

The Composition and Production of Anglo-Saxon Glass

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Introduction

The chemical composition of Anglo-Saxon glass has been the subject of a number of published studies over the past three decades (e.g. Sanderson *et al.* 1984; Henderson 1993b; Hunter and Heyworth 1998).¹ However, there has been limited success in relating glass composition to broader aspects of the processes of production and distribution. Ironically, one reason for this may result from the focus upon glass from Britain and, until recently, the dearth of analyses of early medieval glass from other regions. Without a more general context of glass technology and production in Late Antiquity and the early medieval period, an understanding of the specific conditions in a peripheral area such as Britain has inevitably been difficult to attain. For this reason we have conducted, in parallel to our study of Anglo-Saxon glass, an investigation of the major glass-producing industries of the eastern Mediterranean, which began under the auspices of the British Museum's *Glass After Rome* project, sponsored by the Renaissance Trust (for recent summaries see Freestone 2005; 2006). Furthermore, the corpus of early medieval glass analyses from elsewhere in Europe has significantly expanded in recent years (Wedepohl 1997; Wedepohl, Pirling and Hartmann 1997; Wedepohl, Winkelmann and Hartmann 1997; Wolf *et al.* 2005; Mirti *et al.* 2000; 2001; Verità 1995), and allows more detailed inter-comparisons to be made. Comparison of Anglo-Saxon glass with glass from these areas allows a model for glass production in early medieval Europe to be developed.

The raw materials and technology of early glass – background

Previous studies have shown that Anglo-Saxon glass is *soda-lime-silica* glass, composed predominantly of the oxides of sodium, calcium and silicon. Most of the glass of the ancient and early medieval world, from western Europe through to central Asia, is of this fundamental type, as is modern container glass. It was demonstrated by Sayre and Smith (1961), that ancient soda-lime-silica glasses falls into two principal sub-groups. *Low-magnesia, low-potash* glasses, with the oxides of potassium (K_2O , potash) and magnesium (MgO , magnesia) each below about 1.5%, are characteristic of the Roman world and were the dominant glass type from the middle of the 1st millennium BC until the 9th century AD. On the other hand, *high-magnesia, high-potash* glasses, with K_2O and MgO in excess of 1.5% are found throughout the Near East before the 7th century BC, in the Islamic world after the 9th century AD and increasingly in Europe from about the 12th century.

There is general agreement on the interpretation of the two main types of soda-lime-silica glass. The high-magnesia, high-potash type was produced using a soda-rich plant ash as a flux. The use of such ashes is widely recorded in traditional Near Eastern glassmaking, and later they were extensively imported

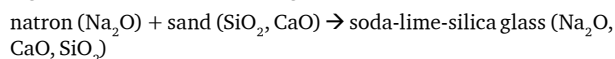
into Europe to be used, for example, by the Venetian glass industry (Ashtor and Cevdalli 1983). Produced by burning halophytic plants (those adapted to growing in a saline environment) from the desert, or from a brackish water environment, such ashes are typically rich in both soda and lime, and also contain significant amounts of potash and magnesia (Brill 1970; Verità 1985). To make a glass from using such a material would have involved mixing an appropriate proportion of ash with a relatively pure source of silica, such as quartz-rich sand or crushed quartz pebbles. Glass of this type will be termed *soda ash* or *plant ash* glass.

To produce low-magnesia, low-potash glass a relatively pure inorganic or mineral soda source was utilised. Natron from Egypt was a major source of soda for glassmaking, according to Pliny (Eicholz 1962). Indeed, at the present time, the only generally recognised sources of such material in the ancient world are in Egypt, particularly the Wadi Natrun, some 50km northwest of Cairo, where trona, a sodium carbonate mineral, is deposited as an evaporite from a series of lakes. Substantial glassmaking remains have been documented in this area (Nenna *et al.* 2000; 2005). Glasses of this type are generally termed *natron* glasses.²

Previous studies (Sanderson and Hunter 1981) have indicated that Anglo-Saxon glass, like the Roman glass that preceded it, is composed predominantly of low-magnesia, low-potash natron glass. However, from the 8th or 9th century AD new glass compositions, rich in potash (potassium oxide), begin to appear in northwestern Europe and these replace natron glass over several centuries (Sanderson and Hunter 1981; Henderson 1993b; Wedepohl *et al.* 1997; Wedepohl 2003). The potash-rich composition reflects the use of the ashes of inland trees, such as beech, in the manner described by Theophilus in the early 12th century (Hawthorne and Smith 1979). It is significant that, at the time that natron-based glass was being supplanted in the northwest, it was displaced almost entirely in the East, where a change from natron to soda ash glass occurred in the late 8th–9th centuries (Sayre and Smith 1974; Gratuze and Barrandon 1990; Freestone and Gorin-Rosen 1999). It is not unreasonable to suppose that the same or similar factors were responsible for a similar technological change occurring in both regions and that difficulty in the procurement of natron, or of glass made using natron, is likely to have been important in this context. This restriction in the supply of natron has been linked to political events in the Delta region of Egypt (Whitehouse 2002; Shortland *et al.* 2006). The linkage of major technological change in glassmaking in northwestern Europe and the Near East is very significant in terms of understanding glass production in the 1st millennium AD, as it suggests that the glass supplies of both regions were largely dependant upon the same source of natron.

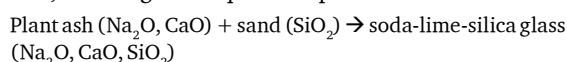
Lime (calcium oxide, CaO) is a critical component of soda-

lime-silica glass for, if it is not present in concentrations more than a few weight percent, the glass is readily attacked by water. Most authors consider that most ancient and medieval glass was made by mixing two components, alkali and silica (Brill 1988; Freestone and Gorin-Rosen 1999; Henderson *et al.* 2004). Thus natron, a relatively pure form of soda, was mixed with a sand that, in addition to grains of quartz, contains just the right amount of lime, as fragments of shell or limestone:



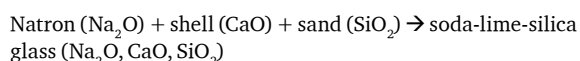
This is the approach that appears to have been used by many of the major glass producers of the Near East in the 1st millennium AD (Brill 1988; Nenna *et al.* 1997; Freestone, Gorin-Rosen and Hughes 2000; Freestone, Leslie, Thirlwall and Gorin-Rosen 2003; Freestone 2006).

Plant ash is usually rich in lime as well as alkali. If an ash was melted with a calcareous sand similar to those believed to have been used to produce natron glasses, the resultant glass would have a very high lime content, derived from both raw materials. This would have made it more difficult as a material from which to shape glass vessels as it would have required higher working temperatures and also would have tended to devitrify to calcium silicates, so that it was hard to manipulate on the blowpipe and brittle when cooled. An example of such a failure appears to be the 8-tonnes slab of glass at Beth She'arim in Israel (Fig. 1), which probably dates to around the 9th century (Freestone and Gorin-Rosen 1999). It has a high lime content, about twice the typical value of most soda-lime-silica glass, and has formed extensive calcium silicate crystals. When making glass from using plant ash, glass makers therefore typically used sands which were low in lime, or other sources of silica, such as ground quartzite pebbles:



It can be seen that the composition of the glassmaking sand was very important and, in particular, the lime content was critical to the manufacture of a successful glass. The coastal sands of the Levant commonly contain about the right amount of lime to make a stable glass with added natron, which probably explains the importance attributed to them by classical authors such as Strabo and Pliny (Trowbridge 1930; the compositions of the sands are discussed by Freestone 2006).

It should be noted that some authors have preferred a procedure whereby glass was made by mixing three materials - natron, silica sand and lime, the latter being added separately as crushed marine shell or limestone:



Wedepohl and Baumann (2000) have presented a strong case for such a practice in the Eifel region of Germany in the 4th century, although other studies suggest that the evidence is less compelling than might initially appear (Freestone, Leslie, Thirlwall and Goren-Rosen 2003; Freestone, Wolf and Thirlwall 2005). In this account we follow the two-component model.

The division of glass production in the Near East

The traditional approach to the chemical analysis of glass was strongly influenced by writers of the medieval and early-



Figure 1 The glass slab at Beth Shearim, Israel. The slab weighs around 8 tonnes and is believed to have been melted from a mixture of sand and soda *in situ*. It was off-composition, so abandoned. (Photo: Freestone/Milton)

modern periods and by the organisation of forest glass production in late-medieval and post-medieval Europe. It assumed that each glass-worker obtained his glassmaking sand locally, or at least within his region, and melted the local sand with imported alkali in the workshop where he fabricated vessels. As summarised in Fig. 2, this model implied that the glass vessels produced by each workshop have a characteristic chemical fingerprint which allowed their source to be identified. Anticipating that certain vessel forms were made in specific workshops, a relationship between composition and form was anticipated. Such patterns have not been observed in glass of the 1st millennium AD and it has become clear that a very different model applies to most glass production in this period.

Recent archaeological evidence from the eastern Mediterranean region, summarised by Nenna *et al.* (2000) and Gorin-Rosen (2000) suggests that, from Roman times through to the Islamic period, the practice of making glass from its raw materials was carried out in a relatively limited number of locations (see Aldsworth *et al.* 2002 for 10th-century furnaces in Tyre). These were separate from the workshops where the glass was worked into vessels or windows. The installations where glass was made appear to be located near sources of raw materials, such as natron and sand. Rectangular tank furnaces described from sites in the coastal strip of modern Israel, such as Beth Eli'ezer (Hadera; Gorin-Rosen 1995; 2000) and Appolonia-Arsuf (Tal *et al.* 2004) produced massive blocks of glass weighing of the order of 8 tonnes, similar to the slab at Beth She'arim (Fig. 1). Their location undoubtedly owes much to the high-quality glassmaking sands of the eastern Mediterranean coast. Other installations that specialised in the production of raw glass have also been reported from Egypt, particularly in the vicinity of the Wadi Natrun, where the famous sources of natron were located. These large masses of glass were broken up into chunks and distributed to workshops where they were remelted to be made into vessels, windows, beads etc. In particular, work by Danielle Foy and colleagues

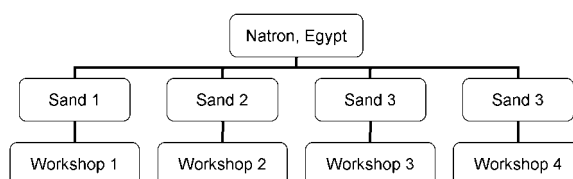


Figure 2 Chart showing the traditional model for natron-based glass production. Imported natron was blended with sand in individual glass workshops. Each workshop would have produced glass of distinctive composition.

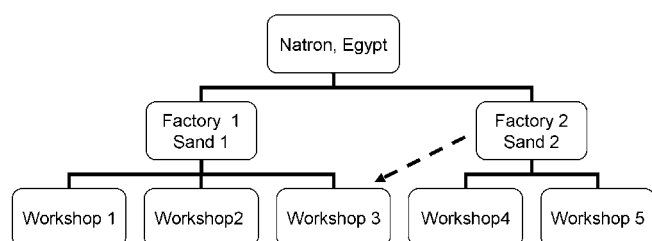


Figure 3 Revised model for natron-based glass production. Natron is melted with sand in primary production centres, and raw glass is distributed to workshops. The composition of the glass represents that of the primary glassmaking sand, so that many workshops can make vessels of the same composition, and a single workshop, shown here as number 3, may in principle produce vessels from more than one primary glass.

has demonstrated that glass chunks were traded throughout the Mediterranean and into southern Europe in the Roman period (Foy, Picon and Vichy 2000; Foy, Vichy and Picon 2000; Foy, Picon, Vichy and Thirion-Merle 2003), while it has been suggested that all Roman blue-green transparent glass originated in Palestine (Nenna *et al.* 1997; 2000; Picon and Vichy-Merle 2003). Unfortunately, archaeological evidence for the glassmaking furnaces which melted Roman blue-green glass has yet to be discovered. However, there is increasing evidence that raw glass produced in this region in the Byzantine and early Islamic periods was widely traded in the eastern Mediterranean (Freestone, Gorin-Rosen and Hughes 2000; Freestone, Greenwood and Gorin-Rosen 2002; Freestone, Ponting and Hughes 2002). This division of production between *primary workshops*, that made raw glass from sand and alkali, and *secondary workshops*, that fabricated vessels from raw glass, has major implications for the interpretation of glass chemistry. The chemical compositions of glass vessels primarily reflect the location of the primary workshop, rather than the workshop that made the vessel. Thus, depending upon the extent of the trade in raw glass, widely separated workshops may produce vessels of the same compositions, while a single workshop may, in principle, produce vessels of very disparate compositions, reflecting supplies of raw glass from more than one primary glassmaking installation, as shown in **Fig. 3** (Freestone, Ponting and Hughes 2002). The relationship of glass production in early-medieval north-western Europe to the glass makers in the Byzantine and Islamic Near East has yet to be fully established. However, the major Near Eastern factories were producing large quantities of unfinished glass, and it would be surprising if their influence was not felt in some way, if not directly. Recently we have suggested that the glass used to make the windows in the monastery at Jarrow, Northumbria, was originally derived from sources in Egypt or the Levant (Freestone 2003; Freestone and Hughes 2006).

Possible origins of Anglo-Saxon glass in Britain

In the light of the division of production model and our general understanding of glass compositions in the 1st millennium AD, the glass from which Anglo-Saxon glass vessels were made could have originated in a number of ways. First, it could have been made in Britain or the near continent, using local sands and imported natron, according to the traditional model (**Fig. 2**). A second possibility is that, following the departure of Rome, British glassworkers continued to recycle old Roman vessels and windows, resulting in a progressively diminishing

and deteriorating stock of material. Thirdly, the supply of fresh glass from abroad that appears to have existed during the 1st–4th centuries may have continued after the departure of the Roman army. If so, it is of interest to determine if the source area of the glass is likely to have remained the same, or if there was a change in trading conditions and routes, opening up supplies from other sources.

In terms of quantity, the relatively small amount of glass recovered from the early to middle Saxon periods allows any of these models. However, it will be seen that chemical analysis can help to resolve the issue. Our intention here is to determine the ultimate source of the glass with a view to understanding how raw material availability may have affected glass vessel production in early-medieval Britain.

Analysis

Glass analysed

We have analysed 29 glass vessels, comprising those from the British Museum collection that were fragmentary and could therefore be sampled without risking their integrity. Three vessels included had been analysed in the context of an earlier programme (Bimson and Freestone 2000). The analysed glasses date to AD 400–700, and are evenly spread between Vera Evison's Periods I (AD 400–550) and II (AD 550–700) (2000 and this volume). Although a relatively small group, this represents in excess of 5% of the total glass vessels recovered from early Anglo-Saxon England, according to the estimates of Evison (2000). Thus, in the present context, this sample, although arbitrary, is statistically significant. Details of the analysed vessels are given in **Table 1**.

Analytical methods

For the determination of major elements, small fragments were removed from the selected glasses, set in epoxy resin blocks, ground flat and polished using diamond pastes down to 1 μ m grade. The polished sections were vacuum-coated with a thin conductive layer of carbon and analysed for major elements in a JEOL JSM 840 scanning electron microscope, using an Oxford Instruments ISIS energy dispersive X-ray spectrometer, with a GEM germanium detector (SEM-EDXA). Conditions were 35° take-off angle, beam current of 1.7 nA, accelerating potential 15 kV and counting livetime 200 s. Count rate on metallic cobalt was around 3000 cps.

The X-ray spectrometer was calibrated using pure elements, oxides and simple compounds of known composition. Results were checked against Corning Museum ancient glass standards A and B (Brill 1999), along with a number of commercially available glass standards. On the basis of the standard analysis, it is expected that a single analysis is within 2% relative of the SiO₂ content, 4% of the Na₂O and CaO, 6% of the Al₂O₃ and 20% of the MgO and K₂O (Freestone, Gorin-Rosen and Hughes 2000).

For trace elements, small fragments of a subset of 15 of the sampled glass fragments were abraded using a diamond burr to remove weathered material, then powdered in an alumina ball mill. Samples of c. 20 mg were accurately weighed into 10 ml PTFE beakers with covers and digested with hydrofluoric and nitric acids. After evaporation to dryness, including a repeated addition of nitric acid, the residue was taken up in 20 ml dilute nitric acid with a small amount of hydrochloric acid added.

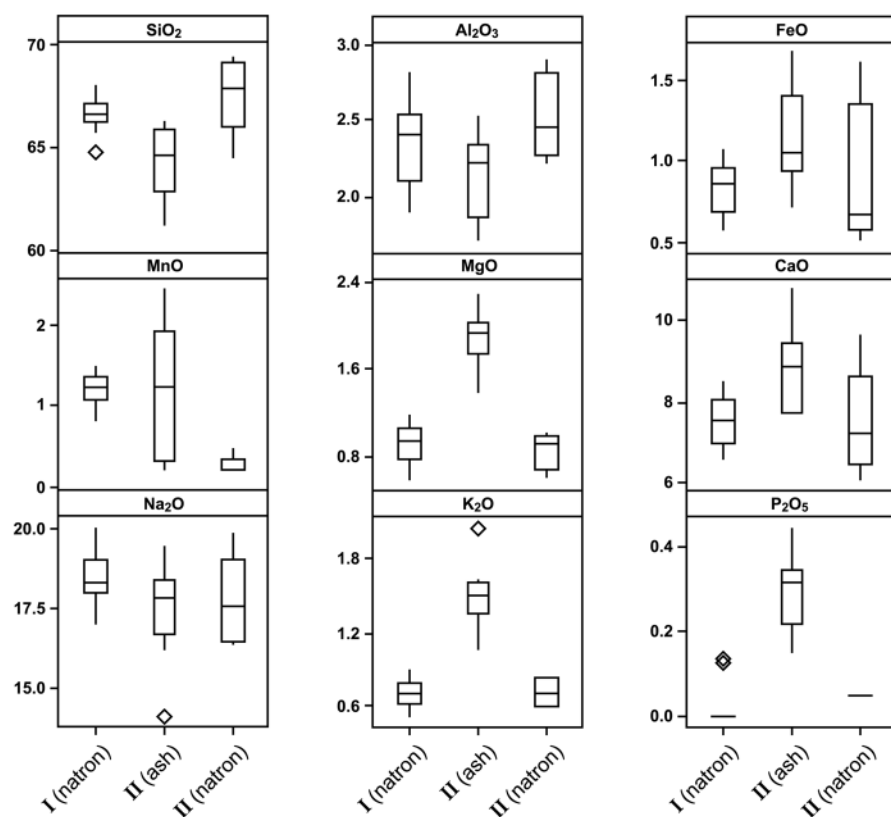


Figure 4 Box and whisker plots for major and minor oxides in Anglo-Saxon glasses. Each panel shows the variation of the oxide indicated at the top. The glasses have been subdivided into Period I (all are natron glass), Period II (ash-bearing glasses) and Period II (natron glasses). The boxes indicate the interquartile range (i.e. the compositional range of the central 50% of samples) and the whiskers indicate the full range, excluding outliers which are shown as diamonds. The lines through the boxes are median values.

These solutions were submitted for analysis using inductively coupled plasma mass spectrometry (ICP-MS) to CARE, Imperial College, London, under the supervision of Dr J.G. Williams.

Sb, Sn, Cu, Pb were analysed by inductively coupled plasma atomic emission spectrometry (ICP-AES) by M.J. Hughes at the Natural History Museum, London, using aliquots of the solutions prepared for ICP-MS analysis.

Results of SEM-EDXA and ICP-AES analyses are given in **Table 2**, and of ICP-MS analyses in **Table 3**.

Results and interpretation

As anticipated, all vessels analysed are of soda-lime-silica glass (**Table 2**). However, preliminary inspection reveals clear differences in the assemblages from Periods I and II. Period I vessels show typical characteristics of glass made using natron, with magnesia and potash below 1% each. Most Period II glasses, however, contain higher MgO and K₂O, in some cases in excess of 2% each. In addition a smaller group of Period II vessels are more typical of natron glass. These findings are summarised in the box and whisker plots of **Fig. 4**, which also shows that the Period II natron glasses are distinguished from those of Period I by their much lower manganese oxide (MnO) contents.

Interestingly, beyond the fact that the deep blue vessels are coloured by cobalt, at 300–500ppm (= parts per million; 500ppm = 0.05 weight per cent; **Table 3**) there appears to be little relationship between glass colour and elemental composition. Blue-green and red-brown vessels may each have high or low contents of iron and manganese oxides, which are the only colourants present in significant quantities. This suggests a different melting history for glass of each colour, so that some are more or less oxidised than others.

Anglo-Saxon vessel glass, Period I (c. AD 400–550)

Period I vessels (about AD 400–550) comprise claw and cone beakers. Soda contents vary from 17.0–20.4% by weight, and are typically around 18%, while lime varies from 6.8–8.5%, but is typically 7–8% (**Table 2**, **Fig. 4**). Potash is typically below 1%, while magnesia can be quite high for natron glass but is variable, between 0.58% and 1.17%. Alumina (Al₂O₃) is also variable, 1.88–2.8%, but within the range typical for glasses of the 1st millennium AD. Iron oxide (FeO) is on the high side, with a range 0.56–1.06%. Iron is a strong colourant of glass in the reduced state, but high levels of manganese oxide (0.83–1.50% as MnO) appear to have been added to oxidise the iron and minimise the colouration effect.³ There appear to be no special compositional characteristics that distinguish the cone from the claw beakers and the Period I vessels appear to comprise a relatively coherent compositional group. In a general sense, they are similar in composition to natron glasses believed to have been made in the eastern Mediterranean region, and a detailed comparison is worthwhile.

In previous work, we have identified at least five major glass production groups in the Levant and Egypt between the 4th–9th centuries AD (Freestone, Gorin-Rosen and Hughes 2000; Freestone, Greenwood and Gorin-Rosen 2002; Freestone, Ponting and Hughes 2002). All are natron-based glasses and each is believed to represent a particular glassmaking centre. These groups are shown in **Fig. 5**, which is a plot of lime (CaO) versus alumina (Al₂O₃). These oxides are particularly useful in the discrimination of production centres of natron-based glasses, as they reflect the amounts of lime (in the form of shell or limestone) and feldspar in the sands used to make the glasses. Each group therefore reflects the use of a different source of sand and production in a different location.

Of the groups shown in **Fig. 5**, only the *Beth Eli'ezer* group can at present be allocated to its precise source with complete

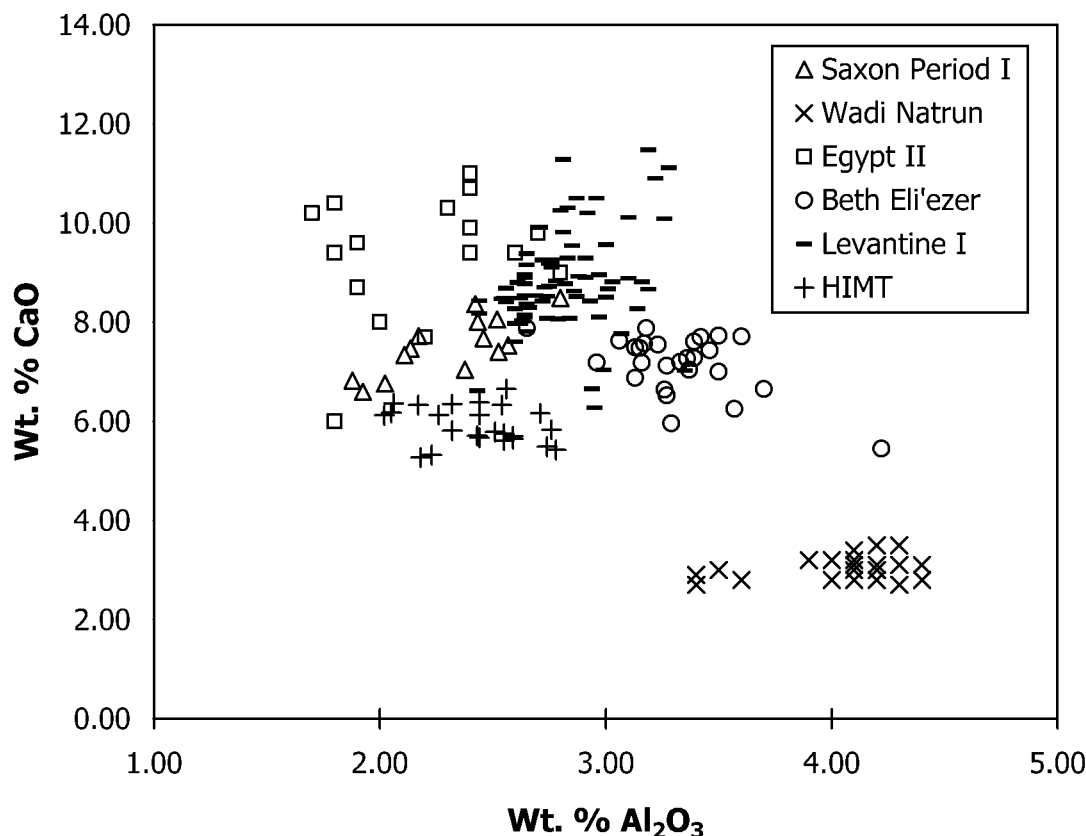


Figure 5 Lime versus alumina for selected glass groups of the 1st millennium AD and for Anglo-Saxon Period I glass.

confidence as the samples were collected from the glassmaking furnaces at this important site near Hadera in Israel (Freestone, Gorin-Rosen and Hughes 2000). The *Wadi Natrun* group is based mainly on analyses of Egyptian Islamic glass coin weights (7th–8th centuries; Gratuze and Barrandon 1990), but is linked to the Wadi by well-provenanced samples of similar low-lime, high-alumina composition from the glassmaking furnaces there (Sayre and Smith 1974; Nenna *et al.* 2000). The *Levantine I* group appears to have been the dominant glass type in Israel between 4th–7th centuries and is the type particularly characterised by glass from Jalame (Brill 1988), but also other sites including Beth Shean, Dor and Apollonia (Freestone, Freestone, Gorin-Rosen and Hughes 2000); it is believed to have been made using the famous Belus sand from the Bay of Haifa. The *Egyptian II* group, identified by Gratuze and based on his analysis of Islamic coin weights (Gratuze and Barrandon 1990), was utilised in Palestine in the 8th–9th centuries, for example at Ramla (Freestone, Greenwood and Gorin-Rosen 2002) and also in the workshop at Tell el Ashmunein, Egypt (Bimson and Freestone 1985). Finally, HIMT glass is a category introduced across the Roman world from the mid- to late 4th century. The term HIMT was derived from the High Manganese, Iron and Titanium contents of a group of unformed chunks of glass from 4th–6th centuries contexts in Carthage (Freestone 1994); Mirti *et al.* (1993) identified a similar compositional group from 4th-century contexts at Aosta, Italy, where it replaces earlier low-iron Roman glass. Recently, further evidence of a trade in unformed chunks of this glass has been presented by Foy, Picon and co-workers (2000; Foy, Picon, Vichy and Thirion-Merle 2003). We have identified HIMT glass in Italy, London, North Sinai and Cyprus (Freestone, Greenwood and Gorin-Rosen 2002; Freestone, Wolf and Thirlwall 2005). HIMT glass can be separated from

other glass groups by its lime and alumina contents (**Fig. 5**) but is particularly distinguished by high iron, titanium, manganese and magnesium oxides. A summary of the major element, trace element, strontium and lead isotope compositions of HIMT has recently concluded that it represents a single glass source, probably in Egypt, which was supplying most of the Roman world in the 4th–5th centuries (Freestone, Wolf and Thirlwall 2005). Further compositional groups of glass in use in the 1st millennium AD have been recognised by Foy and co-workers (Foy, Picon and Vichy 2003; Foy, Picon, Vichy and Thirion-Merle 2003).

The spread of the Period I data in **Fig. 5** appears very similar to the spreads of the groups that are believed to represent major glassmaking (as opposed to glass-working) centres. It suggests that Period I glass is likely to have been derived ultimately from a single primary production centre, and represents the use of a single glassmaking sand, probably from a single factory. One glass, the blue-green claw beaker from Faversham (**cat. no. 59**) lies somewhat to the upper right of the rest of the group in this diagram (**Fig. 5**), but there are no other features in its composition to suggest that it is an outlier.

The high iron, magnesium and manganese oxide contents of the Saxon Period I glasses resemble those of HIMT glass, which was in use in Britain immediately before the withdrawal of Rome. In particular, both HIMT and Period I glasses show distinctive positive correlations of FeO, MgO, MnO and Al₂O₃ (e.g. **Fig. 6**). However, the iron and titanium contents of Period I glasses are relatively lower, so that the slopes of the correlations are different (**Fig. 6**). Furthermore Period I glass has higher CaO contents than 4th-century HIMT glass (**Fig. 5**), and there is a positive correlation between CaO and Al₂O₃, whereas in HIMT these components tend to show a slight negative correlation. Even so, the similarities in behaviour of

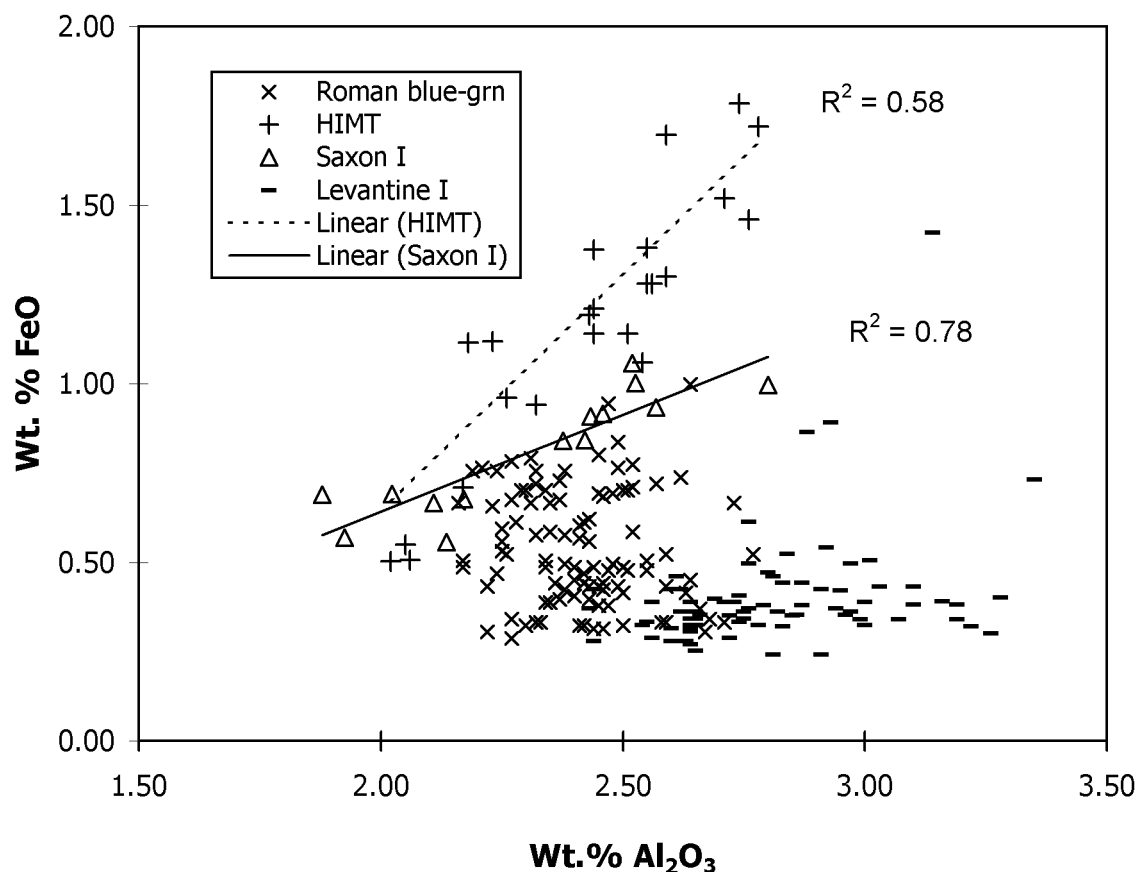


Figure 6 Iron oxide versus alumina for Anglo-Saxon Period I glass, late-Roman HIMT glass (Mirti *et al.* 1993), Roman 1st–3rd centuries blue-green glass (Jackson 1994; Jackson *et al.* 1991) and Levantine I glass (Freestone *et al.* 2000). Note the strong positive correlation coefficients (R) for Saxon I and HIMT.

the various elements suggests that the Period I glasses are related to HIMT either technologically, or geochemically, or both.

In the past it has been considered that the higher FeO and TiO₂ (titanium dioxide) contents of Anglo-Saxon relative to Roman glasses indicate different sand sources, which by implication excludes the possibility that the recycling of Roman glass explains the similar Anglo-Saxon composition (Sanderson and Hunter 1984). Certainly, it appears to exclude the recycling of Roman glass of 1st–3rd centuries, which is clearly distinct from HIMT and Period I Saxon vessel glass (Fig. 6). However, as it is now understood that high-iron and titanium HIMT glass was widely used in the late Roman period, an argument based solely upon these elements is not valid. The more detailed compositional distinctions between 4th-century HIMT glass and Saxon Period I vessels noted in the present study (Figs 5, 6) appear to rule out Saxon I as representing a reservoir of old recycled Roman glass, although some aspects of its composition could be replicated by a mixture of earlier types, such as 3rd-century Roman blue-green and HIMT glasses.

The trace element composition of a glass can provide some evidence of recycling or mixing. When glasses are recycled, the colours are rarely separated perfectly, and some coloured glass becomes incorporated in the cullet (broken vessels). The remelted batch will therefore include additional colourant elements, such as cobalt, copper and lead, in excess of levels typically found in glass newly made from raw materials (Jackson *et al.* 1995; Mirti *et al.* 2000; Freestone, Ponting and Hughes 2002). Figure 7 shows profiles for the concentrations of cobalt, copper, zinc, lead and silver in several series of glass

samples. The typical profile for a glass with little or no contamination from old coloured glass, is that shown for glass from Levantine sites, which is a simple curve, with no or a very limited inflection around Zn. The Period I glasses, however, show a much more marked M-type profile (Fig. 7); in particular, lead occurs in concentrations of several hundred ppm in most of the glasses analysed. Such high concentrations of lead are not typical of glassmaking sands and are likely to represent contamination of the batch by lead from recycled cullet. Lead may be expected to have occurred in a range of strongly-coloured or opaque glasses, and would become elevated as small quantities of these were incorporated in batches of recycled material. This indicates that the Period I glass contains some recycled material, although it is not possible to realistically estimate the amount of recycling at this stage.

In spite of this evidence for some recycled component in the Period I Saxon glass, it seems unlikely that it represents mainly recycled earlier material, for example a mixture of HIMT and earlier Roman glass. If this were the case, linear correlations such as those between iron and aluminium oxides (Fig. 6 and also Fig. 8, below), would not have been maintained.

An alternative approach to the origin of the Anglo-Saxon glass is to compare it with contemporary material from elsewhere. Table 4 compares the mean composition of Saxon Period I vessel glass with analyses of glass from a number of early-medieval sites from elsewhere in Europe, reported in the literature: Frankish glass from Krefeld-Gellep, Germany (Wedepohl, Winkelmann and Hartmann 1997), Merovingian glass from Vicq, France (Velde 1990, 210; see Servat 1984, 1989 for the site⁴) and slightly later 7th-century material from the

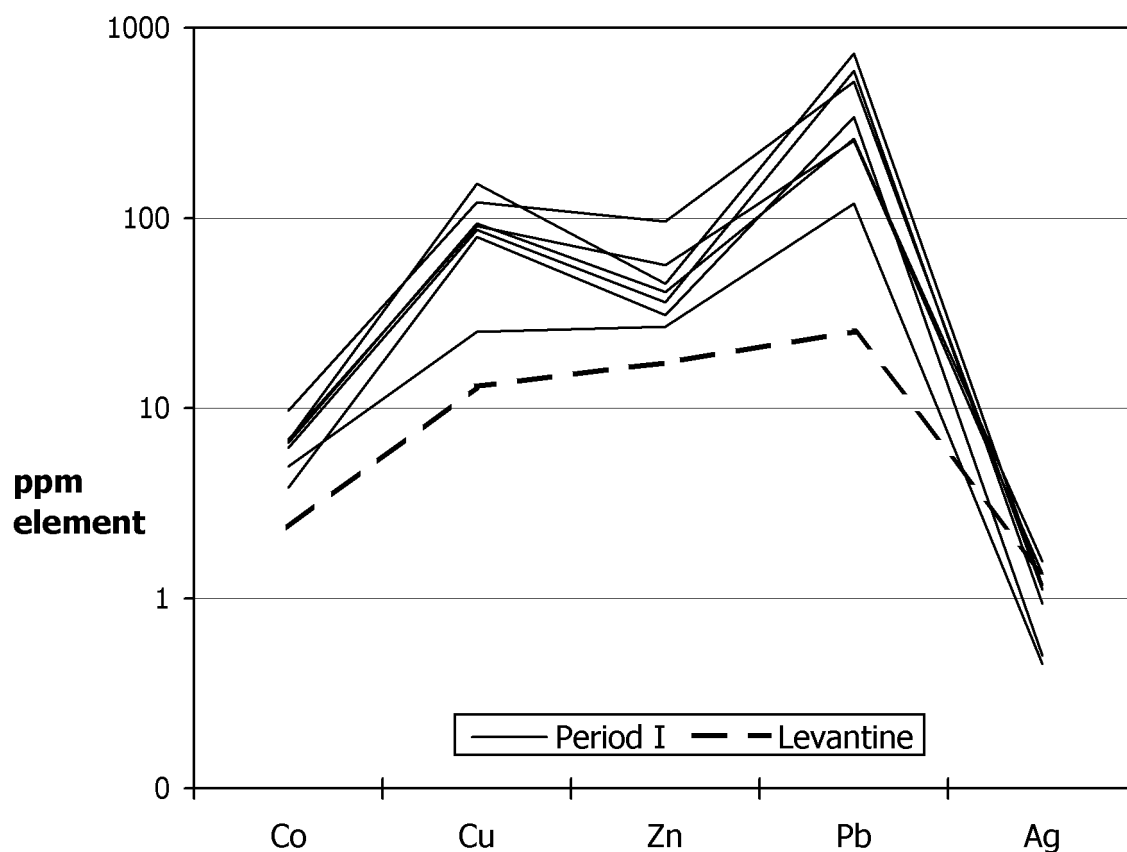


Figure 7 Concentrations of colourants and related elements in individual Anglo-Saxon Period I glasses and in the mean of 14 Levantine glasses from Beth Eli'ezer and Apollonia, Israel. Note that the scale is logarithmic.

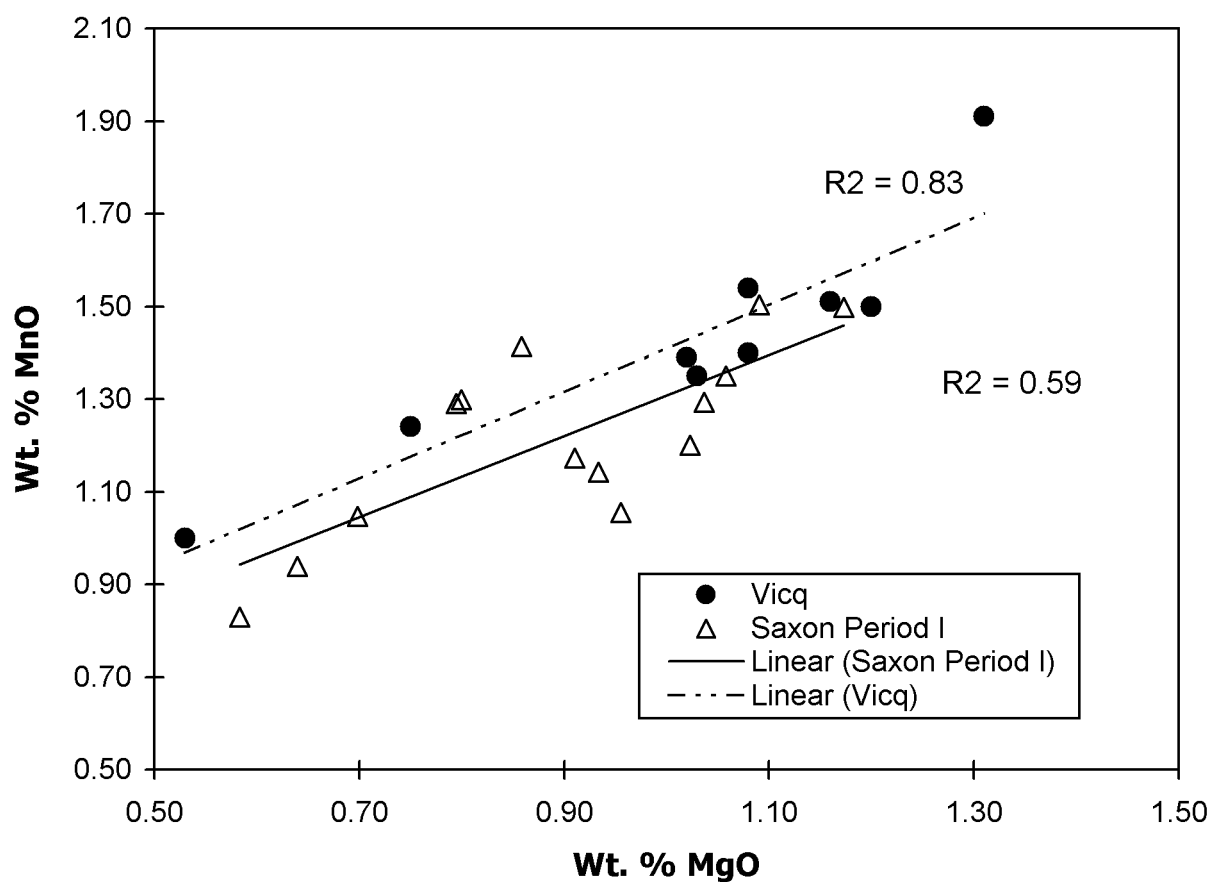


Figure 8 MnO versus MgO for Anglo-Saxon Period I glasses and Merovingian glasses from Vicq. Note the virtually identical correlation trends.

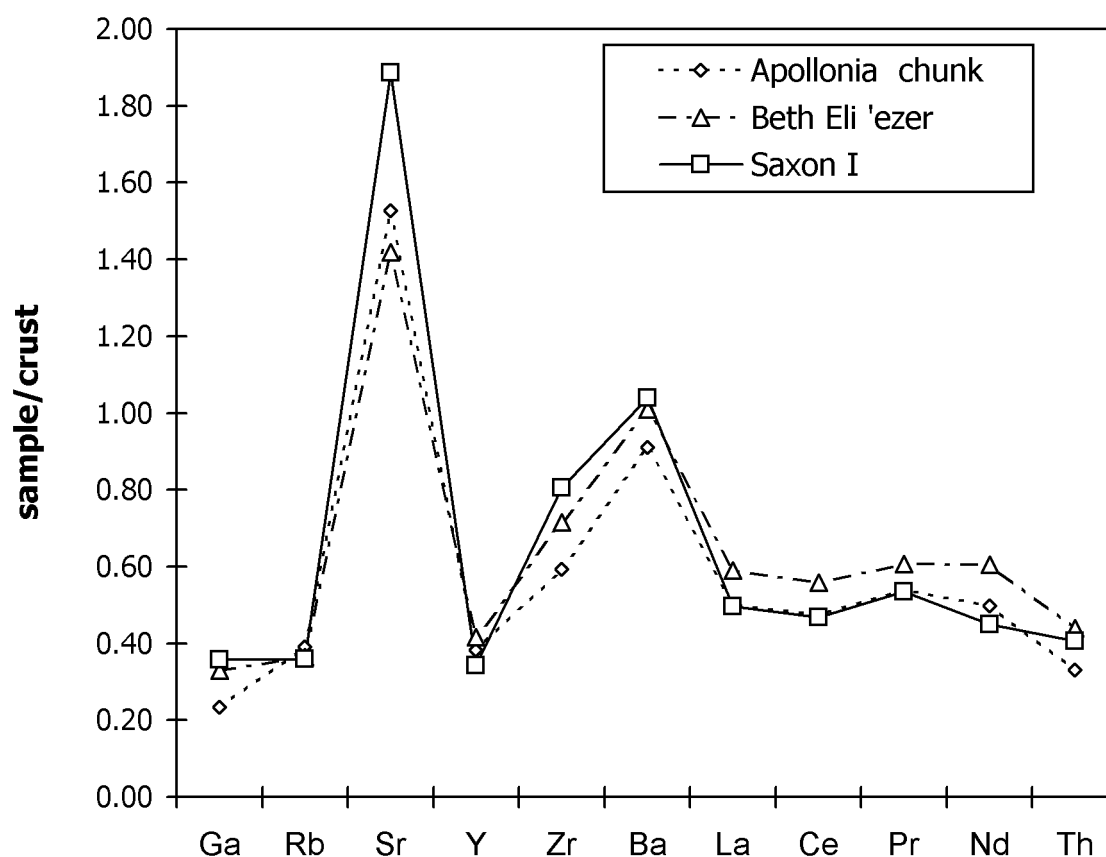


Figure 9 Trace elements in Anglo-Saxon Period I glasses (mean of 8) and Levantine glasses from Apollonia (mean 4) and Beth Eli'ezer (mean 5). The raw concentrations have been normalised by dividing them by the mean composition of the continental crust.

Crypta Balbi, Rome (Mirti *et al.* 2000). These compositions are very similar. All are characterised by high FeO, MgO, MnO and (where analysed) TiO₂ relative to, for example, most Roman or Levantine glasses. Like the Anglo-Saxon vessels they share this characteristic enrichment with HIMT glass, although they differ in degree. A very close relationship is shown between the Anglo-Saxon Period I glasses and the Merovingian glasses from Vicq, which are similar in many details, including the correlations between aluminium, iron, manganese and magnesium oxides (e.g. Fig. 8). The close compositional similarities shown by the Period I glass to roughly contemporary assemblages elsewhere in Europe suggests that it represents a widely traded glass type. Where this glass originated cannot be stated with certainty, but the parallels with HIMT glass – enrichment in FeO, MgO, MnO and strong correlation of these with Al₂O₃ – suggest a similar origin. Raw HIMT glass is likely to have been produced on the south-eastern coast of the Mediterranean, between the mouth of the Nile and Gaza, as suggested elsewhere (Foy *et al.* 2003; Freestone, Wolf and Thirlwall 2005). To determine if Period I glass is likely to be of similar origin, we may compare its trace elements with those of glasses known to have been made in the south-eastern Mediterranean region.

Following our earlier approach (e.g. Freestone, Ponting and Hughes 2002; Freestone and Hughes 2006), we have selected a range of trace elements in the glasses which are unlikely to have been constituents of colourants inadvertently added in a recycling process (p. 34, above) but to reflect the sand or sands used in the manufacture of the base glass. We have normalized the compositions of these glasses to the average composition of the continental crust (Taylor and McLennan 1985). **Figure 9**

compares the mean trace element compositions of seven Period I glasses with the means of glasses from Beth Eli'ezer and Apollonia on the Levantine coast. The compositional profiles are very similar, although not identical. As has been argued elsewhere (Freestone 2006), the trace element compositions of the eastern Mediterranean beach sands between the Nile and Haifa are likely to show strong geochemical similarities, as the mineral assemblages of the sands of this coast are largely derived from the sediment load of the Nile and are moved up the eastern coast of the Mediterranean by longshore drift and tidal currents. Local variations, however, will be expected. The HIMT group, for example, which appears to originate close to the Nile, has variable and high zirconium and barium relative to Palestinian glasses (Freestone, Ponting and Hughes 2002). The trace element compositions of the glasses are consistent with the idea that the Period I glasses were made from the coastal sands of the Levant, or from the geochemically similar sands which are likely to occur between the Nile and southern Israel. However, in our current state of knowledge they cannot be used to prove this.

To summarise, it appears that, in the post-Roman period elsewhere in Europe, vessels were made from glass that shows compositional characteristics closely similar to the glass used by the Anglo-Saxons. These glasses also show some affinities to the earlier HIMT compositions of the 4th–5th centuries, believed to have originated in the region between the Nile and Southern Israel. They also show general similarities in trace element composition to glasses made from Levantine sands. These observations suggest that the raw material for Anglo-Saxon glass vessels was widely traded, and was ultimately obtained from the eastern Mediterranean region. There is

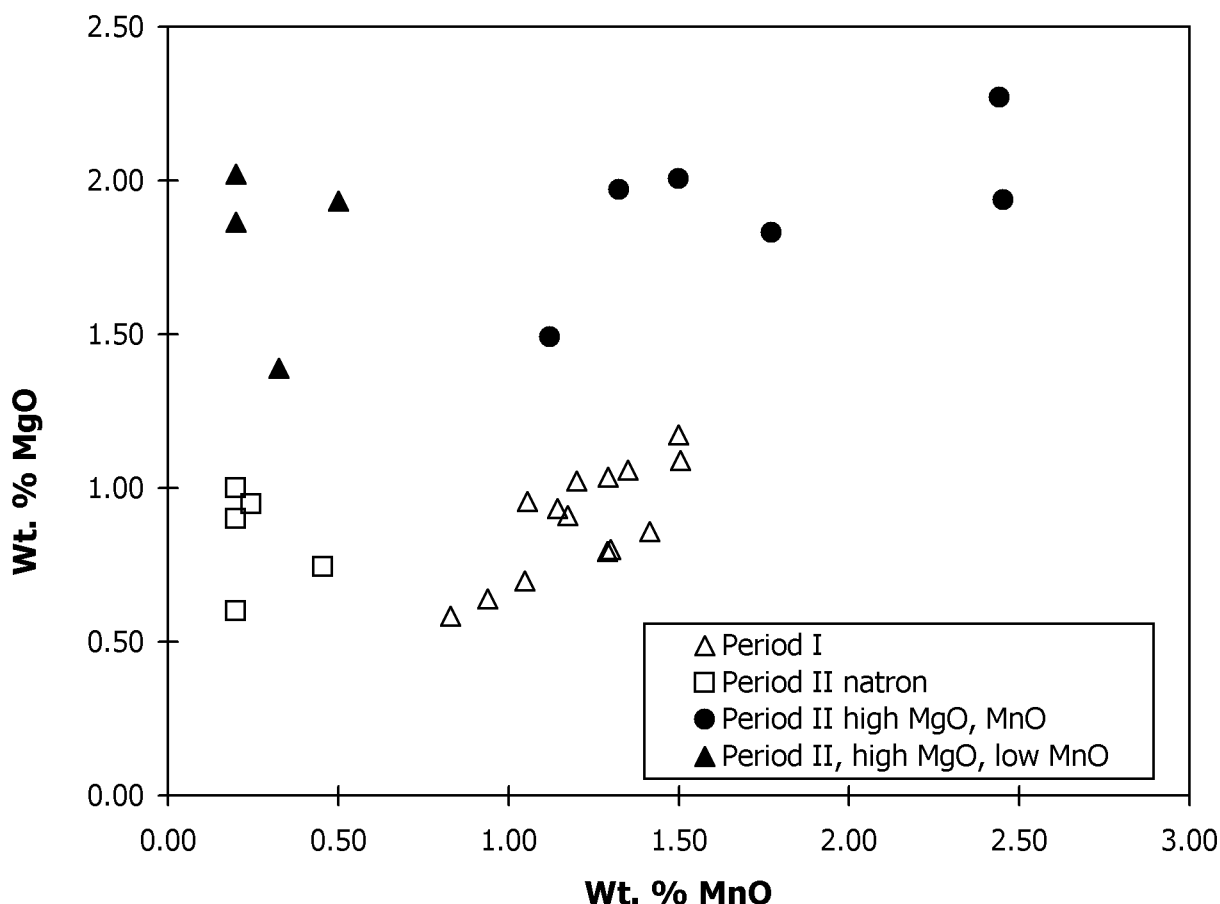


Figure 10 Magnesium versus manganese contents of Anglo-Saxon glasses, showing compositional sub-divisions.

some evidence of recycling from the elevated trace levels of colourant elements in the glasses but it does not seem possible to explain all aspects of the glass compositions by mixing specific proportions of different types of Roman glass. The close similarities to contemporary glass used on the Continent suggest that this was a widely traded glass rather than some local product of a recycling process. It appears that, directly or indirectly, a supply of contemporary glass from the East was reaching Britain. The similarities between HIMT and Saxon I glasses suggests that Anglo-Saxon glass was from the same region and that, although the glass supply was reduced in the post-Roman period, its region of origin had not changed.

Anglo-Saxon vessel glass, Period II (c. AD 550–700)

Vessels analysed from the period c. AD 550–700 comprise mainly globular beakers and palm cups (**Table 1**). One claw beaker is present, from Taplow, Bucks. (**cat. no. 79**). Noteworthy is the appearance of deep-blue vessels in this assemblage: the palm cup from Kempston (**cat. no. 88**), the globular beaker from Faversham (**cat. no. 134**) and the pair of globular beakers with lattice decoration from Broomfield (**cat. nos 150, 151**). These owe their colour to the presence of cobalt which, where analysed, was found to be in the range 300–500ppm in the deep-blue vessels (**Table 3: Co**). Lead was found to be elevated at concentrations up to 0.8% in the cobalt blues (**Table 2**); this is a characteristic typical of much cobalt blue Roman glass and may indicate the addition of old blue cullet as a colourant. The majority of the analysed glasses, however, are pale greenish colours, in this sense similar to the Period I vessels.

All Period II vessels analysed are soda-lime-silica glasses

but as noted above, in the discussion of the box and whisker plots (**Fig. 4**), there are two main types of glass in the Period II assemblage. There is a smaller group of five glasses which are fairly typical of the natron type. However, they differ from the Period I natron glasses in their lower MnO contents (**Table 2, Fig. 4**). The majority of the Period II glasses have higher MgO and K_2O than is normally associated with natron glass. The clear distinction between Period I and the two groups of Period II glasses is clearly shown, for example, in a plot of MgO vs MnO (**Fig. 10**). In this figure it may also be observed that the Period II glasses with high MgO (plant ash) show a wide range of MnO contents, which allows a sub-division into low- and high-manganese types.

The larger group of Period II glasses shows potash and magnesia values significantly higher than those typical of natron glasses, with over 2% of each oxide in the horn from Rainham (**cat. no. 48**), which is the glass with the highest K_2O and MgO contents. Furthermore, K_2O and MgO are strongly correlated, and also correlate with phosphate, P_2O_5 (**Figs 11, 12**). The presence of P_2O_5 at levels in excess of 0.3%, coupled with the high and correlated MgO and K_2O , is a clear indication of the use of plant ash in the starting materials. This finding is surprising, as plant ash glass is uncommon in the West until the generally accepted switch from natron in the late 8th–9th centuries. However, these are not ‘pure’ plant ash glasses, as the linear correlations shown by their MgO, K_2O and P_2O_5 contents, and their relationship with natron glass (**Fig. 12**) indicate that they are a mixture of a natron-rich material with a plant ash-rich material. The form in which the ash-rich material was added is not entirely clear. A possibility which must be considered, however, is that the glasses showing linear

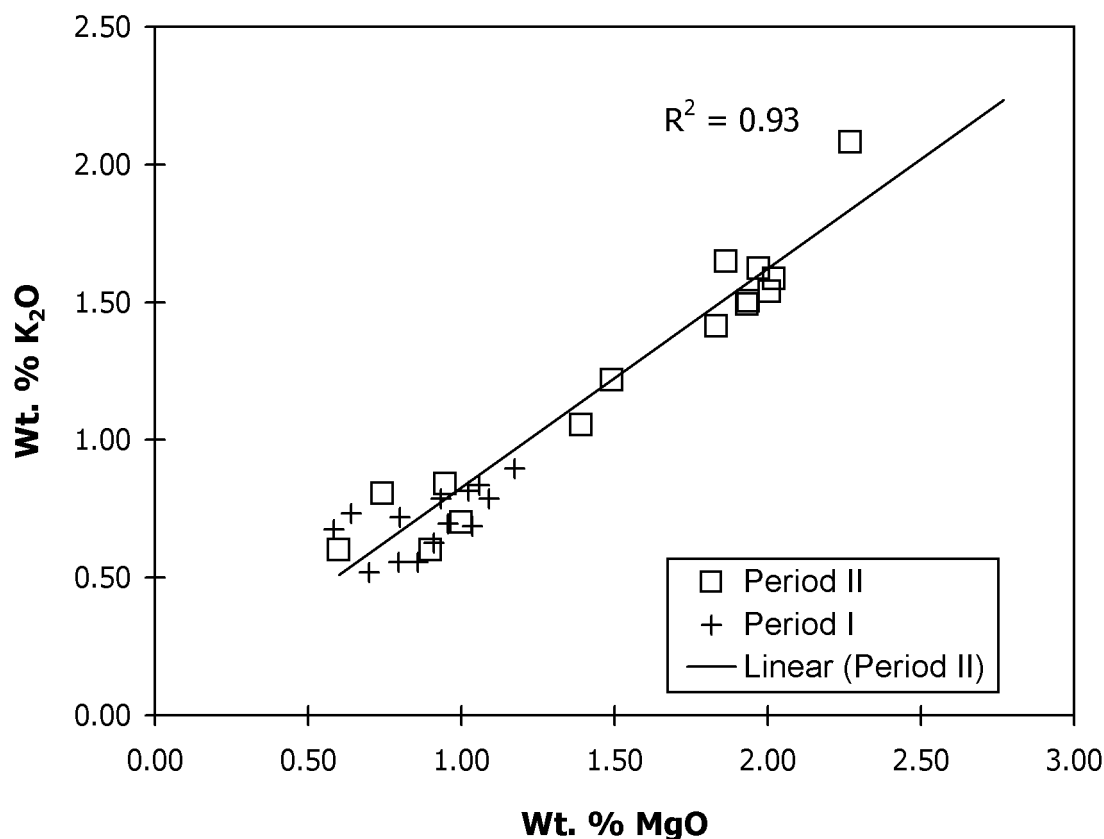


Figure 11 Potash versus magnesia in Anglo-Saxon Periods I and II glasses, with trend line and correlation coefficient for Period II.

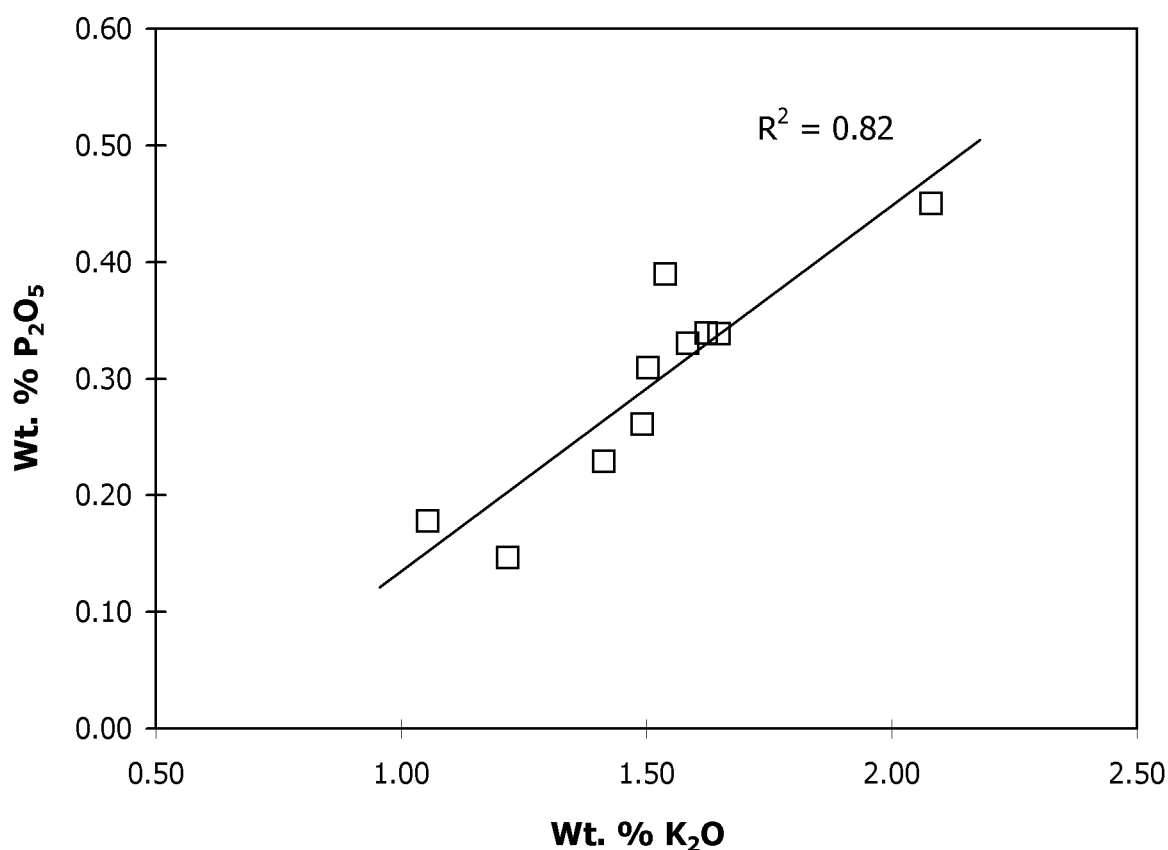


Figure 12 Phosphate versus potash in Anglo-Saxon Period II glasses, with trend line and correlation coefficient.

correlation are the result of mixing a primary glass of natron type, such as Period I glass, with a primary glass made from soda-rich plant ash, such as that from which the Rainham Horn was made.

There are some features of the data which do not tend to favour the idea that a soda-rich plant ash glass, closely

resembling the Rainham horn (*cat. no. 48*) in composition (*Table 2*), was mixed with a natron base. In particular, the high-MgO Period II glasses are very rich in strontium, containing over 1000ppm in some cases (*Table 3*). In our reconnaissance investigations of soda-rich plant ash glass from the Near East, we have not in general found strontium at such a

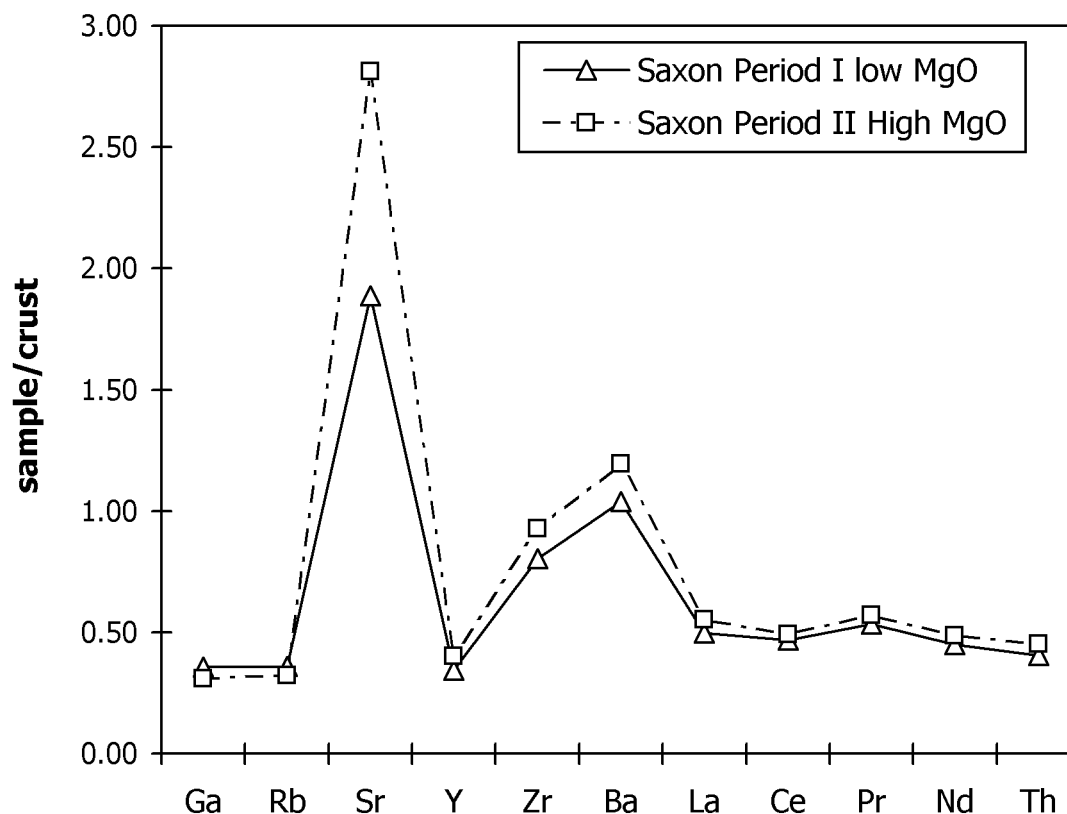


Figure 13 Mean trace element concentrations in Period I and Period II glasses, normalised to the continental crust.

high level; it is more typically in the 400–600ppm range (Freestone, Leslie, Thirlwall and Gorin-Rosen 2003). High levels of strontium, in the order of 1000ppm, are more common in the potash-rich wood ash glasses of later medieval Europe. Furthermore, a comparison of the mean trace element distributions in Period I, low-MgO glasses and Period II high-MgO glasses indicates that they are closely similar in other respects (Fig. 13). As discussed above, the manufacture of plant ash and natron glasses requires the use of different silica sources, because natron glass requires that the lime be supplied in the sand, while plant ash glass incorporates the lime from the ash. The Period I and Period II glasses have closely similar trace element distributions (except for strontium, Sr, added with the ash, see above). This suggests that the sand sources for the two materials were more-or-less identical. This favours the addition of a small amount (up to 20%) of ash-rich material, which did not significantly perturb the concentrations of most trace elements. Finally, there is the question of the source of the putative soda ash glass. Published studies indicate that the change from natron to plant ash-based glass in the eastern Mediterranean occurred in the 9th century. Throughout this period, plant ash glass was in use in the Sassanian Empire, in Mesopotamia and to the east. However, our unpublished analyses of Sassanian glass, coupled with those of Robert Brill (1999) indicate that it does not match the Period II compositions, typically having rather high magnesia relative to potash and lime and also somewhat lower phosphate. For these reasons, we conclude that the Period II glass compositions are not the result of mixing 'Rainham Horn glass' with natron glass but are the result of adding a relatively small proportion of ash-rich material to Period I-type glass, so that the trace element composition was not greatly perturbed.

The first four columns of **Table 5** present the mean compositions of the four compositional groups of Anglo-Saxon

glass identified in the present investigation (Fig. 10). Of the two high-MgO groups, the variety with high manganese (**column 4**) shares this characteristic with Period I glass. In fact, high MnO levels such as these, in excess of 1.0% are unusual in early medieval glass and the fact that the Period I glasses share this feature with some of the Period II high-magnesia types suggests that they may represent a modification of a Period I-type composition. This modification is likely to have involved the addition of an ash-rich material to a Period I glass base. **Column 5** gives such a hypothetical ash-rich material ('ash glass') which has been calculated to derive high-Mn Period II glass from Period I, and **column 6** shows the result of mixing 10% ash-rich material with 90% Period I glass. The close correspondence between **columns 4** and **6** is clear, but for this exercise to have any meaning, an explanation of the 'ash-rich material' is essential. The high lime, magnesia, potash and phosphate contents, coupled with low soda, are typical of the wood ashes used in medieval-European glassmaking, for example beech ash (Wedepohl 2003). While iron oxide and manganese oxide are on the high side, this may reflect a slightly different balance in the populations of glass sampled. The silica content of the postulated 'ash' is rather high, a silica content of around 10% appears to be more typical. Thus the material added to the natron glass may represent a rough 'glass' – a mixture of silica and ash which, while not a glass suitable for blowing vessels, was a glassy material, suitable for extending a limited supply of glass.

The situation with respect to the remaining high-MgO Period II glasses, which have low MnO, is less clear cut, as these have relatively high Na_2O and low CaO (**Table 5**) but even so there is a strong antipathetic relationship between Na_2O and MgO (negative correlation with $R^2=0.83$), suggesting that the ash-rich material added was low in soda and high in magnesia and potash.

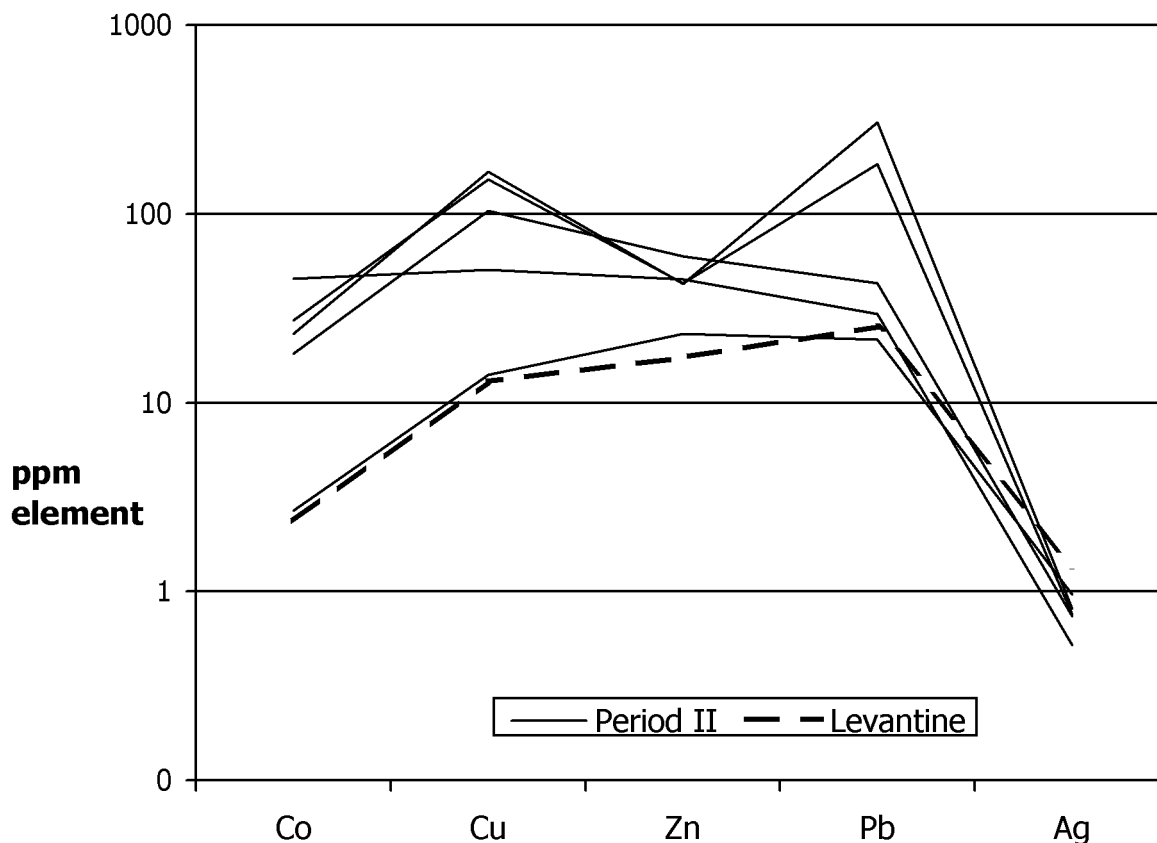


Figure 14 Concentrations of colourants and related elements in individual Anglo-Saxon Period II glasses and in the mean of 14 Levantine glasses from Beth Eli'ezer and Apollonia, Israel. Note that the scale is logarithmic.

The transition metals (Co, Cu and Zn) show significant enrichment in several of the Period II glasses, suggesting that some old glass was being recycled (**Fig. 14**). While this effect is not as pronounced as in the glasses of Period I, it should be noted that this may reflect the nature of the glass available for recycling in Period II (less coloured glass) rather than the extent of the recycling process.

The five analysed glasses of Period II with low magnesia (below 1%) are fairly typical natron-type glasses. Two of these are the lattice-decorated globular beakers from Broomfield, and may be supposed to represent the output of the same workshop/craftsman. They are not identical, however, and are unlikely to have been blown from the same pot. The remaining glasses show some compositional scatter suggesting that the raw glass used may not have had a common origin.

Discussion

These results suggest that early Anglo-Saxon glass was not made in north-western Europe, although it was worked into vessels there. The glass-workers who made the claw- and globular beakers followed a long tradition of remelting and working glass which was originally made from soda and sand in the eastern Mediterranean region. Although the possibility of the incorporation of some recycled Roman glass cannot be eliminated, and is quite likely, the Anglo-Saxon glass compositions differ sufficiently from those of Rome to suggest that the bulk of the material was post-Roman. Period I glass is a single compositional group, suggesting that it was manufactured in a single primary production centre. It is a natron-type glass characterised by high manganese, which is correlated with other components such as FeO, Al₂O₃ and MgO. The similarity of Period I glass to glass from continental

Europe, notably Merovingian Vicq, indicates that the glass makers were able to continue to access the international trade in raw glass or glass cullet which had existed in the Roman period and continued in the Mediterranean world throughout Late Antiquity.

Thus there was an element of continuity in the supply of glass in Britain between the late-Roman and the early-post-Roman period. While Period I glasses are not identical to late-Roman HIMT glass, they show sufficiently similar characteristics to indicate that their origins also lay in the south-eastern Mediterranean region. The form in which the glass reached Britain is not entirely clear. It may have been carried directly from the south, in the form of raw lumps or chunks, broken out of the glassmaking furnaces. Alternatively, it may have arrived in the form of broken glass vessels. This cullet may have arrived directly from the Mediterranean by ship, or it may have been old glass from elsewhere in northern Europe. The trace element compositions clearly suggests that Period I glasses contain an element of recycled glass, but it is not possible to determine at what point in the history of the material it was incorporated, nor the proportion in the batch, as our understanding of the elemental patterns is not sufficiently developed.

At some point in the 6th century AD a marked change in glass compositions is observed with the introduction of plant ash into the majority of the glass analysed. Our data suggest that ash-rich material was added to at least two compositional groups of glass, a high manganese group similar to the glass of Period I, and a manganese-poor group. The manganese-rich group appears to represent Period I-type glass to which around 10% of potassic ash-rich material was added. The second group of glass with a mixed natron-ash composition has lower

manganese and is not directly related to Period I glass. However, with some caution as our conclusion is based upon just four analyses, it also appears to represent a natron glass adulterated with a potassic wood ash-rich material.

The potash-rich nature of the additives suggests that the glasses were adulterated in the north west, possibly but not necessarily in Britain, probably to extend a restricted supply of natron glass from the south. While this type of glass has not been widely recognised, a vessel with a similar composition was identified in the Dalriadan capital of Dunadd (Henderson 2000). As far as we are aware, mixed glass of this type and period has not been identified outside the British Isles, supporting the view that the composition was modified in Britain.

The evidence for adulterating standard natron glass with a poor quality material suggests that glass was in short supply and that the glass workers could not obtain sufficient glass raw material. This might have been the result of the limited international trade at the time or possibly as the result of a specific disruption in the supply of natron. The mid-6th century was a time of considerable economic disruption, due to the effects, for example, of the Justinian Plague, which may have disrupted supply networks (Mitchell 2007, 372–4). There is also a possible explanation based upon environmental evidence assembled by Baillie (1995) and Keys (1999), which indicates a major cold period between AD 536–545 (Mitchell 2007, 375–7). The formation of natron depends critically upon the evaporation of the soda lakes of the Wadi Natrun and of others in the Nile Delta. A severe cold spell could have interrupted the formation of natron, so that there was a reduction in the supply of natron-based glass and ways had to be found to extend it.

It is concluded that, for a period from around AD 550, the natron glass typically used by the Anglo-Saxon glass workers was adulterated by a small proportion of wood ash or wood ash-based glass. Although this may have made the glass a little more fluid and perhaps improved its workability, it seems more likely that the practice was undertaken in response to a shortage of raw glass, so that more vessels could be produced from an equivalent amount of natron glass. This modification may have been carried out by the glass workers themselves, but it is also possible that it was carried out at some central place. The ratio of MgO to K₂O in the glasses is constant, as shown in **Fig. 11**. As wood ash is notoriously variable in composition, depending on species of tree and local environment, it would appear that the additions made were of a constant material, although the amount added was variable. This suggests either that the glass was adulterated further up the supply chain than the individual glass workshops, or that there were very few workshops operative in this period, and that just one or two of these were modifying their glass in this way. The need to extend the available glass suggests that the rarity and consequent high status of glass vessels in early Anglo-Saxon England was not due to a shortage of glass-working skills but due to a shortage of the raw glass itself.

The typologically distinctive Period II blue globular beakers from Broomfield (**cat. nos 150, 151**) are of apparently unadulterated natron glass, as is the Taplow claw beaker. These are likely to have been produced in different workshops, or at different times, from the ash-rich Period II vessels. The fact

that Period II glasses may be subdivided compositionally into three or more groups suggests that there is considerable potential for investigating the relationships of vessels of this period using a combined typological and chemical-analytical approach

Later Anglo-Saxon glass

Although we have analysed no later glass specifically for this catalogue, we have analysed and reported on glass from the Anglo-Saxon monastery at Jarrow, which was founded in the late 7th century (Freestone 2003; Freestone and Hughes 2006). The Jarrow glass is of the natron type, without an added ash component and appears to have originated in the eastern Mediterranean. It therefore seems likely that the practice of using an ash-based material to extend the glass was very restricted, in time or in place. However, the Jarrow glass is characterised by high concentrations of colourant elements such as antimony (average 0.25% as oxide), lead (0.20%) and copper (0.25%).

A large corpus of some 270 glass fragments dating to the 8th–9th centuries from Hamwic has been analysed by Heyworth and Hunter (1998). Once again these are of low-magnesia, low-potash natron glass, and have significantly higher concentrations of copper (mean 0.1%), lead (0.36%) and antimony (0.35 %) than early Anglo-Saxon glass. Similar results have been obtained for glass from elsewhere. For example in the glass recovered from the excavation of the Crypta Balbi, in Rome, Mirti and co-workers (2001) report a significant increase in colourants in glass of the 8th century relative to that of the 7th century, and our own work on 8th–9th centuries glass from Italian sites such as San Vincenzo, Brescia and Cividale has yielded similar results (Freestone and Dell'Acqua 2005). Although these results do not allow it to be stated with confidence that more recycling of glass in general is occurring at this time, this is a possible explanation. What is clear is that more coloured glass has been recycled into the general stock in use. Furthermore, this coloured glass was of the antimony-opacified variety, i.e. old Roman glass, rather than Byzantine glass, which tended to be opacified with tin.

The increase in the amount of coloured glass in the general stock in the 8th–9th centuries is likely to represent an increasing dependence upon old Roman material. In view of the relatively low concentrations of this material in the glass of the 5th–7th centuries, it is unlikely to have been carried through in the recycling processes of this intervening period. Rather it may represent a move on the part of society towards a deliberate strategy of recovering old materials. It is quite possible that large amounts of glass were recovered from abandoned buildings which were being scavenged for *spolia*, to be recycled in new buildings. For example the Baths of Caracalla in Rome contained an estimated 200 tonnes of glass in vault and wall mosaics, most of which has now disappeared (DeLaine 1997). Much of this material is likely to have found its way as a colourant into the glass used to make beads, enamels and coloured windows, a practice which continued into at least the 12th century, as recorded by Theophilus (Hawthorne and Smith 1979). Some of it, however, particularly the less intense colours, may have gone directly into the general stock of weakly coloured glass, used to make vessels and windows.

By the 9th–10th centuries, glass compositions in Britain, as

elsewhere, were in flux, and a change from natron to ash-based glass begins (e.g. Henderson 1993b). This marks the beginning of the medieval forest glass tradition, which was to become widespread in the succeeding centuries.

Conclusions

Anglo-Saxon glass in the 5th–mid-6th centuries (Period I) was produced using natron-type glass, in the Roman technological tradition. It differed from Romano-British glass of the 1st–3rd centuries particularly in its high iron and magnesium oxide contents. However, it shares some characteristics with late-4th-century glass, and is likely to have originated in the eastern Mediterranean from where it was imported into Britain, in the form of raw chunks or vessel cullet. In this sense it represents a continuity with the preceding Roman tradition and an indication that the glassworkers had access to the same sources of glass, albeit on a much more limited scale. Some of this glass was recycled material, as the trace elements indicate the presence of some old coloured glass in the batch. Therefore it may have arrived in Britain as cullet from the continent.

The mid-6th century, i.e. the beginning of Period II, saw a change in composition in that a substantial proportion of the vessels analysed contain a plant or wood ash component. Although the data are not without ambiguity, the interpretation preferred is that a base natron composition was adulterated with potash-rich wood ash or a raw glass made from wood ash. This is likely to have occurred in northern Europe, possibly in Britain itself. The rarity of this glass type would certainly support the interpretation that the addition of the ash-based material was carried out in Britain, although the number of analyses of glass from early-medieval Europe as a whole is still pitifully small and hardly likely to be representative. The practice is likely to represent an attempt to extend the available glass by the addition of around 10% poor-quality wood ash glass. It reflects a shortage of natron glass from the Near East and is likely to reflect the disruptions to trading networks that occurred at this time. The compositions of later glasses from the 7th–9th centuries provide evidence of further attempts to extend the available material by adding old Roman glass, probably scavenged from old buildings. Buildings containing large amounts of glass were most common in the cities of Italy and north Africa, and the recycled glass is likely to have originated in the south, and brought north as cullet.

The attempts to extend the available glass to allow the manufacture of more vessels suggests that the limited amounts of glass recovered from early- and mid-Saxon Britain are not primarily a reflection of a shortage of glassmaking skills, because the glass workers appear to have been stretching their raw materials as far as they could. Rather, the controlling factor was the shortage of glass material. At this time, the glassmaking furnaces of the Levant were producing large quantities of raw glass in a single firing, but only limited quantities of this material appear to have reached north-western Europe.

Notes

- 1 We thank Dr Sonja Marzinzik and Dr C.M. Jackson, who kindly commented on an earlier version of this chapter. Responsibility for the interpretation is ours, however.
- 2 In fact the term *natron*, although well established in the archaeological and historical literature, is mineralogically

inaccurate as it describes the sodium carbonate 10-hydrate. The sodium carbonate mineral precipitated by the soda lakes of the Wadi Natrun is *trona*, which is the sodium carbonate 2-hydrate. See Shortland 2004.

- 3 The addition of pyrolusite, MnO_2 , to reduce the colour due to iron, was a common practice from around the 2nd century BC onwards; see Sayre 1963.
- 4 We thank M. Hubert Cabart for information about the site of Vicq.

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Table 1 Details of analysed vessels

Cat. no.	Registration	Analysis no.	Provenance	Form	Colour	Period
21	1902,7-22.85	6599-19	Droxford	cone beaker	red-brn	I
37	1936,5-11.71	6599-21	Howletts	cone (Kempston)	lt bl-grn	I
39	1936,5-11.113	6599-6	Howletts	cone (Kempston)	lt grn	I
43	1880,2-14.22	6599-10	Longbridge	cone beaker	lt grn	I
48	1952,2-5.1	6599-2	Rainham	horn	grn-brn	II
57	1970,4-6.1675	6599-26	Mucking	claw beaker	lt grn	I
58	1947,10-9.1	6599-25	Castle Eden	claw beaker	lt bl-grn	I
59	1336a.'70	6599-13	Faversham	claw beaker	lt bl-grn	I
63	1936,5-11.30	6599-4	Howletts	claw beaker	lt olive	I
64	1936,5-11.48	6599-8	Howletts	claw beaker	grn-brn	I
65	1336b.'70	6599-5	Faversham	claw beaker	olive grn	I
69	1905,4-18.10	6599-7	Sittingbourne	claw beaker	red-brn	I
70	1964,7-2.407a	6599-24	Great Chesterford	claw beaker	red-brn	I
71	1970,4-6.7	6599-11	Mucking	claw beaker	lt grn-brn	I
72	1893,7-16.3	6599-20	East Shefford	claw beaker	red-brn	I
79	1883,12-14.14	B&F	Taplow	claw beaker	olive grn	II
88	1891,6-24.3	6599-18	Kempston	palm cup	deep bl	II
93	1318.'70	6599-16	Faversham	palm cup	grn	II
97	1890,4-12.2	6599-12	Bishopsbourne	palm cup	olive grn	II
101	1876,5-4.11	6599-29	Desborough	palm cup	olive grn	II
121	1883,12-13.596	6599-1	Sittingbourne	globular beaker	red-brn	II
125C	1335.'70	6599-14	Faversham	globular beaker	lt grn	II
126B	1337c.'70	6599-3	Faversham	globular beaker	lt grn	II
134	1322a.'70	6599-15	Faversham	globular beaker	deep bl	II
148	1893,6-1.195	6599-27	Wye Down	globular beaker	lt bl-grn	II
150	1894,12-16.18	B&F	Broomfield	globular beaker	deep bl	II
151	1894,12-16.19	B&F	Broomfield	globular beaker	deep bl	II
161	1321.'70	6599-28	Faversham	bag beaker	lt olive grn	II
163	1893,6-1.206	6599-9	No Provenance	bag beaker	olive grn	II

Note: B&F refers to samples analysed by Bimson and Freestone (2000)

Table 2 Major and minor element composition of Anglo-Saxon glass vessels (weight percent)

Cat. no.	Analysis	SiO ₂	TiO ₂	Al ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	Cl	SO ₃	PbO	Pb	Sb
Period I vessels																
58	6599-25	67.97	0.11	2.11	0.67	0.83	0.58	7.34	18.28	0.68	0.13	0.84	0.46	<0.2	n.a.	n.a.
57	6599-26	67.98	0.13	2.14	0.56	0.94	0.64	7.47	18.15	0.73	0.00	0.83	0.44	<0.2	n.a.	n.a.
64	6599-8	66.93	0.14	1.92	0.57	1.05	0.70	6.59	20.09	0.52	0.00	0.85	0.65	<0.2	0.041	0.027
70	6599-24	66.25	0.15	2.02	0.69	1.29	0.79	6.76	20.08	0.56	0.00	0.89	0.51	<0.2	n.a.	n.a.
21	6599-19	66.59	0.00	1.88	0.69	1.30	0.80	6.82	19.96	0.72	0.00	0.79	0.46	<0.2	n.a.	n.a.
37	6599-21	66.40	0.14	2.17	0.68	1.41	0.86	7.72	18.80	0.56	0.00	0.82	0.44	<0.2	n.a.	n.a.
72	6599-20	67.03	0.16	2.38	0.84	1.17	0.91	7.04	18.45	0.63	0.00	0.94	0.46	<0.2	n.a.	n.a.
39	6599-6	66.43	0.17	2.57	0.93	1.14	0.93	7.53	18.35	0.79	0.00	0.68	0.48	<0.2	0.050	0.085
71	6599-11	66.99	0.16	2.46	0.92	1.06	0.96	7.67	17.89	0.70	0.00	0.75	0.47	<0.2	0.069	0.042
63	6599-4	66.57	0.13	2.53	1.00	1.20	1.02	7.40	18.01	0.81	0.14	0.80	0.40	<0.2	0.072	0.077
43	6599-10	66.94	0.17	2.42	0.84	1.29	1.04	8.36	17.02	0.69	0.00	0.75	0.47	<0.2	n.a.	n.a.
69	6599-7	66.12	<0.10	2.52	1.06	1.35	1.06	8.05	17.97	0.84	0.00	0.64	0.39	<0.2	b.d.	b.d.
65	6599-5	65.60	0.11	2.43	0.91	1.50	1.09	8.01	18.33	0.79	0.00	0.77	0.46	<0.2	0.024	0.077
59	6599-13	64.59	0.18	2.80	1.00	1.50	1.17	8.49	18.36	0.90	0.00	0.58	0.44	<0.2	0.044	0.059
Period II vessels, low MgO																
79	B&F	67.8	<0.10	2.9	0.5	<0.2	0.6	9.6	16.6	0.6	0.05	n.a.	n.a.	<0.2	n.a.	n.a.
148	6599-27	68.71	0.00	2.45	0.66	0.45	0.74	7.21	17.64	0.81	0.05	0.99	0.34	<0.2	n.a.	n.a.
150	B&F	64.4	<0.10	2.3	1.6	<0.2	0.9	6.8	19.9	0.6	0.05	n.a.	n.a.	0.8	n.a.	n.a.
93	6599-16	69.37	0.18	2.72	0.62	0.24	0.95	7.66	16.36	0.84	0.05	0.78	0.29	<0.2	n.a.	n.a.
151	B&F	67.5	<0.10	2.2	1.1	<0.2	1.0	6.1	18.3	0.7	0.05	n.a.	n.a.	0.6	0.358	b.d.
Period II vessels, high MgO, high MnO																
97	6599-12	65.79	0.10	2.51	0.95	1.12	1.49	8.83	16.93	1.22	0.15	0.63	0.28	<0.2	0.041	b.d.
163	6599-9	63.22	0.24	2.20	1.54	1.77	1.83	8.86	17.59	1.41	0.23	0.52	0.58	<0.2	b.d.	b.d.
161	6599-28	64.46	0.11	1.82	1.01	2.45	1.94	9.08	16.22	1.50	0.31	0.82	0.28	<0.2	n.a.	n.a.
126B	6599-3	61.34	0.21	2.22	1.07	1.32	1.97	10.76	17.77	1.62	0.34	0.77	0.62	<0.2	0.016	b.d.
125C	6599-14	61.10	0.20	2.28	0.98	1.50	2.01	10.55	18.30	1.54	0.39	0.76	0.58	<0.2	0.064	b.d.
48	6599-2	64.75	0.17	2.19	1.67	2.44	2.27	8.88	14.14	2.08	0.45	0.59	0.36	<0.2	b.d.	b.d.
Period II vessels, high MgO, low MnO																
134	6599-15	64.59	0.16	2.44	1.06	0.33	1.39	7.71	19.53	1.06	0.18	0.72	0.54	0.31	0.261	b.d.
101	6599-29	65.78	0.16	1.69	0.70	0.00	1.86	7.75	18.83	1.65	0.34	0.83	0.41	<0.2	n.a.	n.a.
88	6599-18	64.09	0.21	2.02	1.34	0.50	1.93	8.90	17.89	1.49	0.26	0.55	0.48	0.33	n.a.	n.a.
121	6599-1	66.18	0.16	1.86	0.83	0.00	2.02	7.74	18.07	1.58	0.33	0.85	0.37	<0.2	b.d.	b.d.

As weight percent oxide, determined by energy dispersive X-ray analysis in the scanning electron microscope, except for Pb, Sb, Sn as weight percent element, determined by ICP-AES.

n.a. = not analysed b.d. = below detection < = less than

Table 3 Trace element concentrations in Anglo-Saxon glass in parts per million, by ICP-MS

	Co	Cu	Zn	Pb	Ag	Ga	Rb	Sr	Y	Zr	Ba	La	Ce	Pr	Nd	Th
Period I																
6599-8	3.8	80	31	341	0.50	8.7	13.2	331	5.7	69	181	8.7	16.9	2.10	7.8	1.50
6599-4	6.7	151	45	734	1.17	7.4	12.1	416	6.3	72	263	7.4	14.7	2.06	6.6	1.36
6599-6	9.7	121	96	520	1.11	5.7	12.1	485	7.1	83	259	7.7	15.5	1.90	7.0	1.56
6599-11	6.2	87	36	595	0.94	5.7	9.8	585	8.1	99	235	7.5	15.1	2.10	6.6	1.35
6599-7	4.9	25	27	119	0.45	5.6	8.5	412	5.7	67	258	6.8	12.9	1.78	6.1	1.37
6599-5	6.6	93	41	260	1.57	5.6	12.5	595	7.3	83	293	9.1	17.5	2.29	8.6	1.34
6599-13	6.8	91	56	254	1.35	6.4	12.5	611	7.6	90	330	8.3	15.6	2.36	7.6	1.45
4260-25340R	416	>1000	37	>1000	0.80	7.0	12.7	425	7.3	91	170	9.2	18.9	2.46	8.3	1.90

Period II (high-MgO glasses)

6599-15	330	1062	66	>1000	1.08	6.8	10.3	498	6.9	90	206	8.7	16.6	2.17	8.4	1.50
6599-12	23.1	167	43	305	0.81	5.4	10.9	679	8.5	81	368	8.1	14.8	2.11	7.9	1.44
6599-9	45.4	51	45	30	0.52	5.7	12.8	696	9.4	96	384	12.3	19.5	2.88	9.9	1.74
6599-3	27.2	152	43	183	0.76	5.5	8.9	>1000	7.8	113	311	7.3	15.7	2.08	7.9	1.54
6599-14	19.2	132	36	601	1.05	5.8	12.5	683	7.2	99	256	9.5	18.8	2.28	7.3	2.07
6599-1	2.7	14	23	22	0.96	3.7	7.9	564	6.0	82	151	6.1	13.3	1.71	5.5	1.30
6599-2	18.2	104	59	43	0.74	6.1	9.1	>1000	10.3	90	416	9.9	14.8	2.32	7.5	1.47

Table 4 Mean compositions of early-medieval glasses (weight percent)

	Frankish Krefeld- Gellep Wedepohl	Merovingian Vicq Velde	7th Century Crypta Balbi, Rome Mirti <i>et al.</i>	Anglo-Saxon Period I This study
No. of anal.	13	8	40	14
SiO₂	68.49	67.63	67.26	66.60
TiO₂	0.13	n.a.	0.14	0.13
Al₂O₃	2.37	2.38	2.37	2.31
FeO	1.05	0.82	0.85	0.81
MnO	0.86	1.43	0.69	1.22
MgO	0.88	1.02	0.83	0.90
CaO	7.18	7.67	7.21	7.52
Na₂O	16.37	18.07	17.30	18.55
K₂O	0.68	0.76	0.60	0.71

Table 5 Mean compositions of Anglo-Saxon glass groups and hypothetical ash glass (weight percent)

	Period I (n=14)	Period II Low Mg (n=5)	Period II High Mg, low Mn (n=4)	Period II High Mg, high Mn (n=6)	Ash glass Hypothetical	90% Period I 10% ash glass
SiO₂	66.6	67.6	65.2	63.4	35	63.4
Al₂O₃	2.3	2.5	2.0	2.2	1	2.2
FeO	0.8	0.9	1.0	1.2	5	1.2
MnO	1.2	0.3	0.3	1.8	5	1.6
MgO	0.9	0.8	1.8	1.9	10	1.8
CaO	7.5	7.5	8.0	9.5	30	9.8
Na₂O	18.6	17.8	18.6	16.8	1	16.8
K₂O	0.7	0.7	1.4	1.6	10	1.6
P₂O₅	<0.1	0.1	0.3	0.3	3	0.3