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1. Introduction

The 'Silk Road' extended from as far as Scandinavia in the west to Japan in the east. It is in fact a network of connections with several possible routes extending east-west and north-south. Part of it is recognisable from as early as the 4th century BC with Alexander the Great's incursions into Afghanistan, Sogdiana and Bactria; others would argue that there is evidence for an earlier 'Silk Road' back into the bronze age (Li *et al*. 2010). Whilst Liu (2010, 62) suggests that the Han, Kushan, Parthian and Roman empires can be seen to have created a network that formed a 'Silk Road' but the contacts that formed the Silk Road more fully only occurred after these empires collapsed. The Silk Road formed a complex and fascinating international corridor along which humans, religions, ideas, technologies, languages and diseases travelled. Groups such as the Persian Sasanians, the Tang Chinese, the Middle Eastern Arabs and the central Asian Turkic and Sogdian peoples were involved in production, exchange and trade over different parts of the Silk Road. The existence of such a network of contacts, and its links to the waterborne spice route, is reflected in the occurrence of a wide range of materials such as silk, spices, ceramics, metals, glass and minerals. Materials may have moved as diplomatic gifts or as a result of trade, exchange, wars and diaspora - these distribution patterns are in fact more analogous to a modern day "virtual network" than to a physical road structure. These materials have been found in a range of contexts on the Silk Road including cosmopolitan trading hubs, palaces, burials and temples but a full review of precisely what materials are associated with which sites and context types on the Silk Road- and how such materials were used in a variety of social contexts - is awaited.

An exciting period when two great empires located on the Silk Road peaked is during the Chinese Tang Dynasty (618-906) and the earlier part of the 'Abbasid caliphate (750-1258) in the Middle East. Both empires were highly centralised with complex administrative systems that controlled very effectively vast swathes of territory- and both had highly successful economic systems tied to the mass production of a range of materials across a wide area of influence that were characteristic and diagnostic of the cultural contexts in which they were made. The Tang capital was in Chang'an (modern Xi'an), Shaanxi province, northwestern China; the 'Abbasid capital was primarily in Baghdad, Iraq. Other powers such as the Byzantine empire also controlled wide stretches of Europe and parts of the Mediterranean but the Caliphate became increasingly dominant from c. 750 AD. Other multi-ethnic hubs linked by the Silk Road that lay between the Mediterranean basin and central Asia included Venice, Thessaloniki, Constantinople, Cairo, Damascus, Beirut, Al-Raqqa, Baghdad, Samarra, Nishapur, Rayy, Merv, Samarkand (Afrasiab), Bukhara and Balkh. Some of these hubs would have had extensive industrial complexes feeding materials into the exchange and trade networks on the land-based Silk Road and the connected water-borne Spice route, both ultimately leading to south-east Asia. The 'Silk Road' was therefore affected by a complex of multiple factors. If we consider the material culture, especially glass, some of the factors that would have affected the west Asian part of the Silk Road (the focus of this paper), include:

(1) the structure of the economy in urban and rural contexts and the roles that governors and caliphs played in determining the scale and organisation of industries;

(2) the social hierarchy including the status of artesans who made glass and pottery;

(3) the social values of materials and they ways in which were used in urban and rural life (e.g. dining rituals);

(4) the presence of 'men of science' and the role of 'alchemy';

(5) production specialisations;

(6) sourcing of raw materials such as fuel, plant ash and sand, scrap glass, clay for making furnace bricks and crucibles and glass working equipment (Henderson 2000), some of which was determined by the agricultural cycles;

(7) transport and trade/exchange of raw materials and finished products.

This is not an exhaustive list but these factors both singly and together would have impacted on the inter-related urban and rural networks that formed the Silk Road at different times

One intriguing question is whether we can use the scientific characterisation of early Islamic glass to provide evidence for links between the cosmopolitan hubs that formed the Silk Road and thereby help to define interactions along it. This paper builds on the publication and discussion of 97 samples of Islamic glass dating mainly between the 8th and 10th centuries from sites between Egypt and northern Iran, across a distance of some 2000 miles (Henderson *et al*. 2016). We consider more closely features of the Middle Eastern early Islamic political and economic landscapes as a means of interpreting glass production models and we reconsider the same chemical data in somewhat more detail in terms of the evidence for provenance.

Changing economies, changing caliphates, production and trade

The communities that lived along the Silk Road experienced changing economic and social conditions which affected production and trade in different ways at different times. Factors such as wars, diaspora and diseases (such as the plague during the Umayyad caliphate in the Middle East) would all have made an impact on residents of cosmopolitan hubs and on surrounding areas. It would be simplistic to suggest that the outbreak of war and associated diaspora always caused the demise of an industry. For example, political disruptions in the late 7th and 8th centuries creating a Syrian diaspora of many Byzantine Greeks (referred to as the Rūm by the Arabs) from the Levantine littoral (Kennedy

2010, 191) may well have impacted on industries such as glass production that would have involved Jews, Muslims and Christians. Furthermore, during the Umayyad caliphate changes in the political and diplomatic links that existed between the Byzantine and Muslim worlds would have impacted on the supply of glass and other materials (Graber 2004; Henderson 2013, 255-257). Another political factor that would have had an impacted on the economy of Middle Eastern countries was the transfer of centralised power from Damascus in Greater Syria to Baghdad in Iraq when the 'Abbasid caliphate displaced the Umayyads in 750 (Wickham 2004, 168). Indeed the economic boom that occurred under the 'Abbasids, with the associated centralisation of administration, had a measurable effect on production and trade in and between the connected centres of Basra, Baghdad and Samarra in Iraq - and undoubtedly in the palace city of al-Raqqa in Syria. The positive effect of such a boom was felt as far away as southeast Asia (Stargardt 2014).

Basra was described by the 10th century geographer al-Muqaddasi as 'a port on the sea, and an emporium of the land' underlining its important role linking Iraq and the Persian Gulf and to Arabia east Africa, India and south-east Asia (Whitcomb 2009). In the late 8th-early 9th centuries Harun al-Rashid and subsequent caliphs developed a taste for Chinese porcelain: 70,000 pieces of Chinese stoneware and porcelain were found on the wreck of the Belitung which sank off the coast of Belitung island, Indonesia and is preserved in astonishing condition (Krahl 2011). It dates to c. 830-850 and is thought to have been sailing to the Middle East. The Cerebon, thought to date between 960 and 930 was wrecked in the Java sea. It had on board, amongst other things, 250,000 Chinese ceramics, 20 Islamic glass flagons (not obviously prestigious) and a large amount of broken glass on board and is thought to have been sailing eastwards (Stargardt 2014, 45-46). The trade between southeast Asia and the Middle East therefore occurred on an enormous scale. In the 9th and 10th centuries enormously rich financiers gained their wealth from overseas trade, such as Abū Bakr whom Ibn Hawkal met in Basra in 961 (Banaji 2010, 175). Ashtor (1976) has described the 'Abbasid economy as 'pre-capitalist'. Excavations of the early 11th century wreck of the Serçe Limani revealed tons of raw and scrap glass and is evidence, if needed, for glass trade in the Mediterranean at the time (Bass et al 2009).
Even though the focus of trade shifted from the Mediterranean to the 'Mesopotamian' region (Wickham 2004), with Baghdad becoming a centre of the 'Abbasid economy (Lapidus 2014) with its links along the land-based Silk Roads to central Asia and China and via Basra and Siraf to south-east Asia, Damascus continued to be an important centre for production and trade on the Silk Road (though diminished in political terms). With this shift in the centre of power, northern Syria, linked to Baghdad by the river Euphrates would have become more integrated into 'Abbasid political realm; indeed Al-Raqqa by the Euphrates developed into a palace city during the time that Hurun al-Rashid resided there between 796 and 808 before he moved back to Baghdad in 809 (Henderson *et al*. 2005, Heidemann 2006). During this time Al-Raqqa was an important industrial centre, where both glass and ceramics were produced on a very large scale.

Glass raw materials

Although both natron and plant ash glasses were found on some of the sites that form the focus of this project we have selected plant ash glasses to focus on. Such glass was made using a combination of ashed halophytic plants and sand, or possibly crushed quartz (Henderson 2013, 260-266). The plant ash glass made in Islamic tank furnaces is of a range of colours including pale green, olive green, pale blue and purple. These colours are due to a range of factors (Henderson 2000) one of which is the presence of iron-bearing minerals in the sand used to make the glass (so-called 'naturally coloured glass'). Another colorant that is found universally in Islamic glass is manganese oxide. It would seem that this was added deliberately to the glass melt as part of Islamic glass technology (Sayre and Smith 1961, Henderson *et al*. 2004). Another important factor that determined the final glass colour was the gaseous atmosphere of the furnace: the combined presence of iron and manganese oxides and the balance of oxygen and reducing gases like carbon monoxide and carbon dioxide during melting produced the range of glass colours noted above.

Very low levels of mineral-rich colorants, such as cobalt and copper, were added deliberately when glasses were remelted prior to them being blown. This produces a wider range of glass colours, including deep translucent blue and turquoise green. Some of the associations of trace elements with both raw materials (including colorants) and contaminants are discussed in the results section below.

Archaeological and historical evidence for Islamic glass production

Reliable archaeological evidence for the fusion of ancient glass from raw materials in furnaces is still relatively rare, especially in inland locations stop (Aldsworth *et al.* 2002, Gorin-Rosen 2000, Henderson 2103). Excavations at the 8th or 9th century site of Beth She'an (Scythopolis) in the Levant produced evidence for primary glass production (and for late Roman linen and Umayyad ceramic production) (Goren-Rosen 2000, Tsafrir 2009).

Interdisciplinary research at the cosmopolitan hub of al-Raqqa, northern Syria, has revealed an 8th-12th century industrial complex, including evidence for glazed and unglazed pottery production and for primary glass production using ashed halophytic plants and sand (Henderson *et al.* 2004, Freestone 2006, Barkoudah and Henderson 2006) and the discovery of frit (Henderson 1995), a semi-fused glass (see Figs. 1 and 2 for the context of its location). Production occurred on a massive scale in rectangular tank furnaces. The most recent discovery, in 2010, was a probable new type of ancient glass furnace: an early Islamic downdraft furnace at Tell Abu Ali within the Al-Raqqa industrial complex (Khalil and Henderson 2011): see Figs. 3, 4 and 5. This glass technology has formed part of a period of technological innovation and experimentation that characterised the flourishing economy of the Abbasid caliphate, and may be related to the presence in al-Raqqa of a famous scientist, Jabir ibn Hayyan who is regarded as one of the fathers of modern chemistry and may have worked with the caliph, Harun al-Rashid. He wrote extensive treatises on, amongst other things, the production of glass, glass coloration and even on the techniques involved in making lustre decoration (Ullmann 1970, Haq 1994, Al-Hassan 2009). Possible evidence of experimentation with plant ash glass technology at Al-Raqqa has been discovered using scientific analysis (Henderson et al 2004). Production was on a massive scale - the industrial complex was 2 kms long with deposits of industrial refuse being up to 7 metres deep. There is evidence from excavations that the manufacture of glass and ceramics occurred in the late 8th, 9th, 11th and 12th centuries. It would have required a high level support, potentially up to that of the caliph (Henderson *et al.* 2005). The glass and ceramics made there were probably traded in the nearby markets, the latest of the two occupying the area between Al-Raqqa and Al-Rafica (Heidemann 2006, 38).

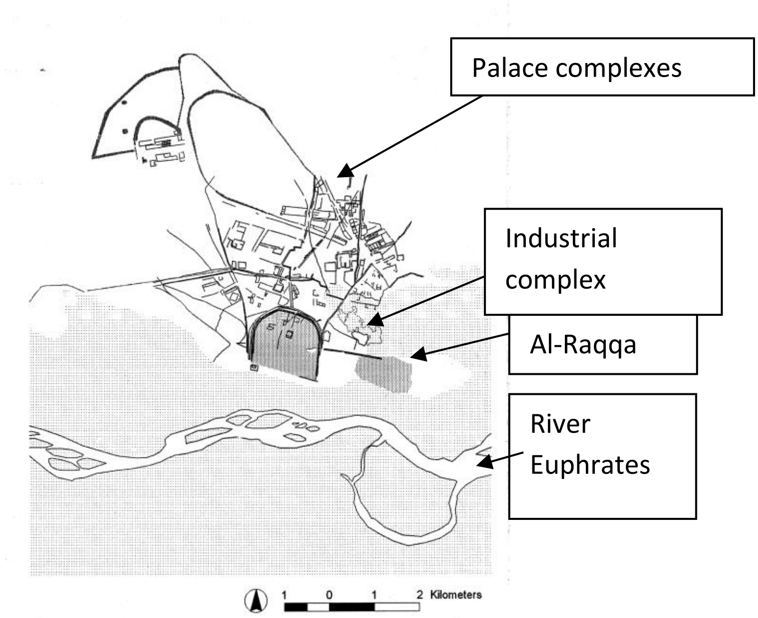

Fig 1. GIS map of the medieval landscape of Al-Raqqa, northern Syria. The horseshoe shaped walled enclosure is Al-Raqqa's twin city, al-Rafica (the companion). The map is based on a 1967 declassified corona satellite image.

Fig. 2. Close up of the 1969 declassified Corona satellite image of the Al-Raqqa industrial complex showing sites excavated. 1= 11th ceFntury Tell Fukhar, 2= 11th-12th century Tell Belor; 3= 9th century Tell Zujaj; 4 = Late 8th-9th century Tell Aswad; 5= 9th century Tell Abu Ali.

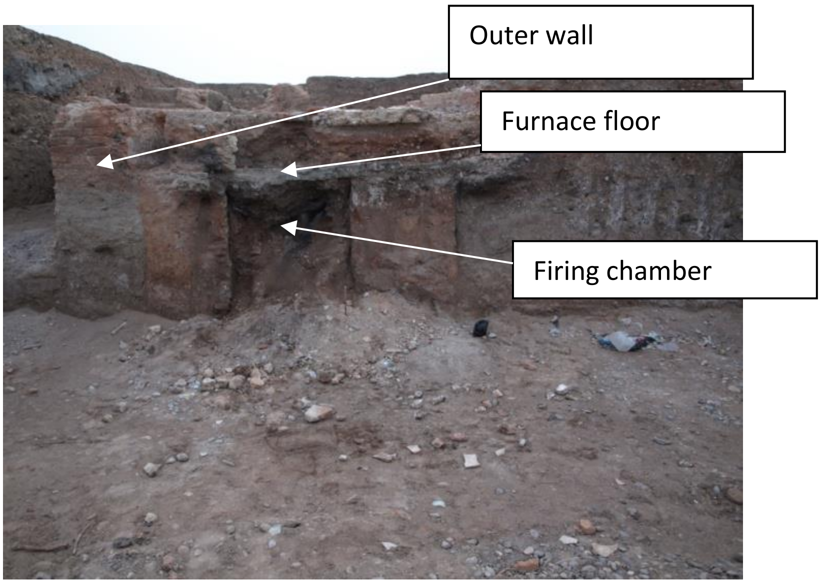

Fig 3 Section through the probable downdraft glass furnace, Tell Abu Ali, Al-Raqqa, Syria.
The height from the top of the section of the furnace wall to the base of the firing chamber is 1.05m. The furnace measures 3.7 x 2m and has a sloping floor. The grey left hand outer wall measures 0.4m. Photo: J. Henderson

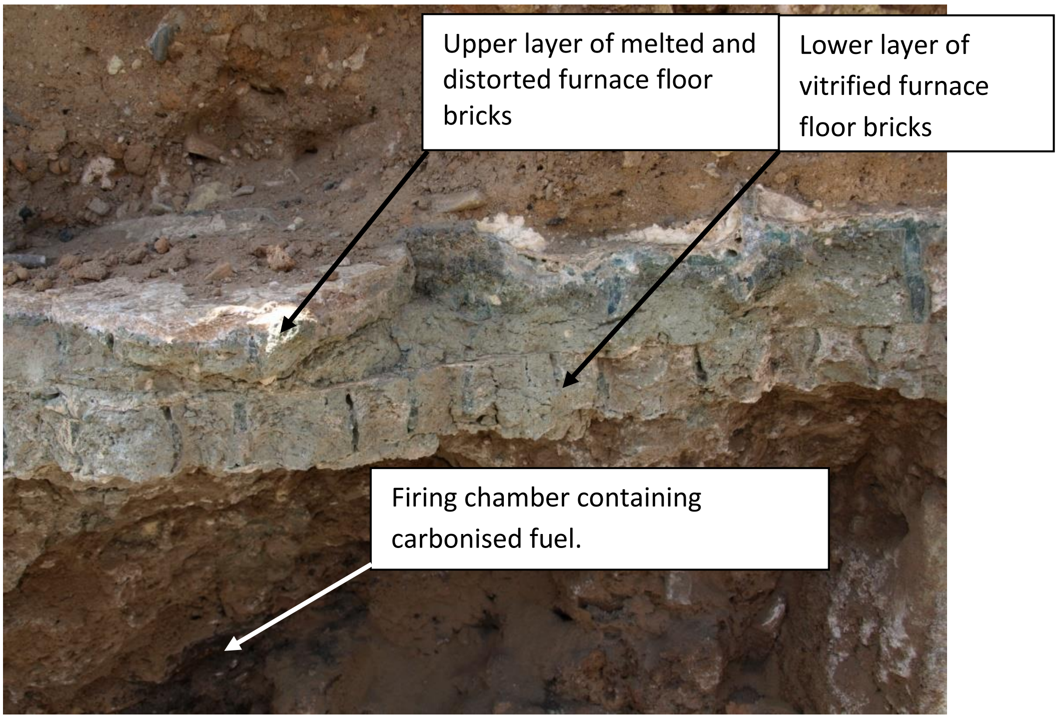

Fig 4 A close up of the top of the melted firing chamber in which carbonised fuel is still visible, with 2 courses of melted bricks above it. Dark vertical glass is visible between the lower course of melted bricks; the upper course is almost completely deformed and melted so it has evidently received more heat than the lower course. This supports the interpretation that the source of heat was from above as part of a downdraft furnace. Photo: J. Henderson

Fig 5. The glass furnace at Tell Abu Ali formed part of a cluster of other high temperature structures: in this photo a line of circular and rectangular pottery kilns can be seen. The closest one is a large (2.5m diameter) kiln used for the production of glazed ceramics in which glazed kiln bars were found *in situ.* Undoubtedly technological knowledge was exchanged between artisans involved in glazed pottery and glass production. Photo: J. Henderson.

Up to now the most complete Islamic glass furnaces have been found at Tyre in the Lebanon (Aldsworth *et al*. 2002). Here the maximum height of the tank furnace walls that survived was 1.2 m. It is estimated that as much as 32 tons of raw plant ash glass (Freestone 2002) would have been produced in each batch. The furnaces probably date to between the 10th and 12th centuries. Unlike al-Raqqa, where minimal historical references to glass production have been found, (Heidemann 2006, 41, n. 54) those for Tyre are quite extensive (Irwin 1998, Carboni *et al*. 2003). Al-Muqaddasī states that cut and blown glasses were produced there; in 1163 Benjamin of Tudela, a Spanish Rabi, reported that 400 Jews were involved in glass production and ship owning there (Wright 1848, 80); in the 12th century al-idrīsī reported that Jews made both glass and ceramics in the suburbs of Tyre (Chebab 1979, 429).

The Tyre and al-Raqqa glass furnaces were excavated relatively recently using modern techniques. During a survey of Samārrā, Iraq, Northedge and Faulker (1987) found evidence for glass production close to palaces on the north bank of the Tigris in an area known locally as m'mal al-Zujāj (Zujāj is one Arabic word for glass). Here, unsurprisingly there is evidence for an industrial estate (*ibid*. 149, Milwright 2010, 146).Moreover, there are historical references to glass production in the Qadisiyya quarter of Baghdad (Lamm 1929-30, 498) and in Aleppo during the time of the Ayyubids: Yāqūt describes a source of fine white sand that was used for making glass. Lamm (1929-30) has suggested that Basra was an important centre for glass production and Ettinghaussen (1984) has suggested that it was the centre for the production of the finest early Islamic glassware, including lustre ware. Ettinghausen *et al*. (1987, 72) describes some of the evidence for glass production there. Basra was also an important centre for ceramic production (Watson 2014). In support of this, Ya'qūbi notes that potters and glass makers were sent from Basra to the new capital of Samarra. Lustre painting on glass and ceramics may have been a secret that was retained within the families associated with the art, such as the 13th-14th century Abu'l-Tahir family based in Kashan, of which the famous Abu'l Qasim was a member (Komaroff 2004, 39). Nevertheless, although there is a great likelihood that glass was fused from raw materials at Basra currently there is no archaeological evidence of it.

Glass was also produced in other parts of the Islamic world: for example, there is archaeological evidence for glass making in 12th century Islamic Spain and for glass working in 14th century Crimea (Henderson 2013, 269). There were also centres that specialised in making specific vessel forms (Shatzmiller 1994, 224-226). Large numbers of glass vessel fragments in centres like Nishapur (Iran) and Hama (Syria) may suggest that glass vessel and perhaps glass was made there but this is not proof.

Islamic glass vessel types

Most Islamic glass would have been undecorated and made into a range of forms such as bottles, cups, beakers, jugs, rose water sprinklers and alembics. A range of rather more diagnostic decorated glass vessel types have also been found in Islamic contexts. These include lustre-decorated, mould decorated, cameo decorated, pinch decorated, scratch engraved, line decorated, wheel cut, trail decorated and enamelled (Carboni 2001, Carboni and Whitehouse 2001, Whitehouse 2010). In addition, glass wall plaques and beads have been found. Some of these glasses show the continuation of Roman/Sasanian techniques into the Islamic period. Examples are trail-decorated vessels (characteristic of eastern Mediterranean production), applied plastic decoration, impressed (pinched) decoration, marvered decoration, facet cut vessels, moulded vessels (such as bowls with 'pillar moulded' decoration), enamelled and gilded decoration and the use of the *millefiori* technique to decorate vessels and exquisite Samarra wall plaques (Carboni 2001, 15-17). Others are new Islamic types; these are lustre decorated (Carboni 2001, 51-53, Carboni and Whitehouse 2001, 52) and relief- and scratch-decorated vessels. As noted, although facet cut glasses were manufactured by the Romans and Sasanians, Islamic glass workers built on this, producing a wide range of variations including scratch-decorated vessels (Carboni 2001, 71-73, Hadad 2000, Kroger 2005, Whitehouse 2010). That both lustre and scratch decorated vessels could have a high value is demonstrated by their occurrence in the Famen temple (Famensi) royal treasury in Shaanxi province, northwestern China sealed in 874; the glass was found together with silk, gold, silver and porcelain objects (AnJiayao 1991, Jiang Jie 2010, Li *et al.* 2016). The elite social and ritual context of the Famen temple is quite exceptional.

The social roles and associated values that Islamic glass vessels had has hardly been explored. With the expansion of the 'Abbasid economy in the 9th century and the associated increased production of ceramic and glass vessels in the economic boom it is likely that dining habits and associated rituals were affected. Quite how such changes affected the use of glass vessels in lower levels of society is difficult to gauge. Hadith literature stated that ceramics and glass vessels should be used as tableware rather than vessels made from fine, especially precious, metal (Komaroff 2004, 37). Undoubtedly the feasts arranged by the caliph and his retinue would have used the highest quality of glass and ceramic vessels. Mamluk enamelled lamps would have been used to light madrasas, mausoleums, mosques and Sufi khanaqahs (Komoroff 2004, 44).

Glass characterisation: materials and techniques

In our earlier paper (Henderson *et al.* 2016) we reported on the results of 97 analyses of Islamic glass. The glass samples were derived from the cosmopolitan centres of 9th century Beirut (the Lebanon), 11th-12th century Damascus (Syria), 9th century Al-Raqqa (Syria), 9th century Samarra (Iraq), 9th-10th century Ctesiphon - Islamic al-Madā'in (Iraq), 9th-10th century Nishapur (Iran) and 14th-15th century Cairo (Egypt). We also included samples of glass from a late phase (8th-10th century) of the important palatial site of Khirbat al-Minya (Israel). The site of Khirbat al-Minya is an Umayyad palatial building of the 8th century. Later settlements within the palatial building date from the 11th.-14th c. The glass window pane fragments belong to the Umayyad period. The production centre for 'Cairo' glass is a suggested one based on the dedications on the mosque lamps to specific emirs who ruled in Cairo: the glass for the lamps is likely to have been made there. The emirs reigned between c. 1300-1340, c.1350-1365 and c. 1412-1415 (Carboni 2003).

The vessel types sampled include some that are discussed above. They are colourless and green cut and ground vessels from Nishapur, Samarra and Ctesiphon, vessels with applied decorative strings with green bodies from Nishapur, vessels with applied knobs from Nishapur, colourless pinched vessels from Nishapur and Samarra, scratch decorated vessels from Samarra, cameo decorated vessels from Samarra and enamelled mosque lamps probably from Cairo. We also analysed undecorated vessels. These include bottles, beakers, bowls, phials, vases, flasks and grenades from Beirut, Damascus, Khirbat al-Minya, Al-Raqqa and Ctesiphon. For comparison we included samples of coloured wall plates from Samarra and window glass from Khirbat al-Minya and Al-Raqqa. So as to test the provenance of glasses from the only archaeologically proven primary glass making site for which we had samples, we included samples of raw furnace glasses from Al-Raqqa, Syria of a range of colours (see above).

The techniques used were electron probe microanalysis (EPMA) and laser ablation inductively coupled plasma mass spectrometry (LAICPMS). The techniques and the experimental conditions employed are described in detail elsewhere (Henderson *et al*. 2016). EPMA was used to determine major and minor elemental concentrations in the glass samples; LAICPMS was used to determine the trace element concentrations in the glass samples.

Results

The association of trace elements with particular raw materials or 'contaminants' in all of the glass samples analysed is given in Fig. 6. This figure was produced by performing cluster analysis on all the trace elements detected in 97 glass samples in order to investigate any association between the elements in the glasses. The degree of 'similarity' is given on the Y axis.

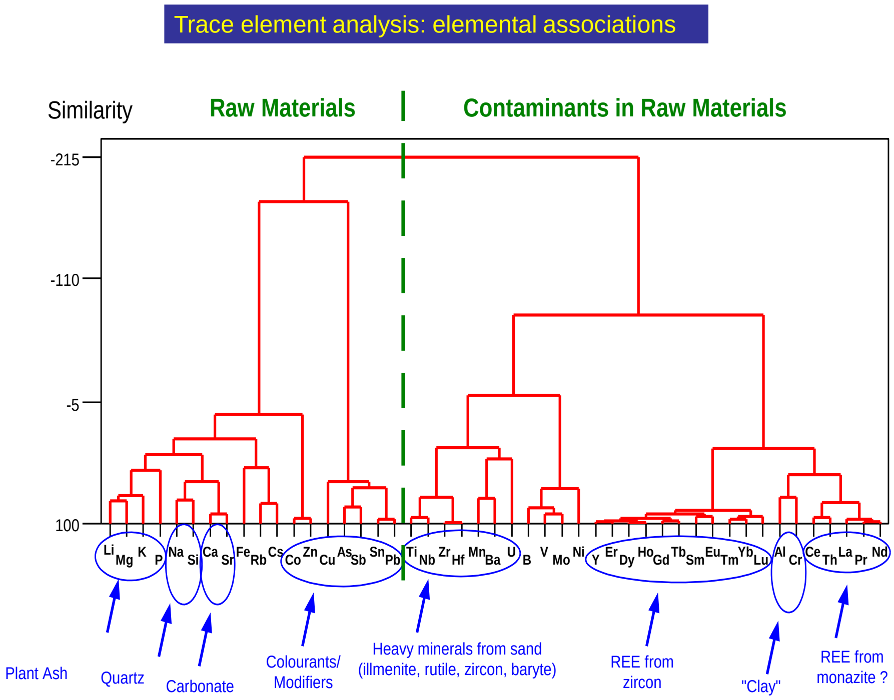

Fig. 6 Cluster analysis created from the trace element results for 97 plant ash glass analyses, showing the level of similarity (association) between the elements detected in the glasses.

First, it can be seen that there is a clear association between the trace elements and the primary raw materials used: the plant ash, the quartz and calcium. Even when elements that would be expected to be associated very closely with each other are not, they occur close to the expected location in the plot. For example Li, Mg, K and P are associated in the alkaline plant ashes. Nearby on the plot are Na, Rb and Cs. Since the technique is measuring association, silicon and sodium would not be expected to be associated because they are negatively correlated. Nevertheless, overall there is a satisfactory grouping of associated elements that can influence the development of glass colour or cause it and/or opacity consisting of copper (Cu), arsenic (As), antimony (Sb), tin (Sn) and lead (Pb). Cobalt (Co) and zinc (Zn) are adjacent but separated from the rest; it has been established that zinc tends to be associated with the cobalt source used in Islamic glasses and glazes (Hill et al (2004, 602, Fig. 6, Table 3, Wood et al 2007, Henderson 2013, 74) Hill et al (*ibid.*)refer to such cobalt blue glazes as a 'high nickel group' but they are also characterised by high zinc.. On the right hand side of the figure are the contaminants which are elements found in minerals such as illmenite, zircon, rutile, baryte and monazite. The close association of Al and Cr could be due to their occurrence in clay and/or mafic minerals in one or more raw materials. It is worth emphasising that some elements can be found as impurities in more than one raw material (Henderson *et al*. 2016, 139). For example, Al can be associated in minerals such as feldspars (calcium, potassium or sodium aluminium silicates) in sands. Aluminium and ~~chromium~~ Cr may also be found in both sands and plant ashes.

Until we carried out this research, some compositional distinctions had been identified for Islamic glasses mainly using major and minor element oxides and radiogenic isotopes (Gratuze and Barrandon 1990, Freestone *et al*. 2003, Henderson *et al*. 2004, Brill 2001, Henderson 2013, Henderson *et al*. 2009) but less work had been published on the use of trace element analysis to investigate such glasses (Kato *et al*. 2009, 2010, Freestone *et al*. 2000).

In order to place this further consideration of the results into a context, a summary of the published results (Henderson *et al*. 2016) will be presented here, including a more detailed discussion of Levantine glasses, followed by an extended interpretation, especially for the distinction between Levantine and other glasses, evidence for the use of very similar raw materials in Sasanian and early Islamic glass from Iraq and evidence for centralised and decentralised production of glass.

Summary of results

These results formed the first broad analytical survey of 8th-15th century CE plant ash glass using major, minor and trace elements from the Middle East across a 2000 mile area stretching from Egypt to northern Iran. The following primary results have been produced:

● Trace element fingerprinting of glasses made from ashed halophytic plants and sands together with colorants and associated impurities.

● Trace element characterisation for glass deriving from selected cosmopolitan hubs on the Middle Eastern Silk Road has provided far clearer provenance definitions for regional centres of production in the Levant, northern Syria and in Iraq and Iran than detected till now. There is an especially clear distinction between the Levant and the rest according to trace impurities largely derived from sands such as Fe and Cr (Henderson *et al*. 2016, Fig. 4). Moreover Cr/La and Li/K values tend to increase moving from west (the Levant) to east (Iraq and Iran).

● This trace elemental characterisation has provided evidence for sub-regional production zones such as between Beirut, Damascus and Cairo and between Ctesiphon and Samarra. Plots of Cr/La versus 1000Zr/Ti (trace elements largely derived from sands) and Cs/K versus Li/K (trace elements largely derived from plant ashes) are especially good as distinguishing between glasses made in these sub-regional production zones (Henderson *et al*. 2016, Figs. 5 and 6).

● The results also provide evidence for locations where specialisation in the production of particular types of decorated vessels occurred. The fact that specific vessels types have distinctive compositions shows first that the vessels with that decoration were made in the same place or possibly made in locations within the same constricted region with the same geochemical characteristics.

● The identification of compositional groups for glass found on the same site is exceptional and shows with quite a high degree of certainty that raw materials with the same or very similar compositions were used to make them. It would be somewhat obtuse to suggest the following alternative interpretation was valid: that raw glass of separate compositional types was consistently and routinely exported from a range of distinct primary production centres to other centres where the vessel types were made from the (remelted) raw glasses and that the vessels were not made on the same sites as the glass.

● This glass characterisation makes it possible to indicate when glass was traded between centres of production and consumption.

● If mixing of glass from different production centres occurred, it appears to have occurred in a highly restricted number of instances. If it occurred commonly we would not have been able to define our distinct groups. However, the pattern for Samarra glasses does suggest that a level of recycling occurred but that it was largely confined to the mixing of glasses made in the Samarra zone.

●The following can be suggested for glass analysed from the following sites:

Samarra

Pale green mould-decorated vessels, cameo decorated vessels, a pinch-decorated vessel, scratch decorated vessels and wall plaques were made in Samarra. A green phial, a green beaker and green window glass found at Al-Raqqa in northern Syria were probably imported from Samarra along the river Euphrates some 430 miles away. A small pale green ovoid vessel found at Ctesiphon was also probably made at Samarra.

Ctesiphon

Pale green and colourless facet cut vessels, a colourless bowl and an ovoid bowl found at Ctesiphon were probably made there. They form a distinct group with high Cr/La values (Henderson *et al*. 2016, Fig. 5).

Nishapur

Colourless cut and engraved vessels and colourless pinch decorated vessels were made in Nishapur. Six colourless facet cut vessels found at Samarra with distinctively lower Cr/La values than found in Samarra glasses were probably imported from Nishapur. Four green trail decorated glass vessels were imported from the Levant.

Al-Raqqa

The raw furnace glasses from the primary glass-making site at Al-Raqqa have a distinctive composition and their Cr/La and Li/K signatures are more constrained than levels found in scrap glasses derived from glass working and in vessel glasses from Al-Raqqa. This is probably because vessel and scrap glasses will have been produced as a result of a degree of glass mixing- but are nevertheless characteristically of an Al-Raqqa composition. Two fragments of nearly colourless beakers decorated with applied knobs (with a yellowish tinge) found at Nishapur plot with Al-Raqqa samples and were therefore probably exported to Nishapur from Al-Raqqa; a colourless facet cut vessel found at Ctesiphon was also probably made in Al-Raqqa.

Beirut

Beirut glasses generally have lower 1000Zr/Ti ratio vales than Damascus glasses and this provides evidence for a separable production sub-zone (Henderson *et al*. 2016, Fig. 5). These are for a single colourless, pale green and pale brown beakers, and for single purple and colourless bowls. Two samples have significantly lower 1000Zr/Ti values than the others. These are colourless and green bottles.

Damascus

A trace element compositional fingerprint for Damascus glass is less coherent than for Beirut glasses though the distinction mentioned above is valid. The glass objects probably made there are three pale green, one purple and one colourless beaker and two grenades. A remaining grenade is a Levantine product but less obviously a Damascus product,

Khirbat al-Minya

As already suggested (Henderson *et al*. 2016) these glasses may have been made in a nearby urban centre such as Amman. Five out of six samples form a compositional group falling between Cairo glasses and Beirut/ Damascus based on Cs/K values. These consist of 4 green flasks and one purple flask. The sixth sample found at Khirbat al-Minya is brown window glass. Based on the Cs/K vs Li/K plot (ibid., Fig. 6) appears to have been made further east, perhaps in northern Syria or in Iraq.

Cairo

All samples analysed are of 14th-15th century Mamluk mosques lamps. The vessels may have been manufactured in Cairo according to their dedications (see above). Six of the 14th-15th century lamps tested contain Cs/K ratios of above c. 2.E-05 which distinguishes them from Khirbat al-Minya, Beirut and Damascus as does their higher Li/K ratios. The lamps which do not fall into the core group are not obviously visually distinct from the others according to their colour- or their date. The glass for one of these may have been made in Beirut.

Compositional distinctions between 'eastern' and 'western' glasses

As already noted Cr/La and Li/K ratios and a plots of Fe versus Cr provides clear distinctions especially between Levantine and non-Levantine glasses in this study (Henderson et al 2016, Figs 4-6). With very few exceptions Fig. 7 also shows a clear compositional distinction between Levantine and non-Levantine glasses. Levantine glasses contain tightly constrained low nickel and chromium concentrations, Samarra and Nishapur glasses contain similar concentrations of both elements whereas both Ctesiphon and Al-Raqqa secondary glasses contain higher and more variable levels of both. Nevertheless when the Levantine glasses contain similarly low chromium concentrations as found in eastern glass they also contain slightly elevated nickel contents. It is significant that nickel does not group with the other transition metal elements (colorants and opacifiers) in the cluster diagram in Fig. 6. A possible source of nickel (and chromium), which explains the patterns in Fig. 7 is mineralogical impurities in plant ash. The maximum concentration of Ni detected in a range of ashed semi-desert plants from Syria was 55 ppm (Barkoudah and Henderson 2006, Table 2) so this could account for the levels detected here although a contribution from sands cannot be ruled out. The raw materials used to make Levantine glasses therefore appear to contain lower levels of nickel and chromium than a considerable number of glasses from Samarra and Ctesiphon- and many Al-Raqqa glasses.

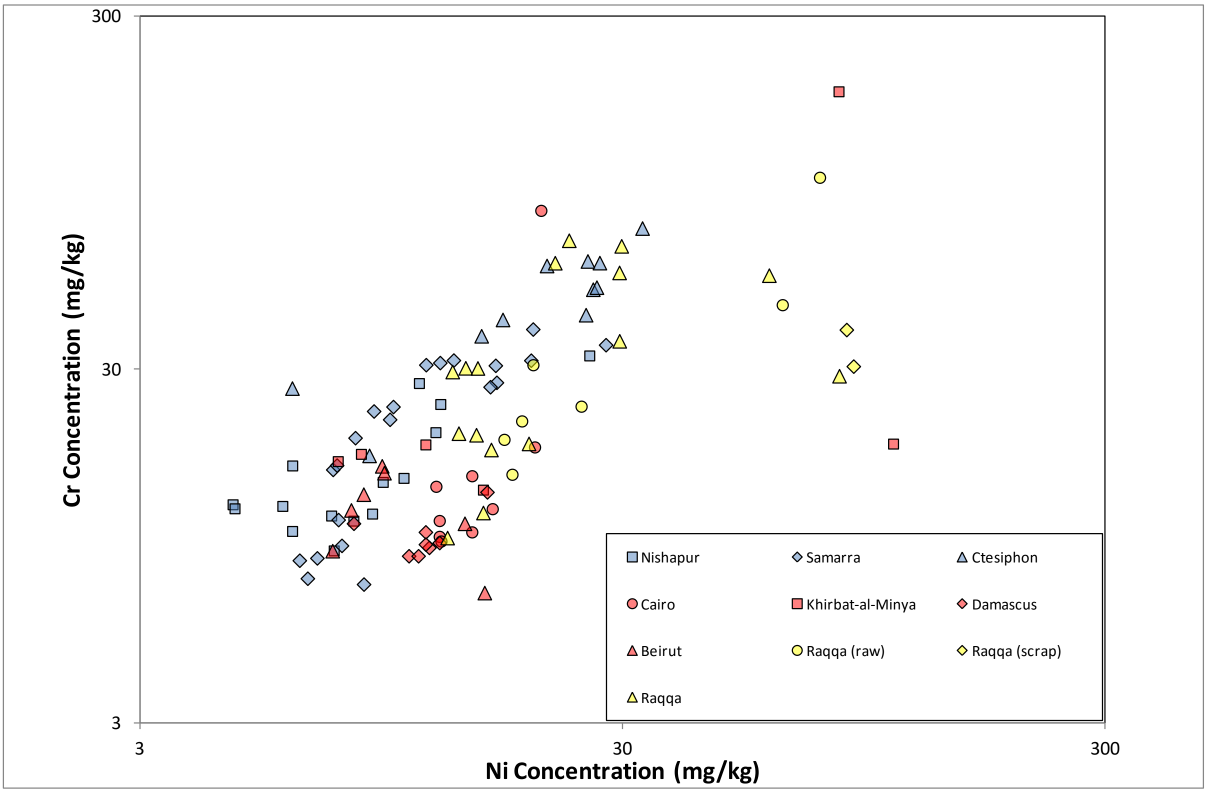

Fig. 7 A bi-plot of nickel versus chromium log concentration (mg/kg) in the glasses analysed

As noted elsewhere (Henderson 2013,294-296; Henderson *et al*. 2016, 138, Fig. 3) there is a general decrease in the concentration of calcium oxide and an increase in magnesia found in early Islamic glasses moving from west to east, from the Levant to Iraq and Iran. Even when tons of raw, scrap and vessel plant ash glass were traded, as in the case of the Serçe Limani, Turkey (Bass et al 2009), an overall Levantine source for the glass is provided by this characterisation (Henderson *et al*. 2016, Fig 3) and this also underlines that mixing of glass made in the Levant and further east as refelcted in the scientific analyses of Serçe Limani glass was rare or minimal. The primary source of lime in these glasses is ashed halophytic plants- although not all contain sufficient levels for glass making and an additional lime source may have been added. It is likely that one additional source was shell fragments in beach sands used (associated with feldspars) from the same source (Freestone *et al*. 2003, Henderson *et al.* 2005a). In Fig 8 we show a relatively clear distinction between Levantine and other glasses, with Levantine glasses generally having both higher calcium and strontium oxides. There is a clear distinction in this figure between most Levantine glasses and glasses found at Samarra and Nishapur. Significant exceptions are the glasses from al-Raqqa and some from Ctesiphon, which fall amongst Levantine glasses. This could suggest that Levantine plant ash glasses were made from sand containing shell fragments. However, plant ashes can sometimes contain high strontium (up to 1100 ppm) and calcium concentrations (Barkoudah and Henderson 2006, Henderson et al 2009) and they tend to be correlated. A plot of weight % magnesia versus weight % calcium oxide provides a relatively clear distinction between Levantine and eastern glasses (Henderson *et al*. 2016, Fig. 3) isotopic (Nd and Sr) analysis of Levantine and Al-Raqqa glasses provides a clear distinction between them (Henderson *et al*. in prep). The lime used to make the Al-Raqqa plant ash glasses is geologically older than that used for the Levantine plant ash glasses.

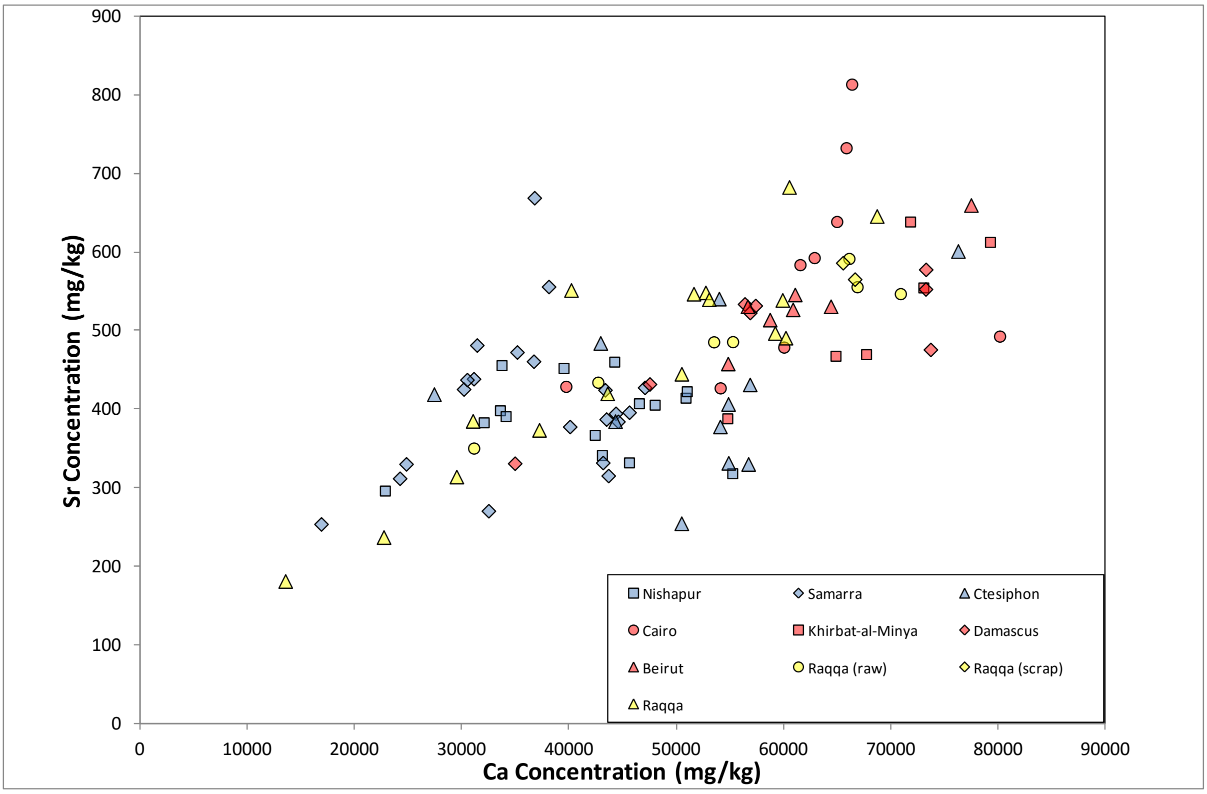

Fig. 8 A bi-plot of calcium versus strontium concentrations (mg/kg) in the glasses analysed

In Figs 9 and 10 we compare the data published by Mirti *et al*. (2008, 2009) for Sasanian natron and plant ash glasses from 4th-5th century Seleucia and Veh Ardašīr in Iraq with our own data for Islamic plant ash glasses. We have briefly discussed the results plotted in Fig 10 before (Henderson *et al*. 2016, 139) but we have not published or discussed fully Figs 9 and 10 before. In Fig 9 it can be seen that, along with glasses from Nishapur and Samarra, Sasanian plant ash glasses from Veh Ardašīr mainly have higher Mg/Ca ratios than Levantine glasses. Some plant ash glasses with low Mg/Ca ratios overlap with Al-Raqqa glasses. Other plant ash glasses from Veh Ardašīr with Mg/Ca ratios above 0.7 plot in a correlated pattern mainly with glasses from Samarra (both Iraqi sites are geographically quite close). Another cluster has constrained Mg/Ca ratios of between 0.5 and 0.6, with variable Sr/Ca ratios but this is not an especially distinctive characteristic. All but one of the glasses from Seleucia fall into a distinctive tight group of natron glasses with the lowest Mg/Ca ratios in Fig. 9

The Levantine Cr/La ratios plotted in Fig 10 mainly occupy a tightly constrained field with values of between c. 2-3 with Raqqa raw glasses having overlapping and slightly higher ratios. Most Samarra glasses contain higher Cr/La ratios than Levantine glasses and a few plot amongst Veh Ardašīr glasses. Eight early Islamic plant ash glasses from Ctesiphon share the same characteristically high Cr/La ratios, of above 10, as some Sasanian glasses from Veh Ardašīr. That the results for these 8 glasses are so similar should not be a surprise because Ctesiphon, Seleucia and Veh Ardašīr are different names for more or less the same location at different times (Wolski 1996, 134). Raw materials with these similar Cr/La and Zr/Ti ratios were evidently used to make them. The plant ash glasses from Veh Ardašīr with characteristically lower 1000Zr/Ti ratios of below c. 50 and high Cr/la ratios of up to 40 is distinct from all but 2 other early Islamic glasses and shows that slightly different sand sources were being used to make glass there (or somewhere close by). Therefore, the results suggest strongly that glass was made from similar primary glass raw materials at Ctesiphon/ Veh Ardašīr rather than in Baghdad in both the Sasanian and early Islamic periods proving a clear link and a continuity in plant ash glass technology used in the 2 periods. To place this is a broader context it would be helpful to scientifically test early Islamic glasses made in Baghdad, if it were possible.

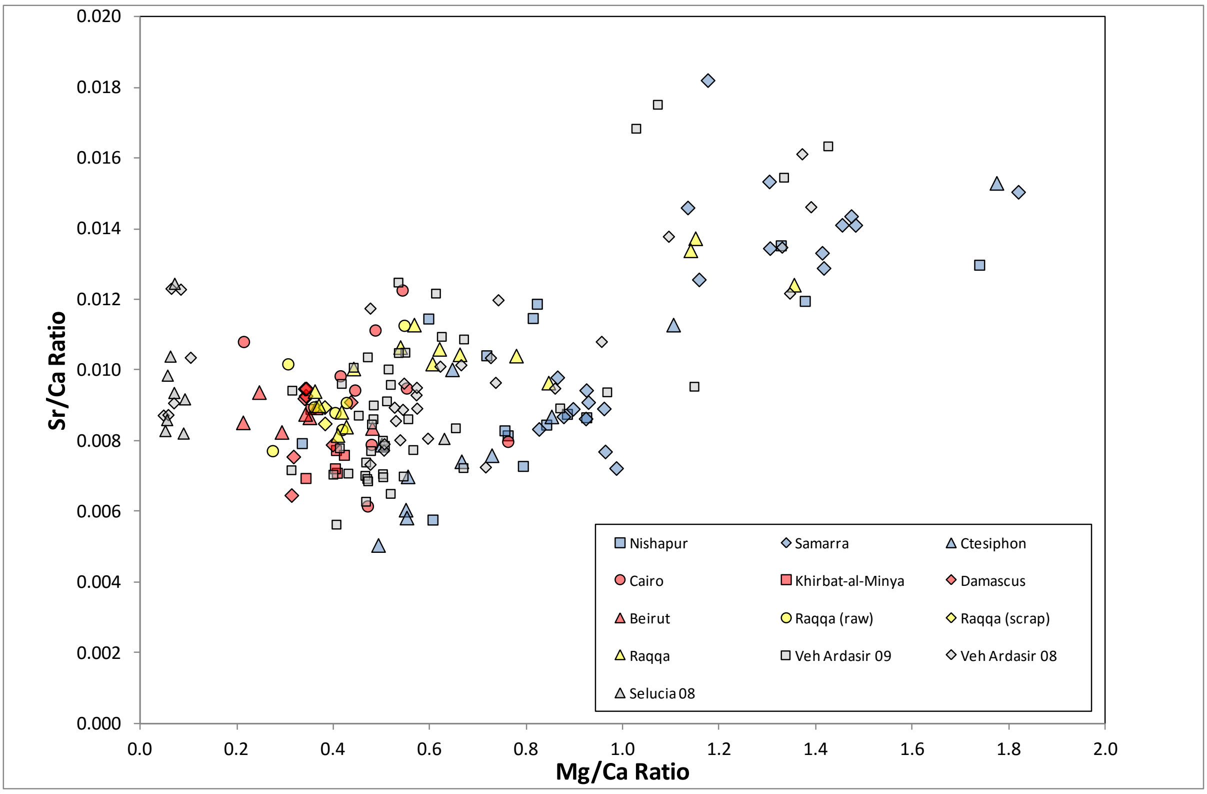

Fig. 9 A bi-plot of Mg/Ca ratios versus Sr/Ca ratios in the glasses analysed compared to data for Sasanian glasses from Seleucia and Veh Ardašīr, Iraq published by Mirti *et al*. (2008 and 2009)

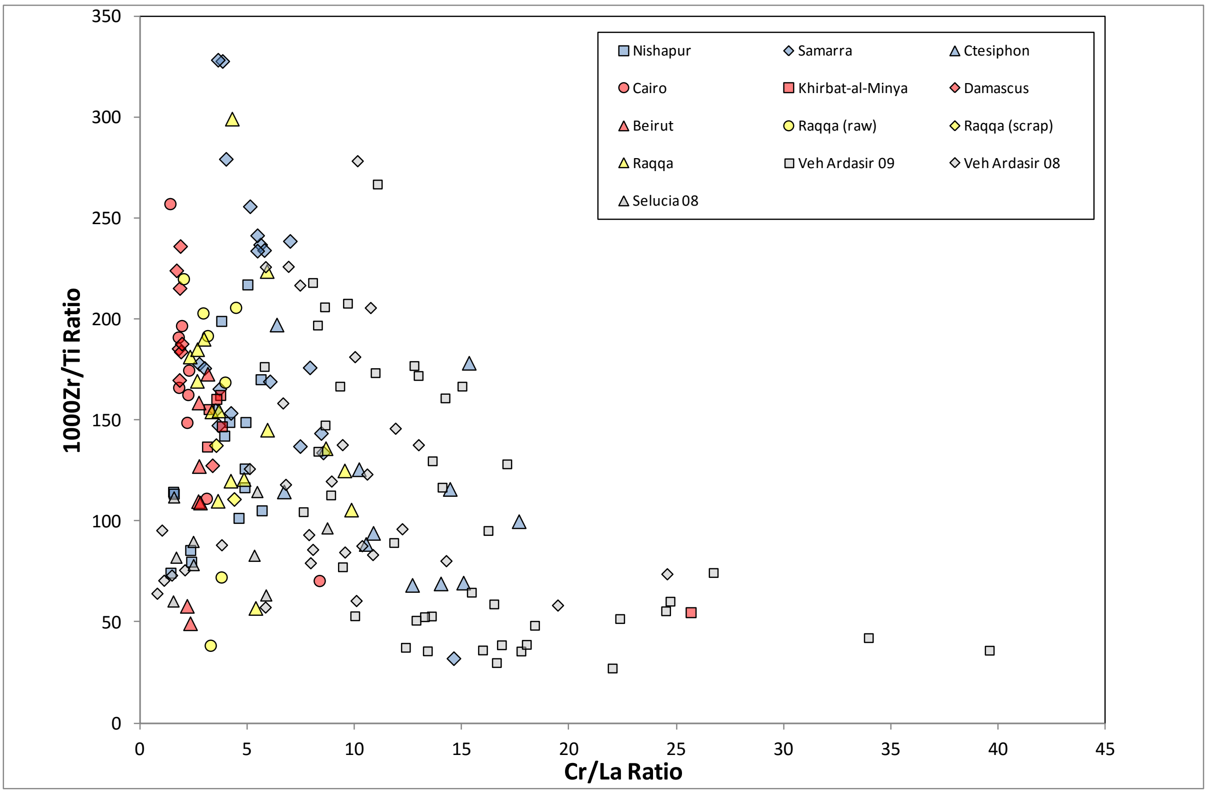

Fig. 10 A bi-plot of Cr/La ratios versus 1000Zt/Ti ratios in the glasses analysed compared to data for Sasanian glasses from Seleucia and Veh Ardašīr, Iraq published by Mirti *et al*. (2008 and 2009)

Discussion

Production models

In addition to being able to identify the raw materials used to make ancient glass and to be able to define some broad geographical origins for dated glass (Sayre and Smith 1961, Dussubieux *et al*.2008, Freestone *et al*. 2000, Freestone 2006, Jackson 2005, Arletti *et al*. 2010, Schibille 2011, Henderson 2013, 83-126, Conte *et al*. 2016), one of the primary areas of scientific research that has become increasingly more achievable over the last 15 years or so, is the provenance of glass using sensitive techniques such as trace element and isotopic analysis (Freestone et al 2000, Freestone *et al.* 2003, Henderson *et al*. 2009, Degryse *et al*. 2015). For some periods and areas, it has been possible to create trade networks for glass. Since it is the primary glass itself rather than the vessels made from it that is being sourced this doesn't necessarily give us a (secondary) source for vessel manufacture. However, one thing that can be suggested is the production models involved: for natron glass found in the 'west' a centralised production model has been suggested whereby raw glass was fused at primary glass making centres and then chunks or ingots were exported to secondary glass making centres, often by boat in the eastern Mediterranean and further afield, where they were remelted and blown into vessels or made into other objects (Henderson 1989, 39; Freestone 2000; Freestone et al 2008; Nenna et al. 2005; Fontaine and Foy 2007, 236; Nenna 2015, 19; Jackson and Foster 2015, 50; Phelps et al. 2015, Phelps *et al*. 2016). The location of primary glass making furnaces for natron glass, at least in the Levant, is close to the coastal deposits of beach sand and easy access to natron (Freestone *et al*. 2000). The other primary production area that is proven archaeologically is in Egypt. Here the furnaces are mainly centred on the natron deposits there (Nenna 2015). An alternative model is for widely dispersed primary decentralised glass making centres (Henderson 1989, 39) where vessels and other objects were made on the same site as primary glass making occurred (Jackson and Foster 2015). Glass provenance can also be used to help to interpret the glass found in specific context types, the use of 'local' raw materials to make vessels still found in the area in which the glass and vessels were made and the degree of glass recycling (Henderson 2013, 307).

The correlation of a geological provenance provided by trace elements and the occurrence of specific colourless cut and engraved plant ash and pinch decorated glass vessels in Nishapur substantiates the claim that the production of these vessels constituted a tradition and a regional specialisation building on the production of colourless wheel cut vessels in the Sasanian period. On the other hand, a somewhat different tradition was revealed by Ctesiphon glasses: both colourless and pale green wheel cut facetted glass vessels were probably made there (Kröger 1995, 7). A further contrast is provided by the glass found at the immense urban complex of Samarra, a 9th century capital of the 'Abbasid caliphate (Northedge 2005). A wide range of vessel types were made here: mould decorated, cameo decorated, pinch decorated and scratch decorated vessels as well as wall plaques; whilst colourless, including cut vessels, were apparently being imported from Nishapur.

As noted above, Levantine and Al-Raqqa plant ash glasses are analytically distinguishable from these eastern glasses. There is a general decrease in the Cs/K ratio found in glasses from locations moving from north to south down the Levantine coast (and including Damascene glasses) reflecting changes in the geology, as discussed elsewhere (Krom *et al* 1999, Be'eri-Shlevin *et al*. 2014, Henderson *et al.* 2016, 142).

In order to be able to distinguish between primary glass production centres in a decentralised system (however far apart the centres were) there needs to be sufficient contrast in the geochemistry of the raw materials used to make the glasses. If this is the case, it should therefore be possible to define both regional and sub-regional production zones. In Figs. 11 and 12 we provide schematic representations of centralised (natron) and decentralised (plant ash) glass production models.

While we have referred to production sub-zones (Henderson *et al.* 2016), questions remain as to whether the sub-zones equate to one main production centre in a cosmopolitan hub, to several production centres in the same hub or to production centres both within the hub and within its immediate vicinity. In terms of glass fingerprinting using trace elements, the definition of sub-zones is determined entirely by contrasts in the geochemistry.. Certainly the suggestion has been made that for natron glasses primary and secondary glass production occurred on the increasing numbers of glass making sites that have been found in the Levant (Gorin-Rosen 2016) and as noted above the sites tend to be close to the coast. Decentralised production of *natron* glass, without archaeological evidence of production locations outside Egypt and the Levant, has been suggested (Degryse *et al.* 2015, Baxter *et al*. 2005) but with limited evidence for a link between vessel type/ decoration and chemical compositions (Jackson 2005, Degryse *et al.* 2015)

For plant ash glasses, a centralised production model within the Levant has recently been suggested (Phelps *et al.* 2015). The Levant was evidently an important area for both natron and plant ash glass making. However, our data does suggest that for plant ash glasses there were separate production sub-zones associated with the cosmopolitan centres of Beirut, Damascus, probably Cairo and perhaps Amman that used local sand and plant sources .These centres occur in more inland locations in the Levantine area than natron primary glass making centres and can therefore be described as being part of a more decentralised production model

We are able to show distinctions between plant ash glasses found at Ctesiphon and Samarra in the eastern zone which are only 84 miles apart. Since there is a correlation between some vessel types and chemical composition, this provides evidence for specialised vessel production in these locations. Although undecorated vessels can also be provenanced in this way, this does not currently provide scientific evidence for separate production centres for the range of glass objects that are attested to in historical sources, such as window glass, lamps, drinking glasses, bottles and flasks and beads (Schatzmiller 1994, 201, 224–226).

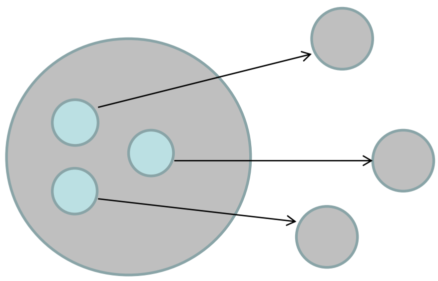

Fig. 11. A model for the production and distribution of natron glass in the Levant and Egypt. In this model natron glass was fused at separate furnace sites (primary production) often on sites separated from urban centres and the raw glass produced was exported to sites where glass vessels were blown (secondary production). There is limited evidence that glass vessels were made on the same sites as those where glass was fused from raw materials.

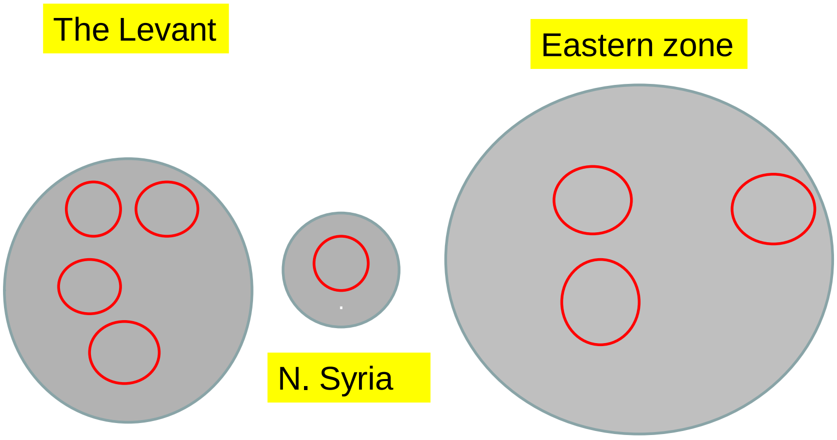

Fig. 12. A new schematic model for ancient plant ash glass production based on trace element analysis of Islamic glasses showing regional (grey) and sub-regional (red outlines) zones. The glass was probably manufactured on industrial estates, mainly in cosmopolitan centres.

The political changes that occurred when the 'Abbasid revolution occurred in the mid-8th century inevitably had a knock-on effect on the economy. With the move of the centre of power from Damascus to Baghdad a number of modifications and changes will have occurred in both the way in which production was organised and its consequent effect on trade. Although these changes are difficult to quantify, one clear result was the economic boom that occurred in the 9th century and the so-called Samarra horizon. Stargardt (2014) has made the case strongly that a boom in the production of 9th century Changsha and the Yue porcelain and 10th century Jingdezhen and Longquan ceramics occurred because of the coming together of social, economic and technological factors leading to mass production. 'Abbasid glass and pottery production also experienced a boom - and due to the same factors. Perhaps then it is no coincidence that there was a major change in Islamic glass technology in 9th century, from natron to plant ash glass. A variety of explanations have been put forward for this change (Henderson 2013, 97-102, Phelps et al 2016, 67). One is that increasing rainfall would have reduced the evaporation and formation of natron, and its supply (Foy and Nenna 2001,26) - reflected in the overall reduction in the sodium oxide content in 7th-8th century natron glasses (Henderson 2002). A second is that the political disruption caused by the 21 years long civil war in Egypt until 826 may have disrupted the supply of natron causing Levantine glassmakers to use plant ash instead (Whitehouse 2002). However, in a later context, during the Crusades, there was flourishing trade between Syrian cities and the ports of Tyre and Acre which was almost completely unaffected by the military operations (Gibb 2004, 57-8). This 'political' explanation may have contributed to the situation but it's affect need not be exaggerated. What does not seem to have been suggested before is that the move of the political centre from Damascus to Baghdad essentially therefore moved from a 'Levantine' oriented centre to a 'Mesopotamian' one and that this would have made access to an essential raw material, natron, far more difficult, leading to a growth in the exploitation of local resources across the region. Riverine and geological sources of sand are quite widespread. However, natron only occurs in a relatively restricted number of deposits: as far as we know the Wadi natrun deposit in Egypt was the main one that was exploited in antiquity (Shortland *et al*, 2006; Henderson 2013, 51-53) and it would have been relatively difficult to transport it to Syria and far more difficult to transport it to Iraq. It is significant that the change from natron to plant ash glass technology occurred around 100 years later in Egypt than it did in the Levant due to the proximity of the natron (Phelps et al 2016, 67). The alternative flux for making glass is halophytic plants. A variety of species grow widely in the semi-desert environments of Iraq and Syria (Zahory 1966; Barkoudah and Henderson 2006) so this would have been an obvious alternative. Moreover, the Sasanians manufactured plant ash glass (Mirti *et al*. 2008, Mirti et al 2009, Simpson 2014, 204) and we have demonstrated here that Sasanian and early Islamic glass appears to have been made on the 'same' location (even if there was a chronological gap between the production). Furthermore, the high level of glass production in the 9th century formed part of the Samarra horizon which until now has mainly been defined in terms of the mass production of specific ceramic types. A further implication therefore is that the shift of the political centre from Damascus to Baghdad contributed to the demise of natron glass production and the increased domination of plant ash glass production (allied to plant ash glazes). Overall, it is likely that a number of factors caused this important change in glass technology, including this political one. If plant ash glass continued to be made and used once the 'Abbasid control on its production diminished, quite how it may have been modified or transformed with the subsequent shifts in power involving the Tahirids, the Saffarids and the Samanids, amongst others is yet to be examined closely.

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