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Re-used Roman Rubbish: a thousand years of recycling glass

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Abstract

The suitability of glass for re-melting and recycling was widely exploited in the past. This paper reviews the evidence, particularly for the 1st millennium AD, using examples from Western Europe. For much of this period glass was produced on a large-scale at a relatively small number of specialised glassmaking sites, which supplied numerous dispersed workshops where glass was modified and shaped. This is only part of the picture however, because the glassmakers, glassworkers and consumers were also linked by a complex, interdependent cycle of supply, use, discard, salvage and re-use, making recycling an essential part of interpreting archaeological glass.

Introduction

Glass can be repeatedly re-melted and re-used. This property was exploited by the earliest producers of glass in Egypt and the Near East in the second millennium BC, where glass ingots were made and then traded to be re-melted at sites which produced beads, inlays and vessels, in a variety of colours. In addition to melting newly-made glass, scrap glass could also be recycled. This re-use and recycling of glass was common even in the earliest glass-using societies and sometimes undertaken on a large scale. By the early Roman period for instance, recycling is documented in texts which hint at the infrastructure and organisation of the trade in broken glass, or 'cullet', across the empire (see Keller 2005, pp. 67-68).

The importance of glass recycling to our understanding of where and how glass was produced, and who used it in the past, is increasingly recognised, especially by those studying glass compositions (Jackson 1996, 2005a; Silvestri *et al.* 2008; Schibille, Freestone 2013; Jackson, Paynter 2015; Freestone 2015). Nevertheless, there is still much to discover about how and why the scale, economic significance, motivation and methods for recycling varied in the past (Grünewald, Hartmann 2015). The act of recycling is an essential and integral part of the *chaîne opératoire* and biography of glass production, which has to be considered in order to fully understand the range of glass forms, colours and compositions found in archaeological material. Unaltered glass compositions, those which have not been mixed through recycling, contain chemical markers that allow us to investigate the origins of the raw materials, and hence the locations, of glass production. When glass is recycled however, these compositions become contaminated and mixed, potentially diminishing our ability to access that inherent archaeological information that allows us to trace the movement of glass from source. Our challenge now is to reveal the repeating and interlocking trails of production, trade, working, use, discard and re-working in recycled glass; this can be done by linking a variety of different forms of evidence.

This paper focuses on the 1st millennium AD, exploring the different ways in which recycling can be detected in the archaeological record. A combination of contextual and scientific analysis, documentary accounts and typological studies are used to illustrate the difficulties faced by archaeologists when interpreting chemical data for glasses, but also how a more nuanced interpretation is often possible when recycling is considered. Our examples have been chosen to represent a wide geographical and chronological spread, from the Roman period through to the 12th century AD, for both transparent and strongly coloured opaque glass.

Glass production in the 1st millennium AD

Wide reaching studies, for example by Sayre and Smith (1961), Turner (1956) and Brill (1999), have shown that the raw materials used for glass production, and the sources of those materials, have varied over time. This makes glass special: unlike pottery which could be made with a variety of available materials processed in any number of ways resulting in a virtually infinite range of compositions and textures, glass was made with very carefully selected raw materials, which for most of the 1st millennium AD were only obtained from a small number of locations. As a result early glass compositions, before about the 10th century AD in the western world, tend to be relatively homogenous over long periods of time and space. When changes do occur in compositions, they are quite marked and perhaps reflect significant social, economic or political upheavals, affecting trade routes, the social groups controlling production, the production process or the raw materials used.

The common denominator in ancient glass production was a source of silica, which was often sand or alternatively crushed quartz, flint or other siliceous stone. The silica was combined with fluxes and heated to make a molten glass that could be shaped into objects. A variety of fluxes were used in the past, including the ashes of plants, lead compounds or the alkali-rich evaporitic deposit natron. Whilst plant ashes were favoured in the ancient western world prior to the mid-1st millennium BC and again in the 2nd millennium AD, mineral alkalis (natron) tend to dominate the archaeological record in the 1st millennium AD in Europe, Egypt and parts of the Near East (Smith 1963; Uboldi, Verità 2003). Roman accounts of glassmaking describe using natron from the Wadi Natrun in Egypt, which was harvested seasonally from the edges of salt lakes, in combination with sand (Jackson *et al.* in preparation). The glass appears to have been made on a vast scale in large tank furnaces located at sites in the Eastern Mediterranean (Brill 1988; Nenna 2015). In tank furnaces the glass cooled as a massive slab, which was later broken up into large lumps and redistributed to workshops throughout the empire and beyond for shaping into vessels and window panes, or coloured and shaped into beads, bangles or tesserae (Foy *et al.* 2000; Keller 2005; Freestone 2006; Paynter *et al.* 2015).

Freshly made natron glass was transparent but often had a light blue or green tint (known as naturally-coloured blue-green glass) ranging to olive green or brownish tones. The colour was derived from small quantities of iron minerals in the raw materials (fig. 1). Some of this glass was modified by adding manganese or antimony oxides, which could partially or completely neutralise the colour; antimony oxide was a particularly effective decolouriser resulting in high quality colourless glass (Jackson, Paynter 2015). Alternatively the glass could be given a strong colour, and made opaque, by adding metal minerals or compounds, for example copper produced blue, green or red, cobalt a dark blue and manganese (in sufficient quantities) a dark purple (fig. 2). An understanding of the colouring and decolourising of glass is important for our understanding of glass recycling.

Fig. 1: A collection of naturally-coloured cullet from Roman London (courtesy of MOLA).

Establishing the way in which the composition of glass changes overtime, how widely available each glass type was, and what different types were used for, has been an important first step in detecting recycling. This is particularly the case for the 1st millennium AD, because of the unique way glass production and distribution was organised (Freestone 2006; Nenna 2015). It has been shown that the majority of new glass was made in a limited number of locations and so only a relatively small number of natron glass compositions have been identified. Each of these compositions, or 'production groups', has a particular lifespan and exhibits diagnostic chemical characteristics. This 'Roman glass' was consumed widely during the Roman period throughout Western Europe and the regions bordering the Mediterranean sea. Typically some of these glasses were used selectively only for certain objects (Foy *et al.* 2003) so it is easier to identify glass that has been altered, mixed, reused or contaminated (Jackson, Paynter 2015). Even during this period when glass was relatively plentiful, there is evidence of extensive recycling and natron glass continued to be used and recycled into the beginning of the 2nd millennium AD within the region. Subsequently the organisation of production changed dramatically such that glass was made in numerous locations from diverse locally available raw materials (rather than natron), resulting in a vast range of compositions, and it is at this point recycling becomes more difficult to detect.

Detecting recycling in the past

Archaeological evidence

The archaeological context and typological examination of an assemblage often provide the first clues that recycling has taken place. Large collections of cullet, sometimes numbering thousands of fragments of broken glass and glass waste collected for recycling, are relatively common finds throughout the period discussed here. Cullet dumps in the Roman world have been found associated with military camps, villas and towns (Keller 2005; Grünewald, Hartmann 2015); a number of large collections of cullet have been found in Roman London alone (Price 1998, pp. 337-38) including 70kg from a pit in Basinghall, London (Shepherd, Wardle 2009) (fig. 1). Other assemblages of cullet appear to be from the point of collection, such as the basket of fragmentary glass found in a villa at Pisanella, Italy (Keller 2005) or the 8th/9th-century AD collection in Tower 1 at Butrint, Albania (Jennings, Stark 2012). There is also some evidence to show how cullet was transported to workshops, for example the barrel of broken glass discovered on *Iulia Felix*, a ship wrecked off the coast of northern Italy (Silvestri *et al.* 2008). These collections of glass can be identified as cullet because they include fragments from vessel forms spanning several centuries, and no complete objects.

Whilst most of the evidence described above relates to transparent glass (both naturally-coloured blue-green or colourless), opaque coloured glass was also sought after for recycling. Coloured glass was sometimes re-melted and re-used directly, or diluted by mixing it into a glass batch to make a larger volume but with a weaker colour. Coloured glass was sought particularly for making tesserae and increasingly for windows for churches and monastic buildings. Analytical evidence, discussed later, suggests that much of this coloured glass was made using recycled Roman coloured glass, but there is also archaeological evidence to support this, notably from the site of the 9th-century monastery of San Vincenzo, Italy. Here glassworkers made vessels, windows, imitation gemstones and enamels in a wide range of hues. Glass mosaic tesserae were found, which glassworkers were adding to the glass melts for colour (Dell'Acqua 1997; Schibille, Freestone 2013). Some of the crucibles with remnants of glass contained occasional stone tesserae that had been added to the melt by mistake with the glass ones. Similar evidence has been found at Müstair in Switzerland (Kessler *et al.* 2013) and is corroborated by analyses of glass from numerous sites (Mirti *et al.* 2000; Foy *et al.* 2003; Wolf *et al.* 2005).

The previous examples all involve glass being melted down during the recycling process but sometimes glass objects were recycled without being re-melted. These are most easily identifiable as recycled if they are of a particular style or have decorative elements which link them specifically to a particular location or period. Items such as the mask medallions from Roman jugs and the decorated bases of late 4th-century bowls with images in gold leaf (Price, Cottam 1998; Howells 2013) were often reused. They were trimmed to function as keepsakes, lids and counters. Similarly broken coloured vessels were sometimes cut up to make mosaic tesserae (Paynter *et al.* 2015).

Documentary evidence

Recycling within the Roman world was so common that it was documented by a number of Roman authors. Roman poets, writing in the 1st century AD, such as Strabo and Martial, describe street peddlers collecting broken glass in exchange for sulphur, which was used for matches (Stern 1999, p. 450; Keller 2005).

The recycling of Roman glass continued in subsequent centuries, being used and re-melted by other societies and cultures. Perhaps the most famous description of this is Theophilus' treatise *De diversis artibus* in the 12th century AD (Dodwell 1986, pp. 44-45). Whereas the Roman recycling references probably apply mainly to transparent vessel and window glass, Theophilus specifically mentions opaque coloured glass tesserae, 'little square stones' in white, black, green, yellow, blue, red, and purple that were taken from the mosaics of ancient buildings, and small vessels of coloured glass. He emphasises that French glassworkers used the blue for windows, having sometimes diluted it with fresh colourless glass, and used purple and green in a similar way.

Analytical evidence

Chemical analysis, in combination with typological study and sound contextual information, can strongly indicate the use of recycled glass. In some instances the case for recycling is clear cut, such as when the glass used to make an object is a type that was no longer made by then, *i.e*. the glass is far older than the object itself. The examples given later in this paper both relate to the re-use of coloured Roman glass in the early 2nd millennium AD, both for window glass (Cox, Gillies 1986) and for vessels (Phelps 2011). More typically recycling is identified because the mixing or re-melting of cullet has resulted in changes to the glass composition (Jackson 1996; Jackson, Paynter 2015). These can be major changes, through the mixing or amalgamation of different raw glass compositions, or more subtle, with the accidental incorporation of tiny amounts of coloured glass containing added colouring minerals, or minor contamination from the furnace materials, glassworking tools or fuel.

Mixed glass compositions result when at least two different types of glass were recycled together and the end product is a hybrid composition somewhere in between. Sometimes the glass types that have been mixed were so clearly different visually that they must have been combined intentionally, for example when strongly coloured Roman tesserae were used to colour glass batches for making windows in the later 1st and early 2nd millennia AD (Cox and Gillies 1986; Wolf *et al.* 2005), confirming the descriptions by Theophilus. In other instances hybrids may have been created by accident because the glass types were visually similar and so were not properly separated when the cullet was sorted before re-use. This may have been the case in the Roman period because analysis has shown that a large proportion of the naturally-coloured blue-green glass in circulation is actually a recycled mixture of two originally colourless types; one type decolourised with manganese and the other with antimony. These colourless glass types were superficially similar and so more likely to be mixed together inadvertently (Jackson, Paynter 2015). Perhaps unexpectedly, the resulting recycled glass was sometimes colourless but sometimes blue-green depending on the proportions of each component. This demonstrates that the glassmaker might have more difficulty controlling the colour of the glass with recycled material as different elements would behave unpredictably when in combination. Particular care must be taken when recycling colourless glass if it is to remain colourless.

These hybrid compositions have formed the basis for many of the discussions of recycling in the literature (for example Jackson 1996, 2005a; Foster, Jackson 2010; Jackson, Paynter 2015; Freestone 2015). The real difficulty though is identifying recycling when the cullet *has* been carefully sorted into different compositional types and so 'like' is mixed with 'like', or in those periods or regions when one type of glass dominates the market and so the mixing of very small amounts of other primary groups is almost masked. How do we spot recycling then? In some instances it may not be possible to detect it. However, this is where the concept of 'contamination' becomes more important, because even with careful sorting eventually some coloured opaque glass would find its way into batches of transparent glass, perhaps by including fragments with coloured trails *etc*. Over time, this leads to slightly increased amounts of elements such as copper, lead and antimony in the glass compared to its starting composition (Jackson 1996, Uboldi, Veritá 2003; Jackson 2005a; Freestone, Hughes 2006; Grünewald, Hartmann 2015). Therefore when colourants are present in colourless or naturally-coloured glass compositions, that originally would not have had any colourants added, it implies that recycling has allowed a small amount of coloured glass to find its way into the batch.

Fig. 2: Roman colourless glass and opaque strongly coloured glass (from Binchester, Durham, and Great Bentley, Essex, respectively) both containing high concentrations of antimony, characteristic of much Roman colourless and coloured glass.

Accidental contamination also arises from the fumes or ash from the fuel used to heat the furnace, the walls of the furnace tank or crucible in which the glass was heated, or scale from the iron blowing iron used to shape the glass (Paynter 2008) (figs. 3, 4). The level of contamination is unpredictable but is likely to increase with the number of rounds of recycling, and if high temperatures are used for long periods. In modern gas-fired furnaces some of the alkali (notably sodium oxide) is lost from the glass as a gas during prolonged or repeated heating, which can affect the working properties of the glass, but this is not the case in the furnaces used in antiquity. These furnaces used wood fuel instead, which released another alkali gas, potassium oxide, on burning so the alkali content may have actually increased (Paynter 2008). Particles of wood ash may also be absorbed by the glass leading to increases in calcium, magnesium and phosphorus oxides. Although tank furnaces were used to produce primary glasses, both tank and crucible furnaces were used for re-melting. The extent of the contamination from the crucible or furnace materials depended on the composition of both, the surface area to volume ratio (particularly high for small crucibles), as well as time and temperature, and could lead to increased concentrations of iron and aluminium oxides in the glass (Jackson, Paynter 2015). Therefore if the levels of potassium, phosphorus and iron oxides, and to a lesser extent aluminium oxide, are elevated in a glass it can also indicate contamination during recycling. Eventually special clays, more resistant to high temperatures and chemical attack, were used to make glass crucibles but this was not until later in the medieval period (Paynter 2009).

Fig. 3: Fragments of broken glass vessels and waste surrounding a wood-fuelled crucible furnace used for experimental glassworking by Mark Hill and David Taylor. Much of this material would have been recycled, perhaps introducing contamination (see fig. 4).

Fig. 4: Iron oxide scale from a blowing iron dissolving in a Roman-type glass during an experimental glassworking project by Mark Hill and David Taylor; the affected glass turns green demonstrating how contamination can alter the glass colour.

Key changes in glass composition in the 1st millennium AD

Recognising recycling in glass is about being able to identify elements that should not be present, *i.e*. they are not found in the glass originally, when it is first made, and are unlikely to have been added intentionally since. So it is important to first establish the compositions of the main types of newly-made glass in circulation in a particular time and place. The successful identification of these 'production groups' for Roman glasses has provided a basis for our understanding of the primary compositions in circulation at any one period and show that there are two key technological changes in the 1st millennium AD. One of these is related to the additives used both to decolorise and colour the glass and the second is a fundamental change in the raw materials used to form the glass. Recognising these changes, and when they take place, allows us to better identify recycled material in the archaeological record.

The first change concerns antimony, which was an important component of high status colourless glass and also opaque coloured glass in the Roman period. The replacement of antimony with alternatives from around the mid-4th century AD suggests that the mineral containing antimony either was unavailable to the glassmakers or became scarce around this time. The second development is that plant ash glass begins to increasingly replace natron glass types, particularly from the 9th century AD. These important changes which influence glass compositions can be used to explore recycling in glasses using an analytical approach, and are described in more detail below.

Decolourisers and opacifiers: the importance of antimony

A key development in the 1st millennium AD was the widespread distribution of glass with added antimony oxide, thought to originate in Egypt (Sayre 1963; Jackson, Paynter 2015). Antimony oxide was very effective at neutralising the natural colour of glass (when dissolved in it), resulting in a colourless glass that was used fairly exclusively for high status tablewares (see fig. 2). Sometime in the mid-4th century AD however, this antimony decolorised glass essentially disappears, not just in Europe but in the Eastern Mediterranean as well (see fig. 5). It is replaced to some extent by glasses decolorised by manganese, another element used widely as a decoloriser although slightly less effective in this role. Antimony compounds could also be used as additives to make glass opaque (fig. 2). In this case the antimony is not dissolved in the glass, it is combined with other substances to make tiny crystals that scattered light. Although antimony opacifiers are found in glass objects from the 2nd millennium BC onwards in the Near East and Egypt (Lilyquist, Brill 1993; Jackson 2005b), they only become widespread across Europe in the Late Iron Age and Roman period, particularly the 1st and 2nd centuries AD. By the 5th century AD however, alternatives were being sought and there was a switch to tin-based opacifiers in some regions (Rooksby 1962, 1964; Paynter *et al.* 2014). Elsewhere glassworkers resorted to adding quartz (Arletti *et al.* 2010) or crushed bone to their glass to make it more opaque (Marii, Rehren 2009; Silvestri *et al.* 2016). These technological adaptations imply a shortage of antimony to make colourants and opacifiers for coloured glass as well.

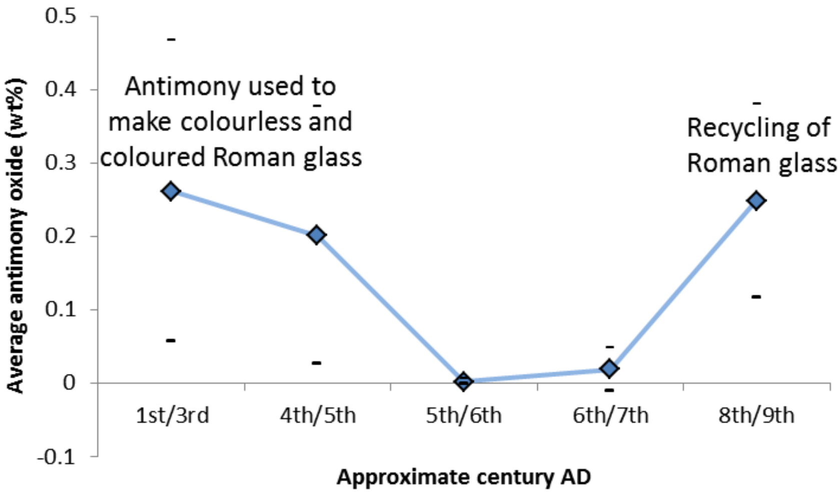

Fig. 5: The average concentrations of antimony oxide observed in assemblages of colourless and naturally-coloured glasses by broad date, from the 1st to 9th century AD. The increasing antimony content in the 7th/8th centuries is due to the recycling of Roman glass. Data taken from Jackson and Paynter 2015 (193 samples, 1-3rd), Foster and Jackson 2009, 2010 (644 samples, 4th/5th), Hunter and Heyworth 1998 (230 samples, 8th/9th), all assemblages from the UK, plus Foy et al. 2003 (16 and 22 samples respectively, 5th/6th and 6th/7th), all assemblages from France. The bars show 1 standard deviation either side of each datapoint. The average is influenced by the proportion of colourless to naturally-coloured glass in the assemblages, and so representative mixed assemblages have been used. Although a smaller sample, the 5th/7th-century assemblages are nonetheless representative (e.g. Cholakova et al. 2015).

Thus, the mid-4th century AD is a pivotal time in glass production because antimony appears to become scarce. It is no longer used to make fresh antimony-decolourised glass on any significant scale and producers of coloured opaque glass start using alternatives to antimony, such as tin oxide, bone or quartz, or recycling old coloured glass. When small concentrations of antimony are found in glass post-dating the 4th century AD there is therefore a strong possibility that it contains recycled Roman glass (Jackson 2005a).

Fluxes: natron and plant ashes

Glasses produced with the naturally occurring evaporite, natron, have a distinct chemical composition, with relatively low concentrations (generally below 1.5wt%) of potassium oxide and magnesium oxide. In contrast glasses made with plant ash fluxes vary considerably in their composition, depending on the type of plant, where it grew, when it was harvested and how the ash was prepared. Plant ash glass was produced before and after the Roman period in the western world, but the generic types of plant ashes differed between the two periods. Early plant ash glasses, such as those made in Egypt and the Near East in the 2nd/1st millennium BC, were made with were made with the ashes of salt-tolerant plants. These glasses were high in sodium oxide, very like natron glasses, but their compositions differ in the concentrations of potassium oxide and magnesium oxide which are generally between 1.5wt% and 5wt%. Glasses produced in Western Europe from around the 10th century AD and later used wood ashes derived from hardwoods and forest plants. These glasses are distinctive as they usually contain less sodium (below 10wt%) but more potassium oxide (up to 20wt%) and magnesium oxide (above 5wt%) (fig. 6). Glasses made with plant ashes often contain increased levels of phosphorous oxide as well.

Therefore the concentrations of potassium, magnesium and phosphorus oxides in a glass can be used as an indicator of the use of plant ashes. This characteristic can be useful for identifying recycling because towards the end of the 1st millennium AD, and beginning of the 2nd, as natron glass production declined and plant ash glass production spread, glasses often have characteristics of both natron and plant ash (Smith 1963; Gratuze, Barrandon 1990; Henderson *et al.* 2004). There is an increase in potassium, magnesium and /or phosphorus, but not to the levels observed in glasses produced with plant ash as the sole flux. The transition between natron and plant ash glasses has been charted for tesserae and coloured window glass, but where examples have characteristics of both it can be difficult to determine whether the plant ashes were added deliberately or accidentally through contamination (Freestone *et al.* 1990; Uboldi ,Verità 2003; Arletti *et al.* 2010; Caple, Barnett 2012). It is also important to bear in mind that plant ash glasses were used continuously throughout the Roman period in some parts of the Near East, rather than the more typical natron glasses, and that plant ashes were added to some coloured Roman glass as part of the colourant, particularly red, green and black (Paynter et al. 2015; Jackson, Cottam 2015) (only opaque blue coloured glasses have been included in fig. 6 below).

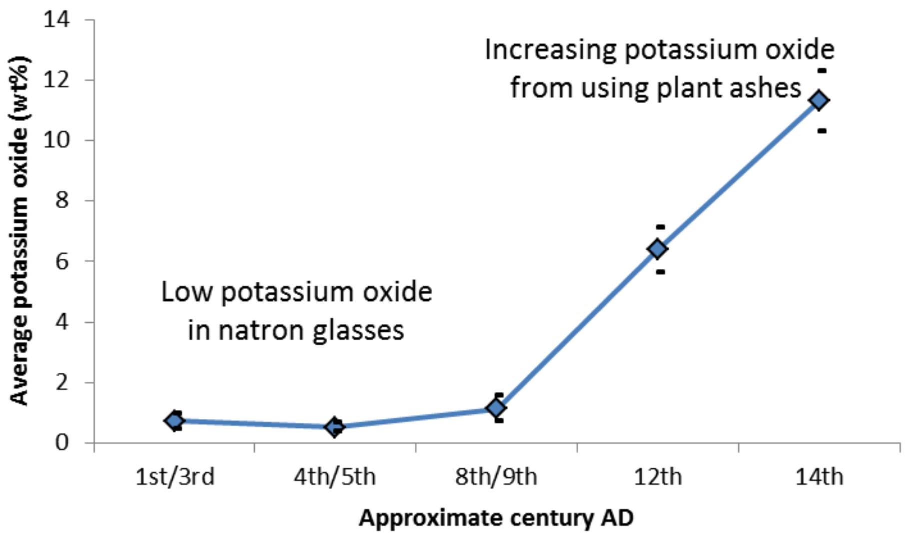

Fig. 6: The average concentrations of potassium oxide observed in UK assemblages of colourless, naturally-coloured and blue coloured glasses by broad date, from the 1st to 14th centuries AD. The rising potassium content after the 9th century is due to the increased recycling and the use of plant ashes to make glass. Data for natron glasses are taken from Jackson and Paynter 2015 (193 samples, 1-3rd), Paynter et al. 2015 (19 samples, 1-3rd), Foster and Jackson 2009, 2010 (644 samples, 4th/5th) and Hunter and Heyworth (230 samples, 8th/9th). These are compared to window glass from Glastonbury, which are plant ash glass mixed with older natron glass (3 samples, approximately 12th century, Caple and Barnett 2012), and 14th-century glasses made from plant ashes in Staffordshire

(28 samples, Meek et al. 2012 and author's unpublished data). The bars show 1 standard deviation either side of each datapoint.

Discussion

Chronological variations in recycling

There was a significant reduction in the amount of glass being used in the western regions from the mid-4th century AD onwards (Tyson 2000) but it is evident that new glass was still being produced, because furnaces dating to this period have been excavated in the Syria-Palestine region of the Eastern Mediterranean. In regions near to furnace sites (for example at Dor, Appolonia and Jalame, and at Bet Eliezer) the glass made in those furnaces dominates nearby assemblages (Greiff, Hartmann 2013; Nenna 2015) but it makes up only a minor proportion of the material from Western Europe from the mid-4th to the 7th or 8th centuries AD (Foy *et al.* 2003), and so the supply of new glass outside the immediate contact zone was more sporadic.

Analytical studies of glass from the Roman, antique and early medieval periods in Europe show successive waves of new glass, each with a slightly different composition and a lifespan varying from decades to centuries. Each of these compositions has a relatively broad distribution in Western Europe and further afield (Foy *et al.* 2003; Foster, Jackson 2009, 2010; Cholakova *et al.* 2015; Ceglia *et al.* 2015, Maltoni *et al.* 2015). This is an indication that glass was still being made on a large scale and widely distributed but that there were a number of changes over time in the raw materials used, and perhaps where the glass was being made and by whom. These changes suggest that the supply to Western Europe during this later Roman and early antique period is biased towards production centres as yet unidentified, rather than those known in Syria-Palestine. The olive green glass that dominates in the later 4th/5th centuries AD is thought to originate in Egypt (Foster, Jackson 2009), and this is followed by other distinctive compositions in the 5th/6th centuries AD (Foy *et al.* 2003; Cholakova *et al.* 2015) and another in the 6th/8th centuries AD (Foy *et al.* 2003; Freestone 2008; Ceglia *et al.* 2015). These supplies are interrupted at intervals however, and it is in these transitional periods that evidence for more intensive recycling of transparent glass has been identified. For example Grünewald and Hartmann (2015) used analyses of closely dated glass vessels from burial contexts to argue that recycling increased in certain periods, particularly from AD260 to 370, and from about AD430 to 500. This interpretation was based on elevated levels of lead, antimony and copper in the glass from these date ranges.

With each wave of fresh glass, both new and old compositions would be in circulation for a while and might be recycled together, particularly if they appeared visually similar. An example is provided by Foster and Jackson (2009), who studied glass from the mid-4th/5th centuries AD from sites in Britain and identified two naturally-coloured glass types; one with a stronger olive green to brown hue and the other a paler colour. A major proportion of the paler glass analysed contained minor amounts of antimony. This contamination suggested that the more weakly coloured of the new glasses was being recycled with the outgoing old Roman glass, which was by then becoming increasingly rare (fig. 7).

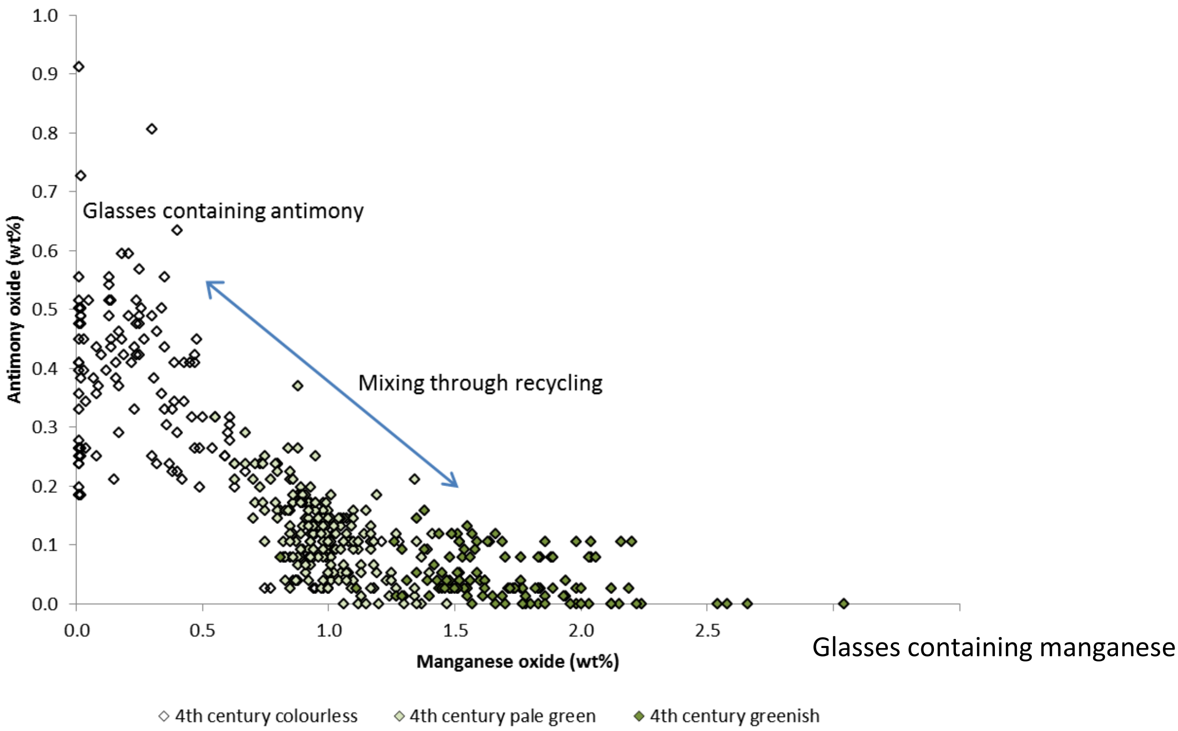

Fig. 7: The chart shows the concentrations of antimony oxide and manganese oxide in 4th-century colourless, pale green and darker green glass from the UK (Foster and Jackson 2009, 2010). When made, each type of glass would have contained either antimony or manganese: as a result of recycling however, many now contain both.

The widespread re-introduction of plant ash glass from around the 9th century AD would eventually lead to numerous alternative sources of transparent glass for glassworkers in Europe, and a change in how the glass industry was organised, with glass often being made and worked at the same site. However the production of *coloured* glass was also dependent on sources of particular metal minerals, and the knowledge of how to use them to make colourants and opacifiers. It appears that these materials or skills were in short supply because demand for brightly coloured glass was often met by recycling coloured Roman glass, and this continued through the remainder of the 1st millennium AD and into the early 2nd millennium AD. The presence of antimony opacifiers or low levels of colourants in the 5th/6th-century windows from Sion and the 7th-century window glass used at Jarrow in England (Freestone, Hughes 2006) suggest that the glass contained a proportion of recycled Roman material. By the 8th century in Hamwic, England, glass with similar levels of contamination was used for vessels (Hunter, Sanderson 1998). In fact the recycling of Roman glass continued into the 12th century, 700 hundred years after it was first made, even though fresh plant ash glass was now available. For specialist, high status vessels it seems that coloured Roman glass was sometimes re-used undiluted (Gratuze *et al.* 1997; Phelps 2011), but more often it was mixed with plant ash glass to produce larger volumes and more dilute colours (Cox, Gillies 1986; Caple and Barnett 2012; Kunicki-Goldfinger *et al.* 2014).

Regional variations in recycling

The previous examples illustrate that glass recycling was common and widespread, but interestingly much of the analytical data to indicate recycling has come from studies in Western Europe (for example Sayre, Smith 1961; Foy *et al.* 2003; Wolf *et al.*. 2005; Foster and Jackson 2009; Schibille, Freestone 2013; Jackson, Paynter 2015; Grünewald, Hartmann 2015). In contrast, the furnaces producing new glass during this period have so far been found in the Eastern Mediterranean (Nenna 2015) near the sources of natron and suitable sand necessary to make the glass. The distant workshops and consumers using glass in Western Europe were therefore dependent on trade networks extending from the Eastern Mediterranean and across Europe (Grünewald, Hartmann 2015). These sites, at some distance from the main production centres, tend to be supplied by glass from more than one source whereas a single glass type often dominates at sites near to a particular production centre (Greiff, Hartmann 2013). They would also have been further along in the supply chain and so would have been more likely to be melting cullet in addition to raw glass supplied directly from the production centres. Recycling is easier to detect through analysis in these areas because of the diverse range of glass compositions in use; with analysis it is far easier to identify recycling when dissimilar glasses are mixed than when like is mixed with like. Archaeological sites remote from production centres therefore provide an ideal opportunity to study and detect recycling but recycling in other areas should not be discounted, it may simply be more difficult to detect.

The organisation of recycling

Recycling is often discussed in general terms, but the evidence drawn together in this paper reveals vast differences in scale, motivation and practice, varying between routine or specialised and potentially large-scale recycling followed by redistribution. There is ample evidence that glassworkers routinely collected and used cullet for recycling, this was the case even when glass was in relatively plentiful supply as in Roman London (fig. 1, fig. 8). For some specialised applications glassworkers recycled particular types of glass where they were unable to otherwise achieve the effect that they wanted. This was particularly important for the production of coloured glass, which led to Roman coloured glass being sought and selectively recycled as late as the 12th century AD. Finally some glass workshops may have recycled on a larger scale and redistributed the recycled glass widely. There is tentative evidence for this from the Roman period, for example analysis suggests that a cake of turquoise coloured Roman glass found in southern Britain was made by adding colourants to recycled glass (Paynter *et al.* 2015). The coloured glass was then formed into a cake and traded on before being used to make tesserae (shown in fig. 2). Similarly much of the naturally-coloured Roman glass found in Britain is recycled, made from a mixture of antimony and manganese decolourised glasses, as mentioned previously (Jackson, Paynter 2015). However manganese decolourised glass appears to be fairly rare in Britain during this period. This raises the possibility that most of this hybrid glass was mixed before reaching Britain, at the end of a long supply chain. The recycled hybrid mixture was often used for bottles and windows (fig. 8), which required large volumes of naturally-coloured glass and so glassworkers may have recycled glass on a larger scale to make these products, and could be less discriminating in the range of cullet that they used. In Britain, glassworkers recycled these objects once again, at glassworking sites like Leicester and Mancetter where these hybrid compositions are seen in cullet and in melted waste (Jackson *et al.* 1991).

Fig. 8. Partially melted Roman windows amongst a cullet dump from Basinghall, London (courtesy of MOLA). The adhering material would result in contamination of the glass.

Conclusions

Scientific analysis has helped archaeologists to better understand the complex lifecycle of glass in the past. Large analytical programmes studying glass compositions during different periods and across wide regions, in combination with thorough archaeological recording and expert typological study, have demonstrated that the recycling of glass was prolific. Antimony, in particular, has proved to be a very useful element for detecting the recycling of Roman glass but this element is difficult to detect in small quantities with some instrumentation and so unfortunately is not always included in published studies.

Contemporary or consecutive glass types were most often recycled together, but there are exceptions where ancient glass has been reused many centuries later. There is no time limit on recycling natron glass because it tends not to spoil over time; once made it joins the reservoir available for recycling for centuries to come. As the picture of recycling grows through scientific analysis and archaeological discovery, patterns in the archaeological record will become apparent and it will be possible to enhance this exploration as to why recycling was more prevalent in particular times and places or for certain applications, and how glassworkers sorted and reworked glass during recycling. We have demonstrated here that the extent, scale and purpose of recycling differ chronologically, regionally and by application. Whilst the availability of fresh glass appears to have been an important factor when considering larger scale recycling and the redistribution of recycled glass, recycling was also undertaken routinely at workshops and selectively for specialised applications, particularly where there was demand for certain glass colours after the 4th century AD. The examples given here show that 'recycling' encompasses many different practices, varying greatly in scale and significance, and undertaken for a range of reasons, which analytical studies now have the potential to reveal.

Regions far removed from the furnace sites making the fresh glass, such as Western Europe, make useful case studies. They were dependent on long distance trade routes and were supplied with glass from multiple or varying sources, which tends to make recycling both common and easier to detect, because mixtures of dissimilar glasses are easier to identify. But there are other more subtle indicators of recycling too, such as the contamination from furnace and crucible materials, tools and fuel, which may point to the likelihood of recycling. By using chemical analysis to actively look for recycled glass in collections of cullet, in traded chunks or cakes of glass, in waste from glass workshops and in finished items, we are able to build a far clearer picture of the lifecycle of glass in the past; a cycle that sometimes lasted a thousand years.

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Captions

Fig. 1: A collection of naturally-coloured cullet from Roman London (courtesy of MOLA).

Fig. 2: Roman colourless glass and opaque strongly coloured glass (from Binchester, Durham, and Great Bentley, Essex, respectively) both containing high concentrations of antimony, characteristic of much Roman colourless and coloured glass.

Fig. 3: Fragments of broken glass vessels and waste surrounding a wood-fuelled crucible furnace used for experimental glassworking by Mark Hill and David Taylor. Much of this material would have been recycled, perhaps introducing contamination (see fig. 4).

Fig. 4: Iron oxide scale from a blowing iron dissolving in a Roman-type glass during an experimental glassworking project by Mark Hill and David Taylor; the affected glass turns green demonstrating how contamination can alter the glass colour.

Fig. 5: The average concentrations of antimony oxide observed in assemblages of colourless and naturally-coloured glasses by broad date, from the 1^{st} to 9^{th} century AD. The increasing antimony content in the $7^{th}/8^{th}$ centuries is due to the recycling of Roman glass. Data taken from Jackson and Paynter 2015 (193 samples, 1-3^{rd}), Foster and Jackson 2009, 2010 (644 samples, $4^{th}/5^{th}$), Hunter and Heyworth (230 samples, $8^{th}/9^{th}$), all assemblages from the UK, plus Foy et al. 2003 (16 and 22 samples respectively, $5^{th}/6^{th}$ and $6^{th}/7^{th}$), all assemblages from France. The bars show 1 standard deviation either side of each datapoint. The average is influenced by the proportion of colourless to naturally-coloured glass in the assemblages, and so representative mixed assemblages have been used. Although a smaller sample, the $5^{th}/7^{th}$-century assemblages are nonetheless representative (e.g. Cholakova et al. 2015).

Fig. 6: The average concentrations of potassium oxide observed in UK assemblages of colourless, naturally-coloured and blue coloured glasses by broad date, from the 1^{st} to 14^{th} centuries AD. The rising potassium content after the 9^{th} century is due to the increased recycling and the use of plant ashes to make glass. Data for natron glasses are taken from Jackson and Paynter 2015 (193 samples,

1-3rd), Paynter et al. 2015 (19 samples, 1-3rd), Foster and Jackson 2009, 2010 (644 samples, 4th/5th) and Hunter and Heyworth (230 samples, 8th/9th). These are compared to window glass from Glastonbury, which are plant ash glass mixed with older natron glass (3 samples, approximately 12th century, Caple and Barnett 2012), and 14th-century glasses made from plant ashes in Staffordshire (28 samples, Meek et al. 2012 and author's unpublished data). The bars show 1 standard deviation either side of each datapoint.

Fig. 7: The chart shows the concentrations of antimony oxide and manganese oxide in 4th-century colourless, pale green and darker green glass from the UK (Foster and Jackson 2009, 2010). When made, each type of glass would have contained either antimony or manganese: as a result of recycling however, many now contain both.

Fig. 8. Partially melted Roman windows amongst a cullet dump from Basinghall, London (courtesy of MOLA). The adhering material would result in contamination of the glass.