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Summary

A selection of predominantly Roman glass-working waste and glass fragments was analysed by inductively coupled plasma spectrometry. Some analyses were undertaken of glass fragments adhering to remains of a ceramic tank furnace in which they had been melted. The analyses showed evidence for an exchange of chemical constituents between the clay and the glass. The glass was all of standard soda-lime silica composition. However, there were significant differences in the levels of decolourisers, such as manganese and antimony, which relate to iron contents and suggest some preselection of the raw materials.

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## Introduction

Excavations undertaken by archaeologists from the Museum of London in the area of the Upper Walbrook Valley have revealed a number of sites with evidence for glass-working and glass-blowing. In particular the sites of Copthall Avenue and Moorgate have revealed evidence for an industrial quarter dating to the late first and second centuries AD on what would have been the northern fringes of the contemporary Roman city. This activity pre-dated the construction of the city wall (to the area's immediate north) but was contemporary with the fort and amphitheatre to the immediate west.

The material from these sites displays the most complete glass-working assemblage so far recovered from the Roman city. Included are numerous tank furnace fragments, moils (the waste glass left on a blow-pipe or pontil after the removal of the vessel or object), pot or tank metal fragments (metal is used in this context as the technical term for bulk molten glass), droplets and amorphous blobs of glass and small fragments from possible waster vessels. In collaboration with John Shepherd of the Museum of London a set of objectives was established for an analytical programme to investigate the composition of the different groups of material. The main objectives were related to investigating the composition of the glass associated with the furnace and of the tank metal fragments, and comparing this glass with moils and other waste fragments, and also with vessel fragments.

## The Glass

The glass samples included in the analytical programme came from a number of Roman sites in London, particularly the Moorgate site, and also sites in Copthall Avenue, Watling House, and Norton Folgate. A sample from medieval glassworking remains at the Tower of London was also analysed for comparison. The material from the different sites vary in date as follows:

| Site name | Site Code | No. Of Samples | Date Range |
|---|---|---|---|
| Moorgate | (MGT) | 26 | 100 - 150 AD |
| Watling House | (WAT) | 6 | 50 - early Flavian |
| Copthall Avenue | (OPT) | 4 | 100 - 150 AD |
| Norton Folgate | (NRT) | 4 | 180 - 300 AD |
| Tower of London | (TOL) | 1 | medieval |

Most of the analysed glass samples were lightly tinted blue-green glasses (sometimes called naturally coloured) with a small number

being deliberately coloured. The lightly tinted glasses, which are the most common glass types found on all sites in the first millennium AD, are tinted due to the presence of iron in the glass. This tint is a result of the use of raw materials, such as sand, in the primary glass-making which contain iron as an unrecognised impurity.

The glass adhering to the tank furnace from the Moorgate site showed a considerable variety of blue-green tints. This could be due to minor variations in composition, though other factors can influence the colour, such as variations in redox conditions, ie the presence or absence of oxygen in the furnace, or variations in temperatures throughout the parts of the furnace. Roman glassmakers were able to produce completely decolourised glass, but it is unlikely they had sufficient control over the glass production to produce a specific light tint colour on demand. Theophilus, writing in the twelth century, describes how a colourless glass could, with further heating, turn to either saffron yellow becoming redder with time or a tawny, flesh colour which deepens to a reddish purple with prolonged heating (Hawthorne & Smith 1963). However there is no evidence to suggest that Theophilus knew how to control whether the glass turned yellow or tawny in the first place, which would have depended on the levels of the transition metals in the glass batch, particularly iron and manganese, and their state of oxidation.

The glassworking waste from the Moorgate site was predominantly associated with the tank furnace and a number of samples were taken from the surface of the furnace where they were still adhering to the clay matrix.

## Analytical Method

The analyses were undertaken using inductively coupled plasma atomic emission spectrometry (ICPS). The ICPS technique is becoming increasingly widely used in the analysis of archaeological materials (Heyworth et al 1988) as it has a number of advantages over other analytical techniques. In particular it gives compositional data for a wide range of elements at the major, minor and trace levels (Thompson and Walsh 1986). This is particularly important for the analysis of glass where major and minor elements determine the general type of glass and minor and trace elements have an important influence on its colour. In the present programme data was obtained for 32 oxides and elements: $Al_2O_3$, $Fe_2O_3$, MgO, CaO, $Na_2O$, $K_2O$, $TiO_2$, $P_2O_5$, MnO, Pb, Sb, Ba, Co, Cr, Cu, Li, Nb, Ni, Sc, Sr, V, Y, Zn, Zr, La, Ce, Nd, Sm, Eu, Dy, Yb and $SiO_2$. The figure for silica was obtained by difference as the silica is removed in the sample preparation procedure. Some minor oxides, such as sulphur and tin, which may be present in the glass, were not included in the analytical programme (which was primarily established for silicate rock analysis). The analysis of tin and sulphur is possible using ICPS, though a different sample preparation procedure would be required for the analysis of sulphur.

Samples of glass for analysis were cut from the glass fragments using a low speed diamond blade saw and milled to a fine powder. A powdered sample of 100 mg was then evaporated to dryness with

perchloric and hydrofluoric acid, and the residue dissolved in hydrochloric acid and distilled water before diluting to a standard solution strength. The sample preparation and ICPS analysis was undertaken in the Department of Geology at Royal Holloway and Bedford New College, University of London, under the supervision of Dr J.N.Walsh.

The ICPS analysis was carried out using a Philips polychromator ICPS system calibrated for quantitative analysis with multi-element rock standards. The glass solutions were run through the system twice, the first time the majority of major, minor and trace elements were measured, and the second time the solution was diluted to 10% of its original strength to obtain the soda figures. The dilution was necessary to maintain a linear calibration for the soda signal. Multi-element rock standards were analysed at regular intervals during the analytical run to allow for correction of any short-tern fluctuations in the system. Three glass substandards were also analysed to check the ICPS calibration.

Forty-one analyses were undertaken of glass fragments from the various sites. The full compositional data is listed in Table 1, together with relevant information on the archaeological context in which the glass was found and a description of the glass type and colour.

## Analytical Results and Discussion

All the glass is of the durable, soda-lime-silica type which previous work (eg Sanderson et al 1984) has shown to be the standard glass composition in the Roman period in north-west Europe. However there were other features of the analytical data which showed significant differences between the samples.

Whilst all the glass was of similar major oxide composition, there was a wide variation in the range of values for some of the minor oxides (see Table 3), particularly iron oxide which ranged over an order of magnitude from about 0.2% to over 2.0% (see Figure 1). The variation in iron oxide content correlated with similar variation in the levels of aluminium and titanium oxides, all elements likely to be present at significant levels in the clay of the furnace wall. All the samples with high levels of iron oxide were of glass taken from the surface of the tank furnace and it is therefore likely that there has been some movement of these elements from the clay of the furnace into the glass via some form of exchange mechanism. Great care had been taken when removing the samples for analysis to ensure that no particles of furnace material were left adhering to the glass before the sample was put into solution and any possibility of sample contamination can therefore be ruled out.

A cross section was cut through one of the furnace fragments and this shows a number of distinct layers between the clay of the furnace on the outside and the translucent light blue-green glass on the inside (see Figure 2). Further investigation of the movement of elements from the clay to the glass would need to look at the level of particular elements in each layer from the clay through to the glass. This could be achieved using a scanning electron microscope (SEM) in the backscattered mode to

look at the distribution of individual elements through the layers shown in Figure 2. It would also be possible to investigate the mineralogical composition of the layers using X-ray diffraction.

Similar work has been reported on glassmaking crucibles from the Wadi el-Natrun in Egypt which were also dated to the Roman period (Saleh et al 1972). Three layers were distinguished through a vertical section of a fritting crucible which were labelled A, B and C. These layers were distinguished on the basis of their colour and appearance, though they lacked sharply defined boundaries. Layer A is the outside, ie that subjected to firing, layer C represents the inner surface of the crucible wall which was in direct contact with the glass layer, and layer B is the middle part of the wall. Analysis of the three layers showed that whilst layers A and B were of similar composition, they were quite different to layer C. In particular the aluminium, iron and titanium oxide levels were reduced in layer C, and the silicon, calcium and sodium oxide levels were increased, in comparison to the composition of layers A and B. This is likely to be a result of the reaction between the crucible material and the glass material. Comparison of the Egyptian data with that obtained from the analysis of different samples of the Moorgate tank furnace showed that a similar pattern could be identified in the latter group (see Table 2).

This clearly has important implications for any attempts to link material from furnaces or crucibles to any waste or finished products from glass production sites. Excavations of archaeological sites do occasionally uncover evidence for glassworking in the form of crucible fragments containing melted glass. As there is only a thin layer of glass usually left adhering to the crucible (often only 1-2 mm) it will clearly be important to investigate the variations in composition through the glass before any assertions can be made as to the exact composition of any glass vessels or objects produced using glass melted in the crucible. It may be that trace elements will be more important in establishing links between glass from crucibles and glass from vessels or objects and the use of multi-element techniques such as ICPS, NAA or electron microprobe will be important to obtain the full glass composition, down to trace element level, for this purpose.

The iron levels in the glass, even allowing for the contamination problem, suggest that the sand source being used was not a particularly pure one. It is therefore likely that the glassmakers would have attempted to decolourise the glass. The principal decolourants used in the Roman period were manganese and antimony (Sayre 1963) and the analytical data from London suggests that both were in use there, though it is not clear whether both were deliberately, and separately, added to the glass batch or whether the use of cullet containing either manganese or antimony can be suggested. It is often difficult to judge the level at which something becomes a deliberate addition to the glass. The glass from the London sites frequently had a manganese oxide level of about 0.25% however there were one group of fragments analysed which had a higher manganese level than most and these fragments also tended to have lower iron oxide contents (see Figure 3). This suggests that the glassmakers readily understood the properties of manganese as a decolourant

and also preselected the raw materials containing less iron oxide in an attempt to produce a more colourless glass. The levels of manganese added would not have been sufficient to have had a significant decolourising effect on glass with a high iron content.

Antimony is a more effective decolourant than manganese and tends to produce a more brilliant colourless glass. It was therefore of particular interest to find that the glasses containing higher levels of iron usually contained a significant level of antimony (see Figure 3), but only an average amount of manganese, though in some cases the measured iron oxide level is affected by the diffusion from the furnace wall. The use of antimony in these glasses suggests that the glassmakers knew that a more effective decolourant was needed to cope with the less pure raw materials used in glass production. These results suggest a high level of technical skill and knowledge on the part of the Roman glassworkers.

From the glass fragments found associated with the tank furnace at Moorgate, and vessel fragments of similar date found in other contexts on the site, it is likely that the production of glass tableware was carried out in the area in the second century A.D. The glasses are not completely decolourised so, if antimony and manganese oxides were deliberately added, it appears that their use as decolourisers in the glass was not intended to produce a pure colourless glass but may have been an attempt to vary the tint of the glass to a paler shade. It is, however, possible that the differences result from the use of cullet in the vessel production. Further work is now needed to see if it is possible to link specific decolourants or glass "recipes" to the production of specific glass vessel types which may indicate a more sophisticated technological knowledge. The main problem in any study of this nature is the fragmentary nature of the vessels recovered which often makes it difficult to identify specific typological form variations.

The analyses of the waste glass fragments has shown that there is considerable variation in their composition and it is not possible with this small number of samples to suggest any meaningful groupings within the data. It is particularly interesting to note that there is very little difference in composition between the medieval glass waste from the Tower of London and the earlier Roman waste glass. A larger group of samples that can be securely dated and identified will be needed before any compositional patterns can be expected to emerge.

This work shows the value of an analytical component to the study of ancient glass production, particularly when the compositional studies can be undertaken in close collaboration with archaeologists and specialists in glass typology, in order to gain a better understanding of glass production in the past. It is only by this combination of evidence that it will be possible, in an archaeologically meaningful way, to reconstruct the technology of ancient glass production.

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**Table 1**

**ICPS data**

Forty-one glass samples were analysed using inductively coupled plasma atomic emission spectrometry (ICPS) and data was obtained for 31 oxides/elements. The data from each analysis is divided into the major and minor oxides (listed as oxide weight percentages), minor elements (listed as weight percentages) and trace elements (listed as parts per million). The figure for silica is obtained by subtracting the total figure of the measured oxides/elements from 100%. Consequently the sum of the concentrations, including silica, is always exactly 100%.

The data is listed together with information on the site code, accession number, context number, colour and glass type. The site names and glass colours are coded as follows:

| Site code | Colour code |
|---|---|
| MGT - Moorgate | LB - Light Blue |
| NRT - Norton Folgate | LG - Light Green |
| OPT - Copthall Avenue | LB/G - Light Blue/Green |
| TOL - Tower Of London | B - Blue |
| TIM - The Times | G/Y - Green/Yellow |
| WAT - Watling House | Br/Y - Brown/Yellow |
| | C - Colourless |

| Site | | MGT | MGT | MGT | OPT | WAT | WAT |
|---|---|---|---|---|---|---|---|
| Acc. No. | | 366 | 708 | 451 | 1024 | 12 | 11 |
| Context | | 515 | 796 | 1100 | 524 | - | - |
| $Al_2O_3$ | (%) | 2.49 | 2.46 | 2.49 | 2.46 | 1.82 | 2.53 |
| $Fe_2O_3$ | (%) | 0.56 | 0.37 | 0.31 | 0.29 | 0.22 | 0.63 |
| MgO | (%) | 0.56 | 0.56 | 0.53 | 0.49 | 0.31 | 0.65 |
| CaO | (%) | 6.85 | 7.84 | 7.58 | 7.63 | 5.61 | 6.24 |
| $Na_2O$ | (%) | 17.3 | 16.5 | 17.0 | 15.3 | 17.1 | 17.6 |
| $K_2O$ | (%) | 0.84 | 0.87 | 0.85 | 0.58 | 0.41 | 0.91 |
| $TiO_2$ | (%) | 0.10 | 0.08 | 0.07 | 0.07 | 0.06 | 0.14 |
| $P_2O_5$ | (%) | 0.13 | 0.18 | 0.14 | 0.14 | 0.11 | 0.17 |
| MnO | (%) | 0.33 | 0.55 | 0.38 | 0.33 | 0.02 | 0.53 |
| Pb | (%) | 0.03 | 0.02 | 0.01 | 0.01 | 0.00 | 0.05 |
| Sb | (%) | 0.25 | 0.03 | 0.00 | 0.00 | 0.00 | 0.13 |
| Ba | (ppm) | 223 | 1298 | 213 | 220 | 145 | 275 |
| Co | (ppm) | 10 | 13 | 11 | 11 | 8 | 15 |
| Cr | (ppm) | 18 | 17 | 18 | 15 | 10 | 19 |
| Cu | (ppm) | 52 | 80 | 22 | 27 | 17 | 713 |
| Li | (ppm) | 13 | 4 | 4 | 4 | 2 | 7 |
| Nb | (ppm) | 2 | 1 | 2 | 2 | 2 | 3 |
| Ni | (ppm) | 15 | 21 | 19 | 18 | 14 | 20 |
| Sc | (ppm) | 1 | 1 | 1 | 1 | 1 | 2 |
| Sr | (ppm) | 426 | 441 | 430 | 426 | 285 | 370 |
| V | (ppm) | 16 | 16 | 14 | 13 | 7 | 18 |
| Y | (ppm) | 9 | 9 | 9 | 9 | 7 | 9 |
| Zn | (ppm) | 70 | 65 | 53 | 31 | 31 | 38 |
| Zr | (ppm) | 53 | 38 | 36 | 33 | 34 | 70 |
| La | (ppm) | 14 | 12 | 13 | 12 | 12 | 14 |
| Ce | (ppm) | 16 | 16 | 17 | 16 | 15 | 19 |
| Nd | (ppm) | 20 | 19 | 20 | 20 | 21 | 21 |
| Sm | (ppm) | 2.9 | 2.7 | 3.3 | 3.3 | 2.8 | 3.3 |
| Eu | (ppm) | 0.5 | 0.5 | 0.5 | 0.5 | 0.4 | 0.5 |
| Dy | (ppm) | 1.8 | 1.9 | 2.0 | 1.9 | 1.5 | 2.0 |
| Yb | (ppm) | 0.8 | 0.8 | 0.9 | 0.9 | 0.7 | 1.0 |
| $SiO_2$ | (%) | 70.5 | 70.3 | 70.6 | 72.6 | 74.3 | 70.3 |
| Colour | | LB | LB | LB | LB | G/Y | LB |
| Type | | Waste | Bottle | Window | Waste | Vessel | Bottle |

| Site | | MGT | WAT | OPT | NRT | NRT | MGT |
|---|---|---|---|---|---|---|---|
| Acc. No. | | 366 | 6 | 1023 | 219 | 219 | 709 |
| Context | | 515 | - | 524 | 596 | 596 | 854 |
| $Al_2O_3$ | (%) | 2.50 | 2.20 | 2.65 | 2.25 | 2.41 | 2.67 |
| $Fe_2O_3$ | (%) | 0.29 | 0.75 | 0.34 | 0.49 | 0.50 | 0.29 |
| MgO | (%) | 0.52 | 0.41 | 0.56 | 0.55 | 0.58 | 0.53 |
| CaO | (%) | 7.64 | 5.87 | 8.02 | 6.38 | 6.54 | 7.68 |
| $Na_2O$ | (%) | 15.9 | 16.1 | 14.1 | 18.9 | 18.6 | 16.5 |
| $K_2O$ | (%) | 0.63 | 0.57 | 1.01 | 0.65 | 0.77 | 0.61 |
| $TiO_2$ | (%) | 0.07 | 0.07 | 0.07 | 0.09 | 0.10 | 0.07 |
| $P_2O_5$ | (%) | 0.16 | 0.15 | 0.17 | 0.11 | 0.13 | 0.13 |
| MnO | (%) | 0.64 | 0.92 | 0.48 | 0.26 | 0.34 | 0.24 |
| Pb | (%) | 0.01 | 0.01 | 0.01 | 0.03 | 0.04 | 0.01 |
| Sb | (%) | 0.01 | 0.00 | 0.00 | 0.34 | 0.32 | 0.00 |
| Ba | (ppm) | 247 | 245 | 264 | 199 | 216 | 237 |
| Co | (ppm) | 12 | 791 | 10 | 10 | 8 | 10 |
| Cr | (ppm) | 14 | 14 | 15 | 15 | 17 | 16 |
| Cu | (ppm) | 15 | 1502 | 13 | 69 | 61 | 12 |
| Li | (ppm) | 4 | 3 | 6 | 7 | 12 | 3 |
| Nb | (ppm) | 2 | 2 | 2 | 2 | 2 | 1 |
| Ni | (ppm) | 21 | 64 | 19 | 17 | 18 | 19 |
| Sc | (ppm) | 1 | 1 | 1 | 1 | 1 | 1 |
| Sr | (ppm) | 449 | 389 | 459 | 412 | 419 | 425 |
| V | (ppm) | 18 | 21 | 21 | 14 | 17 | 13 |
| Y | (ppm) | 9 | 8 | 9 | 8 | 9 | 9 |
| Zn | (ppm) | 15 | 33 | 17 | 30 | 28 | 14 |
| Zr | (ppm) | 33 | 34 | 36 | 47 | 54 | 32 |
| La | (ppm) | 12 | 13 | 12 | 13 | 13 | 12 |
| Ce | (ppm) | 17 | 14 | 16 | 16 | 17 | 16 |
| Nd | (ppm) | 20 | 21 | 19 | 20 | 21 | 20 |
| Sm | (ppm) | 3.3 | 2.8 | 3.0 | 2.6 | 2.8 | 3.0 |
| Eu | (ppm) | 0.5 | 0.4 | 0.5 | 0.4 | 0.5 | 0.5 |
| Dy | (ppm) | 2.1 | 2.3 | 2.0 | 1.6 | 1.8 | 1.7 |
| Yb | (ppm) | 0.9 | 0.9 | 0.8 | 0.8 | 0.9 | 0.9 |
| $SiO_2$ | (%) | 71.5 | 72.6 | 72.5 | 69.9 | 69.6 | 71.2 |
| Colour | | LG | B | LB | LB | LB | LB |
| Type | | Waste | Vessel | Waste | Waste | Waste | Waste |

| Site | | NRT | NRT | MGT | MGT | TOL | MGT |
|---|---|---|---|---|---|---|---|
| Acc. No. | | 219 | 219 | 717 | 718 | 18 | 710 |
| Context | | 596 | 596 | 1080 | 1222 | - | 796 |
| $Al_2O_3$ | (%) | 2.33 | 2.27 | 2.56 | 2.48 | 2.35 | 1.92 |
| $Fe_2O_3$ | (%) | 0.49 | 0.47 | 0.32 | 0.44 | 0.49 | 0.28 |
| MgO | (%) | 0.54 | 0.54 | 0.58 | 0.56 | 0.55 | 0.40 |
| CaO | (%) | 6.60 | 6.33 | 7.57 | 6.91 | 6.43 | 5.78 |
| $Na_2O$ | (%) | 18.5 | 18.9 | 16.5 | 18.3 | 18.8 | 19.8 |
| $K_2O$ | (%) | 0.68 | 0.80 | 0.51 | 0.76 | 0.72 | 0.53 |
| $TiO_2$ | (%) | 0.09 | 0.10 | 0.07 | 0.09 | 0.10 | 0.05 |
| $P_2O_5$ | (%) | 0.12 | 0.11 | 0.12 | 0.16 | 0.12 | 0.05 |
| MnO | (%) | 0.29 | 0.21 | 0.17 | 0.50 | 0.24 | 0.01 |
| Pb | (%) | 0.02 | 0.02 | 0.01 | 0.05 | 0.02 | 0.13 |
| Sb | (%) | 0.30 | 0.35 | 0.00 | 0.15 | 0.32 | 0.39 |
| Ba | (ppm) | 208 | 193 | 221 | 230 | 205 | 135 |
| Co | (ppm) | 10 | 9 | 10 | 16 | 11 | 6 |
| Cr | (ppm) | 16 | 16 | 21 | 17 | 18 | 13 |
| Cu | (ppm) | 41 | 53 | 14 | 145 | 41 | 9 |
| Li | (ppm) | 9 | 13 | 4 | 6 | 10 | 2 |
| Nb | (ppm) | 2 | 2 | 1 | 2 | 1 | 1 |
| Ni | (ppm) | 17 | 20 | 16 | 20 | 17 | 11 |
| Sc | (ppm) | 1 | 1 | 1 | 1 | 1 | 1 |
| Sr | (ppm) | 405 | 382 | 405 | 415 | 392 | 413 |
| V | (ppm) | 15 | 14 | 13 | 16 | 14 | 6 |
| Y | (ppm) | 8 | 8 | 9 | 9 | 8 | 7 |
| Zn | (ppm) | 25 | 45 | 14 | 24 | 28 | 13 |
| Zr | (ppm) | 47 | 51 | 35 | 45 | 52 | 22 |
| La | (ppm) | 13 | 13 | 13 | 13 | 13 | 13 |
| Ce | (ppm) | 16 | 17 | 16 | 17 | 16 | 15 |
| Nd | (ppm) | 20 | 20 | 20 | 20 | 20 | 21 |
| Sm | (ppm) | 2.8 | 3.0 | 3.1 | 3.0 | 2.8 | 2.6 |
| Eu | (ppm) | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.4 |
| Dy | (ppm) | 1.7 | 1.7 | 1.7 | 2.0 | 1.8 | 1.3 |
| Yb | (ppm) | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 0.7 |
| $SiO_2$ | (%) | 70.0 | 69.8 | 71.5 | 69.5 | 69.8 | 70.6 |
| Colour | | LB | LB | LB/G | LB | LB | C |
| Type | | Waste | Waste | Waste | Bottle | Waste | Beaker |

| Site | | MGT | WAT | MGT | MGT | WAT | MGT |
|---|---|---|---|---|---|---|---|
| Acc. No. | | 292 | 4 | 712 | 716 | 20 | 292 |
| Context | | 300 | - | 796 | 1222 | - | 300 |
| $Al_2O_3$ | (%) | 2.30 | 5.74 | 2.76 | 2.48 | 2.39 | 2.40 |
| $Fe_2O_3$ | (%) | 0.44 | 0.30 | 0.30 | 0.26 | 0.32 | 0.47 |
| MgO | (%) | 0.55 | 0.36 | 0.52 | 0.45 | 0.47 | 0.56 |
| CaO | (%) | 6.73 | 3.53 | 7.69 | 7.62 | 7.23 | 6.96 |
| $Na_2O$ | (%) | 18.9 | 19.8 | 17.4 | 17.6 | 18.6 | 19.7 |
| $K_2O$ | (%) | 0.69 | 1.56 | 0.60 | 0.56 | 0.66 | 0.76 |
| $TiO_2$ | (%) | 0.09 | 0.10 | 0.07 | 0.06 | 0.08 | 0.10 |
| $P_2O_5$ | (%) | 0.11 | 0.18 | 0.12 | 0.14 | 0.13 | 0.11 |
| MnO | (%) | 0.27 | 0.03 | 0.08 | 0.30 | 0.48 | 0.27 |
| Pb | (%) | 0.10 | 0.01 | 0.01 | 0.01 | 0.01 | 0.19 |
| Sb | (%) | 0.32 | 0.00 | 0.00 | 0.00 | 0.04 | 0.30 |
| Ba | (ppm) | 205 | 320 | 217 | 230 | 225 | 211 |
| Co | (ppm) | 10 | 6 | 9 | 11 | 13 | 10 |
| Cr | (ppm) | 16 | 46 | 17 | 14 | 15 | 17 |
| Cu | (ppm) | 53 | 10 | 9 | 11 | 80 | 56 |
| Li | (ppm) | 9 | 5 | 4 | 3 | 7 | 13 |
| Nb | (ppm) | 2 | 3 | 2 | 1 | 2 | 2 |
| Ni | (ppm) | 17 | 15 | 20 | 17 | 18 | 19 |
| Sc | (ppm) | 1 | 1 | 1 | 1 | 1 | 1 |
| Sr | (ppm) | 417 | 181 | 410 | 398 | 414 | 417 |
| V | (ppm) | 14 | 8 | 10 | 11 | 14 | 15 |
| Y | (ppm) | 8 | 9 | 9 | 9 | 9 | 9 |
| Zn | (ppm) | 27 | 15 | 13 | 14 | 18 | 28 |
| Zr | (ppm) | 48 | 66 | 33 | 31 | 38 | 52 |
| La | (ppm) | 13 | 13 | 12 | 13 | 13 | 13 |
| Ce | (ppm) | 17 | 16 | 16 | 16 | 17 | 17 |
| Nd | (ppm) | 20 | 23 | 20 | 19 | 20 | 20 |
| Sm | (ppm) | 3.0 | 2.6 | 3.2 | 3.0 | 3.1 | 3.0 |
| Eu | (ppm) | 0.5 | 0.4 | 0.5 | 0.5 | 0.5 | 0.5 |
| Dy | (ppm) | 1.6 | 1.7 | 1.7 | 1.7 | 2.0 | 1.7 |
| Yb | (ppm) | 0.9 | 1.0 | 0.9 | 0.9 | 0.9 | 0.9 |
| $SiO_2$ | (%) | 69.4 | 68.3 | 70.4 | 70.4 | 69.5 | 68.1 |
| Colour | | LB/G | Br/Y | LG | LB | LB | LB |
| Type | | Waste | Vessel | Bowl | Vessel | Waste | Waste |

| Site | | MGT | OPT | MGT | MGT | MGT | MGT |
|---|---|---|---|---|---|---|---|
| Acc. No. | | 415 | 1478 | 437 | 444 | 445 | 448 |
| Context | | 298 | 306 | 949 | 847 | 819 | 495 |
| $Al_2O_3$ | (%) | 2.34 | 2.51 | 3.85 | 4.59 | 3.62 | 3.21 |
| $Fe_2O_3$ | (%) | 0.45 | 0.38 | 1.06 | 1.22 | 1.47 | 0.92 |
| MgO | (%) | 0.56 | 0.53 | 0.71 | 0.77 | 1.02 | 0.60 |
| CaO | (%) | 6.97 | 7.06 | 5.95 | 5.90 | 7.45 | 6.58 |
| $Na_2O$ | (%) | 20.2 | 18.7 | 16.2 | 17.4 | 17.7 | 17.9 |
| $K_2O$ | (%) | 0.78 | 0.75 | 1.27 | 0.93 | 1.44 | 0.95 |
| $TiO_2$ | (%) | 0.09 | 0.08 | 0.19 | 0.23 | 0.18 | 0.16 |
| $P_2O_5$ | (%) | 0.12 | 0.15 | 0.13 | 0.14 | 0.28 | 0.13 |
| MnO | (%) | 0.27 | 0.53 | 0.19 | 0.22 | 0.28 | 0.32 |
| Pb | (%) | 0.11 | 0.04 | 0.03 | 0.11 | 0.08 | 0.02 |
| Sb | (%) | 0.30 | 0.09 | 0.35 | 0.25 | 0.19 | 0.18 |
| Ba | (ppm) | 209 | 232 | 218 | 218 | 247 | 221 |
| Co | (ppm) | 10 | 14 | 9 | 11 | 14 | 12 |
| Cr | (ppm) | 16 | 16 | 27 | 33 | 29 | 23 |
| Cu | (ppm) | 57 | 95 | 64 | 67 | 80 | 55 |
| Li | (ppm) | 13 | 5 | 75 | 15 | 51 | 18 |
| Nb | (ppm) | 3 | 2 | 4 | 5 | 2 | 4 |
| Ni | (ppm) | 16 | 20 | 23 | 22 | 29 | 23 |
| Sc | (ppm) | 1 | 1 | 3 | 4 | 3 | 2 |
| Sr | (ppm) | 418 | 418 | 367 | 350 | 392 | 380 |
| V | (ppm) | 15 | 16 | 30 | 39 | 31 | 23 |
| Y | (ppm) | 9 | 9 | 11 | 13 | 12 | 12 |
| Zn | (ppm) | 30 | 22 | 34 | 38 | 127 | 31 |
| Zr | (ppm) | 50 | 39 | 63 | 76 | 67 | 86 |
| La | (ppm) | 13 | 13 | 18 | 19 | 17 | 15 |
| Ce | (ppm) | 17 | 16 | 25 | 27 | 25 | 23 |
| Nd | (ppm) | 20 | 19 | 23 | 23 | 21 | 22 |
| Sm | (ppm) | 3.1 | 2.8 | 3.9 | 4.3 | 4.2 | 3.8 |
| Eu | (ppm) | 0.5 | 0.5 | 0.6 | 0.7 | 0.6 | 0.6 |
| Dy | (ppm) | 1.8 | 1.9 | 2.1 | 2.4 | 2.4 | 2.2 |
| Yb | (ppm) | 0.9 | 0.9 | 1.0 | 1.3 | 1.1 | 1.2 |
| $SiO_2$ | (%) | 67.7 | 69.1 | 70.0 | 68.1 | 66.2 | 68.9 |
| Colour | | LB | LB/G | LB | LB | LB | LB |
| Type | | Waste | Waste | Furnace bottom | Furnace top | Furnace top | Furnace top |

| Site | | MGT | MGT | MGT | MGT | OPT | MGT |
|---|---|---|---|---|---|---|---|
| Acc. No. | | 446 | 437 | 447 | 445 | 1440 | 448 |
| Context | | + | 949 | 819 | 819 | 94 | 495 |
| $Al_2O_3$ | (%) | 5.03 | 6.66 | 3.34 | 3.57 | 3.54 | 2.96 |
| $Fe_2O_3$ | (%) | 1.67 | 2.07 | 0.88 | 0.86 | 1.09 | 0.84 |
| MgO | (%) | 1.03 | 1.05 | 0.71 | 0.67 | 0.71 | 0.61 |
| CaO | (%) | 6.92 | 4.91 | 6.59 | 6.45 | 6.76 | 6.81 |
| $Na_2O$ | (%) | 15.4 | 14.6 | 18.8 | 17.0 | 15.7 | 17.6 |
| $K_2O$ | (%) | 1.62 | 1.00 | 1.08 | 0.91 | 1.44 | 1.16 |
| $TiO_2$ | (%) | 0.25 | 0.35 | 0.16 | 0.16 | 0.20 | 0.14 |
| $P_2O_5$ | (%) | 0.24 | 0.16 | 0.13 | 0.15 | 0.16 | 0.14 |
| MnO | (%) | 0.25 | 0.16 | 0.22 | 0.25 | 0.25 | 0.32 |
| Pb | (%) | 0.13 | 0.17 | 0.06 | 0.32 | 0.03 | 0.02 |
| Sb | (%) | 0.16 | 0.24 | 0.35 | 0.25 | 0.26 | 0.18 |
| Ba | (ppm) | 271 | 223 | 215 | 220 | 251 | 240 |
| Co | (ppm) | 13 | 15 | 10 | 9 | 11 | 10 |
| Cr | (ppm) | 38 | 50 | 23 | 23 | 29 | 22 |
| Cu | (ppm) | 57 | 60 | 84 | 53 | 49 | 60 |
| Li | (ppm) | 36 | 15 | 24 | 15 | 43 | 31 |
| Nb | (ppm) | 3 | 6 | 4 | 3 | 4 | 4 |
| Ni | (ppm) | 33 | 31 | 20 | 18 | 24 | 24 |
| Sc | (ppm) | 5 | 6 | 3 | 3 | 3 | 2 |
| Sr | (ppm) | 378 | 301 | 399 | 384 | 358 | 398 |
| V | (ppm) | 43 | 60 | 27 | 25 | 27 | 21 |
| Y | (ppm) | 14 | 16 | 11 | 10 | 13 | 11 |
| Zn | (ppm) | 74 | 50 | 37 | 33 | 48 | 31 |
| Zr | (ppm) | 90 | 86 | 70 | 57 | 108 | 75 |
| La | (ppm) | 19 | 25 | 16 | 15 | 17 | 15 |
| Ce | (ppm) | 30 | 38 | 21 | 20 | 25 | 21 |
| Nd | (ppm) | 23 | 38 | 22 | 21 | 22 | 21 |
| Sm | (ppm) | 4.2 | 5.4 | 3.6 | 3.4 | 3.8 | 3.7 |
| Eu | (ppm) | 0.7 | 0.9 | 0.6 | 0.5 | 0.6 | 0.6 |
| Dy | (ppm) | 2.5 | 3.1 | 2.2 | 2.0 | 2.4 | 2.2 |
| Yb | (ppm) | 1.4 | 1.5 | 1.1 | 1.0 | 1.3 | 1.1 |
| $SiO_2$ | (%) | 67.2 | 68.5 | 67.6 | 69.3 | 69.8 | 69.1 |
| Colour | | LB/G | LG | LB | LG | LB | LB |
| Type | | Furnace top | Furnace top | Furnace top | Furnace bottom | Tile frag | Furnace top |

| Site | | WAT | MGT | MGT | MGT | MGT |
|---|---|---|---|---|---|---|
| Acc. No. | | 13 | 307 | 366 | 715 | 366 |
| Context | | - | 343 | 515 | 1192 | 515 |
| $Al_2O_3$ | (%) | 2.60 | 2.62 | 2.46 | 2.69 | 2.33 |
| $Fe_2O_3$ | (%) | 0.27 | 0.71 | 0.51 | 0.38 | 0.44 |
| MgO | (%) | 0.45 | 0.63 | 0.58 | 0.60 | 0.55 |
| CaO | (%) | 7.33 | 6.58 | 6.82 | 7.76 | 6.65 |
| $Na_2O$ | (%) | 16.4 | 16.8 | 17.7 | 15.1 | 17.2 |
| $K_2O$ | (%) | 0.65 | 1.24 | 0.85 | 0.71 | 0.70 |
| $TiO_2$ | (%) | 0.07 | 0.12 | 0.10 | 0.08 | 0.09 |
| $P_2O_5$ | (%) | 0.14 | 0.12 | 0.12 | 0.17 | 0.12 |
| MnO | (%) | 0.17 | 0.23 | 0.27 | 0.65 | 0.27 |
| Pb | (%) | 0.01 | 0.04 | 0.06 | 0.01 | 0.10 |
| Sb | (%) | 0.00 | 0.34 | 0.31 | 0.02 | 0.32 |
| Ba | (ppm) | 213 | 207 | 211 | 265 | 205 |
| Co | (ppm) | 10 | 10 | 11 | 16 | 10 |
| Cr | (ppm) | 13 | 20 | 18 | 18 | 18 |
| Cu | (ppm) | 9 | 58 | 57 | 39 | 55 |
| Li | (ppm) | 4 | 62 | 18 | 3 | 11 |
| Nb | (ppm) | 2 | 3 | 2 | 1 | 2 |
| Ni | (ppm) | 18 | 20 | 18 | 22 | 19 |
| Sc | (ppm) | 1 | 2 | 2 | 1 | 1 |
| Sr | (ppm) | 396 | 394 | 415 | 471 | 416 |
| V | (ppm) | 10 | 19 | 16 | 19 | 14 |
| Y | (ppm) | 9 | 10 | 9 | 9 | 8 |
| Zn | (ppm) | 15 | 38 | 30 | 20 | 28 |
| Zr | (ppm) | 34 | 66 | 54 | 37 | 48 |
| La | (ppm) | 13 | 14 | 14 | 12 | 13 |
| Ce | (ppm) | 16 | 20 | 18 | 15 | 17 |
| Nd | (ppm) | 19 | 22 | 20 | 18 | 21 |
| Sm | (ppm) | 3.0 | 3.7 | 3.0 | 2.5 | 3.0 |
| Eu | (ppm) | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 |
| Dy | (ppm) | 1.7 | 1.9 | 1.8 | 2.0 | 1.7 |
| Yb | (ppm) | 0.9 | 1.0 | 1.0 | 0.8 | 0.9 |
| $SiO_2$ | (%) | 71.8 | 70.5 | 70.1 | 71.7 | 71.1 |
| Colour | | LG | LB | LB | LB | LB |
| Type | | Vessel | Waste | Waste | Vessel | Waste |

**Table 2**

**Compositional evidence for chemical exchange of elements between the glass and the clay in glass-melting crucibles**

a) Data from Egyptian crucible (from Saleh et al 1972)

| | Crucible rim Layer A | Crucible rim Layer B | Crucible rim Layer C |
|---|---|---|---|
| $SiO_2$ | 57.8 % | 57.3 % | 62.1 % |
| $Na_2O$ | 6.2 % | 5.9 % | 11.0 % |
| CaO | 6.9 % | 6.8 % | 7.4 % |
| $Al_2O_3$ | 14.7 % | 15.3 % | 9.5 % |
| $Fe_2O_3$ | 6.7 % | 6.9 % | 4.4 % |
| $TiO_2$ | 1.4 % | 1.4 % | 0.8 % |

Layer C, the layer in contact with the glass, shows reduced levels of aluminium, iron and titanium oxides suggesting they have migrated from the clay into the glass, and increased levels of silica, sodium and calcium oxides suggesting they have migrated from the glass into the clay.

b) Data from Roman tank furnace found at Moorgate, London

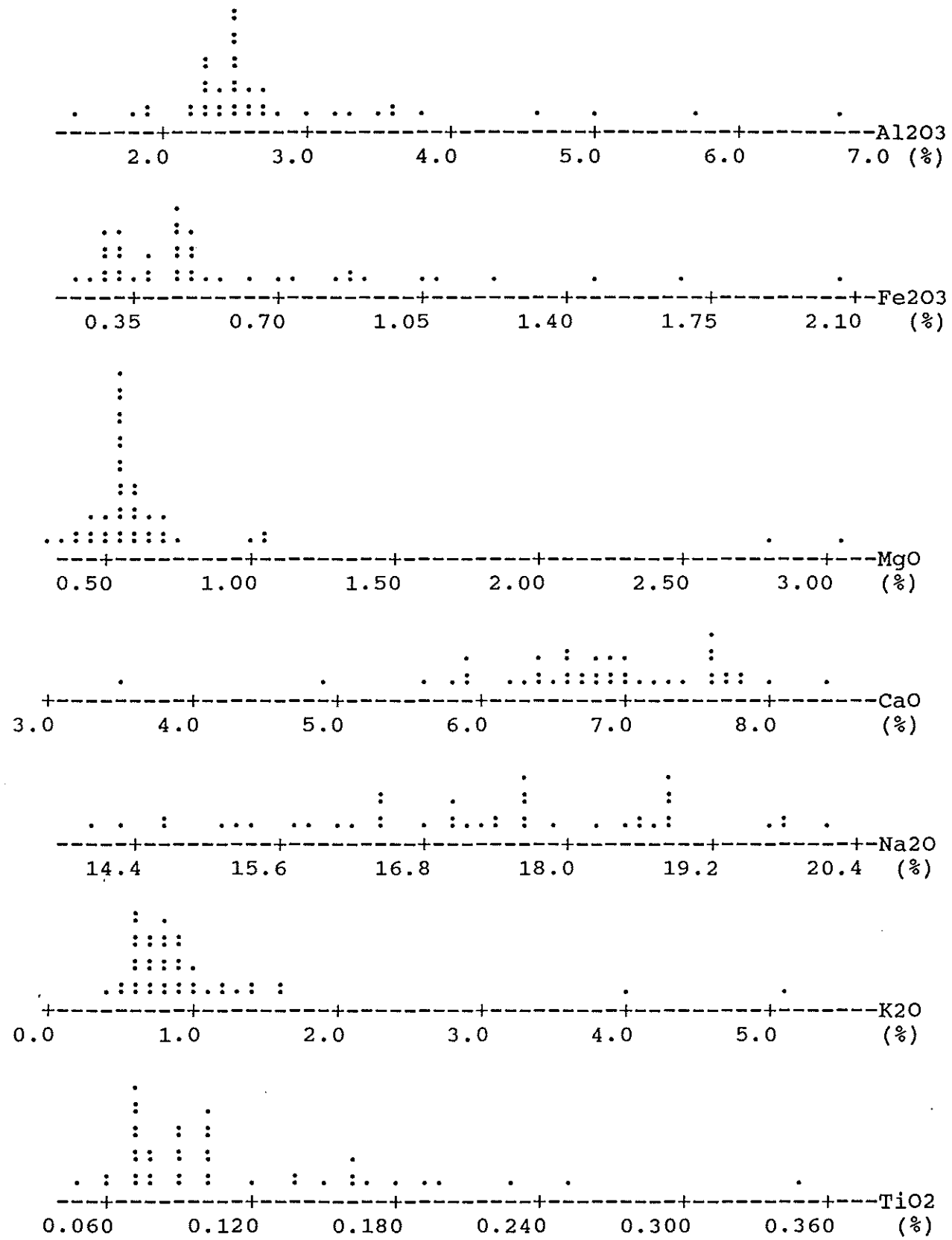
| | Glass fragment adhering to furnace wall | Glass fragment likely to come from the furnace |
|---|---|---|
| $SiO_2$ | 68.5 % | 71.1 % |
| $Na_2O$ | 14.6 % | 17.2 % |
| CaO | 4.9 % | 6.7 % |
| $Al_2O_3$ | 6.7 % | 2.3 % |
| $Fe_2O_3$ | 2.1 % | 0.4 % |
| $TiO_2$ | 0.4 % | 0.1 % |

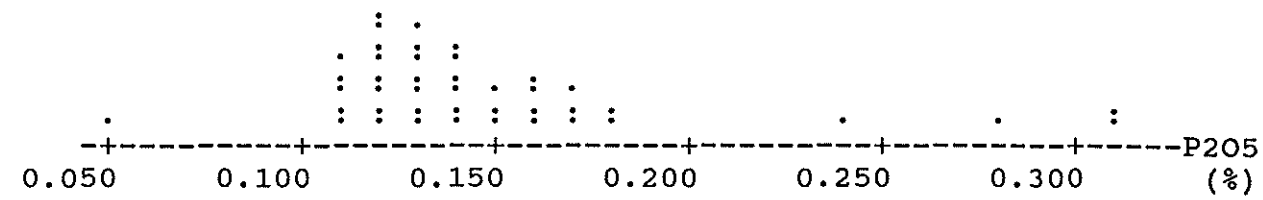
The glass adhering to the furnace wall shows increased levels of aluminium, iron and titanium oxide suggesting these have migrated from the clay into the glass, and reduced levels of silica, sodium and calcium oxide suggesting these have migrated into the clay from the glass.

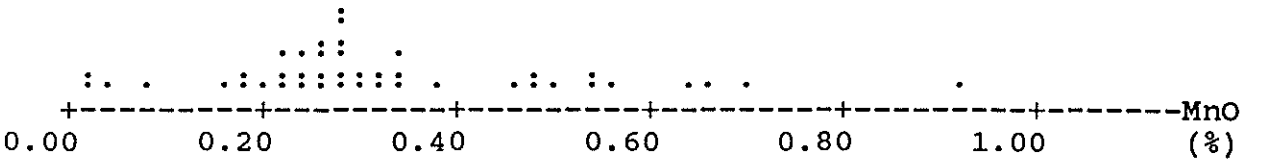
NB. However it is possible in the case of some oxides, particularly silica, that the apparent differences are due to the nature of percentage data where a real fall in one component leads to an apparent rise in others.

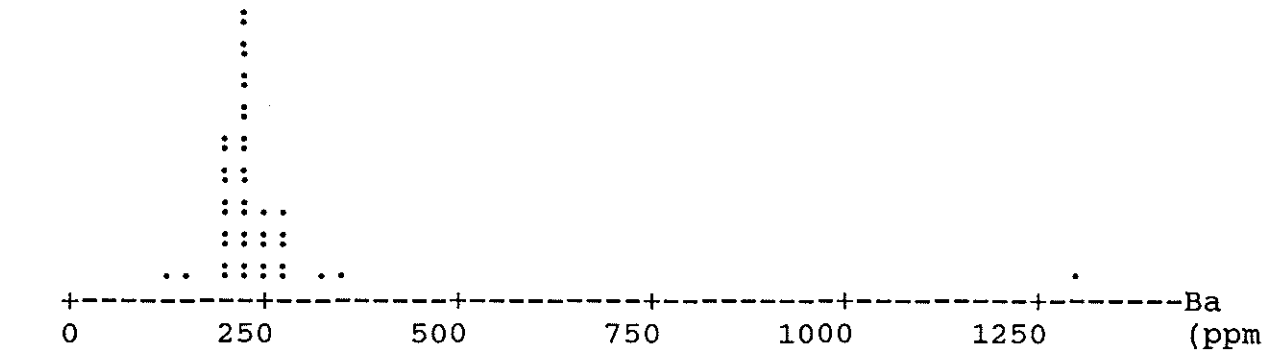
**Table 3**

**Single element dotplots for all the London glass data**

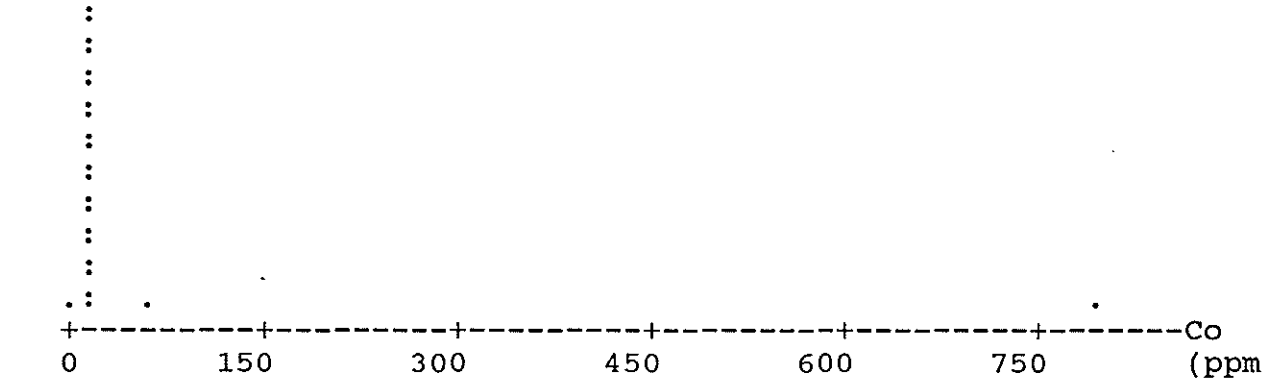


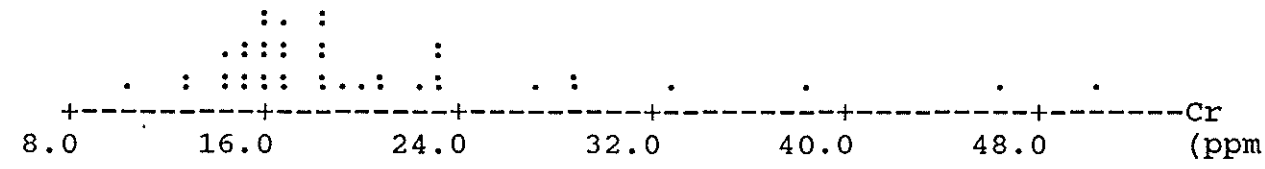


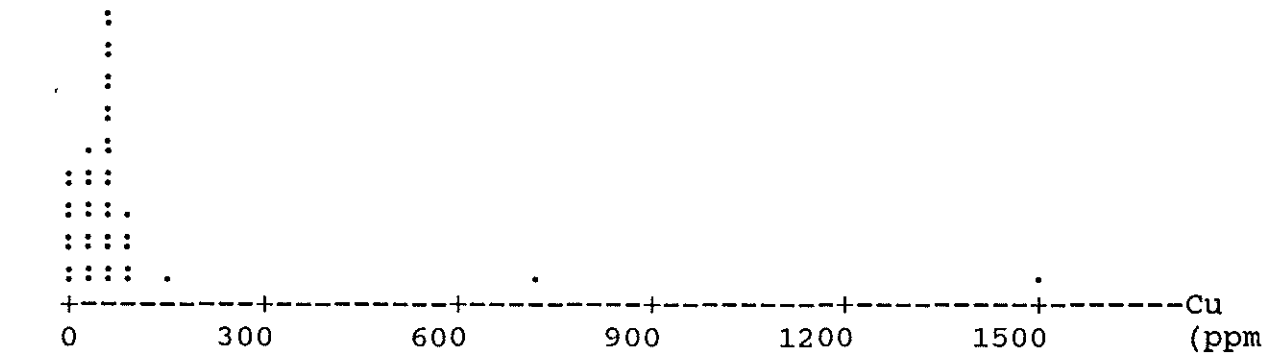



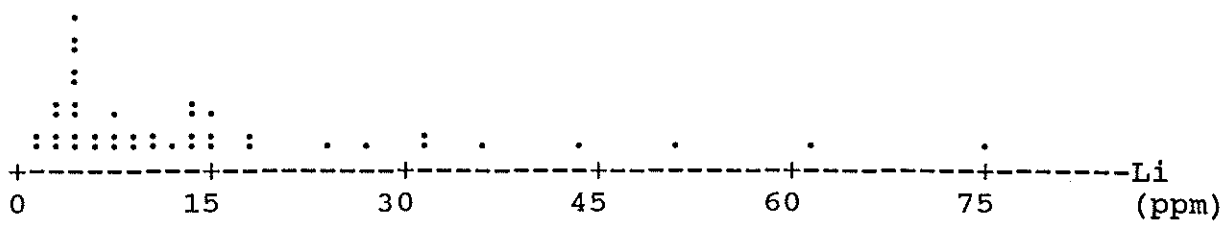



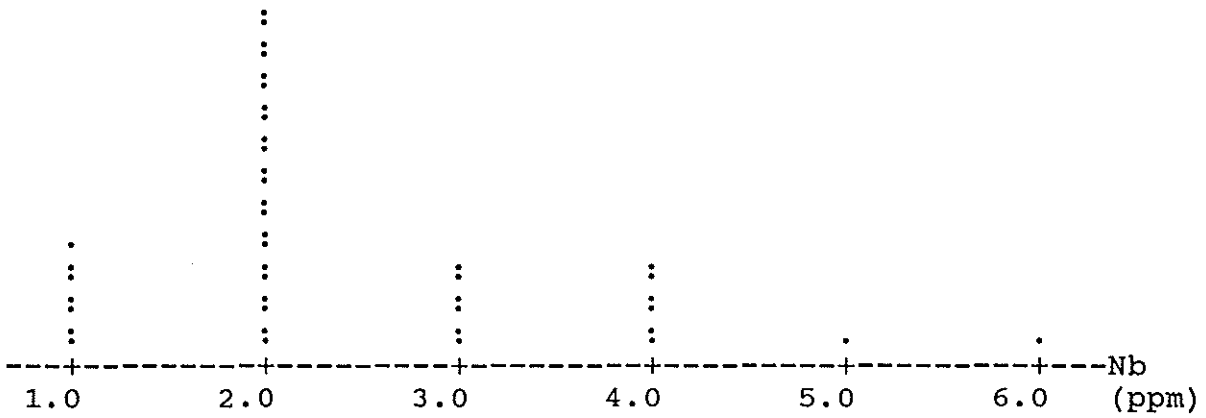

Each dot represents 2 points

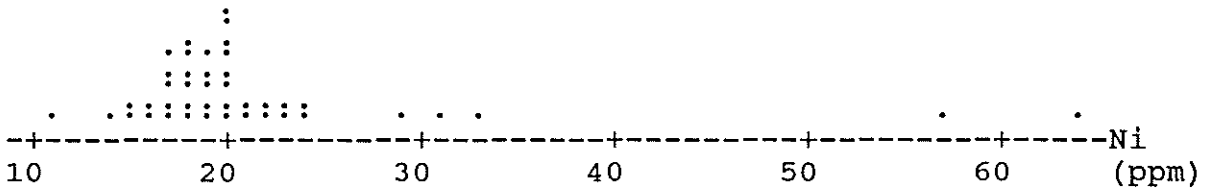


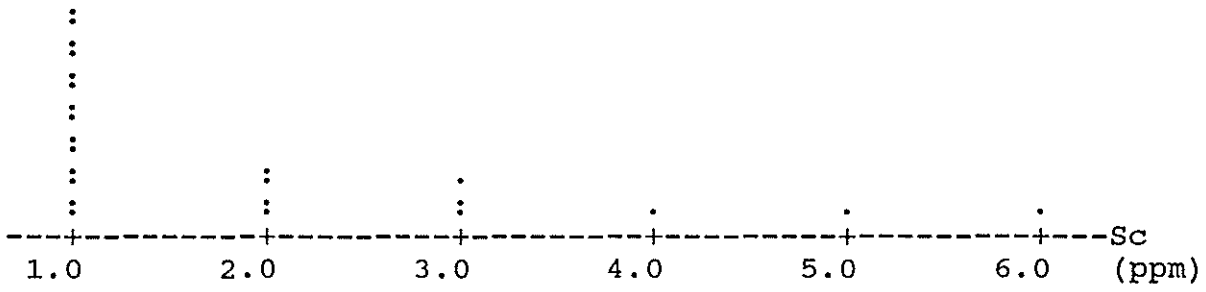



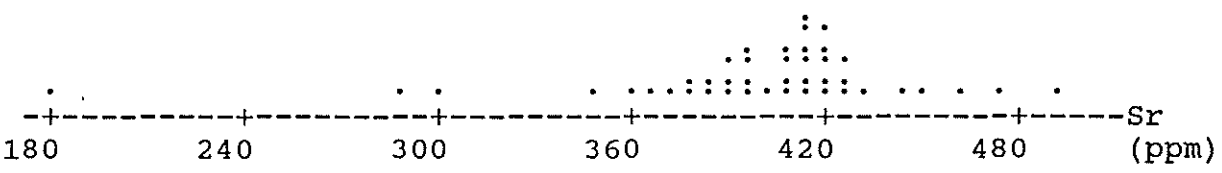


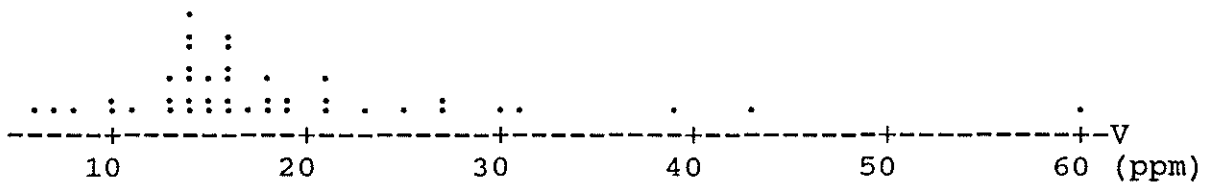



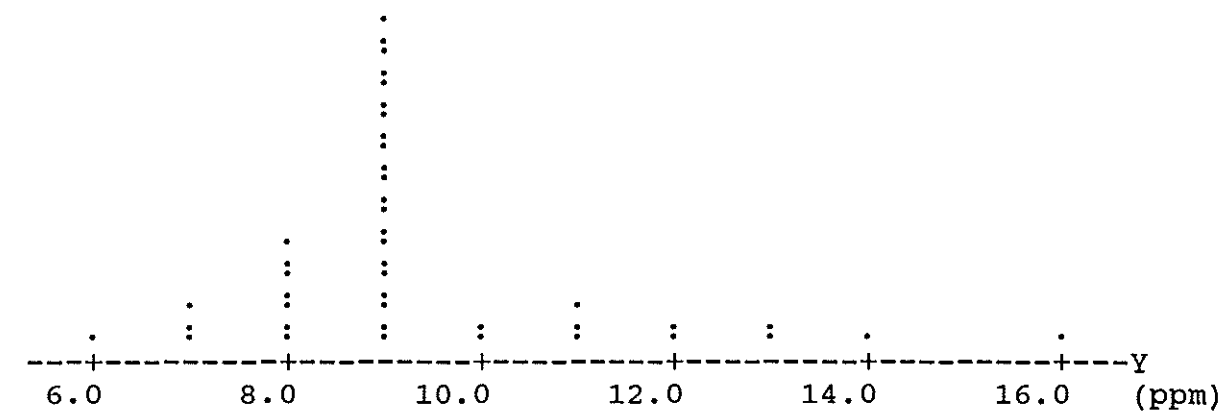



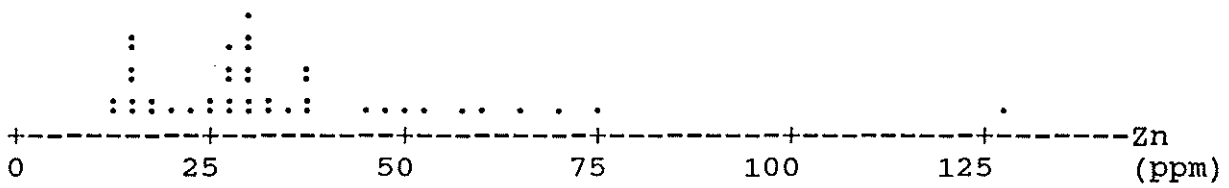

Each dot represents 2 points

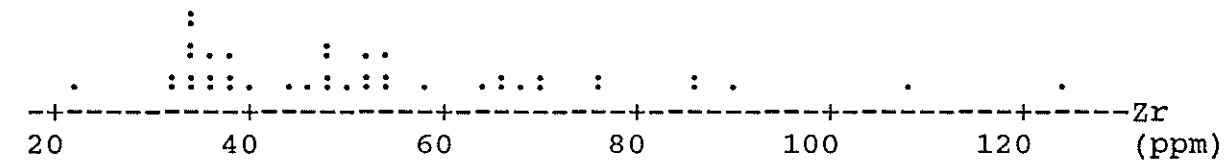


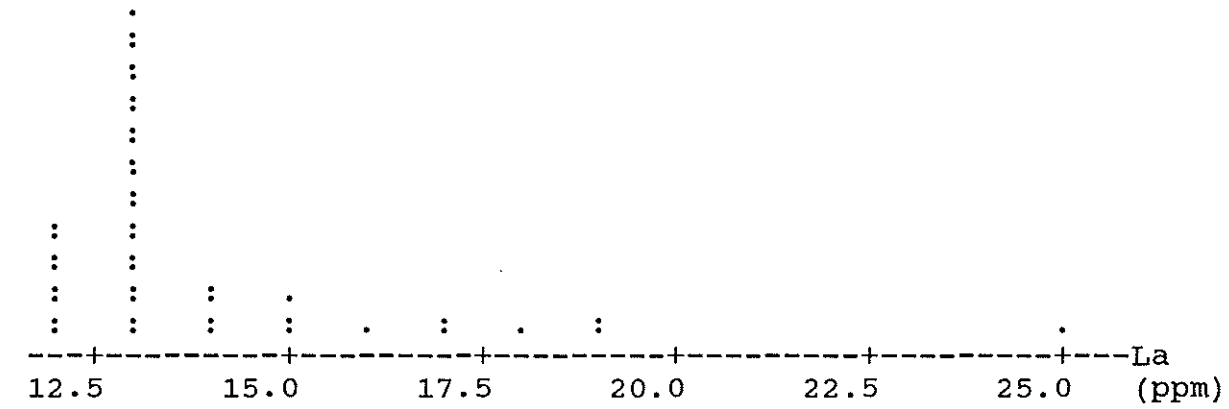



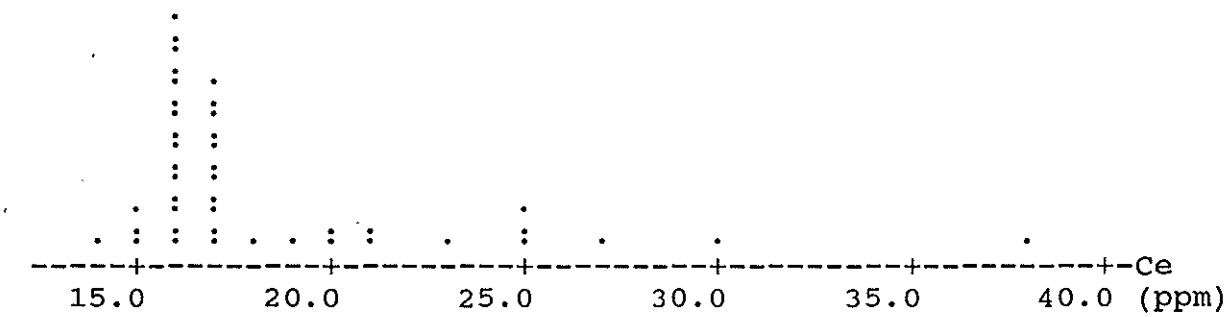



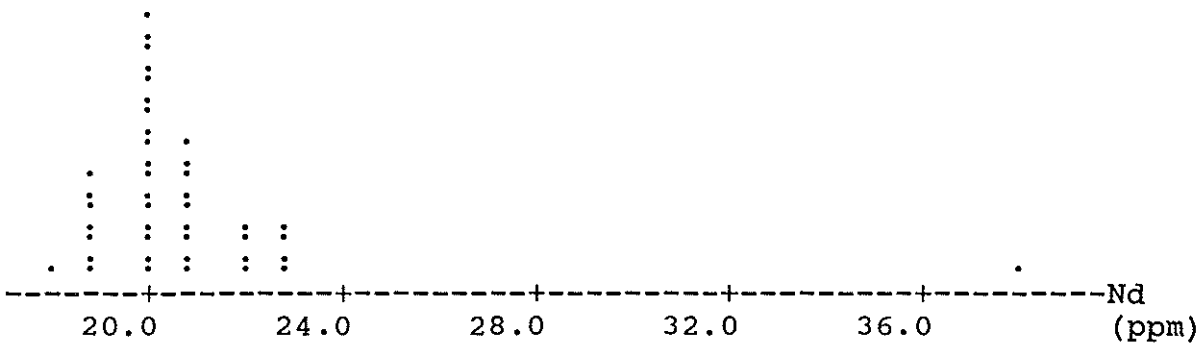

Y
6.0
8.0
10.0
12.0
14.0
16.0
(ppm)

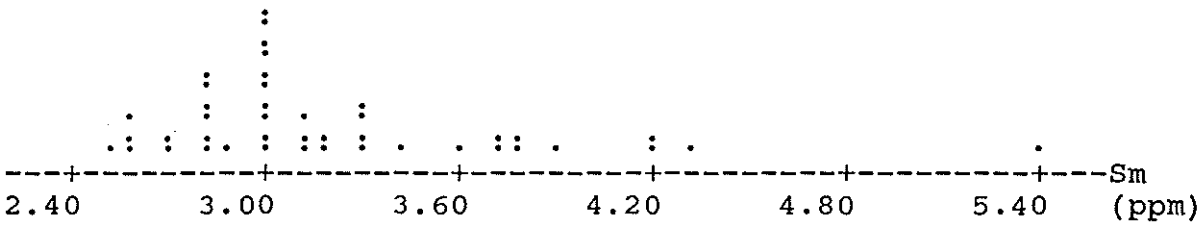

Zn
0
25
50
75
100
125
(ppm)

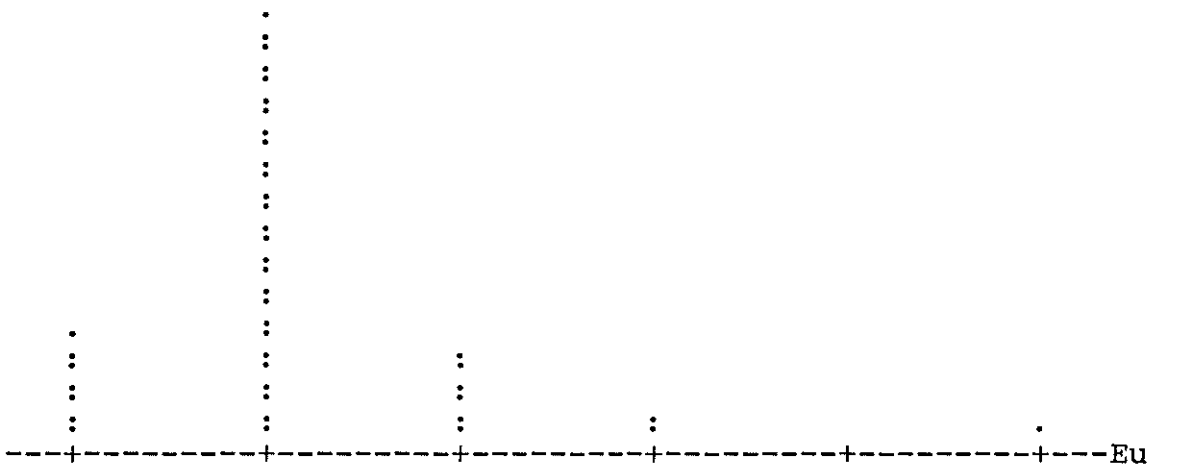

Zr
20
40
60
80
100
120
(ppm)

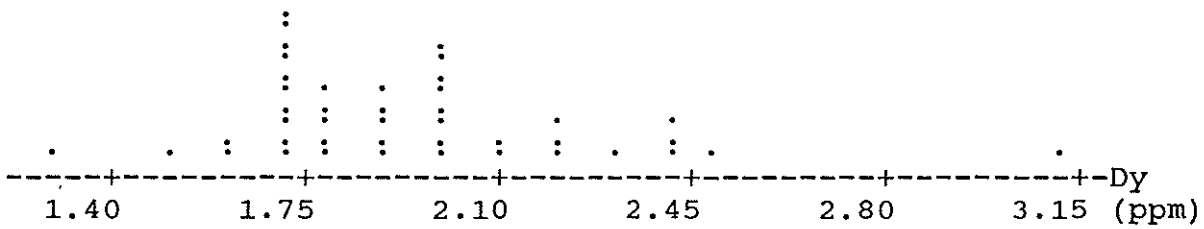

La
12.5
15.0
17.5
20.0
22.5
25.0
(ppm)

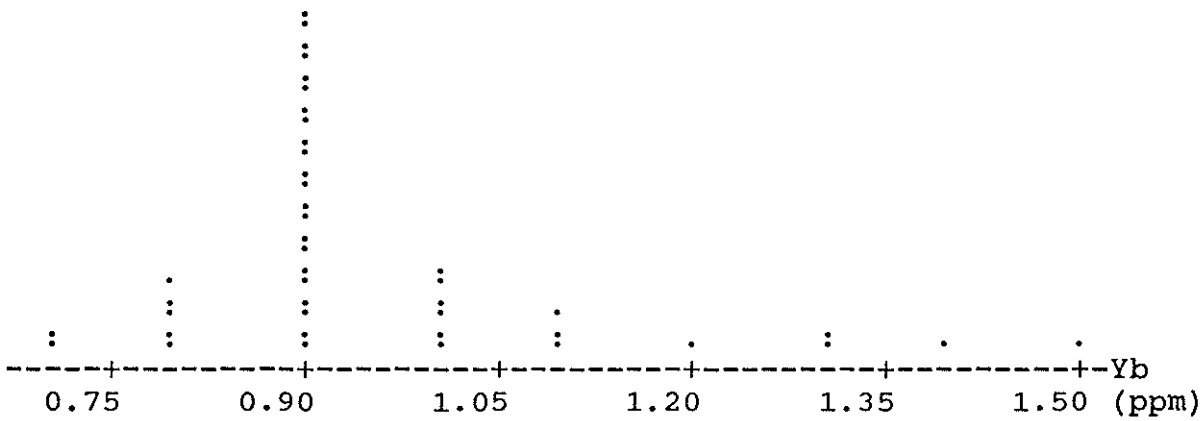

Ce
15.0
20.0
25.0
30.0
35.0
40.0
(ppm)


Nd
20.0
24.0
28.0
32.0
36.0
(ppm)


Sm
2.40
3.00
3.60
4.20
4.80
5.40
(ppm)


Eu
0.40
0.50
0.60
0.70
0.80
0.90
(ppm)


Dy
1.40
1.75
2.10
2.45
2.80
3.15
(ppm)


Yb
0.75
0.90
1.05
1.20
1.35
1.50
(ppm)

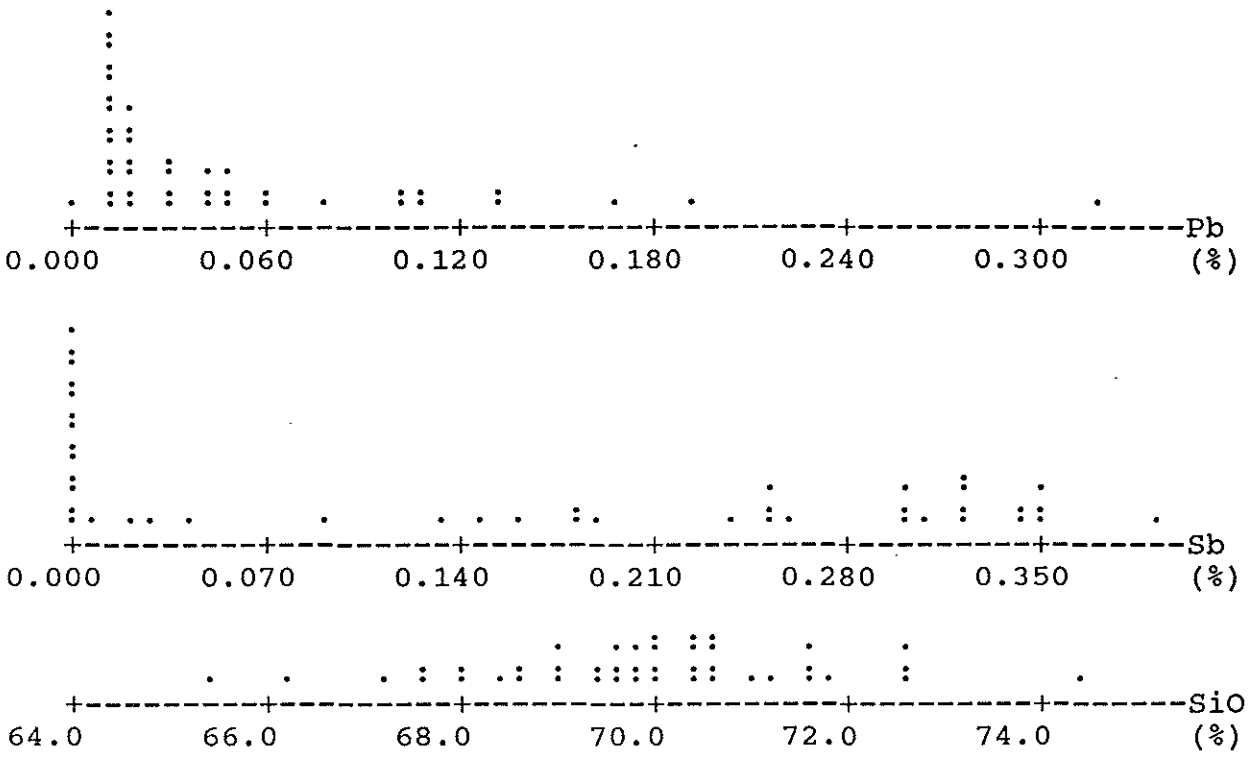

Pb
0.000
0.060
0.120
0.180
0.240
0.300
(%)
Sb
0.000
0.070
0.140
0.210
0.280
0.350
(%)
SiO2
64.0
66.0
68.0
70.0
72.0
74.0
(%)

Figure 1

Bar chart showing iron oxide levels in all samples ranked in ascending order

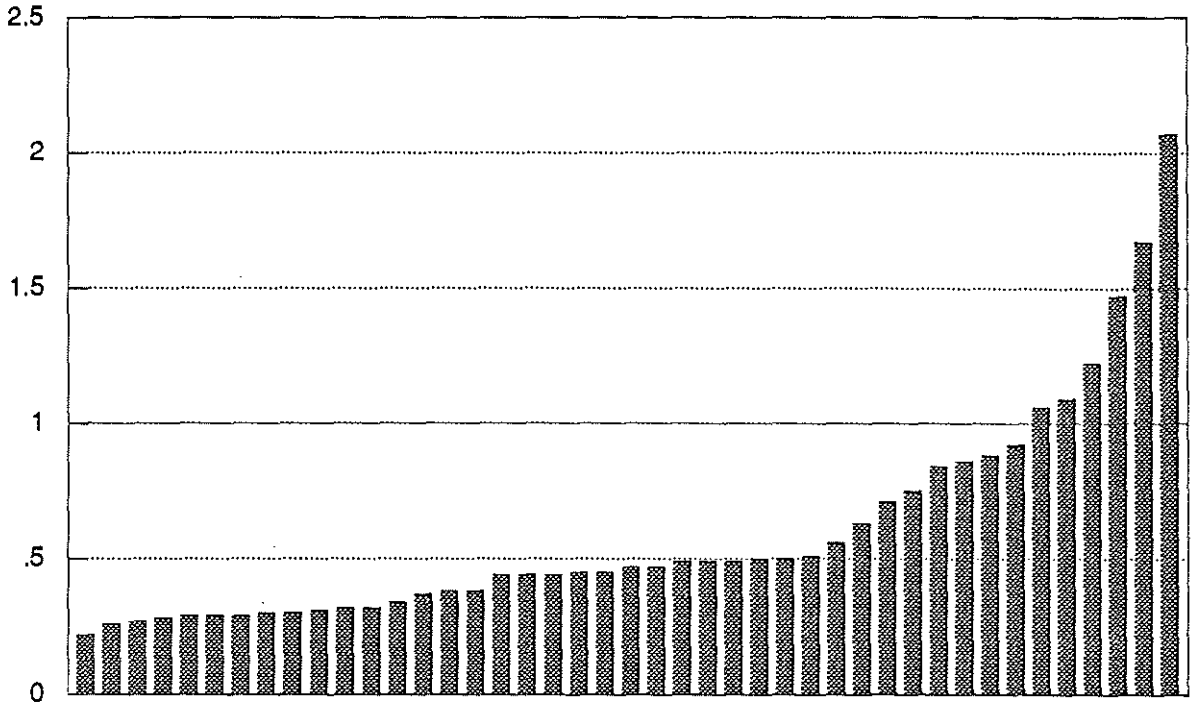



Figure 3

Area chart showing manganese oxide (MnO) and antimony (Sb) levels in all samples analysed, shown in order of increasing iron oxide level (samples are plotted in the same order as in Figure 1)

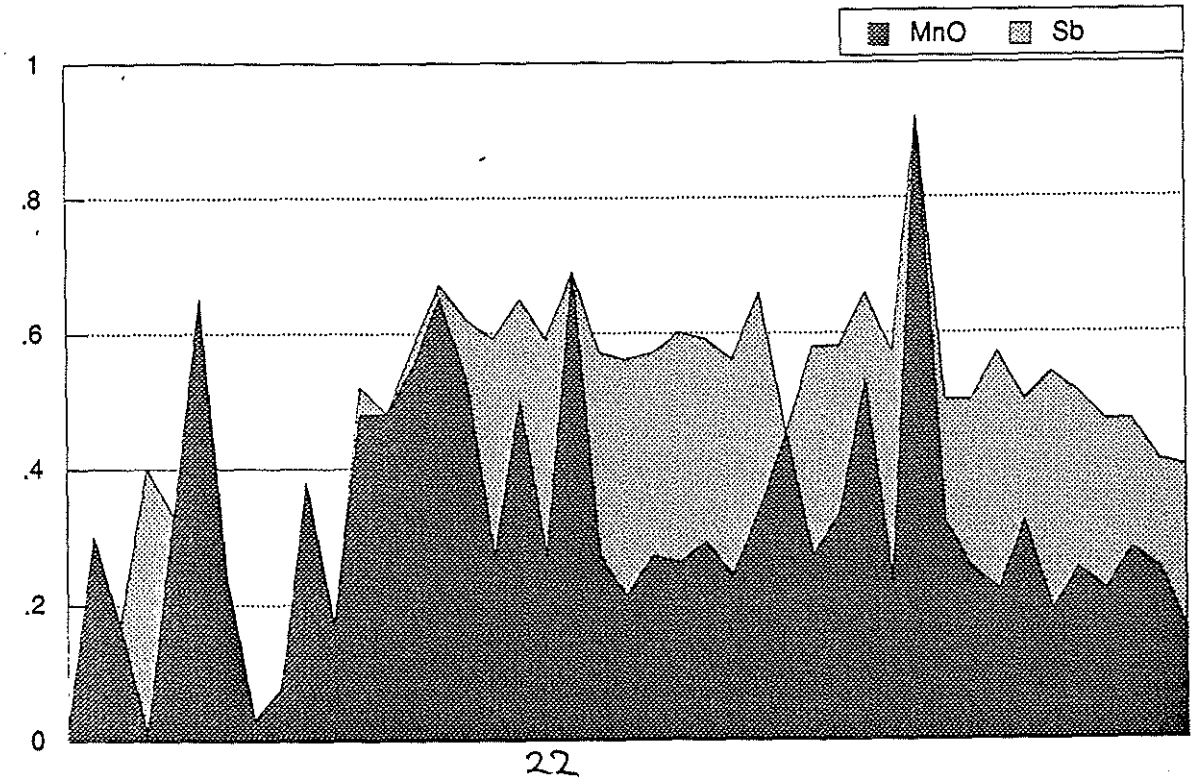


Figure 2

Photograph showing cross section through a fragment of tank furnace and the glass adhering to the inner surface (from the top of the clay to the bottom of the glass is approximately 1 cm)