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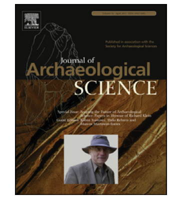

Ancient glass: from kaleidoscope to crystal ball

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ABSTRACT

Research over the last few decades has greatly enhanced our understanding of the production and distribution of glass across time and space, resulting in an almost kaleidoscopically colourful and complex picture. We now recognise several major 'families' of glass composition, including plant-ash based glass in Late Bronze Age Egypt and Mesopotamia, and the Islamic World; mineral natron glass in the Greek, Roman and Byzantine Empires; mineral-based lead- and lead–barium glass in Han period China and medieval Europe; and wood-ash and ash-lime glass in medieval Europe. Other glass groups include a peculiar granite-based glass in medieval Nigeria, and probably mineral-based glass in Bronze Age southern Europe. However, despite two centuries of research, we know very little about the actual production locations and technologies for most of these glass groups, and how and where glass making was invented.

The early literature reflects the comparatively limited number of individuals and research groups working on glass; only recently there is a significant broadening of the research community and expansion and refinement of the data base. This enables us now to take stock of our current understanding and identify major lacunae and areas where additional work may make the most significant contributions to our understanding of the complex picture. Hopefully this will help moving from the traditional descriptive and often fragmented opportunistic data-gathering phase (asking 'what', 'where' and 'when') to a more interpretative period looking with fresh eyes at the 'why' and 'how' of compositional and technical developments. This opening of the research field includes addressing the relationship of the different glass industries to the societies that used glass, and how they organised its production and distribution. A major overarching issue remains the question of the initial invention of glass, and how the idea as well as the material itself spread. Major debates should ask whether there were multiple inventions of glass making; how best to identify and interpret long-distance trade; how to ensure data compatibility and quality; and how to integrate different types of data, from archaeology through craftsmanship and typology to chemistry and optical properties.

1. Introduction

The scientific analysis of glass has a relatively short history, despite some very early work going back to the late 18th century (Caley, 1962). The first meaningful analyses were those published in the 1950s in two series of papers by W.E.S. Turner in *Glass Technology* and by W. Geilmann in *Glastechnische Berichte*, respectively, followed quickly in the 1960s by papers by Edward Sayre and then Robert Brill of the Corning Museum of Glass, whose seminal work dominated scientific research on early glass for nearly half a century.

Only for the last few decades though has the analysis of ancient glass attracted the attention of a wider group of scholars, resulting in both a diversity of analytical approaches and the development of a 'critical mass' of research activity that led to the current vibrancy in the field.

Three main factors were behind this: the rapid development of new analytical techniques requiring ever smaller sample volumes (Janssens, 2013); the increasing archaeological interest and excavations targeting more technical sites (Nenna et al., 2000; Gorin-Rosen, 2000; Eramo, 2006; Pusch and Rehren, 2007); and the development of interpretative models based on the series of analyses in a wider theoretical concept (e.g. Lankton and Dussubieux,

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2006). Here, we summarise our perspective on some of the recent thinking about ancient glass making and how the scientific analysis of glass and glassmaking waste can inform our understanding of past societies and the people who formed them.

1.1. Raw materials: fluxes

All ancient glass is based on silica as the main component, combined with a flux to lower the melting or softening point of the silica. The type of flux used in Antiquity often serves to characterise the resulting glass in our modern terminology, even though we have little evidence that this separation ever mattered in the past. The main pre-industrial glass families include plant-ash glass, mineral-natron glass, lead and lead–barium glass, and wood-ash glass, which then each split into more specific compositional groups.

Plant-ash glass is based on the ash of particular plants that typically grow in salt-rich environments (desert, on- and off-shore on the coast) and accumulate sodium and to a lesser extent potassium (Brill, 1970); when the plants are burned these alkalis form a considerable part of the ash component, which reaches up to 25% by weight of the dry matter (e.g. Barkoudah and Henderson, 2006). This plant ash forms the basis of most Bronze Age glass in the Middle East, Iron Age, Roman-period and late Antique glass east of the Euphrates (in particular Sasanian glass: e.g. Mirti et al., 2009; Simpson, 2014), and most of the Islamic glass from Central Asia to Portugal. It is mostly soda-based (10–20 wt% Na_2O), with a few percent each (2–8 wt%) of magnesia and potash.

Mineral-natron glass is also soda-rich, but based on evaporite minerals, in particular from the Wadi Natrun in Lower Egypt (Shortland et al., 2006; Devulder et al., 2014). It is characterised by similar soda levels as the plant-ash glass, but typically has less than 1.5 wt% each magnesia and potash. Ongoing research addresses whether there are other significant natron sources beyond the Wadi Natrun that were exploited in Antiquity, such as in western Turkey (Rehren et al., 2015), and why the Wadi Natrun seemingly stopped supplying natron to the eastern Mediterranean glass industry even in Egypt itself, towards the end of the first millennium AD (Whitehouse, 2002; Shortland et al., 2006).

Lead- and lead–barium glass have heavy metal oxide(s) as the main flux, resulting in a higher specific gravity and a higher refractive index and hence brilliance of the glass. Lead oxide was available in large quantities as a waste or by-product from the refining of silver-containing lead metal, or could have been made specifically by oxidising lead metal, or obtained in mineral form. It has been used continuously but in relatively small quantities as a component of strongly coloured glass across Europe, the Mediterranean and the Middle East since the emergence of glass use, both to make glass beads and for glazes and enamel (Shortland, 2002; Henderson and Warren, 1981; Tite et al., 1998; Brun and Pernot, 1992). Lead–barium glass was probably based on the exploitation of a particular mineral association, and its occurrence is restricted to a few hundred years in central China (Gan, 2005; Cui et al., 2011). In medieval Europe, the use of lead as a flux gave rise to simple lead-silica compositions as well as mixed lead-wood-ash glass (Mecking, 2013), but these leaded glasses make up a very small part of the overall corpus for the period. Isotopic data suggest that the lead oxide in at least some of these glasses is a by-product of silver smelting (Wedepohl and Baumann, 1997). The optical properties resulting from the high dispersion imparted by lead oxide to glass were exploited by English glassmakers in their development of transparent lead crystal glass in the late seventeenth century as a competitor to the famous *cristallo* of Venice. The compositional development of “English crystal” has been charted by Dungworth and Brain (2009), while the origins of this “invention” are significantly more complex than the impression given in the earlier literature (Moretti and Zecchin, 2009).

Wood-ash glass is predominantly based on potash as the main flux, obtained from the ash of timber, shrubs or plants such as fern (Jackson and Smedley, 2008; Smedley and Jackson, 2002). Due to the lower overall ash content of timber compared to the plants used for plant-ash glass making, much larger quantities of wood needed to be burnt for ash-making (Crossley, 1998). In addition, wood ash is less clean than plant ash, in that it contains higher amounts of impurities such as iron oxide resulting in the formation of more strongly coloured lower-quality glass. Wood-ash glass appears first in the eighth century AD north of the Alps and dominated glass-making there by the High Middle Ages (Wedepohl, 1998). The low quality led to different responses of European glassmakers; the Venetian approach was from the outset to import high-quality plant ash from the Levant, where they had a trade monopoly which underpinned the success of the Venetian glass industry (Ashtor and Cevidalli, 1983). Elsewhere, cleaner raw materials such as limestone were eventually added to the wood ash resulting in more lime-rich glass, while the attempts to refine the raw wood ash, through washing, decanting and drying, contributed to the development of modern chemistry. It also gave us the term *potash* for the refined salt crystallising in the bottom of the pot in which the decanted solute from the washed ash was concentrated, and thence the chemical name potassium for the dominant element in potash. With increasing understanding of chemistry came the relatively rapid changes in flux composition from the later Middle Ages, leading eventually, as part of the Industrial Revolution, to the emergence in the early 19th century of glass made from artificially produced soda.

These glass categories based on their flux are not in all cases as strictly demarcated as it may appear. There are lead glasses with potash levels that indicate the addition of refined wood ash, and mineral-natron glass with elevated levels of magnesia and potash that could either indicate the intentional addition of an ash component, or the contamination of the glass by the fuel ash during extended periods of firing (e.g. Paynter, 2008), in addition to the inherent contribution of these oxides from the sand. For other glasses, such as the north Italian Bronze Age glasses associated with the site of Frattesina (Towle et al., 2001; Angelini et al., 2004), African glasses from medieval Nigeria (Lankton et al., 2006; Freestone, 2006a), or the alumina-rich Indian glasses (Dussubieux et al., 2010), we know little about the flux used; these may well include mineral fluxes or self-fluxing sediments that have not been characterised yet.

1.2. Raw materials: silica

Compared to the variability of fluxes used, the silica sources are relatively limited. For relatively small-scale production, crushed and finely ground vein quartz was used, as suggested by the low alumina and trace element levels in the glasses of New Kingdom Egypt and Mesopotamia (Shortland et al., 2007; Rehren and Pusch, 2008; and see below, 4.1.). The large-scale glass production of the Roman to Byzantine and Islamic Empires, on the other hand, was based on quarried sand (Brems et al., 2012). While the high quality colourless glasses of the European glass industry, for example the famous Venetian *cristallo* depended on the availability of quartz pebbles (Verita, 1985), beds of flint nodules were also used, and most potash-lime or wood-ash glass of the medieval industry used relatively impure river sands, as suggested by high concentrations of elements such as zirconium, present as detrital minerals (Wedepohl et al., 2011). For the African, Indian and Chinese glasses, we can only assume that quartz-rich sand or rocks were used. A group of widely traded Indian soda-rich glasses is characterised by varying levels of high alumina, surely indicating the use of a sand raw material (Dussubieux et al., 2010), while the barium–lead-silica glasses of Han China seem to have been based on a pure source of quartz, gathered directly from veins or as pebbles (see e.g. glass compositions reported in Brill et al., 1991). These different quartz sources bring with them different, and sometimes diagnostic, levels of minor and trace elements which are then found in the finished glass.

Late Antique mineral-natron glass is among the most intensively analysed glass types; here, mineralogical differences in the main sand sources lead to chemical differences in the finished glass, which are recognised as different primary compositional groups, and in many circumstances can assist in provenancing the sand source. These groups have been largely based upon simple bivariate inter-element plots and characterise the glasses according to the lime, alumina, iron oxide and titania contents of the glassmaking sands, allowing glasses from primary production centres in Egypt and the Levant to be distinguished (Gratuze and Barandon, 1990; Freestone et al., 2000, 2002a). Statistical analysis of similar data-sets reveals similar groups (Foy et al., 2003; Freestone et al., 2002a; Gliozzo et al., 2013), but even so our current understanding of different production groups in this period needs an extension of geographical coverage, a refinement of chronology and an authoritative revision of terminology leading to a common set of labels.

2. Production technology

A key characteristic that sets glassmaking apart from metal making is the absence of durable slag that would help locate glassmaking sites, and provide clues about the raw materials and the melting conditions. Instead, glass making involved the melting together of raw materials to a chemically complex product, with limited waste in the form of non-reactive salts (but see Tanimoto and Rehren, 2008) floating on top of the glass melt. These were removed one way or the other during the process and due to their solubility in water almost immediately also lost from the archaeological record. Hence only the finished product and remains of the melting installations such as crucibles, kilns and furnaces and some working waste provide information about the production processes.

Investigation of Late Bronze Age glass production debris from Egypt has shown that at this time, glass making involved two firing stages at different temperatures (Rehren and Pusch, 2005; Smirniou and Rehren, 2011). In contrast, there is apparently only a single firing stage in the very large scale Roman to early Islamic production of the eastern Mediterranean coastal plane, where raw materials on a scale of from ten to in excess of thirty tonnes were melted in large tanks, probably for many weeks in a firing (Gorin-Rosen, 2000; Aldsworth et al., 2002). Medieval European glassmaking involved fritting as a first stage hot enough to break down the carbonate molecules of the flux but not hot enough to produce a substantial melt phase. Taking the frit to higher temperatures, typically in large refractory crucibles or pots, would then have led to the formation of a homogenous melt that could be worked directly from the pot before it solidified upon cooling to a glass.

2.1. Firing technology

In order to produce a glass which was transparent and clear, there was a need to keep it clean and as free of contaminants as possible. Mixing the fuel with the charge, common practice in metal smelting, was not an option, and modes of indirect heating were employed, typically involving the use of luminous flames and hence timber rather than charcoal as fuel (Crossley, 1998), and the construction of reverberatory furnaces whose domed roofs project the heat back onto the batch at their sole (e.g. Gorin-Rosen, 2000; Nenna, 2015; see Kock and Sode, 1996; Sode and Kock, 2001 for an ethnographic example). Depending upon the type of firing technology, different approaches were used to minimise contamination of the molten glass by the container material. In Late Bronze Age Egypt, a parting layer of lime was applied to the interior of the crucible to isolate the glass (Turner, 1954; Rehren, 1997), while in late and post-medieval Europe, refractory kaolinitic clays were selected which withstood very high temperatures (Eramo, 2006; Paynter, 2012) as well as the chemically aggressive melt charge. In the Roman period, the low surface area to volume ratios of the large tanks used for glass making and frequently also for working, meant that the risk of spoiling the glass by over-reaction with the container material was much lower. For glass working, smaller kilns were often used holding a number of pots or crucibles (Gaitzsch et al., 2000: 102, 110–113; Jackson et al., 2003; Paynter, 2008; Schibille and Freestone, 2013); again, the heating of crucibles and the glass batch within them was indirect, with the firing technology and airflow more akin to pottery kilns than to metallurgical furnaces.

2.2. Manipulating colours

Ancient glass typically had levels of iron oxide (c. 0.5%) an order of magnitude higher than modern window glass and the reduction of the relatively strong aqua-blue colour imparted by Fe^{2+} appears to have been a major concern of the glassmakers. This was typically attained by adding manganese or antimony oxides to the batch, which oxidised the iron to the ferric state, which imparts a pale yellow tint to glass (Sayre, 1963). The oxidation states of glass have only recently begun to be determined, but significant work has been undertaken on Roman glass, following pioneering work by Schreurs and Brill (1984; e.g. Bingham and Jackson, 2008; Meulebroek et al., 2011; Zoleo et al., 2014). Without additives, glass obtained directly from the primary furnaces was relatively reduced, but the addition of manganese or antimony oxide led to the oxidation of around 90% of the iron (Arletti et al., 2013). However, analysis of common samples is required to determine the extent to which the data obtained using the various methodologies are intercomparable.

Over three millennia, the most important compounds in the colouration of glass, either solely or in combination, include the oxides of only seven metals, namely copper, cobalt, tin, antimony, lead, manganese, and iron, to achieve the full range of glass colours from water-clear decoloured glass to the intense opaque and transparent colours used to imitate all precious stones known in Antiquity, most notably lapis lazuli, turquoise, amethyst, obsidian, jade, alabaster, carnelian, rock crystal, and emerald. The production technologies of the various colours have been investigated to varying degrees (eg. Sayre, 1963; Shortland, 2002; Shortland et al., 2006; Tite et al., 2008; Barber et al., 2009; Freestone and Stapleton, 2014) and there has been a large amount of work on individual assemblages, building a pattern which will allow us to understand change from one compound or method of coloration to another over time and space and its underlying reasons. Outstanding issues include questions of raw material identification and access, in particular for such materials as cobalt or manganese which were not known in their own right (cf. Gratuze et al., 1996 for cobalt in medieval and early modern Europe); reasons for change from one compound or method of coloration to another over time and space; and the practicalities of the addition of these compounds either during the primary production, or the secondary working stage (Lahlil et al., 2010, 2011). Furthermore, the locations of the workshops that produced large quantities of coloured glasses are still not well understood, whether for the large wall mosaics of Antiquity or the stained glass windows of the medieval period.

3. Organising glass making

The production of glass requires a combination of particular chemical skills, access to specific and often exotic or ill-defined raw materials, large quantities of fuel, and a market for the finished product. Several models have been developed to describe the organisation of these factors. For the Bronze Age, Rehren has proposed a model comprising of several elite-attached workshops producing coloured glass ingots which were then provided to also elite-attached glass studios processing glass from different producers, in different colours (Pusch and Rehren, 2007: 162, Fig. 1). This model incorporates the textual and archaeological evidence for long-distance exchange of coloured glass ingots linking Egypt and Mesopotamia with the Levant and Greece, but still does not explain why there is so little evidence (if any) for Egyptian glass in Mesopotamia, and for Mesopotamian glass in Egypt, when the pictorial sources (Thutmose III) and the textual evidence (Amarna letters) indicate a relatively regular flow of glass at least from Mesopotamia into Egypt (Rehren, 2014).

For the Late Roman and Byzantine Empires, Freestone has developed a model that is based on the spatial separation of primary production of glass in a few large-scale production centres and countless secondary working sites processing the primary glass as well as recycled cullet into new artefacts (Fig. 2). The link here between the primary and secondary workshops is provided by irregular fist-to head-sized chunks of fresh glass that have been found across the Roman Empire (Fig. 3). Open questions include the socio-economic organisation of the large production sites, the possible existence of specialised workshops producing coloured glass, the relationship between glass tesserae production for mosaicists and the normal glass industry, among others.

In contrast, the medieval European (Fig. 4a) as well as the later Islamic glass industries (Fig. 4b) both seem to have functioned around integrated workshops, combining the production of glass from the raw materials to the forming of finished artefacts for the local or regional market.

In both regions there is a period of transition from the Late Antique mineral-natron based glass industry and its physical remains to the newly-established indigenous industries; in Europe, this dependency on recycling pre-medieval glass was initially stronger due to the necessity to develop a completely new glass-making tradition, based on wood ash. However, once wood-ash based glass making had been established, the huge demands for glass from first ecclesiastical and later urban customers drove a massive growth in glass making. The need for fire wood and wood for ash production put increasing pressure on European woodlands, in competition with other major wood-consuming industries such as mining and metallurgy; ship-building; urban construction and fire wood; and game hunting by the nobility. In response, large quantities of wood ash were traded from the forested regions of northern Russia and the Baltic into central Europe (e.g. Clow and Clow, 1956: 87, 98), and woodland management strategies such as coppicing and pollarding were implemented to increase timber and firewood production (Crossley, 1998).

In the East, in contrast, plant-ash based glass making had persisted throughout the Roman and Byzantine periods in the Sasanian Empire and Central Asia, and it is generally assumed that this was the route to its relatively easily re-adoption in the Levant and Egypt. The availability of high-quality raw materials and a social environment favourable to the development of the arts and crafts under the early Abbasid rulers led to a flourishing art of glass making. Here, there is a remarkable chemical differentiation between glass made in different parts of the Islamic world (Fig. 5; Freestone, 2006b), most probably reflecting the different soil chemistries

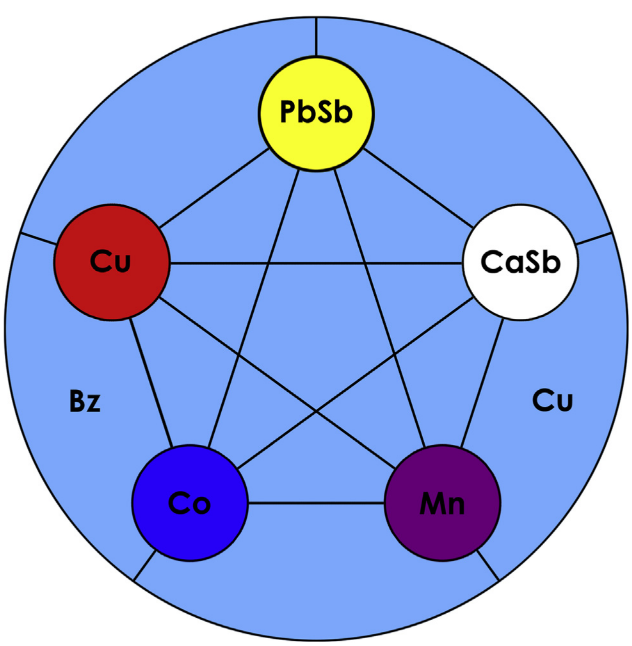

Fig. 1. Schematic of the Late Bronze Age glass industry in Mesopotamia and Egypt, where most workshops were able to make copper-coloured light blue glass, using copper in Mesopotamia and bronze in Egypt. More specialised colours were only made in specific workshops and then exchanged so that each glass studio had the full range of glass colours available, without necessarily being able to make each colour. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

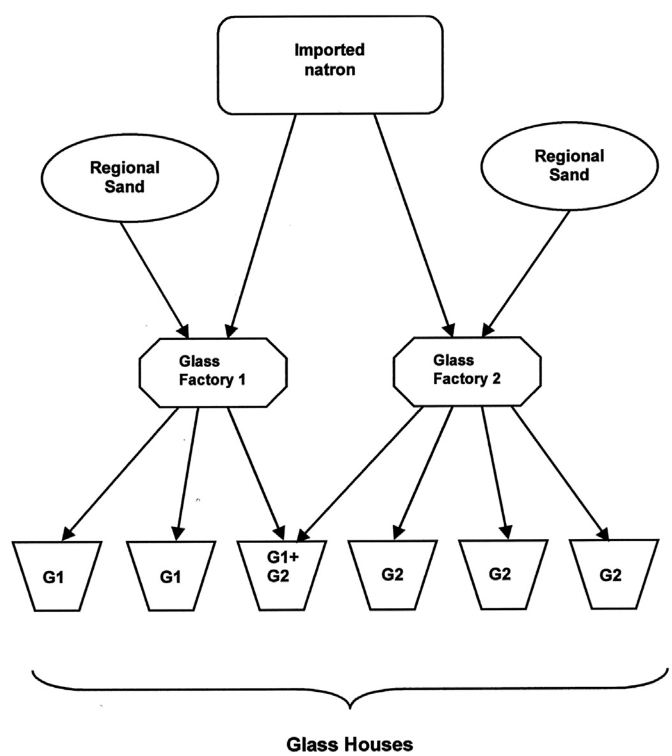

Fig. 2. Model of the Late Antique glass industry, with a limited number of glass factories producing glass from imported natron and regional sand. This primary glass was then shipped to individual glass houses across the Empire who would work the glass into artefacts, serving their regional or local markets (from Freestone et al., 2002b).

Fig. 3. Glass chunks ready for re-melting and blowing into vessels, stored in a pottery vessel in the 6th–7th century workshop at Beth Shean, Israel. (Reconstruction displayed in the Israel Museum, Jerusalem.)

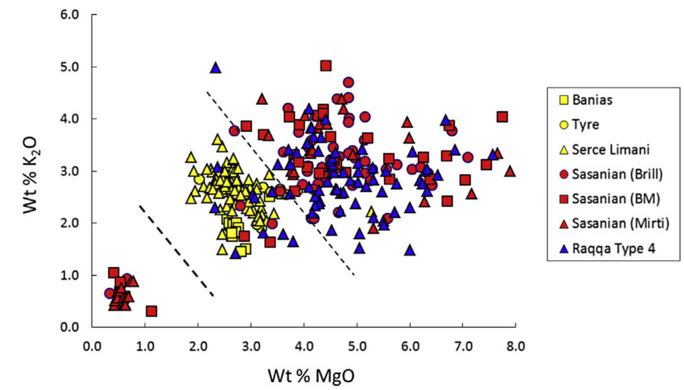

Fig. 5. Potash and magnesia contents of early Islamic glass of the Syrian type (Banias, Tyre and Serce Limani) and Sasanian glass from Mesopotamia. The Raqqa Type 4 glass is early Islamic, showing the continuity of the Sasanian tradition of glassmaking. The presence of natron glass (lower left) indicates a significant trade in material or vessels from the Roman West into the Sasanian Empire. For data sources see Freestone (2006b); Raqqa data from Henderson et al. (2004).

from which the halophytic plants metabolise their inorganic constituents. Barkoudah and Henderson (2006) provide some insight into the variability of plant ashes from different regions, but more work is clearly needed before the glass composition can be used for anything more than the broadest of geographical assignations (e.g. Rosenow and Rehren, 2014: Fig. 7).

Major research *lacunae* exist with regard to the production of Han Chinese glass. Very little can be said about the raw materials used for its production, and nothing about the places of production and the organisation of the industry, if ever it was one and not just an elite-attached production. Remarkable, however, is the way in which Chinese glass sets out to imitate the particular optical quality of jade (*sensu lato*), by achieving an opalescent quality unknown to Western glasses, which in contrast mimic the strong colours of precious stones cherished there. This, in our opinion, strengthens again the idea that ancient glass was very much a substitute for, or at least inspired by, precious stones (Nicholson, 2012; Shortland, 2012).

The primary production of glass in sub-Saharan Africa has only recently been recognised (Freestone 2006a; Lankton et al., 2006), and raises interesting questions not only regarding the raw materials used (Ige et al., 2015), but also about the mechanisms of knowledge transfer or inspiration for invention in a society that values glass highly for its bead-making ability, but lacked the centuries-old experience in glass making shared by the northern societies that provided much of the glass to Africa.

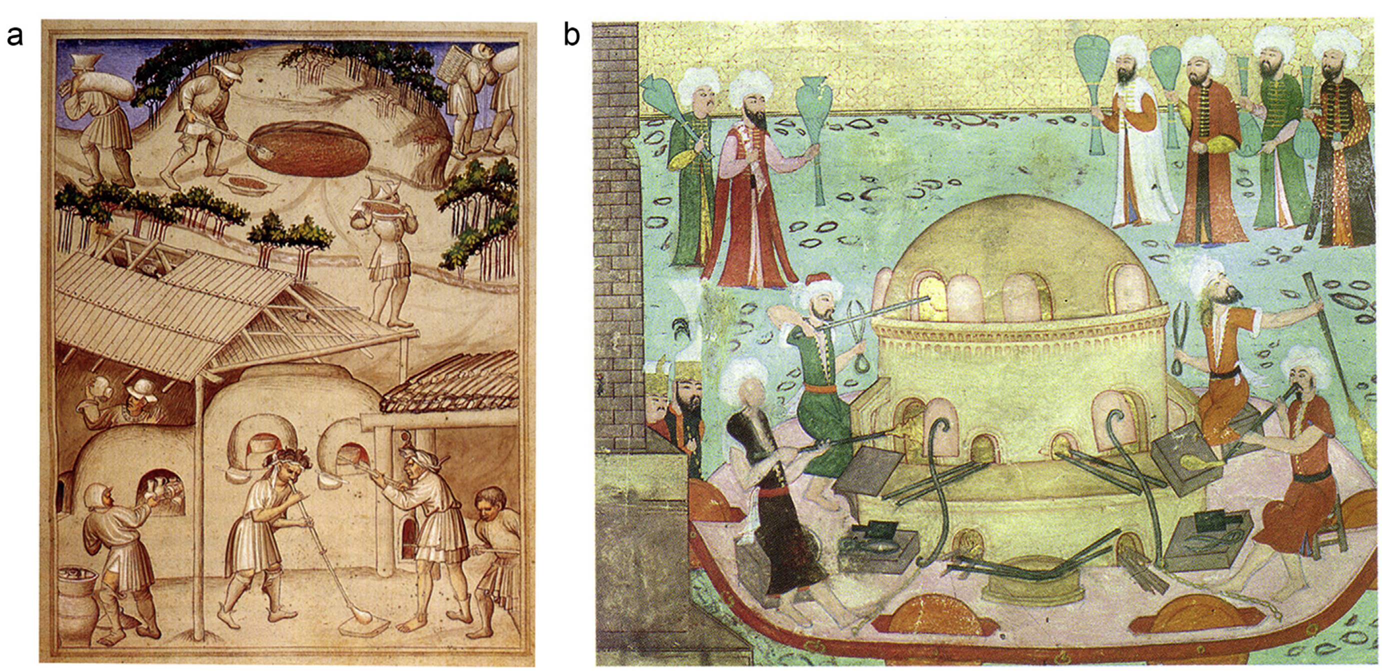

Fig. 4. a: Depiction of a medieval glass furnace, showing the quarrying of sand in a landscape with managed woodlands (background), the actual glass furnace in the foreground with vessels being blown (front), and the inspection of finished vessels as they are retrieved from the annealing chamber (front left). Mandeville manuscript, illustration c 15th century. © The British Library Board, Add. 24189, f.16.b: Procession of glass workers with a working furnace on a float. From a manuscript dated to the reign of the Ottoman sultan Murat III, late 16th century AD (Küçükerman, 1985, 114).

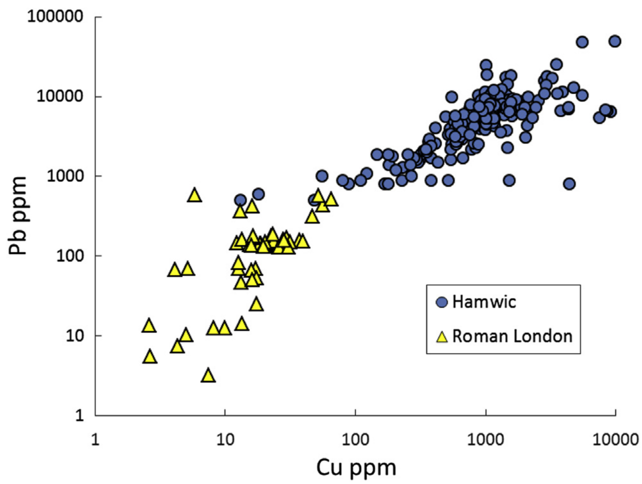

Fig. 6. Lead and copper contents of natron glass from Anglo-Saxon Hamwic (Southampton, 9th–10th century; data of Hunter and Heyworth, 1998) compared with Roman London (2nd century; data of Freestone et al. in press). Note the elevated lead and copper contents in the early medieval glass, indicating the incorporation of substantial quantities of recycled coloured glass.

4. Tracing the glass cycle

The ability of molten glass to incorporate a very wide range of oxides is of major importance, for a number of reasons. The coloration of glass, through the addition of small amounts of transition and base metal oxides, has been briefly mentioned above. Similarly, small amounts of minerals other than quartz which are associated with it contribute to the trace element signature of the finished product. Finally, working and recycling of glass further influences the composition of the glass, providing opportunities as well as challenges for the interpretation of trace element pattern.

4.1. Provenancing

The ability to distinguish production groups based on their raw material characteristics has inevitably led to attempts to provenance glass materials to their primary production centres. As the sand carries many of the trace elements which are useful in this respect, provenancing glass is essentially reduced to provenancing sand. Exceptions include for example post-medieval European glass, where the availability of very clean vein quartz and the diversity in ash compositions used for glassmaking during and after the Renaissance means that glasses attributable to specific regions are characterised by different alkalis (Gratuze and Janssens, 2004).

Fig. 7. Series of seven square bottles from Pompeii (1st c AD), presumably used to contain known measures of a liquid commodity such as oil or wine. The capacity doubles with each step from the smallest to the largest. ©De Agostini/The British Library Board.

For the major industries of the Late Bronze Age and the first millennium AD, trace element and isotopic studies have proven very successful. For example, Shortland et al. (2007) have shown that Late Bronze Age Egyptian glass may be distinguished from Mesopotamian glass by the elements Cr, Zr, La and Ti, thereby resolving a number of issues around their origin and confirming that in the Eighteenth Dynasty, most glass used in Egypt was made from Egyptian raw materials, while LBA glass found in Europe came partly from Egypt and partly from Mesopotamia (e.g. Jackson and Nicholson, 2010; Varberg et al., 2015). The isotopes of neodymium have proved very useful in provenancing sand-based glasses of the Mediterranean. The $^{144}Nd/^{143}Nd$ ratio of a sand essentially reflects the geological age of the rocks of its source terrain, and young rocks tend to have higher $^{144}Nd/^{143}Nd$ than older rocks. The Nile carries a sediment load derived from the young volcanic rocks of East Africa and these sands are carried around the coast of the Mediterranean between the Delta and the Bay of Haifa. The sands of this region therefore have a distinctive isotopic signature which distinguishes them from most other potential sources in the Mediterranean and Europe. In a series of publications, Degryse and co-workers have shown that not all natron glass has Nd isotopes characteristic of eastern Mediterranean sources, possibly indicating the existence of other, so far unknown glass producing regions elsewhere in the Late Roman world (Degryse, 2014).

Trace elements are increasingly coming into play also in the investigation of other glass types. For example Indian beads have been shown to fall into high uranium and low uranium types, of as yet unclear origins (Lankton and Dussubieux, 2006), while Renaissance glass in Venetian style made in the Netherlands or Britain differs from that made in Venice (Janssens et al., 2013). We still have progress to make in our understanding of trace and isotopic data, however. According to Wedepohl and Baumann (2000) fourth century Roman glass from the Hambacher Forest in north-western Germany has a compositional profile characteristic of local production, but its composition and chronology is remarkably similar to HIMT glass, found across the Roman Empire, and probably made in Egypt (Nenna, 2014; Foster and Jackson, 2009).

4.2. Recycling

Intimately linked to the organisation of glass making and glass use is the issue of glass recycling. In particular in areas removed from primary glassmaking centres the recycling of broken glass would have played a significant role in sustaining provision of newly-formed artefacts, and a substantial body of evidence, both archaeological and textual, points to the importance of this in the Roman (Keller, 2004; Silvestri, 2008; Silvestri et al., 2008) and Islamic worlds (e.g. the cullet carried by the Serge Limani wreck; see Bass et al., 2009). Less clear is how to recognise the extent of recycling in the composition of the glass; early work by Jackson (1996) identified elevated trace amounts of the transition metals that were used for colouring purposes as good indicators. This approach clearly shows that by the 9th to 10th centuries AD, a substantial proportion of the glass in use in western Europe comprised recycled coloured glass, probably removed as mosaic tesserae from Roman public buildings (Fig. 6; e.g. Schibille and Freestone, 2013). However, not all recycled glass would include coloured cullet, and what constitutes elevated levels anyway? Additional indicators, such as increased concentrations of fuel ash components, can contribute to the discussion (Paynter, 2008; Rehren et al., 2010), but ash can contaminate glass already during the primary stage. Similarly, while mixing lines have been demonstrated based upon isotopic compositions (Degryse et al., 2006) or the concentration of antimony (Silvestri, 2008), much foundation work still needs to be done before this aspect can be better understood.

Even in primary furnaces, the glass has been shown to be inhomogeneous (Freestone et al., 2000) and this means that consignments of glass chunks sent to different workshops for remelting and fabrication will have varied in average composition from batch to batch. The recycling of old glass will add to the variability between batches. It has been shown that individual batches of vessels may be recognised through analysis of their major elements (Price et al., 2005; Freestone et al., 2009), while trace element analysis of material in a single workshop may identify the products of different campaigns or individual melts (Freestone et al. in press). This opens a way to a finer understanding of consumer assemblages and of a hierarchy of secondary workshops (e.g. Cholakova, 2014).

5. Looking to the future

The kaleidoscopic plethora of isolated case studies has begun to give way to the development of larger pictures, as seen for instance in the development of organisational models, and a better understanding of long-distance movement of glass for instance in Central Asia (Nakai and Shindo, 2013), SE Asia (Lankton and Dussubieux, 2006), or into North America (Hancock et al., 1999). Just as the proverbial crystal ball provides a seductive but not necessarily accurate view of the future, heavily biased by the preconceptions of the gazer, so our emerging picture of the ancient glass industry although clearer, remains vague and potentially erroneous.

Specifically, there are still large geographical and chronological gaps to fill in our knowledge of prevailing glass compositions; such as in the early Iron Age to Hellenistic periods in the Mediterranean; or in much of Central, East and Southeast Asia. Beyond this filling of gaps, however, we believe that major debates would be helpful in a number of key areas. Firstly, how and why was glass invented? Persistent reports of glass finds dated to the 3rd millennium BC (Peltenburg, 1987) point to a precursor tradition of glass making before the emergence of regular glass production in the mid-2nd millennium BC in Mesopotamia. Even after this, there were multiple events of innovation that helped spread glass further, such as the re-emergence of a glass industry in the Mediterranean Iron Age after the collapse of the Late Bronze Age world system, or the emergence of new and seemingly indigenous glass making industries in Han China, medieval Europe, India and Nigeria. To what extent were these inspired by the knowledge of imported glass, and how did they develop their own, often fundamentally different, recipes? Linked to this question is the ongoing need to map the long-distance movement of glass, both as finished artefacts and in raw or ingot form, in order to understand the social and economic drivers of these movements. Furthermore, the chronologies of change are imprecise and need refining, as they are inadequate to understand the relationships between material change or choice, and wider social context.

Secondly, the increasing availability of analytical equipment poses new challenges. The use of hand-held, portable XRF instruments leads to an increase of the quantity of data, but major work is still required to ensure its quality. This does not only concern the analytical capability and proper calibration of the instruments themselves, but also a much clearer understanding of the limitations that come from the surface quality of the analysed objects, and the increasing pressure for non-invasive analysis. Despite its limitations, pXRF has huge potential to revolutionise glass analyses in certain settings (e.g. Dungworth, 2012). On the other end of the spectrum we see a major step change in analytical resolution through the routine application of LA-ICPMS with its sub-ppm sensitivity and often astounding accuracy, opening up a window onto trace element signatures the meaning of which we still need to fully explore (Gratuze, 2013). Similar fundamental progress is being made with new stable isotope studies, most notably $^{144}Nd/^{143}Nd$ in conjunction with the established Sr and Pb systems (Degryse, 2014). Here too we still need to develop a better understanding of the potential of these systems.

Last, but not least, there is an enduring need to better integrate the growing data across the disciplines, integrating the analytical data into meaningful archaeological and anthropological research frameworks and combining it with similarly refined typological and craft studies. In view of inter-regional distribution of massive amounts of chemically relatively homogenous glass it is the identification of workshop traits or particular craft styles that can offer increasing resolution to the hierarchy of glass workshops, from massive primary production centres to elite workshops producing prestige items and large-scale specialist units for mass production, to small shops recycling and working, possibly even making, all sorts of glass depending on their availability and the local demand for objects. Tracing this flow of glass from the production sites to the smallest workshop is another promising topic of research. The role of local landowners and merchants in organising the production and distribution of glass as a major commodity is poorly understood; but even on the level of individual artefacts glass plays a role in daily commerce, be it as a measure for volumes (Fig. 7), or as a tamper-proof material, such as for the Islamic stamped glass weights, or as beads taking on the role of currency in non-monetary societies. Studying this, of course, requires the close integration of scientific approaches into archaeological, anthropological, social and economic research frameworks, as well as the full publication of the archaeological, typological and analytical data for each project. We are very much looking forward to the progress made in this respect by the next generation of scholars.

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