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The Weald (Surrey & Sussex) Scientific examination of Glass and Glassworking materials from three sites

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SCIENTIFIC EXAMINATION OF GLASS AND GLASSWORKING MATERIALS FROM THREE SITES IN THE WEALD (SURREY AND SUSSEX)

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SUMMARY

This report summarises the analysis of glassworking waste from three sites in the Weald: Imbhams Farm, Glasshouse Lane and Lordings Farm. The glassworking remains were excavated between 2013 and 2014 by the Surrey County Archaeological Unit (SCAU) as part of the Wealden Glass Industry Project (Pr5299), which is supported and funded by Historic England (and previously English Heritage). The sites date to the 16th and 17th centuries. The assemblages of glass, crucibles and furnace remains were analysed using SEM-EDS and XRF at the laboratories at Fort Cumberland.

CONTRIBUTORS

The analyses and report were completed by David Dungworth (Historic England), based on assemblages recovered by the SCAU. The fired surfaces at two of the sites were dated by Paul Linford (Historic England). The report was edited by Sarah Paynter.

ACKNOWLEDGEMENTS

Particular thanks to the Historic England geophysics team for completing additional geophysics surveys to locate two of the furnace sites, without whom the excavations could not have proceeded, and for subsequent archaeomagnetic dating of the remains (Paul Linford and Zoe Edwards). Thank you to the SCAU who undertook the archaeological investigation at all three sites. This report also acknowledges colleagues and students, past and present, who have contributed to the interpretation of the glassworking waste, most recently Colin Clark, Vanessa Castagnino and Sarah Paynter.

ARCHIVE LOCATION

The report will be accessible through the Historic England website. The data and samples are retained at Historic England, Fort Cumberland. The material archive will be deposited via Guildford Heritage Services.

DATE OF RESEARCH

2016–17

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INTRODUCTION

This report is a contribution to the Wealden Glass Industry Project (Pr5299) which is supported and funded by Historic England (and previously English Heritage) and carried out by the Surrey County Archaeological Unit (SCAU). Between 2013 and 2014 the SCAU carried out excavations on three glassworking sites within the Weald (Imbhams Farm SU 928 336, Glasshouse Lane TQ 008 237and Lordings Farm TQ 077 244, see Figure 1).

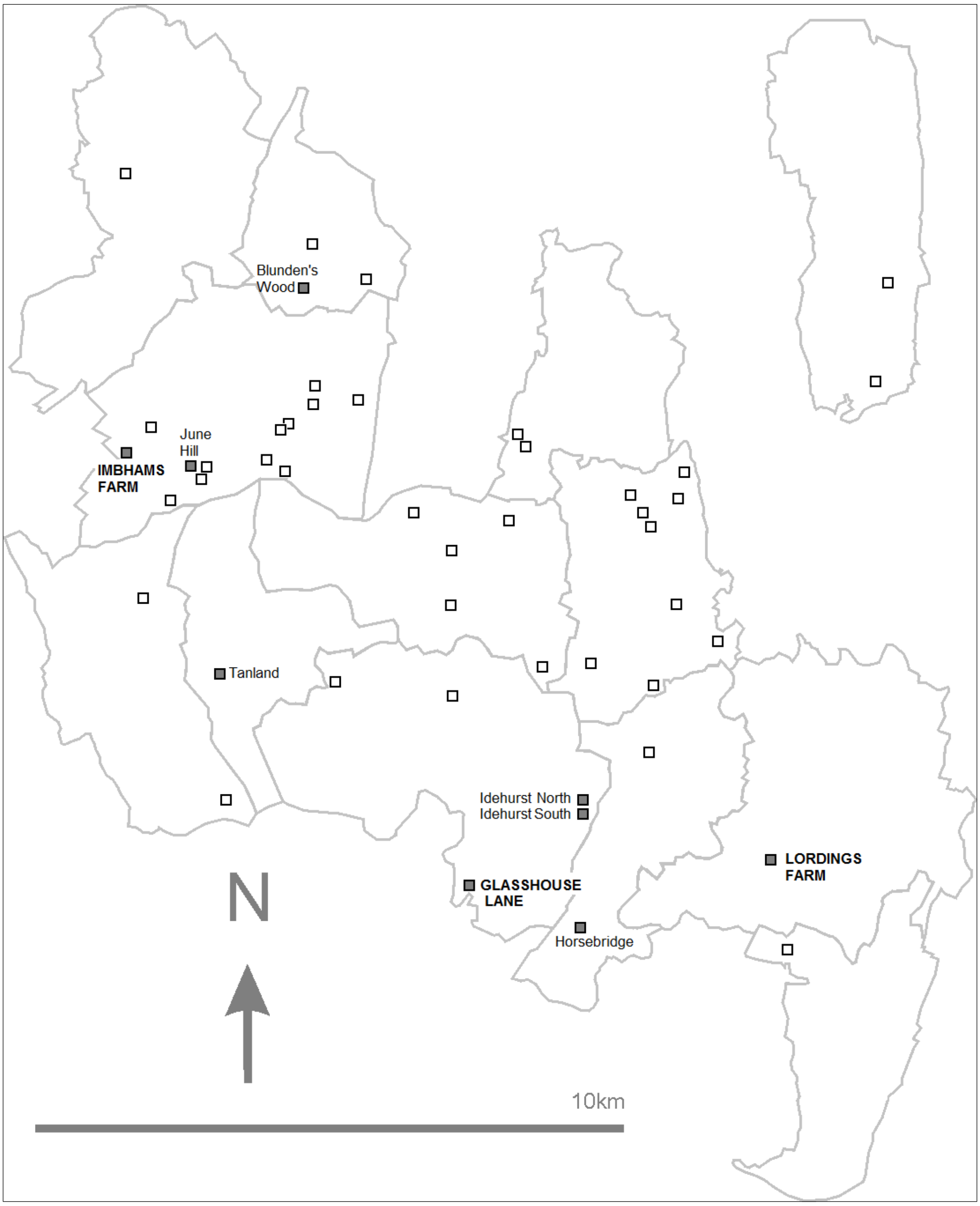


Fig 1: Map of selected parishes on the Surrey-Sussex border showing the location of Wealden glasshouses (key sites named)

Surveys in this area have previously identified 48 glass manufacturing sites (Winbolt 1933, Kenyon 1967; Crossley 1994, Clark 2006) in 12 parishes straddling the Surrey-Sussex border. Most sites have been located through the use of place name evidence and surface recovery of diagnostic glassworking waste. The historical evidence indicates glass manufacture from the 14th century onwards (production could pre-date the earliest historical evidence). In 1567 Jean Le Carré invited French glassmakers (from Lorraine and Normandy) to work in England and they settled initially in the Weald. There are numerous historical references to the activities of these French glassmakers (Godfrey 1975) and many of the known glass production sites in the Weald have been linked to them. The industry rapidly declined in the late 1610s following the ban on the use of wood as a fuel for the furnaces.

Previous researchers have noted that glass recovered from Wealden sites can be divided into two categories and that these are chronologically significant. The early glass is described as ‘primitive’, ‘usually soft with no sharp fracture, semi-opaque, and pale milky-green with a, now rough and often corroded surface’ (Kenyon 1967, 17), and is presumed to have been made before the arrival of French glassmakers. The late glass associated with the arrival of the French glassmakers is described as, ‘at its best indistinguishable from modern glass, mostly hard with a sharp fracture, fairly clear, dark blue-green with a burnished surface which is seldom corroded, and much more uniform in appearance than the earlier, poorer glass’ (Kenyon 1967, 17). Prior to the current project, only two sites (Blunden’s Wood and Knightons) had been archaeologically excavated and independently dated (associated artefacts and archaeomagnetic dating of the furnace remains).

Table 1: Archaeomagnetic dating results

Site	Archaeomagnetic Date
Imbhams Farm	1515–1565
Glasshouse Lane	1555–1650
Lordings Farm	None

The Wealden Glass Industry Project (HE Pr5299) aims to improve understanding of this nationally important industry to inform its conservation. Surveys have successfully confirmed the location of several sites identified by early researchers. Excavations at three sites (Imbhams Farm, Glasshouse Lane and Lordings Farm) have recovered glass and glassworking materials. Imbhams Farm was included in Kenyon’s schedule of sites (Kenyon 1967, site number 8) and considered to be probably a late site (*ie* dating to after the initial arrival of French glassmakers in 1567: ‘with no finished glass, dating is uncertain so I have only provisionally dated it. The quality of the product is fair but the appearance is late’ (Kenyon 1967, 168). Kenyon also suggested that Glasshouse Lane (Kenyon 1967, site number 14) was late based on the ‘uniform fine quality’ of the glass recovered (Kenyon 1967, 174). Kenyon 1967 speculated that Lordings Farm (site number 41) might be late but presented no direct evidence. The recent excavation of these sites provided the opportunity to carry out archaeomagnetic dating of *in situ* furnace remains (Table 1, after Linford 2016). It is very likely that Imbhams Farm operated before the arrival of French glassmakers in 1567 and the years that followed (cf Godfrey 1975), while Glasshouse Lane was probably in use after the arrival of French glassmakers.

AIMS AND OBJECTIVES

The main aims of the research reported here were to better understand the nature of the glass manufactured at three Wealden sites and the range of materials used in its manufacture. This was achieved through the detailed examination and analysis of the glass and glassworking materials. The objectives included establishing the chemical and mineral composition (and in some cases the microstructure) of a range of glass and glassworking materials. The results of this examination and analysis are compared with other available data on contemporary glass manufacture in England.

METHODOLOGIES EMPLOYED

All of the excavated glass and glassworking material was examined visually and selected samples were further investigated using a range of scientific techniques to determine their chemical composition and (where appropriate) their microstructure and mineral composition.

Methods of Visual Examination

All material was examined visually and classified following standard procedures (Historic England 2018; Historic England 2015). The material received had all been washed and some preliminary identification and sorting had been carried out. The categories of material identified (see below for definitions/discussions) were weighed and the results recorded for each context.

Glass and Glassworking Waste

Glass is readily identifiable due to its transparency (or in extreme cases translucency). Most of the glass has a discernible tint or colour which varies from very pale green through various shade of green and blue-green (Figures 2 and 3).

Some virtually colourless glass is present in the assemblage; however, most examples are readily identifiable as modern and are usually restricted to unstratified contexts. Some of the apparent variation in the tint of the remaining glass is a product of the thickness of the glass rather than the differences in the chemical composition of the glass. Much of the glass has thick layers of opaque corrosion covering the surface and this contributed to some of the occasional erroneous preliminary identifications. The glass is mostly present in the form of amorphous lumps, however, a good deal of flat glass (presumably window glass) is present and small quantities of vessel glass and diagnostic glassworking waste (*eg* threads and moils) were also noted (Figures 4 and 5).

Fig 2: Window Glass from Lordings Farm (context [103])

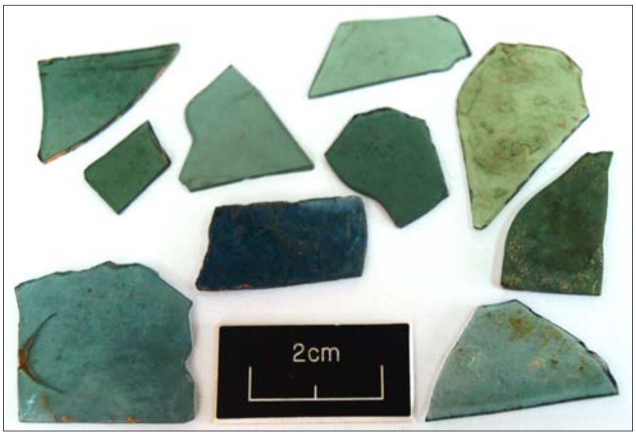


Fig 3: Window glass from Glasshouse Lane (context [103])

Fig 4: Glass waste (threads, runs and droplets) from Glasshouse Lane (context [107])

Fig 5: Glass waste ('stone' pulled with tongs from molten glass) from Glasshouse Lane (context [107])

Stone

Substantial quantities of stone were submitted for analysis. This material appears to have been used as part of the structure of one or more furnace in which glass was melted. The high temperatures required to melt glass have altered some of the stone. In some cases the stone is discoloured and in some cases one or more face has been vitrified (Figure 6). Some of the stone is so highly vitrified that it resembles vitrified ceramic and so some identifications are tentative.

Fig 6: Stone (with vitrified faces) from Glasshouse Lane (context [101])

Fig 7: Rectangular brick from Glasshouse Lane (context [107])

Ceramic Building Materials (CBM) and bricks

Substantial quantities of ceramic material were submitted for analysis. This material appears to have been used as part of the structure of one or more furnace in which glass was melted. In some cases the ceramic forms bricks: most of these are rectangular (Figure 7), however, at least one example is wedge shaped (Figures 8 and 9). A variety of clay fabrics was noticed. The high temperatures required to melt glass have altered some of the ceramic material. In some cases the ceramic is discoloured and in some cases one or more face has been vitrified. Some of the ceramic is so highly vitrified that it resembles vitrified stone and so some identifications are tentative.

Fig 8: Wedge-shaped brick from Glasshouse Lane (front) (context [112])

Fig 9: Wedge-shaped brick from Glasshouse Lane (side) (context [112])

Crucible

Substantial quantities of crucibles were submitted for analysis. These are made from a pale fabric with a cream or slightly yellowish colour. The fabric has been highly fired and partially vitrified. Some of the original surfaces are vitrified or covered with glass. The fragments of crucible are generally rather small and this largely rules out reconstructions of the complete size and shape of the crucibles (Figures 10 and 11).

Fig 10: Crucible fragments from Lordings Farm (interior surfaces) (context [102])

Fig 11: Crucible fragments from Lordings Farm (exterior surfaces)(context [102])

Vitrified Fuel Ash

Fig 12: Vitrified fuel ash from Glasshouse Lane (context [111])

Fig 13: Vitrified fuel ash from Lordings Farm (context [104])

Most sites yielded some light weight porous vitrified material which is tentatively identified as the remains of the inorganic fraction of the fuel used to fire furnaces (Historic England 2015). The vitrified fuel ash mostly occurs as amorphous lumps with a yellow or cream colour at the surface (Figures 12 and 13). There are abundant impressions of wood or charcoal.

"Glass Slag"

Several bags of material submitted for assessment were labelled 'glass slag'. This term appears to have been used to cover a variety of vitreous materials which lacked the transparency of glass. Some of this material might include glass spillages which fell into the fire trench and as a result underwent devitrification (crystallisation). Some of this material could include heavily vitrified stone and/or ceramic which may also have reacted with glass spillages. Some of this material could also incorporate the vitrified remains of wood ash used to fuel the furnaces. It is also possible that this category includes fragments of part manufactured glass (*eg* frit). Visual examination does not provide a certain means of distinguishing these different types of waste and so the term glass slag has been retained here. The highly vitrified nature of much of this material makes any attempt at detailed categorisation unhelpful.

Scientific Methods

The aim of the scientific analysis was to establish the chemical composition of the glass that was manufactured at each site (Imbhams Farm, Glasshouse Lane and Lordings Farm) as well as the raw materials employed in their production. To achieve this, samples were selected and embedded in epoxy resin. The embedded samples were ground and polished to a 1-micron finish using standard methods (SiC abrasive papers and diamond suspension). The microstructure of the polished samples was determined using a scanning electron microscope (SEM), the chemical composition was determined using an Energy Dispersive Spectrometer (EDS) attached to the SEM and using an Energy Dispersive X-Ray Spectrometer. The SEM examination showed that a few samples (primarily the stone and ceramic materials) contained crystalline phases and these were further analysed using X-Ray Diffraction (XRD) to confirm the nature of the mineral phases.

Samples

A total of 205 samples from all three excavated sites were selected for chemical analysis (Table 2). These were selected to cover the complete range of materials recovered but with an emphasis on those materials most likely to address the aims and objectives (cf Dungworth 2003).

Table 2: Numbers of samples selected for scientific analysis

Site	Glass	Crucible	Stone/CBM	VFA
Imbhams Farm	50		5	
Glasshouse Lane	75	10	5	5
Lordings Farm	34	8	8	5

The preparation of the samples varied depending on their nature and size. In some cases the original sample was large and so was sub-sampled (using a geological hammer, rock saw or side-cutters), while in others a very small (up to 10mm) sample was analysed as received. All samples for SEM-EDS examination and analysis were embedded in epoxy resin and ground and polished to a 1-micron finish. XRD samples were powdered (<0.1mm).

Scanning Electron Microscopy (SEM)

All polished samples were examined using a FEI Inspect F field emission Scanning Electron Microscope (operated at 25kV and 1.2nA). The samples were coated in 15nm of carbon to ensure they were earthed using a Quorum QT150RES. The samples were imaged (Figures 14 and 15) using a back-scattered electron detector which provided atomic number contrast images (brightness proportional to average atomic number). The back-scattered images allowed the detection of crystalline phases (where these were present) as well as surface corrosion.

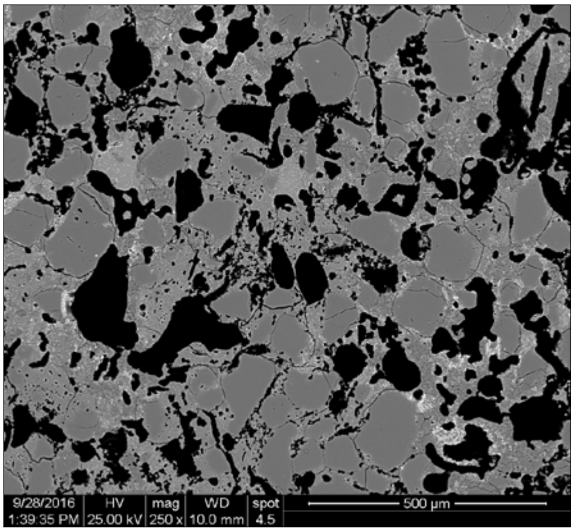


Fig 14: Scanning Electron Microscope (SEM) image of sample 166 (furnace stone) using a back-scattered electron (BSE) detector showing abundant silica grains (grey) in a vitrified matrix (the black areas are porosity)

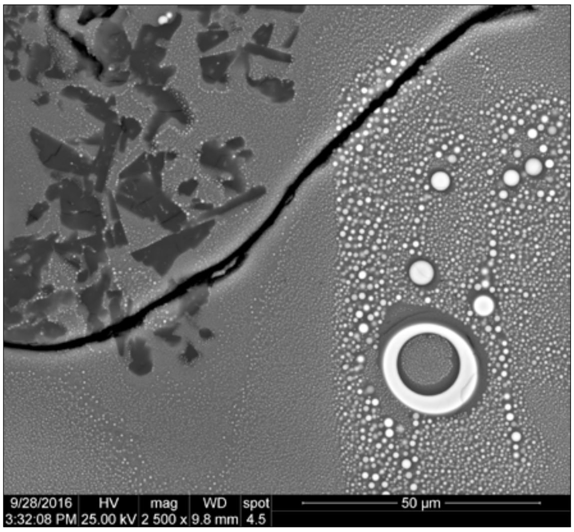


Fig 15: Scanning Electron Microscope (SEM) image of sample 166 (furnace stone) using a back-scattered electron (BSE) detector showing the growth of silica crystals (top left) in a vitrified matrix (with micro-phase separation)

Energy Dispersive Spectrometry (EDS)

The SEM was fitted with an Oxford Instruments X-act silicon drift X-ray detector which allowed the collection of energy dispersive X-ray spectra. The spectra were collected for 100 seconds (livetime) using 25kV and 1.2nA beam conditions. The spectra were collected from selected areas using the SEM. In some cases these areas were relatively large (*eg* $1mm^2$) areas in order to avoid the effects of sample heterogeneity but in other cases small areas (or points) allowed the analysis of individual crystalline phases. Those ceramic and stone samples with vitrified surfaces (or adhering glass) were also repeatedly analysed (while recording x and y coordinates) to allow the investigation of reactions between glass and other materials (cf Dungworth 2008). Each EDS spectrum was processed using Oxford Instruments INCA software. The deconvolution of the spectra was improved through the collection of reference spectra from pure elements and compounds (MAC reference materials). The quantification of the results was calibrated through the regular use of a cobalt standard. With the exception of chlorine, all element concentrations were converted stoichiometrically into oxide concentrations using likely element valencies (no direct evidence was available for the actual valence state of any elements).

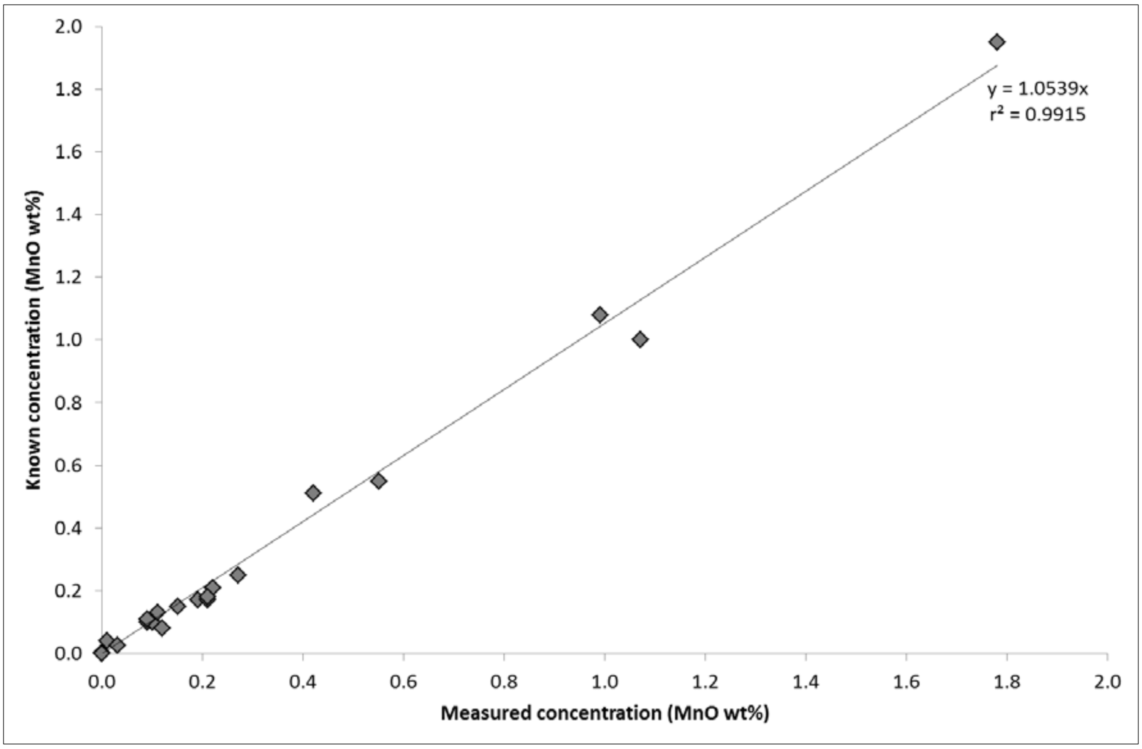


Fig 16: Plot of measured and known values for manganese in the analysed reference materials (SEM-EDS data) showing a strong correlation

The analysis of the 205 Wealden Glass Industry Project samples also included the analysis of 13 reference materials from Corning (Brill 1999; Janssens 2013; Vicenzi *et al* 2002) and Roy Newton (prepared by Pilkingtons, Newton 1977). Comparing known and measured concentrations for all detected elements in the reference materials showed strong correlations (Figure 16). In most cases the least squares fit through this data suggested a slope with a value slightly greater or less than 1 (*ie* the measured values for a particular element were consistently over or under estimated). Where necessary, the measured values for particular elements were corrected using these slope values (cf Dungworth 2003). This also allowed the calculation of the likely analytical errors and limits of detection (Table 3). The error values reported here are those of the regression (measured and known concentrations in the reference materials). These error values are relatively high in some cases (*eg* sodium, silicon, potassium and calcium); however, this is because of the relative high variation in concentration of these elements in the range of standards analysed. In some cases the standard error of the regression may underestimate the likely measurement errors of some elements. This may be particularly significant where the slope factor significantly deviates from a value of 1 (*eg* sulphur and chlorine). The standard error of the regression is also likely to be an under estimate of the measurement errors where the concentration of a given element far exceeds the range of that element in the analysed reference materials.

Table 3: Calibration information relating to the SEM-EDS analysis

Element	Formula	Range	Correlation r^2	Correction factor	Error (2 sd)	Limit of detection
Sodium	Na_2O	0.04–22.2wt%	0.999	1.035	0.5wt%	0.1wt%
Magnesium	MgO	0.04–26.0wt%	0.999	1.040	0.2wt%	0.1wt%
Aluminium	Al_2O_3	1.0–39.1wt%	0.999	0.986	0.2wt%	0.1wt%
Silicon	SiO_2	40.5–75.6wt%	0.992	1.003	1.7wt%	NA
Phosphorus	P_2O_5	0.01–4.3wt%	0.998	1.085	0.1wt%	0.1wt%
Sulphur	SO_3	0.01–0.5wt%	0.938	0.808	0.05wt%	0.1wt%
Chlorine	Cl	0.01–0.15wt%	0.868	0.592	0.03wt%	0.1wt%
Potassium	K_2O	0.03–31.9wt%	0.998	1.047	0.9wt%	0.1wt%
Calcium	CaO	0.1–34.7wt%	0.996	1.021	0.9wt%	0.1wt%
Titanium	TiO_2	0.01–2.6wt%	0.998	0.952	0.06wt%	0.05wt%
Manganese	MnO	0.02–1.9wt%	0.992	1.054	0.1wt%	0.05wt%
Iron	Fe_2O_3	0.01–10.9wt%	0.998	1.083	0.1wt%	0.05wt%

Energy Dispersive X-Ray Fluorescence (EDXRF)

Table 4: EDXRF analysis errors and detection limits

Element	Formula	Error (2 sd)	Limit of detection
Cobalt	CoO	0.05wt%	0.01wt%
Nickel	NiO	0.03wt%	0.01wt%
Copper	CuO	0.05wt%	0.01wt%
Zinc	ZnO	0.05wt%	0.01wt%
Arsenic	As_2O_3	0.02wt%	0.01wt%
Rubidium	Rb_2O	0.01wt%	0.005wt%
Strontium	SrO	0.03wt%	0.01wt%
Zirconium	ZrO_2	0.02wt%	0.01wt%
Barium	BaO	0.1wt%	0.02wt%
Tin	SnO_2	0.1wt%	0.02wt%
Antimony	Sb_2O_5	0.1wt%	0.02wt%
Lead	PbO	0.1wt%	0.02wt%

Previous experience (*eg* Dungworth 2003) has shown that a range of elements (*eg* arsenic, rubidium, strontium and zirconium) may be present in glass at such low concentrations that they cannot easily be detected using SEM-EDS. In order to detect and quantify these elements, the glass samples were also analysed using a bench-top Energy Dispersive X-ray Fluorescence (EDXRF spectrometer). The instrument used was a Bruker M4 Tornado with a rhodium X-ray tube operated at 50kV and 0.6mA. The beam was directed using a 20-micron micro-focus polycapillary and spectra collected for 200 seconds (livetime). The spectra were collected using ambient air pressure with no attempt to collect data on light elements (Z<21) in order to improve the peak to background ratios for heavier elements. The spectra were deconvoluted and the concentrations of individual elements determined using the installed Bruker software. The results were calibrated using a range of reference materials in the same manner as outlined above for the SEM-EDS analyses (Table 4). No attempt was made to acquire EDXRF spectra from non-glassy materials: the material heterogeneity would have required the collection of multiple spectra from different points and the time required would outweigh the benefits. It is hoped to collect trace element data on some of the non-glassy materials using ICPMS in the future.

Bismuth was detected in several samples; however, the absence of bismuth from any of the reference materials makes calculation of actual concentrations (or even an accurate determination of the limit of detection) impossible.

X-Ray Diffraction (XRD)

Those samples which contained crystalline phases (crucibles, bricks, stone, vitrified fuel ash and devitrified glass) were in most cases also analysed using X-Ray Diffraction (XRD) in order to confirm the identity of these phases (a few samples were too small to allow effective XRD analysis). The materials were sampled (geological hammer, rock saw and/or side cutters) to obtain material which (as far as possible) was free of surface vitrification, weathering or other contamination. The samples were typically 1g and were reduced to a fine powder (<0.1mm) through the use of a steel shot mill and an agate mortar and pestle. The powdered samples were analysed using a Bruker D8 X-ray Diffractometer, with a copper X-ray tube operated at 40kV and 40mA and a LynxEye X-ray detector for 20 minutes (from 10° to 70° 2θ). The XRD spectra were deconvoluted and the peaks compared to those in the International Centre for Diffraction Data (ICDD) database (version PDF4+) to identify the mineral phases present.

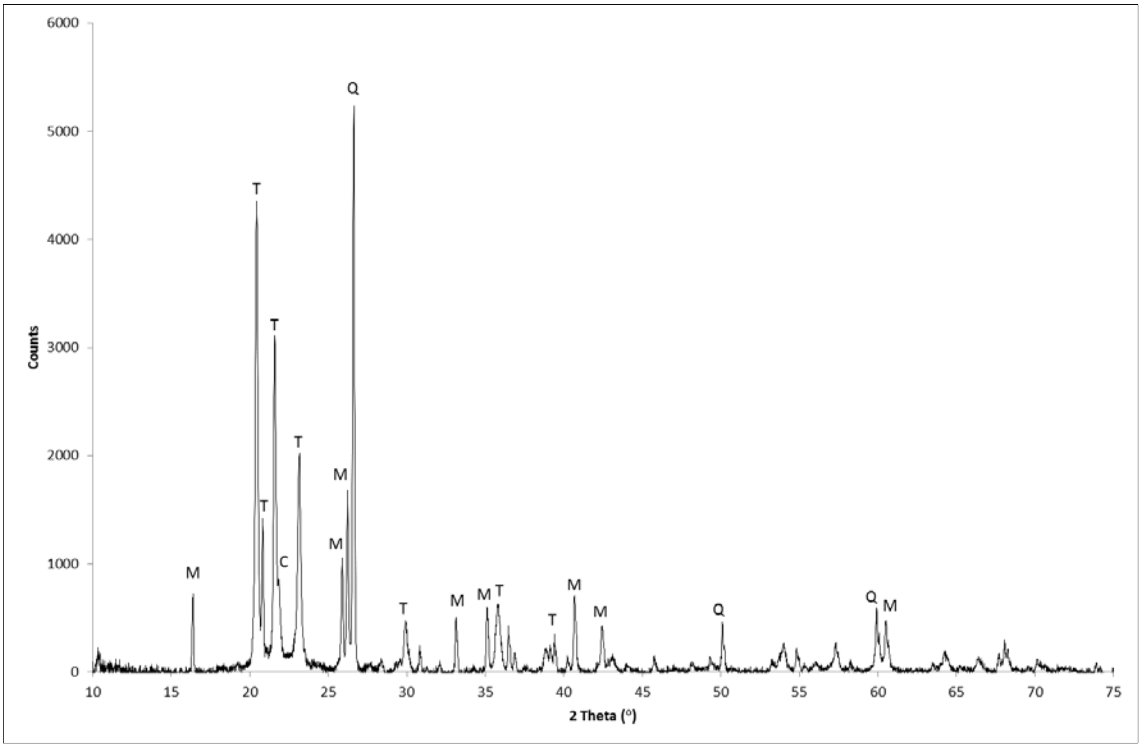


Fig 17: XRD spectrum of a crucible sample from Imbhams Farm (sample 34.1, see Castagnino 2013) showing the presence of quartz (Q), tridymite (T), mullite (M) and cristobalite (C)

RESULTS OF THE VISUAL EXAMINATION OF EXCAVATED MATERIALS

The visual examination of the glass and glassworking materials is reported below for each of the three excavated sites.

Imbham’s Farm (site code IFG14)

The material from Imbhams Farm (Table 5) includes 15.8kg of glass most of which comprises amorphous lumps which are likely to have formed during glass manufacture and/or glass working. The assemblage also includes 2.2kg of miscellaneous vitreous waste (‘glass slag’, etc) and 15.5kg of furnace material (both stone and ceramic). No fragments of crucible were recovered. Most of the recovered material (19kg) came from the topsoil contexts [100] and [101].

Table 5: Assessment of glass and glassworking material from Imbhams Farm (weight in grams)

	Glass (window and/or vessel)	Glass waste (amorphous glass)	Stone	CBM/Brick	Glass ‘slag’ and Vitrified Fuel Ash	Total
100	2	71		43	20	136
101	6	10800		6944	1096	18846
102		1277	743	1649	280	3949
103		3208	3438	167	390	7203
104		137	364	120	275	896
105		61	1586	244	29	1920
113		235	272		84	591
122		1			24	25
Total	8	15790	6403	9167	2198	33566

Lordings Farm (site code LFB13)

The material from Lordings Farm (Table 6) includes 1.5kg of glass most of which comprises amorphous lumps which are likely to have formed during glass manufacture and/or glass working. The assemblage also includes 5.1kg of miscellaneous vitreous waste (‘glass slag’, etc) and 27.5kg of furnace material (both stone and ceramic). Several fragments of a ceramic disc may represent a cover used to close a gathering hole (the aperture in the furnace wall, through which the glassworker collects a gather of glass using a blowing iron) while not in use. 3.8kg of crucible fragments were recovered. Most of the recovered material (28.3kg) came from the contexts [102] and [103].

Table 6: Assessment of glass and glassworking material from Lordings Farm (weight in grams)

	Glass (window and/or vessel)	Glass waste (amorphous glass)	Crucible	Stone	CBM/Brick	Glass 'slag' and Vitrified Fuel Ash	Total
100	4	10	428	30	886		1458
101	10	60	273	65	231	30	770
102	191	487	1128	6	5714		7628
103	56	459	953	93	15900	2950	20514
104	10	157	237		2720	1244	4472
105	5	8	113		1211	834	2276
106	4	1	687		595	34	1427
107	17					5	129
Total	297	1182	3819	194	27257	5097	37846

Glasshouse Lane (GLK14)

The Glasshouse Lane assemblage (Table 7) is the largest of the three sites examined and includes contains 3.0kg of glass and amorphous glass waste. The glassworking waste includes several examples of glass with tong marks (Figure 5). Most of this material (106.1kg) comprises fragments of furnace (both stone and ceramic). Stone forms a fairly modest proportion of the possible furnace material examined and most of this, while heat-affected, lacks vitrified surfaces. The ceramic material includes several rectangular bricks as well as a wedge-shaped brick (Figures 8 and 9) which has one vitrified face. The shape of the brick suggests that it may be a voussoir (cf Farrelly *et al* 2014). The assemblage also includes 8.8kg of crucible and 3.4kg of miscellaneous vitrified waste ('glass slag', etc). Almost half of the material derives from unstratified or poorly stratified contexts [100] to [104].

Table 7: Assessment of glass and glassworking material from Glasshouse Lane (weight in grams)

	Glass (window and/or vessel)	Glass waste (amorphous glass)	Crucible	Stone	CBM/Brick	Glass 'slag' and Vitrified Fuel Ash	Blast Furnace Slag	Total
100							290	290
101	404	254	3706	3333	5785	500	357	14339
102	831	806	3233	13093	17281	1033		36277
103	182	190	680	2601	6480	380		10513
104	1	1	30	463	479	49	8	1031
107	32	151	134	2654	14138	255		17364
109	2		31	200	178	66		477
111	37	63	708	3890	12136	768		17602
112	10	7	103	3245	20159	349		23873
113			174					174
Total	1499	1472	8799	29479	76636	3400	655	121940

Summary of visual examination of glass and glassworking materials

The excavation of three glass production sites has allowed the recovery of substantial quantities of material related to glass manufacture (Table 8). The proportion of finished glass is modest (0.9% of all material) and a visual examination suggests that this includes a small proportion of modern glass (from unstratified contexts). Amorphous glassworking waste, which includes drips, dribbles and trails (a very few of which bear the impression of iron tongs or other tools), makes almost 10% of the assemblage and offers the best opportunity to establish the chemical composition of the glass manufactured. Crucibles account for 6.5% of the material recovered, although no crucibles were found at Imbhams Farm (possibly due to the siting of the excavation trench). Nevertheless, several fragments of crucible from Imbhams Farm found during fieldwalking have already been analysed (Castagnino 2013). Fragments of stone and ceramic (displaying vary degrees of heating) are abundant (77.1% of all material) and probably represent the remains of furnace structures. The ceramic material from Imbhams Farm comprises relatively small fragments none of which appear to be original surfaces. None of this ceramic material can be identified with certainty as bricks. The other two sites (Lordings Farm and Glasshouse Lane) both yielded examples of ceramic bricks and these included a small number of carefully shaped bricks (*eg* wedges) that were probably produced specifically for the construction of a glassworking furnace. Miscellaneous vitrified waste made up a small proportion of the material examined (5.5%). Most of this material defied simple categorisation due to the effects of extreme heating. Nevertheless, some of this material clearly represented the vitrified remains of organic fuel (cf Historic England 2015, 59–60). This vitrified fuel ash was most abundant at Lordings Farm where it was recovered from a ditch; this could represent the dumping of an unwanted waste material on the periphery of a production site.

Table 8: Summary of recovered materials (weight in grams)

	Glass (window and/or vessel)	Glass waste (amorphous glass)	Crucible	Stone	CBM/Brick	Glass 'slag' and Vitrified Fuel Ash	Blast Furnace Slag	Total
IFG14	8	15790		6403	9167	2198		33566
LFB13	297	1182	3819	194	27257	5097		37846
GLK14	1499	1472	8799	29479	76636	3400	655	121940

MICROSTRUCTURE (SEM EXAMINATION)

All samples were imaged using the Scanning Electron Microscope (SEM) with a back-scattered electron (BSE) detector to identify the microstructure. Most of the samples were glass and so largely devoid of crystalline phases. Nevertheless, some of the glassworking waste had devitrified to some extent and all of the crucibles (as well as the stone and ceramic furnace components) exhibited crystalline microstructures.

Devitrified glass waste

A proportion of the glassworking waste examined had undergone varying degrees of devitrification (Figures 18 and 19). This was especially notable for the Imbhams Farm Waste 2, *ie* material which was chemically altered by reactions with fuel and/or refractories. A small amount of the material initially identified as vitrified fuel ash (see below) should also be regarded as (at least partially) devitrified glass waste.

In most cases the mineral phases present in the devitrified glass waste could be identified using the SEM-EDS in spot (or very small area) mode so as to analyse just that phase. Several areas of devitrified glass were also analysed using SEM-EDS to produce X-ray maps showing the distribution of different elements (Figure 20). An examination of the quantitative results (using atomic %) for individual phases, easily identified the presence of wollastonite ($CaSiO_3$) or diopside ($MgCaSi_2O_6$), which was present in almost all samples which had devitrified. Less frequently, leucite ($KAlSi_2O_6$) was identified, and in a few cases a proportion of the potassium had been replaced by sodium. Several samples also contained a calcium phosphate phase (Figure 20); however most of these crystals were too small to allow discrete SEM-EDS spot analysis (*ie* the crystal was smaller than the X-ray interaction volume and so some of the collected spectrum could represent the surrounding material).

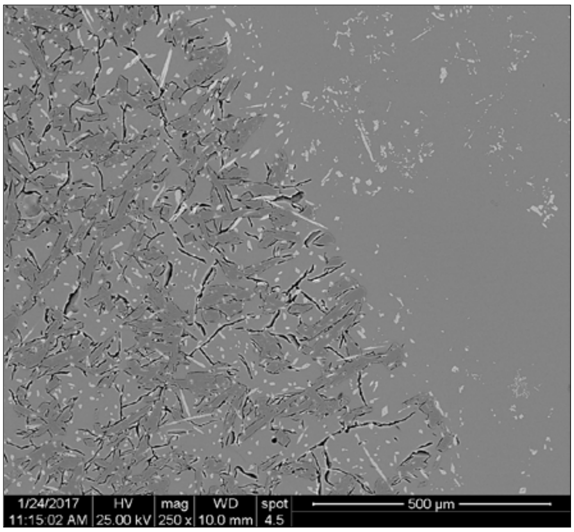


Fig 18: SEM image (BSE detector) of devitrified glass waste from Imbhams Farm (sample 117)

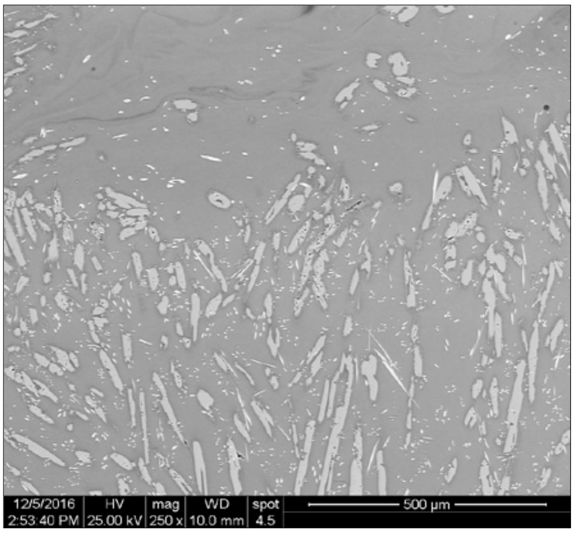
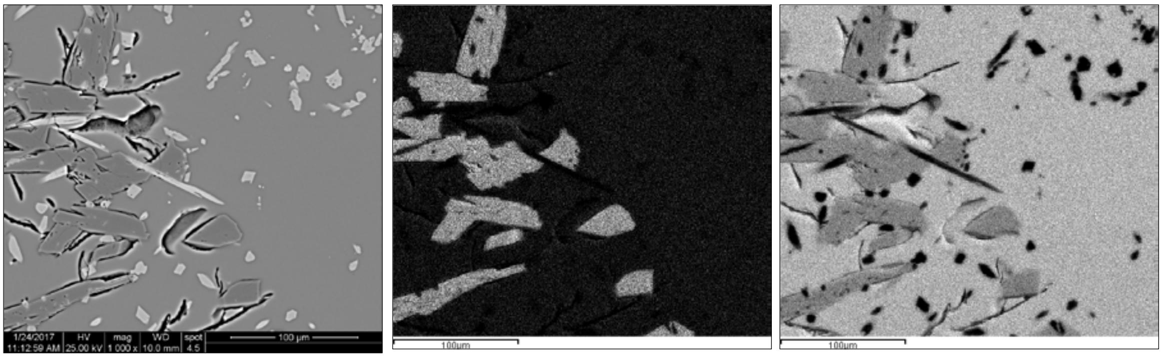
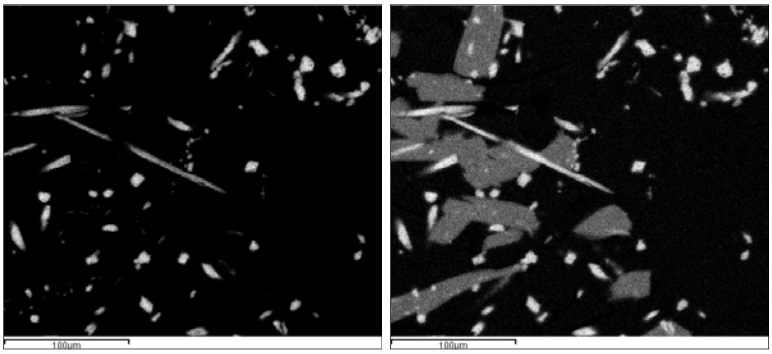


Fig 19: SEM image (BSE detector) of devitrified glass waste from Imbhams Farm (sample 145)



SEM BSE Image Magnesium Silicon



Phosphorus Calcium

Fig 20: SEM image and associated X-ray maps of sample 117 (Waste 2 devitrified glass waste from Imbhams Farm)

Vitrified Fuel Ash

Ten samples of materials which were visually identified as vitrified fuel ash were examined using the SEM. Detailed examination showed that several of these were not vitrified fuel ash. When sectioned and polished, it became clear that sample 016 (from Glasshouse Lane) was actually partially devitrified glass. The sample, which was translucent and green, had a chemical composition which resembled much of the glass working waste from this site. The sample contains a small proportion of crystallised phases (Figures 21 and 22). SEM-EDS analysis (spot mode) suggested that the most common of these had an approximate formula of $CaSiO_3$ (probably wollastonite).

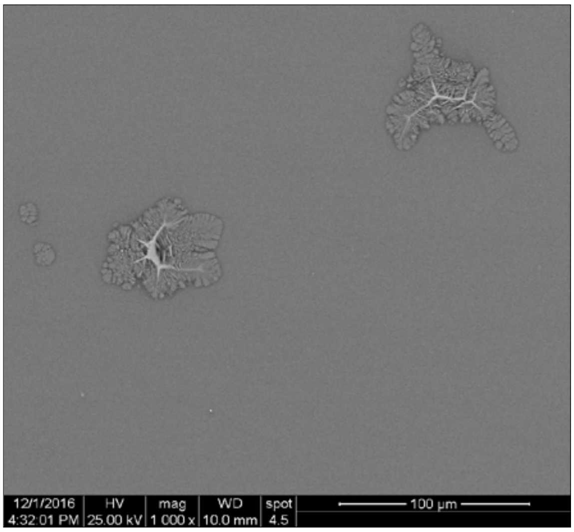


Fig 21: SEM image (BSE detector) of devitrified glass from Glasshouse Lane (sample 016) showing glassy matrix with occasional crystals

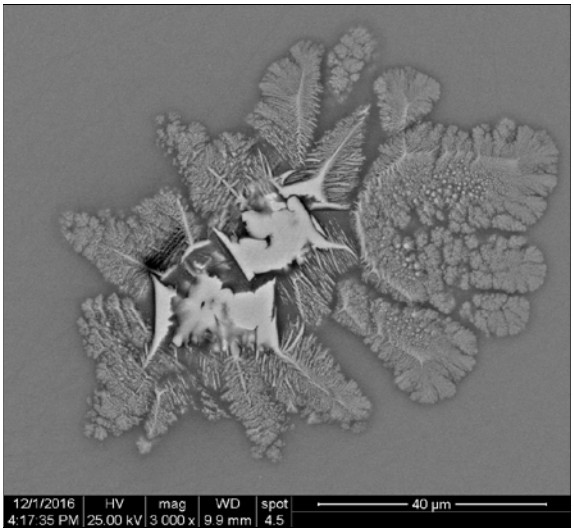


Fig 22: SEM image (BSE detector) of devitrified glass from Glasshouse Lane (sample 016) showing detail of the crystals present

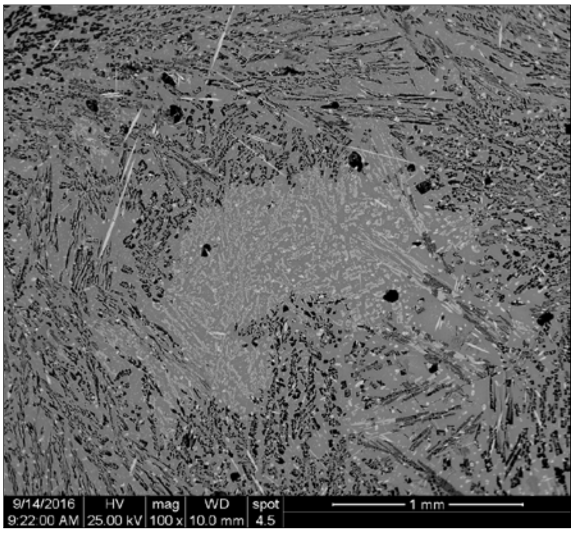


Fig 23: SEM image (BSE detector) of devitrified glass from Glasshouse Lane (sample 018) showing extensive corrosion surrounding unaltered core

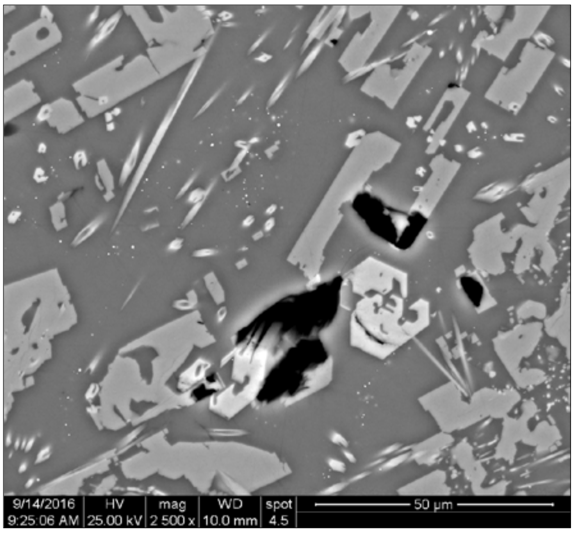


Fig 24: SEM image (BSE detector) of devitrified glass from Glasshouse Lane (sample 018) showing crystals of a calcium phosphate and an iron phosphate

When sectioned and polished, sample 017 (Glasshouse Lane) could be identified as a series of small fragments of crucible cemented by a vitreous film (possibly waste glass and possibly vitrified fuel ash). Sample 018 (Glasshouse Lane) comprised a vitreous matrix which contained three different crystalline phases (Figures 23 and 24). The most abundant was $CaSiO_3$ (wollastonite), while the other two are tentatively identified as calcium and iron phosphates. The overall chemical composition of sample 018 is similar to sample 016 and it is likely that both are devitrified glass rather vitrified fuel ash.

Samples 019 and 020 (both Glasshouse Lane) shared similar microstructures with each other and with all of the samples of vitrified fuel ash from Lordings Farm (samples 167–171). These appeared to comprise fine laths (Figure 25); however, at high magnification (Figure 26) these were revealed to be comprised of fine, multi-phase intergrowths (cf Figures 27 and 28). These regions are too small to allow discrete analysis of the individual phases using SEM-EDS in spot mode. It is possible that these microstructures are the product of micro-phase separation (cf Dungworth and Paynter 2011).

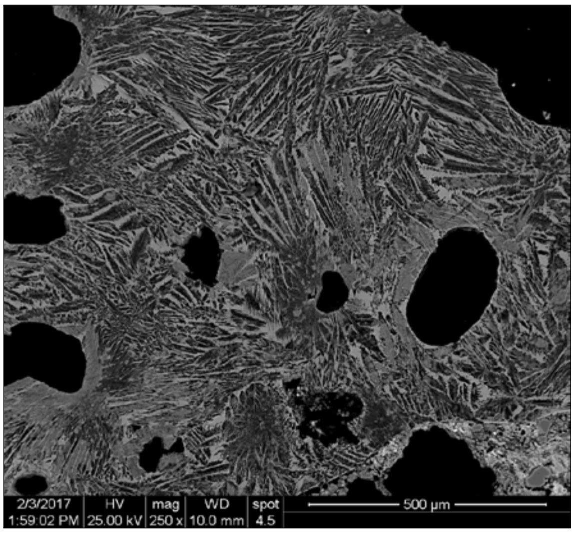


Fig 25: SEM image (BSE detector) of vitrified fuel ash from Glasshouse Lane (sample 019)

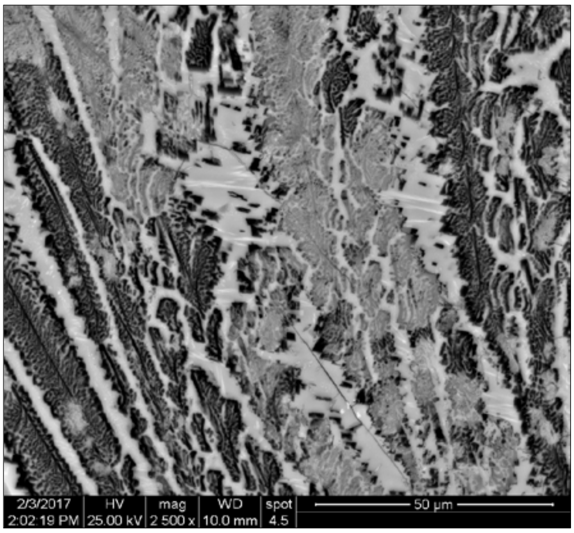


Fig 26: SEM image (BSE detector) of vitrified fuel ash from Glasshouse Lane (sample 019)

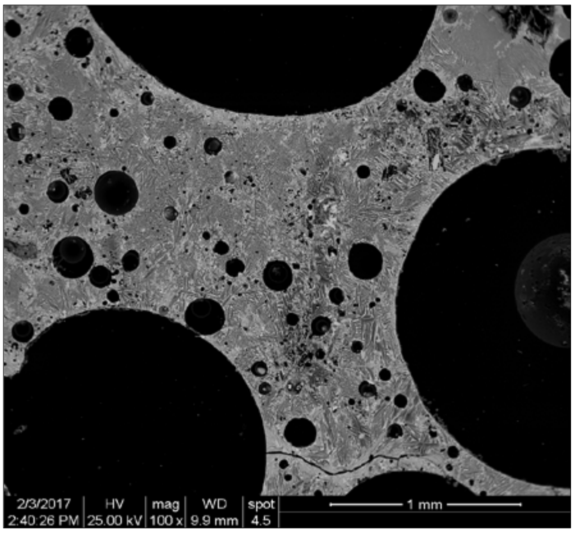


Fig 27: SEM image (BSE detector) of vitrified fuel ash from Lordings Farm (sample 167)

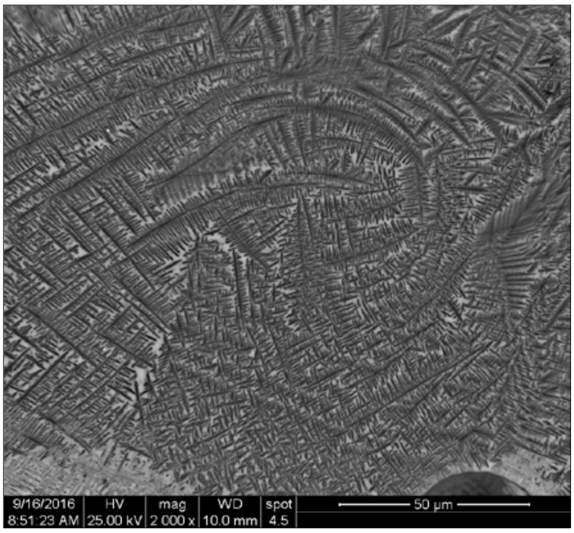


Fig 28: SEM image (BSE detector) of vitrified fuel ash from Lordings Farm (sample 167)

Crucibles

Eighteen crucibles (ten from Glasshouse Lane and eight from Lordings Farm) were examined using the SEM as part of this study (references to crucibles from Imbhams Farm, site code IFG 11, are from previous work (Castagnino 2013)). This showed the presence of significant features such as adhering glass/glaze, porosity and temper (Figures 29–36) (Table 9, which also summarises results from a previous study by Castagnino (2013)). Assessing the ceramic fabric of the crucibles was sometimes limited by the fact that crucibles had been exposed to high-temperatures. It is likely that a fresh crucible would contain a fairly high level of free silica but over time this would react with the vitrified clay matrix and new (mostly aluminium silicate) phases would form and the free silica would disappear (cf Dungworth and Cromwell 2006).

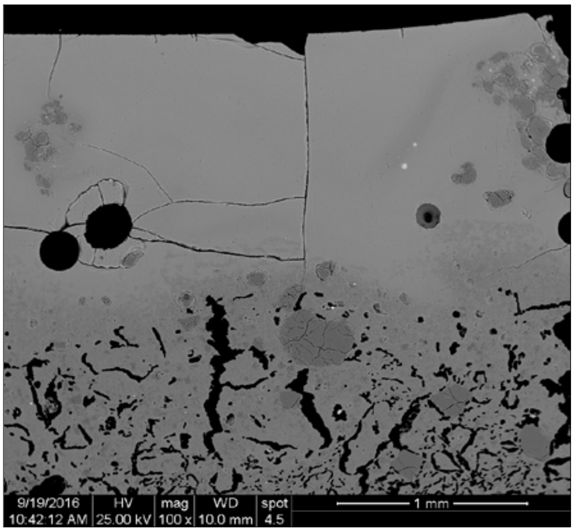


Fig 29: Sample 003 (crucible from Glasshouse Lane) showing the glass adhering to the interior surface (at the top, with the ceramic below)

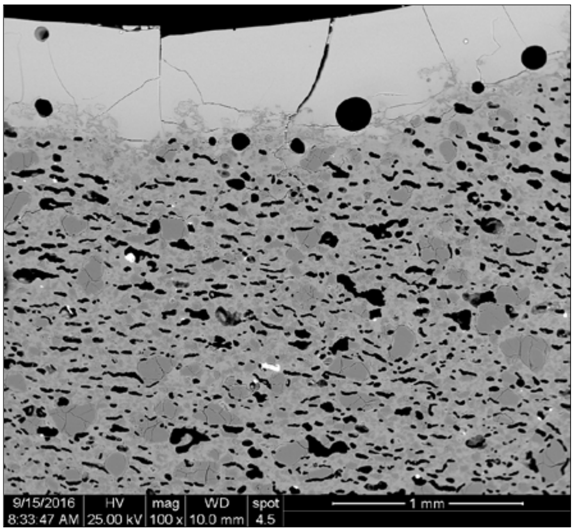


Fig 30: Sample 005 (crucible from Glasshouse Lane) showing the glass adhering to the interior surface (at the top, with the ceramic below)

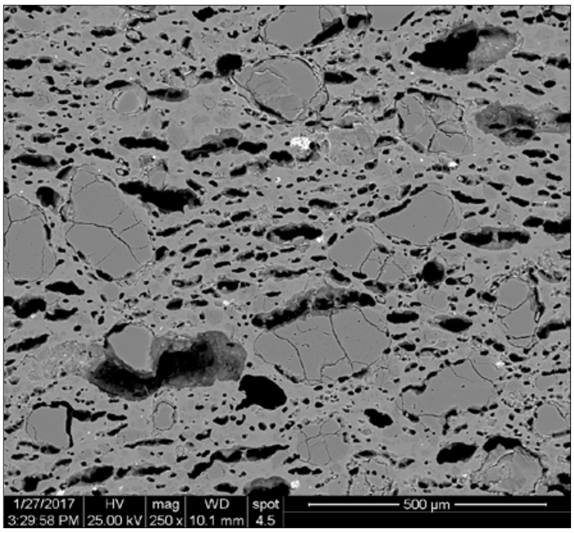


Fig 31: Sample IFG GS43.2 (crucible from Imbhams Farm, see Castagnino 2013) showing numerous smaller silica inclusions and porosity (black)

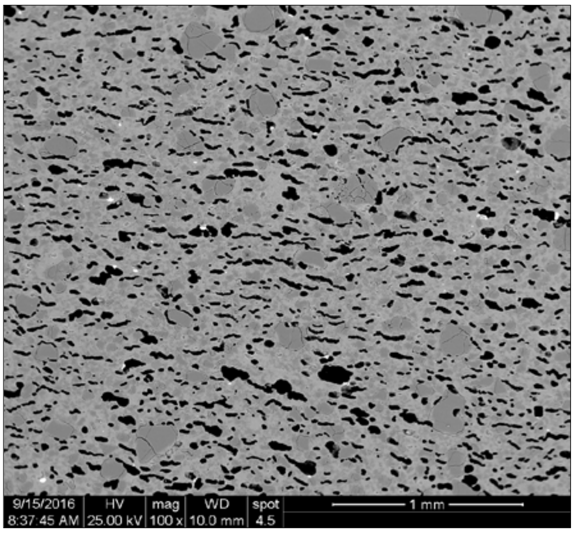


Fig 32: Sample 005 (crucible from Glasshouse Lane) showing numerous silica inclusions (darker grey than the matrix) and porosity (black)

The two types of temper identified were sand (Figures 29–32) and grog (Figures 33–36), although in some cases the identifications are tentative. Some naturally occurring clay deposits contain sand and the presence of sand particles in a fired ceramic may reflect this rather than the deliberate addition of sand temper. Grog (*ie* the ground up remains of old crucibles) is well-attested in later historical sources and can often be identified in fired ceramics due to the presence of shrinkage cracks around a grog particle. Nevertheless, poorly sorted and processed clays can contain clay pellets which also give rise to shrinkage cracks in the finished ceramic (Whitbread 2007).

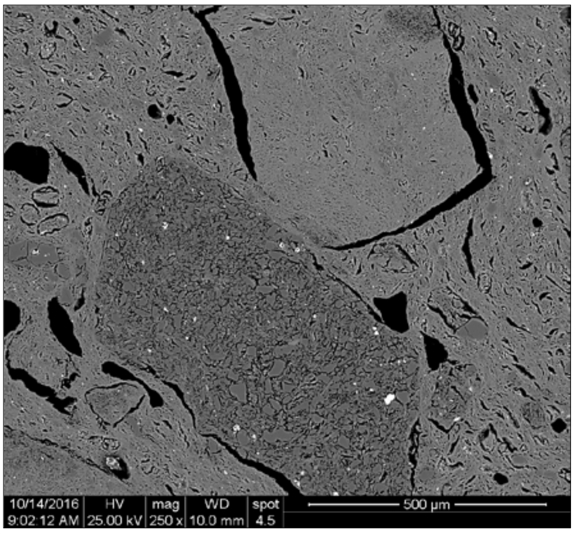


Fig 33: Sample 161 (crucible from Imbhams Farm) showing two large ceramic inclusions (grog?) with some shrinkage gaps, as well as numerous smaller silica inclusions

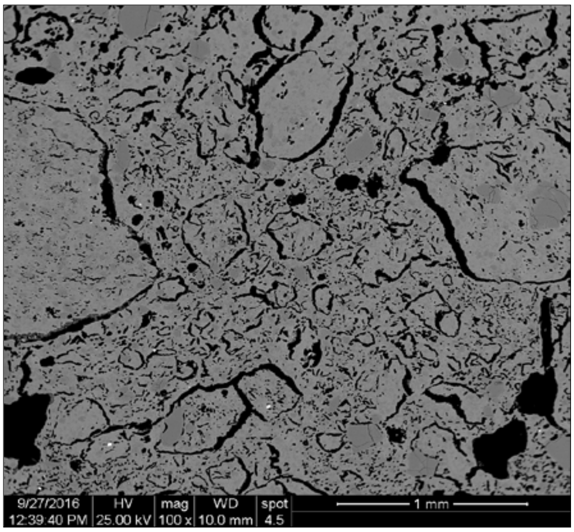


Fig 34: Sample 002 (crucible from Glasshouse Lane) showing numerous grog inclusions with some shrinkage gaps, as well as some smaller silica inclusions

Several grog-tempered samples also contain quartz inclusions, although it is uncertain whether this quartz was deliberately added as a temper or just naturally present in the raw clay. In addition, some samples (*eg* sample 009 from Glasshouse Lane and 159 from Lordings Farm) contained abundant quartz inclusions but also contained what appeared to be shrinkage gaps typical of grog inclusions (Figures 35 and 36). Grog inclusions display a range of microstructures. While a few share essentially the same microstructure as the matrix, many shows signs of greater vitrification (Figure 34). They are often rather glassy, with no relict quartz but with abundant fine recrystallised phases (especially mullite and high temperature silica polymorphs. Other relict inclusions in the ceramic fabric of the crucibles include very small amounts of zirconia (which is seen in all samples) and Fe-Ti-Al-O inclusions (possibly hercynite-ilmenite), although these are only seen in the quartz-tempered crucibles.

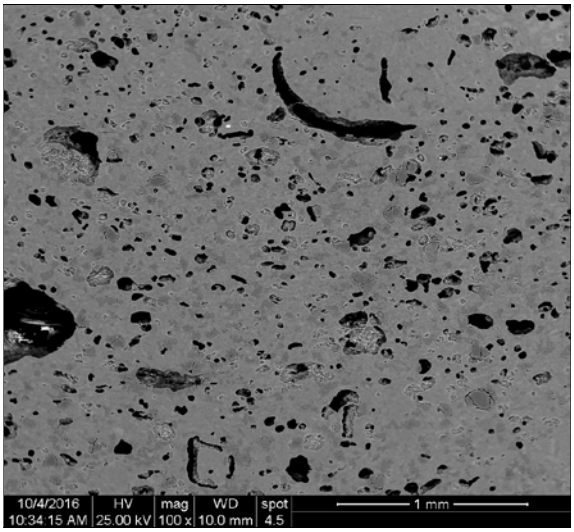


Fig 35: Sample 009 (crucible from Glasshouse Lane) showing abundant fine quartz temper and a few possible grog inclusions

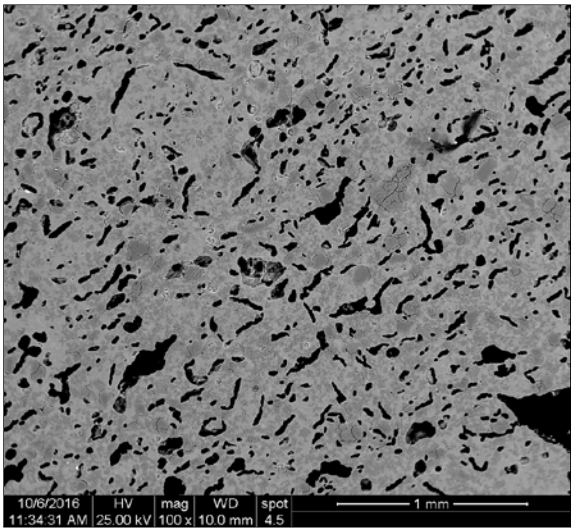


Fig 36: Sample 159 (crucible from Lordings Farm) showing possible grog inclusions with some shrinkage gaps, as well as some smaller silica inclusions

Table 9: Summary of crucible microstructures (Imbhams Farm samples are from a previous study, see Castagino 2013)

Ref	Site	Temper	SiO_2 size (mm)	SiO_2 %
001	Glasshouse Lane	Grog	mostly <0.1 with some 0.1–0.3	~20%
002	Glasshouse Lane	Grog	mostly <0.1with some 0.1–0.3	10–20%
003	Glasshouse Lane	Grog	<0.1	10–20%
004	Glasshouse Lane	Grog	<0.1	~30%
005	Glasshouse Lane	Sand	<0.1	~30%
006	Glasshouse Lane	Grog	<0.1	20–30%
007	Glasshouse Lane	Grog?	mostly <0.1 with some 0.1–1.0	20–30%
008	Glasshouse Lane	Grog	<0.1	10–20%
009	Glasshouse Lane	Grog	<0.1	10%
010	Glasshouse Lane	Grog?	<0.1	10%
152	Lordings Farm	Grog	<0.1	~20%
34.1	Imbhams Farm	Sand	0.1	30%
43.1	Imbhams Farm	Sand	0.1	30%
43.2	Imbhams Farm	Sand	0.1	30%
152	Lordings Farm	Grog	<0.1	10–20%
153	Lordings Farm	Grog	mostly <0.1 with some 0.1–0.5	~20%
154	Lordings Farm	Grog	<0.1	~5%
155	Lordings Farm	Grog	mostly <0.1 with some 0.1–0.5	~30%
156	Lordings Farm	Grog	<0.1	~10%
157	Lordings Farm	Grog	mostly <0.1 with some 0.1–0.5	20–30%
158	Lordings Farm	Grog	mostly <0.1 with some 0.1–0.5	10–20%
159	Lordings Farm	Grog	mostly <0.1 with some 0.1–0.5	~20%

The ceramic fabric of all of the crucibles contained an abundant vitreous matrix which displayed varying degrees of devitrification (Figures 37 and 38). The phases which precipitated in the vitreous matrix are small laths or needles, typically less than 2 microns in width. The small size of these inclusions meant that quantitative SEM-EDS analysis was not possible; however, it did suggest that these were aluminium silicates.

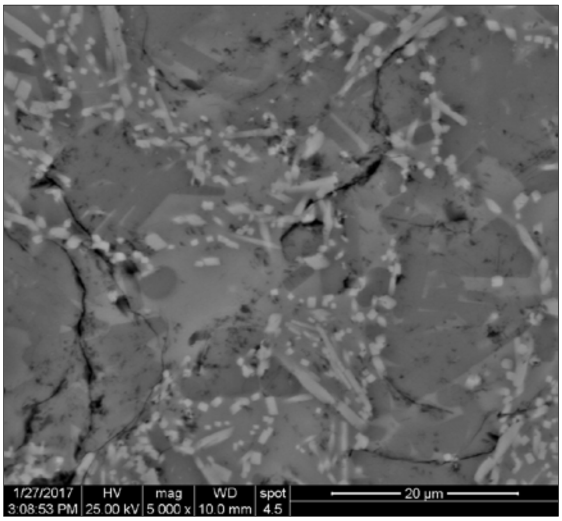


Fig 37: Sample IFG11 GS34.1 (crucible from Imbhams Farm, see Castagnino 2013) showing the vitreous matrix and the growth of aluminium-silicates

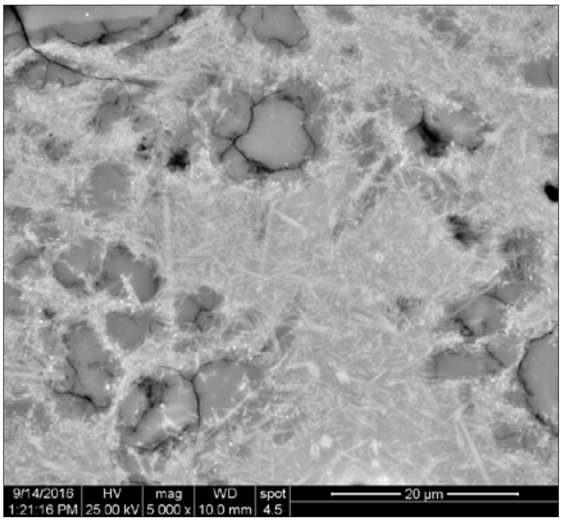


Fig 38: Sample 001 (crucible from Glasshouse Lane) showing the vitreous matrix and the growth of aluminium-silicates

Bricks and other ceramics

A few samples of ceramic material (not including crucibles) were examined, including possible covers/lids for furnace openings (one from Imbhams Farm and three from Lordings Farm) and four furnace bricks (Lordings Farm).

The ceramic cover/lid from Imbhams Farm (sample 147) is quartz tempered and retains irregular shapes of the porosity in the ceramic fabric which suggests limited heating (Figure 39). This object also has a thick vitrified surface which would appear to indicate exposure to high temperatures and contact with molten glass and/or alkali-rich vapour from the fuel (Figure 40). This apparent contradiction might be explained by considering the precise environment in which a cover for a furnace hole might be used. The cover would periodically be moved aside to access the interior of the furnace and so it would be subject to less sustained heating than the other parts of the furnace. In addition, when replaced, the cover would be one of the cooler surfaces within the furnace and so would perhaps attract greater condensation of alkali-rich vapour from the fuel.

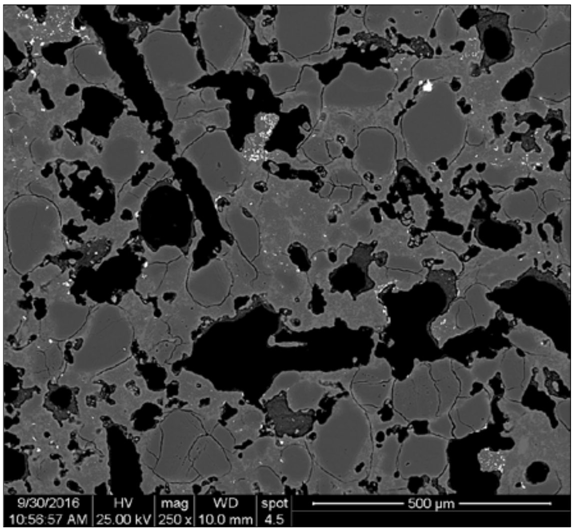


Fig 39: SEM image (BSE detector) of furnace ceramic (cover/lid?) from Imbhams Farm (sample 147) showing relict silica and porosity (black)

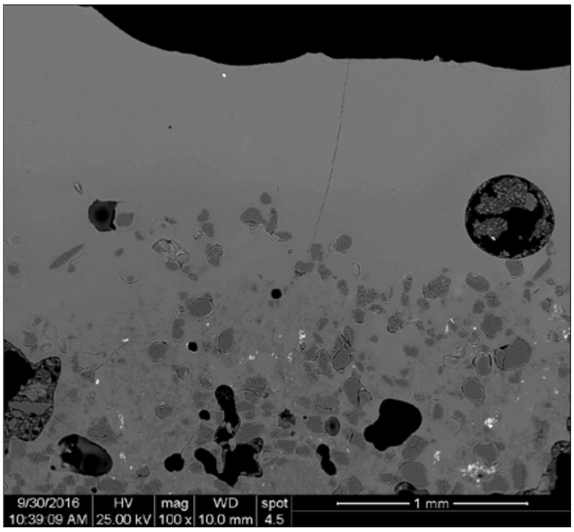


Fig 40: SEM image (BSE detector) of furnace ceramic (cover/lid?) from Imbhams Farm (sample 147) showing vitrified surface (top)

The three covers/lids from Lordings Farm all appear to grog tempered (Figures 42, 43 and 45). The first two show signs of significant vitrification of the ceramic matrix (Figure 44) but the third shows rather less vitrification (Figure 46); this difference may simply be a product of varying degrees of use of the covers/lids. Only one of the Lordings Farm covers/lids shows evidence of a vitrified surface layer (Figure 41).

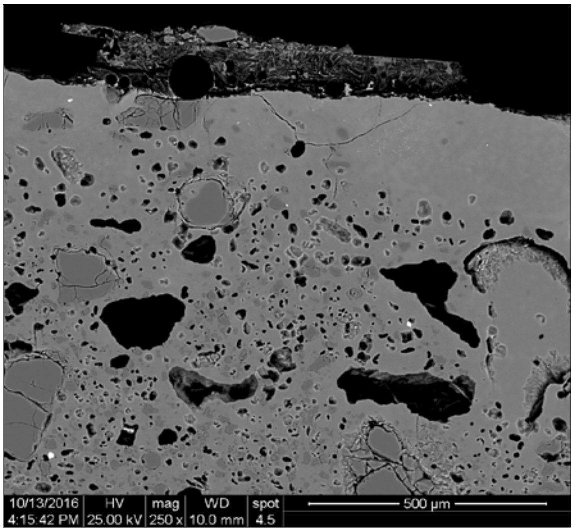


Fig 41: SEM image (BSE detector) of furnace ceramic (cover/lid?) from Lordings Farm (sample 151) showing vitrified surface (top)

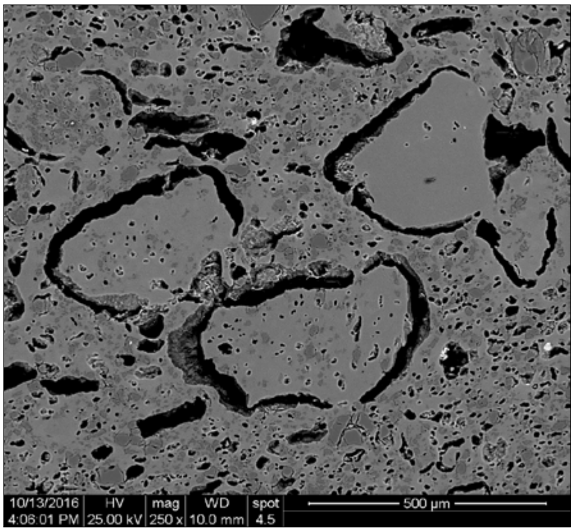


Fig 42: SEM image (BSE detector) of furnace ceramic (cover/lid?) from Lordings Farm (sample 151) showing grog inclusions with characteristic shrinkage gaps

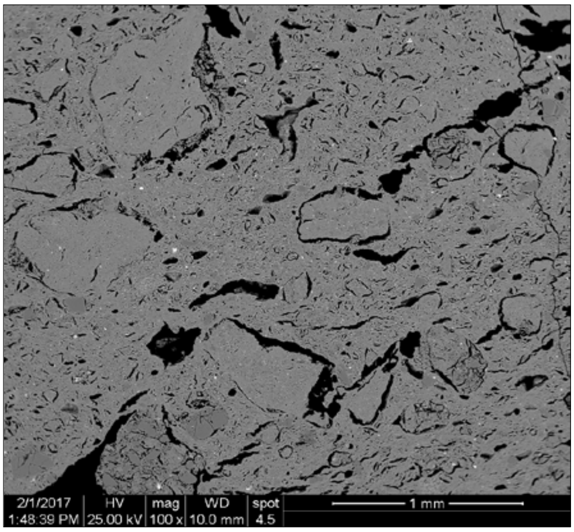


Fig 43: SEM image (BSE detector) of furnace ceramic (lid?) from Lordings Farm (sample 160) showing grog inclusions with characteristic shrinkage gaps

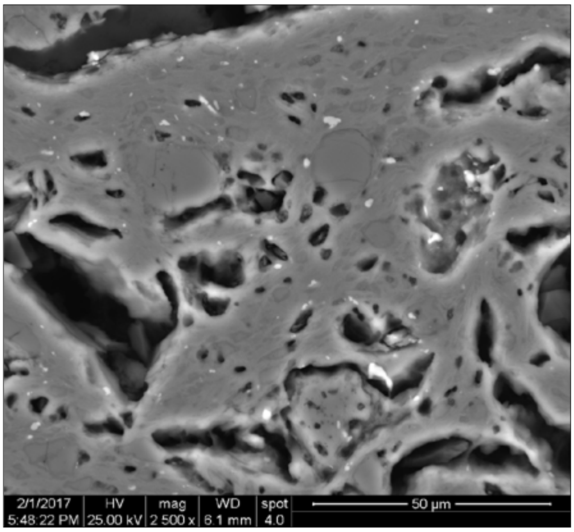


Fig 44: SEM image (BSE detector) of furnace ceramic (lid?) from Lordings Farm (sample 160) showing fine relict silica and irregular porosity (black)

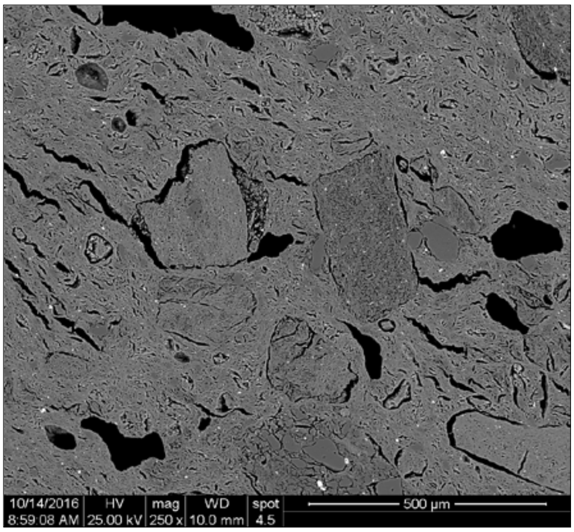


Fig 45: SEM image (BSE detector) of furnace ceramic (lid?) from Lordings Farm (sample 161) showing possible grog inclusions with shrinkage gaps

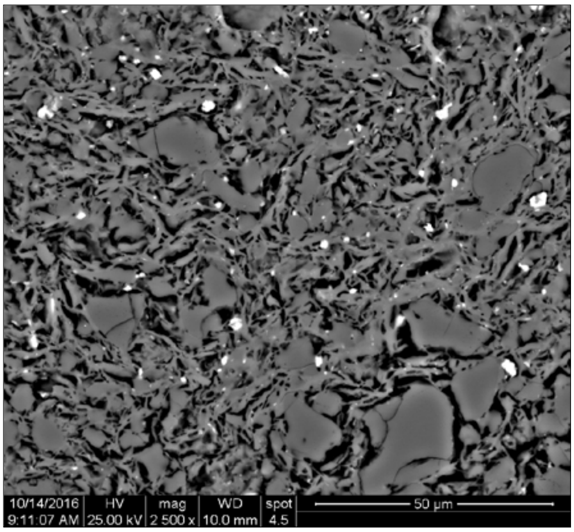


Fig 46: SEM image (BSE detector) of furnace ceramic (lid?) from Lordings Farm (sample 161) showing fine relict silica and irregular porosity (black)

One possible furnace brick from Imbhams Farm (Sample 146) was examined. This was a very small sample and the visual identification of this as a brick was uncertain (the chemical analysis showed [among other things] a high titanium content which is perhaps more consistent with a ceramic than a stone). This sample had a vitrified layer at the surface (Figure 47) and extensive indications of vitrification throughout the sample (Figure 48). Almost all of the mineral phases present appear to have recrystallised at high temperatures, with only the occasional relict silica grains (Figure 48). The extensive vitrification of this sample notwithstanding, no grog particles could be identified.

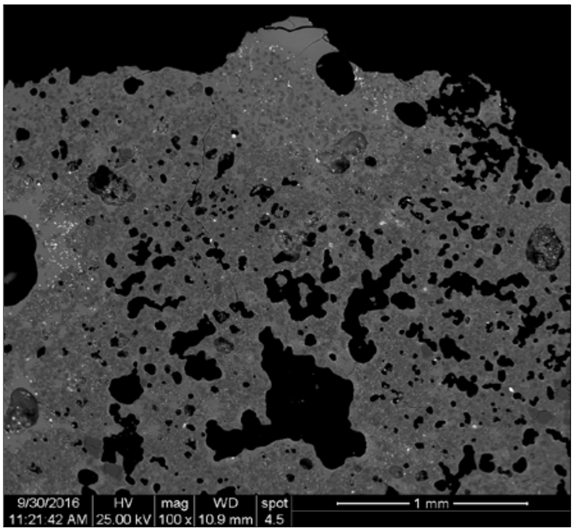


Fig 47: SEM image (BSE detector) of furnace brick from Imbhams Farm (sample 146) showing the vitrified surface at the top

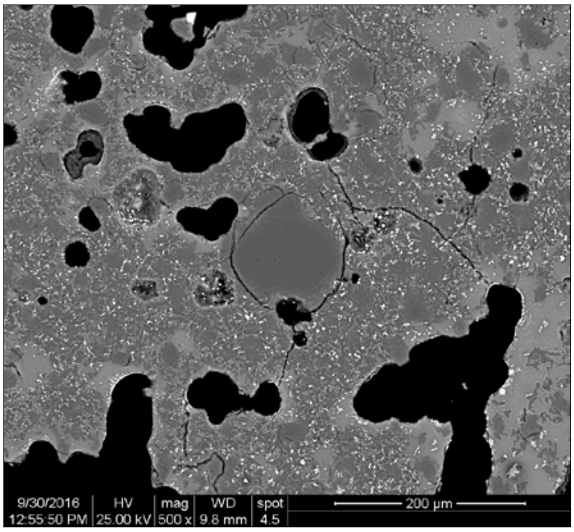


Fig 48: SEM image (BSE detector) of furnace brick from Imbhams Farm (sample 146) showing relict silica grain (centre) and porosity (black)

Five possible furnace bricks from Lordings Farm were examined. These all contained abundant quartz inclusions. One sample (163) contained inclusions which superficially resemble grog particles (Figure 49); however, it is more likely in this context (brick manufacture) that the inclusions are clay pellets and that they represent poor sorting/processing of the raw material. Sample 163 also showed the least effects of heat; the clay matrix showed almost no evidence of having vitrified (Figure 50). The other brick samples from Lordings Farm displayed a quartz-tempered microstructure. In these samples the clay matrix had undergone significant vitrification and new phases (primarily mullite?) had subsequently crystallised (Figures 51 and 52).

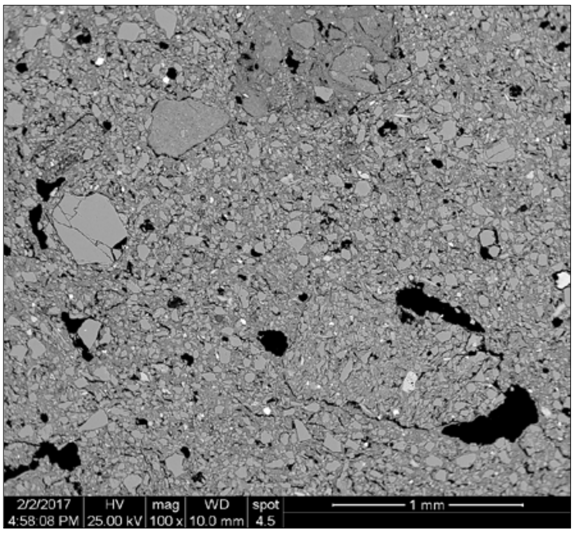


Fig 49: SEM image (BSE detector) of furnace brick from Lordings Farm (sample 163) showing quartz inclusions and clay pellets

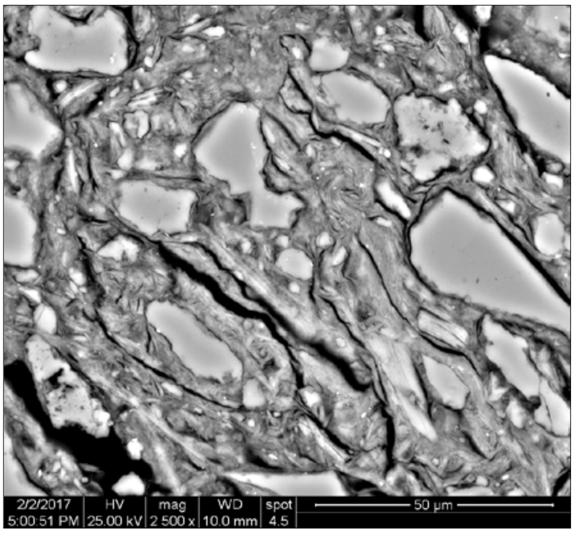


Fig 50: SEM image (BSE detector) of furnace brick from Lordings Farm (sample 163) showing largely unreacted clay matrix and fine quartz inclusions

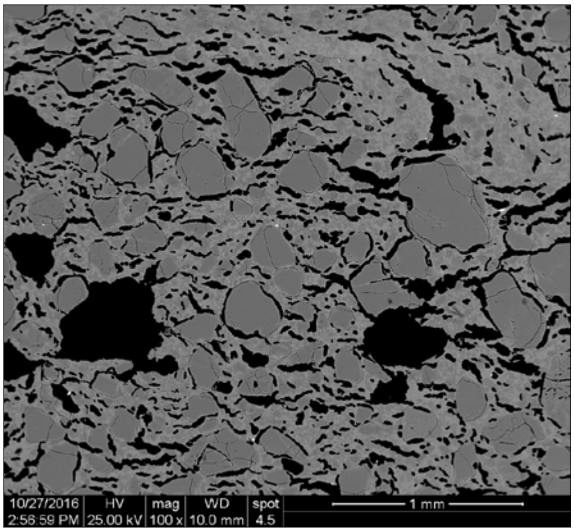


Fig 51: SEM image (BSE detector) of furnace brick from Lordings Farm (sample 164) showing quartz inclusions

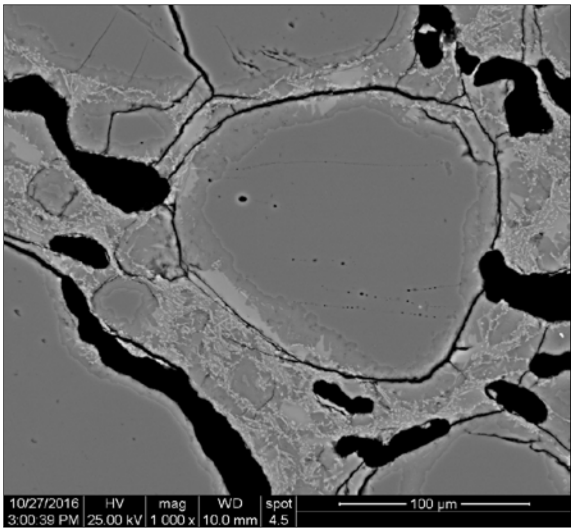


Fig 52: SEM image (BSE detector) of furnace brick from Lordings Farm (sample 164) showing quartz inclusions and vitrified matrix (with mullite crystals)

Furnace stones

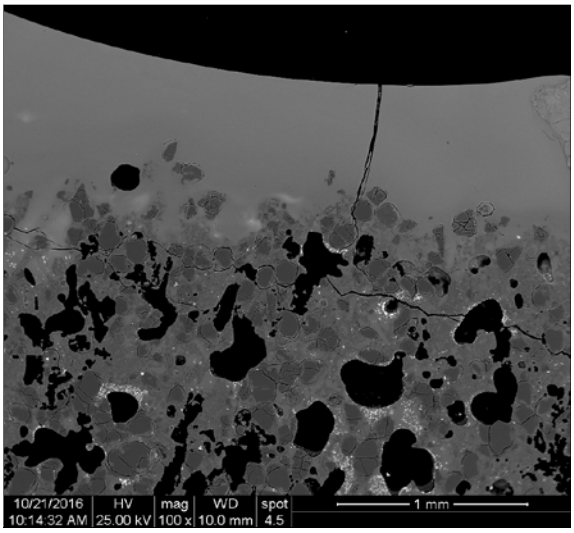


Fig 53: SEM image (BSE detector) of furnace stone from Imbhams Farm (sample 148) showing vitrified surface (top)

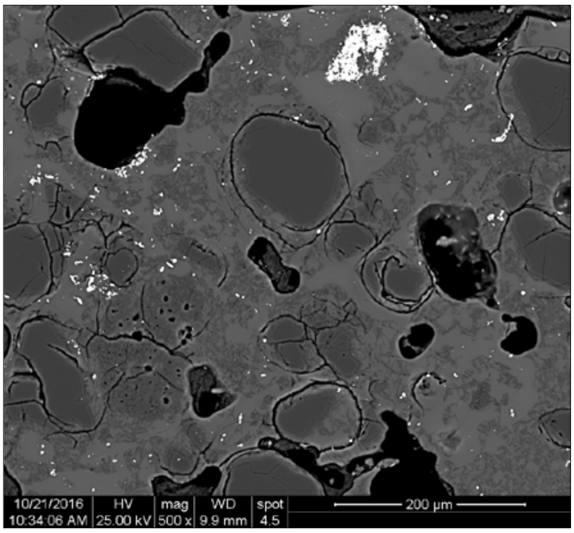


Fig 54: SEM image (BSE detector) of furnace stone from Imbhams Farm (sample 148) showing relict and recrystallised silica within the core

Fragments of stone from Imbhams Farm and Glasshouse Lane were selected for examination. The samples from Imbhams Farm showed evidence of having been subjected to high temperatures (Figures 53 and 54). This was evident visually, as these samples all had vitrified surfaces. The Imbhams Farm stones contained a high proportion of silica crystals. Sometimes these were the remains of the original quartz crystals which had undergone a degree of chemical erosion, but more frequently, the silica was present as small euhedral crystals which had formed from a molten matrix as the material cooled down (Figures 53 and 54). Porosity was abundant and tended to be present as relatively large and rather rounded voids, typical of extended heating at high temperatures.

The samples of stone from Glasshouse farm showed much less evidence of having been heated (Figures 55 and 56) - none had vitrified surfaces. These often contain accessory minerals such as feldspars. Minerals such as these usually melt quite easily and form a glassy matrix; their survival in these samples suggests limited exposure to high temperatures. In addition, these samples contain porosity which tends to have rather irregular shapes which is consistent with limited heating. While these stones *may* have performed a role in the construction of a furnace, it is unlikely that they were exposed to temperatures above 800°C (*ie* they were not located close to the hottest parts of the furnace).

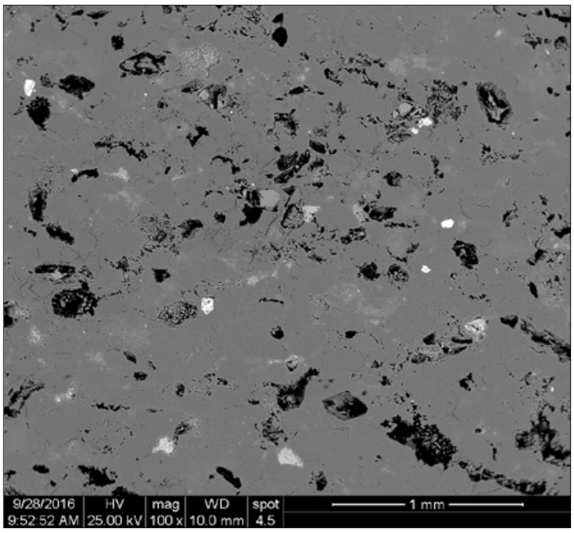


Fig 55: SEM image (BSE detector) of stone from Glasshouse Lane (sample 011) showing abundant relict silica grains, additional minerals (eg feldspars) and porosity (black)

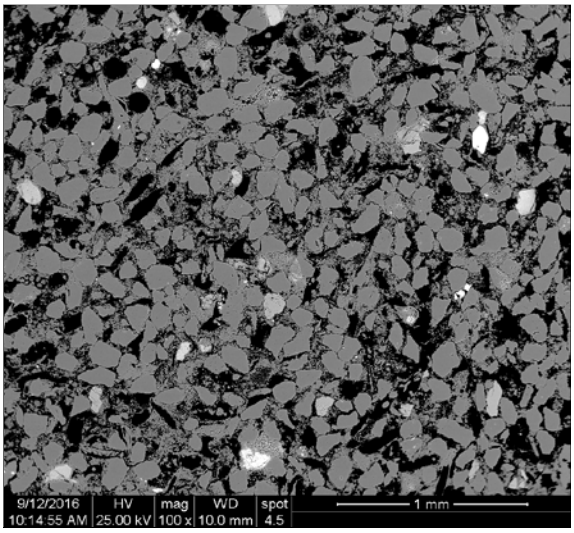


Fig 56: SEM image (BSE detector) of stone from Glasshouse Lane (sample 014) showing abundant relict silica grains, additional minerals (eg feldspars) and porosity (black)

MINERAL COMPOSITION OF SELECTED MATERIALS (XRD ANALYSIS)

Those samples which contained mineral phases were also analysed by X-ray diffraction (XRD) to determine the nature of the minerals present. While the use of the SEM-EDS in spot mode had allowed some mineral phases to be identified, the use of XRD allowed the identification of mineral phases that were too small for EDS analysis. It also allowed the identification of different minerals that shared the same chemical formula, *eg* the silica polymorphs: quartz, tridymite and cristobalite (all share the same chemical composition - SiO_2). Quartz is stable at temperatures up to 867°C, tridymite in the range 867–1470°C and cristobalite in the range 1470–1713°C, although the high temperature polymorphs can form at lower temperatures depending on the presence of other elements (cf Eramo 2005). The results of the XRD analysis are summarised in Table 10 and selected XRD results are presented below (samples 016, 034, 091, 098, 132, 133, and 195 were also analysed but produced XRD spectra with no peaks).

Devitrified Glass

The XRD analysis of samples of devitrified glass (including those initially identified as vitrified fuel ash) provided some evidence for the presence of mineral phases. In most cases (samples 016, 034, 091, 098, 132, 133 and 195) the XRD spectra contained no diffraction peaks (even though some crystals could be detected using SEM imaging). The XRD spectra obtained from samples 018, 138 and 145 (Figures 57–59) did show the presence of some minerals (principally quartz, wollastonite and apatite); however, the peak to background ratio was low and some of the identifications must remain tentative. There is some discrepancy between the XRD results and the SEM-EDS examination. The latter had identified the presence of diopside ($MgCaSi_2O_6$) and leucite ($KAlSi_2O_6$) but characteristic diffraction peaks for these minerals were not found using XRD. The failure to detect these phases using XRD (and the generally peak to background ratios for those peaks that were detected) is probably due to the fact that the bulk of these samples were still vitreous.

Table 10: Summary of phases detected using XRD, (IFG14 = Imbhams Farm), (IFG11= Imbhams Farm material from a previous study, see Castagnino 2013), (GLK14 = Glasshouse Lane, LFB14 = Lordings Farm, VFA = Vitrified Fuel Ash; DVG = Devitrified Glass)

Sample	Site	Material	Phases
34.1	IFG11	Crucible	Quartz, Tridymite, Mullite and Cristobalite
43.1	IFG11	Crucible	Quartz, Tridymite, Mullite and Cristobalite
43.2	IFG11	Crucible	Quartz, Tridymite, Mullite and Cristobalite
001	GLK14	Crucible	Cristobalite, Quartz, Tridymite and Mullite
002	GLK14	Crucible	Tridymite, Mullite, Quartz and Cristobalite
003	GLK14	Crucible	Tridymite, Quartz, and Mullite
004	GLK14	Crucible	Tridymite, Mullite, Quartz and Cristobalite
005	GLK14	Crucible	Quartz, Tridymite, Mullite and Cristobalite
006	GLK14	Crucible	Tridymite, Mullite, Quartz, Cristobalite
007	GLK14	Crucible	Tridymite, Mullite, Quartz and Cristobalite
008	GLK14	Crucible	Mullite, Tridymite, Quartz and Cristobalite
009	GLK14	Crucible	Mullite, Tridymite and Quartz
010	GLK14	Crucible	Mullite, Cristobalite, Tridymite and Quartz
012	GLK14	Furnace stone	Quartz
013	GLK14	Furnace stone	Quartz
014	GLK14	Furnace stone	Quartz
015	GLK14	Furnace stone	Quartz
017	GLK14	VFA (Crucible)	Quartz, Mullite, Tridymite and Cristobalite
018	GLK14	VFA (DVG)	Apatite
019	GLK14	VFA	Quartz
020	GLK14	VFA	Quartz
138	IFG14	DVG	Quartz, Wollastonite and Apatite
145	IFG14	DVG	Wollastonite and Apatite
150	IFG14	Stone	Quartz and Tridymite
151	LFB13	Lid/cover?	Quartz, Mullite and Cristobalite
152	LFB13	Crucible	Tridymite, Mullite and Quartz
153	LFB13	Crucible	Tridymite, Quartz, Mullite and Cristobalite
154	LFB13	Crucible	Mullite, Quartz and Tridymite
155	LFB13	Crucible	Tridymite, Mullite, Quartz and Cristobalite
156	LFB13	Crucible	Tridymite, Mullite and Quartz
159	LFB13	Crucible	Tridymite, Mullite, Quartz and Cristobalite
162	LFB13	Brick	Quartz
163	LFB13	Brick	Quartz
164	LFB13	Brick	Quartz, Tridymite and Mullite
165	LFB13	Brick	Quartz, Tridymite and Mullite
166	LFB13	Brick	Quartz
168	LFB13	VFA	Quartz and Apatite
171	LFB13	VFA	Quartz

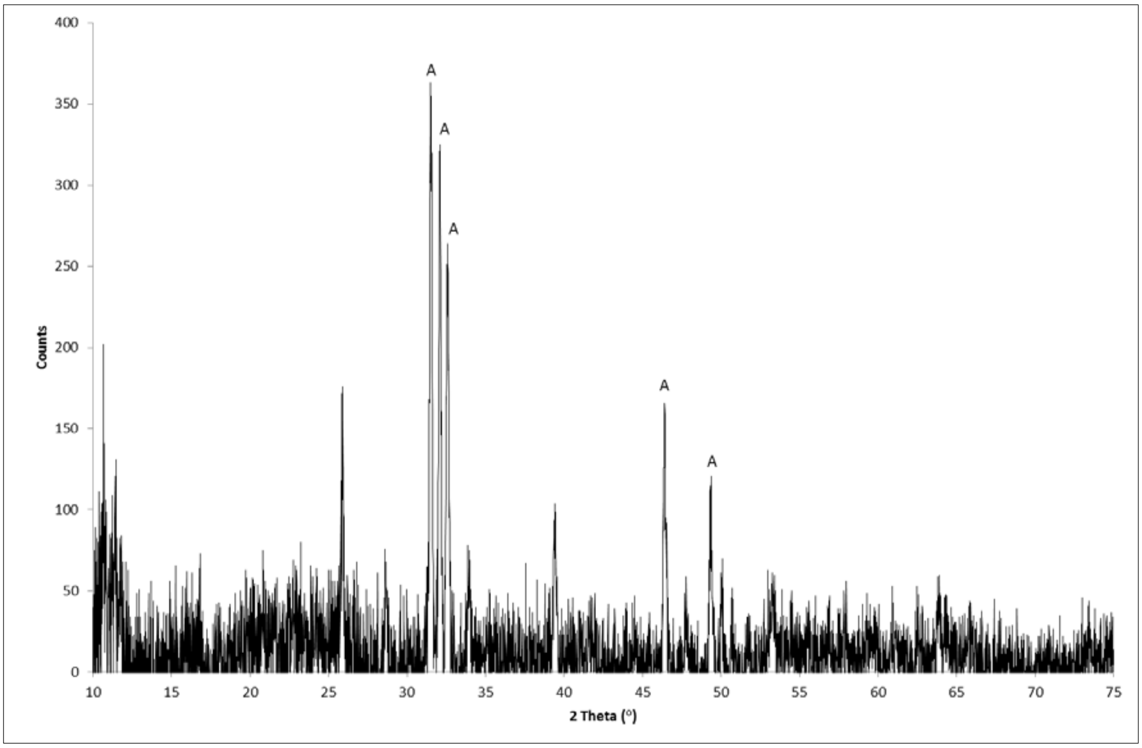


Fig 57: XRD spectrum from sample of devitrified glass showing apatite (Glasshouse Lane, sample 018)

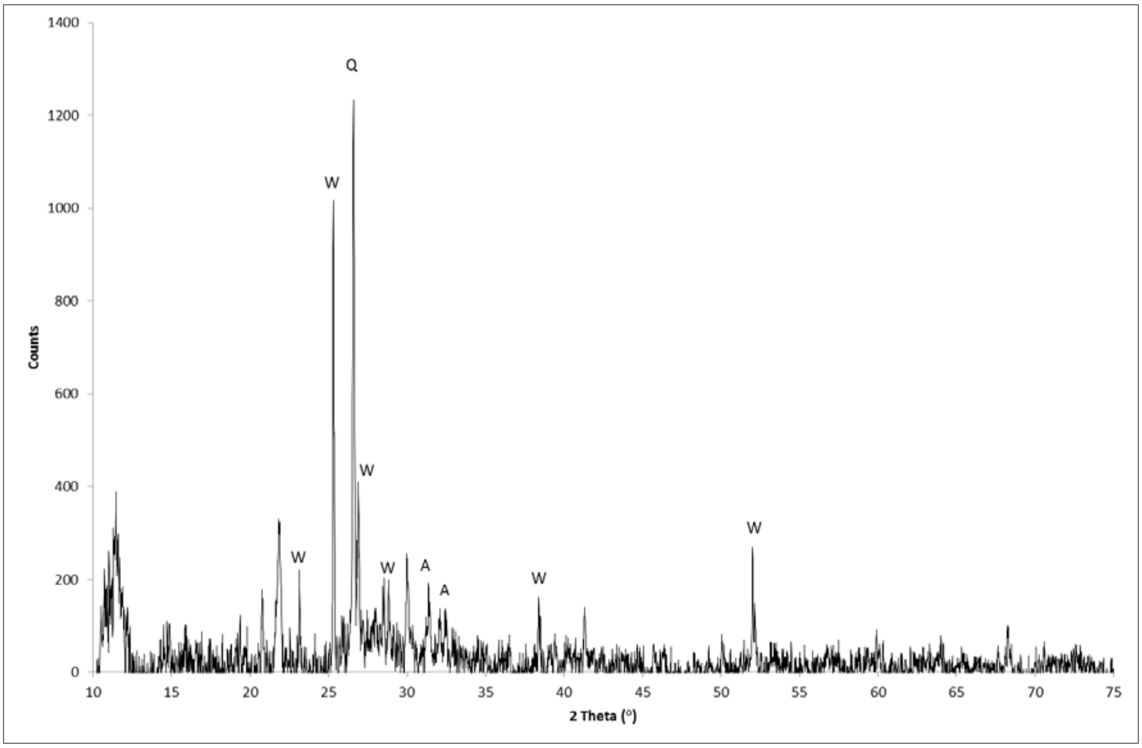


Fig 58: XRD spectrum from sample of devitrified glass waste showing quartz, wollastonite and apatite (Imbhams Farm, sample 138)

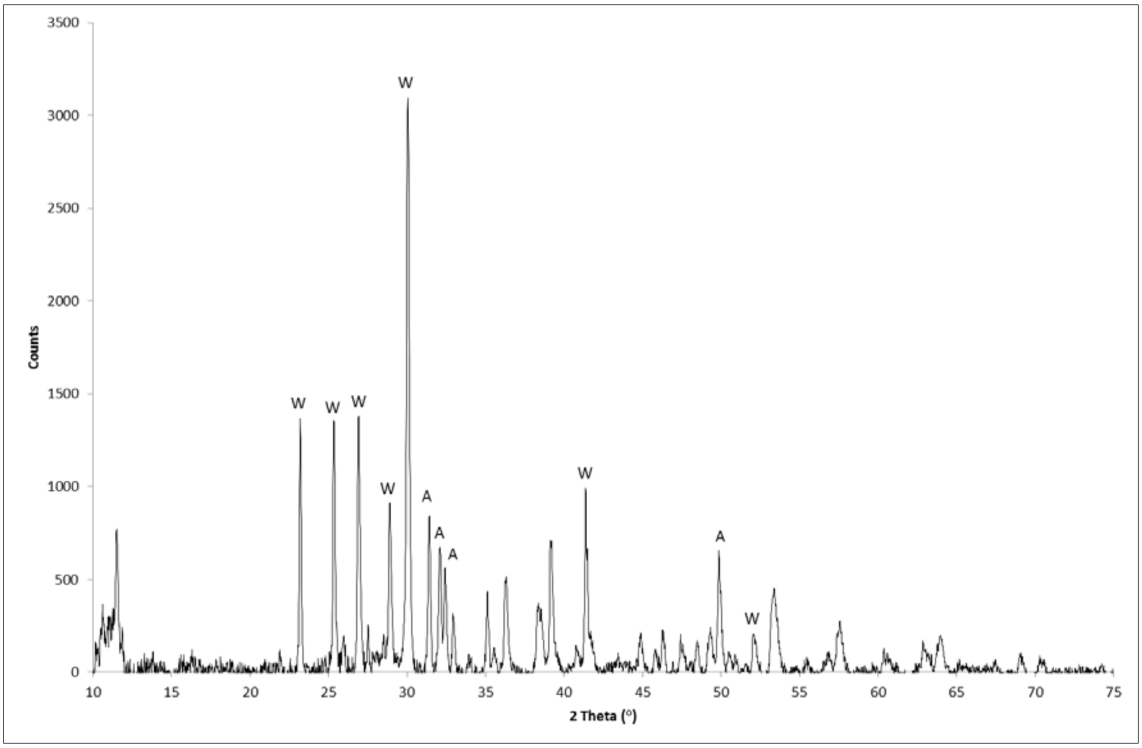


Fig 59: XRD spectrum from sample of devitrified glass waste showing wollastonite and apatite (Imbhams Farm, sample 145)

Vitrified Fuel Ash

Several samples of vitrified fuel ash were analysed using XRD, but the results provided limited evidence for the presence of mineral phases. In almost all cases diffraction peaks were detected for quartz; however, given the rather corroded nature of these samples, it is possible that this quartz is present in the surface deposits adhering to the vitrified fuel ash. One sample (168, Lordings Farm) showed the presence of other peaks which are interpreted as apatite (Figure 60), but the peak to background ratio is very low and the identification must remain tentative. Sample 017 was initially identified as vitrified fuel ash but SEM examination identified the presence of crucible fragments in a vitrified matrix, and XRD analysis of this sample identified mullite and all three silica polymorphs.

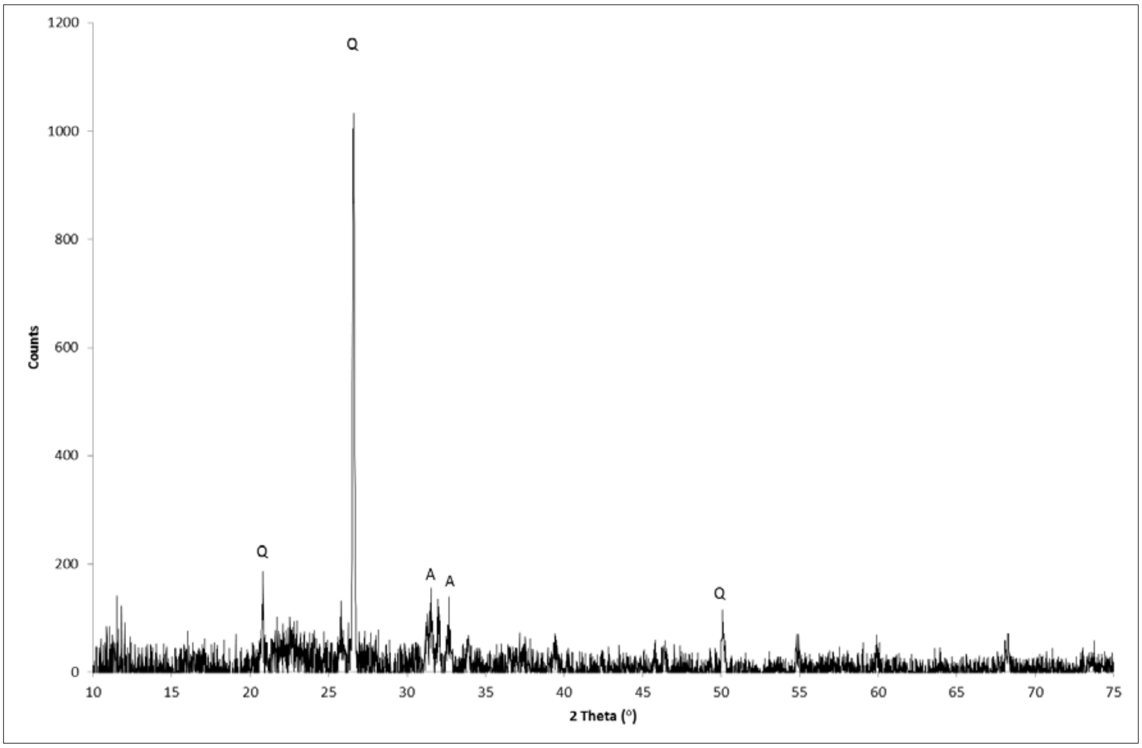


Fig 60: XRD spectrum from sample of vitrified fuel ash showing quartz and apatite (Lordings Farm, sample 168)

Crucibles

A total of 19 crucibles were analysed using XRD, including 10 from Glasshouse Lane, 6 from Lordings Farm and 3 from Imbhams Farm. The three Imbhams Farm crucibles were from the fieldwalking phase (Castagnino 2013) as no crucibles were recovered during the excavation at Imbhams Farm. The XRD analysis of the crucibles revealed peaks for quartz (SiO_2), tridymite (SiO_2), cristobalite (SiO_2) and mullite ($3Al_2O_3.2SiO_2$).

The proportions of the four phases identified using XRD (as estimated simply from peak heights) varied considerably from crucible to crucible (Figures 61–63) and several samples provided no peaks for cristobalite. The presence of high temperature silica polymorphs confirms that these crucibles have been exposed to high temperatures; however, the interpretation of the XRD data also requires an appreciation of their taphonomy. The survival of these phases in the analysed crucibles reflects not just their use, but also how they failed (and especially how they were treated when they did fail). If a crucible was placed in a furnace and heated so that the contents would react and melt to form glass at a temperature of 1200–1400°C, then it is expected that the original phases (largely kaolin and quartz) would be transformed into mullite and tridymite (with possibly some cristobalite). If the crucible subsequently fails while in the furnace (*eg* a crack forms and glass begins to escape) then the glassworkers would attempt to remove the crucible. It is quite possible that the crucible would break up during removal and some fragments would end up inside the furnace and some outside. The fragments that were removed from the furnace would tend to cool very quickly and so would be more likely to retain the high temperature phases that had formed during use, while fragments trapped inside the furnace would be more likely to cool slowly and the high temperature phases would be more likely to transform into low temperature ones. In this way two crucible fragments which had the same use history would contain different proportions of the same mineral phases that related to their discard.

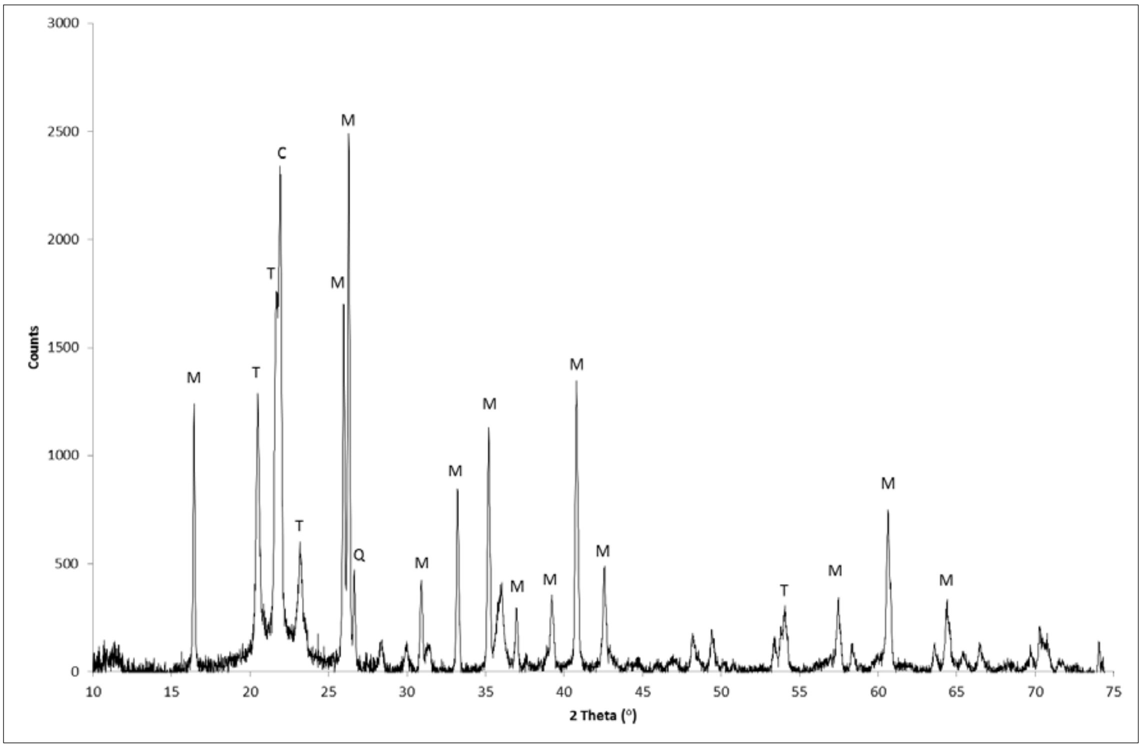


Fig 61: XRD spectrum from sample of crucible showing mullite and silica polymorphs (Glasshouse Lane, sample 010)

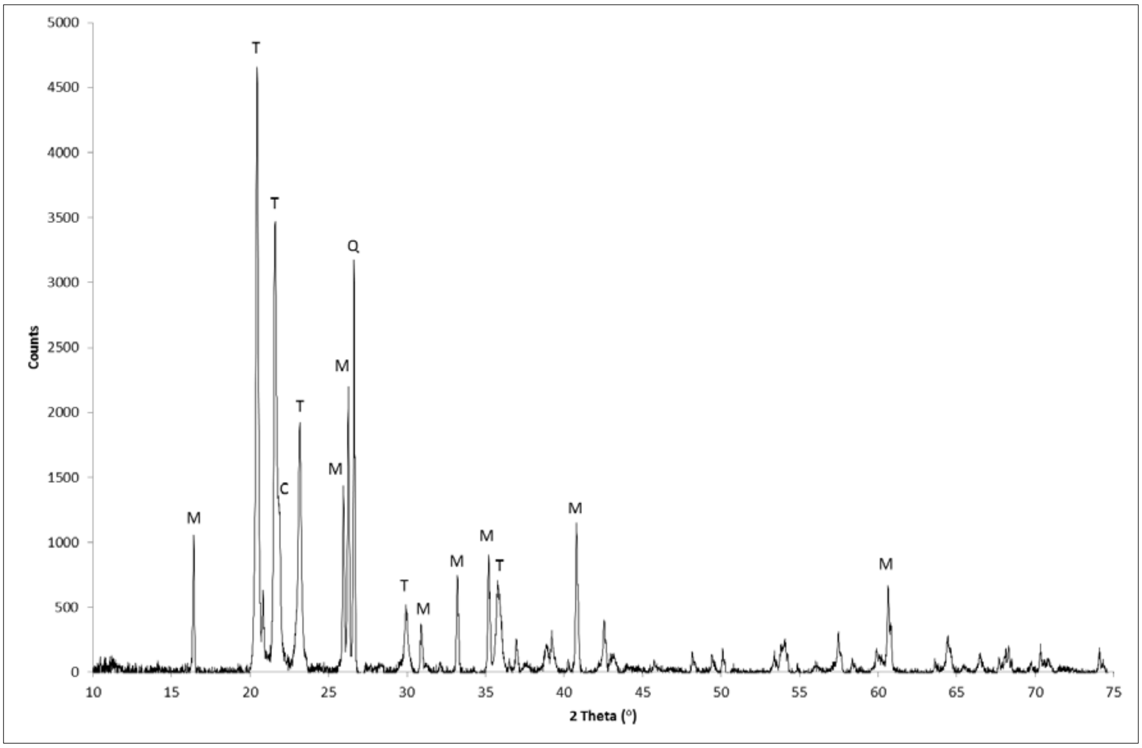


Fig 62: XRD spectrum from sample of crucible showing mullite and silica polymorphs (Lordings Farm, sample 153)

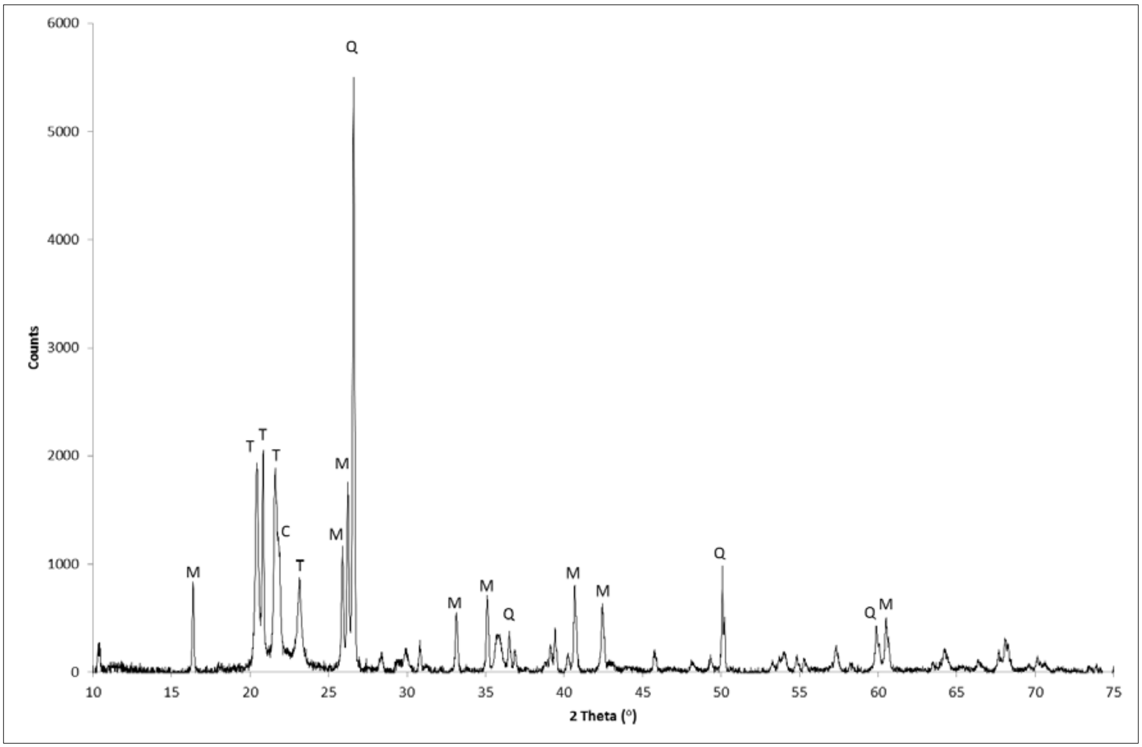


Fig 63: XRD spectrum from sample of crucible showing mullite and silica polymorphs (Imbhams Farm, sample IFG11 43.2)

While taphonomic considerations suggest that variations in mineral phases may be of limited value in determining use history, there is one observed difference which may be significant. Quartz was detected in all of the crucibles; however, the peak heights for the three crucibles from Imbhams Farm (Figure 63) were considerably greater than any of the crucibles from Glasshouse Lane or Lordings Farm. The high proportion of quartz detected using XRD in the Imbhams Farm crucibles could reflect the fact that these are all quartz-tempered. The Glasshouse Lane crucible with the highest quartz peak (Sample 005) is also the single example of a crucible from that site that appears to be quartz-tempered (all the others being grog-tempered).

Bricks and other ceramics

Five brick samples were analysed (all from Lordings Farm) using XRD and the results correlate well with the observed microstructures (SEM) (Table 10). The two bricks which showed extensive vitrification (SEM imaging, samples 163 and 164) provided XRD spectra (Figure 64) with peaks for mullite and tridymite (in addition to quartz) while the other three bricks showed just the presence of quartz.

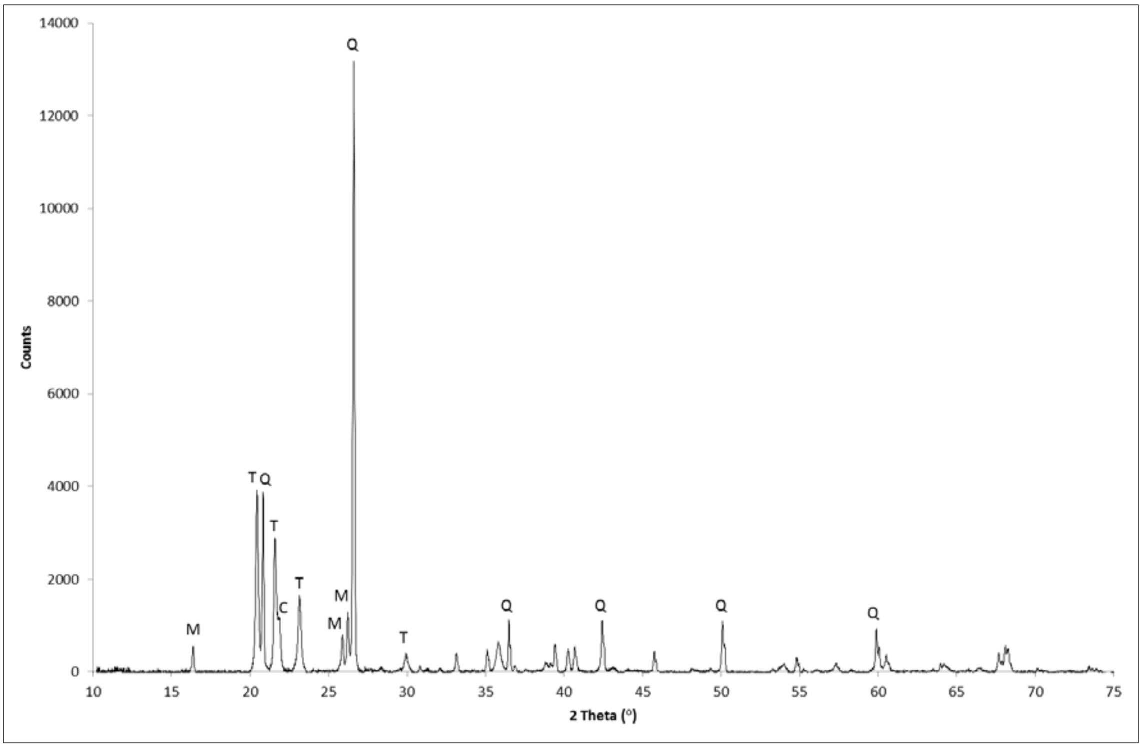


Fig 64: XRD spectrum from sample of brick showing mullite and silica polymorphs (Lordings Farm, sample 164)

A single example of a possible lid/cover from a furnace was analysed using XRD (the other examples were too small to be able to provide enough powdered sample). The lid/cover (Figure 65) contains quartz, cristobalite and mullite but no tridymite (the absence of tridymite is unusual, compared to the crucibles).

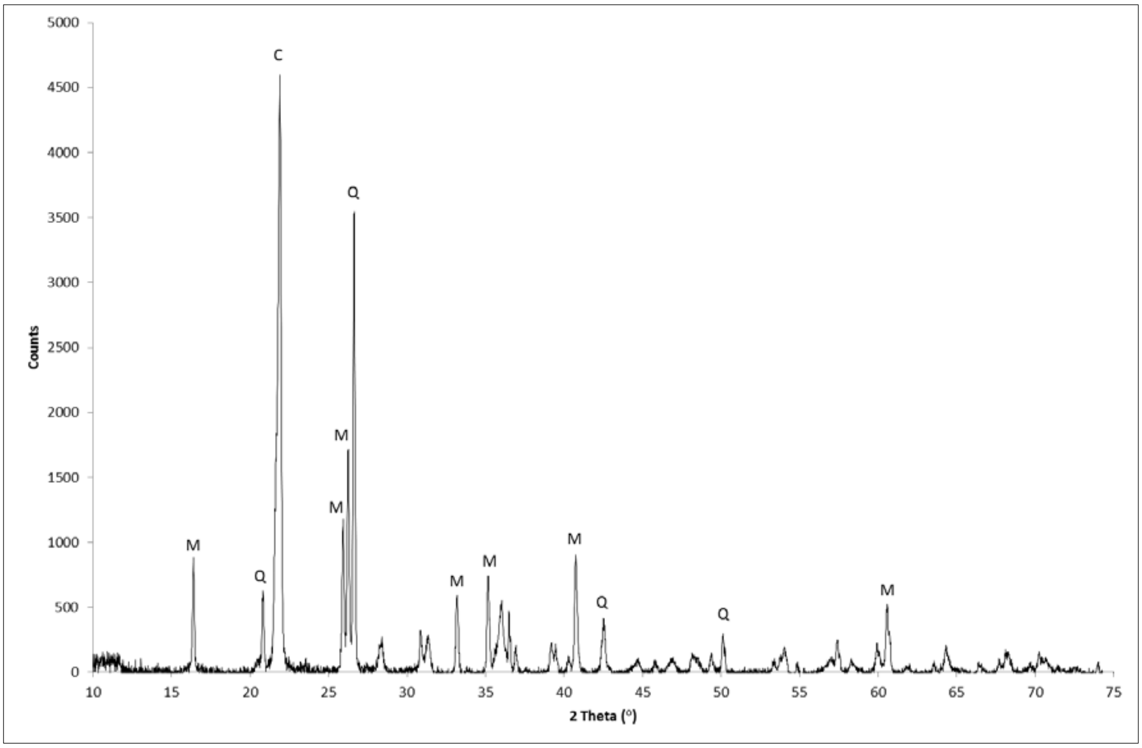


Fig 65: XRD spectrum from sample of ceramic cover or lid stone showing mullite and silica polymorphs (Lordings Farm, sample 151)

Furnace Stones

The four samples of furnace stones from Glasshouse Lane all contain quartz with no peaks indicating the presence of high temperature phases (Table 10, Figure 66). This agrees well with the observed microstructure for these samples which showed limited degrees of vitrification.

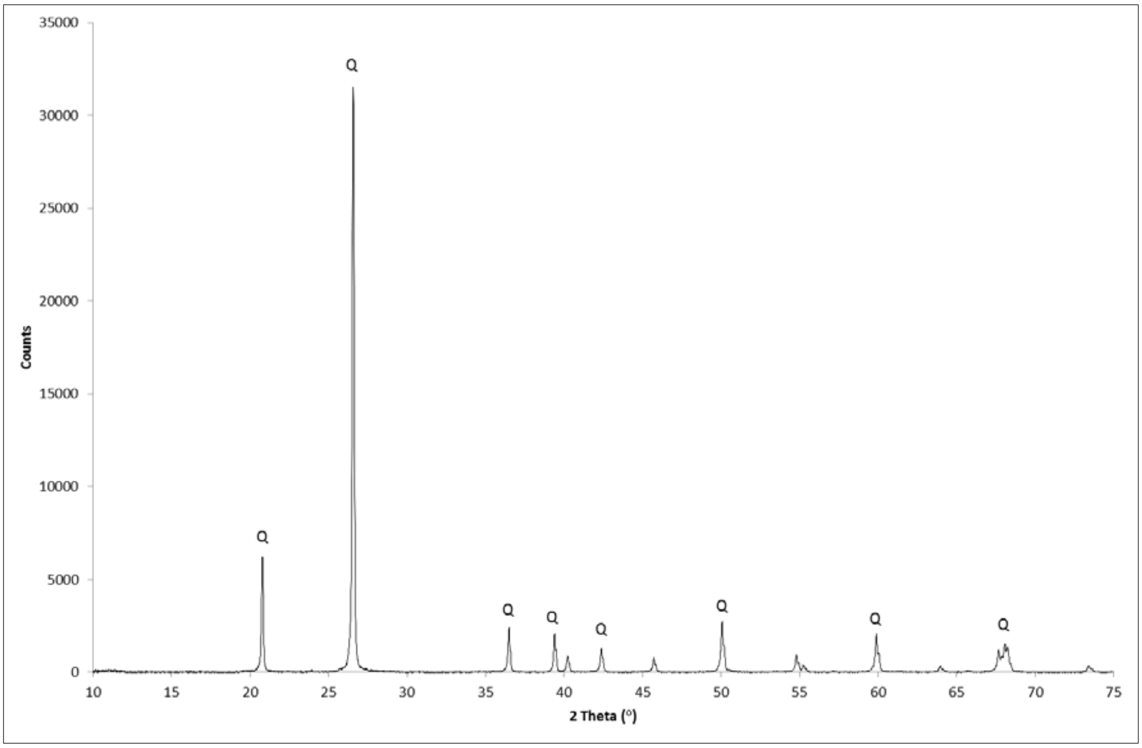


Fig 66: XRD spectrum from sample of stone showing quartz (Glasshouse Lane, sample 012)

CHEMICAL COMPOSITION OF THE GLASS AND GLASS WASTE

The chemical analysis of 159 samples of glass and glass waste presented below demonstrates that each site produced a single type of glass (forest glass in the case of Imbhams Farm; high-lime, low-alkali (HLLA) at the other two sites). Some of the glass waste (especially at Imbhams Farm) has divergent chemical compositions which probably represent contamination by fuel and/or other materials.

Imbhams Farm

The glass and amorphous glassworking waste from Imbhams Farm included a small proportion of finished glass (both window glass and vessel glass but some fragments were too small to distinguish between these two categories). The amorphous waste does not display a single tightly clustered chemical composition (Figures 67 and 68); however, the waste can be divided into two groups (Waste 1 and Waste 2). The first of these displays some compositional clustering and has a composition typical of medieval forest glass (Table 11) while the second shows more compositional variation and does not match known medieval or later glass compositions. Waste 2 generally has magnesium, calcium and strontium concentrations that are too low to match known glass compositions, while silicon, aluminium, iron and zirconium are often too high. Waste 2 also contains low levels of zinc compared to Waste 1 and, while sulphur and chlorine were detected in Waste 1, neither of these elements was detected in Waste 2. These compositional variations are similar to those noted by Welham (2001), particular at Blunden's Wood. The increase in aluminium and iron concentrations in Waste 2 suggests that these have been contaminated by reactions with ceramic and/or stone materials (possibly parts of the furnace structure, cf Dungworth and Mortimer in Jackson 2005). The examination of similar waste from an experimental furnace (Paynter 2008) also showed glassy waste contaminated by fuel ash (as well as vapour rich in volatile elements). The SEM examination of these samples showed that almost all exhibited varying degree of devitrification (see above) but this phenomenon was largely absent from Waste 1 samples. There are no significant differences in the forms of Waste 1 and Waste 2 from Imbhams Farm or the contexts from which they were recovered.

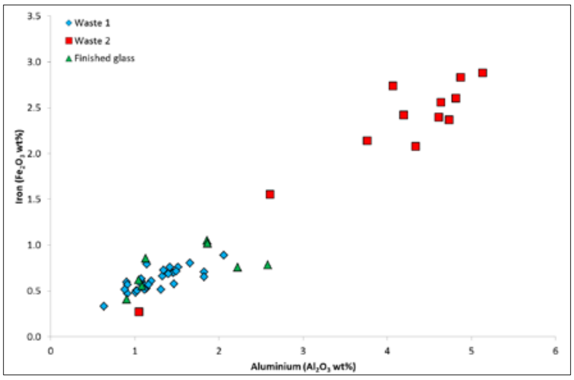


Fig 67: Aluminium and iron content of glass and glassworking waste from Imbhams Farm

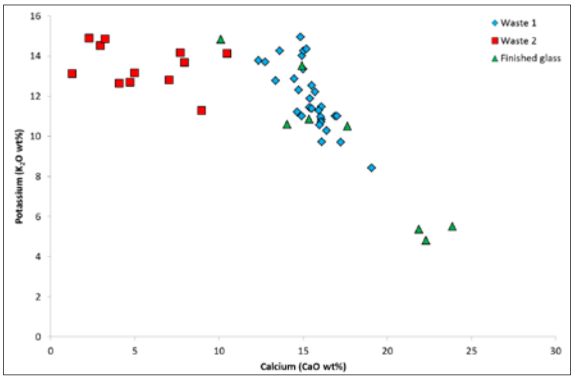


Fig 68: Calcium and potassium content of glass and glassworking waste from Imbhams Farm

Table 11: Average composition (wt%) of selected amorphous glassworking waste (Waste 1) from Imbhams Farm

	Waste 1	Waste 2
Na_2O	2.4±0.3	2.0±0.5
MgO	7.2±0.7	3.1±2.0
Al_2O_3	1.2±0.3	4.1±1.2
SiO_2	55.7±1.6	67.3±4.5
P_2O_5	3.3±0.4	1.2±1.1
SO_3	0.2±0.1	<0.1
Cl	0.3±0.1	<0.1
K_2O	11.9±1.6	13.5±1.1
CaO	15.4±1.3	5.5±2.9
TiO_2	0.12±0.04	0.28±0.08
MnO	1.2±0.1	0.6±0.3
Fe_2O_3	0.6±0.1	2.2±0.7
CoO	<0.01	0.012±0.003
ZnO	0.064±0.005	0.036±0.019
As_2O_3	<0.01	<0.01
Rb_2O	0.035±0.005	0.034±0.003
SrO	0.07±0.01	0.03±0.01
ZrO_2	0.012±0.003	0.022±0.004
BaO	0.07±0.02	0.04±0.02
PbO	0.08±0.07	<0.02

The eight samples of finished glass from Imbhams Farm (all from context [101]) include five made of medieval forest glass and three made of high-lime, low-alkali (HLLA) glass. The three HLLA glasses were not made at Imbhams Farm. Given the context they were recovered from, it is not certain that they were deposited while the furnace was in operation. None of the three samples of finished glass made of medieval forest glass have compositions which match the production waste and it is possible that they were all brought to the site as cullet - the manganese is lower than typical for the Wealden sites.

Glasshouse Lane

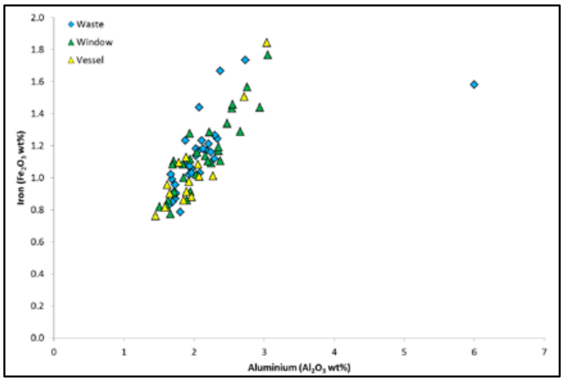


Fig 69: Aluminium and iron content of glass and glassworking waste from Glasshouse Lane

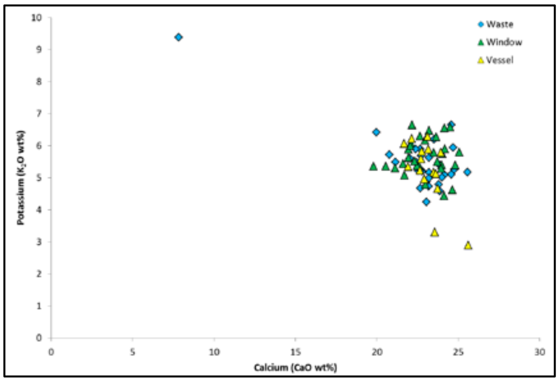


Fig 70: Calcium and potassium content of glass and glassworking waste from Glasshouse Lane

The glass from Glasshouse Lane includes a substantial assemblage of working waste as well as finished glass (both window and vessel glass). Almost all of the working waste shares the same composition (Figures 69 and 70); only three samples (025, 034 and 091) have different compositions (probably due to contamination as discussed above for some of the Imbhams Farm samples). The glass produced at Glasshouse Lane was a high-lime, low-alkali glass, with a composition broadly similar to that produced at many other sites in the Weald. The majority of the finished glass shares the same composition as the waste and was probably produced at Glasshouse Lane (Table 12). The EDXRF spectra showed the presence of traces of bismuth; however, the concentrations could not be quantified.

Table 12: Average composition (wt%) of samples from Glasshouse Lane (amorphous glassworking waste excludes samples 025, 034 and 091, window glass excludes samples 044 and 057, vessel glass excludes 080 and 082)

	Waste	Window	Vessel
Na_2O	0.9±0.1	0.9±0.1	0.9±0.1
MgO	3.0±0.2	3.2±0.2	3.1±0.3
Al_2O_3	2.0±0.3	2.1±0.4	1.9±0.2
SiO_2	60.5±1.7	60.1±1.7	60.9±1.0
P_2O_5	2.1±0.2	2.2±0.2	2.1±0.2
SO_3	0.2±0.2	0.2±0.1	0.2±0.1
Cl	<0.1	<0.1	<0.1
K_2O	5.4±0.6	5.7±0.6	5.6±0.5
CaO	23.2±1.2	23.0±1.3	22.9±0.7
TiO_2	0.27±0.04	0.28±0.04	0.25±0.03
MnO	0.9±0.2	1.0±0.2	0.9±0.2
Fe_2O_3	1.1±0.2	1.1±0.2	1.0±0.1
CoO	0.027±0.008	0.029±0.007	0.02±0.01
ZnO	0.030±0.004	0.033±0.005	0.03±0.01
As_2O_3	0.06±0.03	0.06±0.03	0.06±0.03
Rb_2O	0.007±0.001	0.007±0.001	0.007±0.001
SrO	0.08±0.01	0.08±0.01	0.07±0.01
ZrO_2	0.032±0.004	0.032±0.005	0.03±0.01
BaO	0.03±0.02	0.04±0.01	0.03±0.01
PbO	<0.02	<0.02	<0.02

Lordings Farm

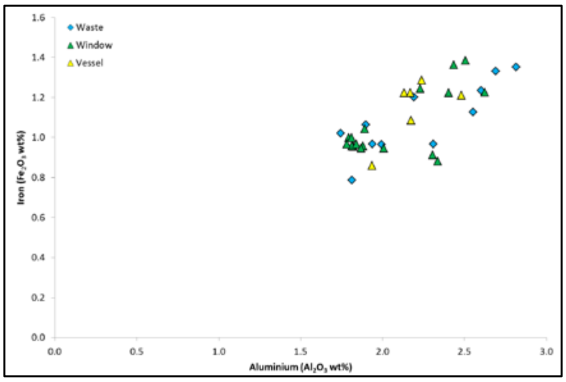


Fig 71: Aluminium and iron content of glass and glassworking waste from Lordings Farm

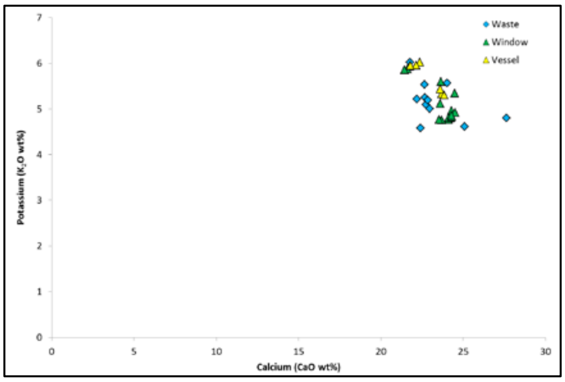


Fig 72: Calcium and potassium content of glass and glassworking waste from Lordings Farm

The glass from Lordings Farm includes working waste as well as finished glass (both window and vessel glass, although only six samples of the latter). Almost all of the working waste shares the same composition (Figures 71 and 72); only one outlier (sample 202) has been excluded from the calculation of the average composition of the waste (Table 13). The glass produced at Lordings Farm was a high-lime, low-alkali (HLLA) glass. The majority of the finished glass shares the same composition as the waste and was probably produced at Lordings Farm. The EDXRF spectra showed the presence of traces of bismuth; however, the concentrations could not be quantified.

Table 13: Average composition (wt%) of samples from Lordings Farm (amorphous glassworking waste excludes sample 195)

	Waste	Window	Vessel
Na_2O	0.9±0.1	0.8±0.1	1.0±0.1
MgO	2.8±0.2	2.8±0.1	2.9±0.1
Al_2O_3	2.3±0.4	2.1±0.3	2.2±0.2
SiO_2	61.4±0.9	60.9±0.6	60.4±0.5
P_2O_5	1.8±0.2	1.9±0.1	2.0±0.1
SO_3	0.2±0.1	0.2±0.1	0.2±0.1
Cl	<0.1	<0.1	<0.1
K_2O	5.2±0.4	5.1±0.4	5.7±0.3
CaO	22.8±0.9	23.7±1.0	22.9±0.9
TiO_2	0.23±0.04	0.22±0.04	0.25±0.02
MnO	0.9±0.1	1.0±0.1	1.0±0.1
Fe_2O_3	1.1±0.2	1.1±0.2	1.1±0.2
CoO	0.024±0.004	0.024±0.005	0.027±0.003
ZnO	0.033±0.008	0.029±0.003	0.034±0.007
As_2O_3	0.04±0.01	0.05±0.03	0.06±0.01
Rb_2O	0.006±0.001	0.006±0.001	0.007±0.001
SrO	0.08±0.01	0.08±0.01	0.08±0.01
ZrO_2	0.019±0.005	0.018±0.003	0.021±0.006
BaO	0.03±0.01	0.03±0.01	0.04±0.01
PbO	<0.02	<0.02	<0.02

Other Wealden Sites

Previous research has established the nature of glass manufactured at a number of Wealden glass furnaces (Castagnino 2013; Dungworth 2007; 2010; Dungworth and Clark 2004; 2010; Dungworth and Paynter 2010; Welham 2001). To aid comparison with results of the three excavated sites, samples from several sites (Blunden's Wood, Horsebridge, Idehurst North, Idehurst South, June Hill and Tanland, see Figure 1 for locations) have been re-analysed using EDXRF, following the methods described above, to obtain improved data on the minor element composition (Co, Ni, Cu, Zn, As, Rb, Sr, Zr, Ba and Pb, see Table 14). Bismuth was detected in the samples from June Hill; however, the concentrations could not be quantified.

Blunden's Wood was dated to the 14th century (Wood 1965), Idehurst North and South have been linked, from documentary evidence, to activity in the 16th century (largely before the arrival of French glassmakers); however, there is no direct evidence for the dates that these sites were in use (Dungworth and Clark 2004;

Kenyon 1967). June Hill (Dungworth 2007), Horsebridge (Dungworth and Clark 2010) and Tanland (Dungworth and Clark 2004) have been dated to the later 16th (or early 17th) century on the basis of surface-recovered pottery. Combining this data with that from Imbhams Farm, Glasshouse Lane and Lordings Farm (Figures 73–76) reinforces the thesis that there are significant differences in the chemical composition of early and late glass (*ie* that made before and after the first arrival of French glassmakers in 1567). These chemical differences are varied and complex; some major elements show significant differences, suggesting significant changes in the raw materials used; however, minor or trace elements also show differences suggesting more subtle changes.

Table 14: Average composition (wt%) of amorphous glassworking waste from selected Wealden glass sites (SEM-EDS data [Na–Fe] from Dungworth 2007; 2010; Dungworth and Clark 2004; 2010; Dungworth and Paynter 2010).

	Blundens Wood	Idehurst North	Idehurst South	June Hill	Horsebridge	Tanland
Number of analyses	11	5	8	9	9	10
Na_2O	2.5±0.3	2.1±0.2	3.0±0.2	1.1±0.2	0.9±0.1	1.5±0.5
MgO	6.9±0.3	7.2±0.2	8.7±0.2	4.2±0.4	3.6±0.5	2.8±0.2
Al_2O_3	0.9±0.2	1.1±0.1	1.4±0.2	2.2±0.3	2.1±0.4	2.2±0.2
SiO_2	58.6±2.8	55.3±1.8	53.3±0.8	66.6±2.0	61.7±2.5	61.2±1.1
P_2O_5	3.2±0.3	3.3±0.5	3.9±0.1	2.2±0.2	2.1±0.3	2.2±0.2
SO_3	0.2±0.1	0.3±0.1	0.4±0.1	0.3±0.1	0.3±0.1	0.2±0.1
Cl	0.6±0.1	0.5±0.1	0.5±0.1	0.4±0.1	<0.1	0.4±0.3
K_2O	11.1±0.8	11.6±0.6	10.8±0.8	7.7±0.6	5.9±0.3	3.8±0.8
CaO	13.7±1.5	17.0±0.3	16.6±0.5	19.3±0.6	20.4±1.3	24.2±1.0
TiO_2	0.09±0.03	0.19±0.03	0.19±0.03	0.28±0.08	0.30±0.05	0.26±0.05
MnO	1.20±0.10	1.15±0.07	0.96±0.06	0.87±0.46	1.68±0.24	0.70±0.07
Fe_2O_3	0.83±0.08	0.56±0.08	0.58±0.06	0.82±0.26	1.00±0.23	1.24±0.09
CoO	0.01±0.01	<0.01	<0.01	0.02±0.02	0.03±0.01	0.03±0.01
ZnO	0.06±0.01	0.06±0.01	0.06±0.01	0.04±0.01	0.03±0.01	0.03±0.01
As_2O_3	<0.01	<0.01	<0.01	0.04±0.05	0.04±0.01	0.07±0.02
Rb_2O	0.021±0.002	0.022±0.001	0.016±0.001	0.010±0.003	0.008±0.001	0.005±0.002
SrO	0.06±0.01	0.07±0.01	0.06±0.01	0.07±0.02	0.09±0.01	0.09±0.01
ZrO_2	0.01±0.01	<0.01	0.01±0.01	0.02±0.01	0.04±0.01	0.02±0.01
BaO	0.05±0.02	0.08±0.01	0.04±0.01	0.03±0.03	0.07±0.02	0.03±0.01
PbO	0.04±0.04	0.04±0.01	<0.02	<0.02	<0.02	<0.02

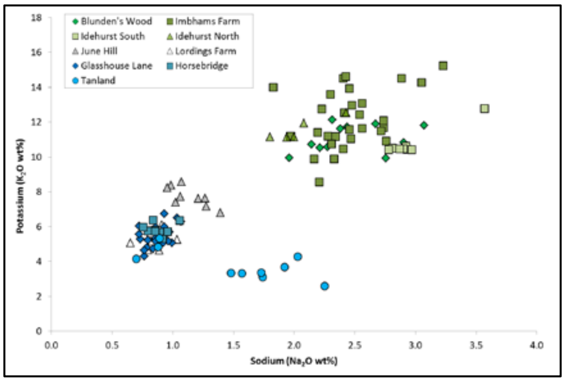


Fig 73: Sodium and potassium concentration of early (green) and late (blue) Wealden glass

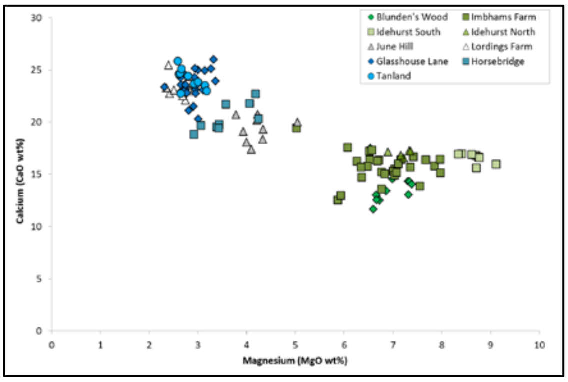


Fig 74: Magnesium and calcium concentration of early (green) and late (blue) Wealden glass

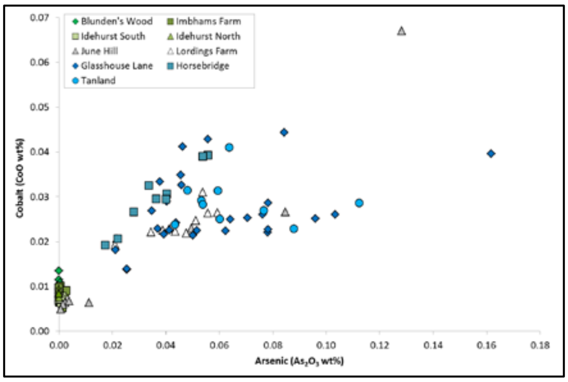


Fig 75: Arsenic and cobalt concentration of early (green) and late (blue) Wealden glass

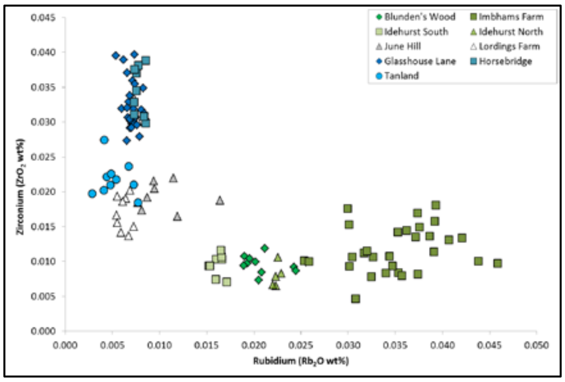


Fig 76: Rubidium and zirconium concentration of early (green) and late (blue) Wealden glass

CHEMICAL COMPOSITION OF THE VITRIFIED FUEL ASH

Ten samples of vitrified fuel ash were selected (on visual criteria) for analysis: five from Glasshouse Lane (samples 103–109) and five from Lordings Farm (samples 167–171); this includes some additional samples to those analysed by XRD and shown in Table 10. The SEM examination showed that several of these samples were not vitrified fuel ash but fragments of devitrified glass or crucibles; although some may have incorporated some vitrified fuel ash. Only two of the samples from Glasshouse Lane (but all from Lordings Farm) are likely to be vitrified fuel ash. The vitrified fuel ash from both Glasshouse Lane and Lordings Farm share the same chemical composition (Table 15). In many respects, the vitrified fuel ash has a chemical composition which resembles the HLLA glass manufactured at both of these sites; nevertheless, there are several significant differences. The vitrified fuel ash contains much lower levels of calcium compared to HLLA glass but higher levels of aluminium, silicon, titanium and iron. The high levels of silicon suggest that the material identified as vitrified fuel ash probably includes a proportion of earthy material.

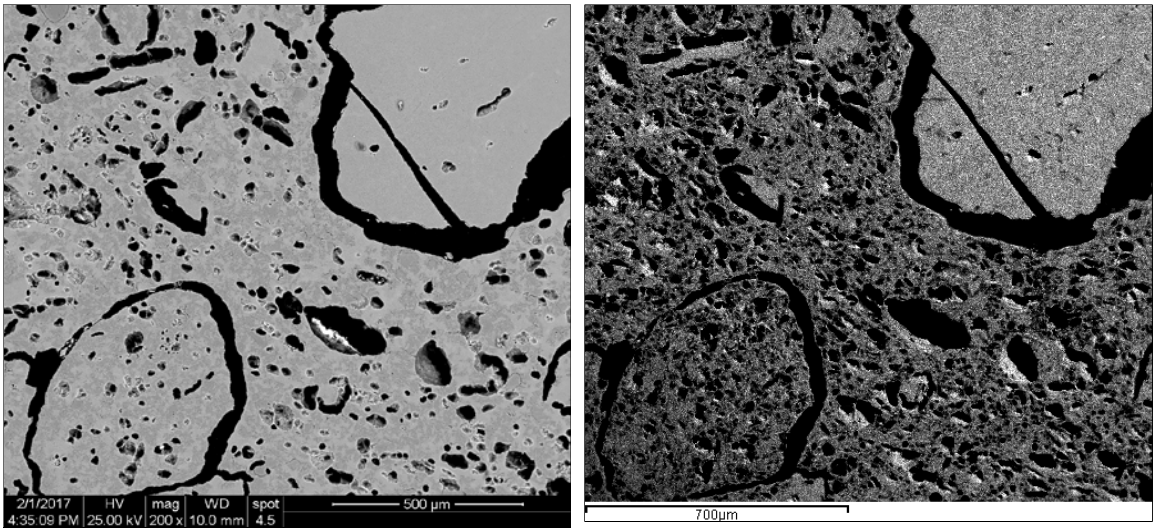
Table 15: Average composition of vitrified fuel ash

	Glasshouse Lane	Lordings Farm
Na_2O	1.1±0.1	0.9±0.2
MgO	2.4±0.1	2.2±0.5
Al_2O_3	4.6±0.1	5.2±1.4
SiO_2	70.4±0.9	73.9±3.7
P_2O_5	3.5±0.1	2.6±0.6
SO_3	0.1±0.1	<0.1
Cl	<0.1	0.1±0.1
K_2O	7.7±0.6	7.1±1.1
CaO	5.8±0.3	4.3±1.0
TiO_2	0.5±0.1	0.4±0.1
MnO	1.4±0.1	1.3±0.3
Fe_2O_3	2.2±0.1	1.6±0.2

CHEMICAL COMPOSITION OF THE REFRACTRORY MATERIALS

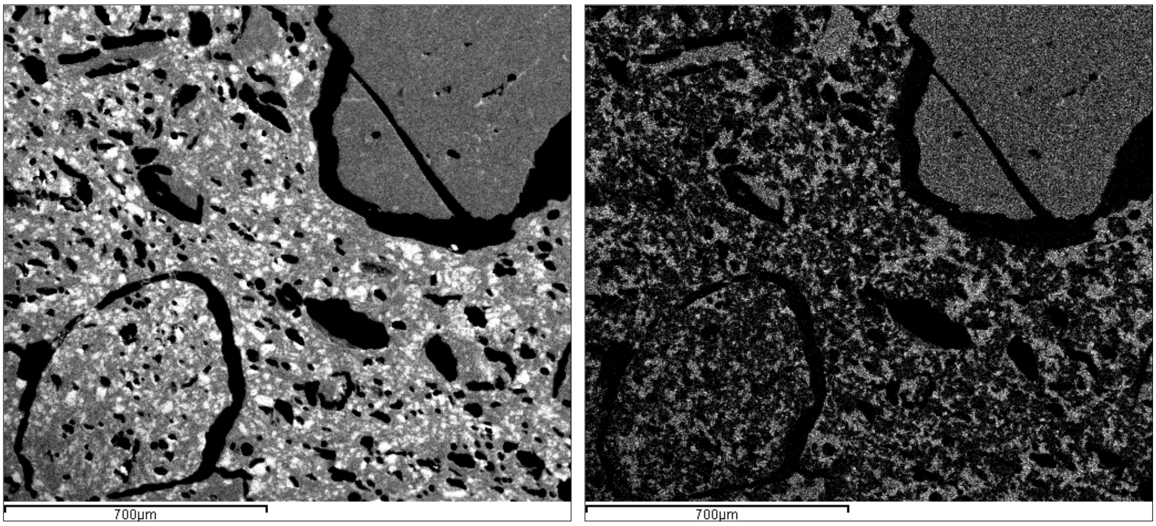
Crucibles

Eighteen crucibles from the excavations at Glasshouse Lane (samples 1–10) and Lordings Farm (samples 152–159) were analysed to determine their chemical composition. As no crucibles were recovered from the excavation at Imbhams Farm, the three samples recovered during the survey phase of this project (previously analysed by Castagnino 2013, site code IFG11) have been used to make comparisons (as well as data from earlier work, see Dungworth and Clark 2010; Dungworth and Paynter 2010).



SEM image (BSE detector)

Aluminium



Silicon

Potassium

Fig 77: SEM image and associated X-ray maps of a grog-tempered crucible (sample 152)

The SEM examination of the crucibles confirmed that these are heterogeneous; while the clay matrix has usually vitrified, inclusions are common (and some are

>1mm in size), and the surfaces have undergone reactions with glass and/or other materials (see below). The heterogeneity of the crucible fabric is illustrated in Figure 77 through the use of EDS X-ray maps: each map shows the relative distribution of one element (the brighter areas are qualitatively richer in that element). Figure 77 also shows that grog particles within a single crucible do not always share the same chemical composition.

In order to overcome material heterogeneity, the chemical composition of the crucibles was determined using SEM-EDS with each crucible analysed at least 10 times (a separate area each time, typically 2–4mm^2). The grog-tempered crucibles were subject to further SEM-EDS analyses to investigate the chemical differences between grog and matrix. Analyses were carried out on ten grog particles (typically 0.1–1mm^2) and ten areas of matrix free from grog particles (typically 0.01–0.05mm^2). Given the high degree of heterogeneity in the ceramic materials, no attempt was made to use EDXRF to determine the concentrations of trace elements (samples have been retained for future ICPMS analysis).

SEM-EDS analysis was also used (qualitatively) in spot mode to investigate some of the inclusions, such as silica, zirconia and ilmenite-hercynite (the presumed mullite in almost all crucibles was generally too small to allow analysis in this way). Where a glazed surface or adhering glass survived, this was analysed using a series of small areas through the glass/glaze and into the underlying ceramic (cf Dungworth 2008). In most cases the glass/glaze was relatively thin and so was contaminated by reactions with the ceramic fabric of the crucible.

Table 16: Average chemical composition of the crucibles from Glasshouse Lane (001–010), Lordings Farm (152–159) and Imbhams Farm (data from Castagnino 2013)

	Na_2O	MgO	Al_2O_3	SiO_2	K_2O	CaO	TiO_2	Fe_2O_3
001	0.1±0.1	0.4±0.1	21.5±1.3	72.8±1.4	1.3±0.1	0.5±0.1	1.7±0.1	1.6±0.1
002	0.3±0.1	0.4±0.1	25.8±0.9	68.6±1.2	1.7±0.1	0.2±0.1	1.4±0.1	1.5±0.1
003	0.2±0.1	0.4±0.1	21.1±0.7	73.5±0.8	1.7±0.1	0.2±0.1	1.4±0.1	1.4±0.1
004	0.1±0.1	0.4±0.1	21.9±0.8	72.3±0.8	1.8±0.1	0.2±0.1	1.4±0.1	1.8±0.1
005	0.1±0.1	0.6±0.1	14.7±1.0	79.7±1.4	2.0±0.1	0.3±0.1	0.8±0.1	1.9±0.2
006	0.1±0.1	0.4±0.1	23.0±0.4	70.8±0.5	1.9±0.1	0.2±0.1	1.4±0.1	2.0±0.1
007	0.1±0.1	0.3±0.1	24.2±2.4	69.6±3.1	1.8±0.2	0.2±0.1	1.3±0.1	2.3±0.3
008	0.1±0.1	0.5±0.1	24.9±0.9	67.9±1.1	2.2±0.1	0.5±0.1	1.8±0.1	1.9±0.1
009	0.1±0.1	0.6±0.1	29.6±1.2	63.8±1.5	1.9±0.1	0.1±0.1	1.5±0.1	2.3±0.1
010	0.1±0.1	0.4±0.1	26.9±0.1	67.6±0.4	2.1±0.2	0.1±0.1	1.5±0.1	1.2±0.1
152	0.1±0.1	0.5±0.1	22.4±1.1	71.2±1.2	2.0±0.1	0.4±0.1	1.5±0.1	1.6±0.1
153	0.1±0.1	0.4±0.1	20.5±0.4	74.0±0.5	1.5±0.1	0.4±0.1	1.6±0.1	1.5±0.1
154	0.1±0.1	0.6±0.1	28.4±0.4	64.0±0.5	2.4±0.1	0.5±0.1	2.0±0.1	1.8±0.1
155	0.1±0.1	0.3±0.1	18.5±0.8	76.8±1.0	1.1±0.1	0.2±0.1	1.4±0.1	1.4±0.1
156	0.1±0.1	0.5±0.1	23.1±1.0	70.7±1.2	1.8±0.1	0.5±0.1	1.4±0.1	1.6±0.2
157	0.1±0.1	0.3±0.1	19.3±0.6	75.4±0.7	1.4±0.1	0.3±0.1	1.4±0.1	1.6±0.1
158	0.1±0.1	0.4±0.1	22.0±0.6	72.2±0.8	1.7±0.1	0.4±0.1	1.6±0.1	1.4±0.1
159	0.1±0.1	0.4±0.1	20.5±0.5	74.0±0.6	1.5±0.1	0.4±0.1	1.5±0.1	1.7±0.1
34.1	0.2±0.1	0.6±0.1	15.0±0.1	79.6±0.3	1.8±0.1	0.5±0.1	0.7±0.1	1.5±0.1
43.1	0.7±0.4	1.0±0.1	19.2±0.5	74.8±0.8	1.8±0.1	0.7±0.1	0.6±0.1	1.1±0.1
43.2	0.3±0.1	0.9±0.1	18.2±0.6	77.0±0.9	1.8±0.1	0.3±0.1	0.6±0.1	1.1±0.1

The average compositions of the crucibles (avoiding areas close to surfaces where adhering glass and other materials could contaminate the ceramic) showed that all were rich in silicon and aluminium (these two oxides accounting for 92–96wt%) with minor concentrations of potassium, iron, titanium, magnesium and calcium (Table 16; Figures 78 and 79). All crucibles were made from materials which would have ensured that they were able to withstand the high temperatures required to melt glass. The Al:Si ratios of the crucibles vary considerably (Figure 78) but the early crucibles (Blunden's Wood, Imbhams Farm and Hogs Wood) all have quite low Al:Si ratios (0.22±0.03) compared to most of the late ones (0.31±0.06). The concentrations of minor elements show relatively little variation; however, the early crucibles generally contain lower levels of titanium compared to most of the later ones (Figure 79).

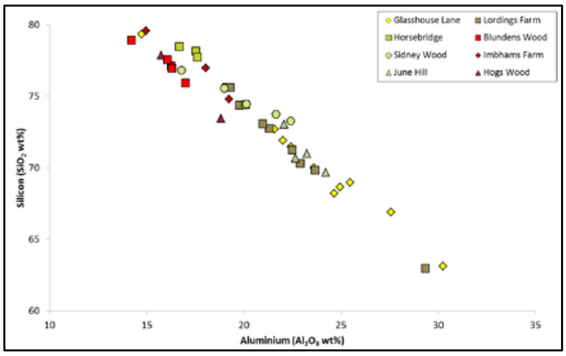


Fig 78: Aluminium and silicon content of crucibles (data from this report; Castagnino 2013, Dungworth 2007; Dungworth and Clark 2010; Dungworth and Paynter 2010)

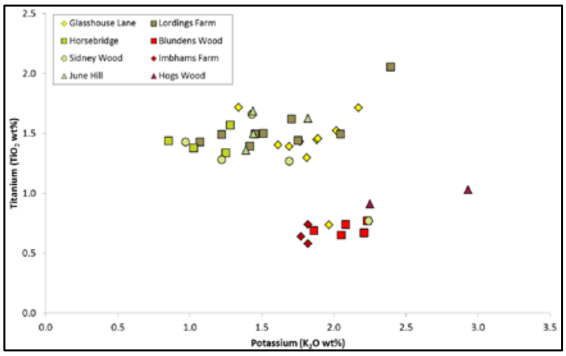


Fig 79: Potassium and titanium content of crucibles (data from this report; Castagnino 2013, Dungworth 2007; Dungworth and Clark 2010; Dungworth and Paynter 2010)

Two crucibles from late sites (one from Glasshouse Lane [sample 005] and one from Sidney Wood [sample SWA11-5, Castagnino 2013]) have compositions which are comparable with the early crucibles, suggesting that they may be residual from earlier activity. These two crucibles do not share the same ceramic fabric texture with the other crucibles from the same sites (see above). Early crucibles are all quartz-tempered while most late crucibles are grog-tempered; the crucibles from late sites with anomalous compositions also have the quartz-tempered fabric. There is a strong correlation between the type of inclusions present in a crucible and the overall chemical composition.

The majority of the crucibles from Glasshouse Lane and Lordings Farm are grog-tempered and these have been analysed in detail to investigate the relationships (if any) between the grog, the ceramic matrix and the overall bulk composition. Seven crucibles each from Glasshouse Lane and Lordings Farm were analysed in this way (Figures 80–107). While some of the grog inclusions share the same chemical composition as the corresponding clay matrix, most have either lower or higher Al:Si ratios. This suggests that some (perhaps even most) of the grog does not represent the re-use of otherwise identical crucibles as a raw material. If the source of the grog was old crucibles then the grog and the matrix would have compositions that were closer to each other. It therefore seems likely that at least some grog was obtained from another source. The wide variation in Al:Si ratios in the grog also suggests that many crucibles were made using grog from more than one source (in a few cases some of the grog has a higher Al:Si compared to the matrix and some has a lower Al:Si).

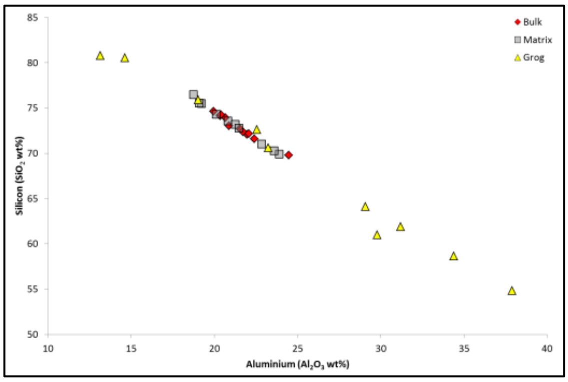


Fig 80: Aluminium and silicon content of Glasshouse Lane crucible (sample 001)

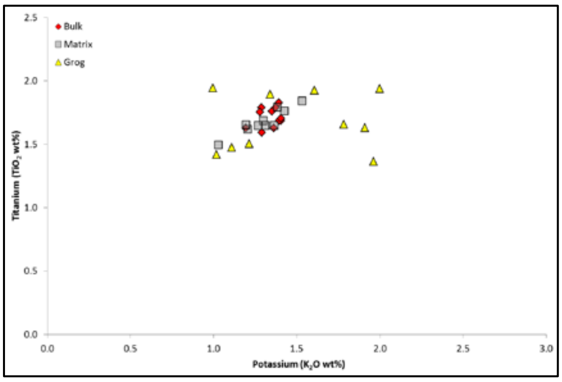


Fig 81: Potassium and titanium content of Glasshouse Lane crucible (sample 001)

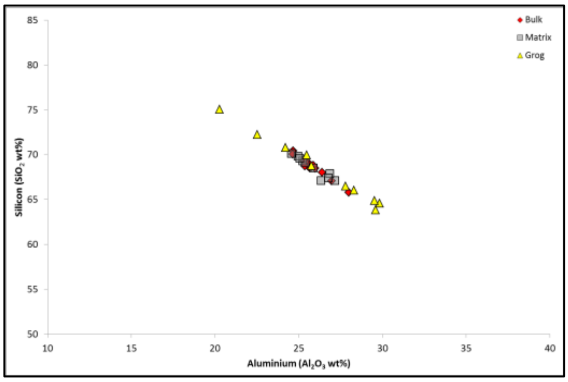


Fig 82: Aluminium and silicon content of Glasshouse Lane crucible (sample 002)

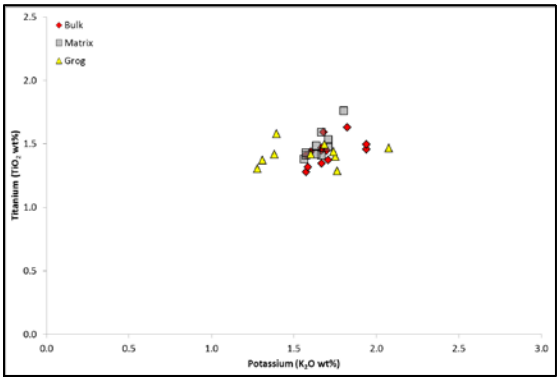


Fig 83: Potassium and titanium content of Glasshouse Lane crucible (sample 002)

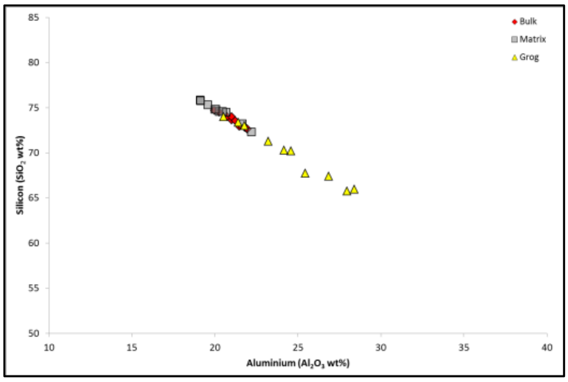


Fig 84: Aluminium and silicon content of Glasshouse Lane crucible (sample 003)

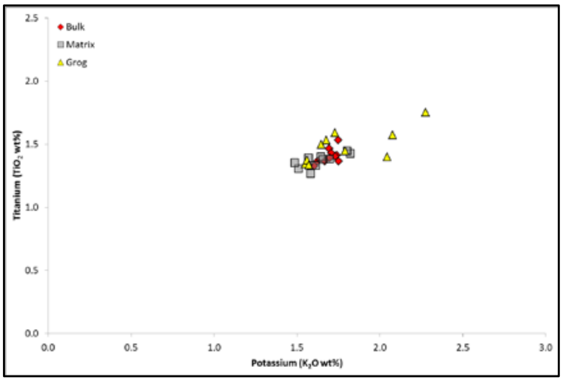


Fig 85: Potassium and titanium content of Glasshouse Lane crucible (sample 003)

In the majority of cases the grog and the matrix have levels of titanium that correspond fairly well with each other. In one case (Sample 008 from Glasshouse Lane) two (or possibly three) three grog inclusions have low Al:Si ratios and also contain significantly lower levels of titanium (Figures 90 and 91). In this case it is possible that one source of the grog was old quartz-tempered crucibles (cf the results for Imbhams Farm and Blunden’s Wood).

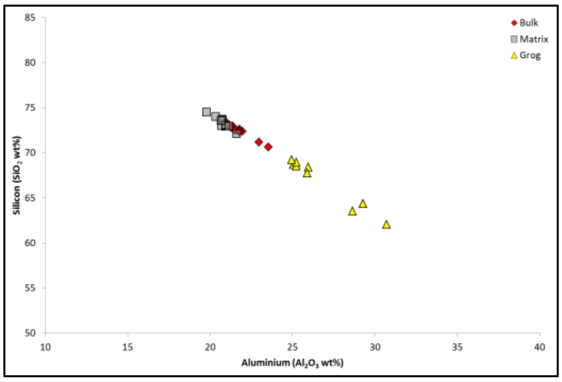


Fig 86: Aluminium and silicon content of Glasshouse Lane crucible (sample 004)

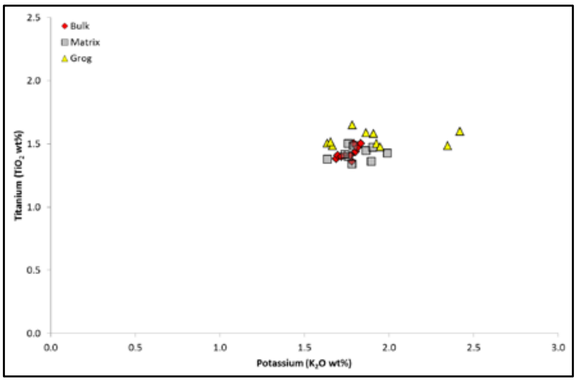


Fig 87: Potassium and titanium content of Glasshouse Lane crucible (sample 004)

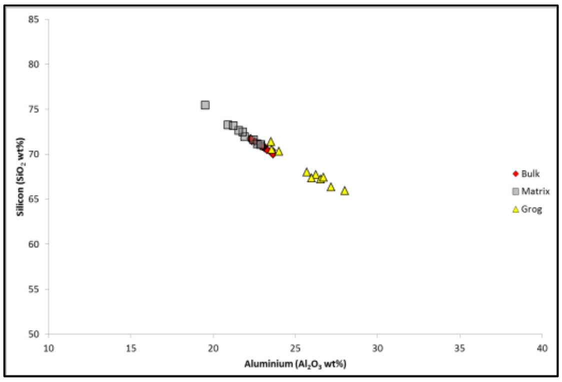


Fig 88: Aluminium and silicon content of Glasshouse Lane crucible (sample 006)

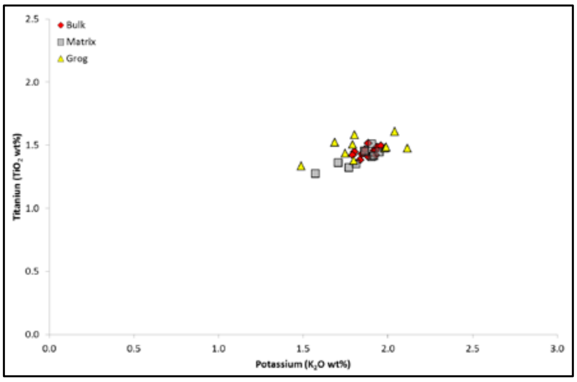


Fig 89: Potassium and titanium content of Glasshouse Lane crucible (sample 006)

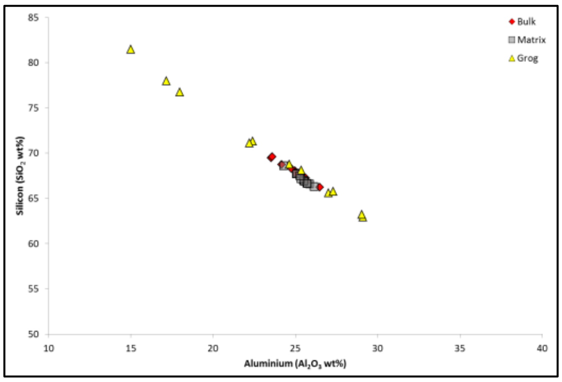


Fig 90: Aluminium and silicon content of Glasshouse Lane crucible (sample 008)

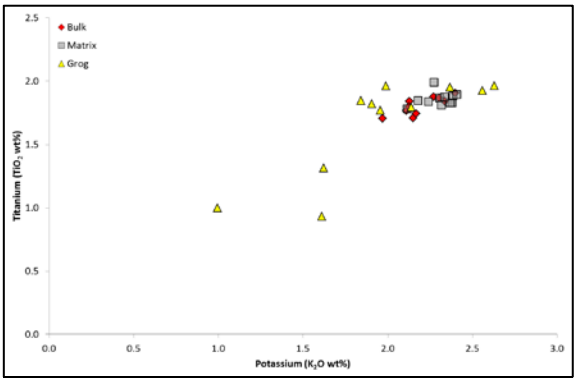
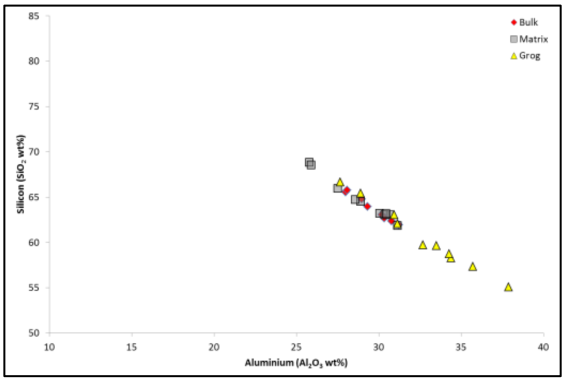


Fig 91: Potassium and titanium content of Glasshouse Lane crucible (sample 008)



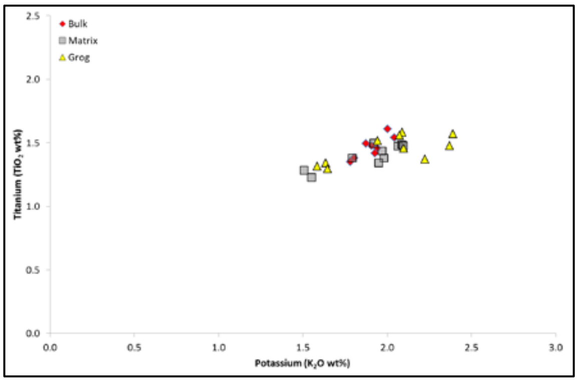
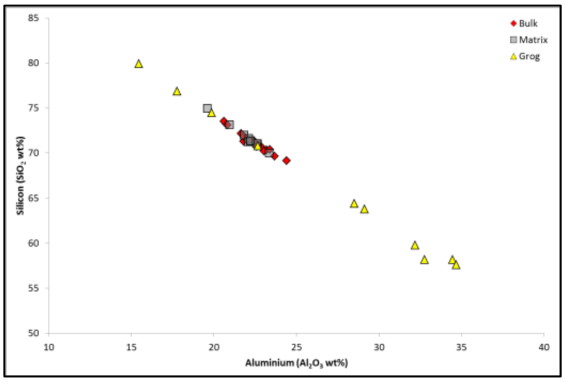


Fig 92: Aluminium and silicon content of Glasshouse Lane crucible (sample 009)

Fig 93: Potassium and titanium content of Glasshouse Lane crucible (sample 009)



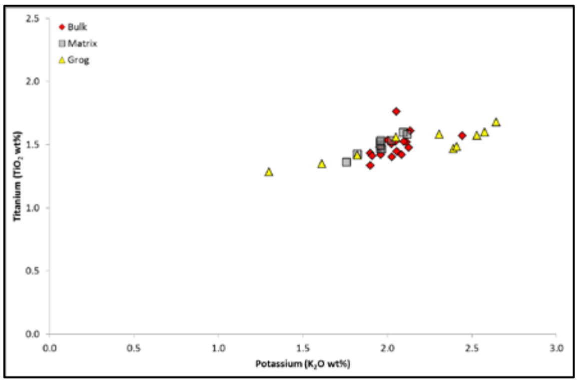
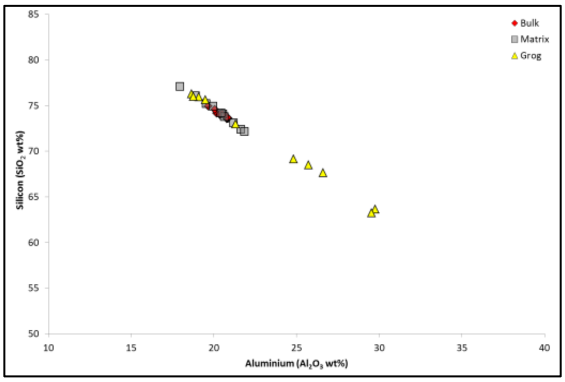


Fig 94: Aluminium and silicon content of Lordings Farm crucible (sample 152)

Fig 95: Potassium and titanium content of Lordings Farm crucible (sample 152)



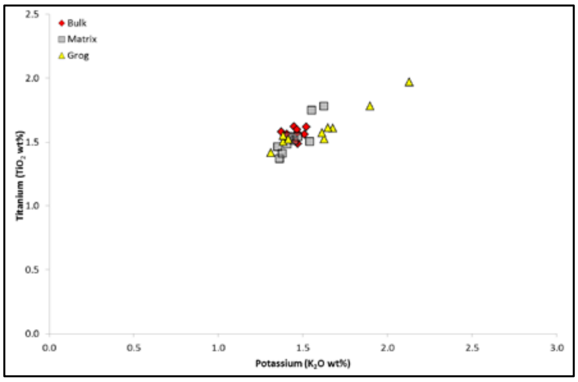


Fig 96: Aluminium and silicon content of Lordings Farm crucible (sample 153)

Fig 97: Potassium and titanium content of Lordings Farm crucible (sample 153)

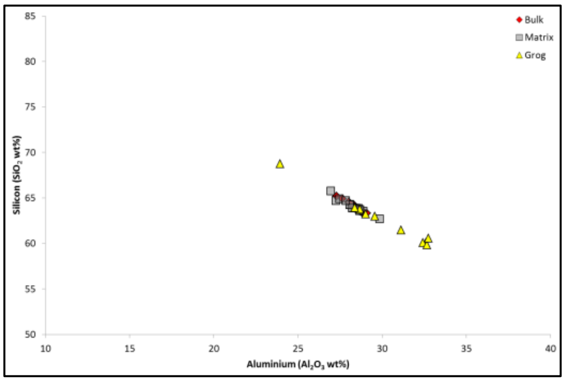


Fig 98: Aluminium and silicon content of Lordings Farm crucible (sample 154)

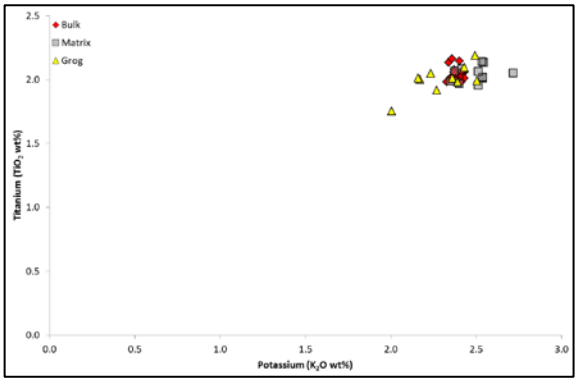


Fig 99: Potassium and titanium content of Lordings Farm crucible (sample 154)

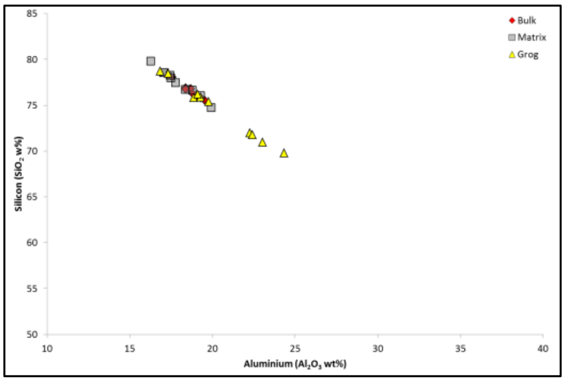


Fig 100: Aluminium and silicon content of Lordings Farm crucible (sample 155)

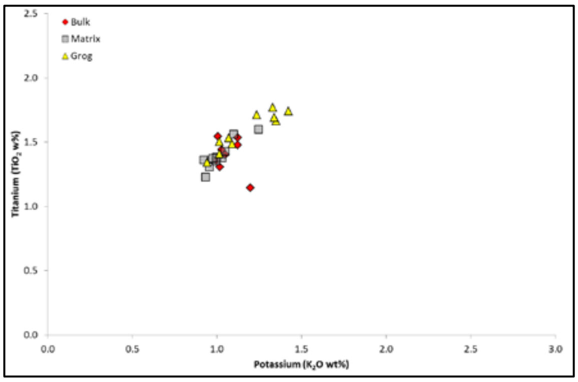


Fig 101: Potassium and titanium content of Lordings Farm crucible (sample 155)

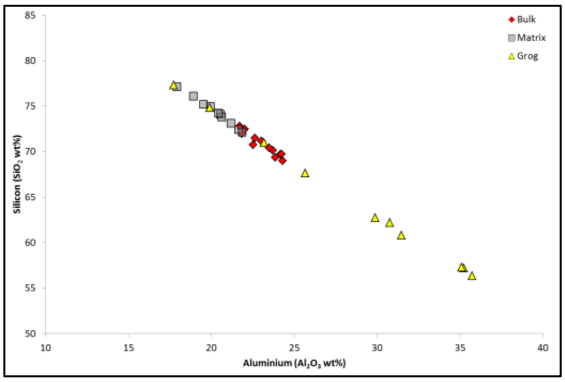


Fig 102: Aluminium and silicon content of Lordings Farm crucible (sample 156)

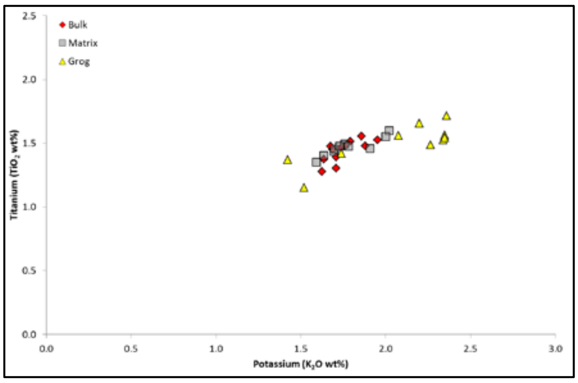


Fig 103: Potassium and titanium content of Lordings Farm crucible (sample 156)

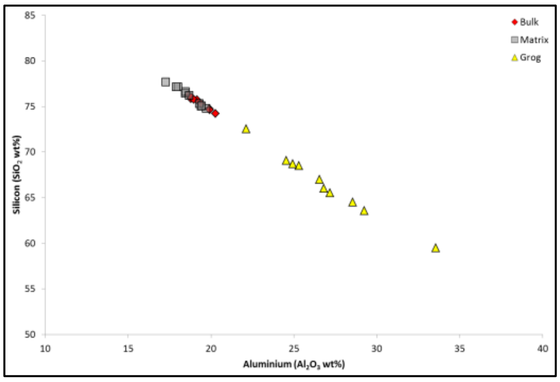


Fig 104: Aluminium and silicon content of Lordings Farm crucible (sample 157)

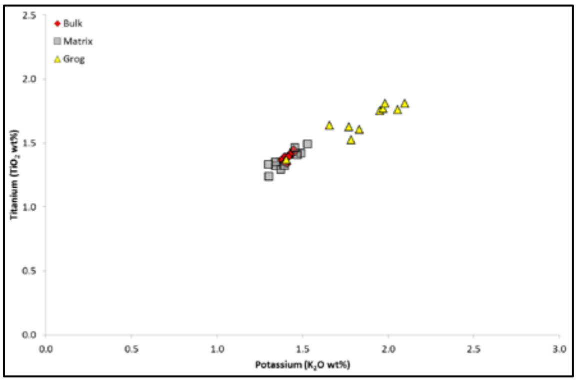


Fig 105: Potassium and titanium content of Lordings Farm crucible (sample 157)

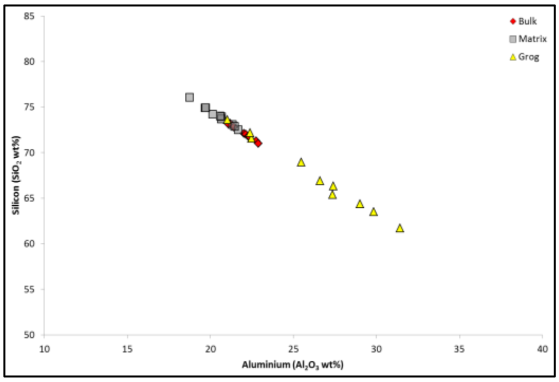


Fig 106: Aluminium and silicon content of Lordings Farm crucible (sample 158)

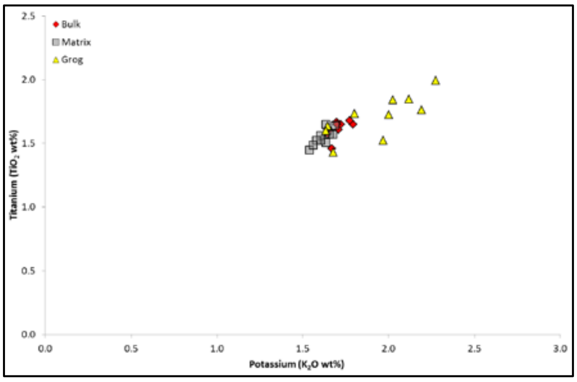


Fig 107: Potassium and titanium content of Lordings Farm crucible (sample 158)

When considering each grog-tempered crucible in turn (Figures 80–107), the impression is gained that much of the grog is (at least slightly) chemically distinct from the corresponding clay matrix. If all of the results for the matrix and grog are now considered simultaneously (Figures 108–111), a slightly different picture emerges. While the matrix of many grog-tempered crucibles is broadly similar, several crucibles have a ceramic matrix with subtly distinct chemical compositions. One of the crucibles from Glasshouse Lane (Sample 009) contains much lower calcium than all of the others, and a second possible cluster of moderately low calcium contents is formed by four crucibles (002, 003, 004 and 006). Similarly, one crucible (155) contains rather low potassium and two (008 and 154) contain high levels of both potassium and titanium. In most cases these variations in the chemical composition of clay matrix are echoed in the variations in the grog inclusions in the same crucible, *eg* the low calcium content of the matrix of one crucible (009) is matched by a low calcium content of the corresponding grog inclusions. This appears to suggest that many of the crucibles were made using (subtly) different clays but that for each crucible there was a close relationship between the raw clay used and the grog.

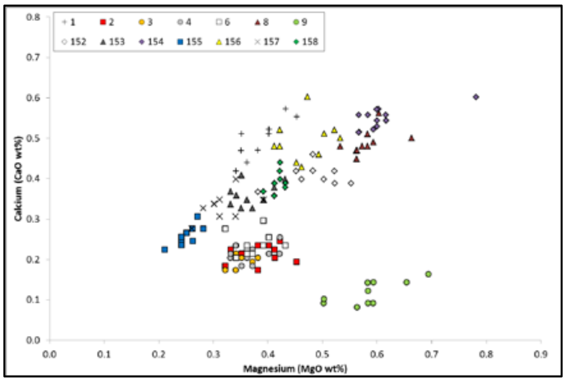


Fig 108: Magnesium and calcium content of grog-tempered crucible: matrix

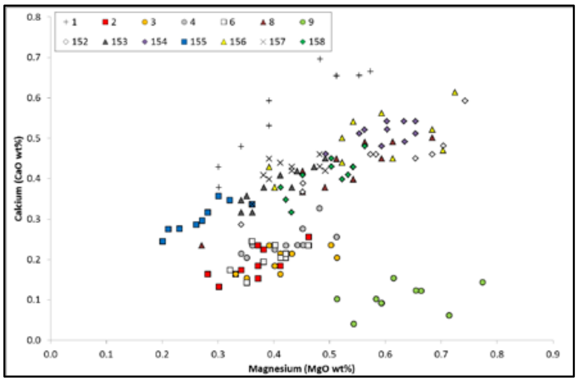


Fig 109: Magnesium and calcium content of grog-tempered crucible: grog inclusions

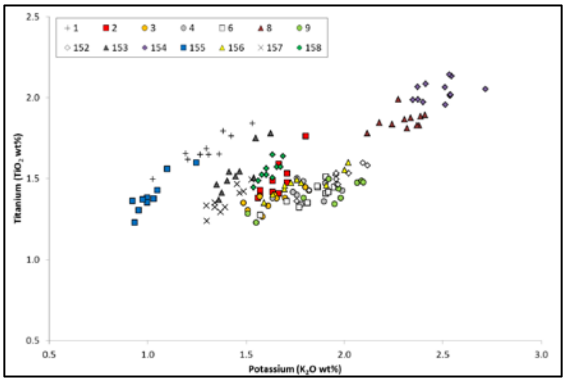


Fig 110: Potassium and titanium content of grog-tempered crucible: matrix

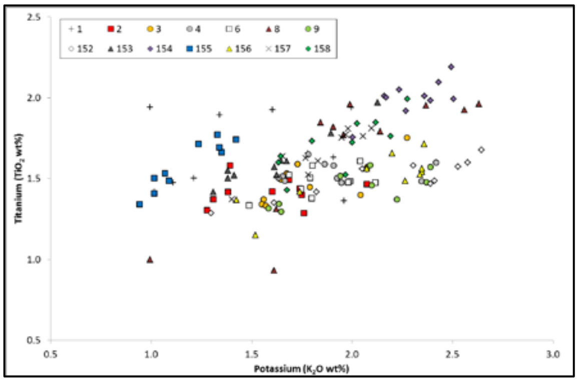


Fig 111: Potassium and titanium content of grog-tempered crucible: grog inclusions

The chemical analyses presented above suggest that there were numerous (and at times complex) variations in the manufacture of the grog-tempered crucibles but crucially these variations do not show any obvious differences in practice between Glasshouse Lane and Lordings Farm.

Most of the crucibles examined had remains of adhering glass and/or vitrification on one or both surfaces; however, in most cases this layer was extremely thin (<1mm, see Figure 112). A series of SEM-EDS analyses were carried out through the thickness of all adhering glass layers into the ceramic fabric of the crucible (cf Dungworth 2008). This showed that the thin vitrified layers generally had elevated levels of aluminium (and reduced levels of alkalis and alkali earths) compared to associated glassworking debris. In these cases the outermost vitrified layers had compositions which could not be reliably linked to a particular glass type (*ie* forest or HLLA).

In only one instance (sample 154) was the adhering glass sufficiently thick to include a layer of glass uncontaminated by reactions with the ceramic fabric of the crucible (Figure 114). Zone A is the unaltered glass (the brightest layer towards the top of Figure 114), Zone B is glass contaminated by elements from the crucible (the slightly darker layer of glass in Figure 114), Zone C is ceramic contaminated by elements from the glass (it usually contains small quantities of relict silica and mullite), and Zone D is the unaltered ceramic fabric of the crucible.

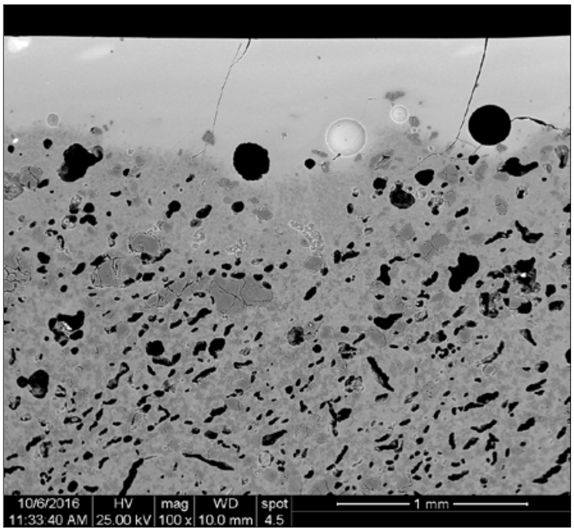


Fig 112: SEM image (BSE detector) of crucible with adhering glass (sample 159)

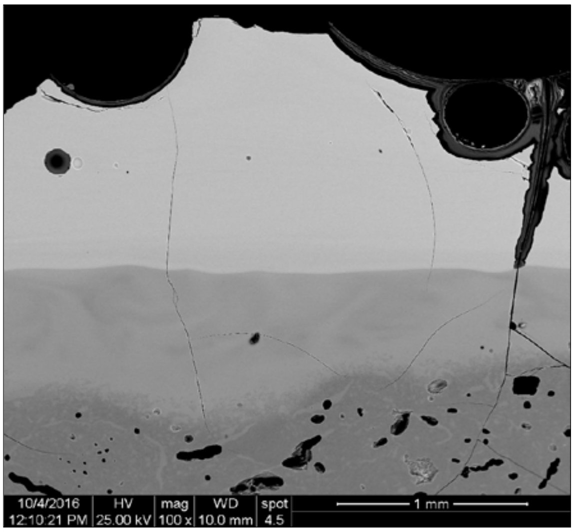


Fig 113: SEM image (BSE detector) of crucible with adhering glass (sample 154)

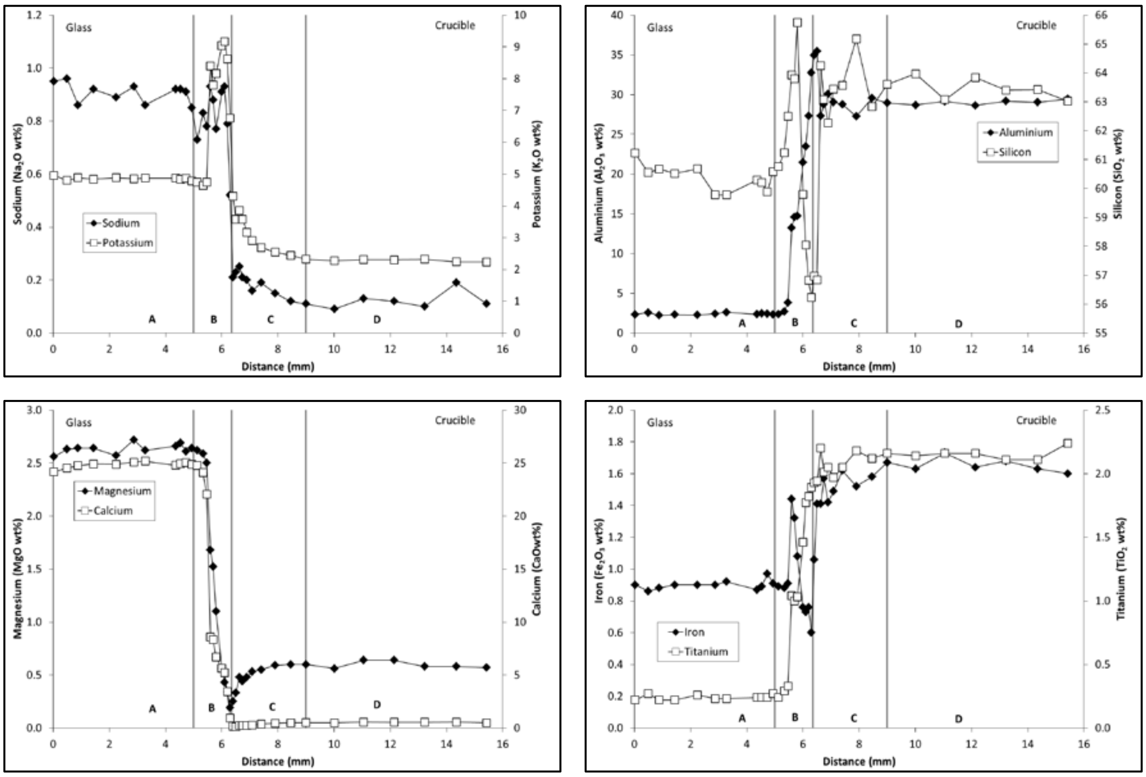


Fig 114: SEM-EDS linescans through the adhering glass and ceramic fabric of a crucible from Lordings Farm (sample 154)

The chemical composition of the adhering glass in zone A of this crucible (Sample 154) is very close to the average composition of glassworking waste from this site (Lordings Farm).

Table 17: Comparison of the chemical composition of glassworking waste and glass adhering to a crucible (sample 154), Lordings Farm

	Crucible 154 (Zone A)	Working Waste
Na_2O	0.9±0.1	0.8±0.1
MgO	2.6±0.1	2.6±0.2
Al_2O_3	2.4±0.1	2.3±0.4
SiO_2	60.4±0.4	61.3±1.0
P_2O_5	1.8±0.1	1.9±0.2
SO_3	0.2±0.1	0.2±0.1
Cl	<0.1	<0.1
K_2O	4.9±0.1	5.3±0.4
CaO	24.8±0.3	23.3±1.0
TiO_2	0.24±0.02	0.24±0.04
MnO	0.66±0.03	0.95±0.07
Fe_2O_3	0.90±0.03	1.12±0.18

The Bricks and Other Ceramic Materials

A small selection of bricks and possible ceramic lids/covers were analysed to determine their chemical composition. The bricks and other ceramics (Tables 17 and 18) are rich in aluminium and silicon, although the compositions are rather variable. In most cases the aluminium content of the bricks is rather low compared to most of the crucibles but this matches the observation of the relevant microstructures — the crucibles are grog tempered, but the bricks are sand tempered. Some of the bricks (163–165) contain low levels of impurities but the others often contain elevated levels of iron and other impurities which would tend to reduce the refractoriness of the bricks compared to the crucibles. The selection of different materials to produce bricks (compared to crucibles) has already been noted at Horsebridge (Dungworth and Clark 2010).

Table 18: Average composition of bricks from Imbhams Farm (sample 146) and Lordings Farm (samples 162–166)

	146	162	163	164	165	166
Na_2O	0.2±0.3	0.5±0.1	0.1±0.1	0.1±0.1	0.1±0.1	0.2±0.1
MgO	0.5±0.1	0.4±0.1	0.7±0.1	0.5±0.1	0.4±0.1	0.5±0.1
Al_2O_3	13.2±1.5	8.8±0.6	17.7±0.3	10.8±0.8	9.4±0.7	5.0±0.5
SiO_2	76.1±1.2	82.0±2.7	76.2±0.3	84.5±1.8	86.2±0.8	88.2±1.4
P_2O_5	0.3±0.1	0.4±0.1	0.3±0.1	0.2±0.1	0.4±0.1	0.7±0.2
SO_3	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
K_2O	2.2±2.5	1.7±0.1	2.0±0.1	1.4±0.4	1.2±0.1	1.1±0.2
CaO	0.1±0.2	0.3±0.1	0.4±0.1	0.4±0.3	0.7±0.1	0.2±0.1
TiO_2	1.6±0.1	0.8±0.1	0.8±0.1	0.5±0.1	0.5±0.1	0.3±0.1
MnO	0.1±0.1	0.4±0.8	<0.1	<0.1	<0.1	0.1±0.1
Fe_2O_3	5.7±1.1	4.8±1.7	1.9±0.1	1.5±0.5	1.1±0.1	3.7±0.7

The possible ceramic lids/covers (Table 19) are also rich in aluminium and silicon. The single lid from Imbhams Lane (Sample 147) contains relatively low levels of aluminium and this correlates with the observation that it (like the bricks) is sand tempered, while the three lids from Lordings Farm have high levels of aluminium (and are grog tempered). Sample 151 has a chemical composition which is largely within the range of the crucibles but samples 160 and 161 contain much higher levels of aluminium.

Table 19: Average composition of other refractory ceramics (possible lids or covers from the furnaces) from Imbhams Farm (sample 147) and Lordings Farm (samples 151, 160 and 161)

	147	151	160	161
Na_2O	0.1±0.1	0.1±0.1	0.2±0.1	0.1±0.1
MgO	0.5±0.1	0.6±0.1	0.6±0.1	0.6±0.1
Al_2O_3	6.1±0.6	22.5±1.7	28.4±0.3	28.3±0.3
SiO_2	88.0±1.2	70.5±1.9	63.7±0.4	64.5±0.5
P_2O_5	0.4±0.1	0.2±0.1	0.2±0.1	<0.2
SO_3	<0.1	<0.1	<0.1	<0.1
K_2O	1.6±0.1	2.2±0.1	2.2±0.1	2.2±0.1
CaO	0.3±0.1	0.6±0.1	0.6±0.1	0.5±0.1
TiO_2	0.3±0.1	1.4±0.1	2.0±0.1	2.0±0.1
MnO	<0.1	<0.1	<0.1	<0.1
Fe_2O_3	2.7±0.3	1.9±0.2	1.9±0.1	1.8±0.1

The Furnace Stones

Eight samples of possible furnace stones were analysed: these are all silicon rich with minor amounts of a range of other elements (Table 20). There are small but marked differences in the composition of the stones from Glasshouse Lane and Imbhams Farm. The former are very silicon rich (95–98wt% SiO_2) while the latter contain less silicon (87–90wt% SiO_2), and more aluminium (5–6wt% Al_2O_3) and potassium (1–3wt% K_2O). Both sites appear to have used sandstone (probably within Greensand formations) but the stone used at Imbhams Farm contains a greater proportion of argillaceous material.

Table 20: Average composition of furnace stones from Glasshouse Lane (samples 11–15) and Imbhams Farm (samples 148–150)

	11	12	13	14	15	148	149	150
Na_2O	<0.1	<0.1	<0.1	<0.1	<0.1	0.1±0.1	<0.1	0.1±0.1
MgO	<0.1	<0.1	<0.1	0.2±0.1	<0.1	0.6±0.1	0.5±0.1	0.5±0.1
Al_2O_3	0.7±0.2	1.1±0.3	0.7±0.1	2.1±0.3	0.6±0.1	5.5±0.9	5.9±0.5	5.3±0.3
SiO_2	97.7±0.3	94.7±3.4	98.2±0.4	95.4±0.7	98.5±0.3	87.6±2.1	88.7±0.5	89.4±0.7
P_2O_5	<0.1	<0.1	<0.1	<0.1	<0.1	0.3±0.1	0.4±0.1	0.4±0.1
SO_3	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
K_2O	0.2±0.1	0.3±0.1	0.2±0.1	0.5±0.1	0.1±0.1	2.6±0.6	1.4±0.1	1.5±0.1
CaO	<0.1	0.1±0.1	<0.1	0.2±0.1	<0.1	0.2±0.1	0.2±0.1	0.2±0.1
TiO_2	<0.1	0.2±0.2	<0.1	0.2±0.1	<0.1	0.2±0.1	0.3±0.1	0.3±0.1
MnO	<0.1	0.2±0.2	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Fe_2O_3	1.1±0.2	3.2±2.8	0.7±0.3	1.3±0.3	0.6±0.3	2.8±0.9	2.6±0.8	2.3±0.4

DISCUSSION

The scientific examination and analysis of over 200 samples of glass and glassworking waste from three Wealden production sites (two of which were independently dated using archaeomagnetic techniques) provides information on the selection of raw materials and the technologies employed to produce glass.

Glass

The chemical analysis of the glassworking samples shows that each site tended to produce glass to a single recipe. Imbhams Farm also produced glassy samples with rather variable compositions but these are best explained as contaminated waste, because the composition is enriched in elements found in the refractories (iron, silica, alumina) and fuel vapour (potassium) at the expense of calcium. Broadly contemporary sites tended to produce glass to the same recipe with only occasional, small differences between different sites. The four certain and assumed medieval glass production sites (Blundens Wood, Imbhams Farm, Idehurst North and Idehurst South) show remarkably similar glass compositions (Table 21) but the glass waste from Idehurst South is characterised by a magnesium content that is higher than any of the others, Imbhams Farm by a high rubidium content, and the two remaining sites can be distinguished from each other by their calcium content.

Table 21: Average composition of medieval (and presumed medieval) glass manufactured in the Weald

	Imbhams Farm	Blundens Wood	Idehurst North	Idehurst South
Na_2O	2.4±0.3	2.5±0.3	2.1±0.2	3.0±0.2
MgO	7.2±0.7	6.9±0.3	7.2±0.2	8.7±0.2
Al_2O_3	1.2±0.3	0.9±0.2	1.1±0.1	1.4±0.2
SiO_2	55.7±1.6	58.6±2.8	55.3±1.8	53.3±0.8
P_2O_5	3.3±0.4	3.2±0.3	3.3±0.5	3.9±0.1
SO_3	0.2±0.1	0.2±0.1	0.3±0.1	0.4±0.1
Cl	0.3±0.1	0.6±0.1	0.5±0.1	0.5±0.1
K_2O	11.9±1.6	11.1±0.8	11.6±0.6	10.8±0.8
CaO	15.4±1.3	13.7±1.5	17.0±0.3	16.6±0.5
TiO_2	0.12±0.04	0.09±0.03	0.19±0.03	0.19±0.03
MnO	1.22±0.14	1.20±0.10	1.15±0.07	0.96±0.06
Fe_2O_3	0.63±0.12	0.83±0.08	0.56±0.08	0.58±0.06
CoO	<0.01	0.01±0.01	<0.01	<0.01
ZnO	0.064±0.005	0.064±0.003	0.062±0.003	0.061±0.002
As_2O_3	<0.01	<0.01	<0.01	<0.01
Rb_2O	0.035±0.005	0.021±0.002	0.022±0.001	0.016±0.001
SrO	0.071±0.009	0.056±0.008	0.072±0.003	0.061±0.001
ZrO_2	0.012±0.003	0.010±0.001	<0.01	0.010±0.002
BaO	0.07±0.02	0.05±0.02	0.08±0.01	0.04±0.01
PbO	0.08±0.07	0.04±0.04	0.04±0.01	<0.02

The major difference in composition in Wealden glass corresponds to the period of manufacture (Table 22). The early glass (that is glass made before the arrival of French glassmakers in 1567 and the following years) is rich in potassium, calcium and magnesium (a medieval forest glass) while the late glass (the glass made by the French glassmakers) is a high-lime, low-alkali (HLLA) glass (cf Mortimer 1991).

Table 22: Average composition (wt%) of amorphous glassworking waste from selected Wealden glass sites.

	Early	**Late**
Na_2O	2.5±0.4	1.0±0.4
MgO	7.2±0.8	3.0±0.4
Al_2O_3	1.2±0.3	2.1±0.3
SiO_2	56.0±2.4	61.0±1.8
P_2O_5	3.4±0.4	2.1±0.2
K_2O	11.7±1.4	5.2±1.0
CaO	15.6±1.6	23.1±1.8
TiO_2	0.13±0.05	0.27±0.05
MnO	1.2±0.1	1.0±0.4
Fe_2O_3	0.7±0.1	1.1±0.2
CoO	<0.01	0.028±0.007
ZnO	0.064±0.004	0.031±0.004
As_2O_3	<0.01	0.06±0.03
Rb_2O	0.028±0.009	0.007±0.001
SrO	0.067±0.010	0.082±0.009
ZrO_2	0.011±0.003	0.031±0.006

The differences in composition between medieval forest glass and the HLLA glass of the French glassmakers probably reflect a change in raw materials and/or recipe used. The significant changes in the proportions of alkalis (and to some extent the alkali earths) suggest a change in the sorts of plant ashes used in the manufacture of the glass. Identifying the exact nature of the plant ashes used is fraught with difficulties as the composition of plant ashes can vary depending not only on the species of plant exploited, but also on the part of the plant used, the nature of the underlying geology on which the plant grew, the time of year that the plant was harvested and the temperature at which the plant was ashed (Jackson and Smedley 2008). Historical sources provide indications that trees and/or bracken were used. Theophilus, who is usually identified as Roger of Helmarshausen (Hesse, Germany), writing in the 12th century, recommended the use of beech trees as a source of ash in glassmaking (Hawthorne and Smith 1979). Welch (1997) cites numerous references to the use of bracken in medieval Staffordshire (cf Jackson and Smedley 2008). It is possible that the change from medieval forest glass to HLLA glass represents a shift from bracken ash to tree ash.

It is also possible that HLLA glass was made using an additional calcium-rich raw material. The ash left from burning wood fuel in a glass melting furnace would not be useable on its own as a flux in glassmaking as the high temperature at which the fuel burnt would have removed most (if not all of the alkalis, cf Paynter 2008). Nevertheless, the ash left from burning wood fuel in these furnaces *could* have been used to supplement other plant ashes. This possibility is weakened by a consideration of the composition of HLLA glass in the 100 years that followed the first arrival of the French glassmakers in 1567 (Dungworth 2011). The use of wood-fired furnaces for glass manufacture was banned in the second decade of the 17th century and coal used instead, but there is no discernible change in the composition of HLLA glass made just before or just after the change from wood-fired furnaces to coal-fired ones (and coal ash has a quite different chemical composition to wood ash).

The change from forest glass to HLLA glass is also apparent in the concentration of those elements that are likely to derive principally from the sand source used (Si, Al, Ti, Fe and Zr). Although the proportion of silicon in HLLA glass is slightly higher (by a factor of 1.1) than that in medieval forest glass, the other elements likely to be in the sand source (Al, Ti, Fe and Zr) are higher by factors of 1.8, 2.1, 1.5 and 2.8, respectively. This suggests that the HLLA glass made by the French glassmakers used a different sand source to that which had been used by the local English glassmakers, for reasons that are currently unclear.

The presence of metals (especially Mn, Fe, and Co) in the two types of glass are largely responsible their colours. Both types of glass contain significant levels of iron, derived from impurities in the raw materials, which give them a green colour. It is unclear whether any of the glass made (forest or HLLA) was thought of as green; medieval sources specify the purchase of ‘white’ (*ie* colourless glass) from the Weald (Marks 1991) whereas (deliberately) coloured glass was imported from continental Europe.

Medieval forest glass also contains manganese (typically 1.1w% MnO) and although this has long been used to reduce the colouring effect of iron, many plant ashes naturally contain manganese (Jackson and Smedley 2008). If manganese was a deliberate addition, then it might be expected that the glass would have a less noticeable green tint. The effective use of manganese as a decolouriser can be seen in the analysis of 17th-century tableware where there is often a strong correlation between iron and manganese (cf Dungworth and Brain 2009, 125). There is no correlation between iron and manganese in any of the medieval forest glass or HLLA glass. The impression that manganese was not a deliberate addition is reinforced by a comparison of medieval forest glass and HLLA glass: although the latter contains slightly more iron, it also contains slightly less manganese

The concentrations of iron and manganese in HLLA glass would have yielded a glass which was more strongly coloured than the earlier medieval forest glass — the reasons for this difference are far from clear. If medieval and 16th-century glassmakers in the Weald were expected to produce ‘white’ (colourless) glass then HLLA glass was ‘worse’ than medieval forest glass. This is in stark contrast with the contemporary sources (*eg* Godfrey 1975) which stress that the French glassmakers who came from 1567 onwards (and presumably brought the recipe for HLLA with them) possessed superior glassmaking technologies (although contemporary sources rarely mention the clarity of plain window glass).

The presence of cobalt in what would appear to be 'white' HLLA glass (Castagnino 2013, Paynter unpublished data) is puzzling. Previous analyses (*eg* Dungworth 2007; Dungworth and Clark 2004; 2010) failed to identify the presence of cobalt in HLLA glass made in the Weald. Castagnino's assessment of glass from an earlier phase of this project identified fragments of blue-coloured glass and established the presence of small amounts of cobalt (Castagnino 2013). The re-analysis of these samples (presented in this report) was undertaken using a new XRF (the Bruker M4 Tornado) with substantially lower detection limits for this element (0.005–0.02wt% Co depending on the amount of iron present). The presence of cobalt in Wealden HLLA glass is quite consistent (it is present in the working waste, the window glass and the vessel glass), and suggests this colourant was incorporated as the result of deliberate and sustained action. It is not present in the medieval forest glass produced in the Weald and it appears to be largely absent from similar HLLA glass produced in other regions (samples of HLLA glass from Shaw House [Dungworth and Loaring 2009] have recently been reanalysed using the Bruker M4 Tornado and less than 10% of these contained detectable levels of cobalt).

Cobalt is an extremely effective colorant in glass: concentrations of as little as 0.02wt% CoO may be discernible (in a glass which contains virtually no other colourants). Cobalt has been used for millennia to produce blue glass (Brill 1999) and its use in a 'white' glass would at first glance appear to be counter-productive. It would seem reasonable to suggest that if the French glassmakers wished to make a blue glass, then they could have added sufficient cobalt to achieve this (typically 0.1wt% CoO, Brill 1999, Dungworth *et al* 2011). Instead, the glass contains perhaps a third of the concentration of cobalt (0.03wt% CoO) normally associated with deliberately blue-coloured glass. The low levels of cobalt used in this glass result in a blue-green (rather than blue) colour. It is unlikely that the cobalt in HLLA glass was an accidental result of the use of recycled blue glass in the cullet. If the cobalt came from cullet, then the 'batch' would have contained a high proportion of blue cullet - perhaps up to one third.

It is possible that the deliberate addition of cobalt to HLLA glass produced in the Weald was a conscious effort to decolourise the glass. The use of zaffre (an impure form of cobalt oxide, often with nickel, copper, zinc and arsenic) is mentioned at the very end of the 16th century, specifically as a decolouriser in glass manufacture. Italian glassmakers in London reported that they used 'mangese and zafer' (*ie* manganese and cobalt oxides) to give glasses clarity (Godfrey 1975, 160). The use of manganese seems to offer the most effective method of counteracting the green colour produced by iron. The manganese would produce a pinkish colour which would combine with the green colour produced by the iron to give a slightly greyish glass (this is often only discernible when the glass is held against a sheet of white paper). A small amount of cobalt would produce a blue colour which could counteract any yellow colour present. The use of blue dyes to improve 'whiteness' is well known in laundry (Mendelson 2005, 75), paper manufacture (Bristow 2009) and even the preparation of royal icing, 'Blue improves the whiteness but care should be taken to that it is not overdone' (Howkins 1968, 16).

The differences in the proportions of the major glass-forming elements (silicon, sodium, potassium, magnesium and calcium) are probably responsible for the differences in the appearance and durability of the two types of glass (forest and HLLA). Glasses with high levels of network modifiers (sodium and potassium) or low levels of network stabilisers (magnesium and calcium) tend to be weakest and most susceptible to chemical weathering. It is also clear that the proportion of network former (silica) is also important: glasses with matching but high levels of both modifier and stabiliser will contain low levels of network former, and so will be weaker and more susceptible to weathering. Medieval forest glass tends to contain a higher proportion of network modifier than HLLA glass (Figure 115). The proportion of network stabilisers in medieval forest glass is only slightly less than HLLA glass but perhaps most importantly, the proportion of network former is usually lower.

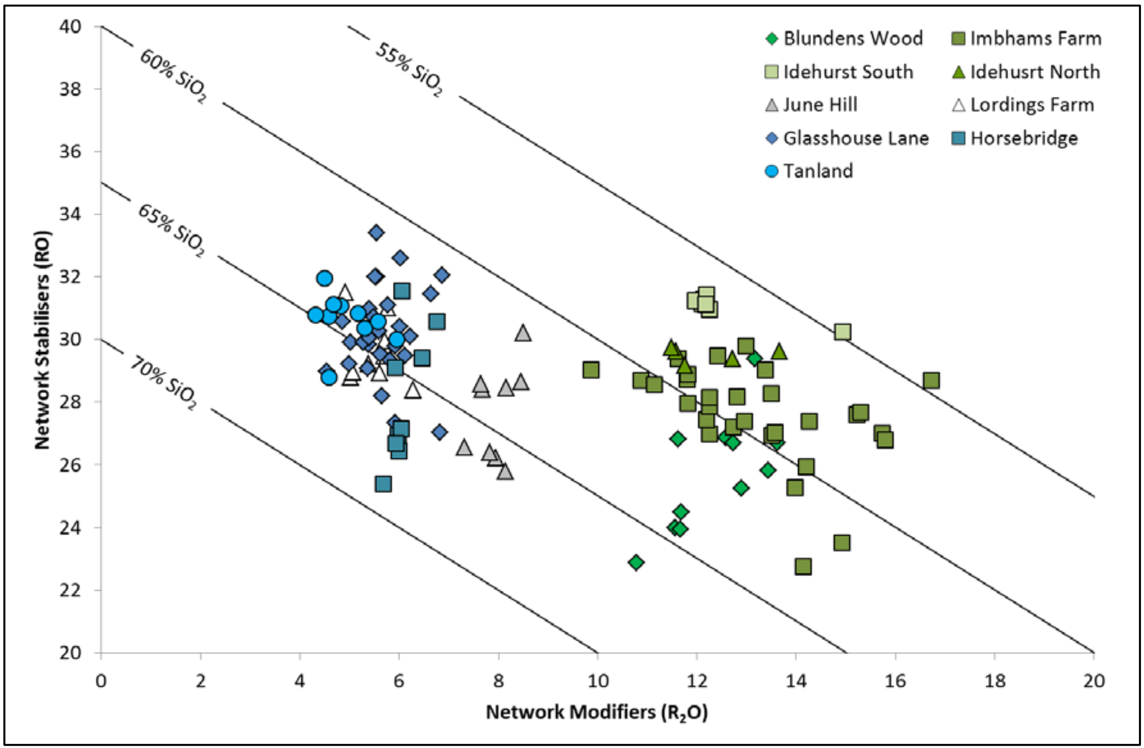


Fig 115: Molecular proportions of network modifiers and stabilisers in Wealden glass (early glass = green, late glass = blue)

The HLLA glass produced at different sites displays limited variation (Table 23). The glass made at June Hill is anomalous in several respects and is discussed in more detail below. The glass made at Horsebridge has slightly lower levels of calcium and higher levels of magnesium and phosphorus than that made at most other HLLA-producing sites. Tanland and Imbhams Farm are distinguished from Glasshouse Lane and Horsebridge by slightly lower levels of zirconium. Some of the Tanland glass contains significantly higher levels of sodium than is usually seen in Wealden HLLA glass. Despite these small variations, the most striking impression is of similarities in the HLLA glass produced at different sites. Presumably, most HLLA glass was made using almost identical raw materials and recipes.

Table 23: Average composition of HLLA glass manufactured in the Weald

	June Hill	Glasshouse Lane	Horsebridge	Tanland	Lordings Farm
Na_2O	1.1±0.2	0.9±0.1	0.9±0.1	1.5±0.5	0.9±0.1
MgO	4.2±0.4	3.0±0.2	3.6±0.5	2.8±0.2	2.8±0.2
Al_2O_3	2.2±0.3	2.0±0.3	2.1±0.4	2.2±0.2	2.3±0.4
SiO_2	66.6±2.0	60.5±1.7	61.7±2.5	61.2±1.1	61.4±0.9
P_2O_5	2.2±0.2	2.1±0.2	2.1±0.3	2.2±0.2	1.8±0.2
SO_3	0.3±0.1	0.2±0.2	0.3±0.1	0.2±0.1	0.2±0.1
Cl	0.4±0.1	<0.1	<0.1	0.4±0.3	<0.1
K_2O	7.7±0.6	5.4±0.6	5.9±0.3	3.8±0.8	5.2±0.4
CaO	19.3±0.6	23.2±1.2	20.4±1.3	24.2±1.0	22.8±0.9
TiO_2	0.28±0.08	0.27±0.04	0.30±0.05	0.26±0.05	0.23±0.04
MnO	0.9±0.5	0.9±0.2	1.7±0.2	0.7±0.1	0.9±0.1
Fe_2O_3	0.8±0.3	1.1±0.2	1.0±0.2	1.2±0.1	1.1±0.2
CoO	0.019±0.020	0.027±0.008	0.030±0.007	0.029±0.005	0.024±0.004
ZnO	0.038±0.009	0.030±0.004	0.030±0.004	0.034±0.004	0.033±0.008
As_2O_3	0.04±0.05	0.06±0.03	0.04±0.01	0.07±0.02	0.04±0.01
Rb_2O	0.010±0.003	0.007±0.001	0.008±0.001	0.005±0.002	0.006±0.001
SrO	0.065±0.019	0.079±0.010	0.088±0.006	0.086±0.006	0.080±0.004
ZrO_2	0.021±0.005	0.032±0.004	0.035±0.003	0.022±0.002	0.019±0.005
BaO	0.03±0.03	0.03±0.02	0.07±0.02	0.03±0.01	0.03±0.01
PbO	<0.02	<0.02	<0.02	<0.02	<0.02

While the HLLA glass produced at Glasshouse Lane, Tanland, Horsebridge and Lordings is distinct from the medieval forest glass produced at Blundens Wood, Imbhams Farm, Idehurst North and Idehurst South, the glass produced at June Hill is less easy to categorise. In most respects the June Hill glass resembles HLLA glass; however, it is distinct from all the other HLLA glass and to some extent its composition sits between HLLA glass and medieval forest glass. The potassium content of the June Hill glass is the highest (and the calcium the lowest) of any Wealden HLLA glass (Figures 73 and 74). The cobalt and arsenic content of the June Hill samples shows a bi-modal distribution: four of the samples contain detectable concentrations of these elements (at concentrations that are comparable with other Wealden HLLA glass) but these elements were not detected in the remaining five samples (and so in this respect resembles medieval forest glass). It is possible that the glass manufactured at June Hill represents a degree of experimentation with new material and recipes.

Refractory Materials

The Wealden glass production sites used a range of refractory materials for crucibles and furnace structures - including ceramics and stones. While some stone was used in the construction of the furnaces, several (although not all) of the analysed stone samples showed no evidence of having been exposed to high temperatures. Ceramics were used in the manufacture of both crucibles and of furnace bricks. The ceramic materials used can be divided into two categories based on their microstructure and chemical composition: those tempered with quartz and those tempered with grog.

Quartz-tempered fabrics were identified by the abundant silica inclusions. While it is possible that naturally sandy clay was used (to which no temper needed to be added), the geological deposits of the Weald (and many surrounding areas) are composed of separate layers of clay and sand. It is more likely, therefore that suitable clays and sands were combined to produce these quartz-tempered fabrics. Some parallels might be sought in the contemporary white-firing pottery made in Surrey (Holling 1971). Pearce and Vince (1988, 11) proposed that, 'Surrey whitewares were made from a white-firing clay containing angular quartz of fine silt and sand grade, and tempered with varying quantities of rounded quartz sand'. Unfortunately, the high temperatures employed in glass manufacture have resulted in the extensive vitrification of the clay and at least partially dissolution of quartz grains at high temperatures (thereby obscuring their original shapes).

Table 24: Chemical composition of Wealden refractories compared with Wealden clay and Claypit Wood

		Na_2O	MgO	Al_2O_3	SiO_2	K_2O	CaO	TiO_2	FeO
QT crucibles	Castagnino 2013	0.3	0.7	16.3	77.5	2.0	0.4	0.7	1.8
	Dungworth and Paynter 2012	±0.2	±0.1	±1.6	±1.6	±0.2	±0.1	±0.1	±0.5
GT crucibles	this report	<0.1	0.4	22.3	71.9	1.6	0.3	1.5	1.5
			±0.1	±3.2	±3.8	±0.4	±0.1	±0.2	±0.3
Laybrook	Phelps 2013	0.3	0.6	12.8	78.4	2.1	0.3	1.0	4.1
Laybrook	Kemp *et al* 2012	0.3	1.0	22.7	63.6	3.1	0.5	0.3	8.3
Beare Green	Kemp *et al* 2012	0.3	1.2	26.2	58.4	3.0	0.4	1.2	9.1
Abinger	Kemp *et al* 2012	0.3	1.0	20.5	66.1	2.5	0.4	1.5	7.4
South Chailey	Kemp *et al* 2012	0.3	0.9	17.0	70.0	2.5	0.8	1.3	6.8
Claypit Wood	this report	0.1	0.7	16.5	76.2	2.0	0.4	0.9	3.1
		±0.1	±0.1	±1.2	±1.1	±0.2	±0.2	±0.2	±0.6

Analyses of Wealden clays consistently indicate iron contents that are significantly higher than the quartz-tempered ceramics (Table 24) and so rule out the use of local clays for crucibles and other refractory ceramics. Given the low iron content of the quartz-tempered ceramics, the white-firing clays of the Reading Beds that outcrop in the Farnham-Tongham area (Holling 1971; Pearce and Vince 1988) would seem to be a plausible source of refractory clay. Some chemical analyses of Surrey whitewares have been published (*eg* Pearce and Vince 1988); however, these Neutron Activation Analyses include mostly trace elements and so offer limited potential for comparison with the data presented in this report. Robert Newell, a potter based in Surrey, kindly provided five samples of fired clay briquettes from Claypit Wood, Farnham (two of them tempered with sand) which were analysed (Table 24). While the Claypit Wood briquettes have compositions which resemble the quartz-tempered fabric in many respects, they contain too much iron to be identified as the source of the clay used.

The change from quartz-tempered to grog-tempered refractories appears to coincide with the arrival of French glassmakers in 1567 and the years that follow. Blundens Wood (dated to the mid-14th century) and Imbhams Wood (dated to the 1515–1565) both made exclusive use of quartz-tempered refractories. Grog-tempered refractories are found on a number of late sites of which Glasshouse Lane (dated archaeomagnetically to 1555–1650) is perhaps the most significant. Other sites which have been interpreted as late (*ie* post-1567) on the basis of surface-recovered pottery (June Hill and Horsebridge) and/or documentary sources (Tanland) have also yielded grog-tempered crucibles.

The grog-tempered crucibles contain higher levels of aluminium and lower levels of silicon than the quartz-tempered crucibles, but the sum of these two oxides does not vary significantly between the two crucible types (94.2wt% and 93.8wt%, respectively). One of the most significant factors in clay refractoriness (that is the temperature at which the clay will soften and begin to melt) is the impurities (especially the alkalis and iron). While grog-tempered crucibles contain slightly lower levels of alkalis and iron oxide (Table 24) this is unlikely to have dramatically improved their refractoriness.

The reason for the shift from quartz-tempered crucibles to grog-tempered crucibles is probably to be sought in the ability of the crucibles to withstand the corrosive effects of molten glass (cf Paynter 2012). Quartz-rich ceramics are more susceptible to chemical erosion by molten glass than aluminium-rich examples (Lee and Zhang 1999). The grog-tempered crucible technology that appears to have been introduced by the French glassmakers who began to work in the Weald from 1567 would have allowed crucibles to be used for longer periods of time before they would need replacing. There is no available data on the chemical composition or microstructure of glass-melting crucibles used in France in the period immediately before some of them began to move to England. Nevertheless, the use of grog-tempering does not appear to be exclusive to glass manufacture — grog-tempered crucibles appear to have been in use at the Tower of London (White and Kearns 2010) for melting and refining base and precious metals in the period before 1560 (*ie* before the first arrival of French glassmakers in 1567).

Although French glassmakers clearly preferred grog-tempered ceramics for the manufacture of crucibles, the same is not true for all of the refractory ceramics they used in glassmaking. The bricks used at both Lordings Farm and Horsebridge (Dungworth and Clark 2010) were made using quartz-tempered clays. The decision to use the traditional quartz-tempered clay for bricks could represent a technological decision based on fact that bricks would be exposed to high temperatures but should not largely be in contact with molten glass. As both quartz-tempered and grog-tempered clays would have been able to withstand similar maximum temperatures, it is arguable that the use of quartz-tempered clay for bricks represents a saving (probably of time rather than cash) in their manufacture. The sand used to temper clay might have required some sieving and washing but grog would require laborious sorting and crushing before it could be used as a temper. Although the bricks at Lordings Farm were made using quartz-tempered clay, the three possible covers/lids were made using grog-tempered clay. Again, this can probably be explained by examining the conditions of use of these furnace components. A cover/lid would serve to retain heat inside the furnace but would periodically be moved aside to allow the glassworker to add ingredients to a crucible or remove molten glass for blowing. A cover/lid would therefore be exposed to high temperatures but would also at times be one of the cooler surfaces within the furnace and so alkali vapour from the wood fuel would be more likely to condense on a cover/lid than almost another other furnace component. The use of grog temper for covers/lids would improve their ability to withstand the corrosive effects of these alkalis.

The chemical analysis of the grog-tempered refractories included the discrete analysis of grog inclusions and ceramic matrix (Figures 80–107). The relationships between the ceramic matrix and the grog inclusions are complex and in some instances the data appear to be contradictory. This is especially striking if it is compared to the simplest possible model of grog production and use. Let us assume that the glassmakers made their refractories using a source of clay and grog derived from old refractories (made with the same clay source). In this case it would be expected that the grog inclusions and the matrix would share the same chemical compositions. The data presented in this report shows that the grog inclusions display much more compositional variability than the matrix. From this it can be concluded that for the most part the grog derived from a different source to the clay. An alternative grog production and use model can be imagined in which the grog used was initially old quartz-tempered crucibles. In this case it would be expected that the grog inclusions would be consistently silica-rich compared to the matrix. Eventually the stock of quartz-tempered refractories that could be used as grog would be depleted and (in later refractories) we might expect to see grog composition more closely approach that of the matrix. The analyses of the many of grog-tempered refractories has shown that grog inclusions often include examples with higher levels of silica *and* examples with lower levels, compared to the matrix. Therefore, a model of grog tempering based on the use of quartz-tempered refractories as a source of grog can be discounted (with the possible exception of two grog inclusions in crucible sample 008). More complex models of grog production and use can be contemplated, for example the use of several clay sources, including different clay sources for the grog and matrix; however, the increasing number of variables makes such models difficult to test using the available currently data. Nevertheless, the variability of the grog composition compared to the matrix, appears to show that grog production and use was complex.

Further examination of the relationship between the grog and corresponding matrix compositions (Figures 108–111) appears to show that the two may be more closely linked than the above discussion would suggest. While grog composition was more variable than corresponding matrix, there was often a correlation between these two components of the refractories. This is to some extent apparent in the major elements present (aluminium and silicon) but can be clearly seen in some of the minor and trace elements (*eg* magnesium, potassium, calcium and titanium). This data suggests that variations in the chemical composition of clay matrix are echoed in the variations in the grog inclusions in the same crucible, *eg* the low calcium content of the matrix of crucible (009) is matched by a low calcium content of the corresponding grog inclusions. This appears to suggest that many of the crucibles were made using (subtly) different clays but that for each crucible there was a close relationship between the raw clay used and the grog.

CONCLUSIONS AND RECOMMENDATIONS

The analysis of 205 samples of glass and glassworking debris from the excavation of three production sites in the Weald (two of which were independently dated using archaeomagnetic techniques) has confirmed that glass made before the arrival of French glassmakers in 1567 was a potassium-rich forest glass. The French glassmakers are traditionally associated with a number of technological changes in the Wealden glass industry and the analyses reported here confirm that the glass they made was a high-lime, low-alkali (HLLA) glass. While it would appear that both the early forest glass and the late HLLA glass were regarded as white (*ie* colourless) both contained sufficient iron to give them a noticeable green tint. In addition, the HLLA glass contains small amounts of cobalt that gave it a blue-green colour. The French glassmakers also introduced the use of grog-tempered ceramics for the manufacture of crucibles. The use of grog probably improved the lifetime of a crucible but the origins and exact mechanism of grog tempering remain unclear. As some grog tempering appears to predate the arrival of French glassmakers in 1567, it would be useful to investigate other refractory using industries in England in the early and mid-16th century.

The use of ICPMS analysis of samples of glass and refractories from the Weald would allow the detection of a greater range of elements than has been available here (SEM-EDS and EDXRF). The detection of many trace elements (*eg* rare earth elements) could provide data to better understand the sources of the raw materials used in the manufacture of refractories and glass. In order to better understand the trace elements present in the clay matrix and grog inclusions, a technique such as laser ablation ICPMS would offer the possibility of obtaining data on these two refractory components.

The arrival of French glassmakers from Normandy and Lorraine in 1567 sees the introduction of several new technological features in English glassmaking. While the systematic survey and excavation of glass production sites in England is providing insights into this important development in English glass manufacture, very little is known about the contemporary activities of French glassmakers in France. It is hoped that future archaeological and scientific investigation within the relevant areas of France will go some way to address this research gap, including the analysis of both glass debris and refractories from production sites.

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Appendix: Chemical composition of samples analysed (SEM-EDS and XRF, wt% oxides, normalised, bd= below detection limit)

S'mple	Site	C'text	Descript'n	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	Cl	K_2O	CaO	TiO_2	MnO	Fe_2O_3	CoO	NiO	CuO	ZnO	As_2O_3	Rb_2O	SrO	ZrO_2	BaO	PbO
1	GLK14	112	Crucible	bd	0.39	21.49	72.79	bd	bd	bd	1.34	0.52	1.71	bd	1.61										
2	GLK14	111	Crucible	0.25	0.37	24.86	69.84	bd	bd	bd	1.61	0.19	1.40	bd	1.37										
3	GLK14	111	Crucible	bd	0.40	21.07	73.61	bd	bd	bd	1.69	0.21	1.39	bd	1.39										
4	GLK14	111	Crucible	bd	0.39	21.90	72.30	bd	bd	bd	1.76	0.23	1.43	bd	1.82										
5	GLK14	113	Crucible	bd	0.63	14.38	80.12	bd	bd	bd	1.96	0.29	0.73	bd	1.81										
6	GLK14	109	Crucible	bd	0.41	23.03	70.84	bd	bd	bd	1.88	0.24	1.45	bd	1.95										
7	GLK14	107	Crucible	bd	0.31	24.36	69.47	bd	bd	bd	1.81	0.18	1.29	bd	2.35										
8	GLK14	102	Crucible	bd	0.58	24.06	69.03	bd	bd	bd	2.17	0.46	1.71	bd	1.78										
9	GLK14	102	Crucible	bd	0.63	29.51	63.91	bd	bd	bd	1.89	0.13	1.45	bd	2.30										
10	GLK14	102	Crucible	bd	0.35	26.91	67.73	bd	bd	bd	2.02	0.07	1.52	bd	1.24										
11	GLK14	107	Furnace - stone	bd	bd	0.78	97.61	bd	bd	bd	0.23	0.08	0.06	bd	1.13										
12	GLK14	107	Furnace - stone	bd	bd	1.10	94.74	bd	bd	bd	0.31	0.15	0.15	0.17	3.21										
13	GLK14	112	Furnace - stone	bd	bd	0.69	98.22	bd	bd	bd	0.17	bd	bd	bd	0.73										
14	GLK14	112	Furnace - stone	bd	0.17	2.11	95.42	bd	bd	bd	0.49	0.16	0.17	bd	1.32										
15	GLK14	111	Furnace - stone	bd	bd	0.60	98.56	bd	bd	bd	0.14	bd	0.02	bd	0.57										
16	GLK14	103	Vitrified fuel ash	1.03	3.15	2.56	59.21	2.45	0.29	bd	6.37	22.18	0.31	1.11	1.35										
17	GLK14	107	Vitrified fuel ash	0.27	0.26	15.49	76.80	0.22	bd	bd	4.21	0.43	1.04	bd	1.34										
18	GLK14	111	Vitrified fuel ash	1.71	3.68	3.20	59.26	3.31	bd	bd	8.20	17.84	0.31	1.10	1.37										
19	GLK14	111	Vitrified fuel ash	1.08	2.46	4.49	70.22	3.52	0.18	bd	8.14	5.91	0.51	1.32	2.18										
21	GLK14	109	Moil	0.84	2.87	1.73	61.69	2.13	0.29	bd	5.16	23.21	0.21	0.59	0.96	0.02	bd	0.01	0.03	0.08	0.01	0.06	0.04	0.01	bd
22	GLK14	112	Blob	0.81	2.45	1.80	63.69	1.61	0.23	bd	4.24	23.05	0.28	0.76	0.79	0.02	0.01	0.01	0.03	0.04	0.01	0.08	0.04	0.01	bd
23	GLK14	112	Window	0.83	3.06	2.38	59.50	1.92	0.20	bd	5.41	23.99	0.35	0.99	1.11	0.03	bd	0.01	0.03	0.03	0.01	0.07	0.03	0.03	bd
24	GLK14	112	Window	0.68	3.54	1.66	57.64	2.57	0.18	bd	6.58	24.50	0.32	1.21	0.77	0.03	0.01	0.01	0.03	0.04	0.01	0.09	0.03	0.06	bd

S'mple	Site	C'text	Descript'n	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	Cl	K_2O	CaO	TiO_2	MnO	Fe_2O_3	CoO	NiO	CuO	ZnO	As_2O_3	Rb_2O	SrO	ZrO_2	BaO	PbO
25	GLK14	112	Lump	1.19	3.05	2.29	60.09	2.07	0.20	bd	5.60	22.03	0.31	1.02	1.12	0.03	0.01	0.01	0.04	0.04	0.01	0.11	0.04	0.09	0.49
26	GLK14	111	Lump (dichroic)	0.77	3.45	2.08	57.49	2.47	0.10	bd	5.94	24.69	0.25	1.37	1.03	0.04	0.01	0.01	0.03	0.05	0.01	0.09	0.03	0.08	bd
27	GLK14	111	Thread	0.78	2.79	1.73	62.36	1.98	0.17	bd	5.22	22.54	0.28	0.93	0.87	0.03	0.01	0.01	0.03	0.03	0.01	0.09	0.04	0.05	bd
28	GLK14	111	Window	0.94	3.06	2.04	59.67	2.00	0.27	bd	5.50	23.71	0.27	0.92	1.16	0.03	0.02	0.01	0.03	0.13	0.01	0.07	0.03	0.02	0.04
29	GLK14	111	Window	0.91	3.09	1.69	61.18	2.24	0.18	bd	6.08	22.10	0.25	1.00	0.90	0.03	0.01	0.01	0.03	0.04	0.01	0.09	0.04	0.05	bd
30	GLK14	111	Lump	0.88	2.97	1.64	63.61	2.01	0.04	bd	5.72	20.77	0.28	0.94	0.83	0.03	0.01	0.01	0.03	0.04	0.01	0.07	0.04	0.05	bd
31	GLK14	111	Window	1.04	3.14	2.22	58.82	2.11	0.31	bd	5.78	23.50	0.30	1.15	1.29	0.03	0.01	0.01	0.04	0.05	0.01	0.08	0.03	0.03	bd
32	GLK14	111	Vessel?	0.83	3.33	1.59	61.93	2.27	0.15	bd	4.96	22.91	0.26	0.64	0.82	0.02	0.01	0.01	0.02	0.09	0.01	0.06	0.03	0.01	bd
33	GLK14	111	Thread	0.77	3.07	2.33	61.90	2.00	0.19	bd	5.48	21.14	0.30	1.12	1.24	0.04	0.01	0.01	0.03	0.16	0.01	0.08	0.03	0.04	bd
34	GLK14	111	Blob	1.07	1.33	6.00	71.04	0.52	0.01	bd	9.38	7.84	0.62	0.52	1.58	0.01	bd	bd	0.01	bd	0.01	0.02	0.04	bd	bd
35	GLK14	111	Moil	0.97	3.27	2.11	59.84	2.18	0.16	bd	5.89	22.69	0.23	0.95	1.23	0.03	0.01	0.01	0.03	0.10	0.01	0.09	0.03	0.05	0.03
36	GLK14	111	Moil	0.97	3.09	1.88	59.61	2.08	0.27	bd	5.39	23.88	0.25	0.97	1.23	0.03	0.01	0.01	0.03	0.08	0.01	0.09	0.03	0.03	bd
37	GLK14	107	Thread	0.97	3.16	1.91	57.44	2.25	0.25	bd	6.64	24.59	0.25	1.07	1.09	0.02	0.01	0.01	0.03	0.04	0.01	0.09	0.03	0.05	bd
38	GLK14	107	Thread	1.10	3.54	2.21	57.96	2.28	0.15	bd	6.19	23.52	0.22	1.17	1.21	0.02	0.01	0.01	0.03	0.06	0.01	0.09	0.03	0.07	0.05
39	GLK14	107	Thread	0.83	2.80	2.30	61.22	2.10	0.14	bd	4.73	23.19	0.32	0.75	1.27	0.02	0.01	0.01	0.03	0.09	0.01	0.07	0.03	0.01	bd
40	GLK14	107	Thread	0.93	2.91	2.08	61.04	2.17	0.22	bd	4.87	23.04	0.23	0.77	1.44	0.02	0.01	0.01	0.03	0.08	0.01	0.07	0.03	0.01	bd
41	GLK14	107	Blob	0.97	3.50	1.93	57.81	2.20	0.27	bd	5.17	25.58	0.27	0.95	1.02	0.03	0.01	0.01	0.03	0.05	0.01	0.08	0.03	0.03	bd
42	GLK14	107	Window	0.93	3.25	1.84	59.46	2.35	0.23	bd	6.17	22.96	0.28	1.10	1.08	0.03	0.01	0.01	0.03	0.06	0.01	0.08	0.03	0.04	bd
43	GLK14	107	Window	0.82	2.84	1.95	61.28	1.81	0.17	bd	4.44	24.14	0.28	0.85	1.12	0.03	0.01	0.01	0.03	0.05	0.01	0.08	0.03	0.01	0.02
44	GLK14	107	Window	1.26	3.57	3.05	55.36	2.72	0.40	bd	5.91	24.19	0.30	1.03	1.77	0.05	0.02	0.01	0.05	0.08	0.01	0.09	0.03	0.03	bd
45	GLK14	107	Window	0.79	3.55	1.51	60.16	2.29	0.25	bd	6.30	22.65	0.30	1.09	0.82	0.02	0.01	0.01	0.03	0.02	0.01	0.07	0.04	0.05	bd
46	GLK14	107	Window (selvedge)	0.97	3.02	2.35	63.63	1.95	0.18	bd	5.36	19.80	0.35	0.94	1.17	0.02	bd	0.01	0.04	0.03	0.01	0.07	0.04	0.03	bd
47	GLK14	107	Pull trail	0.90	3.10	2.73	59.24	2.26	0.27	bd	5.21	22.80	0.35	1.03	1.73	0.04	0.01	0.01	0.04	0.08	0.01	0.08	0.03	0.02	bd
48	GLK14	103	Vessel?	0.98	2.93	1.78	61.53	2.07	0.20	bd	4.66	23.73	0.20	0.54	1.10	0.02	bd	0.01	0.02	0.06	0.01	0.06	0.03	0.01	bd
49	GLK14	103	Moil	0.90	3.10	1.97	58.92	2.39	0.19	bd	5.25	24.77	0.26	0.89	1.05	0.02	bd	0.01	0.04	0.02	0.01	0.08	0.03	0.03	bd
50	GLK14	103	Thread	0.96	2.90	2.18	61.00	2.11	0.17	bd	5.23	22.69	0.28	0.96	1.17	0.04	0.01	0.01	0.04	0.05	0.01	0.08	0.04	0.01	bd
51	GLK14	103	Window	0.90	2.99	2.66	60.95	1.85	0.16	bd	5.63	21.95	0.30	0.98	1.29	0.03	0.01	0.01	0.03	0.05	0.01	0.08	0.02	0.04	bd

S'mple	Site	C'text	Descript'n	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	Cl	K_2O	CaO	TiO_2	MnO	Fe_2O_3	CoO	NiO	CuO	ZnO	As_2O_3	Rb_2O	SrO	ZrO_2	BaO	PbO
52	GLK14	103	Window	0.93	3.15	1.85	60.10	2.36	0.19	bd	5.28	23.97	0.21	0.61	1.00	0.02	bd	0.01	0.03	0.06	0.01	0.07	0.03	0.03	bd
53	GLK14	103	Window	0.95	2.93	1.95	62.39	2.09	0.23	bd	5.44	21.62	0.24	0.87	0.91	0.03	0.01	0.01	0.04	0.05	0.01	0.09	0.03	0.04	bd
54	GLK14	103	Window	0.92	3.02	1.71	61.39	2.01	0.27	bd	5.37	22.61	0.27	0.91	1.10	0.03	0.01	0.01	0.03	0.12	0.01	0.08	0.03	0.04	bd
55	GLK14	103	Window	0.92	3.42	2.16	57.91	2.33	0.24	bd	6.28	23.66	0.24	1.27	1.14	0.03	bd	0.01	0.04	0.09	0.01	0.10	0.03	0.04	bd
56	GLK14	103	Window	0.92	3.08	2.54	57.69	2.18	0.31	bd	5.39	24.82	0.30	0.97	1.44	0.04	0.01	0.01	0.03	0.07	0.01	0.08	0.03	0.03	bd
57	GLK14	103	Window	4.22	3.32	2.94	58.91	2.34	0.19	0.31	5.36	20.55	0.15	0.10	1.44	0.01	bd	0.01	0.04	bd	bd	0.11	0.01	bd	bd
58	GLK14	103	Window	1.00	2.78	1.94	62.38	2.11	0.23	bd	5.07	21.70	0.26	0.89	1.28	0.04	0.01	0.01	0.03	0.06	0.01	0.08	0.03	0.02	bd
59	GLK14	103	Window	0.86	2.99	2.03	61.58	2.06	0.13	bd	4.79	22.98	0.24	0.88	1.02	0.05	0.02	0.01	0.03	0.06	0.01	0.09	0.04	0.03	0.04
60	GLK14	103	Window	1.00	2.89	2.35	62.05	2.15	0.29	bd	5.30	21.13	0.28	1.01	1.19	0.04	0.01	0.01	0.04	0.05	0.01	0.09	0.04	0.03	bd
61	GLK14	102	Lump	0.90	2.88	1.94	60.27	2.16	0.11	bd	5.09	24.16	0.33	0.84	1.07	0.01	bd	0.01	0.03	0.02	0.01	0.07	0.03	0.02	bd
62	GLK14	102	Lump	0.88	2.88	1.69	62.84	2.01	0.16	bd	4.67	22.67	0.18	0.74	0.99	0.02	bd	0.01	0.02	0.05	0.01	0.06	0.03	0.01	bd
63	GLK14	102	Lump	1.03	2.81	1.97	60.43	2.11	0.17	bd	5.01	24.01	0.33	0.84	1.03	0.01	bd	0.01	0.03	0.03	0.01	0.07	0.03	0.02	bd
64	GLK14	102	Lump	1.07	3.17	2.06	61.98	2.24	0.27	bd	6.42	19.97	0.24	0.99	1.17	0.03	bd	0.01	0.04	0.08	0.01	0.08	0.03	0.05	bd
65	GLK14	102	Lump	0.93	2.93	2.24	60.91	2.10	0.15	bd	5.48	22.45	0.32	1.02	1.16	0.03	0.01	0.01	0.03	0.04	0.01	0.07	0.03	0.02	bd
66	GLK14	102	Window	0.94	3.57	1.63	58.81	2.45	0.25	bd	6.48	23.22	0.21	1.19	0.86	0.04	0.01	0.01	0.03	0.05	0.01	0.08	0.03	0.06	bd
67	GLK14	102	Window	0.81	2.83	1.71	61.06	2.13	0.18	bd	4.62	24.64	0.25	0.58	0.91	0.03	0.01	0.01	0.03	0.04	0.01	0.06	0.04	bd	bd
68	GLK14	102	Window	1.00	3.25	1.90	58.26	2.16	0.27	bd	6.56	24.16	0.26	0.94	0.86	0.02	bd	0.01	0.04	0.07	0.01	0.09	0.03	0.04	bd
69	GLK14	102	Window	0.95	3.00	2.76	59.86	2.22	0.22	bd	5.38	22.49	0.21	0.99	1.57	0.03	0.01	0.01	0.04	0.07	0.01	0.07	0.03	0.03	bd
70	GLK14	102	Window	0.97	3.18	2.55	59.65	2.47	0.23	bd	5.89	21.95	0.32	0.96	1.46	0.03	0.01	0.01	0.04	0.06	0.01	0.08	0.03	0.03	bd
71	GLK14	102	Window	1.09	3.36	2.25	59.13	2.07	0.19	bd	6.65	22.16	0.33	1.27	1.09	0.03	0.01	0.01	0.03	0.08	0.01	0.08	0.03	0.05	bd
72	GLK14	102	Window	1.04	3.25	2.47	56.51	2.54	0.38	bd	5.80	25.06	0.29	0.94	1.34	0.02	0.01	0.01	0.04	0.07	0.01	0.08	0.02	0.03	0.02
73	GLK14	102	Window	0.89	3.20	1.69	59.30	2.32	0.19	bd	5.75	24.02	0.24	0.96	1.08	0.03	0.01	0.01	0.03	0.04	0.01	0.08	0.03	0.05	bd
74	GLK14	102	Window	0.96	3.53	2.20	59.91	2.08	0.18	bd	6.00	22.05	0.28	1.26	1.10	0.03	0.01	0.01	0.04	0.10	0.01	0.09	0.03	0.06	bd
75	GLK14	102	Window	0.92	3.31	1.61	61.43	2.26	0.22	bd	5.52	22.31	0.31	1.00	0.83	0.01	bd	0.01	0.03	0.03	0.01	0.07	0.03	0.04	bd
76	GLK14	102	Vessel?	0.94	3.08	1.97	61.02	1.87	0.36	bd	5.59	22.72	0.25	0.95	0.88	0.03	0.01	0.01	0.04	0.05	0.01	0.09	0.03	0.04	bd
77	GLK14	102	Vessel?	0.89	3.24	2.06	60.00	1.87	0.30	bd	5.89	23.17	0.28	0.84	1.08	0.03	0.02	0.01	0.03	0.12	0.01	0.08	0.03	0.03	bd
78	GLK14	102	Vessel?	1.04	3.85	1.45	59.13	2.14	0.25	bd	6.29	23.12	0.24	1.38	0.76	0.02	0.01	0.01	0.03	0.03	0.01	0.09	0.03	0.07	bd
79	GLK14	102	Vessel?	0.84	2.76	1.62	61.65	2.09	0.31	bd	5.18	23.50	0.21	0.58	0.96	0.02	bd	0.01	0.03	0.08	0.01	0.06	0.03	0.01	bd

S'mple	Site	C'text	Descript'n	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	Cl	K_2O	CaO	TiO_2	MnO	Fe_2O_3	CoO	NiO	CuO	ZnO	As_2O_3	Rb_2O	SrO	ZrO_2	BaO	PbO
80	GLK14	102	Vessel?	1.97	5.33	3.04	56.63	1.30	0.61	0.10	2.89	25.62	0.23	0.09	1.84	bd	bd	bd	0.01	bd	bd	0.31	0.01	bd	bd
81	GLK14	102	Vessel?	0.98	3.11	1.89	60.56	2.03	0.37	0.07	5.83	22.76	0.22	0.99	0.91	0.02	0.01	0.01	0.04	0.04	0.01	0.08	0.03	0.04	bd
82	GLK14	102	Vessel?	3.24	2.85	2.71	58.62	2.43	0.11	0.61	3.30	23.57	0.28	0.53	1.51	0.02	bd	0.01	0.04	0.06	bd	0.07	0.03	bd	bd
83	GLK14	102	Vessel?	1.01	3.31	1.65	59.33	2.37	0.27	0.07	5.79	23.94	0.21	0.94	0.90	0.01	bd	0.01	0.03	0.02	0.01	0.07	0.03	0.03	bd
84	GLK14	102	Vessel?	0.96	3.01	2.07	60.67	2.03	0.24	0.06	6.22	22.16	0.28	0.98	1.01	0.02	0.01	0.01	0.04	0.07	0.01	0.08	0.03	0.04	bd
85	GLK14	102	Vessel?	0.78	2.74	2.27	62.48	1.95	0.15	0.06	5.35	21.94	0.26	0.77	1.01	0.02	0.01	0.01	0.03	0.04	0.01	0.07	0.04	0.02	bd
86	GLK14	102	Thread	0.89	3.11	1.74	61.02	1.97	0.26	0.04	5.68	22.73	0.21	1.17	0.90	0.02	bd	0.01	0.02	0.05	0.01	0.08	0.03	0.03	bd
87	GLK14	102	Thread	0.96	2.89	2.02	60.92	2.10	0.21	0.04	4.99	23.21	0.33	0.88	1.18	0.02	0.01	0.01	0.04	0.04	0.01	0.07	0.04	0.02	bd
88	GLK14	102	Thread	0.90	3.12	1.69	61.03	2.11	0.31	0.04	5.89	22.39	0.30	1.07	0.85	0.02	0.01	0.01	0.02	0.04	0.01	0.09	0.04	0.05	bd
89	GLK14	102	Blob	0.81	2.79	2.03	61.19	1.96	0.22	0.03	4.58	23.88	0.24	0.85	1.14	0.03	0.01	0.01	0.03	0.05	0.01	0.08	0.03	0.01	0.02
90	GLK14	102	Blob	1.01	3.15	2.13	59.89	2.26	0.29	0.06	5.62	23.21	0.25	0.67	1.18	0.02	bd	0.01	0.03	0.06	0.01	0.07	0.03	0.02	bd
91	GLK14	102	Lump (dichroic)	0.87	3.16	2.38	59.10	2.23	0.17	0.06	4.79	23.80	0.30	0.84	1.67	0.03	0.01	0.01	0.03	0.42	0.01	0.08	0.03	0.02	bd
92	GLK14	102	Blob (tongs)	1.00	3.32	1.67	59.43	2.24	0.29	0.07	5.10	24.58	0.19	0.82	1.02	0.03	bd	0.01	0.03	0.07	0.01	0.06	0.03	0.02	bd
93	GLK14	102	Tube	1.11	3.59	1.93	60.36	2.46	0.19	0.10	6.06	21.69	0.22	0.93	0.98	0.02	0.01	0.01	0.03	0.04	0.01	0.07	0.04	0.04	0.09
94	GLK14	102	Tube	0.80	3.04	1.85	61.03	1.92	0.24	0.04	5.12	23.63	0.28	0.87	0.86	0.03	0.02	0.01	0.02	0.10	0.01	0.08	0.04	0.03	bd
95	GLK14	102	Tube	0.82	2.74	1.89	61.89	2.06	0.10	0.03	5.23	22.65	0.30	0.91	1.13	0.03	0.01	0.01	0.03	0.05	0.01	0.07	0.04	0.02	bd
96	IFG14	122	Waste?	3.20	8.34	0.90	51.02	3.93	0.25	0.22	14.96	14.85	0.10	1.34	0.60	0.01	bd	0.01	0.06	bd	0.04	0.07	0.01	0.05	bd
97	IFG14	113	Lump	1.98	6.84	1.31	56.06	3.28	0.20	0.28	11.01	16.91	0.16	1.13	0.52	0.01	bd	0.02	0.06	bd	0.02	0.06	0.01	0.07	0.08
98	IFG14	113	Lump	1.90	1.39	4.64	70.90	0.26	bd	bd	14.53	2.94	0.33	0.34	2.56	0.01	0.01	0.01	0.04	bd	0.03	0.03	0.02	0.06	bd
99	IFG14	113	Lump	3.03	7.09	1.19	53.68	3.31	0.21	0.33	14.03	14.93	0.10	1.18	0.61	0.01	bd	0.02	0.06	bd	0.03	0.06	0.01	0.05	0.06
100	IFG14	113	Lump	1.77	3.33	4.19	63.03	1.72	bd	bd	14.17	7.69	0.30	1.13	2.42	0.01	0.01	0.01	0.02	bd	0.04	0.04	0.02	0.08	bd
101	IFG14	113	Lump	1.99	6.90	1.14	56.09	3.26	0.27	0.30	11.02	17.02	0.06	1.10	0.53	0.01	bd	0.02	0.06	bd	0.03	0.06	0.01	0.08	0.07
102	IFG14	105	Lump	1.52	1.54	4.73	71.46	0.36	bd	bd	14.90	2.29	0.30	0.38	2.37	0.01	0.01	0.01	0.02	bd	0.04	0.02	0.02	0.02	bd
103	IFG14	105	Lump	1.64	3.78	4.07	65.31	1.40	bd	bd	12.81	7.03	0.33	0.69	2.74	0.02	bd	0.01	0.02	bd	0.03	0.04	0.02	0.03	bd
104	IFG14	105	Lump	1.44	2.79	4.87	68.10	0.77	bd	bd	13.17	4.98	0.30	0.51	2.83	0.01	bd	0.01	0.02	bd	0.03	0.04	0.02	0.02	bd
105	IFG14	105	Lump	2.28	7.42	0.91	56.96	3.48	0.21	0.32	11.02	14.92	0.15	1.40	0.57	0.01	bd	0.01	0.07	bd	0.04	0.08	0.01	0.10	0.03
106	IFG14	105	Lump	2.46	6.84	1.46	56.07	3.57	0.21	0.25	10.85	16.09	0.15	1.09	0.58	0.01	bd	0.02	0.06	bd	0.04	0.06	0.01	0.06	0.09

S’mple	Site	C’text	Descript’n	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	Cl	K_2O	CaO	TiO_2	MnO	Fe_2O_3	CoO	NiO	CuO	ZnO	As_2O_3	Rb_2O	SrO	ZrO_2	BaO	PbO
107	IFG14	104E	Lump	1.85	6.17	1.12	59.49	3.07	0.11	0.30	13.77	12.34	0.10	0.88	0.56	0.01	bd	0.01	0.05	bd	0.04	0.04	0.02	0.03	0.05
108	IFG14	104E	Lump	2.26	1.69	4.61	69.52	0.49	0.02	0.01	14.87	3.23	0.33	0.39	2.40	0.01	bd	0.02	0.03	bd	0.03	0.02	0.03	0.02	bd
109	IFG14	104E	Lump	2.71	5.83	2.61	58.77	2.12	0.15	0.31	14.13	10.47	0.24	0.89	1.55	0.01	bd	0.01	0.05	bd	0.03	0.04	0.02	0.01	0.02
110	IFG14	104E	Lump	2.55	7.71	0.91	55.71	3.94	0.13	0.23	11.44	15.37	0.09	1.16	0.47	0.01	bd	0.01	0.06	bd	0.03	0.07	0.01	0.06	0.04
111	IFG14	104E	Lump	2.54	7.46	1.08	54.99	3.36	0.23	0.30	12.22	15.72	0.07	1.10	0.61	0.01	bd	0.02	0.06	bd	0.03	0.06	0.01	0.06	0.07
112	IFG14	104W	Lump	2.40	7.42	1.02	53.53	3.65	0.29	0.24	14.26	15.03	0.08	1.27	0.51	0.01	bd	0.01	0.06	bd	0.03	0.07	0.01	0.06	0.04
113	IFG14	104W	Lump	2.40	7.78	1.16	55.88	3.34	0.24	0.19	10.29	16.39	0.07	1.31	0.57	0.01	bd	0.01	0.07	bd	0.03	0.08	0.01	0.08	0.06
114	IFG14	104W	Lump	2.30	7.34	0.88	55.07	3.32	0.24	0.33	13.35	14.99	0.12	1.23	0.52	0.01	bd	0.01	0.07	bd	0.03	0.07	0.01	0.06	0.06
115	IFG14	102E	Lump	2.41	7.15	1.14	55.34	3.77	0.16	0.31	12.31	14.74	0.13	1.26	0.79	0.01	bd	0.04	0.08	bd	0.04	0.07	0.01	0.08	0.13
116	IFG14	102E	Lump	2.34	7.03	1.33	55.79	3.55	0.24	0.28	10.98	16.05	0.11	1.16	0.66	0.01	bd	0.02	0.07	bd	0.03	0.07	0.01	0.08	0.19
117	IFG14	102E	Lump	2.18	3.80	3.76	62.40	2.58	0.06	0.06	13.69	7.93	0.26	0.91	2.14	0.01	bd	0.01	0.04	bd	0.03	0.05	0.02	0.05	bd
118	IFG14	102E	Lump	2.56	6.68	1.34	56.16	3.02	0.30	0.30	12.88	14.47	0.14	1.13	0.73	0.01	bd	0.01	0.06	bd	0.04	0.07	0.01	0.06	0.04
119	IFG14	102E	Lump	2.46	6.23	2.06	57.23	2.39	0.31	0.28	13.71	12.74	0.23	1.15	0.89	0.01	bd	0.01	0.07	bd	0.04	0.07	0.01	0.07	0.04
#REF!	IFG14	104N	Lump	2.23	8.24	0.63	54.84	3.36	0.25	0.39	12.54	15.50	0.02	1.40	0.34	0.01	bd	0.01	0.07	bd	0.03	0.07	bd	0.06	bd
121	IFG14	104N	Lump	2.73	8.34	1.01	54.37	3.33	0.24	0.17	11.48	16.09	0.11	1.31	0.48	0.01	bd	0.01	0.06	bd	0.04	0.08	0.01	0.09	0.03
122	IFG14	104N	Lump	2.20	7.38	1.12	57.29	3.55	0.30	0.28	11.21	14.64	0.11	1.08	0.52	0.01	bd	0.01	0.06	bd	0.04	0.07	0.01	0.06	0.06
123	IFG14	101	Window?	1.95	6.98	1.13	59.66	2.68	0.20	0.24	10.60	14.04	0.15	1.22	0.86	0.01	bd	0.01	0.07	bd	0.02	0.06	0.01	0.05	0.05
124	IFG14	101	Window?	0.93	3.20	1.86	59.70	2.07	0.31	0.06	5.50	23.86	0.27	0.90	1.05	0.03	0.01	0.01	0.03	0.07	0.01	0.08	0.02	0.03	bd
125	IFG14	101	Window?	2.94	3.80	2.58	57.52	3.28	0.13	0.42	4.81	22.29	0.19	1.00	0.79	0.01	bd	0.01	0.03	bd	bd	0.07	0.02	0.13	bd
126	IFG14	101	Vessel?	0.92	3.07	1.86	61.88	2.02	0.18	0.06	5.38	21.89	0.23	1.20	1.02	0.03	0.01	0.01	0.04	0.03	0.01	0.08	0.03	0.05	bd
127	IFG14	101	Vessel?	2.65	5.44	2.22	55.67	3.14	0.17	0.31	10.52	17.63	0.16	0.88	0.76	0.01	bd	0.02	0.05	bd	0.03	0.06	0.02	0.06	0.21
128	IFG14	101	Moil?	2.71	6.56	1.82	55.50	3.49	0.20	0.27	11.29	15.92	0.08	0.90	0.71	0.01	bd	0.02	0.05	bd	0.04	0.08	0.02	0.08	0.23
129	IFG14	101	Thread-rod	1.51	0.84	5.13	74.28	0.21	bd	0.01	13.12	1.27	0.38	0.17	2.88	0.01	0.01	0.02	0.08	bd	0.04	0.01	0.03	0.02	bd
130	IFG14	101	Blown?	1.29	5.99	0.90	62.12	3.09	0.12	0.24	14.83	10.12	0.09	0.63	0.41	bd	bd	0.01	0.05	bd	0.03	0.02	0.02	0.01	bd
131	IFG14	101	Blown?	2.33	7.53	1.09	57.73	2.57	0.12	0.14	10.86	15.36	0.09	1.26	0.56	0.01	bd	0.01	0.06	bd	0.03	0.07	0.01	0.08	0.07
132	IFG14	101	Blob (tongs)	2.82	2.14	4.34	69.44	0.89	bd	0.04	12.70	4.72	0.26	0.36	2.08	0.01	bd	0.03	0.03	bd	0.04	0.02	0.03	0.03	bd
133	IFG14	101	Thread	2.24	2.07	4.81	70.04	0.51	bd	bd	12.64	4.07	0.29	0.50	2.60	0.01	0.01	0.02	0.03	bd	0.04	0.04	0.02	0.07	bd

S'mple	Site	C'text	Descript'n	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	Cl	K_2O	CaO	TiO_2	MnO	Fe_2O_3	CoO	NiO	CuO	ZnO	As_2O_3	Rb_2O	SrO	ZrO_2	BaO	PbO
134	IFG14	101	Lump	1.85	7.83	1.05	64.22	3.57	0.10	0.20	11.30	8.95	0.06	0.43	0.27	0.01	bd	0.01	0.05	bd	0.03	0.03	0.02	0.02	bd
135	IFG14	101	Blown?	3.13	8.51	1.04	52.15	3.96	0.26	0.14	13.52	14.94	0.13	1.27	0.62	0.01	bd	0.01	0.06	bd	0.04	0.08	0.01	0.08	0.03
136	IFG14	101	Pull	2.46	6.81	1.46	56.56	2.82	0.32	0.31	11.39	15.50	0.14	1.18	0.70	0.01	bd	0.01	0.07	bd	0.04	0.07	0.01	0.08	0.06
137	IFG14	101	Lump	2.87	7.92	1.42	53.45	3.60	0.31	0.28	14.26	13.61	0.13	1.08	0.76	0.01	bd	0.01	0.07	bd	0.05	0.07	0.01	0.04	0.04
138	IFG14	101	Lump	2.33	6.37	1.51	56.41	3.34	0.24	0.30	9.71	17.24	0.05	1.14	0.76	0.01	bd	0.03	0.06	bd	0.03	0.08	0.02	0.08	0.24
139	IFG14	101	Lump	2.75	8.04	1.08	54.70	3.81	0.19	0.21	10.72	16.07	0.10	1.37	0.63	0.01	bd	0.02	0.07	bd	0.03	0.07	0.01	0.06	0.04
140	IFG14	101	Lump	2.31	7.01	1.40	56.68	3.17	0.24	0.24	10.56	15.97	0.17	1.18	0.69	0.01	bd	0.02	0.07	bd	0.04	0.07	0.01	0.07	0.10
141	IFG14	101	Lump	2.48	7.11	1.65	57.13	2.56	0.23	0.34	12.77	13.37	0.21	1.11	0.81	0.01	bd	bd	0.06	bd	0.03	0.07	0.01	0.06	bd
142	IFG14	101	Lump	2.17	7.51	1.06	57.40	3.07	0.32	0.17	9.73	16.10	0.13	1.43	0.59	0.01	bd	0.01	0.07	bd	0.03	0.08	0.01	0.07	0.06
143	IFG14	101	Lump	2.42	7.37	1.03	53.42	3.66	0.27	0.24	14.35	15.19	0.12	1.12	0.50	0.01	bd	0.02	0.06	bd	0.03	0.06	0.01	0.06	0.04
144	IFG14	101	Lump	2.73	6.65	1.49	55.74	3.07	0.23	0.31	11.88	15.40	0.16	1.20	0.72	0.01	bd	0.02	0.06	bd	0.04	0.07	0.02	0.08	0.12
145	IFG14	101	Lump (devitrified)	2.21	5.27	1.82	56.98	3.24	0.23	0.34	8.42	19.06	0.12	1.04	0.65	0.01	bd	0.02	0.07	bd	0.03	0.08	0.02	0.10	0.24
146	IFG14	113	Furnace - stone (glazed)	0.20	0.53	13.26	76.14	0.26	bd	bd	2.29	0.11	1.56	0.13	5.55										
147	IFG14	113	Ceramic lid?	0.13	0.55	6.07	88.00	0.42	bd	bd	1.55	0.28	0.32	0.06	2.65										
148	IFG14	113	Furnace - stone (glazed)	0.94	0.71	4.93	81.89	0.26	0.01	bd	7.56	0.63	0.23	0.07	2.78										
149	IFG14	113	Furnace - stone (glazed)	0.10	0.49	5.89	88.75	0.38	bd	bd	1.36	0.19	0.30	bd	2.56										
150	IFG14	103	Furnace - stone (glazed)	0.13	0.55	5.32	89.42	0.36	bd	bd	1.48	0.22	0.31	bd	2.25										
151	LFB13	103	Lid?	0.09	0.56	21.23	71.97	0.17	bd	bd	2.13	0.62	1.42	0.01	1.80										
152	LFB13	103	Crucible	0.11	0.50	22.37	71.25	0.25	bd	bd	2.05	0.38	1.49	bd	1.63										
153	LFB13	103	Crucible	0.10	0.38	20.86	73.80	bd	bd	bd	1.51	0.37	1.50	bd	1.51										
154	LFB13	106	Crucible	0.13	0.62	28.68	63.83	bd	bd	bd	2.40	0.53	2.05	bd	1.79										
155	LFB13	106	Crucible	0.08	0.27	18.70	76.79	bd	bd	bd	1.07	0.26	1.43	bd	1.43										

S'mple	Site	C'text	Descript'n	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	Cl	K_2O	CaO	TiO_2	MnO	Fe_2O_3	CoO	NiO	CuO	ZnO	As_2O_3	Rb_2O	SrO	ZrO_2	BaO	PbO
156	LFB13	105	Crucible	0.13	0.47	23.19	70.92	bd	bd	bd	1.76	0.48	1.44	bd	1.64										
157	LFB13	104	Crucible	0.09	0.31	19.38	75.56	bd	bd	bd	1.42	0.32	1.40	bd	1.56										
158	LFB13	104	Crucible	0.09	0.46	22.00	72.29	bd	bd	bd	1.71	0.42	1.62	bd	1.43										
159	LFB13	103	Crucible	0.10	0.37	20.50	74.07	bd	bd	bd	1.45	0.36	1.49	bd	1.69										
160	LFB13	102	Hole cover?	0.25	0.57	28.46	63.73	0.21	bd	bd	2.24	0.63	2.00	0.01	1.90										
161	LFB13	103	Hole cover?	0.14	0.57	28.35	64.47	bd	bd	bd	2.24	0.51	1.96	bd	1.79										
162	LFB13	103	Furnace - brick	0.48	0.38	8.83	82.01	0.42	bd	bd	1.67	0.26	0.77	0.43	4.74										
163	LFB13	103	Furnace - brick	0.13	0.69	17.75	76.13	0.32	bd	bd	1.97	0.39	0.75	0.01	1.88										
164	LFB13	103	Furnace - brick	0.11	0.52	10.80	84.44	0.23	bd	bd	1.44	0.44	0.52	0.02	1.49										
165	LFB13	103	Furnace - brick	0.14	0.41	9.37	86.18	0.36	bd	bd	1.21	0.71	0.49	0.01	1.12										
166	LFB13	103	Furnace - brick	0.18	0.55	4.98	88.39	0.66	bd	bd	1.13	0.24	0.27	0.10	3.51										
167	LFB13	105	Vitrified fuel ash	0.67	2.54	3.68	77.53	2.02	bd	bd	6.39	3.56	0.38	1.83	1.28										
168	LFB13	105	Vitrified fuel ash	1.15	2.99	4.62	72.10	2.90	bd	0.21	7.76	4.99	0.37	1.22	1.60										
170	LFB13	105	Vitrified fuel ash	1.04	2.75	4.96	71.81	2.88	bd	bd	7.73	5.49	0.39	1.26	1.62										
171	LFB13	105	Vitrified fuel ash	0.82	1.63	4.78	78.95	2.06	bd	bd	5.47	3.10	0.39	1.16	1.53										
172	LFB13	105	Vitrified fuel ash	1.07	2.92	3.38	60.45	1.88	bd	bd	5.19	22.90	0.29	0.79	1.09										
172	LFB13	107	Blown - urinal?	0.99	2.93	2.13	60.44	2.05	0.27	bd	6.02	22.36	0.25	0.96	1.22	0.03	0.01	0.01	0.04	0.06	0.01	0.09	0.02	0.04	bd
173	LFB13	107	Blown - urinal?	1.03	2.92	2.17	60.58	2.02	0.27	bd	5.95	22.15	0.26	1.08	1.22	0.03	0.01	0.01	0.04	0.06	0.01	0.08	0.02	0.05	bd
174	LFB13	107	Blown?	0.96	3.04	2.24	60.65	2.15	0.23	bd	5.95	21.80	0.24	1.08	1.29	0.03	0.01	0.01	0.04	0.06	0.01	0.08	0.02	0.05	bd
175	LFB13	107	Window?	1.11	3.08	2.23	60.65	2.11	0.21	bd	5.93	21.74	0.24	1.08	1.24	0.03	0.01	0.01	0.04	0.06	0.01	0.08	0.02	0.04	bd
176	LFB13	107	Window?	0.96	2.93	2.43	61.05	1.92	0.22	bd	5.87	21.62	0.27	1.05	1.36	0.03	0.01	0.01	0.03	0.07	0.01	0.06	0.01	0.04	bd
177	LFB13	107	Window?	0.96	2.86	2.51	61.04	2.02	0.21	0.10	5.86	21.45	0.25	1.07	1.39	0.03	0.01	0.01	0.03	0.07	0.01	0.07	0.02	0.04	bd
178	LFB13	106	Window?	0.93	2.78	2.34	60.58	1.93	0.18	bd	4.96	24.29	0.16	0.62	0.88	0.03	0.01	0.01	0.03	0.11	0.01	0.07	0.02	0.01	bd

S’mple	Site	C’text	Descript’n	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	Cl	K_2O	CaO	TiO_2	MnO	Fe_2O_3	CoO	NiO	CuO	ZnO	As_2O_3	Rb_2O	SrO	ZrO_2	BaO	PbO
179	LFB13	106	Window?	0.90	2.81	2.31	60.19	1.93	0.18	bd	4.93	24.51	0.26	0.74	0.91	0.03	0.01	0.01	0.03	0.11	0.01	0.07	0.02	0.02	bd
180	LFB13	106	Window?	0.75	2.60	1.79	61.42	1.89	0.20	bd	4.78	24.13	0.21	1.01	1.00	0.02	0.01	0.01	0.03	0.02	0.01	0.08	0.02	0.02	bd
181	LFB13	106	Window?	0.82	2.67	1.89	61.16	1.81	0.29	bd	4.77	24.12	0.18	1.00	1.04	0.02	bd	0.01	0.03	0.02	0.01	0.10	0.02	0.02	bd
182	LFB13	106	Window?	0.63	2.64	1.82	61.30	1.82	0.29	bd	4.81	24.26	0.24	0.97	0.96	0.02	0.01	0.01	0.03	0.02	0.01	0.08	0.02	0.02	bd
183	LFB13	106	Window?	0.71	2.62	1.81	61.33	1.81	0.26	bd	4.80	24.21	0.23	0.99	0.96	0.02	0.01	0.01	0.03	0.02	0.01	0.08	0.02	0.03	bd
184	LFB13	106	Window?	0.75	2.76	2.40	59.65	1.77	0.12	0.03	5.34	24.49	0.26	0.91	1.22	0.02	0.02	0.01	0.03	0.06	0.01	0.09	0.02	0.04	bd
185	LFB13	105	Window?	0.71	2.72	1.88	61.29	1.76	0.27	0.06	4.81	24.12	0.21	1.00	0.96	0.02	0.01	0.01	0.03	0.02	bd	0.08	0.02	0.02	bd
186	LFB13	105	Window?	0.73	2.59	1.84	61.34	1.74	0.25	0.02	4.83	24.31	0.15	1.01	0.97	0.02	0.01	0.01	0.03	0.02	0.01	0.09	0.02	0.02	bd
187	LFB13	105	Window?	0.89	2.85	2.62	60.28	1.93	0.09	0.02	5.12	23.61	0.22	0.86	1.23	0.03	0.01	0.01	0.03	0.07	0.01	0.08	0.01	0.03	bd
188	LFB13	105	Lump	0.95	2.90	1.74	62.08	1.99	0.21	0.04	6.02	21.78	0.18	0.85	1.02	0.02	0.01	0.01	0.03	0.02	0.01	0.08	0.03	0.03	bd
189	LFB13	104	Moil?	0.88	3.01	1.90	61.19	1.99	0.28	0.05	5.53	22.65	0.23	0.97	1.06	0.02	0.01	0.01	0.03	0.04	0.01	0.08	0.01	0.03	bd
190	LFB13	104	Vessel?	0.82	2.87	1.94	60.96	1.95	0.24	0.04	5.33	23.69	0.24	0.82	0.86	0.02	0.01	0.01	0.02	0.04	0.01	0.08	0.01	0.02	bd
191	LFB13	104	Window?	0.90	3.07	2.01	60.22	1.95	0.21	0.03	5.59	23.66	0.18	0.99	0.95	0.02	0.01	0.01	0.03	0.04	0.01	0.08	0.01	0.03	bd
192	LFB13	104	Blob	0.96	2.85	2.55	61.40	1.88	0.22	0.03	5.21	22.19	0.27	1.04	1.13	0.03	0.01	0.01	0.04	0.06	0.01	0.08	0.02	0.03	bd
193	LFB13	104	Lump	0.99	2.81	2.69	60.55	1.90	0.33	0.04	5.25	22.67	0.29	0.89	1.33	0.02	0.01	0.01	0.03	0.04	0.01	0.08	0.02	0.03	bd
194	LFB13	104	Lump	0.84	2.54	2.31	60.24	1.76	0.21	0.06	4.61	25.09	0.23	0.89	0.97	0.02	0.01	0.01	0.02	0.05	0.01	0.08	0.02	0.02	bd
195	LFB13	104	Lump	0.66	3.30	1.99	57.06	1.61	0.19	0.03	4.80	27.63	0.21	1.19	0.97	0.03	0.02	0.01	0.02	0.08	0.01	0.10	0.01	0.05	bd
196	LFB13	104	Lump	0.93	2.56	2.82	61.99	1.64	0.15	0.03	4.58	22.41	0.29	0.97	1.35	0.03	0.01	0.01	0.03	0.05	0.01	0.08	0.02	0.02	bd
197	LFB13	103	Moil?	0.87	2.65	2.60	61.48	1.81	0.16	0.04	5.09	22.75	0.21	0.82	1.24	0.03	0.01	0.01	0.03	0.06	0.01	0.08	0.02	0.03	bd
198	LFB13	103	Lump	1.07	3.09	2.19	60.60	2.06	0.23	0.05	5.19	22.85	0.20	0.96	1.20	0.02	0.01	0.01	0.05	0.05	0.01	0.08	0.02	0.04	bd
199	LFB13	103	Lump	0.70	2.49	1.81	63.18	1.51	0.22	0.03	5.00	22.96	0.21	0.91	0.79	0.02	bd	0.01	0.02	0.02	0.01	0.07	0.01	0.02	bd
200	LFB13	103	Lump	0.86	2.98	1.94	59.93	1.95	0.23	0.05	5.57	24.03	0.26	1.01	0.97	0.02	0.01	0.01	0.03	0.03	0.01	0.08	0.01	0.03	bd
201	LFB13	103	Blown?	1.00	2.86	2.17	60.14	1.93	0.20	0.12	5.31	23.84	0.23	0.84	1.09	0.03	bd	0.01	0.03	0.07	0.01	0.08	0.03	0.02	bd
202	LFB13	103	Blown?	1.00	2.93	2.48	59.46	1.91	0.23	0.05	5.43	23.62	0.28	1.08	1.21	0.03	0.02	0.01	0.04	0.06	0.01	0.08	0.02	0.03	bd
203	LFB13	103	Window	0.73	2.69	1.81	61.11	1.81	0.27	0.02	4.86	24.29	0.16	1.02	1.00	0.02	bd	0.01	0.03	0.02	0.01	0.10	0.02	0.03	bd
204	LFB13	103	Window	0.75	2.71	1.87	61.74	1.80	0.28	0.03	4.76	23.69	0.22	0.97	0.95	0.02	0.01	0.01	0.03	0.02	bd	0.09	0.02	0.02	bd
205	LFB13	103	Window	0.81	2.74	1.78	61.77	1.84	0.30	0.04	4.77	23.55	0.21	0.98	0.97	0.02	0.01	0.01	0.03	0.02	bd	0.09	0.02	0.03	bd

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