Glass trade and chemical analysis : a possible model for Islamic glass production

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The scientific investigation of glass can reveal a range of information of interest to archaeologists, material scientists, art historians and environmentalists. Information about glass technology such as glass working properties and the raw materials used to make it can be inferred from the results of scientific analysis. Glass may even be found to have a chemical composition which is characteristic to a region or across several regions. By investigating the archaeological context of scientifically characterised glass, hypotheses can be advanced in order to explain its distribution, the mode of its production and the use to which it was put in society. Assuming that production sites can be identified, potential inferences about the technological traditions used to make it and trade relations within and between different production zones, can also be suggested. However this hypothetical situation is by far the most optimistic picture for ancient glass!

As is widely known, the majority of ancient glass compositions fall into a category known as soda-lime-silica (Henderson 2000a, p. 50), so one would hypothesise that the likelihood of being able to *provenance* glass is minimal (Wilson, Pollard 2001, p. 507). Even if there were slight compositional variations in the raw materials used on a local basis, recycling and the consequent mixing of the 'foreign' glass into the glass batch might be expected to obliterate these important compositional variations. It is only over the last decade, or so, that bronze age glass chemically characterised by major and minor components (Henderson 1988; Brill 1992; Santopadre, Verità 2000) and Roman and Byzantine glass, mainly characterised by minor and trace components, (Nenna *et al*. 1997; Freestone, Gorin-Rosen, Hughes 2000) have been identified, providing at least a possibility of provenancing these glasses. In these cases the provenance may eventually be shown to relate to a production site or to a region in which production has occurred. The analytical work necessary to build up 'glass interaction zones' (the distribution of chemically characterised glass products around a production centre or zone) is still in its infancy, but these relatively recent results certainly represent exciting developments in the study of ancient glass compositions.

It is with these considerations in mind that this paper will focus on whether it is possible to extend the list of provenanced glasses to include Islamic glasses and thereby contribute to models for production and trade. The first question to be answered is whether localised production of soda-lime Islamic glass can be recognised using chemical analysis. The second is whether the glass can be characterised sufficiently to be able to relate it to trade in glass. Discussion will focus initially on the production of Syrian 8th-9th century glass of the 'Abbasid caliphate and will go on to look at the later Syrian glass and Islamic glass from different areas.

1. Glass production in Syria during the 8th-9th and 11th-12th centuries

During the period between AH 175/796 and AH 187/808 in which the 'Abbasid caliph Harun ar-Rashid resided in al-Raqqa, northern Syria, he built a new city, (al-Rafika), next to al-Raqqa, several palatial complexes (Meinecke 1994) and an extramural industrial complex of *c*. 3 kms in length (fig. 1). During this short period al-Raqqa was the capital of the 'Abbasid empire; the area controlled by the Harun stretched from Spain to northern India.

The Raqqa Ancient Industry project, supported by a full concession from the Director of Antiquities and Museums in Damascus has, over the past ten years, focused on the investigations of the industrial complex (Henderson 2000b). Excavations have revealed production evidence on a massive scale for glass, glazed and unglazed pottery and, on a smaller scale, for iron. The technological characteristics of the evidence of production for the full *chaîne opératoire,* where it has survived, is being examined using a range of compositional and

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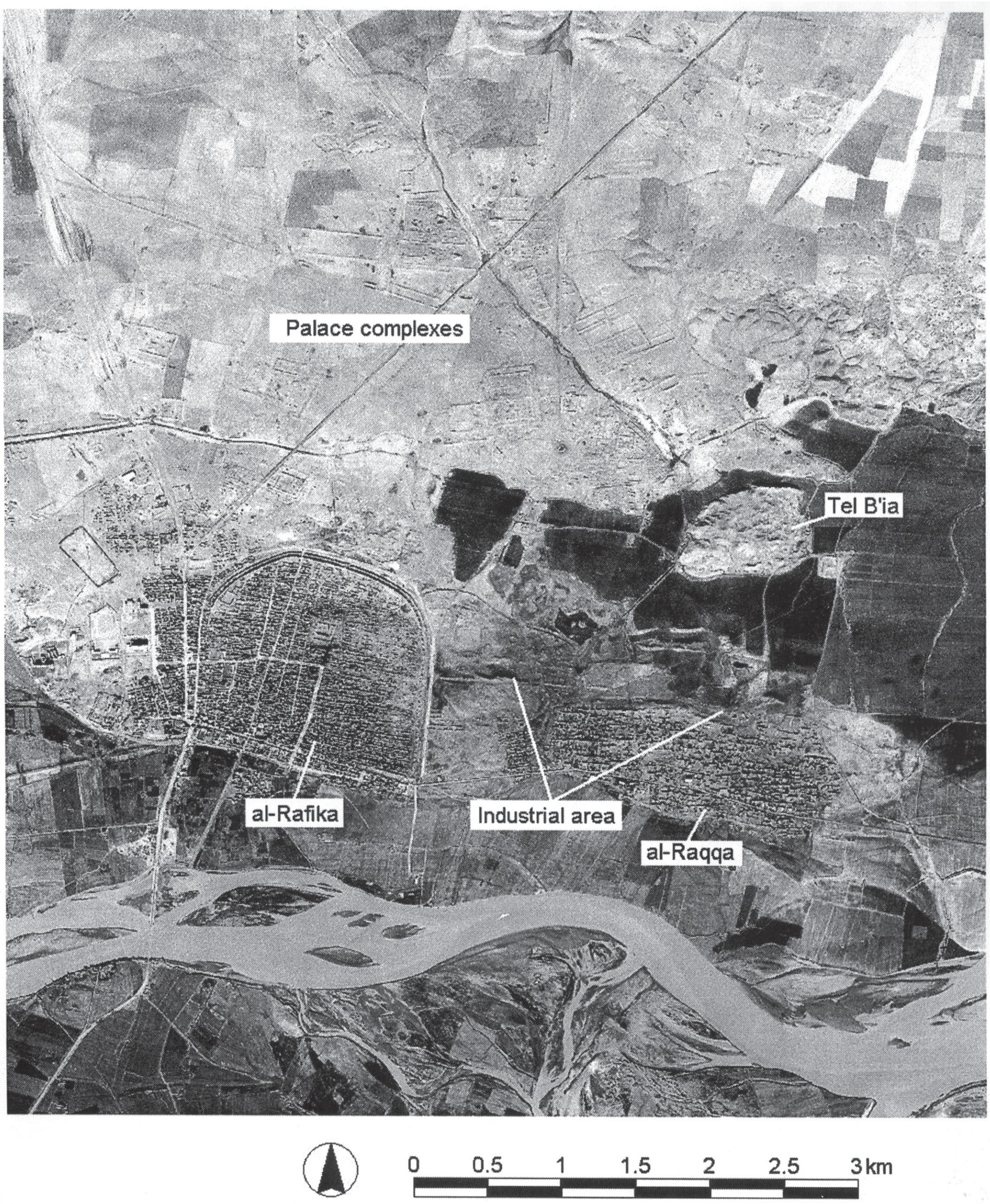

Fig. 1 — The location of the industrial complex at al-Raqqa, Syria. This is a Corona satellite photograph taken in 1967 showing the extent of the 8th-12th century industrial area located between the cities of al-Raqqa and al-Rafika. To the south is the river Euphrates with associated palaeochannels, to the north a series of palace complexes and the Bronze Age site of Tutul (Tel B'ia).

other scientific techniques of analysis including the synthesis of glass. These archaeological and scientific studies of the industries also include the technological relationships between the full range of industries, their spacial organisation using satellite imagery and GIS, their impact on the environment (fuel consumption, pollution) and the historical context in which they occurred. Out of the six locations that have been excavated since 1992, there is evidence for glass production from three of them, one each of 8th-9th, 11th and 12th century dates. Excavations have shown that during the 8th-9th centuries glass was melted using both single-chambered tank furnaces and three-chambered bee-hive shaped furnaces (fig. 2) on the same site; by the 11th and 12th centuries tank furnaces were in use, though the absence of evidence for the bee-hive shaped furnaces at this time does not constitute evidence of absence. Artefactual evidence has been found for a full range of production processes, including the fusion of glass primary raw materials into frit (fig. 3), the casting of glass into blocks and glass blowing (moils).

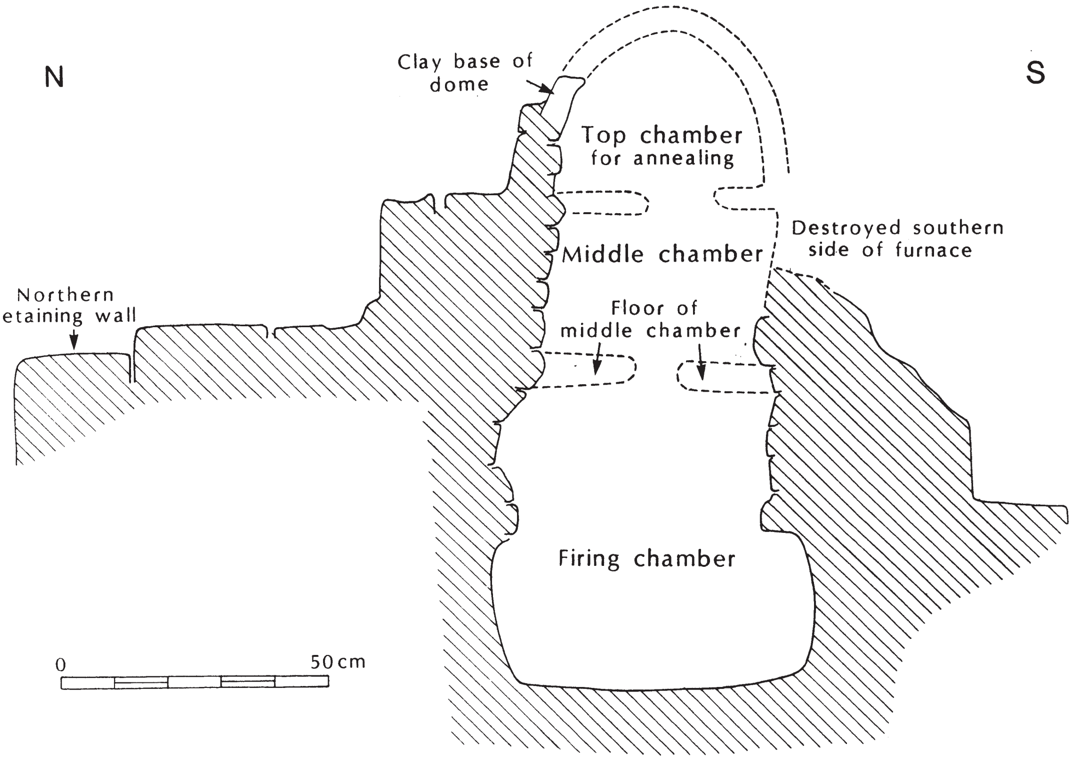

Fig. 2 — A north-south cross section through an 8th-9th century bee-hive shaped glass furnace found at Tell Zujaj, al-Raqqa, one of three glass production sites excavated.

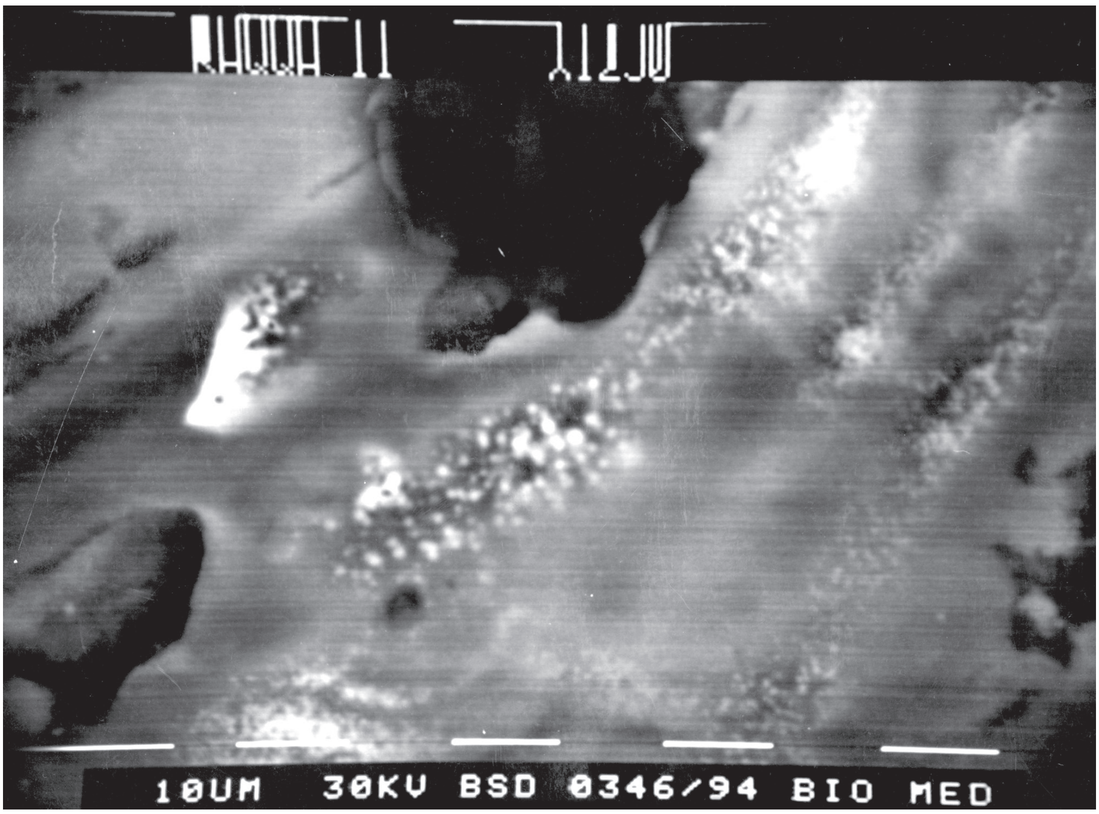

Fig. 3 — A scanning-electron micrograph of a sample of overheated glass frit excavated from 8th-9th century contexts of Tell Zujaj, al-Raqqa. The white inclusions are fragments of bone which may have been added to increase the lime component provided by the plant ash used as an alkali. The black areas are voids; the streaks of pale grey are due to variations in calcium oxide levels. The glassy component of this frit has a type 4 composition.

A range of glass vessel forms was made in al-Raqqa during the early and middle Islamic periods. Many of these vessels are forms that are found commonly in the Islamic world (Dussart 1998; Sablerolles, in prep.), so it appears to be difficult to refer to glass vessel types which are typical of Raqqa as a production centre. A more hopeful approach may eventually be to identify vessel forms which are typical of *zones* of production, but this must be based on the proper quantification of their archaeologically closely dated occurrence (Cool, Price 1995; Cool, Baxter 1996) based on estimated vessel equivalents (Cool, Price 1995, p. 9). Although this technique has been applied to Roman glass, it is only now being applied to the occurrence of Islamic vessel assemblages.

The excavated glass from Raqqa, including representative vessel fragments, chunks of raw furnace glass, glass bracelets, window glass, dribbles of glass, glass moils, frit and vitreous slags from 8th-9th century, 11th century and 12th century al-Raqqa were analysed scientifically so as to investigate whether they were of the typical 'Islamic' chemical compositions already consistently recognised in other studies (Matson 1948 ; Sayre, Smith 1961; Brill 1970; 1995; 1999, section VII; 2001; Henderson 1995a; 1995b; 1998; Henderson, Allan 1990; Freestone, Stapleton 1998; Freestone, Gorin-Rosen 1999; Freestone, Gorin-Rosen, Hughes 2000). If these same compositions were identified amongst the al-Raqqa glass, it would provide little prospect of being able to provenance them since the majority of published data are of the typical low magnesia soda-lime-silica glasses (LMGs) and high magnesia soda-lime-silica glasses (HMGs). Variations from the established compositional types, or the discovery of new ones, could provide a prospect of characterising them chemically and the eventual prospect of provenancing them.

The raw materials which could have been used to make Islamic glasses are two possible sources of silica (sand and quartz) and two possible sources of alkali (the mineral natron and plant ashes). Crushed quartz riverine pebbles are likely to have been a relatively pure source of silica. A third major component, lime, is thought to have been added as a component of the plant ashes or as shell fragments in the sand used. The natron-sand combination produces LMGs whereas the plant ash-quartz combination produces HMGs. Three species of halophytic plants which belong to the Chenopodiceae family could have been used for glass production, *Salsola kali, Salsola soda* and *Hammada scoparia* which grow on the margins of deserts and in maritime environments (Ashtor 1992, p. 494). Representatives of the Chenopodiceae family certainly grew in northern Syria (Ashtor 1992, p. 487-488) in the early Islamic period (Gardner *et al.*, in prep) and according to the Arabic geographer al-Mukaddasi__, writing in about 985, *Ushna__n* (the literary Arabic word for vernacular *Kali*) was exported from Aleppo**.** *Ushna__n* is thought to be *Hammada scoparia* (Ashtor 1992, p. 482). The purification of their ashes (known as *keli* or *kali*) involved solution, filtration, concentration and crystallisation, producing white salts of sodium carbonate and variation in these procedures may have led to variations in the chemical composition of Islamic glass.

Micro-samples of al-Raqqa glass were analysed using an electron micro-probe (Henderson 1995b; 1999, Henderson *et al.* in prep.). Where relevant, such as for the examination of overheated, partly crystalline frit, a scanning-electron microscope was used. The analytical results for 222 samples are to be published elsewhere (Henderson *et al.* in prep).

2. The compositional types

The analytical results for early Islamic ('Abbasid) glass dating to the late 8th and early 9th centuries are far from simple. Given that the 8th-9th century site of Tell Zujaj in al-Raqqa is likely to have been in use for a relatively short period of around 30 years (Henderson 1999, p. 229-230), one might have anticipated that only LMGs and HMGs already identified amongst Islamic glass would be found. As can be seen in fig. 4 and in tables 1 and 2 this was not the case. It is clear that there were four compositional types of soda-lime-silica glass in use at the same time. The inferred raw materials used to make these glass types are given in table 1 and their means and standard deviations given in table 2.

Whilst recycling may be responsible for some compositional variation in restricted cases, particularly the few glasses which are apparent mixtures of types 1 and 3 (= type 2), *random* mixing of the glasses clearly did not take place on a large scale or these relatively discrete groupings (especially types 1, 3 and 4) would not be discernable. This picture of three *principal* compositional types with a small number of a fourth type (type 2) in use at the same time is in stark contrast to much of Roman glass technology which, with some notable exceptions (Baxter *et al.* 1995; Nenna *et al.* 1997), is almost exclusively of a low magnesia soda-lime (LMG) composition with associated

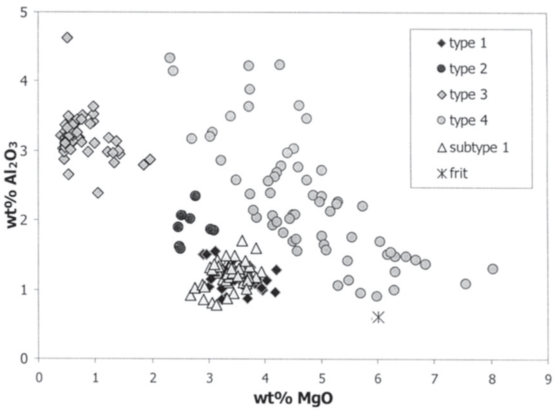

Fig. 4 — Weight percentage aluminium oxide (Al_2O_3) *versus* magnesia (MgO) in 8th-9th and 11th century glasses from al-Raqqa, Syria showing four compositional types. Only type 3 is a natron glass; types 1 and 4 have been made using plant ashes; type 2 is a mixture of natron and plant ash glasses.

Glass type	Silica	Soda	Lime
Raqqa 1	Quartz	Plant ash	Plant ash
Raqqa 3	Sand	Natron	Shell fragments in sand
Raqqa 2	mixtures of glass type 1 and 3		
Raqqa 4 Low MgO	Sand	Plant ash	'Plant ash, Shell fgts.'
Raqqa 4 High MgO	Quartz	Plant ash	Plant ash, (? bone ash)

Table 1 — The raw materials used for the production of the four types of soda-lime-silica glasses from 8th-9th century al-Raqqa, Syria.

characteristic impurity levels. Indeed there is even evidence for the continued use of a (relatively) high aluminia variant of this LMG Roman/ Byzantine glass type at al-Raqqa (type 3 in fig. 4, table 2a), which was made in Palestine (Brill 1988, p. 269; Fischer, McCray 1999, table 2; Freestone, Gorin-Rosen, Hughes 2000, p. 70). Primary evidence for the manufacture of types 1, 2 and 4 has been found in al-Raqqa, but not, so far, for type 3. This suggests that either raw type 3 glass, or the vessels made using that glass, were imported from the Levantine coastal production area.

Aluminia and magnesia have been selected for the biplot in fig. 4 because they reflect the sources of silica and alkali used respectively; a more detailed examination of the relative levels of other oxide components confirms the existence of these compositional types (Henderson *et al*., in prep.), three of which (types 1, 2 and 3) were previously recognised and described using a much smaller data set (Henderson 1995b, table I), where mean compositions of each type are given. A relatively high level of aluminia occurs if sand was used to make the soda-lime glass and a relatively low level if quartz (or a purer sand source) was used. A low level of magnesia indicates that a relatively pure mineral source of alkali, assumed to be natron, was used and a relatively high level if plant ashes were used.

Both types 1 and 4 are of plant ash type compositions with magnesia levels falling between c. 3% and 7%. Type 1 contains low aluminia at c. 1% suggesting a quartz source of silica; this is a clear contrast with the higher aluminia levels found in Roman glass, which would be expected to contain above *c*. 2.5% aluminia (Brill 1988; Jackson 1992) probably due to the use of a sand source of silica. Amongst the debris found at al-Raqqa were large fragments of relict quartz still trapped inside chunks of type 1 furnace glass made from quartz and plant ash.

The difference in composition between type 1 and the range of compositions which form type 4 glasses from 8th-9th century Tell Zujaj in al-Raqqa, both plant ash soda-limes, clearly needs to be explained. A difference of up to 4% in the magnesia levels in the two types (for the highest magnesia content in type 4) suggests that for the glasses containing the highest magnesia levels a different plant species of the genus *Salsola* may have been used (see below). The glassy component of the overheated frit found at al-Raqqa is of a type 4 composition (Henderson 1995b) and its discovery is primary evidence for the production of type 4 with the highest magnesia levels there. The compositional range of type 4 includes glasses with relatively high aluminia levels, comparable with Levantine glasses of Byzantine type to be discussed in more detail below. These type 4 glasses with high magnesia and high aluminia contents are some of the first to be recognised as being a sand-plant ash glass type.

If we look at the distribution of points, forming a loose negative correlation, incorporating al-Raqqa type 4 glasses, an intriguing hypothesis can be suggested. This range of compositions results from a series of different ratios of mixed raw glasses and/ or raw materials. For example, the addition of progressively more quartz and plant ashes to the sand-plant ash glass (high magnesia, high aluminia) would result in the progressive dilution of the aluminia levels while at the same time increasing the magnesia levels and this is what we see. Levels of calcium oxide and phosphorus pentoxide are found to decrease as well (Henderson *et al*., in prep). Overall the shift in raw materials towards the highest magnesia, lowest lime and aluminia glasses would steadily decrease the glass melting temperature and therefore the amount of fuel — the most expensive raw material consumed. The means and standard deviations for five selected oxides for Raqqa type 4 glasses containing high, medium and low aluminia levels are given in table 2c where some of these correlated shifts can be seen.

These type 4 glasses represent the successful results of experimentation, whereas the giant slab of glass from Bet She'arim, Israel (Brill, Wosinsky 1965; Brill 1967), which shares many of the compositional characteristics of sand-plant ash (high aluminia) Raqqa type 4 glasses, including very low silica levels, appears to be the result of an unsuccessful experiment (Freestone, Gorin-Rosen 1999). By calculating what happens to the glass compositions when different proportions of glass types 1 and 3 are mixed, it can be determined that the relative levels of aluminia and magnesia fall into type 2 glass (see below). There is no possibility of producing a glass with magnesia levels as high as the highest found in type 4 glasses simply by mixing different proportions of glasses made using the established technologies of types 1 and 3. As alluded to above, this indicates that a new (plant ash) raw material with higher magnesia levels than used to make type 1 glasses was involved in the production of type 4 glasses with the highest magnesia levels. We can therefore suggest not only that types 1 and 3 glasses were mixed but that at least one new alkali-rich raw material was employed to make type 4 with high magnesia levels. The problem of introducing the excessive calcium oxide levels from two sources (sand and plant ash) found at Bet She'arim has somehow been avoided in the production of the sand-plant ash Raqqa glasses. Presumably some form of filtration or a centrifuge was used to remove (some) shell fragments from the sand. One could envisage that, since the addition of cullet to the glass batch would reduce the overall melting temperature, mixtures of primary raw materials and scrap glasses would also have been used, producing the range of compositions found in type 4 glasses represented by the bi-plot of aluminia vs. magnesia (fig. 4). Combining new raw materials, mixing scrap with raw materials and mixing glasses of the compositions represented by the highest and lowest aluminia levels would have produced the wide compositional spectrum occupied by type 4 glasses.

The third compositional type found at al-Raqqa is of a so-called 'Roman' composition (type 3 in fig. 4 and table 2a) made from a mineral-based alkali, natron. It is, in fact, slightly different in composition from typical western Roman glass and indicates that a basic Byzantine recipe continued in use (Freestone, Gorin-Rosen, Hughes 2000). Although one might expect the proportion of aluminia-rich minerals in beach or desert sand deposits to be highly variable because the minerals can easily be mixed or redeposited, the levels of aluminia in western 'Roman' glasses invariably tend to fall around 2.5%, suggesting that the sand source used to make Byzantine glass from the Levant and that used to make western Roman glasses was different. The dependence on a mineral source of alkali (natron) for Roman glass production led to a very restricted variation of the already low levels of associated impurities such as magnesia, potassium oxide, sulphur trioxide, phosphorus pentoxide and chlorine, which are generally introduced with the alkali (Henderson 1995b, table I ; Henderson *et al*. in prep.). However, when the chemical compositions of 4th century Jalame natron glasses published by Brill (1988, tables 9-1 to 9-5) are compared with the early Islamic natron glasses found at Raqqa (type 3), it is still possible to distinguish them: the Raqqa glasses generally contain lower levels of soda and higher levels of silica and aluminia and would therefore have had a higher melting temperature as a result.

So although made in a similar tradition, both presumably in the Levant, a compositional distinction between these two groups of natron glasses can be recognised.

Type 2 Raqqa glass compositions constitute glasses which fall on a dissolution line between types 1 and 3 and, as previously suggested, are probably the result of mixing types 1 and 3 (Henderson 1999, p. 232).

In sum, the majority of glasses samples analysed from 8th-9th century al-Raqqa fall into four compositional types, with archaeological evidence for the contemporaneous primary manufacture of three of these. In addition there is structural evidence for the use of bee-hive and tank glass furnace types.

3. Regionalism and chronological changes in glass types in the Islamic world

Having defined the compositional variations amongst glasses found at the production site of Tell Zujaj, al-Raqqa, we must investigate how these 8th-9th century compositions relate to later glasses from Raqqa and to Islamic glass from other regions.

The chemical analyses of dated Islamic Egyptian glass weights published by Matson (1948) and by Gratuze and Barandon (1990) clearly show a change in glass compositions in the mid 9th century: from the use of a mineral alkali to that of a plant ash alkali to make soda-lime glasses. There is, however, evidence from the analysed glasses deriving from secure archaeological contexts at al-Raqqa that this change may have occurred earlier, and therefore that it was one of the centres where the change in glass technology occurred.

In a general way, there is also evidence that the compositional changes from mineral to plant-ash soda-limes which occurred in Egypt and Syria also occurred in other Islamic areas. For example, from the 48 analyses of 9th –10th century glass from Nishapur, Iran, published by Brill (1995), all are of a higher magnesia soda-lime type, which is what we might expect if this change had affected other areas of the Islamic world. However, this change is not found on all sites in the Middle East. There is now even an example from Sephoris in the Levant, where it is apparent that mineral-based soda-lime glasses continued to be used uninterrupted through the first millennium (Fischer, McCray 1999). One interpretation of this discovery at Sephoris is that differential exploitation of raw materials and also access to traded cullet or raw glass was influenced heavily by regional and especially political factors.

3.1 Glass from Nishapur

The Nishapur glass samples analysed by Brill (1995, table 3 and 1999, table VIIa) are dated on typological grounds to the 9th-10th centuries. Two principal compositions definable amongst Nishapur glasses are relatable to Raqqa glass compositions, with a third which is completely distinct (fig. 5 and table 2b and 2c). The first is a sand-plant ash glass which contains characteristically high levels of aluminia and magnesia as found in the late 8th-early 9th century al-Raqqa type 4 glasses. It is of interest to note that these coloured Nishapur glasses of type 4 composition fall into only part of the compositional range found in Raqqa equivalents, with only four examples of the type 4 glasses at the low aluminia, high magnesia end of the compositional range (fig. 5).

The Nishapur type 4 glasses which contain an 'average' aluminia level and which fall between the 'end member compositions' (table 2c, Nishapur type 4 mid aluminia) must have been manufactured from combinations of raw glass and raw materials. This combination

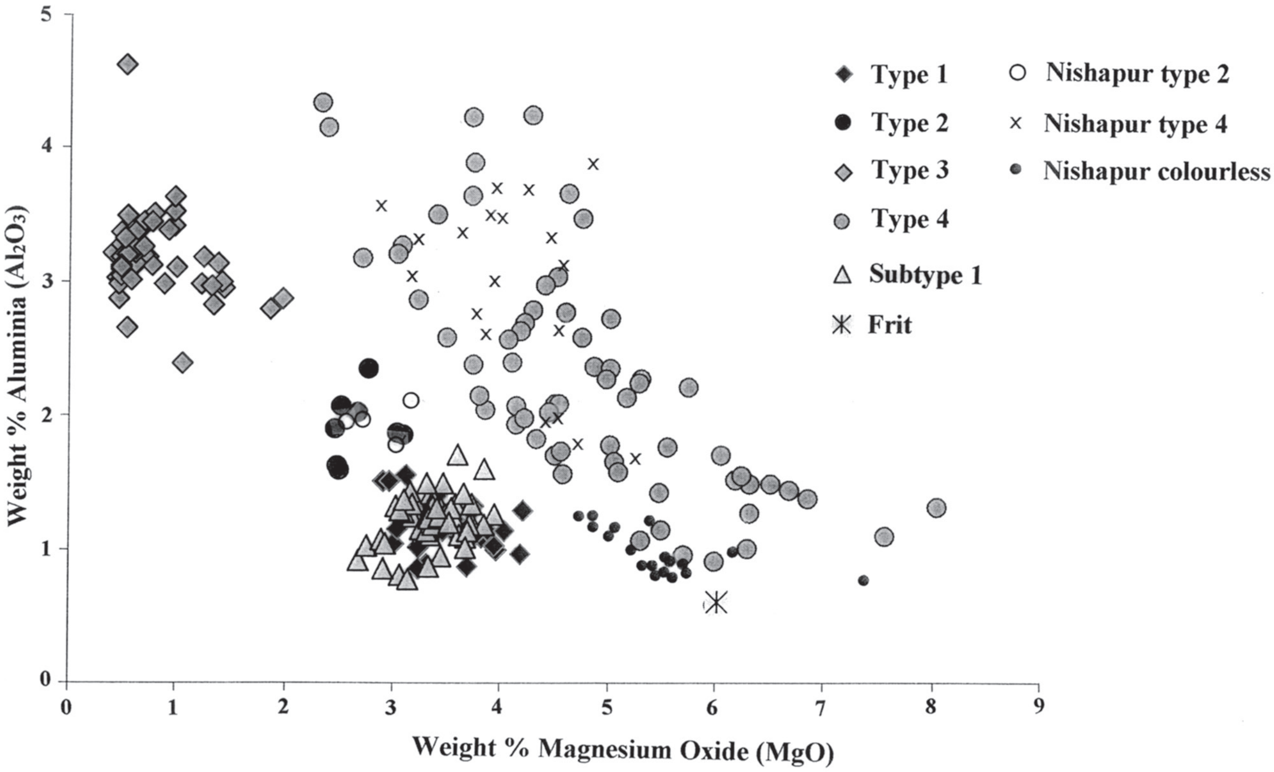

Fig. 5 — Weight percentage aluminium oxide (Al_2O_3) *versus* magnesia (MgO) in 8^{th}-9^{th} and 11^{th} century glasses from al-Raqqa, Syria and Nishapur, Iran showing that the Nishapur glasses are all plant ash glasses and that they are predominantly of type 4 with some type 2 samples. Only 3 – not shown- fall into the expected 'core' composition of type 1.

must have been consistently used to make them in an apparently well-defined tradition. The Nishapur type 4 glasses with high aluminia (table 2c) would have been made from the primary raw materials of sand and plant ash, perhaps mixed with raw glass of the same composition. The interesting thing here is that the Nishapur sand-plant ash glasses contain the lowest silica levels, just like their Raqqa equivalents. However, although the type 4 Raqqa and Nishapur glasses are compositionally very similar, those from Nishapur contain higher soda levels than found in the Raqqa glasses (see table 2c, fig. 8), which would have conferred a lower melting temperature on the Nishapur glasses. This slight compositional distinction has a bearing on where the Nishapur glasses were made. At Raqqa there is primary evidence for the production of type 4 glass, with the discovery of frit having the composition of the quartz-plant ash low aluminia/ high magnesia type 4 'end member' there. This means that a combination of raw materials including plant ashes containing the highest magnesia levels were fritted/melted there. This does not necessarily mean that the coloured Nishapur glasses of type 4 were made at Raqqa. Indeed the higher soda levels in the Nishapur type 4 glasses suggest that they are a sub-type and probably made elsewhere using a slightly different tradition. This compositional variation suggests that we may eventually be able to build up 'glass interaction zones' and that the Nishapur type 4s are a regional variant.

Another suite (of nineteen) Nishapur glasses, all colourless (see table 2c fig. 5) and also plant ash-quartz glasses, contain magnesia levels which fall between type 1 glasses and overlap with the high magnesia end of type 4 glasses. So here there is an indication that it may be possible to identify another distinct glass composition. Indeed these colourless glasses contain considerably lower soda levels than the type 4 glasses found at Nishapur (a mean of 12.66% compared to means of 17.1% and 16.71%), and considerably higher silica levels (a mean of 71.1% compared to 63.03 and 64.1%) which is likely to result in a considerably 'shorter' glass. In this case a combination of raw materials has been used specifically to make colourless glass. The colourless glass would therefore have had predictable working properties, something which is clearly very important to glass workers. Perhaps its working properties were 'recognised'/ selected by its colour. This glass could be characteristic of the time and place of production, but as yet we do not know where the glass was made.

Five other glasses from Nishapur are of the mixed natron-plant ash glasses of type 2 (table 2c), providing more evidence that glass recycling involving the mixture of natron glasses made in the 'older' tradition and plant ash glasses made in the 'newer' tradition had occurred at some point. Even here, however, when we would expect glass recycling to produce a homogeneity which would obliterate compositional variations which could be characteristic of a place/ time of production, we find that the Nishapur mixed natron-plant ash glasses can be distinguished from those found in Raqqa by their higher calcium oxide levels (with a mean of 7.4% as opposed to 5.39% in Raqqa glasses, see table 2). This difference is due to a summed effect of using two calcium-bearing raw materials found in the sand (shell fragments) and in the plant ash. For some reason we can detect a difference in the combinations of these raw materials. In other respects their compositions are very similar.

There may only be as little as 50-100 years difference in the dates of Nishapur and 'Abbasid al-Raqqa so one might expect the glasses to have been produced using the same technological tradition or using recycled glass of broadly the same composition. However, colourless Nishapur glasses are compositionally distinct from anything yet found at Raqqa and it is even possible to identify distinctions between the sand-plant ash (type 4) glasses found at Nishapur and Raqqa. Although the distance between the sites is great, this is, nevertheless, a new discovery. What is, perhaps, more surprising is the almost total absence of the 'core' plant ash-quartz (type 1) composition from the analysed Nishapur glasses, suggesting that we are indeed dealing with glasses made in a rather distinct variation from the established tradition. This is somewhat surprising and suggests that it *may* be possible to distinguish between Islamic glass made in, or supplied by, different production centres. This is where the discovery and chemical analysis of frit and raw glass attached to furnaces is so important: it establishes unambiguously that glass of that composition was made at the site where it was found and links products of that composition to the production site. This doesn't exclude the possibility that the same kind of frit could still have been made at other production sites.

3.2 Tenth and eleventh century glasses from Raqqa, Syria and Serçe Limani, Turkey

If we compare the compositions of later 8th-9th century glasses with 11th century glasses from al-Raqqa, we see that there is a clear chronological shift, with the plant ash type 1 glasses increasing and the proportion of mineral-based soda-limes of type 3 glasses declining dramatically with only four samples having been found (fig. 6). Relatively few type 4 glasses are found amongst the 11th century glasses, — and they were mainly used to make bracelets (Henderson *et al.*, in prep). This is what we

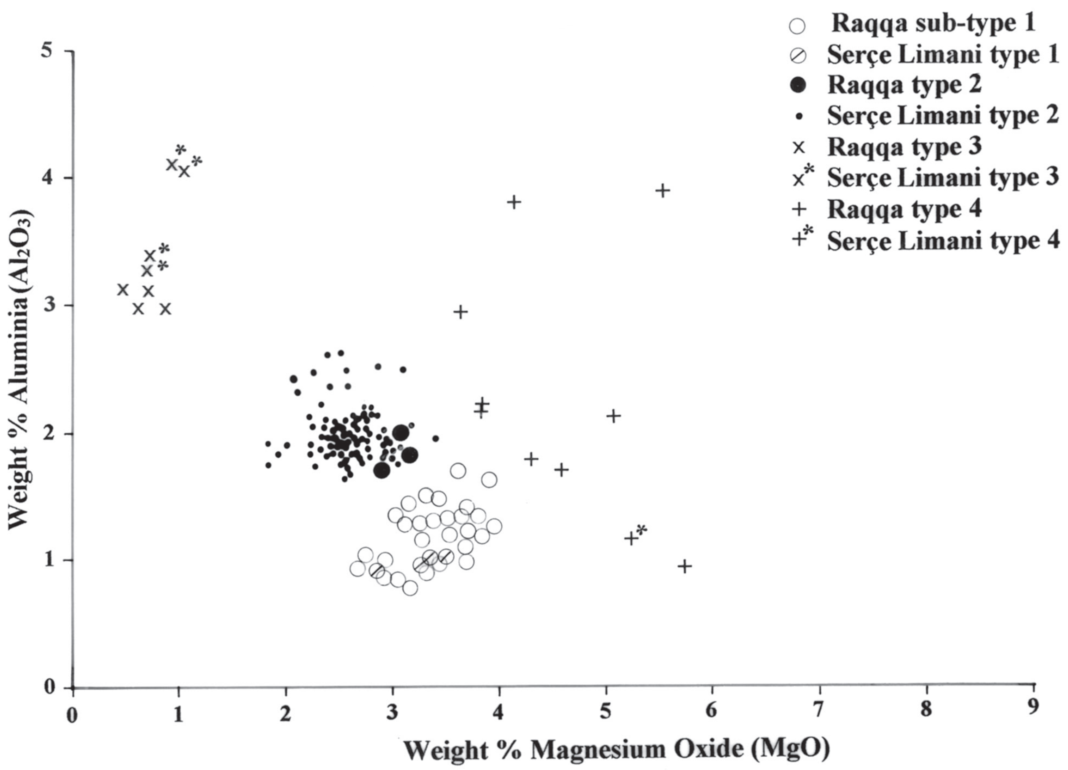

Fig. 6 — Weight percentage aluminium oxide (Al_2O_3) *versus* magnesia (MgO) in 11th century glasses from al-Raqqa, Syria, compared to glasses from 11th century Serçe Limani glass. This shows how the plant ash (sub-) type 1 glasses predominate amongst Raqqa glass, with a few plant ash (type 4) glasses mainly used to make bangles and some 'relic' natron (type 3) glasses. In contrast, the Serçe Limani glasses are predominantly a mixed natron and plant ash glasses (of type 2) which can, nevertheless be distinguished analytically from Raqqa mixed glasses.

would expect if changes in the raw materials used did not occur abruptly. Certainly there would be no way of demonstrating archaeologically sudden changes in technology. It is, nevertheless, possible to distinguish analytically between 8th-9th and 11th century Raqqa type 1 glass; the latter contains lower levels of soda and higher levels of calcium oxide (see fig. 8; Henderson *et al.* in prep.).

One way of investigating the characteristics of traded Islamic glass is through the chemical analysis of glass cargoes/ ballast found on shipwrecks. This kind of investigation could help to shed light on the range of glass types in use (perhaps from a relatively broad area of the Islamic world) at a given time. Such a shipwreck, thought to have originated on the Levantine coast, is that of Serçe Limani found off the coast of Turkey and which dates to *c.* 1025 (Lledó 1997, p. 43). The glass found was therefore probably made in the late 10th/ early 11th centuries. Intriguingly, although there is clear evidence from Serçe Limani shipwreck that glass was traded in the form of cullet, and that most (89 samples) of the glass analysed by Brill (1999, table VII, I) is of a mixed glass composition, it is, nevertheless, distinguishable from contemporary Raqqa glasses of sub-type 1 by its lower magnesia and higher aluminia levels (fig. 6). These Serçe Limani glasses are akin compositionally to the earlier (8th-9th century) Raqqa type 2 glasses (table 2b) but are of a later date and have higher calcium oxide levels than in the Raqqa glasses (relative mean levels of 9.26% and 5.39 respectively: see fig. 8) and therefore represent compositional variants of that type. Although the Raqqa type 2 glasses are highly coloured, many of the suite of eighty-nine analyses from Serçe Limani type 2s are of various shades of pale green, even though they contain comparable transition metal oxide impurities; the determination of glass colour in these cases must relate to the furnace conditions used. The Serçe Limani type 2 glasses provide continued evidence for mixing natron and plant ash glasses in the 10th-11th centuries because they fall compositionally between natron and plant ash technologies. A stock of natron glass (type 3) was clearly available to mix with the plant ash glass as late as the 10th century. The natron glass was therefore being extended by mixing it with plant ash glass. This compositional evidence for glass recycling was first suggested using a relatively small number of 8th-9th century Raqqa type 2 glasses for a time when the transition from natron to plant ash glass was occurring (Henderson 1999, p. 22). It is clear from the available compositional evidence that by the 12-14th centuries the stock of natron glass available for recycling (or access to it) had dried up.

A third technological tradition represented amongst the Serçe Limani glasses is a suite of five calcarious plant ash glasses of type 1 composition (Brill 1999, analyses 3568, 3569, 3573, 3574 and 3586). Although nearly contemporary with 11th century Raqqa plant ash glasses of sub-type 1 they contain slightly lower aluminia levels (a mean of 0.9% rather than 1.24%) – and they contain higher soda levels than found in the 8th-9th century Raqqa sub-type 1 glasses (see table 2c). These compositional differences could eventually provide a fingerprint for these quartz-plant ash Serçe Limani glasses. Indeed, the chemical compositions of Serçe Limani glasses published by Brill also intriguingly include the 'persistence' of four low magnesia natron glasses (table 2a, fig. 6, Brill 1999, samples 3585, 3732, 3595 and 3732) which might well be a relic stock of natron glasses destined for recycling and mixed with plant ash glasses to produce type 2 glasses. Analyses 3595 and 3732 contain very low calcium oxide levels of 2.99% and 3.03% (see table 2a) compared to a more typical level of between 7% and 10%. These low calcium oxide natron glasses represent the persistence of glasses which are typical of those made at a group of workshops for making primary glass at Beni Salama, Wadi Natrun in Egypt. This unusual soda-lime composition was first recognised by Sayre and Smith (1974) and placed into a full archaeological and technological context by Nenna *et al.* (1997, p. 84-85, fig. 2). The production of glass of this diagnostic composition appears to have lasted from the Roman period into the Islamic period; this implies that these two Serçe Limani examples were anywhere between 200 and 600 years old. The fourth technological tradition from Serçe Limani is represented by four lead-silica glasses (Brill 1999, samples 3576, 3577, 3578 and 3579).

3.3 Twelfth to fourteenth century (Ayyubid and Mamluk) Islamic glasses

What about the chemical compositions of Islāmic glasses dating to the 12th to 14th centuries of the Ayy*u*bid and Mamluk caliphates? Glasses of these compositions were used to make the bodies of glass vessels of the marvered type (Allan 1995; Henderson 1995a), enamelled glasses (Henderson, Allan 1990; Freestone, Stapleton 1998 and Henderson 1998) and include the glass matrices of the famous vessels of the Aldravandini type (Verità 1995). In contrast to earlier Islamic glasses, *all* of these glasses so far analysed conform basically to the Raqqa type 1 plant ash soda-lime glasses introduced in the 9th century. The wide compositional variation found in the earlier Islamic glasses is completely absent. This consistency in glass compositions therefore reduces the potential for identifying regionalised production centres based on glass compositions made between the 12th and 14th centuries. It suggests that the glasses were consistently made from the ashes of one of the commoner species of plants available and used in a restricted number of production centres.

	R type 3 (n=61)	SLIM lo lime (n=2)	SLIM hi lime (n=2)	N
Na_2O	13.82+0.88	19-19.7	13-15	N/A
CaO	9.07+1.09	2.99-3.03	9.2-11.4	
SiO_2	71.17+1.67	69.77-69.91	68.84-69.99	
MgO	0.73+0.35	0.8-0.83	0.63-0.77	
Al_2O_3	3.19+0.28	4.01-4.11	3.2-3.26	

2a

	R type 2 (n=9)	SLIM type 2 (n=89)	N type 2 (n=5)
Na_2O	14.5±1.58	12.7±0.87	15.0±1.39
CaO	5.39±0.69	9.26±1.17	7.4±1.2
SiO_2	68.06±1.77	68.38±1.4	67.2±1.88
MgO	2.7±0.23	2.61±0.42	2.9±0.2
Al_2O_3	1.88±0.23	1.92±0.25	1.86±0.2

2b

	R type 1 (n=34)	R Subtype 1 (n=49)	SLIM type 1 (n=5)
Na_2O	13.7+1.11	12.18+0.95	13.86+1.29
CaO	8.51+1.02	10.18+1.0	9.85+1.5
SiO_2	67.55+1.46	67.66+1.49	67.49+0.9
MgO	3.55+0.33	3.38+0.28	3.08+0.15
Al_2O_3	1.17+0.17	1.24+0.17	0.9+0.1

2c

	R type 4 hi Al (n=12)	R type 4 mid Al (n=40)	R type 4 lo Al (n=13)	N type 4 hi Al (n=12)	N type 4 mid Al (n=5)	N 'Colourless' (n=19)
Na_2O	14.6+0.88	13.77+1.12	14.38+1.2	17.1+1.76	16.71+1.76	12.66+1.0
CaO	7.61+0.72	6.12+1.27	4.99+0.8	7.0+0.72	6.68+1.0	6.73+0.4
SiO_2	63.5+2.19	66.76+2.54	67.9+2.4	63.03+3.0	64.1+1.7	71.11+1.32
MgO	3.79+0.71	4.45+0.72	6.31+0.76	3.8+0.28	4.1+0.3	5.24+0.78
Al_2O_3	3.8+0.55	2.33+0.6	1.33+0.2	3.33+0.28	2.2+0.3	1.0+0.15

Table 2— A comparison of Raqqa glass compositions with glass compositions from Nishapur, Iran (9th-10th century) and Serçe Limani, Turkey (shipwreck dates to c. 1025, the glass to 10th-early 11th century). Oxides of soda (Na_2O), lime (CaO), silica (SiO_2), magnesia (MgO and aluminia (Al_2O_3). R= Raqqa, SLIM = Serçe Limani, N= Nishapur.

4. Conclusions: a possible model for the production of Islamic glass

The production of Roman and Islamic glass occurred on a massive scale. In the Islamic world between the 9th and 11th centuries, a production model for glass can be suggested in which a number of centres manufactured raw glass partly from locally occurring primary raw materials, certainly for local consumption and perhaps for export to other glass-working centres. During the 9th century, natron-sand glass (LMG) appears to have been manufactured on the Levantine coast for local consumption and probably exported inland. Although in some contexts *tradition* (as dictated by social/ political expectations and linked to the specific products of particular groups of artisans) can be identified as the dominant parameter in creating a technological *milieu*, a logical explanation for apparently localised variations in Islamic glass compositions would be the exploitation of locally occurring species of *Salsola* and *Hammada* plants which grew on the fringes of deserts. So when the caliph's capital moved (from Raqqa to Baghdad, for example) a proportion of the artisans would have moved with it. Logically they would have exploited locally growing plants as the alkali source.

In sum, it is possible to distinguish between a number of plant ash glasses (HMGs) dating to between the 8th and 11th centuries (fig. 7). Quartz-plant ash (type 1) glasses were made in two different time periods at Raqqa, in the 8th-9th and the 11th centuries (table 2c R types 1 and Subtype 1). Another quartz-plant ash (type 1) composition, from the early 11th century Serçe Limani shipwreck has been produced using a slightly different tradition (table 2c, fig. 6). The two suites of sand-plant ash glass compositions from 8th-9th century Raqqa and 9th-10th century Nishapur (fig. 8, table 2c R type 4 hi Al and N type 4 hi Al) which may well overlap in their production dates, can be distinguished by their different soda levels. This same compositional difference can be observed between the respective suites of mid aluminium type 4 glasses from the two sites, suggesting that a regional version of the same production tradition was practiced. Another suite of quartz-plant ash Nishapur glasses (table 2c), all colourless, has, to the author's knowledge, no published parallels.

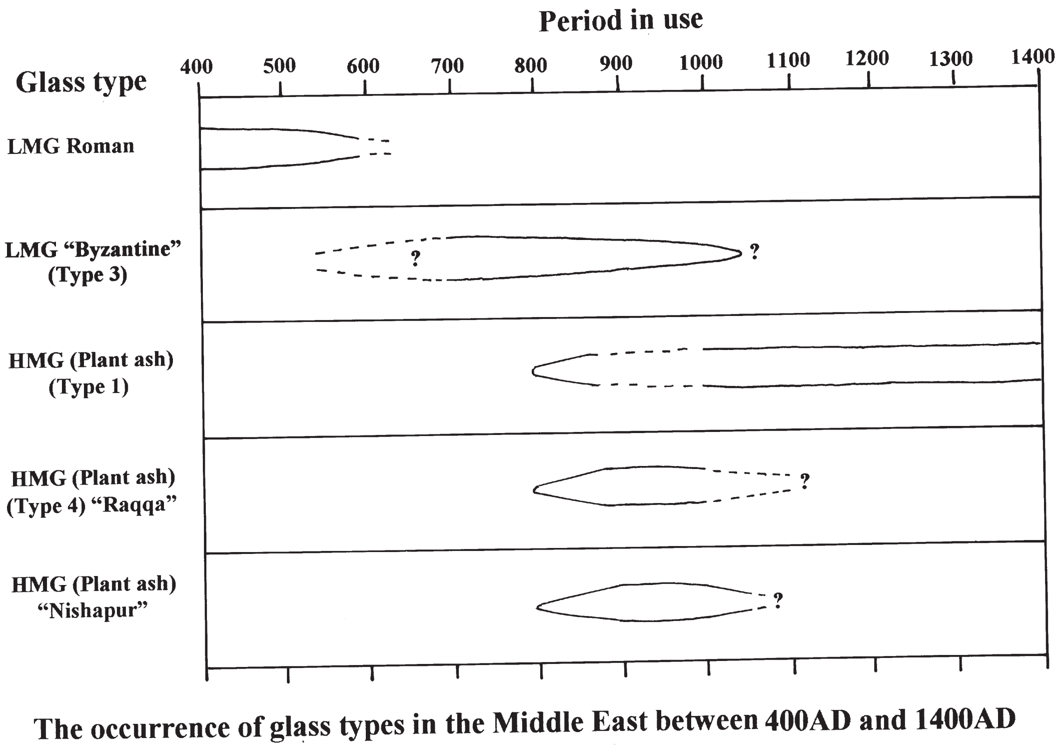

Fig. 7 —The occurrence of compositional types of natron (LMG) and plant ash (HMG) glasses in the Middle East, 5th-14th centuries AD.

In addition, it is possible to show analytically that glasses made using different traditions were recycled. In this case sand-natron glasses and quartz-plant ash glasses were mixed. Eighty-nine analysed samples from Serçe Limani reveal that these glasses resulted from such a mixture (table 2b SLIM type 2). Even here it is possible to distinguish them from the earlier Raqqa mixed glasses (table 2b, R type 2) suggesting that stocks of different glass types were available for mixing. The inference is that the supply of sand-natron glass was slowly running out and was therefore being extended by mixing it with glass made in a 'new' plant ash tradition. By the 12th century the practice apparently no longer occurred, presumably because the stock of natron glass had been exhausted. At this point there was a strict adherence to the quartz-plant ash (type 1) tradition.

The fact that it is possible to recognise the existence of discrete Islamic plant ash technologies in the 9th, 10th and 11th centuries (fig. 8), as well as discrete variations within each tradition, suggests that the ashes of different plant species of the genus *Salsola* or *Hammada* could have been used as alkali sources and, with the overall reduction in the lime contents (perhaps introduced by using different species of plant ashes) that the working properties of different glass batches changed. Where a distinction between plant ash glasses can not be drawn using magnesia vs. aluminia (e.g. between type 4s found at Raqqa and Nishapur) it can be with reference to relative levels of soda and calcium oxide (fig. 8). Figure 8 also shows :

- an analytical distinction between Serçe Limani and Nishapur glasses,

- a distinction between plant ash Raqqa type 1 (8th –9th centuries) and sub-type 1 (11th century),

- a distinction between colourless Nishapur glasses and Nishapur type 4 glasses.

These identifiable variations in quartz-plant ash glass technologies could eventually be relatable to regional production centres. Here compositional data from three geographically widely-separated areas (Iran, Syria and Turkey) have mainly been discussed; the next logical step is to assess whether the distinct compositional glass types discussed are representative of regionalised technological traditions, or reflect a variable use of raw materials within each region.

A somewhat surprising inference from these data is that whilst extensive recycling of Islamic glass of different compositions could create severe problems in identifying regional traditions of production, as reflected in glass compositions, not only can we identify separate subtypes of quartz-plant ash type glasses, but we can also identify analytically where recycling of glass and experimentation with raw materials have occurred. So in the context of 9th-11th century Islamic technology, glass recycling does not necessarily cause problems in identifying separable sub-types of plant ash glass. It may be that normally only glasses of the same compositional type *and therefore with the same working properties* were mixed

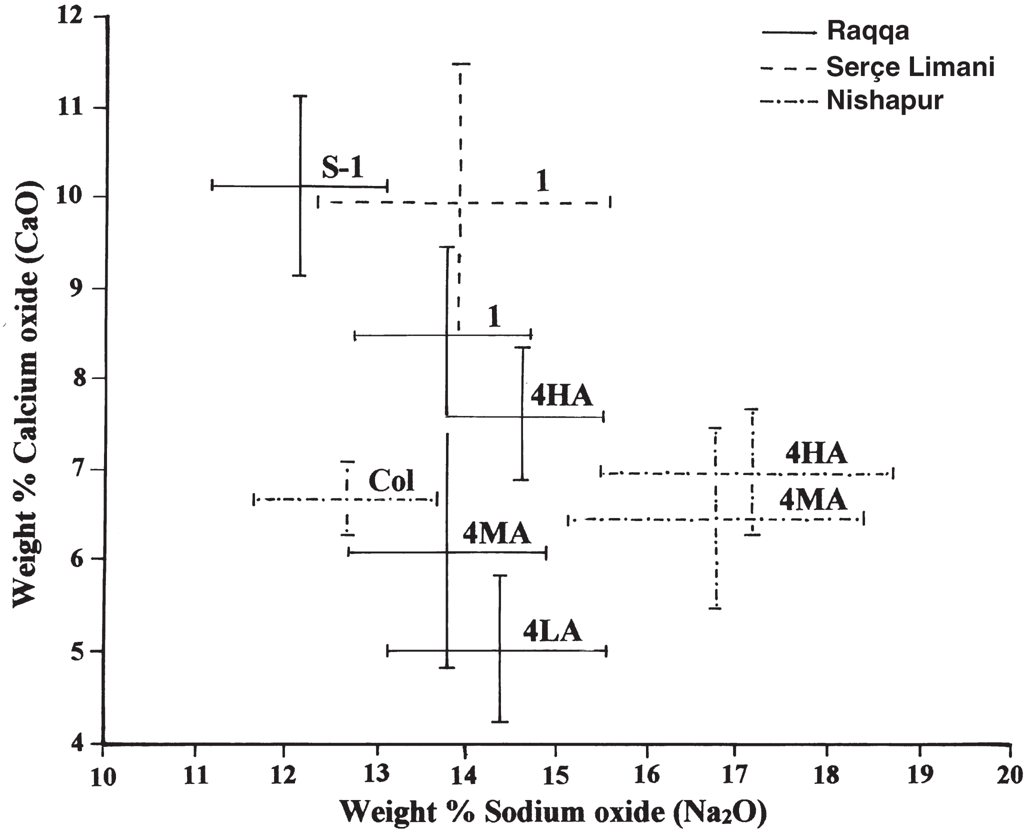

Fig. 8 — The means and standard deviations for relative weight percentage contents of calcium and sodium oxide in Islamic plant ash glasses, not only showing compositional distinctions between glasses from different sites but also that there are regional and chronological compositional variations within types 1 and 4 plant ash glasses.

and although glassworkers would not be aware of these different compositions, the net effect would be to preserve discrete compositional groups. There is some evidence from amongst the Raqqa glasses analysed (Henderson *et al.*, in prep.) that different kinds of green glass colours had different compositions and therefore had different working properties. This would have provided a means for the glassworker to select glasses of known working properties distinguishable by their colour.

It is worth attempting to hypothesise how such variations in glass traditions may have come about in the Islamic world. Dynastic rivalries in the ninth and tenth centuries led to the emergence of independent power centres under the ‘Abbasid caliphs. This in turn led to the establishment of new industrial complexes which included glass workshops and which logically would have used locally occurring alkali-rich raw materials that would have been less dependent on a supply of recycled glass. Already in 836, some time after the decline of al-Raqqa and after Harun ar-Rashid had moved back to Baghdad in 808, the massive new city of Samarra on the river Tigris, in present day Iraq, was founded by al-Mutasim, with its own range of industries, including glass-blowers. Perhaps experimentation with combinations of glass raw materials and raw glass continued in Samarra.

The constantly shifting political allegiances between Islamic groups in the 12th to 14th centuries is not reflected in the chemical compositions of vessel bodies; the conformity of their compositions to the quartz-plant ash (type 1) glass infers that there was a conservative use of primary raw materials and/or that the supply of the alkali raw materials was tightly controlled. Moreover, perhaps glass artisans involved in making the vessel bodies and the supply of glass raw materials during this period, which saw the Crusades, were unaffected by political changes, or quite simply in this case political upheavals which had the potential to affect glass production are not reflected in the production of glass vessels. At least there isn’t the same variation in the alkali types used as is seen in the 8th to 11th centuries. Bass and Van Doorninck (1978, p. 131) have noted that wars in the Islamic world had little affect on trade.

The fact that the working properties of these glasses of the same compositions would have been predictable is an essential consideration. Many of these vessels were highly decorated with enamel that had a relatively wide range of compositions, so the use of vessel glass which had predictable working properties would have provided a useful form of control of the production process. The enamelled vessels produced in Syria include those which had the highest social value, having been donated as gifts to the reigning Ayyubid rulers, Jaziran atabegs and Seljuq sultans of Anatolia (Carboni 2001, p. 5-6). In spite of their high value, the quality of the glass used to make the body of the vessels is often rather poor with inclusions and many gas bubbles. On the other hand, the manufacture of the glass enamels used in the complex decoration of mosque lamps and beakers is of a high quality (Ward 1998) involving a range of colorant and opacifying raw materials (Henderson, Allan 1990; Freestone, Stapleton 1998; Henderson 1998; Verità 1995; 1998). Specialisation, as reflected in raw materials used in the production of 12th –14th century Islamic vitreous materials appears to switch from the rather poor quality plant ash glass used to make the vessel bodies (often nonetheless of a refined shape) to the manufacture of enamels; it is reasonable to suggest that the enamels would have been manufactured in the environment of a souk and once applied as decoration to glass vessels fed into exchange and trade networks, including those extending to Europe (Verità 1998). There is also compositional evidence for export of a cobalt-rich colorant which was used in both glass and enamels in the occident and the orient (Henderson 1998). It is possible that we may be able to identify discrete compositional groupings of enamels which have chronological or geographical significance and there is some historical evidence for the production of Islamic enamelled glass vessels in Aleppo, for example, (Irwin 1998, p. 25), but we are at the very beginning of this task. There will always be the problem of identifying production centres for enamelled glasses archaeologically.

Whether, in the end, we can link this production model to trade links between areas of production and consumption remains to be seen. Given the range of production traditions and identifiable variants from those traditions, each of which may turn out to have regional significance for 8th –11th century glass, this is certainly a potential. It is only because the levels of impurities associated with the use of halophytic plant ashes tend to vary so widely in composition that this is possible. This level of compositional variation is absent from mineral alkali sources (especially natron), so the potential for relating regional glass production to the alkali used for the manufacture of glasses made in the Hellenistic and Roman traditions seems to be absent.

This paper is an interim statement. Further chemical analyses of Islamic glasses and, if possible, glass frits, which derive from *secure archaeological contexts* at production sites, need to be carried out so as to fill in some of the many holes that still exist in our data base through time and space. In this way it may be possible to provide a more secure foundation on which to base an assessment of Islamic glass production and trade using chemical analysis.

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