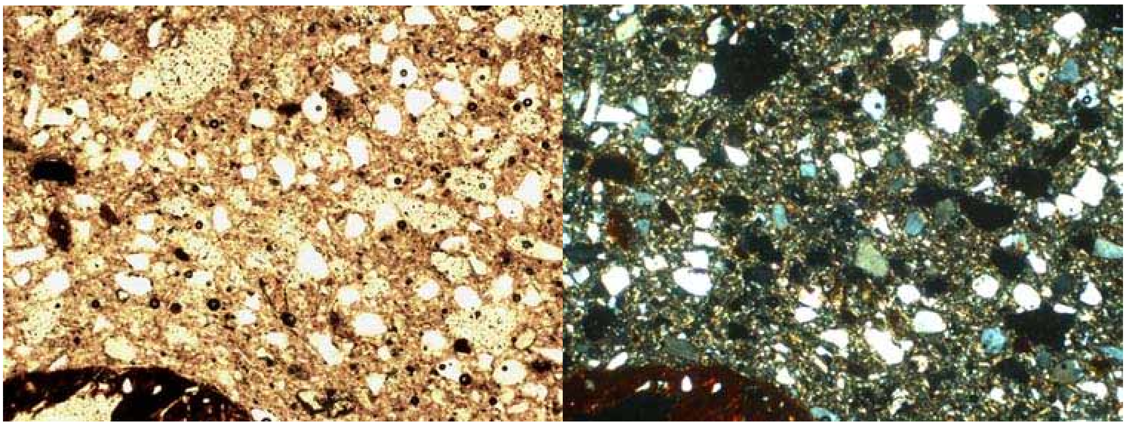


Figure 17. Thin section micrograph of crucible LM 19, Quartz-Tempered Fabric A (left pp, right xp) showing quartz temper (white inclusions) and red clay pellets (bottom left). Width of image is 2.5mm.

mica and very rare glauconite. Textural concentration features occupy about 2% of the total field in this fabric. The occur as orange to red (pp and xp) iron-rich clay pellets and are predominantly 0.10 to 0.15mm in size, though the largest is 1.10mm. They have high optical density, clear to diffuse boundaries and are rounded to elongate. Where elongate they are parallel to the vessel wall. This fabric is close in composition to the Legge's Mount ceramic fabric described by Williams (1981).

Quartz-Tempered Fabric Group B

Samples: LM 18, 76

Hand Specimen Analysis

Colour: this fabric is white (2.5Y 8/1) to light grey (5Y 7/1). Both samples are used.

Hardness: very hard.
Fracture: granular.

Inclusions: predominant, moderately sorted, rounded quartz, and few powdery pale yellow inclusions (Figure 16, top right).

Petrographic Analysis

Sample LM 18 was selected for thin section analysis. In thin section it is characterised by its bimodal grain-size frequency distribution and quartz and micrite inclusions (Figure 18). It is optically active, pale brown in pp and pale yellow brown in xp. Voids are moderately

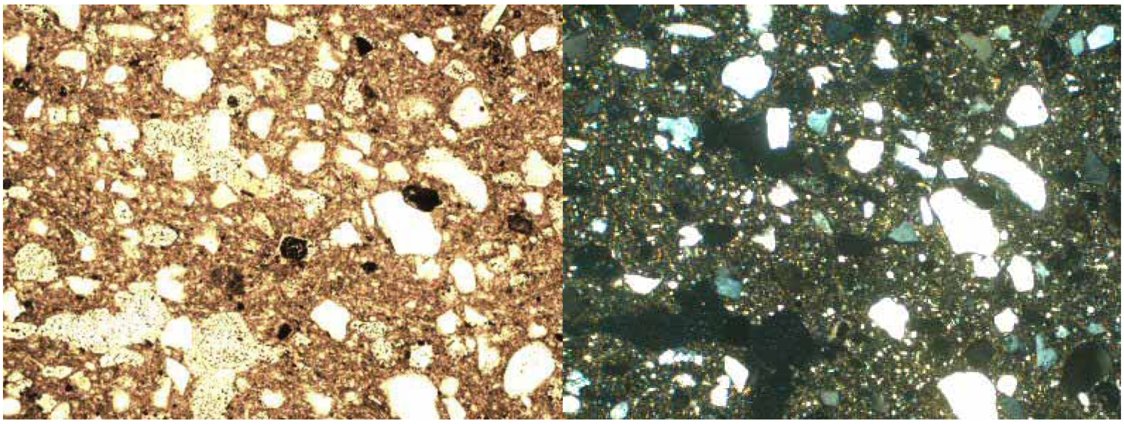


Figure 18. Thin section micrograph of crucible LM 18, Quartz-Tempered Fabric B (left pp, right xp) showing coarser quartz inclusions. Width of image is 2.5mm.

aligned with the vessel wall and occur as macro- and mesoplanar voids. They occupy about 5% of the total field. The coarse inclusions (>0.06mm) occupy about 20% of the total field. They comprise predominant very fine sand to medium sand-sized, sub-rounded to rounded monocrystalline quartz. Medium sand-sized polycrystalline quartz and medium sand to very coarse sand-sized micrite are very rare. The fine fraction (<0.06mm) is composed of predominant silt-sized monocrystalline quartz and white (muscovite) mica. Textural concentration features are absent.

Quartz-Tempered Fabric Group C

Samples: LM 22, 56, 58, 61, 74, 75

Hand Specimen Analysis

Colour: the colour of this fabric in hand specimen is pale red (2.5YR 6/1), light grey (2.5Y 7/1) and light brownish grey (2.5YR 6/2). All samples are used.

Hardness: hard to very hard.
Fracture: granular.

Inclusions: predominant very well sorted quartz (Figure 16, bottom left).

Petrographic Analysis

Crucible LM 56 was sampled for thin section analysis. In thin section it is characterised by its bimodal grain-size frequency distribution and well sorted, packed, quartz inclusions (Figure 19). It has a massive microstructure (voids are very rare) and it is optically inactive. The micromass is dark brown (pp) and dark grey brown (xp). The coarse

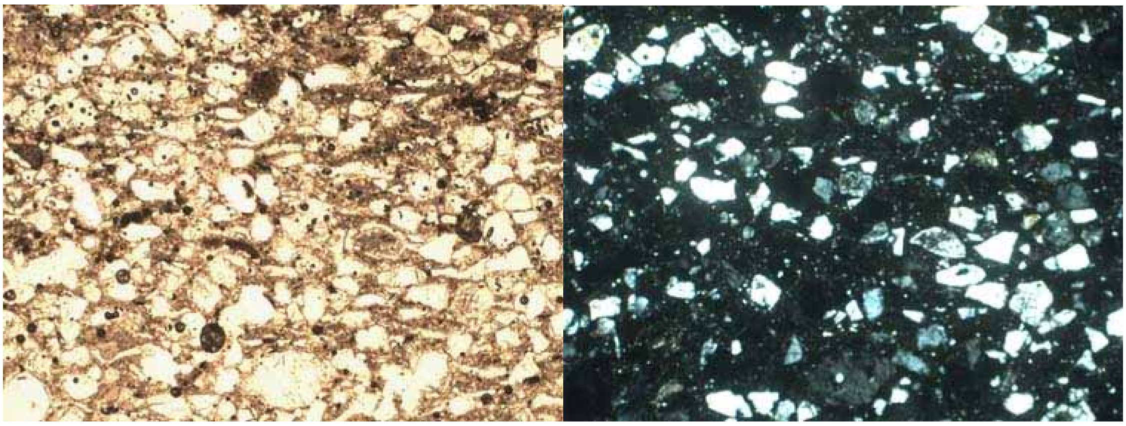


Figure 19. Thin section micrograph of crucible LM 56, Quartz-Tempered Fabric C (left pp, right xp) showing quartz temper (white inclusions in xp) in a quartz silt-rich matrix. Width of image is 2.5mm.

inclusions occupy about 30% of the total field and have a closed- to single-spaced porphyric related distribution. The coarse fraction consists of predominant angular to sub-rounded, fine sand-sized, very well sorted monocrystalline quartz. The fine fraction (<0.06mm) is composed of monocrystalline quartz and white mica silt.

Quartz-Tempered Fabric D

Sample: LM 23

Hand Specimen Analysis

Colour: this fabric is pink (7.5YR 7/3).

Hardness: hard.
Fracture: hackly.

Inclusions: Fairly well sorted, angular medium to coarse sand-sized quartz inclusions (Figure 16, bottom right). This fabric was not sampled for petrographic or SEM analysis so no further description can be given.

The clear bimodal grain-size frequency distribution present in the quartz-rich fabrics indicates that in each case the coarse fraction (sand) was added as a temper by the potter rather than occurring naturally in the clay. While the fabrics are similar in that they can each be characterised broadly by coarser quartz grains in a fine quartz-silt matrix there are sufficient differences in mineral content both in coarse and fine fractions to indicate distinct raw material resources for clay and tempering materials in each group. In terms of chemical composition of the fabrics, the analysis was able to discriminate between the two fabric classes. For example, Figure 20 shows silica v alumina

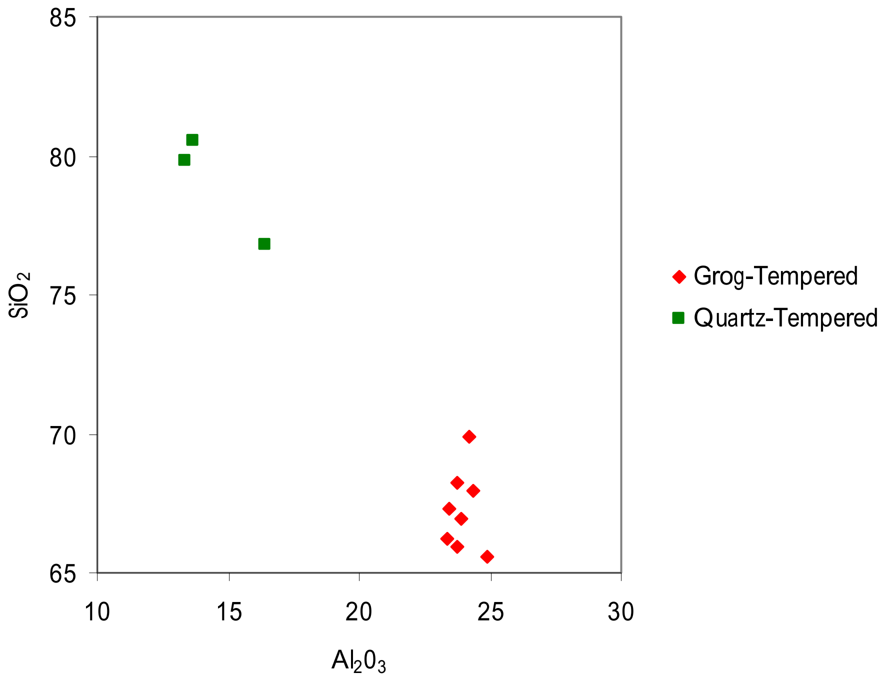


Figure 20. Biplot comparing Al_2O_3 and SiO_2 concentrations of the Grog-Tempered and Quartz-Tempered Fabric Classes.

concentrations of the Grog-Tempered and Quartz-Tempered Classes. The Quartz-Tempered Class has higher silica concentrations and lower alumina concentrations than the Grog-Tempered Class as expected. Some differences were detected in compositions between the quartz-tempered fabrics, for example Quartz-Tempered C has lower calcium oxide than the A and B groups (see Table 1), nevertheless, the 'diluting effect' of silica on other elements analysed for means that the quartz-tempered fabrics could not be characterised further. A future programme of analysis that takes into account trace element concentrations in addition to major and minor element oxides may further discriminate the fabrics and so clarify relationships between raw materials used.

Table 2 shows the correlations between the crucible types and fabrics identified. Based upon the petrographic observations it can be seen that the grog-tempered variants were used in the manufacture of crucible Types 1 and 4, and that within the two classes fabric type is not specific to crucible type. For example, Type 1 was manufactured using both the Grog-Tempered A1 and B Fabrics, while the majority of Type 4 crucibles are manufactured using the Grog-Tempered A1 fabric, but one example is manufactured using the coarser A2 variant. It is clear from macroscopic observations that crucible Types 2 and 3, and a single 'Type 8 Associated' fragment (LM 39) were also manufactured from a grog-tempered fabric. In these instances, however, it is difficult to assign specific fabric group or subgroup to type without additional microanalysis.

Table 2: Showing distribution of fabrics across the crucible types

	Type 1	Type 2	Type 3	Type 4	Type 5	Type 6	Type 7	Type 8	Type 9
Grog-Tempered A1	X			X					
Grog-Tempered A2				X					
Grog-Tempered B	X								
Quartz-Tempered A					X	X			
Quartz-Tempered B					X		X		
Quartz-Tempered C							X		X
Quartz-Tempered D								X	

In contrast to the grog-tempered fabrics which were used in the manufacture of the large crucibles and the small 'Type 4' crucibles, it appears that the quartz-tempered fabrics were used exclusively in the manufacture of the small crucibles (Types 5 to 9). Like the grog-tempered fabrics, the quartz-tempered variations were not used in the manufacture of specific types. For instance, the Quartz-Tempered A fabric was used in the manufacture of Type 5 and 6 crucibles, the B fabric for Type 5 and 7 fabrics and the C fabric for Type 7 and 9 crucibles. These results imply that within the two fabric classes the potters made use of different raw materials to manufacture the required vessels, perhaps according to availability.

Crucible use

Table 3 presents the compositions of metals droplets detected on the crucible surface (EDXRF) and trapped within the crucible fabric (SEM-EDS). The general trend appears to be that base metals are associated with the large crucible types (Types 1 to 3) and precious metals are associated with the small crucible types (Type 4 and 9). The detailed SEM-EDS compositional results are given in Appendix VI. They provide some more information on the nature of the metals or alloys that were processed at Legge's Mount. In the case of crucible LM 64 (Type 1, grog-tempered) the metal droplets were determined to be copper (ranging from 84.0 to 97wt%) containing variable minor amounts of lead, tin, antimony and silver (<1.4wt%) (Figure 23, Appendix VI). Droplets composed of silver, or silver with minor variable amounts of lead, tin, copper, antimony and gold (crucibles LM 24, 47 and 49, figures 24 and 25) were detected in examples of Type 4 crucibles. A particularly striking finding is the composition of metal droplets detected in crucibles LM 14 (grog-tempered) and LM 74 (quartz-tempered). The droplets were determined to be copper with arsenic (25 to 30wt%) and silver (present to 26wt%) in the case of LM 14 (Figure 26 and Appendix VI), while those detected in crucible LM 74 were also copper with high arsenic and silver concentrations (around 15wt%), in addition to gold (4.4wt%) and tin (1.1wt%). These appear to be Cu-As-Ag alloys. Of further note are the alloys detected in crucible LM 37. In two instances the compositions of the metal was revealed to be nickel (around 85wt%) with

Table 3. Results of analysis of metal droplets attached to the crucible surfaces (EDXRF) and metals contained within the fabrics (SEM-EDS). Elements highlighted in bold are the primary elements detected.

Type	Temper	Crucible LM	Method	Base Metal	Precious Metal
Type 1	Grog	1	EDXRF	**Cu**	
Type 1 Associated	Grog	64	SEM-EDS	**Cu**, Sn, Pb,	Ag
Type 2	Grog	6	EDXRF	**Cu**, As	
Type 3	Grog	5	EDXRF	**Cu**, As	
Type 4	Grog	14.1	SEM-EDS	**Cu**, As	
Type 4	Grog	14.2	SEM-EDS	**Cu**, As,	Ag
Type 4	Grog	14.3	SEM-EDS	**Cu**, As	Ag
Type 4 Associated	Grog	24	SEM-EDS		**Ag**
Type 4 Associated	Grog	37.1	SEM-EDS	**Ni**, Cu, Zn, Fe	
Type 4 Associated	Grog	37.2	SEM-EDS	**Ni**, Cu, Zn, Fe	
Type 4 Associated	Grog	37.3	SEM-EDS	Cu	**Ag**, Au
Type 4 Associated	Grog	37.4	EDXRF		**Au**
Type 4 Associated	Grog	47.1	SEM-EDS	Cu, Sn, Pb	**Ag**
Type 4 Associated	Grog	47.2	SEM-EDS	Cu, Pb, Sn	**Ag**
Type 4 Associated	Grog	47.3	SEM-EDS		**Ag**
Type 4 Associated	Grog	47.4	SEM-EDS		**Ag**
Type 4 Associated	Grog	47.5	SEM-EDS	Cu, Pb, Sn	**Ag**
Type 4 Associated	Grog	49.1	SEM-EDS	Cu	**Ag**
Type 4 Associated	Grog	49.2	SEM-EDS	Pb	**Ag**
Type 4 Associated	Grog	49.3	SEM-EDS		**Ag**
Type 4 Associated	Grog	49.4	SEM-EDS		**Ag**
Type 7 Associated	Quartz	75	EDXRF	**Cu**, As, Pb	
Type 7 Associated	Quartz	76	EDXRF	**Cu**, As, **Pb**	
Type 9	Quartz	58	EDXRF		**Au**
Unclassified	Grog	27	SEM-EDS	**Cu**	
Unclassified	Grog	59	SEM-EDS	**Cu**	
Unclassified	Quartz	74.1	SEM-EDS	**Cu**, As	Ag, Au
Unclassified	Quartz	74.2	SEM-EDS	**Cu**, As	Ag

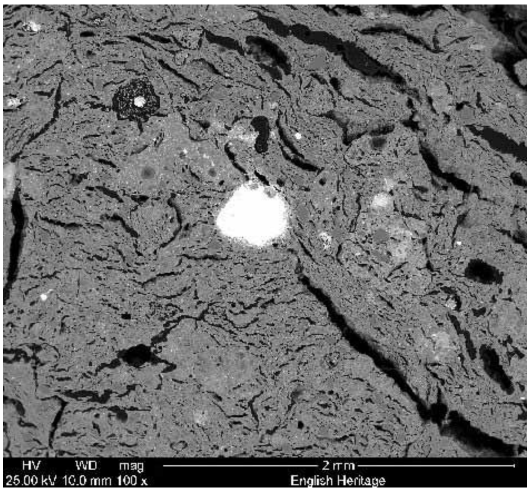


Figure 23. SEM micrograph (BS) of a Type 1 grog-tempered crucible (LM 64). The bright area in the centre of the image is copper with minor amounts of lead and tin.

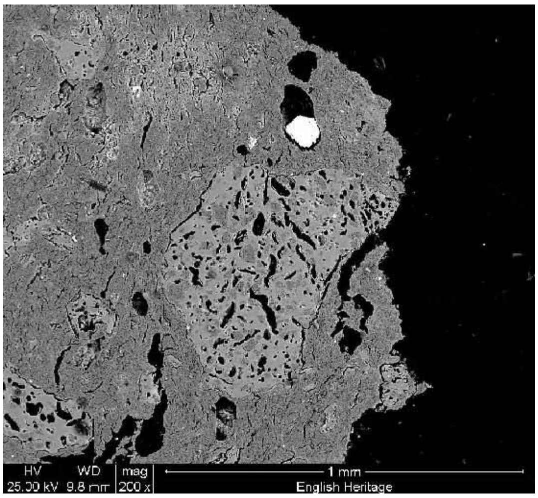


Figure 24. SEM micrograph (BS) of a Type 4 grog-tempered crucible (LM 24). The bright area at the top centre of the image is a droplet of silver.

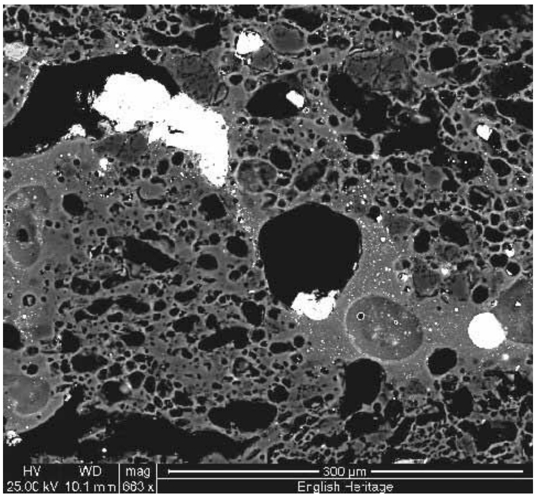


Figure 25. SEM micrograph (BS) of a grog-tempered crucible (LM 47). The metal droplets (bright areas) are silver with variable minor amounts of lead, copper, tin and antimony.

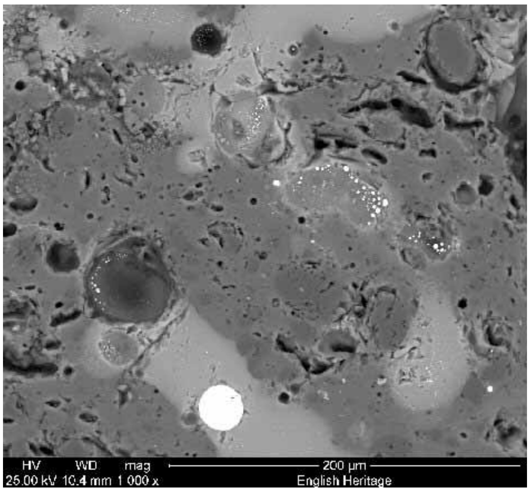


Figure 26. SEM micrograph (BS) of a Type 4 grog-tempered crucible (LM 14). The bright area in the bottom centre of the image is copper with almost equal amounts of silver and arsenic.

copper, zinc and iron also present, while silver with copper and gold was also detected in a third droplet.

DISCUSSION

The results of the analyses provide for several points of discussion relating to crucible manufacture, and crucible use at the Legge's Mount metalworking site. Since crucibles are specialised technical ceramics utilised for high temperature operations they are required to have certain physical and chemical properties to be successful. As noted previously they should have a high thermal shock resistance, be strong enough to hold the weight of the metal they contain, be sufficiently refractory to withstand high temperatures and sufficiently inert so as not to react with the crucible contents. It is clear from the historical literature that there was an awareness of these requirements. Ercker advises that every assayer should be able to manufacture his own utensils such as crucibles, scorifiers and muffles in order that they be of the right quality (Sisco and Smith 1951, 24). Agricola also records that assayers manufacture their own ceramic vessels (Hoover and Hoover 1950, 230). The various authors detail paste preparation and forming methods for crucible manufacture. Ercker (Sisco and Smith 1951, 24) recommends the use of a good potters' clay which turns white during firing (as observed in the unused examples of the Legge's Mount crucibles). This suggests that clay with a low iron content was sought out. Iron-rich clays will turn orange/red to black upon firing depending on the redox conditions of the kiln. A high iron content in clay acts as a flux and reduces the temperature at which the clay particles vitrify, and so make it less refractory. In preparing the clay, Ercker advocates tempering it with crushed pebblestone or fine white sand, and then forming the required vessels in a mould. Again, attesting to the awareness of the requirements of such technical vessels, he recommends assaying a hard to smelt, refractory ore in a crucible or scorifier from the batch of tempered clay to determine if vessels manufactured from the batch will prove reliable and resistant during use. Clay tempered with grog derived from old crucibles or scorifiers is also noted by Ercker as a paste that may be used for crucible manufacture. The use of crushed crucibles as grog in clay paste preparation for crucible manufacture is further observed by Agricola (Hoover and Hoover 1950, 230), and even earlier by Theophilus in the 12th century. Theophilus distinguishes between manufacturing gold- or silver-melting crucibles where the grog should originate from crucibles previously used for gold or silver melting, and brass cementation crucibles where it should come from crucibles previously used for melting copper or brass (Hawthorne and Smith 1979, 96, 142-3). This distinction is presumably to prevent contamination of metals subsequently processed in the crucibles.

It is noteworthy that the Legge's Mount crucibles were manufactured using either the grog-tempering or quartz-tempering technologies. The majority of the crucibles were excavated from the furnace ash pit (Parnell 1993, 59) suggesting they were contemporaneous, and so the differing manufacturing technologies cannot be attributed to chronological divisions. It is possible that the crucibles were obtained from different sources, with each source manufacturing the vessels according to preferred technologies. Documentary evidence, however, indicates that during the 16th century the Tower of London Mint employed a specialist potter to manufacture the required vessels: 'In the yeare 1546 the 27 of April, being Tuesday in Easter weeke, William Foxley, Potmaker for the Mint in the Tower of London, fell asleepe, and so continued sleeping, and could not be wakened... And he lived more then fortie yeares after in the sayde Tower, to wit, vntil the yeare of Christ, 1587, and then deceased on Wednesday in Easterweeke' (Kingsford 1908, Vol 1, 59). The reason for choice of raw materials may then be driven by other factors such as requirements for use.

Two properties particularly important for the success of crucibles during their use is their ability to retain their contents, and to survive rapid changes in temperature (thermal shock resistance). The ability of crucibles to retain their contents is dependant on their withstanding sustained load or stress and so is determined by their fracture strength. Their thermal shock resistance is dependent upon the stresses driving fracture which in turn is dependant on the thermal expansion and conductivity of vessel walls (Tite *et al* 2001, 302). Modern experimental studies show how different types of temper in a ceramic matrix can alter the performance characteristics of ceramic vessels (for example Kilikoglou *et al* 1998; Tite *et al* 2001). The use of quartz temper in amounts of 20% volume or above is known to increase toughness and thermal shock resistance. This is because the differential shrinkage or expansion of the clay and quartz inclusions during the original drying, firing and cooling of the vessel results in a network of microcracks, and debonding between the quartz inclusions and ceramic matrix. The voids that form around the quartz grains as a result of this process can accommodate further expansion of the quartz grains during subsequent firings and so act as a stabilizer for the vessel. Further, the propagation of cracks caused by thermal or mechanical shock is dissipated and arrested by the network of microcracks formed through the body and by the hard quartz inclusions (Kilikoglou *et al* 1998; Tite *et al* 2001; Martinón-Torres and Rehren 2009). Quartz sand is known as the main tempering component of crucibles from other archaeological contexts of late and post-medieval date, such as Hessian crucibles which have been well studied by Martinón-Torres and Rehren (2006; 2009).

A study by West (1992, and reported in Tite *et al* 2001, 316) which investigated loss of strength in ceramic test bars tempered with a range of materials before and after quenching from temperatures of 600°C and above produced some surprising results for the effect of grog as a temper on thermal shock resistance. It was found that with the exception of the untempered test bar, strength loss was greatest for the grog-tempered bar (69% loss), in comparison to the intermediate loss of strength for materials such as marble, quartz and sand (around 57% loss) and low loss of strength for platey materials such as mica (23% loss) and shell (45% loss). It might be expected that since the thermal expansion and contraction rates of grog and the surrounding ceramic matrix are similar, weakening by successive heating and cooling would be minimal. Nevertheless, since grog and the ceramic matrix share similar thermal expansion coefficients, the grog temper remains in close contact to the surrounding matrix (in contrast to quartz temper), and further, they have similar mechanical properties. Therefore, cracks formed during expansion and contraction may pass through the grog fragments rather than being deflected and dissipated by inclusions such as quartz (Tite *et al* 2001, 317).

While grog may not increase thermal shock resistance to the extent that the addition of mineral inclusions such as quartz or mica does, it has the advantage of increasing a clay's resistance to shrinkage, cracking and warping as it dries (green strength) (Rice 1987, 75).

As noted previously a further characteristic important to the success of crucibles are their resistance to chemical attack from its contents. Figure 21 and Table 1 show the difference in composition of the ceramic fabrics. A number of distinctions can be made between the element oxide concentrations of the fabrics belonging to the two fabric classes. Most notably, the quartz-tempered class has lower iron oxide and alumina concentrations than the grog-tempered class (with the exception of the Grog-Tempered B fabric) and these differences indicate that specific clay types were selected for the bodies of the two fabric classes. Moreover, the differences in mineral types within the fine fraction of the quartz-tempered bodies suggest that more than one low iron clay type was exploited for the manufacture of these crucibles.

In terms of performance characteristics, the grog-tempered fabrics are higher in alumina (around 24wt%) than the quartz-tempered bodies (around 15wt%), and the enriched alumina concentrations may increase their resistance to chemical attack during use (Martinón-Torres *et al* 2006, Paynter forthcoming). It is possible that the two fabric types were selected for their different properties: the quartz-tempered fabric for its more refractory properties, and the grog-tempered fabric, with its higher alumina content, for its greater resistance to chemical attack.

In considering the correlations between ceramic fabric and use of crucible, Table 3 shows that there is no clear division between fabric type and use. Precious metals were processed in crucibles manufactured from both the quartz-tempered fabric class (crucible Types 9) and the grog-tempered fabric class (crucible Type 4). The presence of lead, which can react with and digest the silica component of a ceramic body, was detected in crucibles manufactured from both fabric types, and not just the potentially more chemically resistant grog-tempered fabric. There is a clearer relationship, however, between the types of metals processed and crucible size: precious metals or precious metals with only minor amounts of base metals present (for example crucibles LM 24, 47 and 49, Table 3) were melted in the small crucibles (Types 4 and 9), while the copper alloys containing no precious metals (or trace amounts only) were melted in the large crucibles (Types 1 to 3). Presumably, the metalworkers were more cautious where the precious metals were concerned, processing them in smaller quantities due to risk of crucible failure. The loss of larger amounts of base metals would be less costly.

A final consideration for choice of raw materials in clay paste preparation (grog versus quartz-tempering) is that of crucible forming method. All of the quartz-tempered crucibles (with the exception of the large Type 8 fragment with medium to coarse sand-sized quartz inclusions (LM 23)) are wheel thrown as evidenced by rilling present on their surfaces, while none of the grog-tempered crucibles show traces of rilling. This indicates that they were manufactured using an alternative method such as mould forming (as described by Ercker (Sisco and Smith 1951, 25)), or slab/coil building. The variation in rim/wall thickness around the circumference of a number of the large crucibles (in particular LM 2 and LM 31, Type 1) is indicative that the mould forming method was used. The mould building method using grog-tempered clay is perhaps a more suitable method of manufacture for the large crucibles with thicker walls (Types 1 to 3), than wheel throwing. The increased green strength of the clay provided by the grog additions and the support given by the mould walls would help prevent collapse of the vessels during the drying stage. Vessel size alone, however, is not the only criteria which influenced choice of raw material and manufacturing method since the dimensions of the Type 4 crucibles (grog-tempered and slab/coil or mould made) fall within the range of the quartz-tempered wheel thrown vessels (Figure 1 and Appendix 1).

It is clear from assessing the correlations between crucible fabric types, manufacturing methods and crucible use, that there is no one single factor which influenced raw material selection by the potters manufacturing the crucibles. Rather, a number of factors were likely at play, some of which cannot be explained through our modern understanding of material properties or perceptions of functionality.

In examining the metalworking activities that took place at the Legge's Mount site it has been shown that a range of metals and alloys was being processed in different quantities. These include copper or copper alloys containing variable contents of tin, antimony and lead; silver, or silver containing minor amounts of copper, lead and tin; and gold. The presence of precious metals in conjunction with the silver assaying carried out at the site (White 2010) strengthens the association of the furnace and related assemblage with the Tudor Mint. Towards the end of the first half of the 16th century, coinage was progressively debased by means of reducing both the weight of the coins and the fineness of the gold or silver from which they were made (Challis 1967; Challis and Harrison 1973). Following the debasement, in 1560 under Elizabeth I the base coinage was recalled to the Mint for restoration to fineness (Read 1936, Barter 1978). Again, both base and precious metals are likely to be present at the Mint during operations in this recoinage phase.

Of particular interest are the arsenic and silver-rich copper alloys detected in the bodies of crucibles LM 14 and LM 74. To recap, the compositions detected were approximately 47wt% copper with equal amounts of silver and arsenic at around 26wt% (crucible LM 14, Appendix VI) and 63wt% copper, with equal amounts of silver and arsenic at around 15wt%, 4.4wt% gold and 1.1wt% tin (crucible LM 74, Appendix VI). It is recognised that reconstructing the composition of an alloy melted in a crucible from the residues of the metals trapped inside the crucible fabric is problematic due to the behaviour of the different metals according to temperature and redox conditions. Nevertheless, the arsenic and silver concentrations are sufficiently high to assume the original crucible charge also contained high concentrations of these metals. Prior work has shown that it was rare for arsenic to exceed 0.5wt% in most medieval and post-medieval copper alloys (Blades 1995, reported in Dungworth and Nicholas 2004), though cast copper alloy domestic vessels of the same period contained up to 1.2wt% arsenic (Dungworth and Nicholas 2004). This makes the enriched arsenic concentrations detected in the two crucibles extremely distinctive.

A highly speculative explanation is that the residues represent the treatment of the fahlerz ore tennantite ($Cu_{12}As_4S_{13}$). Silver along with iron, zinc, cadmium and mercury can substitute the copper (Ixer and Pattrick 2003). Nevertheless, the low levels of sulphur detected cast doubt on this hypothesis.

The nickel-rich alloy (nickel concentrations around 85wt%) detected in crucible LM 37 is also worthy of note. Like arsenic, nickel is present in medieval and post-medieval copper alloys in minor amounts only. Reported concentrations are commonly <1wt% (for example Dungworth 2005, 233; Dungworth and Nicholas 2004, 26). While nickel was not isolated as a distinct metallic element until up to two centuries later in 1751 by Cronsdedt (Muspratt 1860), experimental metallurgy was a common practice during the 16th century. Both analytical chemistry and the more familiar large-scale metallurgical operations were routinely carried out in official mints (Martinón-Torres and Rehren 2005b, 20), and the presence of this alloy, along with the copper-arsenic-silver alloy may reflect metallurgical experimentation.

CONCLUSIONS

The examination of the Legge's Mount crucibles has provided a number of findings which elucidate the metalworking activities at the site. In terms of crucible manufacture, the fabric analyses have revealed the crucibles were fabricated using two distinct clay paste preparation technologies: grog-tempering and quartz-tempering, both of which are recorded in contemporary texts that describe metalworking and assaying methodologies. There was no clear correlation detected between fabric type and crucible use. The grog-tempered crucibles Types 1 to 3 were used for melting base metals, and the quartz-tempered crucibles and the grog-tempered Type 4 crucibles were used for melting precious metals. It is more likely that choice of tempering material relates to crucible forming method. With the exception of the coarse Quartz-Tempered Fabric D, the fine quartz-tempered crucibles where wheel-thrown, while the grog-tempered crucibles all appear to be mould or slab/coil built.

A range of metals were being processed at the Legge's Mount furnace site as evidenced by the residues left on and within the crucible fabrics. Both base and precious metals, or alloys of copper and gold/silver were present, strengthening the association of the site with the operations of the Tudor Mint. Two highly unusual alloy types were also detected; that of copper with significant concentrations of arsenic and silver, and nickel with minor amounts of zinc, copper and iron. These findings suggest that experimental metallurgy was also practiced at the site, in keeping with official mint operations.

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APPENDIX I
Catalogue of Legge's Mount crucibles

Type	Crucible LM	Height (mm)	Minor ext. rim diameter (mm)	Major ext. rim diameter (mm)	Rim thickness (mm)	Base diameter (mm)	Base thickness (mm)	Sherd	Comment
Type 1A	1	220	150	180	12.6–18.5	100	25	Complete	Used
Type 1B	2	240	140	170	11.1–14.7	95	23	Complete	Used
Type 1B	66							Base	Used
Type 1 Associated	31		150					Rim	Unused
Type 1 Associated	42							Body	Used
Type 1 Associated	43						16	Base (internal only)	Used
Type 1 Associated	64							Body	Used
Type 2	9	150	160	180	11.7	110	25	Complete	Used
Type 2	3	175	150	175	10.8	100	30	Complete	Used
Type 2	4	160	130	180	10.4	105	17	Complete profile	Used
Type 2	6	160		170	10.6	110	22	Complete profile	Used
Type 2	7	150	160	180	11.9	100	33	Complete profile	Used
Type 2	8	150		170	11.7	110	28	Complete profile	Used
Type 2 Associated	10						34	Base	Used
Type 2 Associated	26				11.4			Rim	Used
Type 2 Associated	29			190	9.9			Rim	Used
Type 2 Associated	69							Rim	Used
Type 3	5	170	160	180	14.8-15.9	110	20	Complete profile	Used
Type 3 Associated	30		160		19.8			Rim	Used
Type 4	12	70		95	8.7	65	18	Complete	Used
Type 4	13	70		75	6.8	50	11	Complete	Used

Type	Crucible LM	Height (mm)	Minor ext. rim diameter (mm)	Major ext. rim diameter (mm)	Rim thickness (mm)	Base diameter (mm)	Base thickness (mm)	Sherd	Comment
Type 4	14	50		60	6.2	40	12	Complete	Used
Type 4	15	45		60	5.8	45	10	Complete	Used
Type 4	11	100				70	16	Complete profile	Used
Type 4	16					50	14	Base	Used
Type 4	38					60	14	Base	Used
Type 4 Associated	47			60	7.0			Rim	Used
Type 4 Associated	49				6.0			Rim	Used
Type 4 Associated	24					50	14	Base	Used
Type 4 Associated	34					50	8	Base	Used
Type 4 Associated	37					50	12	Base	Used
Type 4 Associated	35						11	Base	Used
Type 4 Associated	67							Body + spout	Used
Type 5A	17	110		120	8.0	75	10	Complete	Unused
Type 5A	19	100		120	7.4	85	10	Complete	Unused
Type 5B	18	100		100	7.5	70	10	Complete	Used
Type 5B	63			100	8.2			Rim	Unused
Type 6A	20	60	40	70	4.5	45	5	Complete	Unused
Type 6A	73			60	4.6			Rim	Used
Type 6B	21	50	50	70	3.5	30	5	Complete	Unused
Type 7	22	40		40	4.6	30	4	Complete	Used
Type 7 Associated	75					30	4	Base	Used
Type 7 Associated	76					30	5	Base	Used
Type 8	23	65		100	10.5	70	12	Complete profile	Unused

Type	Crucible LM	Height (mm)	Minor ext. rim diameter (mm)	Major ext. rim diameter (mm)	Rim thickness (mm)	Base diameter (mm)	Base thickness (mm)	Sherd	Comment
Type 8 Associated	39							Body	Used
Type 8 Associated	54							Body	Used
Type 9	61				3.0			Rim	Used
Type 9	58							Spout	Used
Type 9	56							Body	Used
Unclassified	25							Rim	Used
Unclassified	28							Rim	Used
Unclassified	32			80	6.4			Rim	Used
Unclassified	27			115	10.0			Rim	Used
Unclassified	48							Rim	Used
Unclassified	55							Rim	Used
Unclassified	57			90	7.0			Rim	Used
Unclassified	59			100	7.0			Rim	Used
Unclassified	60			70	8.2			Rim	Used
Unclassified	62			90	6.2			Rim	Used
Unclassified	65			60	6.1			Rim	Used
Unclassified	50					65	10	Base	Used
Unclassified	74					40	4	Base	Used
Unclassified	33							Body	Used
Unclassified	36							Body	Used
Unclassified	40							Body	Used
Unclassified	41							Body	Used
Unclassified	44							Body	Used

Type	Crucible LM	Height	Minor ext. rim diameter (mm)	Major ext. rim diameter (mm)	Rim thickness (mm)	Base diameter (mm)	Base thickness (mm)	Sherd	Comment
Unclassified	45							Body	Used
Unclassified	46							Body	Used
Unclassified	52							Body	Used
Unclassified	68							Body	Used
Unclassified	70							Body	Used
Unclassified	72							Body	Used

APPENDIX II

Tables explaining terms employed in the petrographic thin section descriptions (after Whitbread 1995, 379–382).

Table 1. Frequency labels

Predominant	>70%
Dominant	50 – 70%
Frequent	30–50%
Common	15–30%
Few	5–15%
Very few	2–5%
Rare	0.5–2%
Very Rare	<0.5%

Table 2. Inclusion boundaries

Sharp	Knife-edge
Clear	<0.06mm
Diffuse	>0.06mm
Merging	Part of boundary is missing

Table 3. Void descriptions

Planar Voids	Linear in thin section but planar in 3-D, sub-angular changes may be noted
Channels	May be linear in thin section but cylindrical in 3-D
Vughs	Relatively large, irregular voids
Vesicles	Regular in shape, smooth surfaces
Mega	>2mm
Macro	0.5–2mm
Meso	0.05–0.5mm
Micro	<0.05mm

Table 4. Optical activity

Optically active	Domains display interference colours and extinction
Optically inactive	No change in optical properties when stage is rotated

Table 5. Porphyric related distribution modifiers

Closed-spaced	Grains have point of contact
Single-spaced	The distance between grains is equal to their mean diameters
Double-spaced	The distance between grains is equal to double their mean diameters
Open-spaced	The distance between grains is more than double their mean diameters

APPENDIX III

Thin Section Descriptions

GROG-TEMPERED FABRIC CLASS

GROG-TEMPERED FABRIC A1

Samples: LM 27, 37, 47, 49, 59, 64

I Microstructure

(a) Voids: Voids occupy 5 to 10% of the total field. They occur as dominant macroplanar voids, frequent macrovughs, common mesovughs and rare to absent mesovesicles.

(b) Inclusions have a single to double porphyric related distribution.

(c) Preferred orientation is moderate to strong, with voids aligned to the vessel margins.

II Groundmass

(a) Homogenous.

(b) The micromass is optically inactive to optically slightly active. The colour ranges from red brown to grey to black (xp x40), and yellow brown to pale grey brown (pp x40).

(c) Inclusions: The grain-size frequency distribution is bimodal, though the mineral content has a unimodal grain-size frequency distribution.

Mineral inclusions occupy about 15 to 25% of total field and comprise:

Predominant – sub-rounded to sub-angular monocrystalline quartz in the silt to very fine sand range.

Absent to very rare – sub-rounded to sub-angular, medium sand-sized chert.

Textural Concentration Features: Tcfs occupy about 40 to 50% of the total field. They comprise rounded to angular grog inclusions. The grog inclusions range in size from 0.2mm to 2.5mm (fine sand to granular-sized). They have sharp to clear boundaries and are commonly surrounded by voids. They range from having high optical density where the grog is black in a matrix of grey (xp x40) (for example LM 47), neutral optical density where the inclusions are hard to distinguish from the matrix in xp and pp x40 (for example LM 27), and low optical density where the grog is grey in a black matrix (xp x40) (for example LM 49). The fabric of the grog has the same composition and grain-size distribution as the surrounding matrix.

GROG-TEMPERED FABRIC A2

Sample: LM 24

Microstructure

(a) Voids: voids occupy about 15% of the total field. They occur as frequent macroplanar voids, few mesoplanar voids and few mesovughs.

(b) The inclusions have a single to double spaced porphyric related texture.

(c) Voids show strongly preferred orientation parallel to the vessel margins.

Groundmass

(a) Homogenous.

(b) The micromass is optically active. The colour is orange brown (xp x40) and orange brown (pp x40).
(c) Inclusions have a bimodal grain-size frequency distribution, though the mineral content has a unimodal grain-size frequency distribution.

Mineral inclusions occupy approximately 15% of the total field and comprise:
Predominant – sub-rounded to sub-angular monocrystalline quartz in the silt to very fine sand-size range.

Textural Concentration Features: Tcfs occupy about 50% of the total field. They occur as angular to sub-rounded fragments of grog which range in size from 0.2mm to 3.5mm (fine sand to granule size). They have sharp to clear boundaries and can be surrounded by voids. They have high optical density and their colour ranges from dark grey brown to black (xp x40) and grey brown (pp x40). The grog fabric has the same composition and grain-size distribution as the surrounding matrix, and may contain bloated pores. The larger grog inclusions contain pieces of grog themselves.

GROG-TEMPERED FABRIC B
Sample: LM 31

Microstructure
(a) Voids: Voids occupy about 20% of the total field. They comprise frequent macroplanar voids, common mesoplanar voids and common mesovughs.
(b) The inclusions have a single to double-spaced porphyric related distribution.
(c) The voids show strongly preferred orientation and are parallel to the vessel walls.

Groundmass
(a) Homogenous
(b) The micromass is optically inactive, and is grey brown (xp x40) and dark brown (pp x40).
(c) Inclusions have a bimodal grain-size frequency distribution, though the mineral content has a unimodal grain-size frequency distribution.

Mineral inclusions occupy about 15% of the total field. They comprise:
Predominant – sub-rounded to sub-angular monocrystalline quartz in the coarse silt to medium sand-sized range.

Textural Concentration Features: Tcfs occupy about 40% of the total field and occur as rounded to sub-angular fragments of grog which range in size from 0.25mm to 1.50mm (fine to very coarse sand-size). The boundaries are sharp to clear and the grog inclusions are commonly surrounded by voids. They have a high optical density and are optically inactive. The colour is very dark brown (xp x40) and brown-black (pp x40). The grog inclusions contain absent to rare monocrystalline quartz in the very fine sand size range, and bloated pores can be present. The fabric of the grog differs from that of the surrounding matrix.

QUARTZ-TEMPERED FABRIC CLASS

QUARTZ-TEMPERED FABRIC A

Samples: LM 19, 20

I Microstructure

(a) Voids: Vughy microstructure with vughs occupying about 5% of total field. They occur predominantly as mesovughs (LM 20) and macrovughs (LM 19).

(b) Fine grained inclusions (<0.06mm) have a single to double-spaced porphyric related distribution; coarse inclusions have (>0.06mm) have a single-spaced porphyric related distribution.

(c) Preferred orientation is moderate to strong. Voids and banding are parallel to vessel margins.

II Groundmass

(a) LM 19 is homogenous, LM 20 is heterogeneous. Banding occurs where the coarse fraction is absent.

(b) The micromass is optically active (LM 20) and optically slightly active (LM 19), and is pale yellow brown (xp x100) and yellow (pp x100).

(c) Inclusions: The grain-size frequency distribution is bimodal.

Coarse inclusions (>0.06mm) are very well sorted and occupy about 20% of the total field. They comprise:

Predominant – sub-rounded to sub-angular monocrystalline quartz in the very fine sand-sized range.

Rare – sub-rounded to sub-angular, very fine sand-sized chert.

Very rare – sub-rounded to sub-angular, very fine sand-sized plagioclase.

Fine inclusions (<0.06mm) occupy about 10% of total field. They comprise:

Predominant – monocrystalline quartz.

Rare – white (muscovite) mica.

Very rare – glauconite.

Textural Concentration Features: Textural concentration features (tcfs) occupy about 2% of the total field. They are orange to red (pp and xp x100) clay pellets, and are predominantly 0.1 to 0.15mm in size though the largest is 1.1mm. They have high optical density, clear to diffuse boundaries and are rounded to elongate (stretched). Where elongate they are parallel to the vessel wall.

QUARTZ-TEMPERED FABRIC B

Sample: LM 18

I Microstructure

(a) Voids: voids occupy about 5% of the total field and occur predominantly as macroplanar voids and few mesoplanar voids.

(b) Fine grained inclusions (<0.06mm) have an open to double-spaced porphyric related distribution; coarse inclusions (>0.06mm) have single-spaced porphyric related distributions.

(c) Preferred orientation is moderate and where present is displayed in voids, which are in alignment with the vessel wall.

II Groundmass
(a) Homogenous.
(b) The micromass is optically active, pale yellow brown (xp x100) and pale brown (pp x100).
(c) Inclusions: The grain-size frequency distribution is bimodal.

Coarse inclusions (>0.06mm) are moderately sorted and occupy about 20% of the total field. They comprise:
Predominant – very fine sand to medium sand-sized monocrystalline quartz. The grains are sub-angular to sub-rounded.
Very rare – polycrystalline quartz in the medium sand-sized range, and medium to very coarse sand-sized, sub-rounded micrite.

Fine inclusions (<0.06mm) occupy about 10% of total field. They comprise:
Predominant – quartz silt.
Very rare – white (muscovite) mica.

Textural Concentration Features: Absent.

QUARTZ-TEMPERED FABRIC C
Sample: LM 56

I Microstructure
(a) Voids: LM 56 has a massive microstructure.
(b) Fine grained inclusions (<0.06mm) have an open to double-spaced porphyric related distribution; coarse inclusions (>0.06mm) have closed to single-spaced.
(c) Preferred orientation is weak.

II Groundmass
(a) Homogenous.
(b) The micromass is optically inactive. It is dark grey-brown (xp x100) and dark brown (pp x100).
(c) Inclusions: The grain-size frequency distribution is bimodal.

Coarse inclusions (>0.06mm) are very well sorted and occupy about 30% of the total field. They comprise:
Predominant – angular to sub-rounded, fine sand-sized monocrystalline quartz

Fine inclusions (<0.06mm) occupy about 10% of total field. They comprise:
Predominant – quartz silt.
Very rare – white (muscovite) mica.

Textural Concentration Features: Absent.

APPENDIX IV

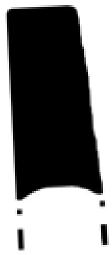
Comparison of qualitative EDXRF and quantitative SEM-EDS results

LM	EDXRF	SEM-EDS
14	Cu, Zn, Sn, Pb, As	Cu-As-Ag alloy
18	Cu, Pb	No metal (trace of Pb in crucible fabric)
19	Cu, Pb	No metal
24	Cu, Pb, As	Pure Ag
27	Cu, As	Pure Cu (trace of As in crucible fabric)
31	Cu, Ag	No metal (traces of Ag in crucible fabric)
37	Cu, Zn, Pb, As	Ni-Cu-Zn-Fe alloy Ag-Cu-Au alloy
47	Cu, Au	Ag-Cu-Pb-Sn alloy
49	Cu, Zn, Sn, Pb, Ni, As, Ag	Ag-Cu-Pb alloy
56	Cu, Au	No metal
59	Pb	Pure Cu
64	Cu, Zn, Sn, Pb, As	Cu-Pb-Sn-Sb-Ni alloy
74	Cu, Sn, Pb, As, Ag	Cu-Ag-As-Au alloy
76	Cu, Zn, Sn, Pb, As, Sb,	No metallic droplets

APPENDIX V

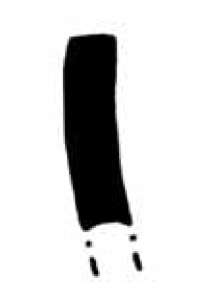
Legge's Mount crucible rim forms (scale is 1:1, vessel interior to the right in each image).

(a) Type 1, LM 31

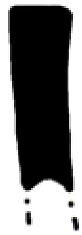


(b) Type 2, LM 29

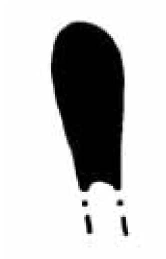
(c) Type 3, LM 5



(d) Type 4, LM 14



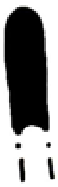
(e) Type 5A, LM 19



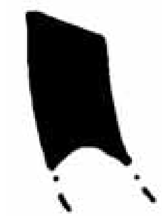
(f) Type 5B, LM 18

(g) Type 6A, LM 20

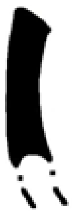
(h) Type 6B, LM 21



(i)Type 7, LM 22

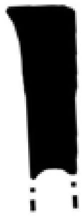


(j)Type 8, LM 23



(k) Type 9, LM 61

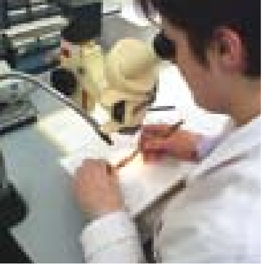
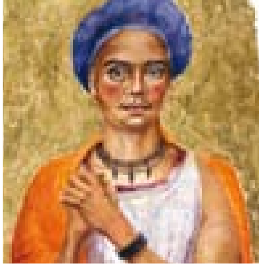
(l)LM 28



APPENDIX VI

Results of the SEM-EDS spot analyses of the metal droplets trapped with the crucible fabrics. The main metallic elements present are highlighted.

LM	S	Fe	Ni	Cu	Zn	As	Ag	Sn	Sb	Au	Pb
14.1	<0.1	0.4	0.1	**69.6**	<0.1	**30.0**	<0.5	<0.5	<0.5	<0.5	<0.5
14.2	0.3	1.4	<0.1	**58.6**	0.5	**30.6**	**8.6**	<0.5	<0.5	<0.5	<0.5
14.3	0.3	1.0	<0.1	**46.8**	0.2	**25.4**	**26.5**	<0.5	<0.5	<0.5	<0.5
24.1	0.1	0.3	<0.1	<0.1	<0.1	<0.1	**99.5**	<0.5	<0.5	<0.5	<0.5
27.1	<0.1	<0.1	<0.1	**100.0**	<0.1	<0.1	<0.5	<0.5	<0.5	<0.5	<0.5
37.1	0.7	**4.4**	**83.0**	**6.9**	**5.0**	<0.1	<0.5	<0.5	<0.5	<0.5	<0.5
37.2	0.7	**2.6**	**85.9**	**5.9**	**5.0**	<0.1	<0.5	<0.5	<0.5	<0.5	<0.5
37.3	<0.1	0.2	<0.1	**15.5**	<0.1	<0.1	**81.9**	<0.5	<0.5	**2.4**	<0.5
47.1	<0.1	0.2	<0.1	**3.8**	<0.1	<0.1	**87.4**	**2.6**	**1.0**	<0.5	**5.0**
47.2	<0.1	0.3	<0.1	**4.9**	<0.1	<0.1	**89.9**	**1.2**	<0.5	<0.5	**3.7**
47.3	<0.1	0.1	<0.1	<0.1	<0.1	<0.1	**99.1**	<0.5	<0.5	<0.5	0.8
47.4	<0.1	0.1	<0.1	<0.1	0.1	<0.1	**98.8**	<0.5	<0.5	<0.5	0.9
47.5	<0.1	0.1	<0.1	**7.2**	<0.1	<0.1	**84.5**	**3.2**	<0.5	**2.2**	**2.8**
49.1	<0.1	0.1	<0.1	**11.2**	<0.1	<0.1	**88.7**	<0.5	<0.5	<0.5	<0.5
49.2	0.2	0.2	<0.1	0.3	<0.1	<0.1	**94.7**	<0.5	<0.5	<0.5	**4.6**
49.3	0.2	0.2	<0.1	0.4	0.1	<0.1	**99.1**	<0.5	<0.5	<0.5	<0.5
49.4	0.1	0.6	<0.1	0.3	<0.1	<0.1	**99.0**	<0.5	<0.5	<0.5	<0.5
59.1	<0.1	0.4	0.1	**99.4**	<0.1	<0.1	<0.5	<0.5	<0.5	<0.5	<0.5
64.1	<0.1	<0.1	0.5	**84.0**	0.1	**1.2**	<0.5	**5.1**	**1.3**	<0.5	**7.7**
64.2	0.1	<0.1	0.4	**93.0**	<0.1	<0.1	0.0	**3.9**	0.7	<0.5	**2.0**
64.3	<0.1	<0.1	0.7	**96.8**	<0.1	<0.1	<0.5	**2.5**	<0.5	<0.5	<0.5
64.4	<0.1	0.1	0.2	**95.9**	<0.1	<0.1	**1.4**	<0.5	**1.8**	<0.5	0.6
64.5	<0.1	0.1	0.3	**95.4**	<0.1	<0.1	0.8	0.6	0.8	<0.5	**1.9**
64.6	<0.1	<0.1	0.2	**94.1**	0.1	<0.1	1.3	1.3	<0.5	<0.5	**3.0**
74.1	0.1	<0.1	<0.1	**63.4**	<0.1	**16.8**	**14.3**	**1.1**	<0.5	**4.4**	<0.5
74.2	0.6	**2.3**	0.2	**68.1**	<0.1	**28.8**	<0.5	<0.5	<0.5	<0.5	<0.5



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