Historic England

Archaeological Evidence for Glassworking

Guidelines for Recovering, Analysing and Interpreting Evidence

Summary

This document provides guidance on identifying, investigating and interpreting the archaeological remains of past glassworking. This includes an overview of the types of glass used in Britain from the Bronze Age to the early 20th century, and how the raw materials, processes and products changed overtime. The guidance summarises how documentary sources, survey, excavation, scientific analysis and experimental archaeology have been used to interpret glassworking remains.

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Front cover:
Crucible and glass fragments from a post-medieval glassmaking site in the Weald.

Contents

Introduction

The aim of this guidance is to help archaeologists to recover, identify and interpret waste from the production and working of glass in Britain, from the Bronze Age to the early 20th century.

Surviving glassworking remains are likely to be regionally, or nationally, important, as archaeological evidence of glassworking is relatively rare. This guidance provides advice on how to approach, investigate and interpret glassworking sites in order to maximise their archaeological potential. The most important points are:

- seek expert advice early on, in order to best anticipate, locate, identify, recover, conserve and interpret glassworking evidence
- sample extensively, including from cut features, layers, working floors and around and within fired features, eg tiny glass threads discovered in samples may provide the only conclusive evidence of glassworking
- retain all evidence from small sites, which will include most early sites, while at larger sites, eg post-medieval and historic glassworks, there may be in excess of 50kg of glass and 500kg of crucibles, so if retaining everything is impractical, record approximately how much of each type of material is present overall and ensure that a representative proportion of each is kept from the full range of phases, contexts and material types
- consider ways of dating the glassworking activity, such as archaeomagnetic or radiocarbon dating
- plan for specialist study of assemblages and scientific analysis of glassworking waste.

The approximate date ranges for the time periods used in the text are as follows:

- Bronze Age 2500 BC–700 BC
- Iron Age 700 BC–AD 43
- Roman AD 43–410
- early medieval AD 410–1066
- medieval AD 1066–1485
- post-medieval AD 1485–present.

Structure

This document is divided into 11 themed sections, plus three case studies.

Background

Section 1 describes the main types of glass made in the past and how they differ from one another.

Section 2 provides a brief overview of how glass was made and shaped, detailing the most common raw materials used to make glass and introducing processes such as fritting, melting, annealing and glass blowing.

Advice and resources

Section 3 provides advice for investigating a potential glassworking site, covering preparation and planning, fieldwork and post-excavation analysis.

Evidence of glassworking

Section 4 describes and illustrates the most common types of glassworking evidence encountered on archaeological sites, such as furnaces, crucibles, waste glass and raw glass.

Section 5 lists common methods of shaping glass and the types of diagnostic waste produced. This enables evidence of particular processes to be recognised, eg glass blowing.

Section 6 describes materials that might be misinterpreted as evidence of glassworking.

Reference material

Section 7 provides a chronological overview, highlighting the different types of glass used, and products made, by period.

Section 8 comprises a table summarising raw materials, processes, products and the state of current knowledge, by period.

Section 10 suggests where to obtain additional help.

Section 11 is the reference list.

Section 12 is a glossary.

Case studies

Three case studies (**Section 9**) demonstrate the potential of sampling strategies and scientific analysis.

Case Study 1:
Sampling for evidence of glassworking

Case Study 2:
Determining the date of glass – windows

Case Study 3:
Provenancing glass – 1st-millennium AD production and trade

1 What is Glass?

'Who, when he saw the first sand or ashes, by a casual intenseness of heat, melted into a metalline form, rugged with excrescences, and clouded with impurities, would have imagined, that in this shapeless lump lay concealed so many conveniences of life, as would in time constitute a great part of the happiness of the world'
Samuel Johnson in 1750 (Johnson 1816).

Figure 1
Glassworker reheating an object in a replica Roman furnace made by Mark Taylor and David Hill.

Glass is a versatile and beautiful material that finds a wide range of uses, now as in the past. Products include tableware, storage vessels, window panes, mirrors, jewellery and lenses, and it was also used to decorate other objects. It can be made transparent or opaque and in a variety of colours. When hot, glass becomes a viscous fluid that can be shaped using many methods, including blowing and casting (Figure 1). When cool, the amorphous glass hardens into a brittle material, with a smooth, glossy surface.

The technology for making glass probably originated in the Near East in the second half of the 3rd millennium BC and became widespread from the mid-2nd millennium BC. A little glass is known in Britain in Bronze Age contexts but it is rare before the late Iron Age.

A glass is formed when a melt cools too quickly to crystallise and so keeps a disordered, non-crystalline structure. Glass can be made from many different materials and with widely varying chemical compositions (see sections 1.1 and 2.1). Glassy materials are found in nature, obsidian volcanic glass being a well-known example, and are also common waste products from high-temperature events, such as fires or metallurgical processes. However, the main focus of these guidelines is glass that has been made intentionally. Some other manufactured materials, such as Egyptian blue and faience, which are part glassy and part crystalline, are described in the glossary but are otherwise not discussed.

1.1 Types of glass

In the past glass was made from silica, which was combined with a range of other raw materials to make glass with widely varying properties (see section 2.1). Archaeological glass can be transparent or opaque, strongly coloured, pale blue-green or colourless. Fragments of vessels or windows can be extremely thin, while other types of vessel or working waste may be thick and chunky.

The survival of glass varies greatly depending on its type and burial conditions (see section 3.2). If it has survived well, the glass retains a smooth surface and is hard but brittle; it breaks with a characteristic conchoidal fracture. The original colours are likely to be bright, although there may be a thin, iridescent altered surface layer. This weathering layer tends to flake off (Figure 2).

Some types of glass, from the medieval period especially, are particularly susceptible to weathering. When recovered, this glass can be very difficult to recognise as it is fragile and soft with a crumbly texture. It can have an extremely altered appearance: transparent glass may become opaque, and brightly coloured glass may appear dull grey or brown (Figure 3 and see Figure 6).

Other symptoms of unstable glass are the development of a network of fine cracks (crizzling) and a greasy feel to the glass as a result of changes to its surface (Figure 4).

Figure 2
Excavated post-medieval glass from Shinrone glasshouse, Ireland, with an iridescent weathered surface; largest fragment 40mm wide.

Figure 3
Roman opaque orange glass vessel from Chichester, West Sussex, weathered to green except for the core; *circa* 22mm wide.

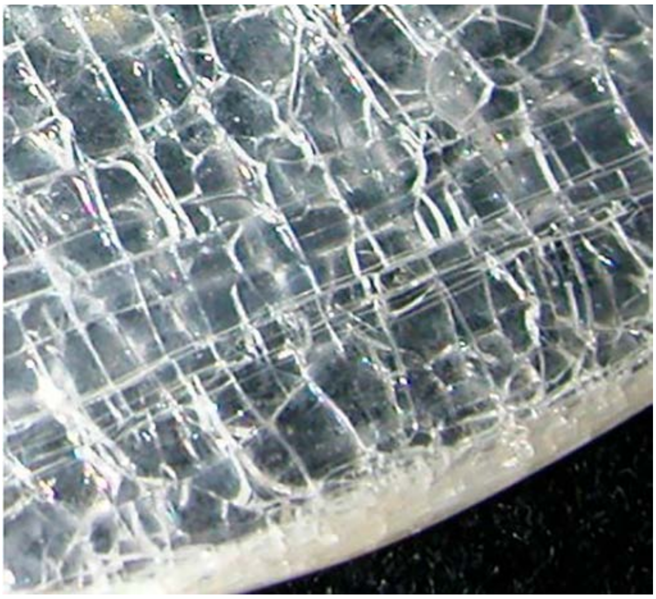


Figure 4
Crizzling in a post-medieval lead glass vessel from Wells, Somerset.

In broad terms, there are four main types of glass that have been made or worked in Britain (see section 8).

Soda-lime-silica glass (including soda-ash and natron glass) is typical of the Iron Age, Roman and much of the early medieval periods, and also more recently from the 19th century. This type of glass often survives burial very well. Soda-lime-silica glass was made in a wide range of colours but the most common was colourless glass, or glass with a pale blue-green hue, especially in the Roman and post-medieval periods (Figure 5).

Potassium-rich potash glass, sometimes known as forest glass, was common in the medieval period. Sometimes it survives only poorly but, when well preserved, it is transparent with a greenish colour (Figure 6).

Figure 5
Lumps of waste Roman glass from Basinghall Street, London, which probably fell into the furnace ash pit. The largest piece is *circa* 95mm.

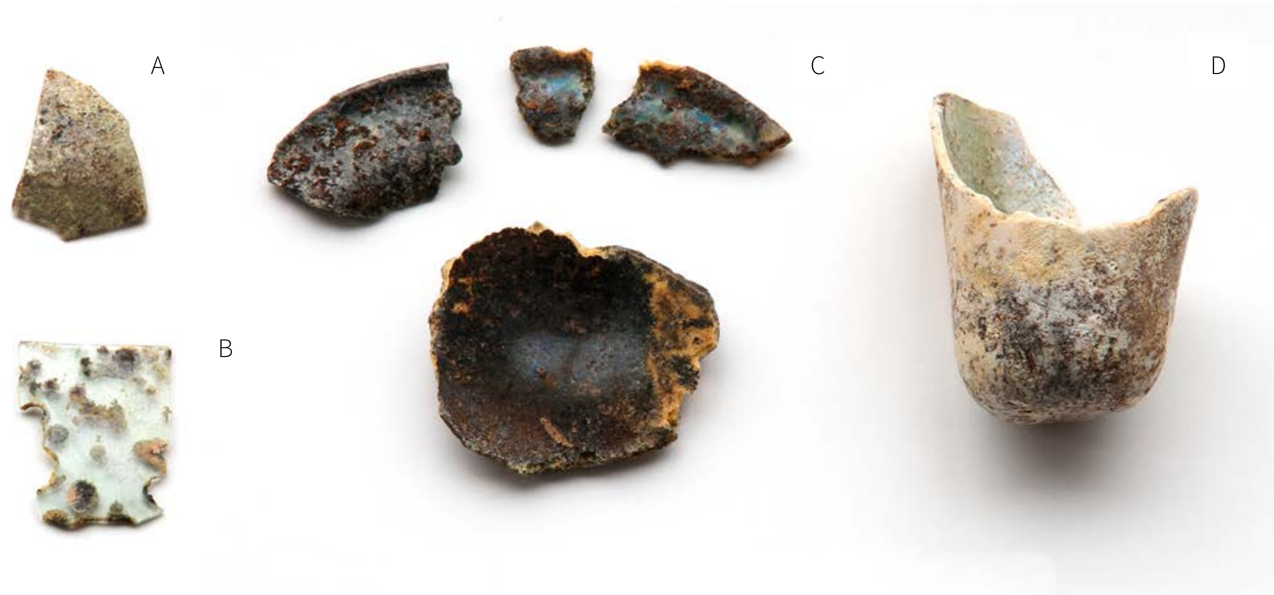


Figure 6
English medieval potassium-rich forest glass, from Plantation Place, London. It would originally have been transparent green. Severely weathered (A) and partially weathered (B) glass fragments, each 20mm wide. Uroscopy base and rim fragments (C) and hanging lamp base (D), each *circa* 30mm wide.

Lime-rich glass, often called high-lime low-alkali (HLLA) glass, is common from the post-medieval period and often survives well. It is generally transparent and greenish in colour (see Figure 2).

Lead glass appears more brilliant than other types of glass, because of a higher refractive index, and is far denser. There are some early medieval lead-rich examples in amber, deep green, red and black. Lead glass vessels were made in Germany and possibly elsewhere in Europe in the medieval period, so imports may be found, although they are rare. Lead glass becomes more common in Britain in the post-medieval period, when it is generally colourless (Figure 7, and see Figures 60 and 61). Some types of post-medieval lead glass are susceptible to problems such as crizzling (Figure 4) and weathered surfaces may occasionally appear blackened.

Figure 7
Mid-17th-century lead glass vessel with patches of black weathering.

2 Making and Working Glass

Making a glass object usually involves two main stages: making the glass by heating and reacting together the raw materials (primary production or founding); then shaping the glass into an object (secondary working). In the medieval and post-medieval periods, these processes took place together at a single site using the same structures. Previously, however, the glass was made in one place and then transported, sometimes vast distances, to other sites where it was remelted and shaped into finished objects.

2.1 Raw materials

A wide range of materials has been used for making glass over the last two millennia, depending on the date and location of glass production and on the product being made (see section 7), and at times the glass industry consumed large quantities of resources. Plant ashes were an important raw material from the 10th century, however plants generally produce very little ash when burnt, eg the amount of ash produced from oak is less than 1wt% of the wood burned. Therefore, to fill six pots with plant ash glass in a 16th-century glass furnace would have required ash from 50 tonnes or more of wood as raw material, in addition to the wood used as fuel.

Before use, the raw materials for making the glass would have been prepared in some way; this was especially the case for colourless glass. Raw materials were sometimes washed, ground up and sieved to remove the large lumps. Documents from the 15th century describe glassmakers extracting alkalis, an important glassmaking material, from plant ashes by repeatedly dissolving and recrystallising them.

2.1.1 Silica

The glass-forming material in ancient glass was silica (SiO_2), which was obtained from sand, flint or quartz pebbles. The silica source used affects the composition and properties (colour, melting temperature and stability) of the glass made. Quartz pebbles and flint are fairly pure but sand often contains shell, made of calcium carbonate, and varying proportions of other minerals. The source of silica was particularly important when making colourless glass as even small amounts of iron-rich minerals would impart a strong colour.

2.1.2 Fluxes

Silica melts at a high temperature, above 1700°C, and so fluxes were added to make a glass that would melt at an achievable temperature. The types of flux used varied over time and depended on the sort of object being made. However, there were two main types of flux that resulted in a glass that was workable at temperatures of *circa* 1000°C or less: alkali and lead.

2.1.2.1 Alkali fluxes

The alkali fluxes are sodium oxide (Na_2O) and potassium oxide (K_2O). They are often found together in ancient glass, so-called mixed-alkali glass, although generally one or the other will dominate, giving rise to the terms soda glass and potash glass.

One source of alkali fluxes was the mineral trona, formed by evaporation, eg at the lakes of the Wadi Natrun in Egypt (Jackson *et al* 2016). These deposits are commonly known as natron and are a fairly pure source of soda. Natron glass was made on a massive scale for over a millennium, spanning the Roman period (Nenna 2015). Glass found in Britain from Iron Age, Roman and much of the early medieval periods is likely to be natron glass.

Another source of alkalis was the ashes of certain plants. Plant ashes have complex, variable compositions, depending on the type of plant, the part of the plant burnt, the geology where the plant grew, the time of year it was collected and the temperature used for burning. The ashes of plants growing in desert or marine areas, eg the *Salicornia* species and seaweed (eg kelp), are often soda-rich. Purified soda-rich plant ashes were used to make the finest quality medieval and post-medieval vessel glass. Large quantities of high-quality ashes, known as barilla, were exported from Spain in the 18th and 19th centuries for glass production. Ash from seaweed (eg kelp) was used as a cheaper alternative from the 18th century in Britain, eg for window glass.

The ashes of fern or bracken species are more potash rich. Such ashes were probably used in the production of medieval forest glass. Plant ashes also contain many other components, in particular lime (CaO) and magnesia (MgO). Although these were often unintentional additions to the glass, they affected its properties, such as durability, and acted as fluxes at temperatures of *circa* 1300°C or more. Ashes from woody species are dominated by lime with less potash. These lime-rich ashes from trees such as beech and oak were probably used during the post-medieval period to make lime-rich HLLA glass.

From the 1830s, synthetic sodium sulphate, or saltcake, was used to make sodium carbonate for use in glassmaking. This very pure alkali flux (Muspratt 1860) was made from common salt by reaction with sulphuric acid, known as the Leblanc process.

Saltpetre (potassium nitrate or nitre, KNO_3) is another potassium-rich flux that was imported and used to make high-quality lead crystal (Muspratt 1860). The addition of saltpetre helped to prevent any metallic lead precipitating and spoiling the glass.

2.1.2.2 Lead oxide

Many of the colourants added to ancient soda-lime-silica glass contain lead, in particular those for opaque red and yellow, and also green if this was made from a mixture of yellow and blue colourants.

Lead oxide (PbO) is also a very effective flux and gives a glass with a low melting temperature that is easy to work. Lead-rich glass was used in the 10th century for beads, trinkets and linen smoothers (see Figures 60 and 61). In the post-medieval period and later, lead oxide was used for making lead glass or lead crystal. Lead-rich glass was prized for its optical properties, because it has a high refractive index and thus looks glossy.

2.1.3 Colorants and decolourisers

Much archaeological glass has a blue or green colour caused by iron oxide from impurities in the raw materials; even small amounts can give glass a strong colour, which was also influenced by the furnace atmosphere, whether oxidising or reducing. Such glass, coloured by iron oxide impurities in the raw materials rather than by added colourants, is sometimes called self-coloured, naturally coloured or blue-green.

In the past, manganese (MnO) or antimony oxides (Sb_2O_5) were widely added to glass to decolourise it.

Over time, a wide range of methods to colour glass was discovered. Colorants that dissolved in the glass produced a translucent colour, including copper oxide (CuO) for turquoise or green, and cobalt oxide (CoO) for dark blue. Deliberate additions of iron gave a range of blue, green or brown colours, depending on whether the conditions were oxidising or reducing, and in large amounts could appear black. Manganese could produce pink or purple colours when present in quantity. Additives that remained as particles in the glass also made it opaque; common examples are lead antimonate ($Pb_2Sb_2O_7$) and lead stannate ($PbSnO_3$) for yellow, calcium antimonate ($Ca_2Sb_2O_7$) or tin oxide (SnO_2) for white, and cupric oxide (Cu_2O) for red. Colourants and opacifiers were sometimes used in combination with each other, eg copper oxide blue and lead antimonate yellow together make an opaque green glass. More rarely glass was coloured by minute nanoparticles, making it dichroic, ie it appears one colour in reflected light and another in transmitted light. An example is ruby glass, which was coloured with tiny particles of gold.

2.2 Fritting

There is documentary evidence that before melting the glass completely, glassmakers often roasted the batch of raw materials for up to a day or more, while stirring the mixture. This fritting stage may have been common when plant ashes were used in glass production, ie from the medieval period until the early 19th century in Britain (Smedley *et al* 1998). Fritting helped to mix and bind the raw materials together, eliminated unwanted gases and made the final melting stage easier and quicker (Paynter and Dungworth 2011). The frit was broken up and stored in a dry place for remelting.

Some records describe how fritting took place in a cooler part of the same furnace used for glassmaking, eg on a shelf within the upper regions of the furnace (Figure 8). Other evidence shows that fritting took place in a separate structure, known as a calcar or oven. Such structures are difficult to identify archaeologically, however, as they are unlikely to have reached very high temperatures so are more fragile and may not survive. Diagnostic waste from fritting is also unlikely to survive; any partially reacted material would dissolve in the post-burial environment, leaving an unremarkable sandy residue.

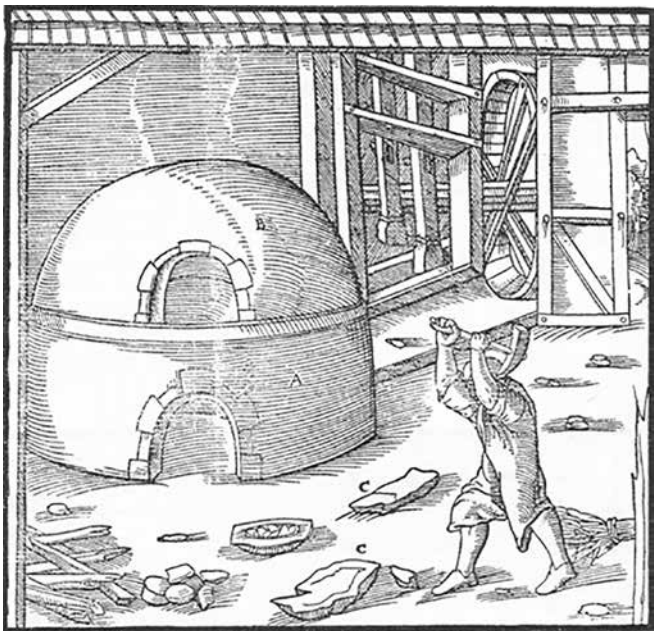


Figure 8
16th-century depiction of fritting from Agricola; the batch was fritted in the upper furnace section, then broken up and melted.

2.3 Recycling and cullet

Recycling glass has been common practice for as long as glass has been in use. Glass that has been collected for recycling is known as cullet. Cullet dumps often comprise broken vessels and windows and scraps of glassworking waste (Figure 9). There are descriptions of cullet being collected and traded from as early as the 1st century AD (Shepherd and Wardle 2009), and analyses of Iron Age glass artefacts indicate that this was recycled material from the Roman world (Henderson 1991).

Figure 9
Cullet dump from Roman London; the pile is *circa* 0.4m.

Glassmakers added cullet to a batch of raw materials or frit to help these dissolve and speed up the melting process. When freshly made raw glass was in short supply, cullet may have been the main source of glass for working. The glass would have been carefully sorted by type, eg to avoid contaminating colourless glass with coloured cullet.

2.4 Melting

Both the making and shaping of glass require considerable heat, which was generated by a furnace. Furnaces were built from refractory materials, such as stone, clay, bricks and tile.

Furnace designs changed over time but there were basically two types: tank furnaces and pot furnaces. Tank furnaces were built with an integral tank to contain the molten glass. There is some evidence for smaller tank furnaces being used in the Roman period in Britain to melt glass for shaping (Shepherd and Wardle 2009) and a number of good examples of tank furnaces used for glass making from the late 19th century (see section 4.1).

Most furnaces were pot furnaces, constructed with platforms or shelves to support a number of ceramic containers, known as pots or crucibles, which held the melted glass. Some pot furnaces had a central fire and ash pit; these were commonly circular in plan but were sometimes rectangular (Figure 10). Others had an elongated fire trench and parallel platforms, known as sieges, on each side for the pots (Figure 11).

Figure 10 (Top)
16th-century depiction of a glass furnace from Agricola, showing glassblowers and moulds on the floor in the foreground.

Figure 11 (Bottom)
A rectangular-plan, 17th-century glasshouse at Shinrone, Ireland. The small holes in the vault are for smoke to escape; there was no chimney. The fire trench runs through the arched openings at each end with low sieges on either side. Gases from the wood fuel have reacted with the stone furnace walls to make a blue glaze-like surface over the inside surfaces.

While the furnace superstructures almost never survive archaeologically, there are a number of depictions of glassworkers and their furnaces that provide us with an idea of how they looked in their entirety (Figure 10). These illustrations show glassworkers gathering glass on the end of a long metal pipe, the gathering or blowing iron, through holes in the furnace walls.

In England, glass furnaces were wood-fuelled until the early 17th century (see section 4.3). Whereas metalworkers used charcoal in their furnaces or hearths to obtain a reducing atmosphere, this was not necessary for glass production or working. Coal-fired furnaces were introduced from the early 17th century. Gas-fired furnaces were introduced in the mid-19th century.

2.5 Shaping an object

Within a temperature range determined by its composition, glass has the right consistency for shaping by moulding, drawing, cutting, pinching, blowing or casting. These techniques leave diagnostic marks on the object and can also produce characteristic types of waste (described in more detail in section 5). An object can be built up in stages using hot forming techniques, by applying trails of molten glass as decoration and to form bases, rims or handles (Figure 12).

There are also many ways of decorating cold glass, eg by grinding, engraving or cutting (see section 5.4).

Figure 12 (top)
Glassworker Mark Taylor, applying a handle to a vessel; the red-hot glass has a toffee-like consistency

Figure 13 (bottom)
Remains of a 17th-century coal-fired glass furnace at Kimmeridge, Dorset, showing the below-ground flue or fire trench running left to right.

2.6 Annealing

Glass objects have to be cooled down in a controlled way, or the glass will shatter. To do this, hot glass objects are annealed: held at an intermediate temperature for many hours. This temperature is much lower than that needed to melt the glass. However, the holding temperature must be hot enough, and the subsequent cooling rate slow enough, to guard against the permanent stresses that would otherwise be created in the glass if it was cooled quickly.

Sometimes annealing took place in a cooler part of the main glass furnace, in an annealing compartment. The winged extensions on some post-medieval furnaces in Britain have also been interpreted as possible annealing ovens (Figure 13).

In other cases, a separate structure, called an annealing oven or lehr, was used (see section 4.2). The glass was loaded into the heated oven, which was sealed and allowed to cool. Documentary sources imply that ovens remained in use until the mid-19th century. Continuous lehrs were used from the 19th century.

3 Investigating a Glassworking Site

Archaeological work may originate as a response to proposed land development, as a project funded by national agencies, or as a part of a university department or community-led archaeology venture (Historic England 2015).

3.1 Anticipating glassworking remains

Before fieldwork, there is often little to indicate the presence of early glassworks, but evidence is more likely to be encountered at certain types of site, eg Roman towns and early medieval monastic sites. However, in some periods the industry is concentrated in particular regions and it is often possible to anticipate the presence of glassworking remains. For example, areas of the Weald and Staffordshire were focal points for the industry from the 13th to the 17th centuries (Kenyon 1967; Welch 1997). Similarly, the approximate location of later, post-medieval furnaces is often known from maps and records. In addition, the following resources and practices can be helpful for assessing the potential of a particular site for providing evidence of glassworking.

3.1.1 Historic Environment Record, research agendas and Step reports

Current knowledge can be reviewed in the Historic Environment Record (HER), which is maintained by local authorities at county, district or unitary level, and in many cases is accessible through the Heritage Gateway website at http://www.heritagegateway.org.uk and in regional research frameworks where these are available [see the website for the Association of Local Government Archaeological Officers (ALGAO) at https://algao.org.uk/england/research_frameworks. An overview of the glass industry is also provided in the Monuments Protection Programme Industry Step 1 report and a list of assessed sites with recommendations for their future management in the Step 3 report, available for consultation at the National Monuments Record (Swindon), the Council for British Archaeology (CBA; York), University of Leicester and the Institute for Industrial Archaeology (Ironbridge). A summary of what to expect at sites of different dates is provided in sections 7 and 8 and further reading is suggested in section 10.

3.1.2 Historic archives

Documentary records, including accounts, maps (Figure 14) and place names, can help to locate glassworking sites, in particular for later periods (Crossley 1994; Historic England 2018).

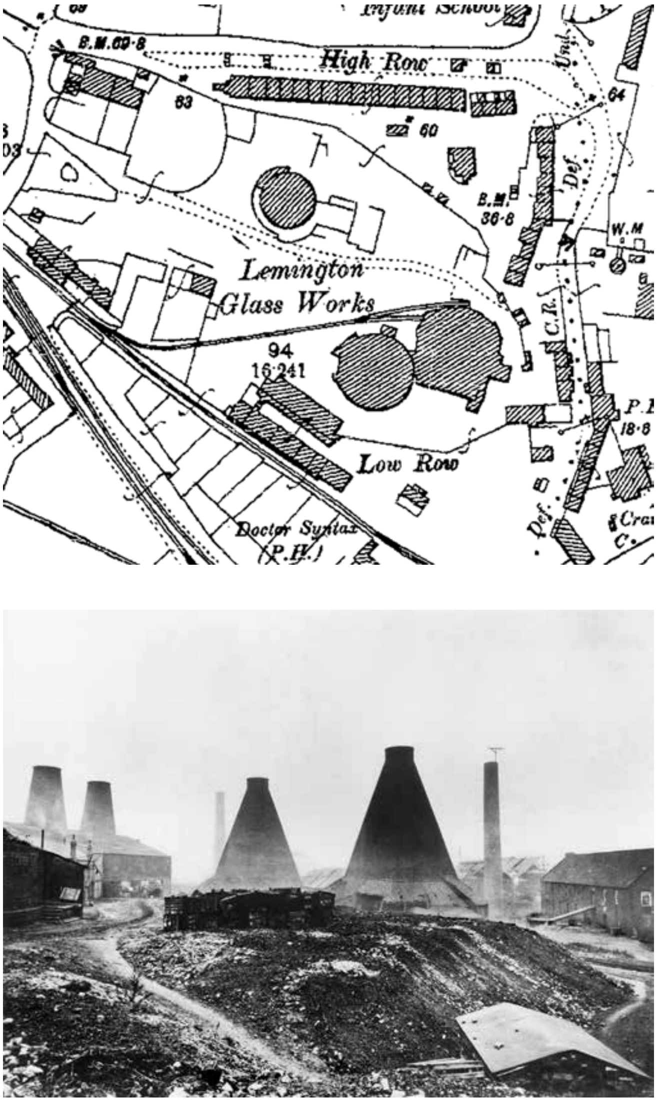


Figure 14
Top: an 1897/98 OS map (1:2 500) of Lemington glassworks, Newcastle upon Tyne, Tyne and Wear, showing the circular footprint of the cones. (This map is based upon Ordnance Survey material with the permission of Ordnance Survey on behalf of the Controller of Her Majesty's Stationery Office. © Crown Copyright.)
Bottom: a photograph of the glassworks *circa* 1900.

3.1.3 Field walking and geophysical survey

Field walking may reveal a scatter of crucible or furnace fragments and glass waste in the area of a glassworks.

Geophysical survey techniques are likely to be successful in locating some furnaces. For example, 13th- to 17th-century furnaces reached high temperatures and are well fired and robustly built. These were also wood-fired and are often located in rural, though sometimes urban, areas and may be relatively undisturbed. The fire trench of these furnaces is often detectable by geophysical survey (Welch and Linford 2005).

3.2 Planning the project

Having decided that a site requires archaeological investigation, the historic environment planning officer may produce a brief. The developer selects a contractor to undertake the archaeological project, and this contractor responds to the brief with a written scheme of investigation (WSI) (ACAO 1993; CIfA 2014a, 2014b). The quantity and quality of information provided by the glassworking evidence from a site can be maximised by implementing the following.

- Contacting specialists in glassworking evidence and conservation, who can advise on the types of evidence likely to be encountered (see sections 4 and 5), sampling, recovery and immediate treatment of glass finds (see section 3). In the WSI, the scope of work should be outlined and funds allocated for specialist analysis, eg typological study, scientific analysis, conservation, etc.

- Outlining glassworking research questions, because glassworking evidence is rare for many periods and gaining a better understanding of the glassworking activity is likely to be a major aim for any site where glassworking has taken place. Some research questions that can be addressed by the glassworking evidence for a particular period are highlighted in section 8, and some examples are given below.

- Particularly for historic glassworking sites, as this was a period of rapid, although often secretive, innovation, is there evidence for remodelling of structures, such as furnaces and flues, changes to processes and production of specialised products?

- What evidence is there for ancillary industrial activity in the surrounding area, eg were there shelters for the furnace and workers, where were the raw materials stored, where were the crucibles made and were activities seasonal?

- What labour force was involved in the glassworking, how were the workers organised and trained, what conditions did they work and live in and is there evidence of domestic activity?

- How were resources managed? What fuel was used and is there evidence of woodland management? Were materials such as sand, plant ashes and clay obtained locally or transported to the site?

- Was the glass made at the site; if not, where was the raw glass obtained? What products were made, where was the intended market and how were products transported and sold? How was the glass used?

Figure 15
The view from the west of Little Birches, Wolseley, Staffordshire, a 14th- to 16th-century glassworking site, showing the waste tips (quartered or sectioned black mounds) and furnaces (orange-fired areas).

3.3 Fieldwork

It may be necessary to undertake fieldwork to characterise, understand and record a historic resource. At glassworking sites the furnaces and flues are often the initial focus of the investigation, extending to ancillary structures, such as annealing furnaces, stores, gas ovens and cutting workshops. At earlier sites, geophysical survey (see section 3.1) can guide the positioning of trenches, as can the site topography, eg mounds may indicate waste tips (Figure 15). At later sites it may be possible to position trenches by using contemporary accounts and historic maps to establish the location and preservation of features.

Glassworking remains are rare, particularly upstanding structures. If features are well preserved then this strengthens the case for preservation *in situ*; guidance on conservation planning and recording is provided by Gould (2008). The appointed specialist should be consulted for more detailed advice on a case-specific basis.

Figure 16
Glass waste on the working floor below the gathering hole of the reproduction Roman furnace by Mark Taylor and David Hill. The larger fragments could be recycled.

3.3.1 Sampling

Detailed and often small-scale examination is particularly important for glassworking sites. Sometimes the only surviving evidence of glassworking comprises the small glass threads, trails and droplets recovered from soil deposits (Figure 16). The most efficient way of recovering this small-scale glassworking evidence is to take soil samples and process them by flotation and sieving; glassworking waste is found amongst the residues (see case study 1; English Heritage 2011). It is advisable to sample from layers, including occupation layers if these survive, and from within cut features, such as pits and ditches. If fired features are located, samples should be taken from outside (around the perimeter) as well as from inside, because material from inside is more likely to be chemically altered and so less representative (see section 3.4).

3.3.2 Lifting and short-term storage of glass

First Aid for Finds (Watkinson and Neal 2001) provides advice for the recovery and storage of glass on site. The condition of glass is dependent upon the burial environment and the composition of the glass; the latter varies depending on the type of object and when it was made. Water is the main factor causing deterioration of glass, and in damp atmospheres potash (forest) glass is more liable to decay than soda-lime-silica glass (Pollard and Heron 1996).

It is important for the condition of the glass to be assessed upon excavation, eg by a finds specialist or conservator, and to seek advice if necessary (see section 10), even if the glass initially appears to be in relatively good condition. Glass is often physically and chemically altered, or weathered, during burial (see section 3.4.2). However, when weathered glass is damp it can appear unaffected, with a translucent and shiny surface, because there is water in between the weathering layers and the glass. When the glass dries out the weathering layers collapse and form a fragile weathering crust, which has a tendency to flake off. Conservation treatment can prevent the loss of this integral weathering crust and safeguard the information that it may contain, in particular surface detail and painted decoration.

It may be necessary to lift glass within the surrounding matrix of earth. Glass should also be well supported during storage or it is likely to break.

3.3.3 Deciding what to keep

Deciding what to retain from archaeological contexts is a complex issue, particularly on large-scale sites. The most important factors are the research questions specific to the site being excavated: it is best to select material that helps to address these. As a general guide, all evidence from earlier, smaller sites, generally those pre-dating the 15th century, should be retained. Post-medieval and historic sites, however, may be on such a large scale that this becomes impractical (eg see Figures 14 and 15). If it is not possible to retain all of the evidence, it is good practice to retrieve examples of the full range of materials present and estimate and record the quantity at the site overall. Make sure that all types of artefact (crucibles, wasters), deposit (raw materials, fuel waste, glass waste, cullet dumps, working floors), context types and phases are represented in this sampling.

3.3.4 Dating methods

Archaeomagnetic dating has been used successfully to date the last firing of furnaces, where the fired surface is undisturbed (Welch 1997; Welch and Linford 2005). This technique is most precise for the post-medieval period (Linford 2006).

Radiocarbon measurements may be obtained from single-entity organic samples (eg short-lived furnace fuel) (Ashmore 1999; Bowman 1990; Waterbolk 1971).

In addition, information on date can be obtained from documentary sources, by typological study of the glass and by scientific analysis of the glass or crucibles (see sections 3.4 and 4.4, and case study 2).

3.4 Post-excavation analysis

Further scientific or typological investigation of the glass is usually warranted to help with the interpretation and achieve the project aims.

3.4.1 Typological study

Specialists in archaeological glass can provide information from examining fragments of excavated glass. Familiarity with a wide range of glass enables them to use typological information to determine date, original form and function, and source of manufacture. The glass can provide further information about life on the site, such as who would have used the glass and in what situations, the status of its owner, and the rarity and significance of the glass both on the site and in a wider context. Specialists will also advise whether scientific analysis of the glass would be beneficial to address further questions. Many specialists are independent researchers and can be found by contacting the organisations listed in section 10.

3.4.2 Conservation

Much has been written on the condition and deterioration processes of glass (Newton and Davison 1996; Knight 1996; Pollard and Heron 1996) and it is only summarised here (see also section 1.1). The deterioration of buried archaeological glass can take different forms, such as weathering, lamination, pitting and opaqueness; post-excavation deterioration includes the formation of weathering crusts and, in the case of historical glass objects, weeping or crizzling.

- When glass weathers the soluble components, such as sodium and potassium, are leached out, creating physical stresses in the glass. The glass contracts and splits into a series of silica-rich weathering layers (lamellae) that reflect light unequally and appear as an iridescent weathering crust (see Figure 2).

- Corrosion and pitting can occur where leached alkali becomes concentrated on the surface in cracks or surface scratches. The pH in the pit increases and the corrosion continues downwards. White deposits, eg consisting of hydrated silica and sulphate salts, may form in the pit (see Figure 6).

- Weeping or crizzling glass is a phenomenon of historic glass that appears as a network of fine cracks and/or an oily film or small aqueous droplets. It is attributed to the chemical instability of certain types of post-medieval glass (Kunicki-Goldfinger 2008) (see Figure 4).

- As glass decays, any iron or manganese present can oxidize *in situ*, making the glass brown or black and contributing towards its opacity (Knight 1996) (Figure 17).

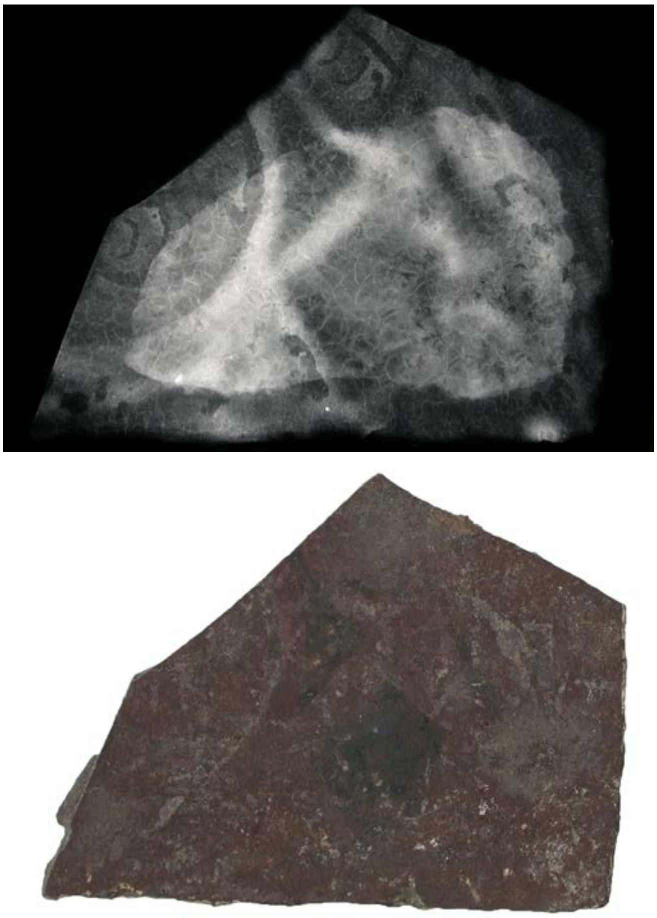


Figure 17
An X-radiograph (X-ray) (top) of a fragment of late 13th- to early 14th-century, decorated, potash forest glass, *circa* 40mm wide, from the evaluation at Chesterton Manor, Warwickshire, by English Heritage. The X-ray reveals the decoration otherwise obscured by weathering and that the core of the fragment is denser and better preserved than the edges

The conservation of glass should be undertaken by an appropriately qualified conservator (see section 10 on where to get help) following the principles outlined in the Historic England Investigative Conservation guidelines (English Heritage 2008) and in texts such as Newton and Davison (1996) and Tennent (1999). Conservation can include investigative conservation, cleaning, consolidation, reconstruction and repacking for long-term storage. The level of conservation, and how much of the assemblage is included, depends on whether the glass is classed as a bulk or as a small find, its condition, and the research questions posed. For example, investigative conservation may include the use of X-radiography (X-ray) to record the condition and any applied painted decoration (Figure 17).

3.4.3 Scientific analysis

Scientific analysis often focuses on the composition of the glass manufactured (or worked) at a specific site. However, some glassworking waste is accidentally chemically changed by reacting with other materials, so may not provide an accurate picture of the original glass composition. This is particularly true of waste from within the furnace itself, and of glass adhering to fragments of crucible or furnace. Therefore moils, off-cuts and raw glass are generally the most useful types of waste for establishing the type of glass made and how this may have changed from one batch to another. Glass waste recovered from soil samples is likely to be dominated by tiny fragments but these can still be used for analysis (Dungworth and Cromwell 2006; Historic England 2018) (see case study 1).

Different analytical methods are used to investigate glass because they give varying types and levels of information, have wide-ranging costs and need different amounts of material. With all analytical work, it is advisable to include standards of known composition, to check the accuracy and precision of the analyses. A larger number of glass specimens is also more likely to provide a statistically significant answer than only a few specimens.

3.4.3.1 Scanning electron microscopy and energy dispersive spectrometry

Scanning electron microscopy (SEM) is used to look at objects at magnifications of tens of thousands of times, eg to identify the tiny particles colouring glass or to study weathering phenomena. If an energy dispersive spectrometer (EDS) is attached to an SEM, the glass can be analysed for chemical composition at the same time. Only a small piece, a millimetre or more in size, is required. Using an EDS is one of the standard techniques for detecting the major constituents of glass, present in amounts greater than 0.1wt%, but is not suitable for detecting trace amounts of elements.

3.4.3.2 Inductively coupled plasma spectrometry

There are several variations on the inductively coupled plasma (ICP) spectrometry method. ICP atomic emission spectroscopy (ICP-AES) is a cheap method of obtaining compositional information for large numbers of specimens. For this procedure, 0.1–0.2g of glass is required per analysis, which is ground up and dissolved during the process. The technique can detect trace amounts (parts per million) of many elements, usually *circa* 20 at a time. This information can be used to answer questions of provenance and recycling, and to differentiate between glass batches (eg Jackson 2005). The preparation method used for ICP results in the loss of silica, the main component of glass. However, the amount originally present can be calculated if all of the other elements in the glass have been found and measured accurately; including known standards is therefore particularly important for ICP work. ICP can also be used with a mass spectrometer (ICP-MS), which is more expensive but can measure even lower levels of elements. Laser ablation ICP (LA-ICP) can be used to analyse very small fragments of objects (a fraction of a millimetre) and can even obtain results from the surface of a display object, with virtually no visible damage.

3.4.3.3 Mass spectroscopy

Mass spectrometry techniques, such as transmission mass spectroscopy (TIMS), are used for isotope analysis. Isotope measurements can indicate what types of raw materials were exploited, eg the use of seaweed ash, sea shells and limestone have all been deduced from strontium isotope data (see case study 2). Around 30–50mg of glass are required for each analysis or laser ablation can again be used.

3.4.3.4 X-radiography fluorescence spectrometry

X-ray fluorescence spectrometry (XRF) is a rapid and fairly cheap technique that can be used to determine the composition of glass. A disadvantage of XRF is that it is less sensitive for light elements, such as sodium and magnesium, which are important for characterising glass. However, a great advantage is that portable XRF machines are available (see case study 2), which can be used to analyse the surface of glass objects without damaging or moving them, eg window glass or display objects. Glass surfaces are often altered after burial, however, which affects how the results for archaeological specimens should be interpreted.

3.4.4 Treatises and historic archives

Technical treatises and historic archives can provide information for those aspects of glassworking that leave little archaeological evidence. For example, our knowledge of raw material collection and preparation and the fritting process derives mainly from contemporary accounts (see section 2.2). Illustrations and photographs contain information on the scale and deployment of the labour force and working conditions, as well as details of equipment and processes.

Several early technical treatises on contemporary glassworking traditions have survived. The best known are those of Theophilus, who wrote in the 12th century (Hawthorne and Smith 1979), and Agricola, who was active in the mid-16th century (Hoover and Hoover 1950). There are others, eg Neri, dating to the 17th century (Cable 2001), that describe processes that were widely used in earlier centuries. There are also some references to glassworking in Roman texts (Jackson *et al* 2016; Price 2002, 81).

For more recent sites, technical textbooks, such as Cable (2008), Muspratt (1860) and Pellat (1849), are good sources of detailed information. In addition, paintings, illustrations, engravings and photographs can be useful resources. Sometimes catalogues of wares produced by glass companies still survive (eg Miller 2007). A fuller summary of the types of records that are useful in investigating historic sites is given by Crossley in Historic England (2018).

3.4.5 Experimental archaeology and ethnographic evidence

Practising glassworkers are able to comment on archaeological glassworking waste, eg how particular types of glass waste, or tool marks on artefacts, were made. Some glassworkers have experimented with replica furnaces and glass compositions similar to those of ancient glass (Taylor and Hill 2008). These experiments greatly aid the interpretation of archaeological glassworking features (Paynter 2008; Shepherd and Wardle 2009). Photographs from these experiments and online video clips are very informative.

A variety of glassworking practices from around the world have also been documented. As well as publications (Küçükerman 1988; Sode and Kock 2001), videos and photographs of glassworkers are increasingly available on the Internet. Ethnographic studies include observations on attitudes, practices and materials, including division of labour, seasonality and glassworking tools and techniques, which can help with the interpretation of archaeological finds and documentary records.

4 What You Might Find

This section describes characteristic types of evidence indicating that glass production and/or working took place at a site, the most common being:

- furnace structures and fragments
- crucible fragments
- cullet dumps
- raw glass
- glass waste.

Detailed examples of the waste produced by specific working methods are provided in section 5 to help with the interpretation of these finds.

4.1 Furnaces

Only furnace types found in Britain are discussed here. There is no evidence from the Bronze or Iron Age for furnaces (see sections 7.1 and 7.2). Roman archaeological remains in Britain suggest the use of two furnace types. An early Roman furnace in London contained a built-in, tile-lined tank for holding the molten glass (Shepherd and Wardle 2009). The size and shape of the furnace is unknown but it is likely to have had an ash pit and at least one stokehole for adding wood fuel to the fire.

In the later Roman period, however, it appears that the glass was held in ceramic crucibles or pots. The crucibles were seated on a shelf or platform within a furnace (Cool *et al* 1999). This type of furnace continued in use into the early medieval period (Bayley 2000a). A replica furnace of this type is shown in Figure 18. Typical remains are an oval or circular, orange-fired feature *circa* 1m in diameter, sometimes tile-lined, which is the remains of the ash pit. Fragments of vitrified or fired furnace superstructure may also be found. These generally have a glassy surface on the inside as a result of reactions with the corrosive furnace gases or spills of glass.

Similar pot furnaces, round or oval in plan, were used in the early medieval period. Furnace remains at Glastonbury, Somerset, of Middle Saxon date, consisted of ash pits, 0.9–1.2m in diameter, incorporating reused pieces of Roman tile, with partial remains of clay walls along the edges (Bayley 2000b). Stone was used around the furnace base and at the stokehole entrance. The furnaces may have had a domed superstructure and had been rebuilt several times.

Medieval and post-medieval furnaces had a different type of design. They were typically rectangular in plan (3m wide and between 4m and 5m long). There were two parallel platforms known as sieges on either side of a central ground-level fire trench, all of which often survive

Figure 18 (top)
Reproduction Roman glassworking furnace made by Mark Taylor and David Hill, *circa* 1.5m in external diameter, showing the domed superstructure with two of the three gathering holes (one open), the marver (raised block on the right), blowing irons with ends heating (centre front) and fuel pile at the rear.

Figure 19 (bottom)
The remains of a 16th-century glass furnace at Little Birches, Wolseley, Staffordshire, looking along the fire trench with glass-coated sieges on each side, where circular impressions from the bases of the crucibles remain.

archaeologically (see Figures 11 and 19). A fire was set at the end of the trench and the crucibles sat on the sieges. Late medieval furnaces were generally stone built, whereas post-medieval furnaces made more use of refractory brick, which was not available earlier.

A coal-fired furnace for melting glass was developed in the second decade of the 17th century. A patent for manufacturing glass using coal was granted to Sir Robert Mansell and a royal proclamation issued that banned (in England) the use of wood fuel in glass furnaces. This had implications for the location and design of glass furnaces (Crossley 1990, 2003).

The earliest coal-fired furnaces retained the two parallel sieges with a central fire trench, but the base of the trench was made *circa* 1m below ground level, so is sometimes referred to as a flue. The fire was typically supported above the trench on iron bars placed mid-way along it (eg Pellatt 1849, 57). The changes were necessary because coal requires a greater draught to burn effectively, produces a shorter flame than wood, and leaves much more ash. The subterranean flue ensured that sufficient air reached the fire and allowed the ash (and clinker) to collect where it would not restrict the flow of air. Partial remains of the underground flues often survive archaeologically (Crossley 1990; Tyler and Willmott 2005) (see Figure 13).

The characteristic conical furnace cover building appears to be a late 17th-century to early 18th-century development (Crossley 1990, 2003). The earliest surviving cone, dating to 1740, is at Catcliffe, Yorkshire, and is 18m high (Figure 20), but some were taller. They were typically between 12m and 15m in diameter at the base. The cone was essentially a chimney, covering the furnace and working area. The fire was set in a firebox at ground level, with air supplied through subterranean flues (Figure 21). The tall cone helped to induce a strong draught to feed the furnace fires and remove the fumes generated.

The flames and heat entered the furnace through a hole, or eye, in the centre of the floor, and were drawn towards the crucibles, which were set in a circle around the eye. Hot gases exited the furnace through small flues positioned over the crucibles, passing into the cone. There were up to 10 gathering holes in the furnace walls, one for each pot.

The coal-fired glass industry thrived in the areas of Lancashire, Tyneside and the West Midlands. Later an important industry became established in Manchester, with more than 25 glassworks in operation by the 1870s (Miller 2007).

The furnaces were accompanied by many ancillary buildings, such as annealing sheds, cutting and engraving workshops, offices and warehouses (Miller 2007). A number of cones has now been excavated (eg Ashurst 1970) and the flues and evidence of the sieges often survive. Sometimes flue entrances can be seen in the walls of nearby canals.

Regenerative glass furnaces were developed in the 1860s. These were still pot furnaces but used gas fuel and achieved higher temperatures. The gas was normally produced in gas ovens at the glassworking site and the remains of these structures can be expected (Figure 22). The regenerators comprised brick-filled chambers, connected by valves to the incoming and outgoing furnace gases (Figure 23). The hot furnace exhaust gases passed heat to the regenerators, which then preheated incoming combustion gases, making the furnaces much more efficient (Crossley 2003; Krupa and Heawood 2002).

In the 1870s, continuous tank furnaces were introduced that produced better quality glass more cheaply. The furnace was charged with raw materials at the melt end and the molten glass was drawn off at the working end. Floating bridges in between prevented any unreacted batch from passing into the working end.

Figure 20 (top)
The 18th-century cone at Catcliffe, Yorkshire.

Figure 21 (bottom)
An 18th- to 19th-century glass cone under excavation at Dudley Flint Glassworks, Stone Street Square, West Midlands.

Figure 22 (top)
One of a bank of 19th-century gas producers excavated at the Powell and Ricketts glassworks in Bristol, Somerset.

Figure 23 (bottom)
The remains of an early regenerative furnace excavated at the Powell and Ricketts glassworks in Bristol, Somerset.

4.2 Annealing structures

Annealing has been described in section 2.6. This process sometimes took place in a dedicated part of the main furnace (see Figure 13), and so little specific evidence is likely to survive.

Some examples of stand-alone annealing structures have been proposed, such as at the 16th-century glassworking site at Knightons, Surrey (Wood 1982), where quantities of large window glass fragments were found associated with a fired feature near the glass furnace. This was thought to be an oven for annealing window glass crowns (see section 6.3). However, as annealing did not require very high temperatures, such structures are less robust and survive less well.

Continuous lehrs, used from the 19th century, are more substantial; there can be archaeological evidence of a brick structure and, if the floor survives, perhaps rails or grooves remaining from the system used to move the glass through the lehr (Cable 2008; Miller 2007) (Figure 24).

4.3 Fuel waste

Wood was the principal fuel used to heat glass furnaces until the 17th century, so ashy or charcoal-rich deposits may be found at glasshouse sites. In such furnaces, corrosive gases from the wood fuel reacted with the furnace walls to make a glassy layer on the inside surfaces (see Figure 11). Droplets of this bluish glassy material are found at furnace sites and are easily confused with intentionally made glass.

From the early 17th century, furnaces were coal-fired. The vitrified coal ash formed clinker, amorphous lumps of which can be found in large quantities on glasshouse sites. Clinker is formed wherever coal is burned, so is not restricted to glasshouses. It is dark coloured, light in weight and vesicular (Figure 25).

Gas-fired furnaces were used from the 1860s (see section 4.1).

Figure 24 (above)
The entrance to the lehr at Red House Cone, Stourbridge, West Midlands; the stokeholes are at the bottom of the image and the trays of glassware on the upper level, in the tunnel.

Figure 25 (left)
Clinker from the 17th-century coal-fired glasshouse at Silkstone, South Yorkshire; the pile is 180mm wide.

4.4 Crucibles

Crucibles, also known as pots, are the ceramic containers used to hold molten glass. Crucibles were used for most glassworking before the late 19th century. Many crucibles, especially late medieval and post-medieval ones, are extremely robust and so crucible fragments are common field-walking finds. They are usually fragmentary and the inside surfaces sometimes have a glassy layer on them. Lead-rich glass layers usually survive well, but other types of glass tend to spall off in chunks, leaving a pitted, and often bleached, inner surface to the crucible. If only a thin layer of glass survives on a crucible, its composition will have been significantly affected by the dissolved ceramic and this must be taken into account when undertaking or interpreting analyses. Crucibles were also used for metalworking but it is possible to tell them apart (see section 6).

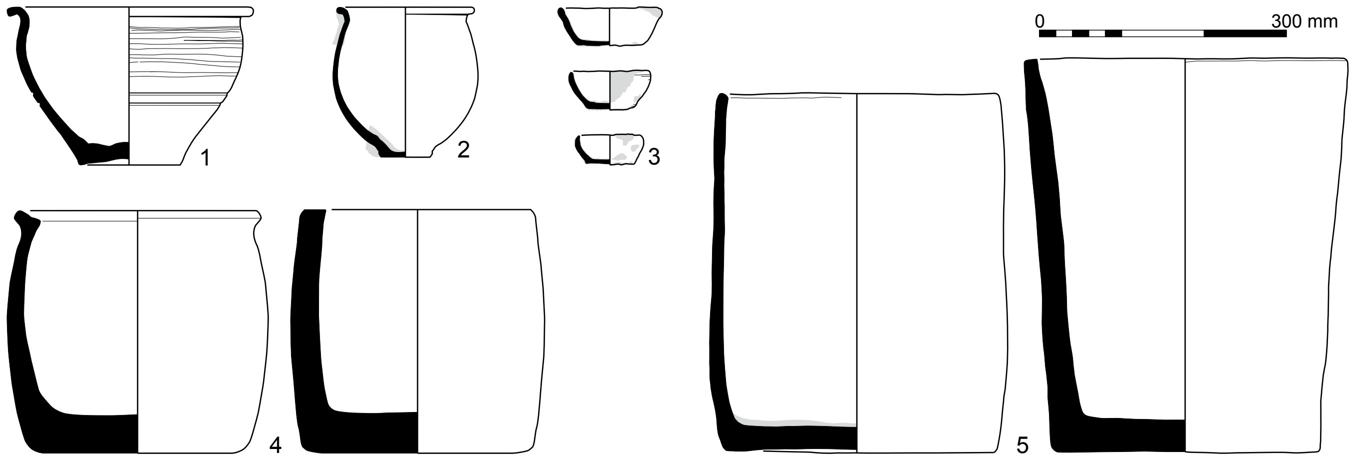


Figure 26
Crucibles through the ages. 1 Roman crucibles from York, North Yorkshire. 2 Middle Saxon crucibles from Glastonbury, Somerset. 3 Late 10th- to early 11th-century crucibles for lead glass from Flaxengate, Lincoln, Lincolnshire. 4 Mid-14th-century crucibles from Blunden's Wood, Surrey. 5 Early 17th-century crucibles from Kimmeridge, Dorset.

Crucible size, shape and fabric vary over time, and these characteristics can indicate the date of glassworking activity (Figure 26). Roman and early medieval crucibles tend to be of contemporary pottery forms (Figure 27). These crucibles can be identified by the coating of glass surviving on the inside surface. Roman and early medieval examples mostly contain pale blue or green natron glass, although some crucibles used for melting yellow and white glass have been found from 3rd- to 6th-century contexts (Bayley 2000a, 2000b; Cool *et al* 1999).

Medieval crucibles used for melting lead glass are known from Gloucester, Lincoln and York, dating from the 10th and later centuries (Bayley 2000a; Bayley and Doonan 1999). Contemporary Stamford-ware bowls were used in York (Figure 28) but custom-made vessels were used in Lincoln and Gloucester.

After the 10th century, when plant ash glasses came to dominate, higher temperatures were needed to melt the glass. Medieval and post-medieval crucibles were made especially for the purpose, from clays that were known to be temperature resistant.

Figure 27 (above)
Saxon crucible fragments from Glastonbury Abbey, Somerset, used to melt pale blue-green natron glass; the rim fragment is *circa* 65mm wide.

Figure 28 (right)
A 10th- to 11th-century crucible from Coppergate, York, North Yorkshire, *circa* 150mm in diameter, containing traces of lead glass.

Examples from the 13th to the 16th centuries have sandy fabrics and are greyish in colour, becoming paler towards the surface. They often have glassy coatings on both the inner and outer surfaces, caused partly by the glass they contained but also caused by reactions with the corrosive furnace atmosphere. These crucibles tend to be bucket- or barrel-shaped and are *circa* 0.3–0.5m tall. Examples are known from Staffordshire (Crossley 1967; Welch 1997) and the Weald (Kenyon 1967) (Figure 29).

By the end of the 16th century, white-firing, chemically resistant clays were specifically sought for glass crucibles. Previously used crucibles were also ground up to make grog, which was added to the clay used for new ones (Paynter 2012). These grog particles can be seen in broken sections using a low-power microscope. Crucibles from coal-fired furnaces have a more matt brown to purple outer surface, different from the blue-green, glassy outer surfaces typical of crucibles from wood-fired furnaces.

By the 19th century most crucibles were made using refractory Stourbridge clay and were massive, standing 1.4m tall. Crucibles used to melt lead glass in coal-fired furnaces were made with lids or integral covers to prevent fumes from the fuel spoiling the glass (Figure 30).

Sometimes atypical crucibles are found that are smaller than most from the same site. These generally contain residues of brightly coloured glass (Kenyon 1967), which was required in smaller amounts. These pots, sometimes known as piling pots, were set on top of larger crucibles in the furnace.

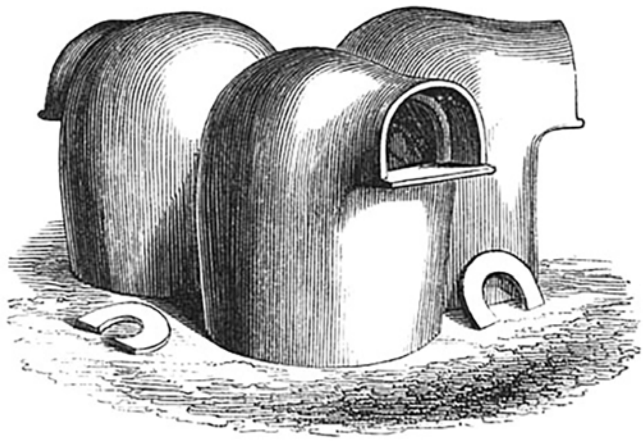


Figure 29 (top)
A large crucible fragment from an early 16th-century wood-fired furnace at Bagot's Park, Staffordshire.

Figure 30 (bottom)
19th-century closed crucibles, which were *circa* 1.4m tall.

4.5 Frit

Although fritting is known to have taken place (see section 2.2), frit is rarely found archaeologically: such a friable, partially reacted material is unlikely to survive (Paynter and Dungworth 2011). Crystalline, amorphous lumps of waste from glassworking sites are common but these are often lumps of chemically altered glass, which cannot therefore be recycled and so are discarded (see section 4.8). At Vauxhall glasshouse, London, however, some partially reacted glassy material survived (Tyler and Willmott 2005).

4.6 Cullet

Cullet dumps (see section 2.3), made up of glass for recycling, are one of the most useful resources for understanding a glassworks, as they can contain large amounts of diagnostic glass waste, including fragments of broken products. Cullet assemblages need to be interpreted with caution, however, as not all the glass was necessarily made at the site; in most periods glass for recycling was traded over large distances. Chemical analysis can help to establish the type of glass made at the site, by identifying a common glass composition among waste and finished items (Dungworth and Cromwell 2006).

4.7 Raw glass

In earlier periods, chunks and lumps of raw glass were imported and brought to glasshouses for melting, and these are sometimes found. They are of variable size but have fracture surfaces where they have been broken from larger masses when cold (Figure 31). Very rarely, large flows or blocks of glass that have cooled in the furnace or ash pit are found.

Figure 31
Fragments of raw Roman soda-lime-silica natron glass excavated at Basinghall Street, London; the width of the top fragment is 128mm.

4.8 Waste glass

Much of the glass recovered from glassworking sites is an assortment of lumps and trails (see Figure 2); very small, fine trails are often described as threads. There may be tool marks at one end. This glass waste is helpful in indicating that glassworking took place and can be useful for scientific analysis, to help establish the composition of glass being made at the site (Dungworth and Cromwell 2006). However, lumps and trails are not often diagnostic of the type of glassworking being undertaken.

Glass lumps, trails and threads are dropped around the furnace during glassworking (Figure 32). Experimental work (Taylor and Hill 2008) suggests that the highest concentrations are likely to be found near the gathering holes (see Figure 16).

While larger trails were recycled, smaller ones were trampled into the working surface. Tiny threads of glass are thus often present in floor layers and dumps at glassworking sites but, because of their size, are only recovered from processed soil samples (Dungworth and Cromwell 2006) (see case study 1).

Sometimes the glassworker would spot an inclusion in the gather of glass and hook it out with a tool, and so an inclusion can be seen at one end of some glass trails (Figure 33).

Occasionally wasters (products that have gone wrong) survive at glassworking sites, although these are generally fragmentary, distorted and discoloured by heat. Even though these wasters are not chemically changed, the appearance of the glass can be drastically altered. In particular, the transparent green, lime-rich (HLLA) glass typical of the post-medieval period sometimes becomes opaque and dichroic (Figure 34).

Glass that has fallen into the ash pit, fire trench or flue of a furnace also tends to have an altered appearance, either because of the temperatures and atmosphere it has been exposed to, or because it has been chemically changed by reacting with the fuel ashes and furnace gases or the materials used to construct the furnace or crucibles. This is sometimes apparent by the different colour or opacity of this glass relative to the majority of the assemblage and the presence of bubbles or crystals. Because of its strange appearance, this type of material is sometimes misidentified as specific types of production waste, such as frit (see sections 2.2 and 4.5).

Figure 32 (top)
Trails of glass from Belmont Row, Birmingham, West Midlands, excavated by North Pennines Archaeology; the longest pieces are *circa* 30mm. Waste from the production of colourless lead glass is often pale green because of contamination, and may contain tiny visible droplets of metallic lead.

Figure 33 (bottom)
Roman glassworking waste from London, formed when inclusions were removed from the glass; the length of the top fragment is 58mm.

The final appearance of the altered glass depends on its original type and what has happened to it. Altered HLLA glass often turns from transparent green to an opaque blue or cream colour, and is sometimes dichroic (Figure 35). Altered lead glass may turn from colourless to pale green and, although it generally remains transparent, small silvery droplets of metallic lead often form (Figure 32). Altered glass waste was not suitable for recycling as it would contaminate the batch. Altered glass is not suitable for analytical work where the aim is to establish the original composition of the glass.

4.9 Tools

As with other crafts, glassworking tools (Figure 36) are rarely found on archaeological sites. Valuable metal tools are unlikely to have been discarded and wooden tools would not survive. There are occasional examples, however, such as the post-medieval blowing iron found at Bagot's Park, Staffordshire (Crossley 1967).

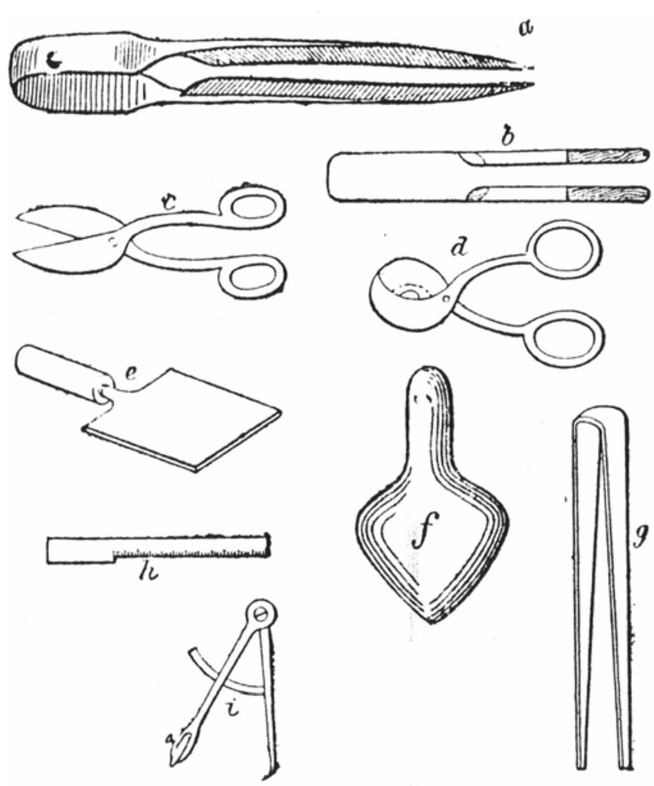


Figure 34 (top left)
Late 17th- to early 18th-century glass bottle waster from Lime Kiln Lane, Bristol, Somerset (7.5mm wide). Originally transparent green, this high-lime low-alkali (HLLA) glass has turned opaque cream/blue after prolonged heating and exhibits dichroism.

Figure 35 (left)
Opaque cream-blue waste from the 17th-century glassworks at Silkstone, South Yorkshire; each fragment is 10–15mm wide.

Figure 36 (top right)
19th-century glassworking tools.

5 Interpreting Finds

The basic principles of glassworking and some general forms of archaeological evidence have been described in sections 2 and 4. This section describes different methods of forming glass objects in more detail, with particular emphasis on the types of waste produced by each method and any characteristic evidence left on the glass object itself.

5.1 Beads, bangles and counters

5.1.1 Hot shaping

Simple objects like gaming counters could be formed by heating small blobs of glass, or sections from glass canes, on a flat surface until the top surface rounded naturally. The base could be finished by grinding. Rings and bangles were made with the aid of a central former, such as wooden or metal rod, which could be used to perforate, and then enlarge, a hole in a blob of glass. Alternatively, softened glass was wound around the former and the ends joined (Hawthorne and Smith 1979, 73–4).

5.1.2 Core forming

Core forming was an early method of shaping glass vessels and objects, eg for making beads in the Bronze Age and Iron Age. Softened glass was shaped around a core, eg of tempered clay, which was later broken-up and removed to leave the inside hollow.

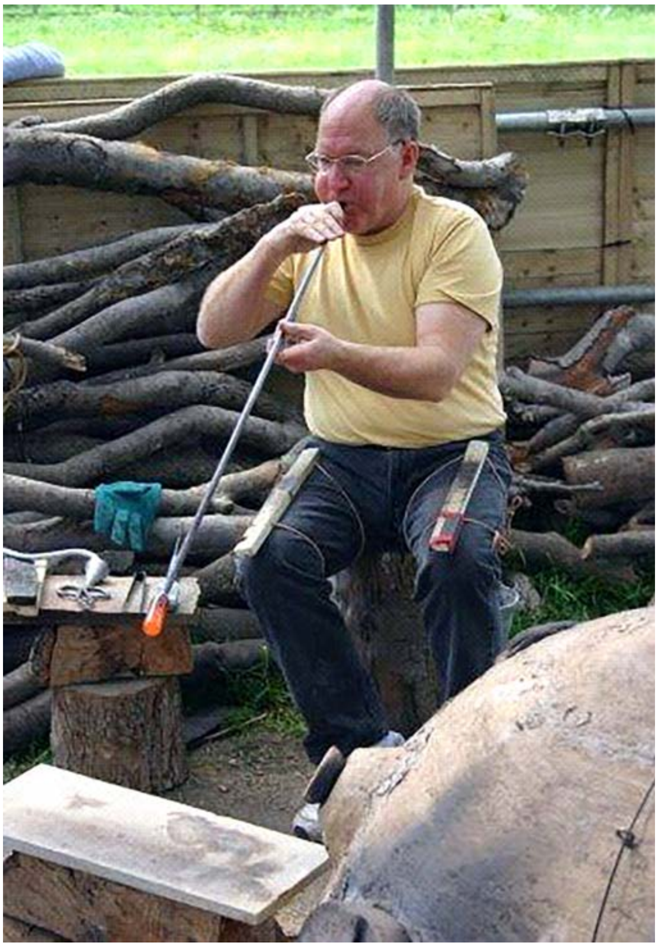


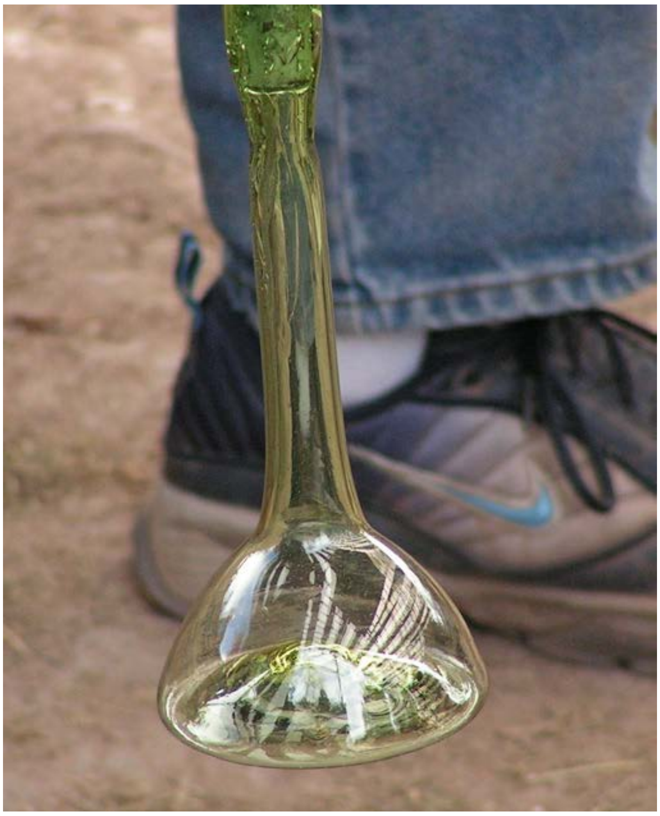
Figure 37
Glassworker William Gudenrath inflating a glass bubble, with the experimental furnace (made by Mark Taylor and David Hill) to the right and the marver in the foreground. The bubble has ribbed decoration that was obtained using an optic mould.

5.2 Vessels and bottles

5.2.1 Free blowing

The first evidence of glass blowing in Britain dates to the 1st century AD and the technique has been widely used since (Price and Cottam 1998; Shepherd and Wardle 2009).

A blob or gather of hot glass is collected on the end of a long metal pipe known as a blowing iron. The glassworker blows down the pipe to inflate a bubble in the glass (Figure 37). The bubble of glass, known as a paraison, is shaped further using tools (Figure 36) to constrict some



areas, or by blowing to expand others. While shaping an object, glassworkers often roll it over the flat surface of a stone block, known as a marver (Figure 37), or rotate it in a hollow wooden former.

When blowing certain types of vessel, like wineglasses, the glassworker needs to pinch the end of the gather to form the bottom of the wineglass bowl (Figure 38). This forms a small protrusion, known as the paraison end, which is cut off. These cut-off protrusions look like a marble with a pinch on one side.

The part of the vessel attached to the blowing iron becomes the neck or rim of the vessel, while the inflated glass bubble generally becomes the body of the vessel. It can be left with a rounded base, as on a flask or palm cup, or the base can be pushed in to make a more stable 'kicked' base (Figure 39) or a foot-ring.

The object remains attached to the blowing iron during the process, so that it can be repeatedly returned to the furnace and reheated. Glass can be added to the semi-formed object while it is still on the blowing iron, eg as decoration in the form of trails or prunts (cone-shaped protrusions of glass). Sometimes glass is applied to the vessel base to form a foot-ring or base-ring to make it more stable or for decoration.

The glassworker removes the blowing iron by weakening the glass at the point where it is attached to the iron, eg by filing a groove in the glass or by dropping a spot of cold water there. A sharp tap then breaks the object from the iron. The collar or cylinder of glass left on the blowing

Figure 38 (top)
A glassworker removing the paraison end: the rounded knob to the left of the pincers.

Figure 39 (middle)
A blown vessel, still attached to the blowing iron, with a kicked base, from the experiments by Mark Taylor and David Hill.

Figure 40 (bottom)
A Roman moil from London, showing a stepped profile, *circa* 13mm in diameter.

iron is generally known as a moil, although other terms such as knock off or rod end cullet are sometimes used. Moils are a useful indicator of glassblowing, and are ideally suited for analysis to determine the composition of the glass. Some of the Roman moils from London have small crizzled areas that indicate the use of water to weaken the glass there (Shepherd and Wardle 2009), and have a stepped profile on the opposite side (Figure 40).

Moils have different lengths and shapes, in part depending on the type of object being made. Distinctive lid moils indicate the production of particular vessel types, where the moil was cracked off when the vessel was cool and the rim cold-finished by grinding (Shepherd and Wardle 2009). Alternatively, the moil could be removed by dunking it into cold water. Surviving moils of this type are usually crazed, ie completely covered in a network of fine cracks as a result of being cooled quickly, and some may be fragmented beyond recognition. Sometimes moils have black flakes of iron oxide on the inside surface, which is scale that has detached from the blowing iron. Occasionally, longer moils were produced, eg if there was an impurity or bubble in the glass near the blowing iron, the glassblower could detach the vessel at a more distant point so that the blemish remained in the moil rather than the finished object (Figure 41).

If an object is going to need more hot working, then before it is removed from the blowing iron another iron, called the pontil iron or punty, is attached to the object at the base, using a small blob of glass to secure it (Figure 42).

Figure 41 (above)
A long moil from Basinghall, London, with black specks and streaks caused by iron scale from the blowing iron, *circa* 36mm tall.

Figure 42 (below)
Glassworker Mark Taylor detaching the neck-end of a vessel from a blowing iron. The vessel is supported by the pontil iron attached to the base. The furnace is at the rear and the marver to the right.

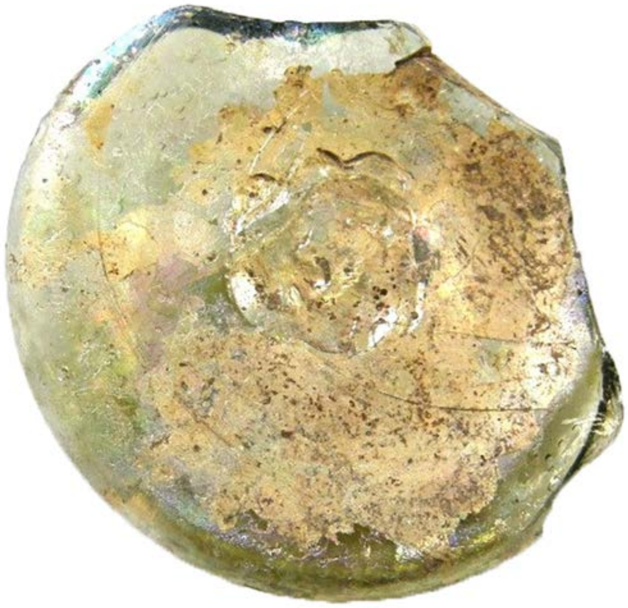


Figure 43 (left)
Formation of wavy ribbons in a mid-18th-century illustration of goblet production by Diderot.

Figure 44 (top right)
Reproduction wavy ribbons of glass; the longest is 130mm.

Figure 45 (bottom right)
The base of small post-medieval jug from Shinrone, Ireland, made of green high-lime low-alkali (HLLA) glass with a pontil scar in the centre and iridescent weathering of the surface (45mm diameter).

Once attached to the pontil, glass can be trimmed from the rim of the vessel using shears, eg to level the edge of a wineglass bowl. These strips of glass have a wavy appearance (Figures 43 and 44).

An object is reheated by re-inserting it into the furnace through a gathering hole, so that the rim softens and can be shaped further (see Figure 1); reheated rims become smooth and 'fire rounded'. Other types of rim are made by folding; spouts can be shaped and handles attached to the rim.

Handles are applied last, to an otherwise completed vessel (see Figure 12), usually while it is on a pontil. When working is finished, the pontil is detached, leaving a diagnostic round scar on the base (Figure 45), although on post-medieval finewares such scars were removed by grinding.

5.2.2 Mould blowing

Vessels and objects can be blown into a reusable mould, transferring the shape and decoration of the mould to the glass paraison when it is inflated within it. Moulds are known from the Roman period, usually made from clay but sometimes from stone, wood or metal (Foy and Nenna 2001; Price 1991). Multi-piece moulds are used for vessel forms that cannot be removed intact from a single-piece mould: the former results in objects with seam lines where the mould pieces joined. The vessel can then be finished in a similar way to free-blown vessels. Mould blowing was used to create decorative fins on medieval goblets (Tyson 2000) and to make decorative stems for goblets (Willmott 2002).

In later periods, more complex and robust moulds were developed, made from iron or copper alloys and hinged. Initially, the moulds were for shaping the base of post-medieval bottles, but in the 19th century glassmakers developed a series of multi-piece moulds, used for mass production, that shaped the complete bottle. The most famous of these was the cast-iron three-part mould patented by Ricketts in 1821, which enabled the production of the body and neck of a bottle, as well as moulded decoration, from one mould. However, the glass was still inflated by a glassworker blowing down a blowing iron; the mechanised production of bottles, using compressed air, did not become widely adopted until the 20th century.

5.2.3 Optic blowing

A gather of glass can be partially inflated in a mould to transfer a pattern onto the gather. Stone moulds are known but other materials, such as metal, would also be suitable (see Figures 10 and 37). The vessel is completed by free blowing, so that the final pattern has a flowing distorted appearance. This technique was used in the Roman period and to produce fluting (vertical ribs) and other designs on early medieval and post-medieval vessels (Evison 2008; Tyson 2000; Willmott 2002).

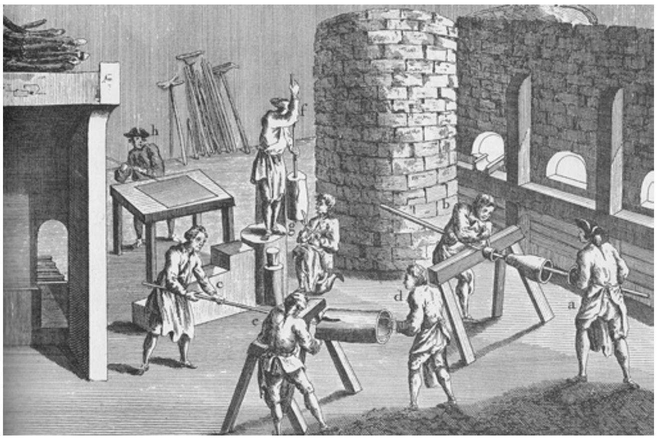
5.2.4 Casting or slumping

Experimental work by Mark Taylor and David Hill has shown that forms such as Roman cast bowls may have been made by slumping the glass over a convex mould. A gather of glass is pressed on a flat surface to form a disc, which is then placed over a hemispherical mould and reheated so that it sags into shape. Thin slices from preformed multi-coloured, patterned glass canes can also be fused together to form the initial disc, but with an elaborate pattern in the style known as millefiori (a thousand flowers).

5.2.5 Pressing glass

Pressed glass is manufactured by placing an appropriate-sized lump of molten glass in a hinged cast iron mould (Cable 2008; Pellatt 1849). This process has been used to produce a wide range of simple vessel forms, which can nevertheless have complex decoration, and objects such as cathode ray tubes (Figure 46). Pressing was introduced in the early 19th century and was used to produce vessels in imitation of cut glass.

Figure 46
Removing the glass cone for a cathode ray tube from a hand press, comprising a plunger and mould, at Osram glassworks, Newcastle upon Tyne, Tyneside, in the mid-20th century.



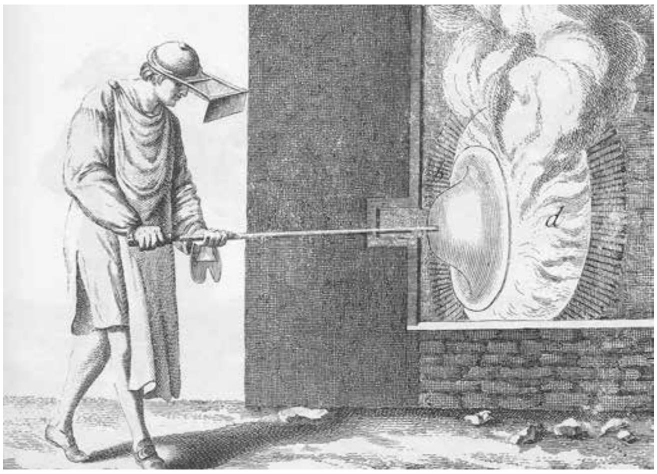


Figure 47 (top)
Broad glass production shown in a mid-18th-century illustration by Diderot.

Figure 48 (bottom)
Spinning a crown of glass in a mid-18th-century illustration by Diderot.

5.3 Windows and flat glass

5.3.1 Broad and cylinder glass

Broad glass (also known as muff glass) was made by blowing a bubble of glass, elongating this into a cylinder shape, removing both ends and then cutting the cylinder along its length while it was hot (Figure 47). The cut cylinder of glass was then flattened on a stone or metal surface to produce a rectangle or square of glass. This took place while the glass was hot, so the bottom surface tends to be slightly rough, although this could be improved by grinding and polishing (see section 5.4.3). Broad glass windows were made from the 3rd century.

Cylinder glass was made in Britain from the 19th century using a variation of the broad glass method. Longer cylinders, and therefore larger sheets, of glass were made by swinging the cylinder during blowing so that it further elongated under its own weight, eg by standing on steps or alongside a swing pit. At Pilkington's 19th-century glassworks, Merseyside, there were swing pits *circa* 2.5m deep at the working end of the furnace. The cylinder was allowed to cool before being scored or cut and then was reheated in order to open it out; cylinder glass retained a better finish on the bottom surface than broad glass because of this process.

5.3.2 Crown glass

Crown glass was produced by blowing a spherical bubble of glass, transferring this to a pontil and then spinning it until the centrifugal forces caused the glass to flare out and expand into a large disc (Figure 48).

Crown glass did not need flattening and so tended to have a superior surface finish compared with broad glass. Crown glass could also be produced thinner than broad glass, which helped improve its transparency. However, crown glass had two draw backs: the central portion where the pontil was attached, the bull's eye, was thick and so discarded, and the general shape of crown glass meant only small panes of glass, known as quarries, could be cut from the disc. Like broad glass, crown glass had subtle imperfections, such as a slight curve or wave, which tended to distort the view through the finished glass.

There is unlikely to be much evidence at a glassworks to indicate crown glass production, as the crowns were cut to size by a glazier at the point of use. However, the remains of broken crowns have been reported from some sites. These might be identified by bull's eyes and disc rims (Figure 49). The size of the glass discs increased over time, from medieval examples of *circa* 0.7m diameter up to 1.4m by the mid-19th century. The edge may be slightly thickened, and there may be discernible concentric markings or bubbles on the glass (Crossley 1990).

5.3.3 Cast glass

Some Roman window glass was made by pouring molten glass onto a surface and then using tools to manipulate it into an approximate square. The resulting pane often has an irregular thickness, with a rough, matt under side and a smooth upper side (see section 7.3.3). Casting was again used for window glass from the 18th century, for making cast plate.

5.3.4 Plate glass

Plate glass usually refers to large panes of flat glass with a good-quality polished surface. Blown plate glass was produced from the early 17th century, and was made by making thicker than normal broad glass and then polishing it. It was expensive and used rarely.

Cast plate glass was made in Britain from the later 18th century. Molten glass was ladled from the furnace onto an iron casting table and then rolled into large flat sheets, which were subsequently ground and polished in a number of stages on both sides (see section 5.4.3) (Krupa and Heawood 2002) (Figure 50). The initial sheet of glass was made considerably thicker than usual to allow for losses during the grinding process (Louw 1991).

In the late 1830s an improved polishing technique was developed, in which large thin sheets of glass made by the cylinder process could be polished without breaking by supporting them on a thick bed of wet leather. The product, called patent plate, was much cheaper to produce than cast plate.

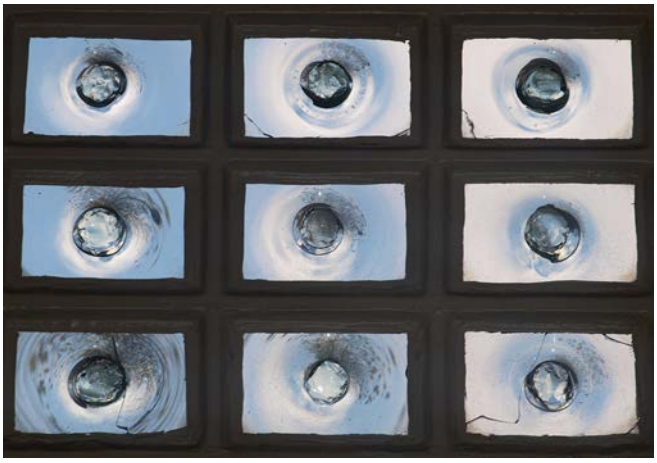
5.3.5 Mechanised drawing

In early 20th century glassmakers developed a mechanised method of drawing glass, which became commonplace from the 1930s (Cable 2004; Krupa and Heawood 2002; McGrath and Frost 1937).

5.4 Decoration

5.4.1 Applied glass decoration

Additional glass, often in different colours, could be applied as decoration. Hot glass was trailed onto the surface of vessels (Figure 51) or used to make prunts. Beads and other objects were also decorated in this way.



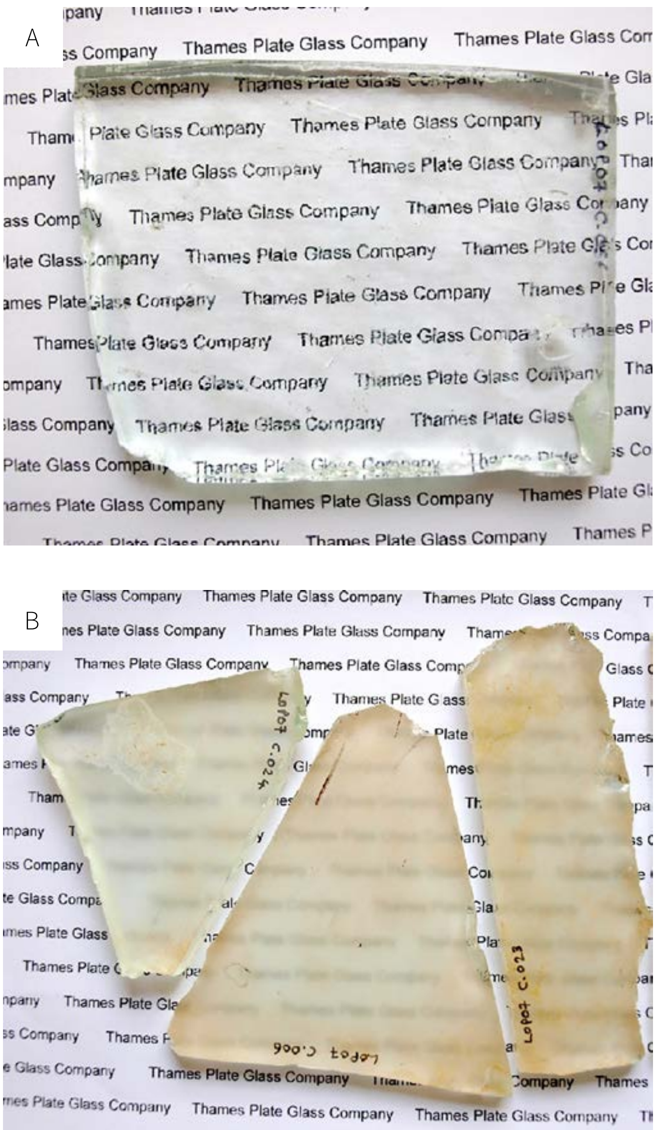


Figure 49 (top)
Bull's eyes used decoratively in glazing.

Figure 50 (bottom)
Transparent, finished cast plate glass (A) compared with partially ground cast glass (B), which appears matt, from excavations at the site of the Thames Plate Glass Company, London.

Figure 51 (top)
Applying hot glass from a gathering iron to a vessel surface, forming a decorative trail, from the experiments by Mark Taylor and David Hill.

Figure 52 (bottom)
Fragment of a colourless Roman glass tray or plate from Binchester, County Durham, with cut facets, *circa* 80mm wide.

A glass gather could be rolled in blobs or chips of glass, frequently of different colours, which were then often marvered into the surface (see section 5.2.1). Preformed canes or rods of glass in contrasting colours could be applied to the glass surface to make a design. These canes were sometimes patterned, made from different colours of glass twisted together or from a rod with contrasting colours trailed on it (*reticella*) (see case study 1, Figure CS1.2) (Willmott 2002).

Thin trails of glass or patterned rods have been found at glassworking sites (Bayley 2000b; Jennings 2005). These finds are often very small, however, so are frequently only recovered during processing of environmental samples. Rods may be distorted at one end, with a straight-edged impression from where the glass was gripped with pincers.

5.4.2 Impressed decoration

Various techniques were used to impress patterns onto glass. Stamps were sometimes applied to blobs or prunts of glass while it was hot, eg on jug handles. Tools, such as rasps, files, toothed wheels or pincers, were used to impress patterns into applied trails or rings of glass on medieval vessels (Tyson 2000).

5.4.3 Polishing and grinding

Many glass objects were finished by some form of polishing and grinding, eg to remove tool marks or to finish the surfaces of moulded or cast objects. Evidence of this is sometimes visible on objects and is mentioned in some documentary sources, but is difficult to identify in an archaeological context. Fine, hard materials, such as sand, ground glass, emery or pumice, were used as abrasives. Iron oxide powder was used to obtain a polish in the 19th century.

The term plate glass usually refers to polished flat glass, which was used when larger panes with a good surface finish were required, eg mirrors, coach windows and, later, lighthouse windows and shop fronts (see section 5.3.4). This polishing was initially done by hand, but steam power was used increasingly from the 19th century.

5.4.4 Cutting and engraving

Wheel engraving made use of a rotating wheel, made of stone, copper, wood or iron, with an applied abrasive, such as pumice, emery, corundum or diamond, to engrave the glass. Different wheel profiles were used to create different effects, eg flat, curved or v-shaped cuts. Wheel-cut glass was decorated by patterns of linear cuts or abrasions or with deeper circular or oval facet cuts (Figure 52). Wheel-cutting was also used for intaglio engraving, in which a design was cut into the glass, for relief engraving, in which heavy cutting resulted in a design that protruded from the surface, and for cameo glass, in which the design was in relief in a contrasting glass colour to the base glass. Heavier wheels, such as stone, and coarser abrasives were used for cut glass, particularly the initial rough cutting (Dreiser and Matcham 2006).

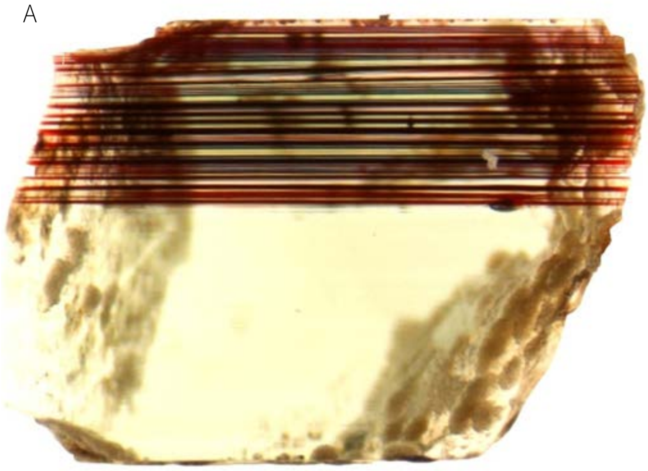
In the Roman period wheel cutting was common and sometimes elaborate, although relief, intaglio and cameo designs were rare. Cut decoration was again popular during the 18th century. Initially wheel-cutting was used for inscriptions, scenes and portraits, in a similar way to point engraving. Geometric patterns became popular in the later 18th and early 19th centuries, but heavily cut glass declined in popularity from the mid-19th century, coinciding with the increased production of pressed glass (see section 5.2.5).

Point engraving used a tool with a fine hard tip, such as a diamond, flint or steel, to make linear or stippled designs, the latter producing a shaded effect using dots. Linear engraving was known, although rare, in the Roman period but became popular on high-quality colourless English glass from the late 16th century to the early 18th century (Charleston 1984). Stippled glass engraving was developed in the 18th century.

5.4.5 Painting, staining, flashing and enamelling

The best-known application of painted, stained and flashed glass is for decorative windows, from the medieval period onwards. The study of stained glass is a large subject area, only briefly described here, but further information can be obtained from some of the organisations listed in section 10.

A



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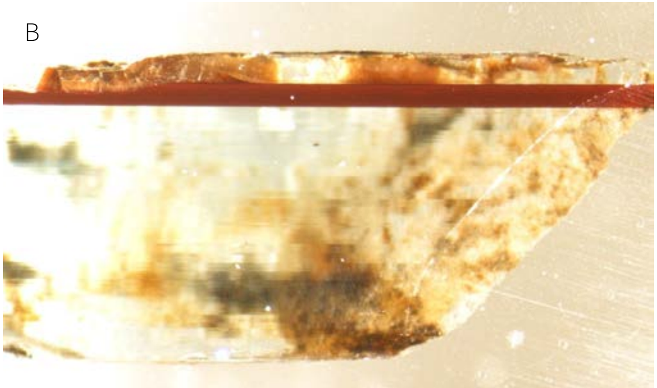

Figure 53
Sections through two types of medieval red flashed glass from York Minster, York, North Yorkshire. Chapter House (A); Great East Window (B); in each case magnified *circa* 10×, with the colourless base window glass at the bottom.

The production of medieval stained-glass panels began with a full size drawing of the design. This template guided the selection, cutting and decoration of differently coloured pieces of glass. Pigment was painted on to the glass to create dark lines. Silver stains were used to produce different shades of yellow (see Figure 17). The glass pieces were then heated to fuse the pigment in place and develop the colour of the stain. Red glass had an intense colour, so a sheet of red glass would be too dark. To obtain a less intense shade, a thin layer of red glass was flashed onto a sheet of colourless glass (Figure 53). Further decorative effects could be created by selectively abrading or etching away the coloured glass, revealing colourless glass beneath, which was most commonly done in the 19th century.

Examples of enamelled glass vessels are known from the Roman, medieval and post-medieval periods, although these tend to be rare.

6 Materials Mistaken for Glassworking Waste

6.1 Metalworking waste

Ashes from charcoal fuel used in metal-working react with any siliceous material to make an accidental glass, as happens on glass furnaces and crucibles. Glassy layers are often found on metalworking crucibles (Figure 54), and these can be particularly misleading as traces of the metal often give the glassy layer a striking colour, eg the presence of copper oxide produces red or blue-green (Bayley *et al* 2001).

Lead-fluxed glasses were formed as by-products of processes such as silver refining or lead smelting (Figure 55). These by-products could be discarded or recycled but in some instances the glass was used, eg waste slag from silver refining was used for red enamel in the Iron Age (Bimson and Freestone 2000) and waste slag from lead smelting was used to make early medieval linen smoothers (Gratuze *et al* 2003).

Figure 54 (top)
A Roman metalworking crucible from Dorchester, Dorset; 120mm high. The glassy material is more likely to be concentrated on the rims and outer surfaces of a metalworking crucible. Crucibles used for metal melting are always reduction-fired.

Figure 55 (bottom)
A Roman crucible containing red glassy silver-refining waste from Chichester, West Sussex; 30mm wide.

Figure 56
Blast furnace slag.

Blast-furnace slag is also easily mistaken for intentionally made glass. In terms of its composition, it is very similar to post-medieval lime-rich (HLLA) glass, so has a similar range of blue-green colours and density but is opaque (Figure 56). Blast-furnace slag can also exhibit the unusual creamy opacity and dichroism seen in post-medieval glass (see section 4.8). In addition, blast-furnace slag tends to be richer in iron than deliberately made glass and sometimes contains small metallic droplets. It is often more bubbly than typical glass waste and is most likely to be found as large angular chunks (Bayley *et al* 2001).

6.2 Other high temperature processes

Glassy materials are common accidental by-products of many high-temperature processes. Accidentally produced glass can be misinterpreted as evidence of intentional glass production or glassworking. Some types of plant, when burned, produce ashes with just the right proportions of silica and alkali fluxes to make a glass. The ashes of wood or charcoal fuel can react with the silica in clay to produce a glass. This often happens with clay that is part of a ground surface, structure or ceramic. The resulting glassy material is blue, green or grey, bubbly and lightweight. It is sometimes called fuel ash slag. Fuel ash 'glazes' can also be found on stones or ceramic lumps, and these can be misidentified as debris from glassworking (see Figure 11).

6.3 Plastic

Drops of molten plastic or thin plastic fragments can appear superficially similar to glass, having a range of colours, variable transparency and a smooth surface. However, plastic is less dense than glass and is often pliable or easily dented with a fingernail. It also melts in contact with something hot, like a heated needle.

6.4 Geological materials

Many naturally occurring materials have colours, transparency, density and lustre reminiscent of glass but scientific analysis can distinguish between them. Obsidian is a black volcanic glass formed naturally, although none occurs in Britain, when lava cools rapidly. Crystalline gemstones tend to break along cleavage planes and so may have a distinctive faceted shape or exhibit a pattern of cracks. Glass tends to produce a flowing, curved break (called a conchoidal fracture) but was often cut to resemble a gemstone.

7 Chronological Overview

7.1 Bronze Age (2500 BC–700 BC)

As yet, there is no archaeological evidence for the primary production of glass during the Bronze Age in Britain, and indications of Bronze Age glass production in Europe are extremely rare. In western Europe, glass artefacts have been identified from sites in Britain, Ireland, Switzerland, Italy and Germany (Angelini *et al* 2004; Hartmann *et al* 1997), dating from as early as the 13th century BC. The glass is generally transparent blue or turquoise, although rare objects of colourless glass are known, and it was probably made using plant ashes. In Britain, glass was used only for simply formed objects such as beads.

Figure 57
Large (*circa* 45mm diameter) late Iron Age beads from Stanway, near Colchester, Essex. The dark blue glass is cobalt-coloured and decoration in different colours has been marvered into the surface.

7.2 Iron Age (700 BC–43 BC)

As yet, there is no archaeological evidence for the primary production of glass (see section 2) during the Iron Age in Britain. Iron Age glass found in Britain was probably imported from the Roman world; it is the same type (soda-lime-silica natron glass) and contains many of the same colourants, opacifiers or decolourisers as glass found at continental Roman sites. Ultimately a wide range of colours came to be used; very dark blue glass was common.

However, there is some archaeological evidence in Britain for secondary production of glass, shaping and colouring, from this period. Finds from probable glassworking sites, such as Meare Lake Village in Somerset (Henderson 1987), consist of lumps of raw glass, misshapen glass objects and concentrations of scrap glass and glass artefacts. Although hearths are sometimes found, it is difficult to prove their association with glassworking. Some of the yellow, or more rarely white, glass from about the 2nd century BC contains colourants (tin-based) different from typical Roman glass (Tite *et al* 2008).

Glass artefacts from Iron Age Britain include beads (Figure 57), and the decoration on glass artefacts tends to be more elaborate on examples from the later Iron Age, eg with blobs or cords of glass in contrasting colours marvered into the surface. In the late Iron Age there are also some vessels, gaming counters, brooch settings and enamels.

7.3 Roman (AD 43–410)

There is no conclusive archaeological evidence for the primary production of glass in Roman Britain. Glass was probably imported from a small number of large-scale production centres elsewhere in the Roman world (Freestone 2006; Jackson *et al* 2016); it is all of the same general type (soda-lime-silica natron glass) and contains many of the same colourants and decolourisers.

Archaeological evidence for secondary glassworking, ie making glass objects, is hard to identify but there is nonetheless a significant body of evidence from London (Shepherd and Wardle 2009) and a number of other urban and military settlements (Allen 1998; Price 2002). The commonest finds are collections of cullet and working waste, including moils from blowing, plus vessel and window fragments. Crucibles have occasionally been found, more commonly attributed to the later Roman periods (Cool *et al* 1999). In Roman Britain, glass was used for many more applications than before.

7.3.1 Jewellery, ornaments, counters and tesserae

Glass featured often in jewellery, as beads, bangles and brooch settings, and also as enamel on brooches. In Britain, glass tesserae were only used very occasionally for mosaics, and so those found may have been traded as a source of coloured glass for other applications, such as enamelling (Bayley 2005). Glass counters were made for board games. Strongly coloured opaque glass was used for many of these applications, and may have been traded large distances in the form of cakes and strips of glass or prepared tesserae (Figure 58).

7.3.2 Vessels

In the Roman period blown vessels (free blown and mould blown) are found in large quantities for the first time in Britain. Much of this was tableware, as well as items for transportation or storage, such as bottles and jars (Price and Cottam 1998).

Colourless or weakly tinted glass was very popular and used mainly for tableware. Pale blue-green naturally coloured glass was most commonly used for vessels in the 1st to 3rd centuries AD, including tableware, bottles and household containers. Strongly coloured glass was only used for certain types of vessel, such as mosaic bowls, particularly in the 1st and 2nd centuries, and there is no evidence for the production of such vessels in Britain.

From the 4th to the 5th centuries AD, an olive-green glass with more noticeable flaws dominates Roman glass assemblages, known as high iron, manganese and titanium (HIMT) glass (see case study 3).

Figure 58
Fragments of Roman glass: a rounded blue cake of raw glass and a tessera (10mm cubed), chipped from a cake, from West Clacton, Essex (excavated by CAT).

Figure 59
Partially melted Roman window glass intended for recycling, from a glassworking site in London; width 94mm, each fragment on average 4mm thick.

Various decorative techniques were also used, including pinched ribs and applied decoration, sometimes in strong colours. Wares were also cut or engraved with bands, facets, scenes or inscriptions.

7.3.3 Windows

Roman window glass is typically *circa* 3mm thick and between 0.3 and 0.4m square, although larger panes are known. It was generally made by casting, resulting in one matt and one glossy surface. The broad glass method was used from the 3rd century onwards (Figure 59) (see section 5.3.1) and a small number of small (0.2m diameter) circular panes has been recorded in Britain.

7.4 Early medieval (AD 410–1066)

There is no good evidence of primary glass production in Britain from this period. Until the 9th to 10th centuries, most of the glass used was the natron type, broadly similar to earlier Roman glass (soda-lime-silica natron glass). Recent research suggests that glass continued to be imported from established sources for some time after the end of the Roman occupation. Subsequently, perhaps when these trade routes were interrupted, there was considerable recycling of earlier glass; in some cases the glass may have been diluted with other glassy materials (Henderson 1993; Paynter and Jackson 2016).

However, there is evidence for secondary glassworking in post-Roman Britain. Crucibles of probable 6th-century date were found at Buckden, Cambridgeshire, containing opaque yellow and white glass (Bayley 2000a). Unusual quantities of glassworking waste were found at Glastonbury Abbey, Somerset, including the remains of furnaces used for glassworking, but not glass manufacture, probably dating from the 7th to 8th centuries, and evidence for the production of trail-decorated, blown vessels (Bayley 2000b). Furnace remains were discovered at Barking Abbey, Essex (Wilmott and Welham 2015), whereas fragments of glass, small glass blobs and *reticella* rods have been found at Whitby Abbey (Jennings 2005) and St Gregory's Minster, both in North Yorkshire (Heyworth 1992; MacGowan 1996).

Figure 60 (top)
Emerald green and amber 10th- to 11th-century lead glass beads from York, North Yorkshire; *circa* 10mm in diameter.

Figure 61 (bottom)
Early medieval linen smoothers from Coppergate, York, North Yorkshire: top right, weathered potash forest glass smoothers; bottom left, lead slag smoothers.

7.4.1 Jewellery and linen smoothers

Glass was used to make beads, often brightly coloured and opaque (Brugmann 2004; Guido 1999; Hirst 2000). Some were tooled, eg melon beads. Glass was also used as an inlay on fine metalwork (Bimson and Freestone 2000).

Evidence for the working of high-lead glass, including crucibles, lumps of cullet and objects, has been found from the 10th century onwards (see section 1.1), but little evidence of manufacture of this glass from raw materials has yet been identified in Britain. This type of lead glass was used to make rings and beads and is generally translucent amber or green to black, coloured by copper and iron, respectively (Figure 60).

Linen smoothers, or slick stones, were used for finishing cloth. A few early examples were made from a black, lead-rich glass, now known to be waste slag from lead smelting (Gratuze *et al* 2003), which was probably imported. Most linen smoothers dating from the 10th century and later were made from dark green or brown potash glass (Figure 61); this type of forest glass became the norm in later centuries (eg Henderson 1993).

7.4.2 Vessels

Vessels were mainly cups and beakers, such as claw and cone beakers and, later, globular beakers and palm cups. Glass in green and blue shades dominated, although some nearly colourless glass was used earlier in this period and a larger proportion of slightly later vessels were in strong hues of blue or green to black (Evison 2008). Vessels were decorated using prunts and trails or blobs of applied glass that were pulled downwards to make the characteristic decoration seen on claw beakers. Ribbed vessels were made using mould blowing, mainly earlier in this period. By the end of the early medieval period lighter tints again predominated (Hunter and Heyworth 1999).

7.4.3 Windows

Small amounts of window glass are found from the end of the 7th century (Cramp 2000), with increased use in the 9th to 10th centuries in churches and cathedrals. There are documentary sources (Harden 1961) that describe workmen being brought from Gaul to glaze monastery buildings.

7.5 Medieval (AD 1060–1485)

There is virtually no evidence for the manufacture of glass in Britain in the 11th and 12th centuries, although greenish potash window glass has been excavated, eg in York. There are also historical records for the Wealden glass industry from the 13th to 17th centuries (Godfrey 1975; Kenyon 1967) and for the Staffordshire industry from the early 14th to the 17th centuries. At this time, the glass was both made and shaped using the same furnace, and the glass was made from the ashes of plants such as bracken (Dungworth and Clark 2004; Jackson *et al* 2005) together with sand.

In the Weald, 48 archaeological sites have been identified (Crossley 1994), two of which have been thoroughly investigated: mid-14th-century Blunden's Wood, Surrey, and mid-16th-century Knightons, Surrey (Wood 1965, 1982). In Staffordshire, glass was produced around Bagot's Park near Abbots Bromley (Crossley 1967, Welch and Linford 2005) and at Wolseley on the edge of Cannock Chase (Welch 1997), from the early 14th to the early 17th centuries (see Figure 15), and near Eccleshall from the late 16th century. The furnaces used, and glass produced, were similar to those of the Wealden industry. Other glasshouses are likely to have existed, although physical evidence is elusive. Brief documentary references include a glasshouse in Inglewood Forest, Cumbria, and imply glassmaking in Colchester, Essex, and at Salisbury Cathedral, Wiltshire (Tyson 2000, 8).

7.5.1 Vessels

The extent of medieval vessel manufacture in Britain is unclear. Excavations have revealed a few fragments of green potash glass vessels such as flasks, hanging lamps and urinals at the same glasshouses that made window glass. These were generally undecorated, although some flasks had optic-blown ribbing. It is possible that slightly more decorative flasks or jugs, and beakers, were made on these sites. Documentary references imply that distilling vessels were also made at English furnaces. More decorative glass tablewares were used on high-status sites in Britain in this period, but they were imported mainly from Europe, and even included a few vessels from the Islamic eastern Mediterranean (Tyson 2000). Imported vessels were made in potash glass from Europe, soda glass from Europe and the eastern Mediterranean, with a smaller number of yellow, bright green and opaque red high-lead glass tablewares produced in the 13th and early 14th centuries in Germany.

7.5.2 Windows

The major products of both the Wealden and Staffordshire industries were plain colourless ('white') window glass. Documentary sources list specific orders, eg from the Weald for the royal chapels of St Stephen's, Westminster, and St George's. Winsor. Excavated fragments show that window glass was made using either the crown or broad glass methods.

7.6 Post-medieval (AD 1485–present)

There were dramatic changes to the English glass industry in the late 16th century following the arrival of glassmakers from continental Europe (Godfrey 1975). One of these glassmakers, Jean Carré, obtained monopoly rights to glass production in England and Ireland in 1567. He established a glasshouse in London for colourless soda-lime-silica plant ash crystal glass and a number of other glasshouses in the Weald (Kenyon 1967), making greenish lime-rich (HLLA) glass from the ashes of hard-wood species like oak or beech. Other immigrant glassworkers followed, establishing glasshouses elsewhere, including Wiltshire, Gloucestershire (Vince 1977), Herefordshire (Bridgewater 1963), Shropshire (Pape 1934) and Yorkshire (Crossley and Aberg 1972). The traditional potash glass of previous centuries was abandoned (Dungworth and Clark 2004).

Initially, the furnaces in this period were similar to earlier ones (see section 4.1 for details). When wood fuel was banned for glassworking in England in the early 17th century, the last of the Wealden glasshouses closed down by 1619. Instead glasshouses were established in areas with easy access to coal, in particular Newcastle, Tyne and Wear (Godfrey 1975), Stourbridge, West Midlands (Guttery 1956), Bristol (Witt *et al* 1984) and Yorkshire (Ashurst 1992; Crossley 2003). Glass furnace design also changed slightly to allow coal firing (see Figure 13).

In the late 17th to early 18th centuries, cone-shaped cover buildings were developed (see Figures 20 and 21, and section 4.1), and in the mid-19th century regenerative furnaces were developed, which used gas but the glass was still held in pots. Continuous tank furnaces were used in Britain from the 1870s.

7.6.1 Fine vessels

Early post-medieval vessel glass is described by Willmott (2002). Fine drinking glasses were made from virtually colourless glass. Examples include the renowned cristallo (crystal glass), imported from Venice, which was made using the purified ashes from specially selected plants. Colourless alkali glass in the Venetian style (crystal or façon de Venise) was also produced by immigrant Italian glassmakers based in London (Godfrey 1975, 17). Similar glass continued to be made throughout the 17th century, even after the development of colourless lead glass in the 1670s, which was also used for fine vessels (Charleston 1984, 97).

The production of colourless lead glass was famously patented by George Ravenscroft (Dungworth and Brain 2009). Lead glass was initially made using flint as a source of low-impurity silica. Lead glass, also known as lead crystal or flint glass, even when white sand was used instead, was quickly adopted by other English glassmakers (Dungworth and Cromwell 2006) and helped establish Britain as a leading glass-manufacturing nation. The import of Venetian and Venetian style vessels virtually ceased (Crossley 2003).

7.6.2 Bottles

The earliest post-medieval bottles were made from greenish HLLA glass and were generally small and thin-walled. From the mid-17th century the dark-green, thick-walled ‘English bottle’ made its appearance. Bottlemakers were unconcerned about impurities in their raw materials as they did not want a colourless glass. Excise rules introduced in 1745 only allowed them to use the cheapest ingredients, but these restrictions were removed in 1845 and some bottles were then made in colourless soda-lime-silica glass (Wills 1974, 52).

The earliest post-medieval bottles were free-blown (Van den Bossche 2001). Mould-blown cylindrical bottles became increasingly popular from the mid-17th century. Piece moulds, which enabled letters and designs to be embossed on the exterior of the bottle, were developed in the 19th century (Wills 1974). At the beginning of the 20th century fully automatic bottle-making Windsor machines could both gather the glass and blow it in to suitable moulds (Cable 2002). Soda-lime-silica glass performed better in these machines, so HLLA glass was finally abandoned (see section 5.2.2).

Figure 62
The characteristic colours of post-medieval window glass, from green (high-lime low-alkali; HLLA), to pale blue (kelp) to colourless (synthetic soda).

7.6.3 Windows

Various types of glass of differing appearance were used to make window glass (Figure 62) (for details see case study 2).

From 1745, taxation based on the weight of glass rather than the window area favoured crown glass, which was thinner, so broad glass production went into decline in Britain until the mid-19th century, and crown glass dominated.

However, broad glass was used for some applications, eg for coach windows and mirrors, where large panes of flat glass with an excellent surface finish were required. These expensive sheets of glass were made thicker than usual and then polished (blown plate) (see section 5.3.1) (Louw 1991). From the later 18th century larger panes were made in Britain by polishing cast sheets of glass (cast plate); in the previous century it was imported from France (see sections 5.3.4 and 5.4.3). In the 1830s, patent plate was developed, in which thinly blown cylinder glass could be polished. Cylinder window glass grew in popularity in the 19th century. From the early 20th century, sheet glass was drawn from continuous tank furnaces (Krupa and Heawood 2002) (see section 5.3.5).

7.6.4 Specialised glass

In the 19th and 20th centuries, the market for specialised glass became increasingly important to glassmakers in Britain. In the 19th century, lenses for lighthouses and observatory telescopes were developed with technical expertise obtained from French glassworkers. New types of glass with particular properties were formulated, such as borosilicate glass, which had increased durability, and resistance to chemicals and heat, and glass that would protect against ultraviolet (UV) radiation. Glass was used for syringes, microscope slides, camera lenses, tubing and reagent bottles. In the 20th century, glass began to be used in cathode ray tubes, initially for radar systems (see Figure 46).

8 Summary table

	Bronze Age 2500 BC–700 BC	Iron Age 700 BC–AD 43	Roman AD 43–AD 410
Glass type	Mixed-alkali or soda-lime-silica plant ash glass	Soda-lime-silica natron glass	1 Mainly soda-lime-silica natron glass 2 Plant ash component in some strongly coloured glass (red and green)
Raw materials	Alkali-rich ashes of halophytic plants and sand	Natron and sand	Sand with: 1 Natron 2 Rarely, with plant ashes
Glass manufacture (primary production)	Unknown, possibly imported	Unknown, probably imported	No conclusive evidence of manufacture yet known from Britain 1 Natron glass probably imported 2 Made in large tank furnaces at a small number of sites and transported as chunks of raw glass 3 Coloured glass traded in form of cakes, strips or tesserae
Glass shaping (secondary production)	No evidence of glassworking in Britain	Rare evidence in Britain. Includes malformed beads, chunks of glass, scrap glass and moulds	Substantial evidence of glassworking in Britain, including moils (from glassblowing), scraps of vessels, glass fragments, trails and dribbles Furnace remains rare: small tank furnaces and pot furnaces *circa* 1m diameter Crucibles often contemporary pottery types, *circa* 100mm diameter

Early medieval AD 410–AD 1066	Medieval AD 1066 –AD 1485	Post-medieval AD 1485–present
1 Soda-lime-silica natron glass Rarely, from the 10th century: **2** Potash-rich plant ash glass (forest glass) **3** Lead glass **4** Black lead slag	**1** Mainly potash-rich plant ash glass (forest glass) **2** Some soda-lime-silica (mostly natron glass, rarely plant ash glass) **3** Rarely, lead glass	As medieval, then from late 16th century: **1** High-lime low-alkali (HLLA) plant ash glass **2** Soda-lime-silica or mixed alkali plant ash glass (*façon de Venise*, crystal or white glass) **3** Lead crystal or flint glass **4** In the 18th and 19th centuries, mixed-alkali kelp glass **5** From *circa* 1830, soda-lime-silica synthetic soda glass
Sand with: **1** Natron **2** Plant ash, such as from bracken **3** Lead oxide Or **4** Lead smelting slag	Sand with: **1** Potassium-rich plant ash, such as from bracken **2** Mainly natron or rarely sodium-rich plant ashes **3** Lead oxide	Sand (or ground flint) with: **1** Plant ashes from woody species, such as beech or oak **2** Purified alkali-rich plant ashes **3** Lead oxide and potassium salts (saltpetre) **4** Kelp (seaweed ash) **5** Synthetic soda (sodium carbonate made from saltcake). Sometimes other materials as well, eg borax, barytes, soap boiler waste and blast furnace slag
No evidence yet from Britain **1** Natron glass probably made in large tank furnaces and imported but also recycling took place **2** Origins of plant ash glass unknown **3** Origins of lead glass unknown **4** Black lead slag probably imported	**1** Some potash-rich plant ash glass imported, but evidence of manufacture in Britain from 13th or 14th century onwards, focused in Weald and Staffordshire **2** Natron glass probably imported **3** Lead glass may have originated in Germany	Glass manufacturing concentrated in the Weald and Staffordshire, as before, then: **1** From mid-16th century, also in London **2** From early 17th century, a change to coal fuel, and industry spreads to Gloucestershire, Lancashire, Nottinghamshire, Staffordshire, Tyneside, Worcestershire and Yorkshire
Some evidence of glassworking in Britain Furnaces roundish in plan, *circa* 1m diameter Crucibles sometimes contemporary pottery types, *circa* 100mm diameter	Glassworking at primary production sites Furnaces rectangular, 3m × 4–5m, with parallel sieges Crucibles custom-made, sandy fabric, *circa* 0.3m tall	Glassworking at primary production sites. Furnaces as medieval, then: **1** From mid-16th century, more refractory bricks used **2** From early 17th century, below-ground fire trench or flue **3** From late 17th or early 18th centuries, cones over furnace from 18m high; extensive subterranean flues; many large associated structures (eg annealing sheds, workshops); crucibles custom-made from grogged, refractory clays; 19th-century crucibles *circa* 1.4m deep; closed crucibles used for lead crystal or flint glass

	Bronze Age 2500 BC–700 BC	Iron Age 700 BC–AD 43	Roman AD 43–AD 410
Glassworking methods	Shaping	Shaping, core forming, applied glass decoration (trails, etc)	Shaping, blowing, mould-blowing, optic blowing, casting or slumping over moulds, wheel-cutting, engraving, applied glass decoration (trails, etc)
Colours	Mainly transparent turquoise (copper oxide)	Dominated by dark blue (cobalt oxide) and also red (cuprous oxide). Other colours were purple (manganese oxide), yellow and white (the tin-based colourants lead stannate and tin oxide, respectively). These were later replaced by the antimony-based colourants: yellow lead anitmonate and white calcium anitmonate	Mainly colourless glass or glass with a blue-green tint (decolourised with manganese oxide or antimony oxide). Some strongly coloured, often opaque, glass in the 1st to 2nd centuries included dark blue, red, yellow and white (as before), turquoise (copper oxide), green (iron oxide, copper oxide or a mixture of yellow and blue colourants), brown (iron and sulphur) and purple (manganese oxide)
Artefacts	Beads	Jewellery (beads) Later: vessels, brooch settings and gaming counters	Jewellery (beads, bangles, brooch enamels and settings), gaming counters Tableware (cups, beakers and bowls), flasks, prismatic bottles, unguent bottles Windows, tesserae
Research status	Artefacts and evidence of glassworking very rare. All aspects would benefit from study	Artefacts and evidence of glassworking rare; existing typologies for beads; technological studies of red enamel Potential for further study of glass sources, technology, trade and use; possibility of refining date	Glassworking evidence fairly rare; existing typologies for artefacts Some comprehensive studies of glassworking waste, particularly in London, plus technology and source. Potential for further study of particular topics such as use of glass, industry organisation, trade and furnace technology

Early medieval AD 410–AD 1066	Medieval AD 1066 –AD 1485	Post-medieval AD 1485–present
Shaping, blowing, optic blowing, mould blowing, applied glass decoration (trails, prunts, *reticella*, etc)	Shaping, blowing, optic blowing, mould blowing, applied glass decoration, painting, flashing	Shaping, blowing, casting, engraving, mould blowing, optic blowing, mechanised mould blowing, applied glass decoration, cutting, grinding and polishing, automated grinding and polishing, pressing, painting, flashing, enamelling
Mainly shades of blue or green. Some colourless and brown earlier vessels. More strongly coloured vessels later Colourants as Roman except return to lead stannate for yellow glass and tin oxide for white	1 Potash-rich plant ash glass: green 2 Soda-lime-silica natron glass: colourless and coloured (colourants as early medieval) 3 Lead glass: mainly yellow, some green or red	1 Plant ash HLLA glass: green 2 Soda-lime-silica or mixed alkali façon de Venise, crystal or white glass: colourless 3 Lead crystal or flint glass: colourless 4 Kelp glass: very pale blue-green 5 Soda-lime-silica synthetic soda glass: colourless Colourants as before, with range increasing over time to include eg uranium, nickel, chromium and gold; bone ash (calcium phosphate) for opalescent glass; arsenic trioxide for decolourising/refining
Jewellery (beads, rings), linen smoothers Vessels (cups, beakers, horns, flasks) Windows	Jewellery (beads, gems) Vessels (beakers, goblets, bowls, flasks, jugs, bottles) Windows, mirrors Lamps, lenses Distilling apparatus, uroscopy flasks	Jewellery Vessels Windows, mirrors Lamps, lenses Scientific apparatus
Artefacts and evidence of glass working rare; potential to refine typologies There is evidence of different glass types being used but further study required to establish glass sources, technologies, trade and use, and industry organisation	Artefacts rare Glassworking evidence regionally localised; generally rare Potential to refine typologies Potential for further study of: 1 Trade and use of English and imported glass 2 Industry resource consumption and landscape management 3 Influences on glass deterioration	Glassworking evidence regionally localised; generally rare Potential for further study: 1 To clarify the distribution of the industry, the type of fuel used and the type of glass produced 2 Of resources consumption and management 3 Of technical innovations (often implemented secretly) 4 Of specialisation, eg industrial glass, photographic glass, optical glass, architectural glass, scientific equipment, etc

9 Case Studies

Case Study 1: Sampling for evidence of glass working

Glassworking furnaces, particularly early ones, rarely survive well and can be difficult to identify as most large pieces of glass were recycled. Sometimes the only evidence for glassworking comes in the form of small glass threads recovered from samples taken during excavation (Figure CS1.1).

Medieval Whitby, North Yorkshire

Whitby Abbey is the site of the monastery of Streaneahalch, founded in AD 656–7, and a later Benedictine monastery. During an English Heritage evaluation at the site, small fragments of glassworking waste were recovered from a posthole, which turned out to be part of an 8th–9th-century building (Jennings 2005). The sampling strategy for the subsequent excavation targeted the other features associated with this building, sampling 100% of posthole and pit fills and processing the samples on site using flotation (English Heritage 2011) (Figure CS1.2). Training was also provided in how to recognise glassworking evidence. The glass recovered included *reticella* rods made up of different colours of glass twisted together, small chunks of raw glass for melting, and assorted drips and lumps, none much bigger than 20mm. A small glass plaque, decorated with similar patterned glass rods, was found during earlier excavations near the ruined medieval abbey (Figure CS1.2), and the new evidence suggested that the plaques were made at the site.

Figure CS1-1
Processing samples on site at Whitby, North Yorkshire.

Figure CS1-2
Pieces of raw glass (right), a 9.5mm long *reticella* rod (bottom left) and a glass plaque (top left) from Whitby, North Yorkshire.

Post-medieval Silkstone, South Yorkshire

A coal-fired glasshouse was established at Silkstone in the middle of the 17th century. Two trenches were excavated in advance of works to a building possibly associated with the glasshouse, one inside and one outside the building. Although no glassworking structures were identified, stratified contexts containing glassworking waste were discovered, which could be dated using a combination of documentary references and clay pipes. Soil samples were taken from these contexts, which were sieved and the >2mm fraction was sorted. Large numbers of tiny glass threads were recovered and a proportion was analysed. This allowed archaeologists to establish what types of glass were made at Silkstone, and when (Dungworth and Cromwell 2006).

References

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Case Study 2:
Determining the date of glass: windows

The composition of glass depends on when it was manufactured, because the ingredients used have changed over time, and these chronological changes can be used to work out the probable date of window glass (Dungworth 2012). Information from documentary sources about raw materials and recipes for window glass has been supplemented with chemical analyses of historic window glass. This has established the distinct glass compositions that have been in use in Britain over the past 700 years (Figure CS2.1).

The earliest window glass included in the project is 14th-century potash-rich forest glass, which contains high concentrations of potassium, magnesium and phosphorus. The window glass of the later 16th and 17th centuries is usually a high-lime low-alkali (HLLA) glass. From *circa* 1700 until the first few decades of the 19th century, almost all windows were made from a mixed alkali glass with distinctively high levels of strontium oxide, probably derived from the use of ash from kelp (seaweed). The widespread use of kelp in the glass industry at this time is corroborated by documentary evidence. At the end of the 18th century, Nicolas Leblanc developed a technique for converting common salt (sodium chloride) into sodium carbonate, and this cheaper, purer flux was used in British window glass from the 1820s. As a result, windows made after *circa* 1830 are almost always soda-lime-silica glass with much lower levels of impurities, such as phosphorus, relative to earlier glass. The mechanisation of the window glass industry in the 20th century can also be traced in the chemical composition of the glass.

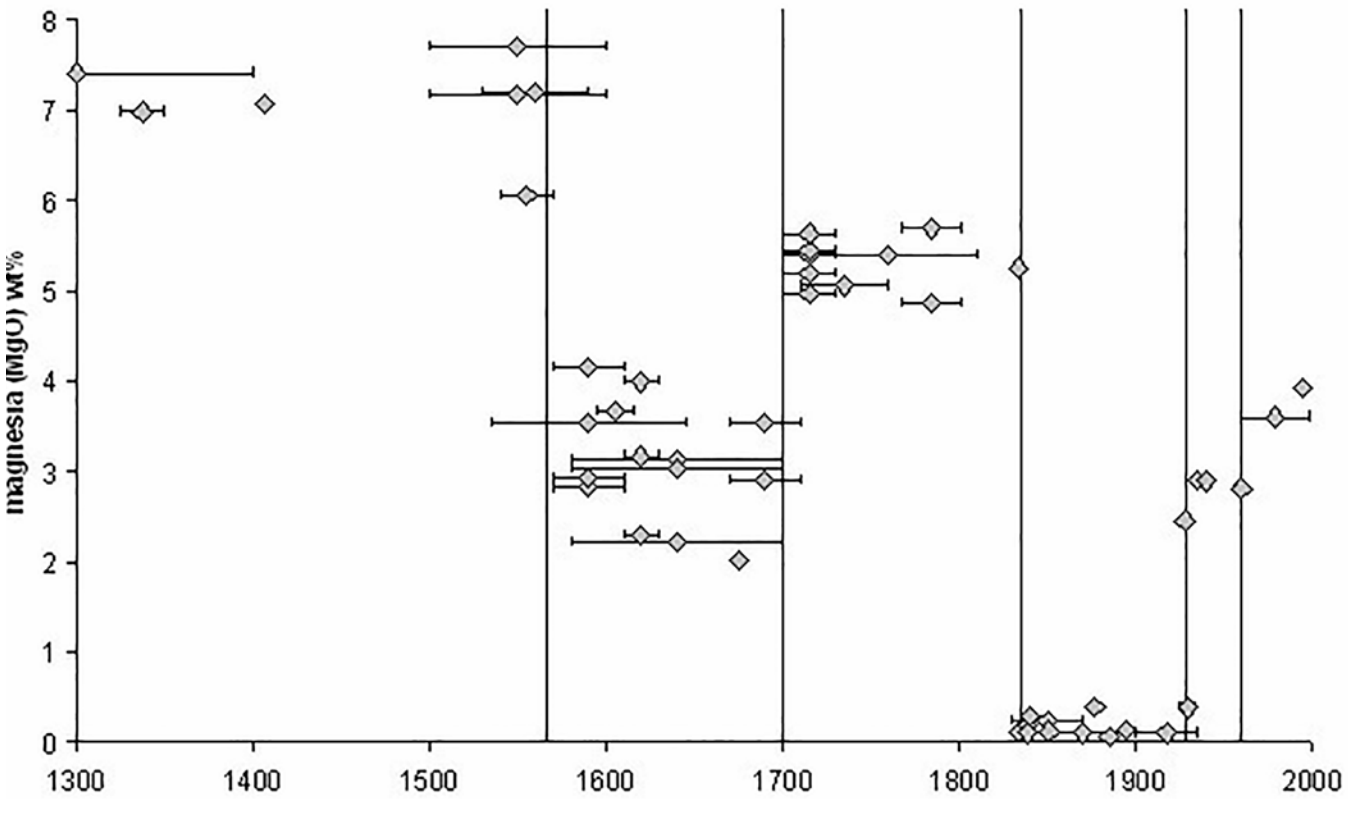

Figure CS2-1
Chart showing how the concentrations of magnesium oxide in historic window glass vary over time, shown in years (AD) on the horizontal axis. Each diamond represents a window fragment and the error bars show the uncertainty in the date of that window.

Window glass can also be analysed *in situ*, using a portable X-radiography fluorescence (XRF) spectrometer (Figure CS2.2). The chemical analyses indicate the date of manufacture of individual historic windows, allowing more informed decisions on their conservation.

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Figure CS2-2
Portable X-radiography fluorescence spectrometry (XRF) machine being used to analyse historic window glass *in situ* (undertaken adhering to safety protocols for using ionising radiation).

Case Study 3: Provenancing glass: 1st millennium AD production and trade

The results from scientific analyses have transformed our understanding of glass production in the 1st millennium AD. Natron glass, made by heating natron with sand, dominates during this period (see section 2.1). Natron is a sodium-rich crystalline material formed by evaporation of mineral-rich lakes like those of Wadi Natrun in Egypt (Figure CS3.1) (Jackson *et al* 2016). It has been established that only a small number of distinctive compositions of natron glass were in use across much of Europe and the Middle East during the Roman, and later, periods (eg Brill 1999; Freestone 2006; Jackson 2005).

This means that there was probably only a small number of centres making glass, in each case with a slightly different composition as a result of the make-up of the sand available there. The glass was made on a massive scale, then broken up and transported as lumps to workshops across the Roman world, where the raw glass was shaped into objects. There is archaeological evidence to support this model: large tank furnaces have been found in the eastern Mediterranean, close to the sources of natron and sand that were the preferred raw materials for most of the 1st millennium AD, and these produced many tonnes of glass in each firing (Jackson *et al* 2016; Nenna 2015) (Figure CS3.2). Chunks of raw glass have also been recovered from Roman shipwrecks: evidence of trade in raw glass during earlier centuries.

Figure CS3-1 (top)
Barnuj, one of the mineral-rich Egyptian lakes, with salts crystallising around the edge.

Figure CS3-2 (right)
A slab of failed glass made in a tank furnace from Bet She'arim, Israel. The slab is *circa* 2m wide and weighs *circa* 9 tonnes. Analysis suggests that it dates to around the 9th century.

Large assemblages of natron glass vessels and glassworking waste have now been analysed, focusing initially on colourless and weakly coloured glass, using techniques such as inductively coupled plasma–atomic emission spectroscopy (ICP-AES), inductively coupled plasma–mass spectrometry (ICP-MS) and transmission mass spectroscopy (TIMS) (see section 3.4). These techniques can detect even trace amounts of elements and the information has enabled archaeologists to determine where the raw glass came from (Freestone 2006). Analyses can also suggest how much recycling has taken place (Paynter and Jackson 2016).

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10 Where to Get Advice

10.1 Further reading

Prehistoric and Roman beads are described by Guido (1978) and compositional data are provided in papers by Henderson (1987, 1991).

Shepherd and Wardle (2009) provide a well-illustrated summary of the Roman glassworking waste found in London. The various Roman vessel forms and colours are described by Price and Cottam (1998). Compositional data for Roman glass from Britain from the 1st to 3rd centuries AD are discussed by Jackson (2005). A summary of analytical approaches to glass is given by Freestone (2006).

Evison (2008) covers the different forms of early Anglo-Saxon glass. For further information on glass from the later end of this period, including compositional data, see Hunter and Heyworth (1999). Whitehouse (2010) includes colour images of vessels plus contemporary artwork showing vessels in use.

Tyson (2000) describes glass vessel forms from AD 1200 to 1500. The medieval Wealden glass industry is discussed in great detail by Kenyon (1967) and reviewed by Crossley (1994), with detailed examples published by Wood (1965, 1982). Welch (1997) on Wolseley and Crossley (1967) on Bagot's Park provide comprehensive descriptions of the late medieval industry in Staffordshire. The post-medieval glass industry is summarised concisely by Crossley (1990, 2003). Willmott (2002) summarises glassmaking in the period AD 1500–1670 and classifies glass vessels found in England.

Examples of the application of sampling strategies and scientific analysis to English glassworking waste feature in Bayley *et al* (2008), Dungworth and Cromwell (2006) and Historic England (2018). Brill (1999) contains a vast compilation of compositional data on glass from many locations and periods.

For information on treatises and records about glass, see Hoover and Hoover (1950) and Cable (2001). Examples of the use of other types of documentary evidence are included by Crossley (1972), Godfrey (1975) and Historic England (2018) in their discussions of the medieval and post-medieval glass industry.

10.2 Specialist advice

The Historic England Science Advisors are based in the regional offices and are available to provide independent, non-commercial advice on all aspects of archaeological science. For contact details see https://www.HistoricEngland.org.uk/advice/technical-advice/archaeological-science/science-advisors/.

Specialists at Fort Cumberland, Portsmouth, can advise on the identification, scientific analysis, interpretation and conservation of archaeological remains from glassworking, and provide contact details for individuals and institutions undertaking commercial investigations and analyses of glassworking assemblages. For contact details see https://historicengland.org.uk/research/methods/archaeology/ancient-technology/.

Currently there is no one source for finding active glass specialists. However, contact details of consultants are available from the Chartered Institute for Archaeologists (CIfA; https://www.archaeologists.net/) and Association for the History of Glass (AHG; http://www.historyofglass.org.uk/) plus from specialists at Fort Cumberland, Historic England.

The Conservation Register of the Institute of Conservation (ICON) is a register of privately practising conservators and conservation laboratories that are accredited by the ICON and are required to work to professional standards set out by ICON. The register is free to use and it is possible to search for a conservator by location and specialism: www.conservationregister.com.

10.3 Useful organisations

Association for the History of Glass (AHG)
http://www.historyofglass.org.uk/
An educational charity interested in all aspects of glass, with strengths in archaeology and archaeometry of all periods; it organises meetings and publishes a newsletter.

Chartered Institute for Archaeologists (CIfA)
http://www.archaeologists.net/
A professional body providing general information, including standards, on the practice of archaeology and allied disciplines.

Corpus Vitrearum Medii Aevi (CVMA)
http://www.cvma.ac.uk/index.html
A resource for medieval stained glass in England, including a digital archive of painted and stained window glass, plus conservation guidelines.

The British Society of Master Glass Painters
http://www.bsmgp.org.uk/
A website exclusively for historic and contemporary stained glass. Resources include a journal, newsletter and reference library.

The Corning Museum of Glass, New York
http://www.cmog.org/
Information and images of ancient through to contemporary glass in the museum collection.

The Glass Association
http://www.glassassociation.org.uk/
Based at the Broadfield House Glass Museum, with strengths in post-medieval and contemporary glass and glassmaking.

The Glass Circle
http://www.glasscircle.org/
With an emphasis on glass collections, it lists dealers, auction houses and museums. It also publishes the newsletter Glass Circle News.

The Glassmakers
http://www.theglassmakers.co.uk/index.htm
A website focusing on the glassworking methods used to make different types of Roman vessel, including information on the experimental Roman furnace projects, and on 13th to 17th-century glassworking techniques.

The Guild of Glass Engravers
http://www.gge.org.uk/
A professional body for glass engravers with descriptions and examples of different engraving techniques.

The Institute of Conservation (ICON)
http://www.icon.org.uk/
ICON represents those concerned with the conservation of cultural heritage in the UK. The site includes the Conservation Register of accredited conservators/restorers and a range of guidance material.

The Society of Glass Technology
http://www.sgt.org
A resource for all aspects of glass, but with strengths in scientific studies and post-medieval glass. It organises meetings and publishes a journal.

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12 Glossary

Annealing The process of gradually cooling worked glass, which would otherwise shatter if cooled quickly

Annealing oven The structure in which annealing takes place (see also lehr, annealing and sections 2.6 and 4.2)

Barilla A term for the ashes of halophytic (salt-tolerant) plants, which provided a fairly pure source of sodium oxide flux. Prized for making high-quality glass (see section 2.1), large amounts were imported from Spain in the 18th and 19th centuries

Batch The raw materials for making glass

Blowing iron A long iron tube that was dipped into the molten glass to collect a gather for subsequent inflating and shaping (see section 5.2)

Broad glass Window glass made by blowing a gather of glass, elongating it into a cylinder, removing the ends, slitting the glass tube along its length and opening it up (see section 5.3)

Cane A multicoloured glass rod, made by heating, perhaps twisting and extending together a number of individual rods of different colours

Cast plate A method introduced in the 18th century to make large sheets of flat glass with a good surface finish. Molten glass was cast onto a metal table and rolled into a flat sheet, then polished (see section 5.3)

Clinker A fused material produced at high temperatures, here used to describe the waste from coal-fired glass furnaces (see section 4.3)

Cone A conical chimney covering the working area and furnace, from the late 17th/early 18th centuries (see section 4.1)

Cristallo Colourless, high-quality glass imported from Venice, which was made using purified plant ashes (see section 7.6)

Crown A disc of window glass made by blowing a gather of glass, then transferring this to a pontil iron and spinning it until it opened up (see section 5.3)

Crizzling A network of fine cracks that forms in unstable glass, particularly post-medieval lead glass (see Figure 4)

Crucible The ceramic container used to hold the melted glass in pot furnaces (see also pot and section 4.4)

Cullet Glass collected for recycling, which is likely to be a mixture of glass made at the site and glass made elsewhere (see section 2.3)

Cylinder glass See broad glass

Decolouriser Compounds such as antimony or manganese oxides, which were added to glass to make it appear colourless by counteracting the colour produced by impurities in the raw materials, such as iron oxide

Dichroic Glass that appears one colour in reflected light and another in transmitted light

Drawing Mechanised methods of extracting a cylinder or, more commonly, a sheet of glass from a melt. Sheets were drawn from tank furnaces using equipment that gripped a layer of glass as it started to solidify

Egyptian blue A pigment that predates glass and is a striking bright blue. In Britain it is more common from Roman sites. It is made from crushed quartz or sand, mixed with alkali fluxes and a copper colourant, which is then fired. It is not completely glassy and contains many cuprorivaite crystals, which cause the colour

Enamel Coloured glass fused onto the surface of another material, such as metal, glass or glazed pottery

Eye The hole in the centre of the furnace floor in coal-fired furnaces through which the flames and heat enter (see section 4.1)

Façon de Venise Colourless alkali glass in the Venetian style, also referred to as crystal glass, produced from the mid-16th century (see section 7.6)

Faience Made by shaping a moist paste of crushed quartz or sand, mixed with fluxes and a colourant, followed by firing. Faience has a glassy surface but the inside is pale and opaque because it contains numerous quartz grains. Faience predates glass and was commonly used for beads

Fire rounded Using heat to soften and round the rim of a glass vessel (see section 5.2.1)

Flashing A thin layer of coloured glass applied to the surface of colourless glass (see section 5.4)

Flint glass Originally the name given to post-medieval lead glass made with flint pebbles as the source of silica, but then a general term used for all lead crystal glass (see sections 1.1 and 7.6)

Float glass From the mid-20th century, a method for making sheet glass of uniform thickness with smooth surfaces by floating glass on a bed of molten tin

Forest glass A greenish coloured, potash-rich glass made from plant ashes, common in the medieval period and prone to weathering (see section 1.1)

Fritting The process of roasting the glass batch prior to melting

Gather A mass of glass collected on a blowing iron or punty, for subsequent working

Glass A non-crystalline solid

Grog Ground-up ceramic that, when added to clay, helps to reduce shrinkage and prevent drying defects (see section 4.4)

HLLA glass A green-coloured, high-lime low-alkali (HLLA) glass, common from the second half of the16th century, made from plant ashes (see section 1.1)

Inlay A solid piece of material set into, and usually level with, the surface of an object

Kelp A term for a type of seaweed, and also ash from burning the seaweed, which was used as a source of sodium oxide flux in glassmaking in the 18th and early 19th centuries (see sections 7.6 and 2.1 and case study 2)

Kicked base When the base of a vessel has been pushed upwards (see section 5.2.1)

Lead glass Glass made with lead oxide flux, including colourless lead crystal or flint glass, which became popular for luxury vessels in the later 17th century (see section 7.6.1)

Lehr or **leer** A structure used for annealing. From the 19th century they were constructed as tunnels, heated at one end. The glass passed slowly through the lehr on a system on carriers (see *also* annealing oven and sections 2.6 and 4.2)

Marver A flat surface, of stone or metal, on which the glassworker rolls or presses the glass to help shape it (see section 5.4)

Marvered decoration Glass decoration, such as trails or blobs in different colours, that are flush with the surface of the glass; the decoration is pushed into the glass while it is hot using the surface of the marver

Metal A term sometimes used for molten glass

Mixed-alkali glass Glass containing significant amounts of both the alkali fluxes sodium oxide and potassium oxide

Moil The leftover top of a blown object where it was joined to the blowing iron, generally in the form of a cylindrical collar or tube of glass. This waste is diagnostic of glass blowing (see section 5.2) and is sometimes referred to as rod end cullet

Natron Sodium-rich salts formed by evaporation at mineral-rich lakes, eg at the Wadi Natrun in Egypt. Natron was the alkali flux used to make late Iron Age, Roman and early medieval glass (see section 2.1)

Obsidian A black, volcanic glass that occurs naturally, although not in Britain

Opacifier Small particles of a substance in a glass that scatter light, making the glass opaque

Optic blowing A gather of glass is blown into a mould with a pattern on the inner surface, which transfers to the glass. Continued free blowing results in movement and distortion of the pattern (see section 5.2)

Overblow A by-product of mould blowing, referring to the glass that remains outside the mould, which is removed and recycled

Paraison The partially inflated gather of glass at the end of the blowing iron

Paraison end A marble-shaped blob of glass pinched from the end of the gather during the blowing of particular forms, such as the bowls of goblets (see section 5.2 and Figure 43)

Patent plate Large sheets of glass made by the cylinder method and polished, used for mirrors and large windows (see section 5.3.4)

Pontil or **punty** A solid iron rod onto which a blown article is transferred for further hot working (see section 5.2)

Pontil scar The circular protrusion of glass left on a glass object after removal of the pontil iron, although it was ground away on finer vessels

Pot See crucible

Pot furnace In furnaces from the Roman period onwards, the glass was held in ceramic pots or crucibles (see section 4.1)

Potash Potassium carbonate, an alkali flux used in glassmaking, obtained from plant ashes

Potash glass Potassium-rich glass, made from plant ashes and dominating from the 10th to the late 16th centuries (see sections 1.1 and 7.5)

Prunt Decoration in the form of cone-shaped protrusions of applied glass, eg on early medieval vessels (see sections 5.4 and 7.4)

Quarry A diamond- or square-shaped pane of glass cut for glazing windows

Reticella A pattern created by twisting glass canes of contrasting colour (see case study 1)

Rod end cullet Sometimes used for describing glass moils that were directly in contact with the blowing iron during glass blowing, and were later recycled. Some have oxidised iron scale attached. More commonly referred to as moils

Saltcake A high purity, synthetic sodium sulphate made from sea salt, used in glass production from the 1930s

Saltpetre Potassium nitrate, a potassium-rich flux used in the production of post-medieval lead glass (see section 2.1)

Siege The two low, parallel platforms in medieval and post-medieval furnaces on which the crucibles of glass sat (see section 4.1)

Soda ash Sodium carbonate, an alkali flux (see section 2.1)

Soda-lime glass Includes soda-ash and natron glass. Soda-lime glass is typical of the Iron Age, Roman and much of the early medieval periods, and also from around the 19th century (see section 1.1)

Tank furnace A furnace in which the molten glass is held in an integral tank, rather than pots. In Britain, small tank furnaces may have been used in the Roman period. Large tank furnaces were introduced in the late 19th century (see section 4.1)

Uroscopy Diagnosing medical conditions by the visual examination of urine

Wasters Failed products that maybe discoloured, distorted, broken or contain faults (see section 4.8)

Weathering Physical and chemical alteration of glass, particularly the surface, varying with the type of glass and the environmental conditions

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