

Composition, Technology and Origin of Glass from the Workshop at Basinghall Street

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Introduction

Pliny wrote in around 70AD that glass in his time was made by mixing sand and *natron* from Egypt (*Natural History* xxxx). His description is thought to have been essentially correct (Freestone 2008). About fifty kilometres northwest of Cairo, the soda lakes of the Wadi Natrun begin to evaporate in the Spring, precipitating a range of sodium carbonates, sulphates and chlorides. By late summer, the lakes are covered by a thick hard crust of sodium compounds. These and similar deposits elsewhere in the Nile Delta are believed to have fed the Roman glass industry and have been the subject of a number of studies (Shortland 2004, Shortland et al 2006; Fig. 1).

Archaeological survey and excavation in the Wadi Natrun has revealed the presence of a number of large glass making furnaces dating to the Greco-Roman period, each of which would have melted many tons of glass in a single firing and (Nenna et al. 1997, 2000, 2005).



Figure 1 Salts forming around the edge of a soda lake in the Nile Delta.

Chemical analysis of natron indicates that it consists almost entirely of sodium compounds and contains negligible quantities of other minerals (Brill 1999). The relative purity of the material is reflected in the composition of the glass that was made with it, which is remarkably consistent from the middle of the first millennium BC for the following fifteen hundred years. It is widely accepted that the vast majority of glass from the Roman period through to the ninth century was manufactured with natron. This remarkable consistency in a key raw material has meant that it is only in the last decade or so, with the increasing availability of sensitive and accurate analytical equipment, that we have begun to unravel the details of the manufacture and trade of glass of this type, and there are still many questions to be answered (Freestone 2006).

The importance of natron to the glassmaker was that it allowed him to melt his sand. Without it, temperatures in excess of 1700°C, well beyond the range of ancient furnaces, would have been required to convert the powdery charge into a liquid that could be manipulated. However, a mixture of natron and sand could be melted at temperatures of around 1100°C or less, not a great deal higher than those achieved in the pottery kilns which produced numerous everyday wares for the Roman table.

The source of the sand used in Roman glassmaking is more of an open question. It is tied closely to whichever model is preferred for the manufacture of glass. Was glass made in glass-blowing workshops across the Empire using local sand with imported natron? Or was it made in just a few locations, then broken up and distributed to glass workshops in the form of raw glass lumps or chunks? There is considerable evidence to support the latter model in the form of cargoes of chunks of raw glass in shipwrecks such as that Embiez wreck, off the coast of France (Foy and Jezegou 2004)), and the occurrence of large furnaces in the eastern Mediterranean, which appear to have been used only to make raw glass, not to shape it into vessels (Gorin-Rosen 2000, Nenna et al 2000). It has been argued that most of the glass in Europe of the first millennium AD originates from Egypt and the coast of Palestine (Nenna et al 1997, Freestone et al 2002a,b, 2008, Picon and Vichy 2003). However, some authors prefer to interpret their findings in terms of local or regional manufacture of glass (eg.

Wedepohl and Baumann 2000, Baxter et al 2005, Sylvestri et al 2006, Huisman et al 2009). In Britain, in particular, detailed analysis of melting pots from York has been interpreted to indicate local manufacture of glass (Jackson et al 2003). Furthermore, neodymium isotope analysis of glass from continental Europe by Degryse and Schneider (2008) suggests more than one source for Roman glass. Finally Pliny indicates that, although in earlier times the glass industry had depended on sand from the Palestinian coast, by the late first century AD, glass was being made from sand in Gaul and Spain. The origin of glass in the Roman period is therefore still a matter for debate.

Questions to be answered about the Basinghall workshop therefore include those about the origins of the glass used and how it was obtained. Is it standard Roman glass? To what extent is the glass material itself a local product? How dependent was the workshop upon cullet, the broken fragments of old vessels and windows, which had been deliberately collected for recycling? To what extent were the craftsmen able to obtain special glasses for particular purposes? It would also be helpful to understand how much glass working took place at Basinghall. Do the furnace remains represent a single aborted campaign (season) or an extensive period of glass working lasting years or decades? Finally, the relationship between the large masses of glass from the furnace and the products themselves needs to be established.

Methods of Analysis

Progress can be made in all of the areas listed through the scientific analysis of the glass itself. In the preparation of this report we have undertaken four types of analysis. Determination of the most abundant components of the glass, the *major elements*, which are present in concentrations of above 0.1%, was carried out using energy dispersive X-ray analysis in the scanning electron microscope (SEM-EDXA). We have analysed 132 samples of glass from Basinghall using this technique. Major element analysis by EDXA is fast, relatively inexpensive and allows the analysis of millimetre-sized fragments of glass. It allows the distinction of various compositional groups and gives a first indication of the relationships between them.

The disadvantage of SEM-EDXA is that it cannot readily measure concentrations below about 0.1%, and becomes increasingly imprecise at concentrations below 1%. However, the minor elements (those below 1%) and trace elements (below 0.1%) can be very helpful in determining differences in the origins of glasses, and in determining the effects of recycling. Therefore we have analysed a subset of fifty of the samples using *inductively coupled plasma - atomic emission spectrometry* (ICP-AES) and *inductively coupled plasma – mass spectrometry* (ICP-MS). These have provided the concentrations of a wide range of trace elements and have provided more precise data for some of the minor elements such as manganese and iron.

Finally, recent work on the isotopes of strontium and neodymium has shown that they can be highly diagnostic in determining the origins of the raw materials used in glassmaking (Freestone et al 2003, 2009, in press, Degryse et al 2008). Therefore we have analysed a further subset of 11 samples from Basinghall, plus a small number of comparative samples from elsewhere, by *thermal ionisation mass spectrometry* (TIMS) for their $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ ratios. These isotopic data allow us to comment on the origins of the glasses and their relationship to Roman glass from elsewhere.

The details of the experimental methods and full analytical data are presented in the appendices.

Samples analysed

Although there are a small number of finds of blue and amber coloured glass from the workshop, their numbers are minor relative to the mass of colourless and weakly coloured glass (glass coloured by the small amounts of iron naturally present in the raw materials). The colourant of blue glass is well understood to be cobalt, and amber glass is coloured by specifically reducing conditions in the melt (Scheurs and Brill 1984), we do not expect that analysis would yield substantially more information, so the analytical programme was focussed on the more abundant uncoloured material.

The material selected for analysis fell into a number of categories:

1. From the large mass (c 30kg) of glass which appears to have poured out of a furnace. 7 samples were taken from an arbitrary range of positions, to understand the variation in composition.
2. Samples from each of three large blocks of tank glass, which showed top and base of the tank. They are greenish at the top and bluer at the base and contain numerous white balls. These balls are spherulites – masses of crystals which grew as the glass cooled slowly in the tank (see for example Keith and Padden 1963, Lofgren 1980).¹ 3-4 samples were taken from the glassy areas of each block, representing the top, bottom and centre.
3. Samples from miscellaneous small lumps of glass, ranging in colour from yellow-green to blue-green. These could represent glass broken out of the furnace or raw glass imported from elsewhere. 20 samples from a range of colours, sizes and textures.
4. Cullet, in the form of broken vessel and window. This is likely to have represented a significant source of the glass being worked. A number of categories were analysed:
 - Green-blue window cullet (10samples)
 - Green-blue vessel cullet (10 samples)
 - Colourless vessel cullet (10 samples)
5. Moils, glass which joined the vessel to the blowpipe. These are important as they are the material available on site which is most representative of the glass that was used in vessel production. A number of categories were analysed:
 - Green-blue moils (9 samples)
 - Greenish moils (10 samples)
 - Colourless moils (10 samples from context 994, 10 samples from context 1710)
 - Colourless lid moils (6 samples)
6. Wasters, fragments of vessel glass which have been distorted by excess heat and are therefore assumed to have been made on site (9 samples).

¹ We attempted to obtain an accurate identification of these crystals using X-ray diffraction, but this failed because the accessible material near the surfaces of the blocks appear to have been altered by contact with groundwater and gave no clear diffraction pattern. This implies that they were a phase rich in sodium, as might be expected.

Composition and colour

Tables 1-3 present average major element compositions for the main groups of glass. As anticipated, they are composed mainly of silica (silicon dioxide, SiO₂), the principal constituent of glass-making sand, with about 70% of this constituent plus 14-20% soda (sodium oxide, Na₂O) supplied by natron. In addition the glasses contain 5-10% lime (calcium oxide, CaO). Lime was added to the batch in the form of calcium carbonate, which occurs naturally as beach shell and limestone. Lime from both of these sources has been shown to have been incorporated into ancient glass (Freestone et al. 2003), but rather than a deliberate addition, it has been argued that in most cases lime was added indirectly, as fragments in the sand (e.g. the shell fragments in beach sand - Brill 1977, Freestone et al. 2003). The Basinghall St glasses are therefore *soda-lime-silica* glasses, a formulation that is still widely used in windows and containers today, but were probably made from two main starting materials, sand (which provided the lime and the silica) and natron (which provided the soda).

		Window cullet	Vessel cullet	Moils g-b	Moils g	Wasters
	No. anal.	10	10	7	10	8
<i>soda</i>	Na ₂ O	15.44	15.45	15.63	15.25	15.64
<i>magnesia</i>	MgO	0.58	0.56	0.47	0.49	0.49
<i>alumina</i>	Al ₂ O ₃	2.37	2.35	2.35	2.34	2.41
<i>silica</i>	SiO ₂	70.43	70.82	71.12	71.14	70.90
<i>sulphate</i>	SO ₃	0.29	0.28	0.25	0.24	0.29
<i>chlorine</i>	Cl	1.06	1.05	1.07	1.03	1.04
<i>potash</i>	K ₂ O	0.60	0.59	0.54	0.59	0.64
<i>lime</i>	CaO	7.90	7.64	7.68	7.85	7.52
<i>titanium oxide</i>	TiO ₂	0.07	0.06	0.07	0.07	0.05
<i>manganese oxide</i>	MnO	0.63	0.50	0.42	0.41	0.47
<i>iron oxide</i>	Fe ₂ O ₃	0.46	0.49	0.39	0.44	0.50
<i>antimony oxide</i>	Sb ₂ O ₃	<0.3	<0.3	<0.3	<0.3	<0.3

Table 1. Average compositions of naturally coloured glass fragments, in weight percent
 "<" signifies "less than", indicating that the component is less than the limit indicated
 g-b = green blue, g = green

		Large mass	Furnace block	Furnace block	Furnace block	Small lumps
	No. anal.	7	4	3	3	19
<i>soda</i>	Na ₂ O	15.35	15.41	15.43	15.32	15.61
<i>magnesia</i>	MgO	0.52	0.49	0.50	0.56	0.53
<i>alumina</i>	Al ₂ O ₃	2.37	2.39	2.34	2.35	2.31
<i>silica</i>	SiO ₂	71.14	70.98	71.07	70.95	70.76
<i>sulphate</i>	SO ₃	0.25	0.26	0.29	0.28	0.26
<i>chlorine</i>	Cl	1.02	1.01	0.95	1.05	1.05
<i>potash</i>	K ₂ O	0.61	0.63	0.65	0.60	0.61
<i>lime</i>	CaO	7.73	7.78	7.79	7.77	7.80
<i>titanium oxide</i>	TiO ₂	0.10	0.07	0.03	0.08	0.07
<i>manganese oxide</i>	MnO	0.42	0.49	0.49	0.47	0.40
<i>iron oxide</i>	Fe ₂ O ₃	0.40	0.42	0.38	0.39	0.43
<i>antimony oxide</i>	Sb ₂ O ₃	<0.3	<0.3	<0.3	<0.3	<0.3

Table 2. Average compositions of unshaped glass lumps and glass from the furnace in weight percent

		Moils (Sb)	Lid moils	Vessel cullet	Moils (Mn)	Wasters
	No. anal.	4	6	10	16	1
<i>soda</i>	Na ₂ O	19.03	19.06	18.97	16.05	18.52
<i>magnesia</i>	MgO	0.43	0.40	0.43	0.54	0.48
<i>alumina</i>	Al ₂ O ₃	1.74	1.71	1.92	2.24	2.20
<i>silica</i>	SiO ₂	69.58	69.00	69.05	69.83	68.70
<i>sulphate</i>	SO ₃	0.44	0.45	0.42	0.35	0.37
<i>chlorine</i>	Cl	1.29	1.31	1.23	0.94	1.11
<i>potash</i>	K ₂ O	0.43	0.39	0.52	0.62	0.67
<i>lime</i>	CaO	5.87	6.23	6.13	7.72	5.92
<i>titanium oxide</i>	TiO ₂	0.06	0.06	0.10	0.07	0.14
<i>manganese oxide</i>	MnO	<0.1	<0.1	0.20	1.14	0.51
<i>iron oxide</i>	Fe ₂ O ₃	0.40	0.41	0.46	0.42	0.58
<i>antimony oxide</i>	Sb ₂ O ₃	0.72	1.03	0.60	<0.3	0.72

Table 3. Average compositions of colourless glass samples, in weight percent

An implication of the sand plus natron model is that because natron consists almost entirely of soda, most of the constituents in Roman glass are derived from the sand used to make it, with a small proportion derived from material added to modify the colour of the glass. Thus in the compositions in Tables 1-3, alumina, magnesia, potash and iron oxides entered the glass incidentally as sand constituents, and were not intentionally added by the glassmakers. This lack of control over the minor constituents was a major challenge for early glassmakers, as it meant that they were not able to easily control the iron content of the glass. Iron imparts a strong bluish to yellowish tint and is largely responsible for the “natural” colours seen in the Basinghall assemblage.

In spite of the dependence of colouration upon iron, and the very variable tints seen in the glasses, it is observed (Tables 1-3) that their iron contents, expressed as Fe_2O_3 , are very constant throughout, at around 0.4%. This is not some imprecision in our analytical technique, as we have analysed for iron by three different methods: SEM-EDXA, ICP-AES and ICP-MS. In all cases, they show no significant difference in iron oxide contents between the weakly coloured green-blue and greenish glasses and the colourless glasses. It is therefore not the total amount of iron which is responsible for the variation in colour seen, but its degree of oxidation. In fact, the amount of iron in these glasses is about ten times greater than in a modern colourless glass and is sufficient to colour them all quite strongly. However, iron occurs in two oxidation states in the glass; in the presence of abundant oxygen it is present as Fe^{3+} ions, which impart a very pale, yellowish tint. Where there is a shortage of oxygen, the iron is present as Fe^{2+} which colours the glass quite a strong blue. Green colours represent an intermediate oxidation state, where both oxidised and reduced iron are present.

The foregoing principles explain many of the characteristics of the Basinghall assemblage. For example, the upper parts of the large blocks from the furnace are yellowish green, while the lower parts are green-blue. This reflects the interaction of the molten glass with the air above it in the furnace. Oxygen diffused from the furnace atmosphere into the glass, turning its original green-blue to green. Even at high temperatures, the rate of oxygen diffusion into glass is slow, so the more bluish glass was preserved in the lower parts of the tank. Green and green-blue glasses

differ in colour because of their oxygen contents. Similarly, green moils were made from a more oxidised batch of glass than green-blue moils.

The relationship between the soda and lime contents of all tinted and colourless glasses is shown in Fig. 2. It can be seen that most of the glasses in this figure fall into an elongate region stretching from upper left to lower right; glasses with higher soda have lower lime and vice versa. In particular, we can see that the tinted glasses form a large group with low soda and high lime, while there is a group with high soda and low lime composed mainly of colourless glasses. This distinction between the base compositions of colourless and tinted Romano-British glasses has been observed before (Jackson 2005, Freestone 2008) and is a general characteristic, not restricted to Basinghall Street.

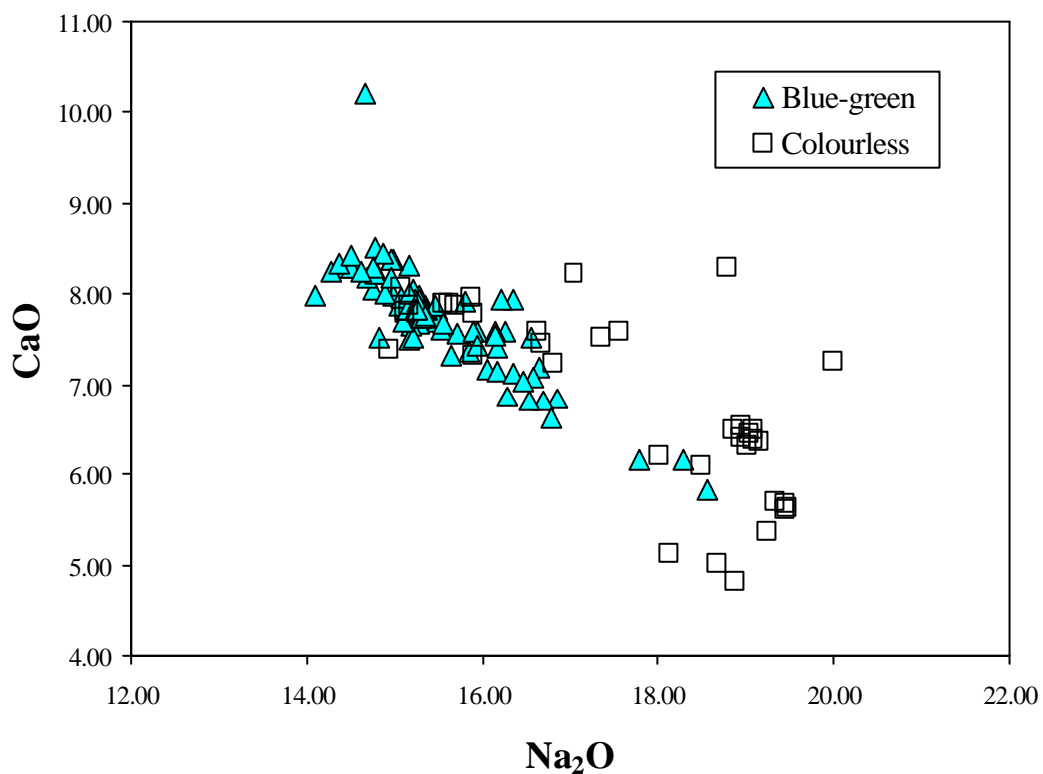


Figure 2. Lime versus soda for colourless and weakly coloured green-blue glasses (weight percent).

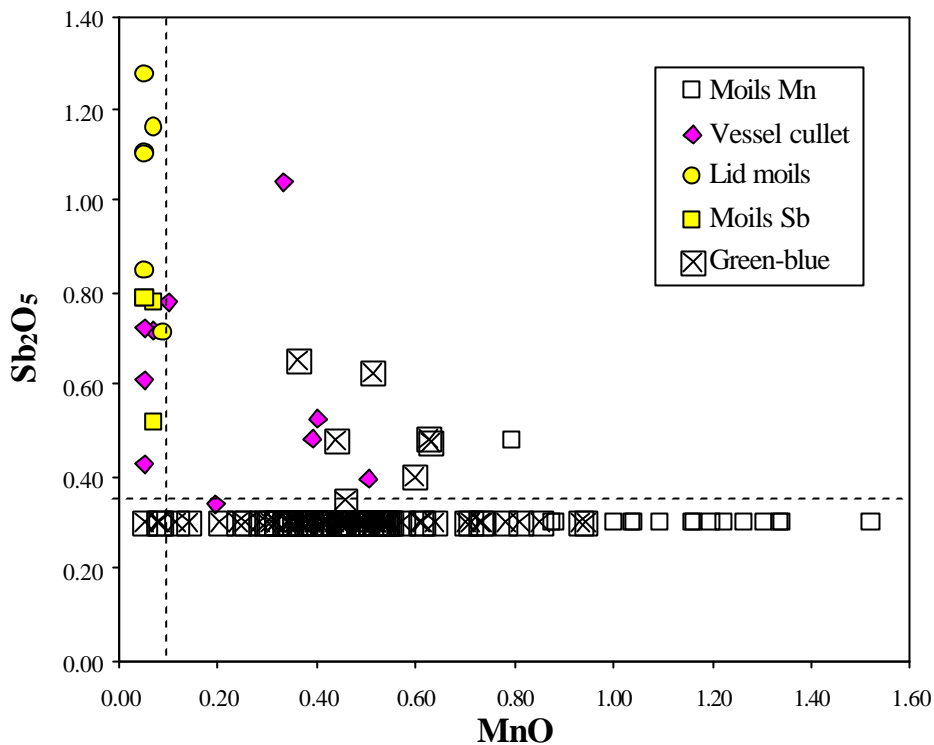


Figure 3 Antimony and manganese oxide contents in glass from Basinghall St. The dashed lines represent detection limits for the components.

Colourless glass and decolourisation

In order to turn what would have been a tinted glass into a colourless one, the Roman glassmakers used a technique known as *decolourisation*. This involved the addition to the glass of a material which caused the iron to oxidise, reducing its colour. Two materials were used, manganese oxide (MnO₂) and antimony oxide (Sb₂O₅) (Sayre 1967, Jackson 2005). Both manganese and antimony were used in the colourless glasses recovered in the Basinghall St. excavations. Fig. 3 shows antimony oxide plotted against manganese oxide, which reveals three groups of colourless glass:

1. A group of moils with high manganese and low antimony, which was deliberately decoloured using manganese.
2. Another group comprising standard moils plus lid moils which has no manganese and is clearly decolourised by high levels of antimony.
3. A group of colourless cullet which typically contains moderate amounts of both antimony and manganese.

Most of the green-blue glass has antimony below the detection limits of the technique but contains up to about 1% manganese oxide, while a small number of green-blue samples contains measurable amounts of both oxides, similar to the colourless cullet (Fig.3). Referring back to Fig. 2, the antimony-decoloured glasses are those at the high soda end of the range, while the manganese-decoloured glasses are those which overlap with the weakly-coloured glasses.

Were these groups of glass showing different tints and methods of decolourisation produced in the Basinghall Street workshop from a single type, by adding different amounts and proportions of manganese and antimony? Or were they brought into the workshop as different consignments of glass? In order to evaluate these possibilities any differences in the origins of the glasses must be considered. If they were made from different sands, then they could not have been produced by manipulating a single glass type.

A first indication of glassmaking sand is provided by a plot of lime versus alumina, shown as Fig. 4, as both of these are believed to have been added to the glass is the sand. There is a large gap between the antimony-decoloured moils (Sb colourless in Fig. 4) and the weakly coloured suggesting that these glasses were originally made from different sands. The Sb-decoloured glasses are characterised by lower lime and lower alumina than the others. The manganese-decoloured moils overlap with the green-blue group, they are not exactly the same but it cannot be stated with certainty at this point that they were made from different materials. Finally the colourless cullet spreads out between the Sb-decoloured samples and the other glasses. These commonly contain significant levels of both antimony and manganese, and it can be speculated that some of these were formed by mixing high-lime and low-lime types in an earlier period of glass-working.

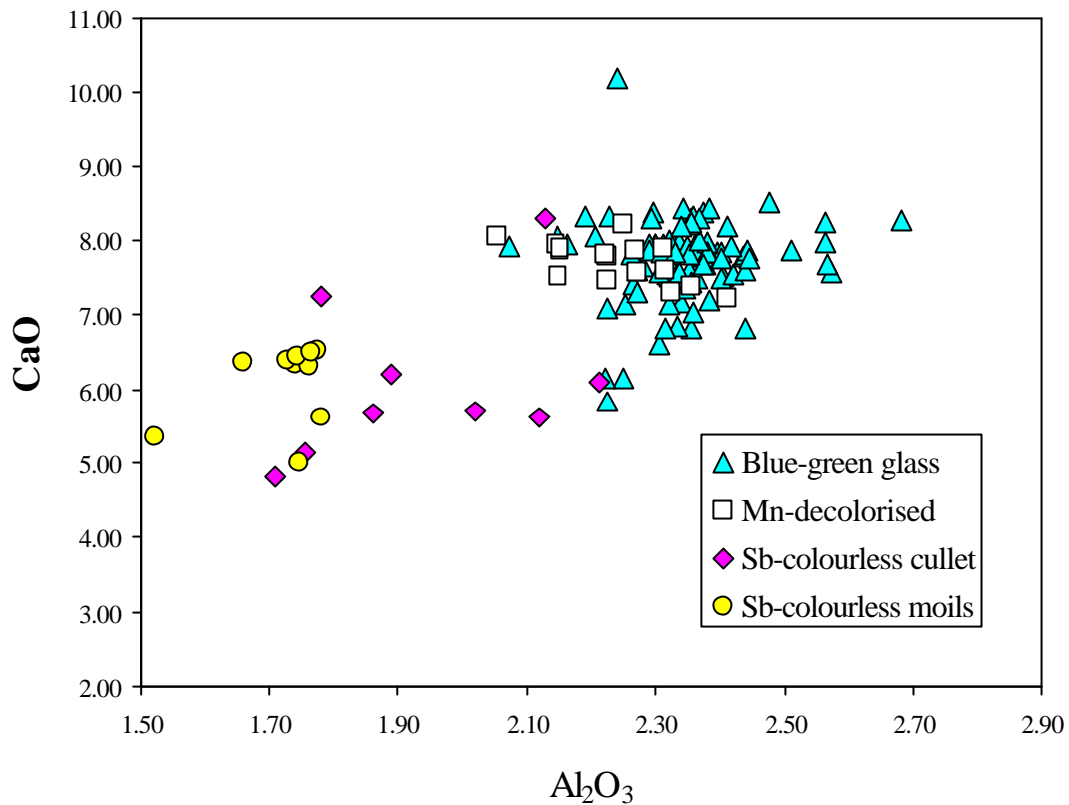


Figure 4 Lime versus alumina for colourless and weakly coloured green-blue glasses (weight percent).

The minor and trace elements yield further important insights. Trace elements can reveal significant differences between samples which have very similar major element compositions. The same raw material will yield trace elements in very similar proportions, while material from a different location will show different ratios. For these components we will use the data obtained by ICP-MS, a highly sensitive technique. This is a smaller dataset than the samples analysed by EDXA.

Fig.5 compares the iron and titanium oxide contents of all of the green-blue samples, the antimony-decolourised, low-lime samples (including cullet with high antimony) and two Mn-decolourised moils. The Sb-decolourised and green-blue glasses form two clear and well defined trends, which are very strongly correlated (the R² values on the graph indicate how well correlated the samples are; a value of 1 is the maximum). This confirms that the green-blue and colourless glasses were indeed

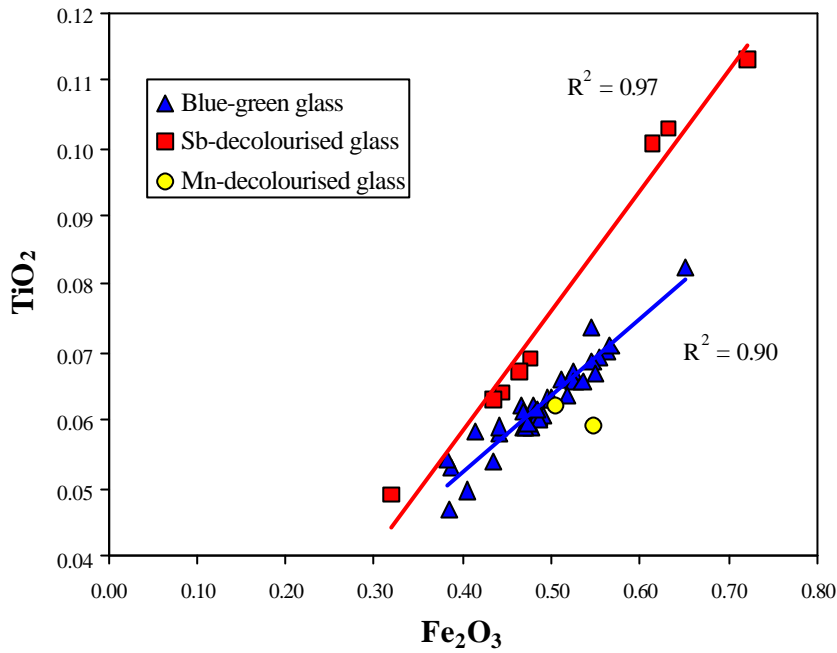


Figure 5 Titanium and iron oxides in weakly-coloured and colourless glasses. The correlation trends suggest that the glassmaking sands of the Sb-decolourised glasses were from a different source. ICP-MS data, weight percent oxide.

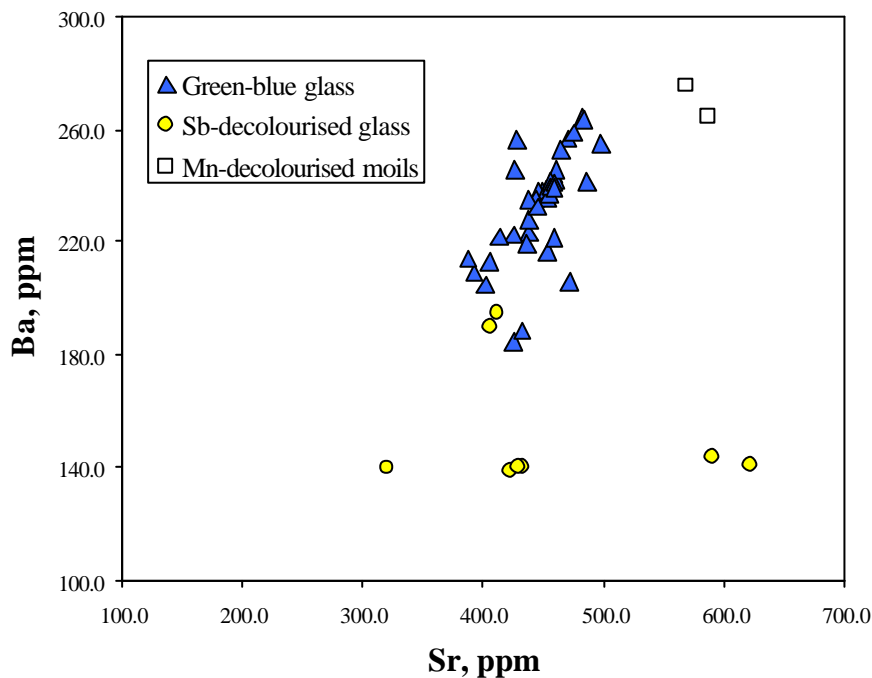


Figure 6 Barium versus strontium in weakly-coloured and colourless glasses (ICP-MS data, parts per million element)

made from different glassmaking sands. The graph is ambiguous with respect to the Mn-decoloured which overlap but do not coincide with the green-blue glasses. However, the Mn-decoloured moils differ in other respects, for example in terms of barium and strontium contents, where they are clearly shown to be a different composition (Fig.6).

To summarise, glasses made from at least three different sands were in use at the Basinghall St workshop:

1. By far the most abundant is typical green-blue to greenish glass of the imperial period, which is widely present as moils, wasters, cullet and virtually all of the small lumps of unformed glass as well as the large blocks from the furnace. It has a very consistent composition, with around 71% silica, 15.5% soda and 7.5% lime (Tables 1, 2). Alumina is relatively high at around 2.4%. These glasses typically contain around 0.5% manganese oxide. Antimony oxide is generally below detection limits but some samples may have a few tenths of one percent, and traces, which we were unable to measure, may be present in many of them. These glasses compare reasonably well with green-blue glass from other Romano-British sites (Jackson 2005, Jackson et al. 1990).
2. A second group comprises Mn-decoloured glasses. They have only been identified in the form of colourless moils, in which they appear to be the largest group. The workshop was clearly producing significant numbers of vessels in this glass at some point. The major element compositions are similar to the green-blue glasses (Tables 1 and 3) but are not identical (Fig.4), and trace elements suggest that they were from a different sand source. The manganese oxide contents are high, typically 1% or greater. These glasses could not have been made by adding manganese to standard green-blue glass and must represent one or more specific consignments of glass, brought to the workshop to produce colourless vessels. These glasses are more-or-less equivalent to the “nearly colourless”, Group 2 glass of Jackson (2005).

3. The third category comprises glasses with higher soda, at around 19% and lower lime, c. 6% (Table 3). These low lime glasses are typically colourless, although one or two examples may be picked out among the green-blue glasses. They comprise standard moils, all lid moils, and some cullet. They have higher antimony oxide than the other groups and were antimony decolourised. While some of the cullet contains significant manganese oxide, the moils analysed contain only 2-300 ppm (parts per million = 0.02-0.03%), which is likely to be the natural level in sand. It would not have been possible for the user of the cullet to distinguish fragments with no manganese from those with some. For this reason, it seems improbable that the glass used to make the colourless standard moils and lid moils was derived from colourless cullet. This must have been one or more specific consignment of glass brought to the workshop to produce colourless vessels. These glasses are more-or-less equivalent to “colourless” Group 1 glasses of Jackson (2005).

Weakly coloured glasses and the main furnace production

The majority of glasses found at Basinghall Street have a green-blue or green tint, and represent what might be termed “common” glass. According to the Price Edict of Diocletian (Whitehouse 200x?), dating to around 300 AD, this green glass was known as “Judean glass” and was cheaper than colourless or white glass, which was known as “glass from Alexandria”. Our aim in examining these glasses in detail is to determine the relationships between the green-blue and green tinted glasses, the furnace products and the various other categories of material.

In addition to the large 30kg mass of poured glass, three large blocks, apparently representing broken sections of tank, were analysed. Fig. 7 shows lime versus soda contents for all analysed samples from these large blocks. There is a total spread of about one percent in soda and 0.7% in lime, which are strongly anti-correlated, as shown by the trend line in the graph. Most of the analyses are concentrated at higher lime values. The spread of composition within a single block is as great as the total spread. Thus, although it is not proven beyond all doubt, these results are fully consistent with the derivation of all of this material from the same tank of glass. This is self evident for the individual furnace blocks, which are of the same thickness and

display similar internal zoning, but it was less clear for the 30kg poured mass of glass, which on the compositional evidence appears likely to have been released from the same campaign of melting.

Fig. 8 compares the compositions of the glass from the large furnace blocks with the known products of the workshop (moils and wasters). The green moils have a very tight distribution. In fact, their compositions are identical within analytical error (within +/- 2 standard deviations) as is to be expected from a single batch of glass (Price et al. 2005, Freestone et al. 2009a). Furthermore, the green moils are identical to the bulk of the furnace glass, implying that they were products of the same melt. The large furnace blocks are likely to represent the material in the furnace at the end of its life, when glassworking was discontinued, otherwise they would have been melted and re-used. The green moils are therefore also likely to have been the product of the last campaign, before the furnace was abandoned. This is fully consistent with the green colour of the glass at the top of the blocks from the furnace. Green is a less common colour than green-blue in Romano-British glass and it indicates that furnace conditions were more oxidising than is typical. This appears to have occurred at the end of the life of the furnace and it may be envisaged that the furnace was not functioning properly throughout the last campaign.

The green-blue moils show a wider distribution than the green ones, and commonly do not coincide in composition with the furnace glass (Fig. 8). They are likely to have been the products of earlier campaigns of melting and working. The wasters are dispersed still further. On the basis of the spread of compositions of the wasters and moils relative to the furnace glass, it seems likely that the assemblage represents several campaigns of melting before the final one. In order to address this issue robustly, however, the origin of the glass itself must first be considered.

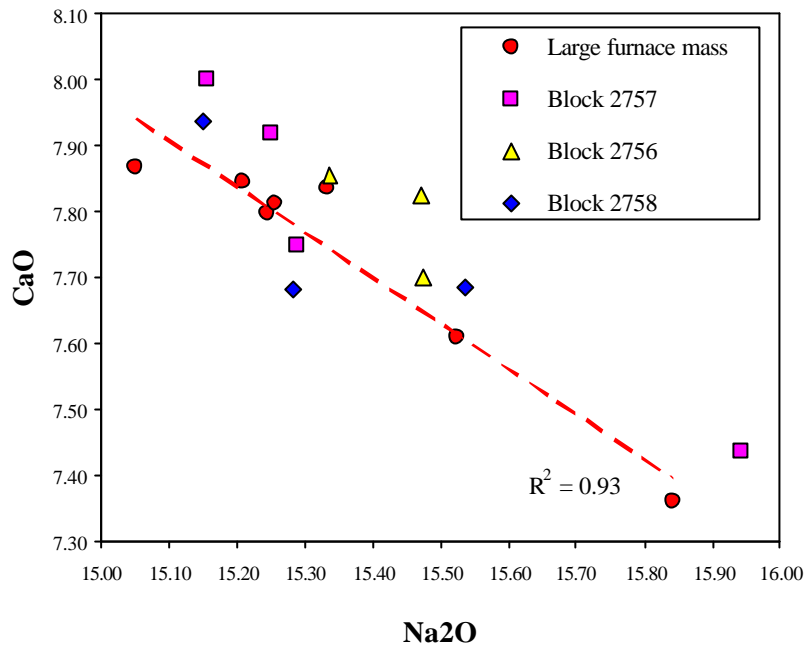


Figure 7 Lime versus soda for large masses of glass related to the furnace (weight percent).

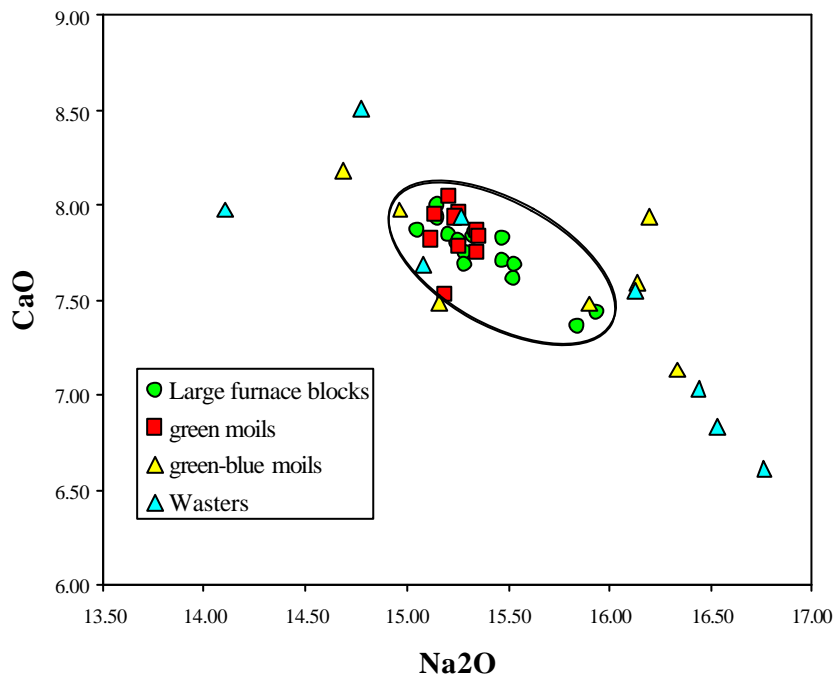


Figure 8 Lime versus soda for large furnace blocks, moils and wasters. Green-blue glass, weight percent.

Origins of the Glass: Isotopic Composition and Rare Earth Elements

One of the aims of this investigation was to determine whether glass was being made on site from its raw materials. The absence of deposits of sand for glassmaking in the vicinity and the absence of incompletely fused raw material in the glass samples suggest that glass was not made from sand and soda at Basinghall Street. However, to determine just where the glass was made, we need to consider its chemistry in detail, to gain some insight as to the origin of the glass making sand.

We have already seen that there are likely to be three different glasses made from different sands in our assemblage: (1) weakly coloured greenish or green-blue glass, (2) antimony-decoloured glass and (3) manganese-decoloured glass. Were these from closely related sands or were they produced in widely dispersed workshops, and where were these workshops located? Analysis for the isotopes of strontium and neodymium is a useful approach to this issue.

The principles governing the isotopic composition of natron glass are relatively straightforward (Wedepohl and Baumann 2000, Freestone et al. 2003, 2009, Degryse and Schneider 2008, Degryse et al 2009). Strontium (Sr) is a trace element which is incorporated in the glass with the lime, typically calcium carbonate, in the form of shell or limestone particles. The silicate mineral particles in the sand, such as feldspar, are also a source of strontium but in general it appears that the lime is dominant. The $^{87}\text{Sr}/^{86}\text{Sr}$ ratio therefore reflects primarily the origin of the lime, as shells in beach sand have a ratio close to that of modern sea-water, around 0.70920, while limestone typically has markedly different values, reflecting its complex geological history. Thus a glass with $^{87}\text{Sr}/^{86}\text{Sr}$ approaching 0.70920 is likely to have been made using a beach sand, or by adding sea shell to the raw material.

Neodymium is another trace element which is an important indicator of glass origins. It is present in glassmaking sand as a component of heavy minerals such as pyroxene and amphibole. The ratio $^{143}\text{Nd}/^{144}\text{Nd}$ in the sand depends upon the geological region that supplied the sand particles. Geologically young volcanic rocks, derived from the earth's mantle, impart a higher $^{143}\text{Nd}/^{144}\text{Nd}$ than old crustal rocks. The Nd isotope

ratio is often expressed as a simple parameter, ϵ_{Nd} , which varies between about -15 (low) and -3 (high) in ancient glasses. ² High values of ϵ_{Nd} in glass are typically associated with glassmaking in the southeastern Mediterranean, where the sedimentary load of the River Nile, rich in volcanic minerals derived from the East African highlands, supplies the sands of the Levantine coast. Natron and plant ash glasses from Late Roman and Islamic period primary furnaces situated on the eastern Mediterranean coast have ϵ_{Nd} between -6.0 and -3.0 (Freestone et al. 2009, Degryse et al in press). In Britain, on the other hand, and in most other continental regions, geological considerations suggest that ϵ_{Nd} values greater than around -9.0 are unlikely to be encountered in glass making sands (e.g. Degryse and Schneider 2008).

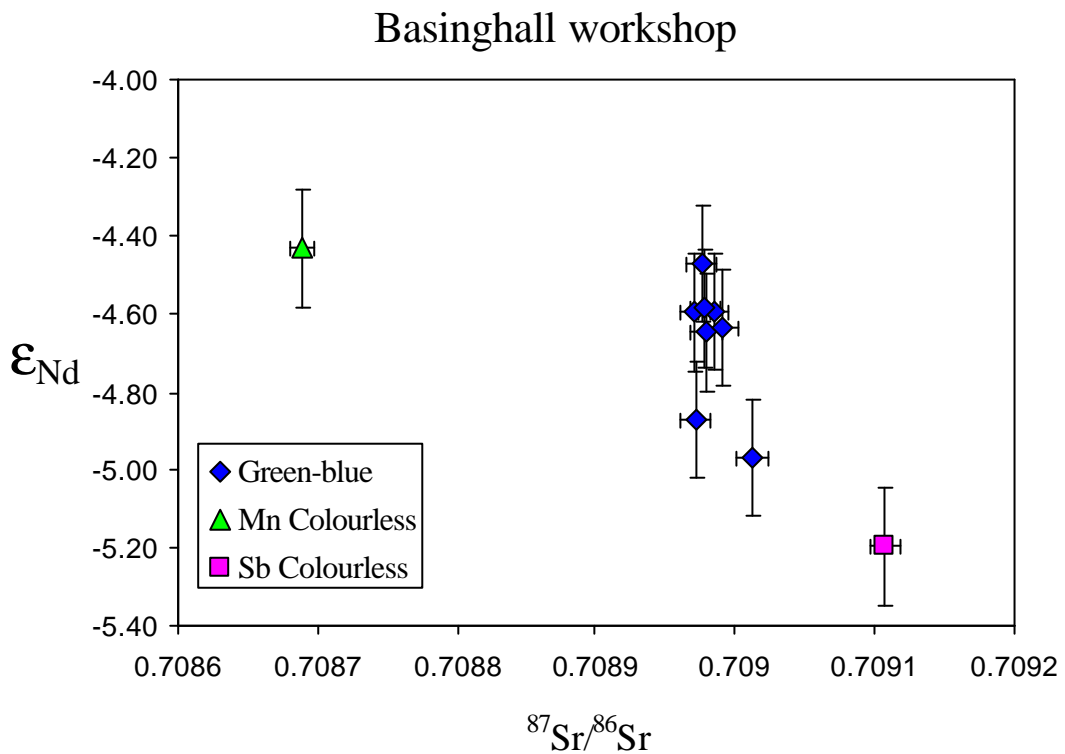


Figure 9 neodymium and strontium isotope results for glasses from the Basinghall Street workshop.

² Calculation of ϵ_{Nd} is explained in Appendix 3

For the present project, strontium and neodymium isotopes were measured for 11 glasses from Basinghall St.; these comprise 9 weakly coloured and two colourless samples. Full results are given in Appendix 3 and are presented graphically in Fig. 9. The range of ϵ_{Nd} is relatively narrow, between -5.2 and -4.4, consistent with all of the glasses being derived from a single region. However, $^{87}Sr/^{86}Sr$ separates the two colourless glasses from the green-blue glasses, suggesting that they were made from slightly different sands. This is consistent with the elemental analyses, for example Figs, 4-6. It may be observed that two of the green-blue samples have ϵ_{Nd} slightly lower than the others (Fig. 9). Given the measurement errors, no significance is attached to this at the present stage, and the forms of the samples do not suggest any reason why there should be a significant difference in isotopic composition.

We have also analysed in this and an earlier pilot study a number of glasses from other sites in London: blue-green glass from cullet dumps at Regius House and Guildhall and colourless vessels from Hibernia Wharf and Leadenhall Court. These and a small group of first century BC manganese-decoloured glass from a workshop assemblage in Jerusalem (Israeli and Knatelson 2006) are compared with the Basinghall St glasses in Fig. 10. Although these few samples are unlikely to be fully representative of Roman glass in London, it is striking that the ranges of isotopic compositions are very similar. This is in particular the case for the green-blue glasses, where it is observed that all lie in a narrow field and that the Basinghall St glasses lie within the compositional range defined by the other London glasses (Fig. 10).

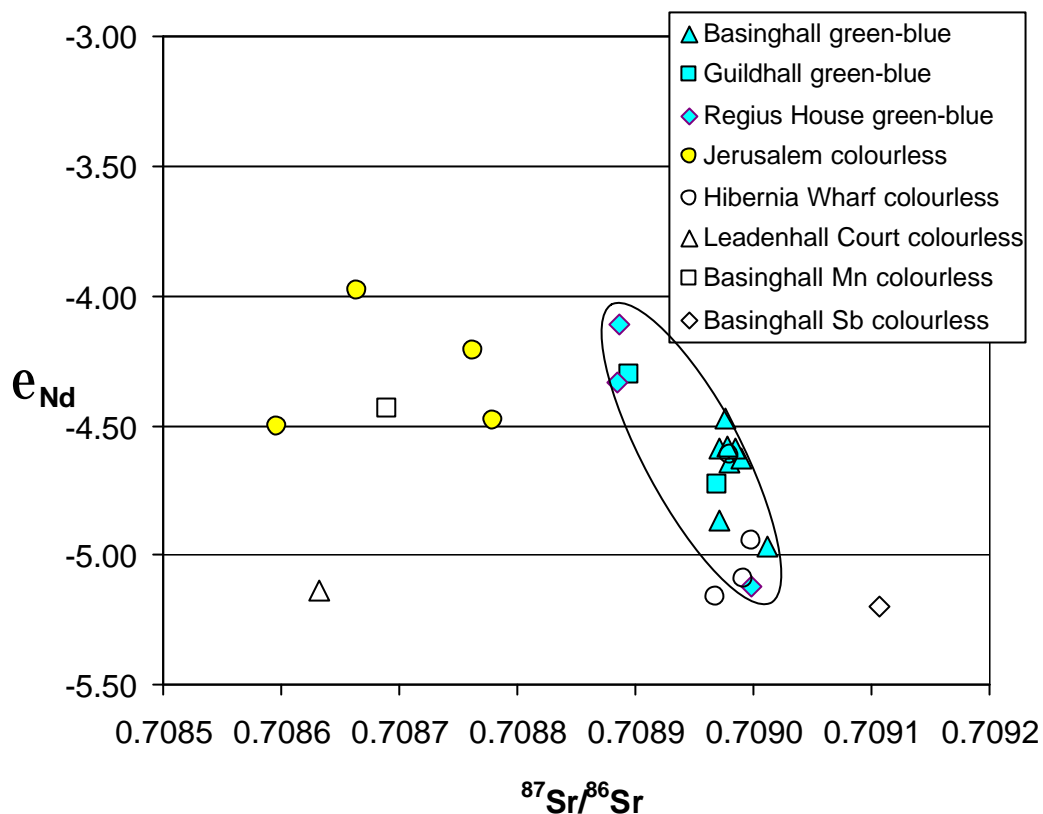


Figure 10 Neodymium and strontium isotope data for green-blue (inc. green) and colourless glasses from Basinghall St. and other sites in London, and the Jerusalem workshop. The colourless samples from Hibernia Wharf (lower right) are Sb-decoloured, and those from Jerusalem and Leadenhall Court (left hand side) Mn-decoloured.

The Jerusalem glasses were included in this study because of the abundant evidence for glassmaking using the sands of the Levantine coast, from the writings of Pliny and Strabo through to the archaeological evidence for large tank furnaces from the late to post-Roman period. Although there are isotopic data available for a small number of glasses from Byzantine and Islamic contexts (6th-10th century) (Freestone et al 2003, 2009b, Degryse et al., forthcoming), there are none for Roman glass known to have been made in the region, and only a few analyses of sand (Degryse and Schneider 2008). The Jerusalem workshop represents a group of glass from an earlier period. According to Pliny, writing around 70 AD, “the old method for making glass”, used sand from the mouth of the River Belus, which flowed into the Mediterranean near the modern town of Akko. Pliny noted that “The beach stretches for not more than half a mile, and yet for many centuries the production of glass depended on this area

alone.....” (NH XXXVI, 190; translated by Eicholz 1962). This supports the view that the Jerusalem glass was made on the Levantine coast. The Jerusalem glass measured here has ϵ_{Nd} of -4.5 to -4.0 and corresponds well with three analyses of Belus sand by Degryse and Schneider (op. cit.) which gave ϵ_{Nd} of -1.0, -4.8 and -4.8.

The $^{87}Sr/^{86}Sr$ ratios of all samples analysed approach the composition of modern seawater (c. $^{87}Sr/^{86}Sr = 0.70917$; De Paulo and Ingram 1985, Hess et al 1986), typical for glasses produced from beach sands, where the strontium is derived mainly from shell particles (Freestone et al. 2003, 2009b, Degryse and Schneider 2008). Once again, this is consistent with an origin for the glasses on the southeastern coast of the Mediterranean, where the sands contain shell particles at concentrations appropriate for glass making (Brill 1988) and where glasses from glassmaking furnaces of other periods have similar strontium isotope compositions (Freestone et al 2003). An interesting feature of the data is that Mn-decoloured samples (Jerusalem, Leadenhall Court, Basinghall Mn-clourles; Fig. 10), have lower $^{87}Sr/^{86}Sr$ than Sb-decoloured samples (Basinghall Sb-colourless, Hibernia Wharf; Fig. 10). It will be of interest to see if this distinction persists as more isotopic analyses of colourless glasses are collected.

The neodymium isotope measurements eliminate the possibility that the Basinghall glass was made from its raw materials in southern Britain, where there are no local materials that might yield such high ϵ_{Nd} . Similarly, the near continent is not a possibility (Degryse and Schneider 2008). The Nile was the main source of such radiogenic glass making sand in the classical world. Measurements of ϵ_{Nd} in primary tank furnaces from Palestine (-5.0 to -6.0; Freestone et al. forthcoming), the Jerusalem glass (above) and Belus sands (Degryse and Schneider op. cit.) all support the view that the glass was made from the Nile-derived coastal sands of the eastern Mediterranean, which is fully consistent with the writings of classical authors such as Pliny, and inferences based upon the archaeological and artefactual evidence (Gorin-Rosen 2000, Nenna et al. 1997, Picon and Vichy 2003). The other main potential source of glass making sands identified by Pliny is the River Volturno, which flows into the sea North of Naples and which is likely to incorporate young volcanic materials from the Italian volcanic province. However, analysis of sands from the

Volturmo suggest that while sands with suitably high ϵ_{Nd} may occur there, these are rich in iron-bearing heavy minerals and would not make suitable raw materials for glass (Degryse and Schneider op. cit.). We may therefore be confident that the isotopic compositions of the London glasses reflect an origin on the eastern Mediterranean coast, the strontium isotopes being largely derived from shell fragments in the sand.

How does the conclusion the green-blue glasses and the two groups of colourless glass all originate on the eastern Mediterranean coast conform to the observation, made above, that these three groups of glass differ in their minor and trace element compositions (see for example figs. 5 and 6)? It seems likely that although the glasses are all of a general “Egyptian-Levantine coastal” type, they derive from different areas of the coast. Other features of the elemental composition are fully consistent with the proposed similar origin for these glasses.

Those elements termed “conservative trace elements” (Taylor and McLennan 1985; Kamber et al 2005) are the least likely to be modified by weathering or mineral sorting. Sands collected along a single river, a stretch of coastline or within a single geological stratum might be expected to show similar ratios of these elements, while if they originate on different coastlines or in different river systems, their elemental ratios may be very different. One of the most conservative elemental ratios is that of zirconium/hafnium, Zr/Hf. These elements behave in an almost identical fashion in nature, so that their ratio in sediments is expected to vary only between regions with very different geological histories, rather than locally. Mean Zr/Hf for all of our samples is 41.7, ranging from 39.4 to 43.6 (standard deviation = 1.2), with no significant difference between the three glass groups. This is rather high relative to the average for sediments on the Earth’s surface (Zr/Hf = 36.9 according Kamber et al. op. cit.) and the similarity between the glass types is consistent with the idea that they were produced from sands in the same region. Similarly, the Lanthanides or Rare Earth Elements (REE) for the green-blue, Mn-decolourised and Sb-decolourised glasses show very similar patterns. Fig. 11 shows the average REE distributions for the three glass groups, normalised against the composition of the weathered continental crust, as represented by the MUQ values of Kamber et al (op. cit.). Note

the marked negative inflection (“anomaly”) around cerium (Ce) and the marked positive anomaly at europium (Eu). These characteristics are repeated in each glass type, although the cerium anomaly is slightly less marked in the weakly-coloured glasses. While the similarities in the behaviours of the conservative elements do not prove an origin in the same region, they are fully consistent with it, and if the glasses had significantly different origins, differences in these distributions might be anticipated.

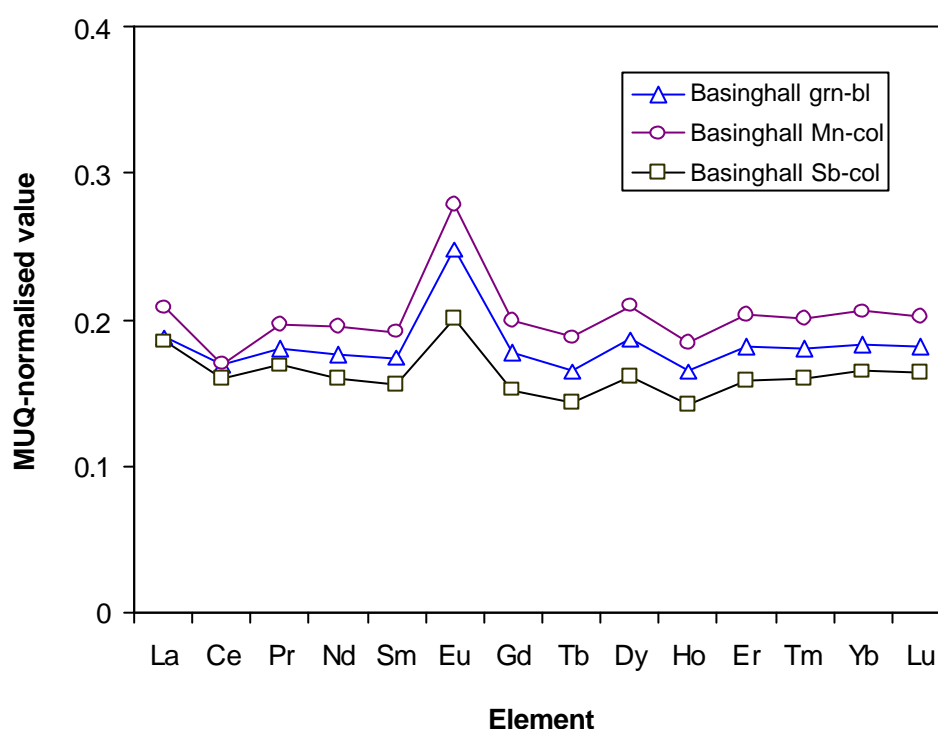


Figure 11 Rare earth distributions for the three glass groups, normalised against the weathered continental crust (MUQ - Kamber et al., 2005)

Recycling, Campaigns and Batches

Assuming that the workshop at Basinghall was melting glass solely derived from the eastern Mediterranean, how was that glass procured? To what extent was the Basinghall St workshop dependent upon cullet, the recycled fragments of old glass, for which there is abundant evidence in the archaeological assemblage, and to what extent did it receive fresh, “raw” glass from the South?

A large number of angular glass chunks have been recovered from Basinghall Street, but their morphology tells us little about their origins. Some could be lumps of imported raw glass but they could represent chunks of glass broken out of the furnace at its destruction, or during periods of cleaning and repair, or from previous furnaces in the vicinity. An approach is needed which allows raw glass from the glassmaking furnace to be distinguished from glass which has been through one or more cycles of reuse. Major element analysis is unlikely to help us here but, as has been noted elsewhere (Jackson 1996, Freestone et al. 2002, Mirti et al 2000), trace element concentrations in glass are often modified when broken vessels and windows are collected and recycled. In the recycling process there is inevitably some inclusion of colourless glass in blue green glass, and strongly coloured glass with colourless and blue-green glass. This is not only because the sorting of broken glass is a laborious business, which is inevitably imperfect, but also because the inclusion of small quantities of other colours in blue-green glass does not matter to the craftsman, as it will not have a major effect on the colour. Thus we might expect small quantities of blue, green, yellow and colourless glasses to be included in the cullet, and these would increase the overall concentrations of elements such as cobalt, copper, lead and antimony. Similarly, mixing manganese and antimony-decolourised glasses would produce a product which contained both elements at elevated levels.

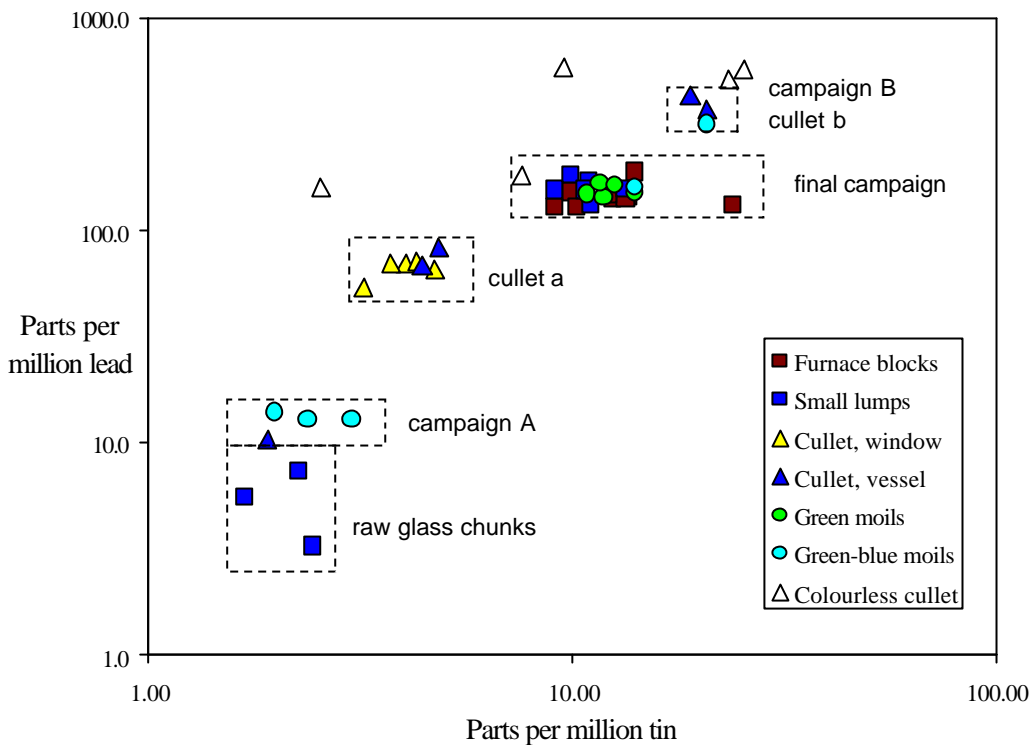


Figure 12 Lead and tin contents of green and green-blue glasses and colourless cullet

Weakly-coloured glasses

Lead, copper and tin are all elements which occur in low quantities in glassmaking sand (typically less than 10 ppm) but which were introduced during colouration. Tin and copper are highly correlated in green-blue glass, probably reflecting the use of the oxidised products of heated bronze³ as a source of copper to colour glass green or blue. Plotting either copper or tin against lead for the Basinghall Street glasses reveals essentially the same pattern, shown for tin and lead in Fig.12.

Note that the axis for lead in Fig. 12 is logarithmic, an approach which allows the detail in the lower values to be seen. A number of groups are indicated on the graph. In the lower left, containing very little tin and lead, is a small group of three bluish glass chunks. These chunks also have low concentrations of other minor and trace

³ Bronze is an alloy of copper with around 10% tin, which when heated in air develops a layer of copper and tin oxide known as “bronze scale”. It is believed that this scale was frequently the source of copper in coloured glasses.

additives such as manganese and cobalt. They represent chunks of raw glass which has not been used to make vessels and contains minimal recycled material.⁴ Just above with about 10 ppm lead is a piece of vessel cullet. This is sufficiently close to the raw glass to suggest that it was imported as part of the same consignment of raw material. Above this are three moils, part of the Basinghall production. These are made mainly from the raw glass consignment but contain some admixed recycled material. It is likely that this group represents the first campaign of blue-green glass production in the workshop, labelled *campaign A* in Fig. 12.

The major group in the diagram comprises all of the large furnace blocks (including the large lump of poured material), the green moils, and most of the small chunks of glass. A single bluish moil is also included. This is the glass that was melted in the final campaign of the furnace, discussed above. Above and below the glass of the final campaign are two groups of cullet, *cullet a* and *cullet b*. Interestingly, these cullet groupings are sufficiently coherent in themselves that they may each represent an earlier campaign of glass working in London. Indeed, all of the window cullet samples are in the lower group, and these could conceivably represent material from the same building. A moil which is associated with the upper group of cullet is likely to represent another campaign of glass working, labelled *campaign B*.

The high lead and tin contents suggest that the glass from the final campaign was composed mainly of cullet, and it lies between the two groups of green-blue cullet in the graph (Fig. 12), indicating that it could have been made by mixing them. Furthermore, colourless cullet occurs at high lead levels, and was available to be used in the green-blue batch.

Significantly more analysis would need to be carried out on the blue-green moils and wasters to indicate the number of tanks of weakly coloured glass that were melted on the site, but the present analysis of the trace elements, coupled with the analyses of the major components, as shown for example in Fig. 8 suggest that the number is

⁴ Kock and Sode, in their study of primary glassmaking in India, observed that a certain amount of pre-formed glass was added with the new raw materials to the furnace. Thus a small amount of cullet may be present even in “fresh” glass from the primary furnace.

likely to have been relatively small, perhaps two-three campaigns in addition to the concluding one. Interestingly, the “wasters” in Fig. 8 show significantly more variation in composition than the moils. This may simply be a sampling issue, i.e. we have not sampled sufficient wasters or moils to accurately represent the full spread in composition. However, the possibility must be considered that some of the vessels identified as wasters are in fact cullet, which has been softened but not fully molten.

Colourless glass

No raw lumps of colourless glass have been recognised in the Basinghall Street assemblage, and this might be taken to suggest that cullet was the raw material for making colourless vessels. However, Fig.3 shows that a significant proportion of the colourless cullet has higher manganese oxide (MnO) and lower antimony oxide (Sb_2O_5) than the antimony-decolourised moils. Given that the glass workers would not have been able to sort the cullet on the basis of its chemical composition, it would have impossible to melt glass of the composition of the moils from the available cullet.

The relationship of the cullet to the moils may be seen in a plot of MnO versus CaO, Fig. 13. MnO and CaO are high in Mn-decolourised glass and low in Sb-decolourised glass. Fig. 13 shows that a substantial proportion of the cullet (*i.e. glass not melted at Basinghall Street but brought into it as old vessel fragments*) lies upon the mixing line for Sb- and Mn-decolourised glasses, indicating that the two glasses types were mixed in some earlier campaign of glassworking, at another workshop. However, all of the Sb-decoloured moils from Basinghall Street, including the lid moils, have very low MnO. This means that the glass used did not contain significant Mn-decoloured (or green-blue) cullet. The small number of analyses of colourless glasses carried out

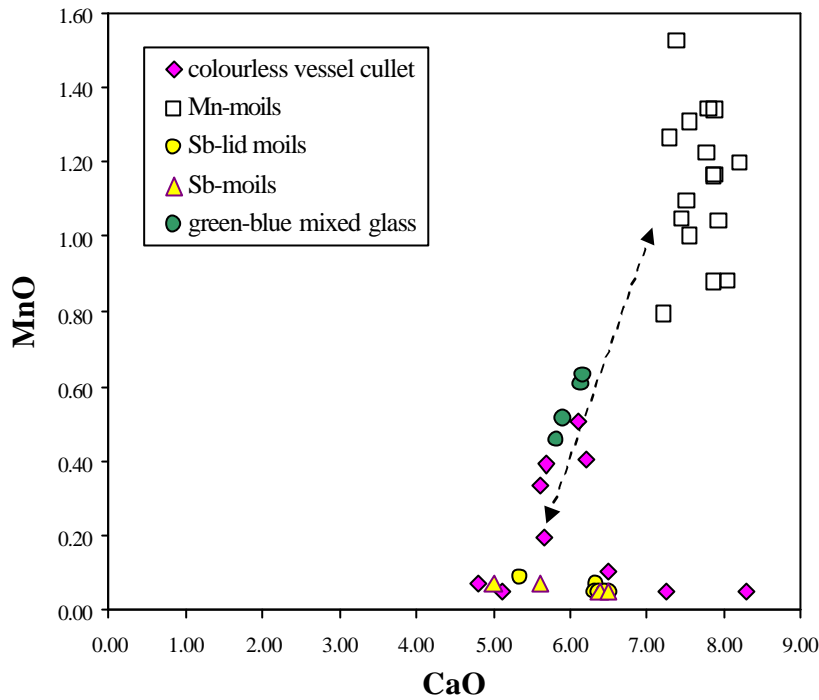


Fig. 13. Weight percent manganese versus calcium oxides for colourless glass, showing probably mixing of Mn- and Sb-decolourised glasses (direction of dashed line). SEM-EDXA data.

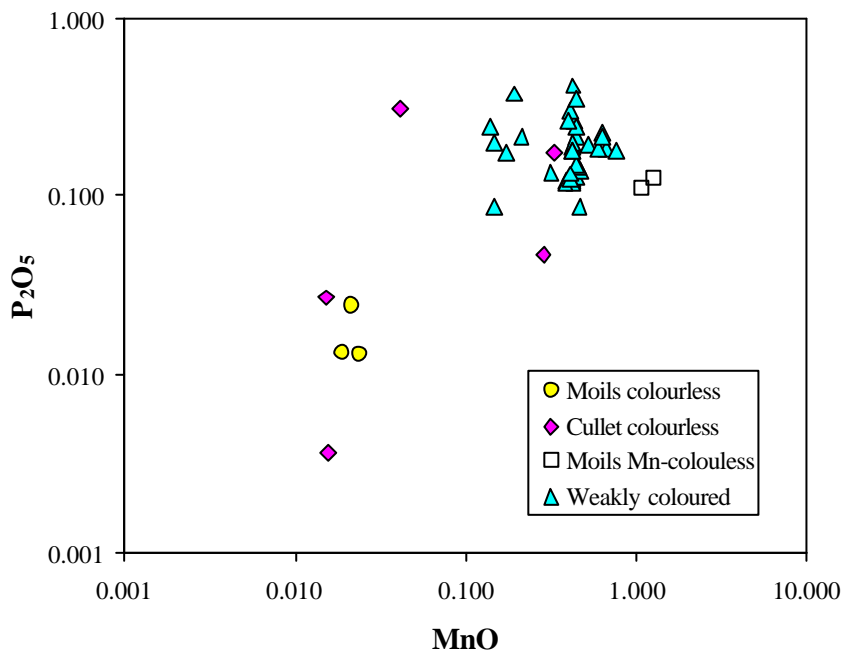


Fig. 14 Weight percent phosphorus versus manganese oxides, showing very low concentrations in Sb-colourless moils and some cullet fragments. ICP-AES data. Note log scale.

by ICP techniques reveal that the Sb-decolourised moils and some of the wasters are characterised by exceptionally low MnO and also very low P₂O₅ (Fig. 14); these appear to represent essentially unadulterated Sb-decolourised glass, with no recycled material. Therefore at some point in the development of the Basinghall Street workshop, a consignment of raw antimony-decolourised colourless glass was procured. Neither colourless cullet nor manganese-decoloured glass was added to this material. Similarly, manganese-decoloured glass is very distinct from antimony-decoloured glass; in particular, its sodium content remains consistently low relative to fresh antimony-decoloured glass and colourless cullet.

There are indications that more than one batch of each of the colourless glass types were melted. The Sb-colourless lid-moils tend to have higher antimony contents than the ordinary moils (Fig. 3), while the data for the Mn-decolourised moils tends to fall into two groups, one characterised by higher Cl and the other by higher K₂O and SO₃, as shown in Fig. 15. These could represent different sacks of raw glass from the same consignment, which were used to top up a tank of molten glass sequentially, but might represent completely separate melts and even separate consignments of raw glass. The differences within the Mn-colourless group are potentially of interest as they at the least reflect a very different melting history when the glass was made, or possibly a different batch of natron. The high antimony contents of the lid moils may suggest that these represent special items for which the “most colourless” glass was used.

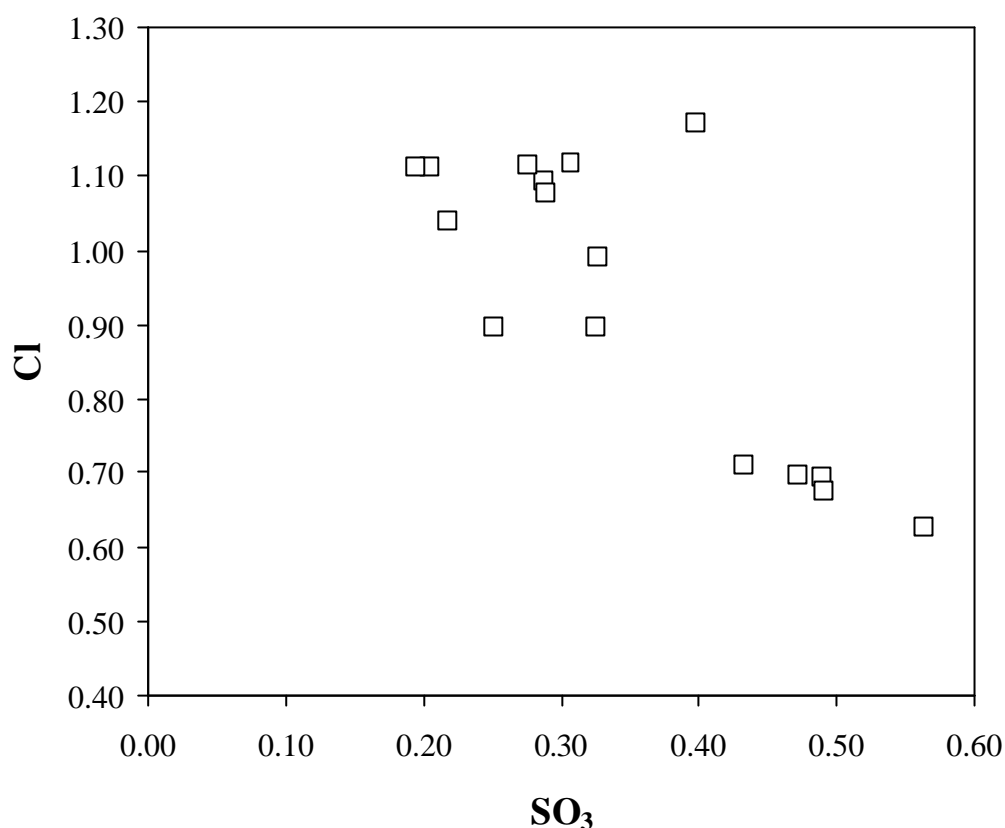


Fig. 15 Weight percent Cl vs SO₃ in Mn-colourless moils, showing possible existence of two groups, one with high Cl and the other with low Cl..

A small group of analysed glass comprising the rim of a jar which has a slight blue tint (anal. no. 100), two green-blue moils (nos. 62, 65) and a greenish lump from the furnace (no. 102) comprise a tight group of almost identical glass, which corresponds closely to the colourless cullet in composition. This group is indicated as “mixed glass” in Fig. 13, because its composition is intermediate to other types. This glass appears to represent a batch produced by melting colourless cullet, perhaps with a small amount of ordinary green-blue or manganese-decoloured glass admixed.

Synthesis: the life of the Basinghall Street glass workshop

The analysis of the Basinghall Street glass has produced a picture of a complex and sophisticated glass-working operation, revealing behaviour which in many respects is not dissimilar from that which might be expected of present-day glass workers. The starting point for our discussion is the recognition of the three fundamental types of glass used on the site: common green-blue glass, colourless glass decoloured by antimony (Sb-colourless) and almost colourless glass decoloured by manganese (Mn-colourless). The data indicate that all three glass types were brought to Basinghall St in the pristine state, as raw glass chunks rather than cullet. Our findings contribute to the growing body of evidence that use of all three types in one workshop was typical of glass workshops in Britannia, as all three types of glass also have been identified in the workshops at Leicester and Mancetter (Jackson 1990, 2005).

The isotopic data for Basinghall allow us to infer for the first time that all three glass types in a single workshop are from the same region of the ancient world, the eastern Mediterranean coast. However, the subtle differences in elemental and isotopic compositions (Figs. 5, 6, 10) indicate that the three glasses were made from different sands at different localities.

In addition to fresh glass from the Mediterranean, the Basinghall Street glassworkers had two other sources of glass. Firstly there appears to have been an abundant supply of blue-green cullet, mainly window fragments. This glass was used particularly towards the end of the workshop, as is shown below. Also a lesser quantity of colourless cullet was obtained in the form of cullet, and this was melted to produce at least one batch of slightly tinted glass (termed “mixed glass” above).

Finally, it should not be forgotten that very small quantities of deep blue and amber glass were recovered from the site. These represent at least two further episodes of glass melting within the life of the workshop.

It seems unlikely that unadulterated raw glass was readily obtainable in Roman Britain, given its origins in the eastern Mediterranean. Given that supplies of unadulterated raw glass originated in the eastern Mediterranean, and that, on the basis of the relatively limited amount of glass in Roman Britain, we suppose that the

workshop at Basinghall Street was established with fresh stock of the three main types of glass. Their occurrence at other workshops (Leicester, Mancetter) indicates that this was common practice. It seems likely that the small amounts of strongly coloured glass remaining in the assemblage were also brought in at this founding stage.

If the glassworkers came to set up the workshop with fresh glass from the Near East rather than cullet, it is fair to assume that they had not moved directly from another workshop in the London region, as they would have surely arrived with cullet, rather than fresh glass. A more likely interpretation might be that they arrived with the raw glass on a ship arriving from the South. Whether they had set off with their consignment of glass from its original source or had joined it *en route* cannot be determined. Nevertheless, it is very likely that the Basinghall Street glassworkers were peripatetic.

While the major campaign of glass working depended upon re-use of blue-green cullet, fresh raw glass from the Levant was used and is represented by a few small chunks of raw glass in our analytical sample. These could be picked out by eye, as their blue is among the least green of the green-blue glass from the site. This is likely to indicate that they are the least oxidised of the green-blue glasses, i.e. that they were not remelted in air after the glass was initially made. Fig. 12 shows evidence for an initial campaign of melting green-blue glass (*Campaign A*), which incorporated only minor cullet. The implication is that this was a campaign carried out before large amounts of cullet had been collected.

During this first campaign, we may envisage that the interest engendered by the establishment of a new glassworking furnace and the production of the first vessels encouraged those holding old glass or cullet in the area to bring it to the new glass house. We know that in Rome scrap glass was exchangeable for items such as sulphur matches and it is likely to have been comparatively more valuable in London, where it was scarcer. This process appears to have resulted in the acquisition of at least two groups of green-blue cullet. *Cullet b* contains around 400 ppm lead and a single analysed moil represents the products of *Campaign B*, which was based largely upon this cullet (Fig. 12). Following this, a major campaign was based upon a second

group of cullet, *cullet a* (Fig.12). *Cullet a* contains around 60 ppm lead, and the 5 window and 2 vessel fragments comprising this group are sufficiently close in composition to suggest that they might have all derived from a single earlier workshop event, rather like the Basinghall one. *Cullets a* and *b* were mixed to produce the glass of the final melting campaign. This produced most of the green-blue glass fragments analysed in the present investigation, and also the natural green samples, all of which plot in the same central area of Fig. 12.

The final melting campaign at the Basinghall Street workshop clearly involved a furnace capable of holding tens of kilograms of glass. The major element, trace element and isotopic analyses each independently link several groups of material to this final event. The large furnace fragments and the 30 kg poured mass are all part of this same melting event, along with most of the smaller lumps of glass, all of the natural green moils and about half of the green-blue moils analysed. In addition, *cullets a and b* were melted as the raw material. The available information suggests that the chain of events leading to this assemblage was as follows:

1. The furnace, which had already been run for at least two earlier melts of green-blue glass, was charged with a mixture of *cullet a and cullet b*. Before blowing began, the furnace was maintained at high temperature for some time to allow the glass to homogenise and de-gas. Vessels were blown in a green-blue glass. However, the aging furnace failed and began to leak glass. Either there was a catastrophic failure of the tank wall, so that glass unintentionally poured out, or the wall was deliberately breached to lower the level of glass and prevent it flowing out elsewhere.
2. The glassworkers patched up or blocked the breach and continued to use the furnace and blow vessels. However, the furnace structure was damaged. More air than typical leaked into the furnace chamber, so that conditions became more oxidising. The oxygen diffused into the glass from the upper surface, and began to turn the upper layers of the glass green.
3. The glassworkers continued to blow greenish vessels, but the furnace was no longer working to full efficiency. The excess air entering the chamber began to

cool the glass. After some time, the glass became too stiff to work and the furnace was no longer fuelled. The remaining glass melt cooled in situ, from the top, where it was less insulated. While the top layers cooled relatively quickly to remain glassy, the slow cooling of the lower layers allowed them to devitrify and form rounded white spherulites and layers of a white crystalline calcium silicate.

4. With a relatively small amount of cullet left to be melted and a failed furnace containing large blocks of devitrified glass which would have been difficult to reprocess, it was not worthwhile for the glassworkers to build a new furnace, and they abandoned their furnace where it stood, without removing the cooled glass. After cooling, the furnace deteriorated naturally or was pulled down by later users of the site. The glassworkers returned to their region of origin, perhaps intending to return at some later time.

The scenario outlined above explains why the Basinghall assemblage is so exceptional. Typically the peripatetic glassworkers would have used up virtually every scrap of glass in their furnace, and would have recycled most of the moils and spills etc. They would have abandon their furnace at the natural end of a cycle, so that, while there may have been green-blue cullet still to use, the tank itself would have been emptied. The large blocks of partially-devitrified glass and the large numbers of moils remaining at Basinghall reflect the catastrophic failure of the furnace and the premature winding down of the glassworking activities. The range of natural colours with an unusually high proportion of greenish glass also reflects this event.

The narrative outlines the history of working of green-blue glass, but what of the coloured and colourless glasses? They would have best been melted in a smaller tank, or in pots or crucibles, to avoid contamination by other colours. However, there is limited evidence for the use of glass pots in Roman glass working at this period, and no evidence for their use at Basinghall. Therefore it seems likely that a tank furnace was used. We have direct evidence only for the single tank in which the final campaign was melted. As glassworking activity appears to have terminated when this furnace failed, it seems probable that it was the only furnace available for glass working at that time. However, the existence of a small subsidiary furnace at some

point might be suggested by the evidence for melting strongly-coloured cobalt blue glass on the site, as it would have been particularly desirable to conserve this glass by using smaller melting containers and to avoid cross-contamination.

It is therefore unclear when in the sequence outlined for the green-blue glasses the batches of colourless glass were melted. There are at least 3 batches of colourless glass, represented by the Sb-colourless moils, the Mn-colourless moils and the “mixed glass” based mainly on the colourless cullet. An understanding of the full significance of the sub-groups within the colourless glasses would require considerably more data, and we cannot be certain that there was more than one period of melting of each type of colourless glass, but it appears at the least that each of the colourless glasses came to the workshop in more than one basket or sack, and that these were used sequentially.

The advantages of using pristine “raw” glass include better colour control and fewer bubbles in the batch. If a single tank furnace was in use, it is likely that colourless glass would have been melted before green-blue, to avoid spoiling the colour. Thus it is suggested that the glassmakers chose to produce colourless glass vessels before the green-blue. This would make sense also as the Price Edicts of Diocletian tell us that colourless glass was more expensive (refs), and it would have probably been advantageous to produce the more expensive items at an early stage, to ensure that they could be sold and also to attract the less affluent customer, who would wait for the cheaper items to be produced.

Concluding Remarks

This investigation represents what is arguably the most detailed analytical investigation of a Roman glass workshop to date. It has delivered a great deal of information about the origins of the glass, the glassworkers, and the history of production. It has allowed us to interpret the archaeological assemblage and to understand the sequence of events which led to the abandonment of the workshop and the failure of the furnace.

There is no doubt that the analytical study would have failed to achieve its potential were not for the extremely painstaking work carried out in sorting and classifying the material in advance of the selection of the sample for analysis. Analysing the right sample is critical in this type of work. Furthermore, the combination of state-of-the-art isotopic and trace element analyses with more routine major element analyses has proved to be immensely valuable. The isotopes proved their potential in allowing the ultimate origins of the glass to be inferred, while the trace elements provided invaluable evidence for the sequence of melting campaigns, the identification of raw glass and the role of cullet as a raw material. These novel findings point to new approaches for the analysis of glass assemblages and it is to be hoped that similar approaches will be adopted elsewhere.

Even so, with the benefit of hindsight, it is clear that we might have selected our analytical material in a slightly different way. We focussed to a considerable degree upon the green-blue and green glasses and in particular the lumps and masses of glass as these represented the furnace at the heart of the workshop. Furthermore, they were the most abundant form of glass and were relatively unusual from a Romano-British perspective. The finding that the vast majority of these were from the same melt was not anticipated and, if it had been, more attention might have been directed to the trace element analysis of the moils, which clearly offers a very powerful technique for unravelling different furnace batches. Although our sample has allowed us to interpret the assemblage in some detail, a modified set of samples, or better still, the addition of more samples, would have improved the outcomes. For the future, the most important methodological lessons of this study are probably the importance of the moil as a source of information and that one could probably double the amount of analysis to optimise the results. This conclusion, however, is the perennial one of the archaeological scientist.

Appendix 1: Analytical Methods

Major element analysis

Small fragments were removed from the edges of sherds of glass and embedded in epoxy resin. The epoxy blocks were ground flat using silicon carbide paper and polished down to 0.25 µm using aqueous diamond abrasive suspensions. They were coated with a thin layer of carbon and analysed in a CamScan Maxim scanning electron microscope fitted with an Oxford Instruments energy dispersive X-ray detector and ISIS spectrometer. Operating conditions were 30° take-off angle, 20kV accelerating potential and 100s livetime, with a count rate of 4000 counts per second on metallic cobalt. The spectrometer was calibrated with pure elements, oxides and minerals and accuracy and precision were monitored using Corning Museum of Glass Ancient Glass Standard B (Brill 1999). In the light of the Corning B results, minor adjustments were made to Na₂O values to correct for instrumental drift. Following previous practice (Freestone et al. 2000), analyses were normalised to 100% for comparative purposes.

Trace element analysis

[TO FOLLOW]

Isotope analysis

The surfaces of small fragments of glass were carefully cleaned with a diamond impregnated burr to remove any surface contamination and corroded glass. Individual samples were then gently crushed to small pieces wrapped in weighing paper. Specimens were first ultrasonicated in deionised water (MQ system) for 15 minutes and rinsed. Ultrasonication was repeated with 2.5M HCl for another 15 minutes. After a second rinse in deionised water samples were dried in cleaned vials and weighed ranging in samples sizes from 6 to 122 mg. A 2:1 mixture of concentrated hydrofluoric and nitric acid was added and the samples fluxed on a hotplate at 180°C with tightly closed lids. Samples were ultrasonicated every 24 hours to allow a better disintegration of the individual glass shards. Within a maximum of five days the samples were completely dissolved. Samples were dried down and re-dissolved three

times in 400 μl concentrated nitric acid. Two millilitres 6M hydrochloric acid were added and the samples ultrasonicated for 15 minutes and fluxed for 24 hours on the hotplate to allow for complete dissolution. After drying the samples were dissolved in 1 ml 1M HCl and Sr and Nd separated following standard separation procedures (Horwitz et al., 1992; Vance and Thirlwall, 2002). Absolute procedural blanks for Sr are below 180 pg and for Nd below 9 pg and are negligible.

Strontium and Nd isotopes were measured on a Thermo Finnigan Neptune Multi Collector-Inductively Coupled Plasma Mass Spectrometer (MC-ICPMS) at the Bristol Isotope Group within the University of Bristol, UK. Interference-corrected $^{87}\text{Sr}/^{86}\text{Sr}$ was adjusted for machine-induced mass bias by normalising to $^{86}\text{Sr}/^{88}\text{Sr}$ of 0.1194. The NBS987 Sr isotope standard reproduced at 0.710254 ± 23 (2σ , $n=19$). All Sr isotope results shown in Table 1 are normalized to a given NBS987 $^{87}\text{Sr}/^{86}\text{Sr}$ of 0.710247. For Nd, correction for the machine-induced mass bias followed Vance and Thirlwall (2002) adjusting the $^{146}\text{Nd}/^{144}\text{Nd}$ to 0.7219. The La Jolla Nd standard yielded an average $^{143}\text{Nd}/^{144}\text{Nd}$ of 0.511865 ± 7 (2σ , $n=20$). Neodymium isotope ratios are normalized to the accepted La Jolla $^{143}\text{Nd}/^{144}\text{Nd}$ of 0.511856. In Table 1 the Nd isotopic compositions are also expressed as ϵ_{Nd} by normalising the sample $^{143}\text{Nd}/^{144}\text{Nd}$ to the Chondrite Uniform Reservoir (CHUR) ratio of Jacobsen and Wasserburg (1980) ($^{143}\text{Nd}/^{144}\text{Nd}_{\text{CHUR}} = 0.512638$):

$$\epsilon_{\text{Nd}} = \left[\frac{{}^{143}\text{Nd}/{}^{144}\text{Nd}_{\text{sample}}}{{}^{143}\text{Nd}/{}^{144}\text{Nd}_{\text{CHUR}}} - 1 \right] \times 10^4$$

References

Baxter, M. J., Cool, H. E. M., Jackson, C. M., 2005. Further studies in the compositional variability of colourless Romano-British glass. *Archaeometry* 47, 47-68

Brill, R. H. (1988) Scientific investigations. In Weinberg G. D., *Excavations at Jalame: Site of a Glass Factory in Late Roman Palestine* University of Missouri, Columbia, pp. 257-294.

Brill R H (1999) *Chemical Analyses of Ancient Glass*. Corning, New York: Corning Museum of Glass.

Degryse P., I. C. Freestone, J. Schneider, S Jennings (forthcoming) Technology and provenance study of Levantine plant ash glass using Sr-Nd isotope analysis. In Keller D (ed) *Proceedings of Mainz Workshop on Byzantine Glass*

Degryse , P. & Schneider , J., 2008. Pliny the Elder and Sr-Nd radiogenic isotopes: provenance determination of the mineral raw materials for Roman glass production. *Journal of Archaeological Science*, 35: 1993-2000.

Degryse , P., Schneider , J. & Lauwers , V., 2006. Sr and Nd isotopic provenance determination of ancient glass. *Annales 17th International Conference of the Association Internationale de l' Histoire de Verre*, Antwerp.

Degryse , P., Schneider , J., Haack , U., Lauwers , V., Poblome , J., Waelkens , M. & Muchez , P., 2006a. Evidence for glass ' recycling' using Pb and Sr isotopic ratios and Sr-mixing lines: the case of early Byzantine Sagalassos. *Journal of Archaeological Science*, 33: 494-501.

Degryse P, Schneider J, Lauwers V, Henderson J, Van Daele B, Martens M, Huisman D J, De Muynck D, Muchez P (2009) Neodymium and strontium isotopes in the provenance determination of primary natron glass production. In Degryse P,

Henderson J and Hodgins G (eds) *Isotopes in Vitreous Materials*. Leuven University Press, pp. 53-72.

DePaulo D.J. and Ingram B.I. (1985) High resolution stratigraphy with strontium isotopes. *Science* 227, 938-941.

Eicholz D. E. (1962) *Pliny – Natural History Books 36-37* Harvard: Loeb Classical Library

Foy D and Jezegou M-P (2004) Sous les vagues de verre. L'épave antique Ouest Embiez I. *Archeologia* 407, 22-31.

Freestone I C (2006) Glass production in Late Antiquity and the Early Islamic period: a geochemical perspective. *Geomaterials in Cultural Heritage* M. Maggetti and B. Messiga (eds) Geological Society of London Special Publication 257, 201-216.

Freestone I (2008) Pliny on Roman glassmaking. In Martinon_Torres M and Rehren Th (eds) *Archaeology, History and Science: Integrating Approaches to Ancient Materials*. University College London: Institute of Archaeology Publications, Left Coast press, Walnut Creek CA; 77-100.

Freestone, I.C., Gorin-Rosen, Y. & Hughes, M.J. 2000. Composition of primary glass from Israel. In: Nenna, M.-D. (ed.) *Ateliers primaires et secondaires de verriers du second millinaire av. J.-C. au Moyen-Age*, Travaux de la Maison de l'Orient Méditerranéen no. 33, Lyon, 65-84.

Freestone, I. C., Ponting, M. & Hughes, M. J. 2002a. Origins of Byzantine glass from Maroni Petrera, Cyprus. *Archaeometry* 44, 257-272.

Freestone I. C., Leslie K. A., Thirlwall M. & Gorin-Rosen Y., 2003. Strontium isotopes in the investigation of early glass production: Byzantine and early Islamic glass from the Near East. *Archaeometry* 45, 19-32

Freestone I C, Wolf S and Thirlwall M (2009) Isotopic composition of glass from the Levant and south-eastern Mediterranean Region. In *Isotopes in Vitreous Materials*, eds P Degryse, J Henderson and G Hodgson. Leuven University Press, pp. 31-52.

Freestone I, Price J and Cartwright C (2009) The batch: its recognition and significance, *Annales 17th Congress AIHV* 130-135

Freestone I, Degryse P, Shepherd J, Gorin-Rosen Y and Schneider J (?2009, to correct ms) Near Eastern Origin of Late Roman glass from London using neodymium and strontium isotopes. *Jour Arch Sci*

Gorin-Rosen, Y. 2000. The ancient glass industry in Israel: summary of new finds and new discoveries. In: Nenna, M.-D. (ed.), *Ateliers primaires et secondaires de verriers du second millinaire av. J.-C. au Moyen-Age*, Travaux de la Maison de l'Orient Méditerranéen no. 33, Lyon, 49-63.

Hess J., Bender M.L., and Schilling, J-G. (1986) Evolution of the ratio of strontium-87 to strontium-86 in seawater from Cretaceous to present. *Science* 231, 979-984.

Horwitz, E.P., Chiarizia, R., Dietz, M.L., 1992. A novel strontium-selective extraction chromatographic resin. *Solvent Extraction and Ion Exchange* 10 (2), 313-336.

Huisman D J, De Groot T, Pols S Van Os B J H, and Degryse P (2009) Compositional variation in Roman colourless glass objects from the Bocholtz burial (The Netherlands). *Archaeometry* 51, 413-439.

Jackson 2005

Jackson, C. M., Hunter, J. R., Warren, S. E. & Cool, H.E.M., 1991. The analysis of blue-green glass and glassy waste from two Romano-British glass-working sites. In: Pernicka E. and Wagner G. A. (eds). *Archaeometry '90*, Birkhauser Verlag, Basel, 295-305.

Jacobsen, S.B., Wasserburg, G.J., 1980. Sm-Nd Isotopic Evolution of Chondrites. *Earth and Planetary Science Letters* 50 (1), 139-155.

Keith H D and Padden F J (1963) A phenomenological theory of spherulitic crystallisation. *J Applied Phys* 34, 2409-2421.

Keller, D. 2005. Social and economic aspects of glass recycling In: Bruhn, J., Croxford, B. & Grigoropoulos, D. (eds.) *TRAC 2004: Proc. 14th Annual Theoretical Roman Archaeology Conference*. Oxbow. 65-78.

Lofgren G (1980) Experimental studies on the dynamic crystallisation of silicate melts. In Hargraves R B (ed) *Physics of Magmatic Processes*. Princeton University Press. 487-551.

Mirti P., Lepora A and Saguì L (2000) Scientific analysis of seventh century glass fragments from the Crypta Balbi in Rome. *Archaeometry* 42, 359-374.

Nenna, M-D., Vichy, M. & Picon, M. 1997. L'Atelier de verrier de Lyon, du Ier siècle après J.-C., et l'origine des verres "Romains". *Revue d'Archéométrie*, **21**, 81-87.

Nenna M-D., Picon M. and Vichy M., 2000. Ateliers primaires et secondaires en Égypte à l'époque gréco-romaine. In : Nenna M.-D. (ed.) *La Route du Verre: Ateliers primaires et secondaires de verriers du second millénaire av. J.-C. au Moyen-Âge*, Travaux de la Maison de l'Orient Méditerranéen no. 33, Lyon, 97-112.

Nenna, M-D., Picon, M., Thirion-Merle, V. & Vichy, M. 2005. Ateliers primaires du Wadi Natrun : nouvelles découvertes. *Annales du 16e Congrès de l'Association Internationale pour l'Histoire du Verre* 59-63.

Picon, M. and Vichy, M. 2003. D'Orient en occident: l'origine du verre à l'époque romaine et durant le haut Moyen Âge. In : Foy, D. and Nenna, M.-D. (eds.). *Échanges et Commerce du Verre dans le Monde Antique*. Éditions Monique Mergoïl, Montagnac, 17-31.

Price, J, Freestone I C and Cartwright C R C (2005) 'All in a day's work?' The colourless cylindrical glass cups found at Stonea revisited. In N Crummy ed., *Image, Craft and the Classical World. Essays in honour of Donald Bailey and Catherine Johns*. Collection 'Monographies Instrumentum' no 29. Montagnac, éditions Monique Mergoïl, 163-169

Scheurs and Brill 1984

Shortland, A.J. 2004. Evaporites of the Wadi Natrun: seasonal and annual variation and its implication for ancient exploitation. *Archaeometry*, **46**, 497-516.

Shortland A, L Schachner, I Freestone and M Tite (2006) Natron as a flux in the early vitreous materials industry –sources, beginnings and reasons for decline. *Journal of Archaeological Science* 33, 521-530.

Sylvestri, A, Molin G and Salviulo G (2006) Sand for Roman glass production: an experimental and philological study on source of supply. *Archaeometry* 48, 415-432.

Taylor S.R. and McLennan S.M. (1985) *The Continental Crust: Its Composition and Evolution*. Oxford: Blackwell.

Vance, D., Thirlwall, M., 2002. An assessment of mass discrimination in MC-ICPMS using Nd isotopes. *Chemical Geology* 185 (3-4), 227-240.

Wedepohl K. H. and Baumann A. (2000) The use of marine molluscan shells for Roman glass and local raw glass production in the Eifel area (Western Germany). *Naturwissenschaften* 87, 129-132.