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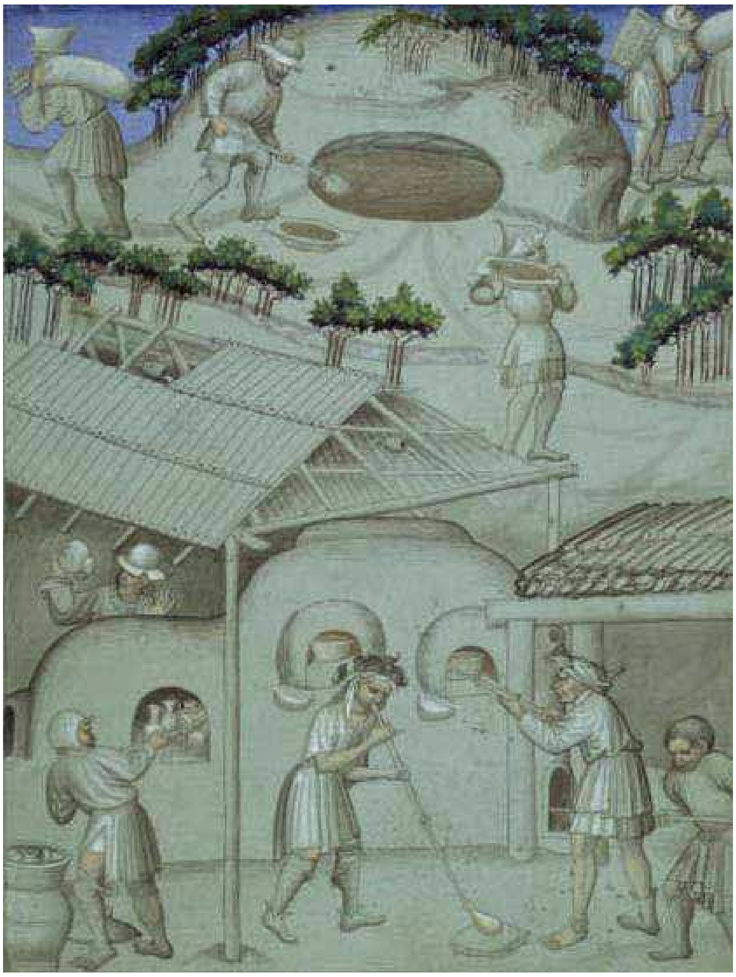

The chemical and isotopic analysis of English forest glass

by

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for the degree of Doctor of Philosophy

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Abstract

Glass is one of several early modern industries where the development from small-scale workshop to large-scale industry offers a valuable insight into wider socio-economic trends. Previously, medieval and early modern forest (wood ash) glass has been studied using a range of analytical techniques. However, characterisations of production centres and exchange systems for forest glasses are difficult to verify, in part because very few examples of raw glass from furnace sites have been investigated. The necessity for an independent means of provenancing glass used in the study of exchange systems is clear.

Compositional analysis can provide evidence for the raw materials used and can sometimes provide compositional groupings specific to sites. However, strontium, neodymium and oxygen isotope determinations can actually provenance the glass by linking the geological ages, or sources, of raw materials to production sites. The potential of using Sr and O isotopes in the study of plant ash glasses has recently been established (Henderson et al., J. Archaeol. Sci., 32, 2005).

Using EPMA-WDS over 179 raw glass samples from 12 English production sites in operation between the 14th and 17th centuries have been analysed. These analyses have shown compositional types which are relatable to the region or, in some cases, the period of production. Over 60 archaeological glass, raw material and model glass samples from these sites have also been analysed using mass spectrometry to determine strontium, neodymium and oxygen isotope ratios. The isotopic analyses have also been very effective in showing differences between sites, even those within the same region. This thesis will argue that the combination of these techniques offers a promising new way of provenancing archaeological glass and provide an insight into the organisation of production at this time.

Cover Image: Fifteenth century illustration of glassmaking at the pit of Memnon, Sir John Mandeville's Travels (Willmott, 2005; plate 11).

Acknowledgements

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The project would not have been possible without the financial assistance of the Arts and Humanities Research Council, who paid for my tuition fees and living expenses, and the Natural Environmental Research Council, who paid for the isotope analyses.

The glass samples analysed came from a large number of museums across England and each one was extremely helpful. They also had enough faith that the results of this thesis would be important to lend me a huge number of archaeological samples. Thanks to: Guildford Museum, Stoke-on-Trent Potteries Museum, Hutton-le-Hole Folk Museum, Southampton Museum, Hereford Museum, Portland Basin Museum, Dorset County Museum and World Museum Liverpool.

A special mention also has to go to all my family and friends who have supported me and helped me to reach this stage.

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Introduction

Background

Glass production in England has had a chequered history. Many of the changes in its organisation and products are reflections of changes in society. This study will focus on glass produced in the Later and Post Medieval periods and, more specifically, on forest glass. This type of glass was used for the manufacture of low value glass products and is a particularly good example of glass produced in a range of well-documented changing political situations. During this period there were a large number of forest glass producers throughout England and the high volume of glass produced means there is plenty available for study. This project is an attempt to develop an analytical protocol in the pursuit of a means of provenancing forest glass.

Chemical analysis of glasses has been used for decades as descriptive tool to characterise groups of glasses and identify possible raw materials used in their production. More recently attempts have been made to link these compositional groups to specific glassmaking sites and technological changes over time. This study aims to be the next step in the development of glass provenance studies. The use of three types of isotopic analysis in combination with chemical analysis will provide information about raw material sources, thereby allowing provenance to be assigned to the glasses.

The extensive use of isotope analysis to provide a provenance is a relatively new feature of archaeological science studies (Degryse et al. 2009a; 23). However, there have already been a great number of success stories in its use in the study of a range of archaeological materials (e.g. Freestone et al. 2003; Montgomery et al. 2003; Henderson et al. 2005; Li et al. 2006; Degryse and Schneider 2008). Glass is only one of the areas in which it can be applied to archaeological problems. The one thing that ties all these studies together is the search for provenance.

Many previous analytical studies of forest glasses from England have been made (see chapter 3). However, each study is limited to one or two sites and the use of different analytical techniques makes their results difficult to compare. This present work will compositionally analyse samples from a large number of sites using a consistent methodology and add to this compositional work with one of the first, and certainly the largest, isotopic analytical studies of forest glasses.

Research questions

This project aims to extend the use of isotopic analysis to systematically characterise the isotopic signatures for forest glass production sites across England. It was devised in collaboration with Julian Henderson at the University of Nottingham and Jane Evans at the NERC Isotope Geosciences Laboratory who have already had a number of successful collaborations focussed on the isotopic analysis of glass (see Henderson et al. 2005; 2009 etc.). These are the aims, objectives and research questions this project endeavours to investigate and answer:

Aims and objectives

- To chemically analyse forest glasses from a range of production sites across England.
- To use strontium, neodymium and oxygen isotopes to characterise raw glass and some raw materials from the above production sites.
- To use the results to provide an independent means of provenancing forest glasses.

Research questions

- How do the chemical compositions of glass produced at each site vary, and can they tell us anything about the raw materials and recipes used?
- Is it possible to discover site or region specific isotopic signatures?
- How do these isotopic signatures relate to the location of the production site?
- How do the isotopic signatures in finished glass relate to those of the raw materials used to produce it?
- Do these results provide us with an independent means of provenancing forest glass?

Methodology

Provenance

The major aim of this project is to provide a methodology capable of independently provenancing forest glasses produced in England. Being able to accurately provenance glasses will help with answering a wide range of questions relating to production, distribution and consumption patterns. The compositional analyses will hopefully reveal compositions, perhaps relatable to recipes or raw materials used, specific to time period or region. It may even be possible to find compositions specific to single sites (see Henderson 1989; 31; Freestone et al. 2000; 74). It is hoped that the determination of strontium, neodymium and oxygen isotope ratios in glasses will be even more helpful for providing signatures which can be used as a means of provenancing.

If these signatures are established it will then becomes possible to link glasses from production centres to, for example, glass found in domestic contexts. This information can then be used to recreate trading patterns. Interpretation of this data in combination with the chemical analyses may also allow the discovery of a trade in separate raw materials or raw glass. The application of this methodology is not limited to the production of wood ash, or even plant ash, glasses and, with its increasing availability to archaeological scientists, will hopefully be used to answer archaeological questions concerning a wide range of time periods and locations (see Degryse et al., 2009c for many recent applications).

Samples

Before embarking on any project there are a number of questions that need to be addressed. Due to the scientific focus of this project and the limitations this imposes, a set of glasses that will generate meaningful results needs to be found. The time period is defined as being between by the time when forest glass comes into production in England in the 13th century and the start of the English Civil War (1642-51). The end date has been chosen so as to focus on a manageable period, but also because of the changes in the industry that occurred at this time. The large number of sites in operation during the chosen period provides great scope for the research.

Samples will only be taken from glass furnace sites. The analysis of glass from other contexts is outside the scope of this project. The sites chosen have already been excavated, no sites have been excavated for the project itself. The glass was therefore sourced from museums and archaeological units. Small lumps of raw glass are generally plentiful on excavations of production sites belonging to the period concerned. These types of samples are generally considered to be inappropriate for museum displays and therefore it is hoped that most museums approached will be happy to allow the destructive analysis of sub-samples of pieces of glass in their collections. These sub-samples will be mounted in resin, for compositional analysis, and powdered, for isotopic analysis. The destruction will be kept to a minimum and the bulk of the samples will be kept for future research and later returned to their place of origin.

A brief study will also be carried out of raw material and model glass samples to discover how the isotopic signatures found in archaeological glasses relate to the raw materials used to produce them. This is not an attempt to recreate glass with the same chemical composition as those found on production sites. It will involve the collection of raw materials that can be used as an isotopic analogue for those used in the production of forest glass, the production of model glasses from them and the analysis of both the raw materials and model glasses.

Scientific analysis

The two types of analytical data to be collected are compositional and isotopic. The compositional analysis will be used in an attempt to determine the types and proportions of raw materials used. The isotopic analysis will be used to attempt to discover where the raw materials used to produce the archaeological glasses came from. There are a number of issues which will have to be addressed when using these two techniques to analyse glass and they are outlined below. The two analytical techniques chosen were electron microprobe analysis-wavelength dispersive x-ray spectrometry (EPMA-WDX) and thermal ionisation mass spectrometry (TIMS).

Compositional analysis

The electron microprobe can provide information on a range of elements to a much greater degree of accuracy and precision than scanning electron microscope-energy dispersive x-ray spectrometry (SEM-EDX). Typical detection limits are 0.08 wt% for EDX and 0.01 wt% for WDX (Kusima-Kursula 2000; 111). It also has the ability to image samples in both secondary electron and backscattered imaging modes. This can provide useful information in characterising inclusions or areas of weathering on the glasses.

The main purpose of compositional analysis in this project is to characterise the glass. This will take the form of looking into differences and similarities between glasses produced at different sites. The next step is to attempt to link the compositional analyses of forest glasses and the composition of the raw materials used to produce them. Previous research on raw material compositions will be used to achieve this. A large amount of previous work has been carried out on chemically characterising archaeological glasses and this will be used to help with the methodological choices.

The determination of isotope signatures is far more expensive and time consuming than the determination of chemical compositions. This project will therefore only isotopically analyse a smaller subset of those samples in the compositional analysis programme.

Isotopic analysis

The most common application of TIMS is in the measurement of isotope ratios in geological samples; however it is becoming increasingly widely used in archaeological studies. It has the ability to provide isotope ratios that are precise to 0.01-0.001%. To use this technique, small samples (~0.5 grams) are taken from the glasses, powdered and dissolved. However, the value of the results greatly outweighs the sacrifice.

The usefulness of the isotopic analysis will rely on one particular factor; that the isotopic ratios present in archaeological glasses are relatable to the places of origin of the raw materials used to produce them. This goes beyond being able to see differences in the isotope ratios in glasses from different sites; it is hoped that the results will provide a link to the sources of the materials. This relies on the isotopic signatures of raw materials being sufficiently different from one another and relatable to their geographical origin. It is hoped that the use of this methodology will provide an independent means of provenance, i.e. that in the future it will be possible to provenance glass without the prerequisite of analysing glass from the production site where it was produced. This would involve directly linking the isotope ratios found in glasses directly to the locations where the raw materials originated and the assumption that the raw materials used were sourced within area local to the production site.

Summary

This thesis is structured in such a way to give a clear introduction to the topic, necessary background information, the methodology used, the analytical data produced, and interpretation, discussion and conclusions drawn from these data. The first chapter focuses on the production of forest glass in England and includes a discussion of the history and organisation of production, as well as the production processes and possible raw materials and recipes employed. The second chapter discusses the sites themselves; their locations, a history of their use, their products and their excavation. Following this is a methodological chapter looking into questions of provenance, sampling, the analytical techniques used in this project, previous analyses of forest glass and the production and analysis of a model glass. The fourth chapter includes the analytical results and a discussion of their meaning and ramifications.

Finally the conclusion will aim to bring all of the findings of this project together and assess the methodology used.

Chapter 1: Glass production

1.1 The History and organisation of glass production in England

1.1.1 Glassmaking 410-1500AD

There is very little evidence for early 5th century glass production in England and Roman vessel forms continue to occur in burials in the 5th century. Some new vessel forms begin to appear in eastern England during the 5th and 6th centuries, probably imported from northern France or the Low Countries (Evison 2000; 47). These forms, including cone, bell and claw beakers, continue in use into the later 6th and 7th centuries. There is still no firm evidence for their manufacture in Britain, however it remains a possibility. The evidence consists of finds of melted cullet and crucibles containing opaque white and yellow glass. It is therefore likely that some glass may have been produced, but only on a small scale and perhaps limited to the manufacture of beads and coloured inlays (Willmott 2005; 35). The evidence for glass production greatly increases from the 8th century onwards including two glass furnace sites, discussed further below.

At the site of Glastonbury Abbey an industrial complex that included four furnaces was discovered, accompanying an early Saxon monastery. Two of these furnaces remained sufficiently preserved to allow their form to be established. They were oval in shape and consisted of a depression in the ground surrounded by Roman tiles, one was 1.2x0.9metres and the other 2x1.2metres. A small quantity of glass was found at each of the four furnaces. The vessel forms all date to the late 7th or early 8th centuries, and thus provide a *terminus ante quem*, and probable date for the furnace somewhere in the 8th century (Bayley 2000; 175).

A glass furnace found at Barking Abbey has been archaeomagnetically dated to 925±50AD. The furnace found at this site, more circular in shape than those at

Glastonbury and about 2.5metres in diameter (Cramp 2000; 107). The base of the furnace was formed of baked clay, and like that at Glastonbury, inset with Roman tiles. The fragments of glass found included reticello or polychrome rods, suggesting that decorated glass vessels were produced. No definitive evidence for primary production was found, but the large scale of some tank shaped crucible fragments makes it likely.

Very little evidence of glass manufacture, or use, has been found from the late 11th and 12th centuries. It is tempting to see this as a result of the Norman invasion. However, evidence for glass use in the decades leading up to 1066 is also scarce (Willmott 2005; 40). Glass is still very occasionally found, but with no evidence for production, it is likely to have been imported. The glass that appears after this cessation in production and use is of a different type.

The earlier glass was produced using a soda-rich source of alkali. The glass which is found in 11th and 12th century contexts is a new type of potash glass, produced using burnt wood or bracken ashes. This glass is easily distinguished from its soda-based predecessor due to its heavy green discolouration. This change is not due to the producers being unable to acquire the necessary raw materials in Britain. A lack of production evidence suggests that this glass was not produced in Britain. Instead it would appear that the suppliers of glass to Britain switched their source of alkali from natron to wood ash. This may have occurred earlier than it is observed in Britain, the potash glass only reaching here in large quantities when domestic production ceased. There is earlier compositional evidence for an attempt to extend the available imported glass by the addition of around 10% poor quality wood-ash glass (Freestone et al. 2008; 42). This may have occurred in Britain, however the lack of evidence from the Continent means this is difficult to prove. The 13th century, like the 8th century, sees a great increase in the quantity of evidence for glass production and use.

There is documentary evidence in the later 14th century of a firm of agents who were based in Chiddingfold, The Weald, supplying window glass to Merton, Winchester and New Colleges (Willmott 2005; 46). Vessel glass was also being produced in The Weald at this time (see Kenyon 1967; 31). This evidence is not limited to The Weald, a furnace was excavated at Little Birches (north site) that was in operation during the 13th or 14th century, however, due to limited evidence it is not possible to be sure of the types of products produced here (Welch 1997; 16, 18).

1.1.2 Glassmaking 1500-1567 AD

There is little historical evidence for British glass production in the early 16th century. This is surprising as there is a large amount of evidence from the preceding two centuries and there was a great increase in the amount of documentation produced in Tudor England in general. There is documentary evidence for three families working in the Weald and an industry established in south-eastern Staffordshire. A reference in a petition of the Glaziers Company to the Privy Council in 1542 clearly implies that no English-made window glass was available (Godfrey 1975; 12).

However, at the site of Knightons, dated to the 1550s, much evidence for the production of crown window glass and possibly vessels was found (Willmott 2005; 68). Similar evidence was also found at the early- to mid-16th century sites of Bagot’s Park and Little Birches, south site, in Staffordshire (Welch 1997; 18). The bulk of evidence for forest glass production is for window glass in the early to mid-16th century. However, the evidence from these three sites cannot be seen as encompassing all the glass production in this period. The discovery of some vessel glass at each site points to the limited production of vessels at these sites or importation, possibly as cullet, from as yet unexcavated contemporary sites.

1.1.3 Glassmaking 1567-1615AD

The lack of skilled glassmakers in Britain in the first half of the 16th century meant the time was ripe for an influx of glassmakers skilled in the art of window and high quality vessel production. A few attempts were made by Italians and Englishmen to establish glasshouses with imported workers, but these were unsuccessful. The man credited with the re-establishing window and quality glass manufacturing in Britain was Jean Carré. He had been involved in some aspect of glass manufacturing in Antwerp and arrived in London in the spring of 1567 with a sizable amount of capital, considerable technical knowledge and extensive contacts with foreign glassmakers, apparently intent on taking over the English glass industry (Charleston 1984; 53).

Arriving in the spring, by July Carré had already secured a licence from the Queen to build window glass furnaces in the Weald and one for crystal in London. Carré set up a company with at least three other immigrant glassworkers. After proving that others were not making window glass in the Weald, Carré's company were able to secure the exclusive right to make window glass in the Lorraine manner for 21 years (Godfrey 1975; 20). The granting of this right came with some additional conditions: that the glass produced had to be sufficient to supply the realm, be cheaper than that which could be imported and that the immigrants must teach Englishmen the art of glassmaking.

The glass furnaces in Weald were run by Thomas and Balthazar de Hennezell, who shared the profits equally with Carré's company. Carré resided in London and took more of an interest in the crystal furnace built within the walls of the Crutched Friars, an abandoned monastery near the Tower of London. He was able to bring a large number of foreign glassmakers to England, presumably due to the same religious and economic factors that influenced his emigration. The following years saw many quarrels over the ownership of the company’s patent, eventually resulting in the de Hennezells leaving their furnace in the Weald. In 1571 Carré left the crystal glass furnace under the control of a Venetian glassmaker Jacob Verzelini and moved to the Weald to set up a forest glass vessel furnace. Before this furnace was completed Carré died at his house in Fernfold Wood in May 1572, just five years after arriving in England.

Following Carré’s death the quarrels over the furnaces and licences continued, however, the situation was now becoming increasingly dire. In 1575 Becku, who was originally part owner of the licence, sued the Bungar brothers, who were operating the Wealden furnace, for debts. In the following year the Privy Council pressed Becku for payment due to the Exchequer in lieu of customs (Godfrey 1975; 26). Peter Appel, Carré’s son-in-law, and Peter Briet, his associate, who had taken over the running of the monopoly applied for a new royal patent prohibiting the importation of glass from the continent. They claimed that they could not compete with this foreign glass. This would appear to be true as in 1571-2 as much glass was entering the Port of London from abroad as was in 1567 (ibid.). This new patent was never granted. Eventually the original patent lapsed through non-observance and the way was left open for other glassmakers to set up furnaces and move throughout the country.

Considerable importation of green glass vessels at this time shows that there was definitely a market for these items, as well as window glass. There was now no longer a monopoly restricting forest glass production and no financial obligations in terms of customs duties or royalties. The emigration of foreign glassmakers into England greatly increased following the massacre of Protestants in Paris in 1572 and their furnaces spread across the country (Vose 1980; 109). Carré's glassmakers remained in the Weald and it was the new glassmakers arriving in the 1570s who spread around the country. As was the case in the preceding decades, Staffordshire and the Weald were the major centres of glass production in the early Elizabethan period (see Welch 1997; Mortimer 1993).

The products of these furnaces were a mixture of vessels and window glass. The glass produced by the immigrants was of a higher quality than that produced in preceding periods, with 'bright shiny surfaces, improved translucency and greater durability' (Crossley 1998; 168). The recipes of glass production clearly changed in this period, previous work has shown a decrease in potash levels and increasing soda levels (see section 3.3 for further discussion). A new alkali raw material seems to have been used at many of these sites.

During the reign of Elizabeth I there were frequent complaints regarding wood shortages and the consequent raising of prices for the fuel. In the Weald wood would still have been relatively plentiful when the immigrant glassmakers arrived in the 1560s and 70s. However, the great increase in glasshouses and iron works in the south of England led to concern about the destruction of timber suitable for the navy (Crossley 1998; 172). This not only affected other industries and the general public, but also the glassmakers themselves. Due to overproduction in areas such as the Weald the glassmakers were met with another serious problem; falling glass prices.

The glassmakers faced three possible solutions to their predicament: move to more heavily wooded areas; remain in the Weald and find new markets or cheaper fuel; or find another fuel. All three of these solutions were attempted by different glassmakers. Some glassmakers became migratory, seeking out new supplies of wood across England, resulting in numerous short-lived sites from Hampshire to the North Riding of Yorkshire dating to the late 16th century (see Willmott 2005; 79-94). Generally they settled near to navigable rivers, as the local markets could not support them. This spread of glassmakers drew attention to wood shortages throughout the country. A number of bills were presented in parliament during the late 16th century to deal with this problem. Solutions ranged from limiting the areas in which new glasshouses could be erected, to moving all glass production to Ireland where wood was cheap. This period also sees the first production of glass by English colonists in America (see Hatch 1941ab; Harrington 1952).

1.1.4 Glassmaking post-1615AD

During this final period there was considerable change in the technology and organisation of the English glass industry (Mortimer 1995; 135). As discussed in the previous section, the end of the 16th century saw a number of attempts to limit the locations, or even existence, of glasshouses in England. The problems of finding new supplies of wood, and the possibility of restrictions led to a period of experimentation with the use of coal as a fuel. On the 28th of July 1610 an agreement was made between the Crown and William Slingesby, by which the latter was given the sole right to ‘erect ovens, furnaces, and engines for brewing, dyeing, baking brick, tile and pot-making, refining and melting glass, ordnance, bell-metal, latten, copper and other metals with sea-coal and pit coal’ for 21 years (Godfrey 1975; 59). Initially he intended to produce furnaces for iron smelting, but their first success was in the glass industry. In 1611 a Crown monopoly was granted to Edward Zouch and a small group of gentlemen, including Sir Robert Mansell, for making glass using coal as fuel (ibid.). Then, on the 23rd of May 1615 James I made a Royal ‘Proclamation touching glasses’:

> ...to provide that matters of superfluitie do not devoure matters of necessity and defence; understanding that of late years the wast of Wood and Timber hath been exceeding great and intollerable by the Glasse-houses…as it were the lesse evill to reduce the times unto the ancient manner of drinking in Stone [stoneware], and of Latice-windowes, then to suffer the losse of such a treasure…Therefore We doe…straightly…ordaine, that…no person…shal melt, make, or cause to be melted or made, any…Glasses whatsoever with Timber or Wood, within this Our Kingdome of England and Dominion of Wales.
>
> (Charleston 1984; 74-5)

Also in 1615 Mansell bought out his fellow monopolists and began to try to make the production of glass using coal more profitable. He set up glass furnaces near coalfields, the first at Wollaton near Nottingham in 1616. While this may have cut the cost of the fuel, it also increased the cost of transportation of the products to the largest markets in the South East (Crossley 1990; 233). This change in fuel source also meant that the glassmakers could no longer use the ashes from their furnaces as their alkali raw material and so wood or plant ashes had to be produced by other means or bought. Evidence for this can been seen in changes in composition of these glasses, with higher soda levels than those produced earlier (see section 3.3).

In 1617 Mansell was involved in an attempt to use oil shale on the Purbeck coast at the site of Kimmeridge (see section 2.6.1), however this was unsuccessful. A third brief attempt was made at Milford Haven, where 'the Cole provided neither serviceable nor transportation of the glass possible to be had' (Godfrey 1975; 84). Eventually he found success on Tyneside in 1618 using local coal, and shipping glass via the established coastal trade route.

Mansell's position was greatly improved from 1618 when all forest glass competition was finally closed down (Willmott 2002; 11). In the following two decades he secured the complete domination of the English market; his patent was re-issued in 1623, then again in 1635 to include Ireland and in 1630 he gained a royal decree banning the importation of all foreign vessels (ibid.). This domination of the market did not lead to as highly profitable an industry as might be expected. The reissuing of the monopoly in 1635 was coupled to an increase in the rents payable to the Crown, which led to higher retail prices. Then, in 1640, the Scottish invaded northern England stopping production at Newcastle and interrupting coal supplies to London. The final blow for Mansell's monopoly was dealt on the 30th of May 1642 when he was ordered by Parliament to surrender his patent. The Lords did not concur, however when the Civil War began in August Mansell lost the opportunity to revive his claims (Vose 1994; 2). Eventually he restored production at his Newcastle furnaces and continued to produce glass up until his death in 1656. These furnaces eventually came into the possession of the Henseys and Tysacks, who were already working there (Willmott 2005; 107).

1.2 Raw materials and recipes

1.2.1 Introduction

> "[It is] a rare kind of Knowledge and Chymistry to transmute Dust and Sand (for they are the only main Ingredients) to such a diaphanous pellucid dainty Body as you see a Crystal-Glass is"

James Howell, Administrator at Mansell's London crystal works, 1620
(see Godfrey, 1975; 156).

Our knowledge of the raw materials used in early glass manufacture relies heavily on historical evidence, which is not entirely infallible. There may be many possible combinations of natural materials, as yet not understood, that could have been used to produce the glass compositions we now observe (Sanderson and Hunter 1982; 27). Recent advances in scientific techniques and their application to archaeological problems have allowed a much better understanding of the raw materials used to produce glass in the past. It is now relatively simple to discern between glasses produced using mineral or plant ash alkali sources, for example, using major and minor element chemistry.

The chemical composition of a glass is based on three variables, first is the natural variability of the materials used and the second is the changes which these materials undergo due to manipulation by the glassmaker, termed as behavioural variability by Jackson et al. (2005; 782) and the third is the melting conditions (Rehren 2008; 1353). The natural variability is very important in terms of provenancing the glasses. On the assumption that this variability is enough between sites and discrete enough to be specific to sites, provenance can be assigned to glasses. However, if the composition of the raw materials is not transferred fully to the glass due to processing and melting conditions such an assumption will not hold. It is therefore the *choices* made by the glassmaker, in terms of both the raw materials and their processing that determine the final composition of the glass.

There is documentary evidence for the raw materials used in the medieval period for the production of glass using plant ashes. In the 12th century the German monk Theophilus prescribed:

> ‘two parts of the ashes [beechwood ashes] of which we have spoken and a third of sand carefully purified from earth and stones, which sand you shall have taken out of water, mix them together in a clean place’

(Dodwell 1961; 39)

A different set of raw materials and proportions were described around 400 years later by Biringuccio. In his book of 1540, *De re Pirotechnia*, he describes:

> ‘The method of composing glass…First one takes ashes made from the saltwort that comes from Syria…Now some say that this ash is made from fern and some from lichen; which of these it does not matter here…some of those sparkling white river stones that are called pebbles and that are clear and breakable and have a certain resemblance to glass. When it is impossible to have these, take in their place a certain white mine sand that has a certain rough harshness. Of whichever of these is taken, two parts are put to one of the said salt [ashes] and a certain quantity of manganese according to your discretion.’

(Price 1959; 127)

A contemporary of Biringuccio, Agricola, published *De re Metallica* in 1556. Within this book is another description of the method for producing glass:

> ‘[Glass] is made from fusible stones and from solidified juices…One part of coarse or fine sand made from fusible stones should be mixed with two parts of soda or of rock-salt or of herb-salts, to which are added minute particles of magnes…when such juices are not to be had, two parts of the ashes of oak or holmoak, or of hard oak or Turkey oak, or if these be not available, or beech or pine, are mixed with one part of coarse or fine sand, and a small quantity of salt is added, made from salt water or sea-water, and a small particle of magnes; but these make a less white and translucent glass’

(Hoover and Hoover 1950; 584-6)

These three sources can give us useful hints at the raw materials being used by the glassmakers in this period. However, it must be remembered that they are not written by glassmakers and therefore cannot be considered as fact. Theophilus notes that purified sand and beechwood were the only two ingredients. Biringuccio describes plant ash, rather than wood ash glass. The addition of manganese and use of quartz pebbles would seem to suggest that this was also a recipe for making clear, colourless glass. Agricola, in De Re Metallica, lists a large number of plants and tree species that can be used as an alkali flux. In addition to these ingredients he also states that rock-salt can be used instead of, or as well as, plant and wood ashes. A third basic ingredient is also listed, that of *magnes*. It is not known what this word describes; some suggestions have been made ranging from limestone to manganese (Hoover and Hoover 1950; 586). It is unlikely that manganese would have been added to forest glasses, but if this third ingredient is limestone, it is something that will impact directly on the compositional and isotopic results of this thesis.

The ingredients thought to have been used in forest glass production, as well as the recipes employed, are discussed below. How the choice of these ingredients and in what proportions they are combined will impact on the results of the scientific analyses carried out, as part of this project, will also be discussed.

1.2.2 Silica

The silica sources used for glass production varied dependent on location and availability. At Venice, for example, it is historically documented that siliceous pebbles from the Ticino and Adige rivers in Northern Italy were imported and used for top quality products in the 16th century (Smit et al. 2004; 721). These pebbles would have been impossible to use as received and to improve reactivity and dissolution would have been crushed. This could have been achieved either by crushing, or by heating and rapid quenching. Quartz undergoes a transformation at 573°C from the $\alpha \rightarrow \beta$ phase and quenching from this temperature would cause breakage and fragments left could be easily powdered (Smedley and Jackson 2002a; 23). Theophilus recommends water-borne sand is used, presumably as this would be naturally sorted to provide a consistent material (ibid.).

Inclusions	Impurity
Feldspar	Al_2O_3, CaO, Na_2O, K_2O
Titinite or Sphene	Cr_2O_3, TiO_2
Chromite	FeO, Cr_2O_3
Epidote	Al_2O_3, FeO, CaO
Shell fragments	CaO

Table 1.1: Some of the common inclusions found in sand and the oxides they will contribute to a glass (after Henderson 2000; 27).

There are a number of different inclusions found in various sand sources. Table 1.1 shows some of the more common inclusions and the impurities they can contribute to glasses produced using them. In sufficient quantities these impurities can alter the working qualities and appearance of the glass. For example iron oxide will impart a green colour to the glass. Sands with low iron oxide contents were therefore sourced for the production of colourless glasses. Calcium oxide (CaO) will assist with the stability of the finished glass, however, in excessive quantities it will have a detrimental effect on the melting process (see Freestone and Gorin-Rosen 1999). The addition of lime to forest glasses is discussed in more detail in section 3.3.

Of great importance to this study is presence of neodymium in sands. Neodymium is present in the heavy mineral fraction of sands and variations in its isotope ratio are relatable to the geological source of the sand (Degryse et al. 2009b; 56). Neodymium isotope ratios will be used in this study to characterise forest glasses.

This study will also use oxygen isotopes to provenance the silica sources used. The oxygen isotope ratio ($\delta^{18}O$) of a silica source will depend on the method of its formation and can be used to characterise silica sources. Some oxygen will clearly enter the glass with the flux and stabiliser, but the majority will be from the silica source (see Brill 1970 and Brill et al. 1999). This will be discussed further in section 3.6.3.

Choosing a sand source free of iron impurities would not be as important in forest glass production compared to crystal glass, as a green glass was expected. The sites of Knightons and Blunden’s Wood were located near a source of sand on Hambledon Common. Another source located at Lodsworth (10 miles from the Wealden glass furnaces) is documented as a supply of sand exploited by glassmakers in 1629 (Kenyon 1967; 35). However, at Little Birches and Bagot’s Park, Welch (1997; 45) believes that a nearby source of white quartz pebbles at Cannock Chase may have been exploited by the glassmakers. Crossley (1998; 177) points out that a small sand quarry is located on a hillside only 600 yards from the north-Yorkshire sites of Hutton and Rosedale

Kenyon (1967; 35) states that specific sand sources were used to produce clear crystal glass, however local sands could be used to produce forest glass and the low price of the finished objects did ‘not allow for the high transport cost of imported sand'. Further evidence is added to this by Godfrey (1975; 157) who notes that 17th century crystal glass producers in London used sand imported from Maidstone in Kent, over 30 miles from London, whereas London's green-glass producers used a source in Woolwich, only 6 miles from the City of London. This can certainly not be considered direct evidence that local sands were used at all the forest glass producing sites in operation during this period. However, it seems likely that any importation of sands to a forest glass furnace site was limited due to the cost associated with its transportation. It cannot be said with absolute certainty that sand was not imported to forest glasshouses, and hopefully this is a hypothesis that can be tested somewhat using the results of this study.

1.2.3 Alkali and lime

Due to the high temperature at which silica melts (*c.* 1700°C), it is necessary to add a flux to lower the melting point to something achievable in an ancient furnace. This flux was a form of alkali and there were three main sources of alkali used by glassmakers from prehistory to modern times. These were the ashes of sodium-rich halophytic plants, a mineral source of sodium, generally known as natron, and the ashes of trees and ferns, rich in potassium. In a very basic sense this is also the chronological order in which they were exploited, but with much overlapping.

During the medieval period there were two glass making 'traditions'; one in the North and one in the South, and they used two different sources of alkali ash (Smedley and Jackson 2002a; 23). The Southern used marine and halophytic plants, rich in sodium. Biringuccio, writing in 1540 describes the use of sodium rich salts or ash derived from the saltwort (see section 1.2.1). He also mentions the use of lichen or fern as an alternative, but this will result in the production of an 'inferior glass'.

The glassmakers in the north of Europe more commonly used potash rich wood or bracken ash. This was written about by Theophilus in the 12th century and Agricola in 1556 (see section 1.2.1). Beech ash was generally preferred according to documentary accounts, but oak and pine were also mentioned (Smedley and Jackson 2002a; 23). The use of different species would result in different melting processes and necessitate the use of different recipes. However, if a particular wood was used to fire the furnace there would be a readily available supply of ashes that could have been used in the glass batch.

However, the ashes from the furnaces were clearly not always used. At Knole in Kent (Lennard 1905; 127-8) the glassmakers purchased ashes at the start of the furnace's operation. However, according to Godfrey (1975; 158), once production was underway, the purchasing of ashes disappears from the financial records of glasshouses. More evidence for the purchase of plant ashes comes from Dawson (1905; 10-11) who notes that in a letter dated to 1567 Jean Carré wrote that he was acquiring a source of soda from Spain to use as his flux. Presumably this source of soda was plant ashes. This source of alkali may have only been used at his crystal glass furnace and not for the production of forest glasses. The introduction of coal as a fuel in the early 17th century would have provided the glassmakers with a problem. The ashes necessary for producing glass would have to be sourced from elsewhere.

Previous analytical work on forest glasses has shown that the quantities of soda and potash, both total and relative quantities, alter depending on the production location and that there may also be patterning by time period (see section 3.3). Based on these studies the approximate chronological pattern, in terms of alkali levels, shows an initial decrease in total alkali levels during the 16th century in the Weald and Staffordshire (see Kenyon 1967; 39), followed by an increase in soda levels, which dominate the alkali content at the latest sites of Bickerstaffe and Haughton Green (see Vose 1994; 57 and 1995; 16). This pattern would appear to fit with the purchasing of soda-rich plant ashes at later sites. Bickerstaffe is not a coal-fired furnace, so the change in recipe may have occurred before the switch to coal was complete.

As introduced above, the different alkali sources thought to have been used by forest glass producers have differing compositions and will produce glass with varying compositions, and therefore melting and working properties. Some work has been carried out on the composition of wood and plant ashes used by ancient glassmakers, and a brief summary of a selection of this work is presented below.

Chemical analysis

Work by Smedley, Jackson et al. (2000, 2001, 2002a, 2002b, 2004, 2006) has involved the analysis of various ashes and the production of model glasses from them in an attempt to reconstruct the recipes used in forest glass production (see discussion on recipes section 1.2.5). A summary of some of their analyses of ashes are presented in tables 1.2 and 1.3 below. Beech, oak, bracken and birch ashes have been analysed and variations in their chemical compositions can be seen. Also presented below are the chemical compositions of seaweed (Dungworth et al. 2009) and a selection of analyses of plant ashes (Barkoudah and Henderson 2006), all possible raw materials used for forest glass production (tables 1.4 and 1.5, respectively).

Variations between the compositions of different species can be seen. However, as noted by the authors and others (also see Sanderson and Hunter, 1981; Hartmann, 1994 among others) the variability between species is overshadowed by the high level of intra-species compositional variation. This compositional variation can be due to the soil upon which the plant is growing, the parts of the plant used, the season it is harvested and the method of ashing (see Barbaste et al. 2002; Horn et al. 1993; Misra et al. 1993; Smedley and Jackson 2006). The compositions listed in tables 1.2-1.5 should therefore only be thought of as a guide to possible compositions of these ingredients, rather than their actual compositions. Perhaps the most important point to note, one that is very clear, is that plant and seaweed ashes have different alkali (Na_2O and K_2O) levels to wood and bracken ash. Glasses produced using plant and seaweed ash will have higher levels of soda than those produced using wood ash, but may have similar soda and potash levels. This pattern can be seen in the composition of previously studied forest glasses, as discussed above. Later forest glasses contain higher levels of soda and are therefore likely to have been made using plant ashes as well as, or instead of, wood and bracken ashes.

Hartmann (1994; 118) notes that there is an increase in chlorine and zinc levels in late medieval glasses found in the Eichsfield region of Germany. This, he suggests, may be due to the addition of chlorine-rich grasses or salt, but both of these suggestions have problems. The addition of salt does not explain the associated increase in zinc levels in these glasses, and the sheer quantity of grass ash needed would seem to discount its use. However, it may have been added to the glass batch along with another plant or wood ash.

	SiO_2	Na_2O	K_2O	CaO	MgO	Al_2O_3	Fe_2O_3	P_2O_5	TiO_2	MnO	SO_3	Total alkali
Beech	18.03	0.59	19.98	31.07	6.95	0.92	0.94	15.26	0.07	6.2	n/a	20.57
Oak	6.99	0.47	14.57	63.37	4.18	1.85	2.45	2.91	0.13	0.36	0.73	15.04
Bracken	15.17	2.24	37.28	9.02	4.88	0.46	3.55	7.55	0.01	0.05	3.68	39.52

Table 1.2: Compositions (wt%) of beech, oak and bracken ashes by WDX (Jackson and Smedley 2004; p.39, t.4).

	SiO_2	Na_2O	K_2O	CaO	MgO	Al_2O_3	Fe_2O_3	P_2O_5	TiO_2	MnO	LOI	Total alkali
Birch	16.82	0.36	10.91	27.78	4.02	3.01	2.45	3.65	0.13	6.31	24.56	11.27
Bracken	24.98	0.48	35.07	8.94	2.27	0.45	0.31	3.08	0.03	1.19	23.2	35.55

Table 1.3: Ash analysis by XRF (wt%) LOI-loss on ignition (Smedley, Jackson and Welch 2001; p.204, t.2).

	$^{87}Sr/^{86}Sr$	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	Cl	K_2O	CaO	TiO_2	MnO	Fe_2O_3	SrO	PbO
Seaweed	0.70932	8.7	8.2	0.6	1.7	1.7	33.3	0.6	14.9	25.6	0.11	2.63	1.34	0.74	<0.05

Table 1.4: Chemical and Sr isotope analysis of seaweed (Dungworth et al. 2009; p.124 t.5.2).

	Na_2O	K_2O	CaO	MgO	Al_2O_3	Fe_2O_3	TiO_2	MnO	Sr (ppm)	Σalkali
Salsola vermiculata	19.4	25.5	4.17	2.26	0.12	0.07	0.01	0.005	97	44.9
Salsola vermiculata	21.2	19.1	5.46	2.57	0.08	0.04	0	0.003	191	40.3
Salsola vermiculata	28.7	11.9	1.96	1.03	0.16	0.08	0.01	0.005	566	40.6
Salsola sp.	16.9	29.4	4.81	3.57	0.34	0.2	0.02	0.057	470	46.3
Salsola sp.	21.2	14.3	4.11	2.21	0.32	0.18	0.02	0.015	358	35.5
Salsola sp.	33.8	10.2	2	2.21	0.25	0.14	0.01	0.028	178	44
Salsola sp.	15.1	29.2	10.58	3.58	0.65	0.36	0.04	0.041	898	44.3
Salsola sp.	11.7	33.7	10.83	3.6	0.83	0.46	0.05	0.037	1174	45.4
Salsola jordanicola	28.6	10.7	1.96	2.44	0.27	0.14	0.01	0.013	208	39.3

Table 1.5: Chemical analyses of plant ashes from Syria (Barkoudah and Henderson 2006; 306).

Isotopic analysis

In terms of the isotopic part of this study it is the strontium content of the ashes that is most important. Strontium isotopes give information on the source of lime present in the glass, and it is assumed that the bulk of the lime present in forest glasses is derived from the plant ash. It is however likely that a certain portion will be present in the sand source used and this will contribute a smaller proportion to the finished glass. As noted above the strontium concentration will depend on the species of plant or wood used, the soil on which it grew, possibly the season it was harvested and the preparation process. It is therefore highly variable. The isotopic ratio of the strontium present in these ashes is a reflection of the isotope ratio of the underlying geology on which it grew (Henderson et al. 2009; 78). The possibility of strontium originating from a separate addition of lime is discussed below.

The use of seaweed as an alkali raw material has also been explored, most recently by Dungworth et al. (2009). Seaweed has a particular strontium signature; a high concentration and $^{87}Sr/^{86}Sr$ close to that of modern seawater (~0.7093). This study was able to show that this strontium signature is also found in glass made using seaweed (ibid.; 124). The samples analysed were glasses produced at the 17th century site of Silkstone in Yorkshire (120 km from the coast). The discovery that glass was being produced using seaweed showed that this material may have been traded large distances to the site. This challenges the commonly held belief that raw materials for forest glass production were always sourced locally due to the low value of the products. This finding will be explored further in this thesis.

Lime content

Some authors have also suggested that lime may have been added as a separate ingredient (see Hartmann 1994; Schalm 2004 among others). This question of the intentional addition of lime in forest glasses has remained an important one in the study of archaeological glasses for a long time. Godfrey (1975; 157) believes lime was never intentionally added to the glass batch as a separate ingredient in England. However, it would have to be intentionally added to some specialised glass batches, such as Venetian cristallo (ibid.). Without this addition these glasses, made from refined ashes and pebbles, were unstable and have devitrified over time. This is due to the use of pebbles, rather than sand, and the refining of plant ashes leading to a lack of lime being added as an impurity. Where wood ashes were used in forest glass production they were not refined and are high enough in calcium to provide the glass with the levels of calcium found by chemical analysis (see tables 1.2 and 1.3)(Verità 2005; 667).

Previous analytical work has shown that there is a chronological patterning in the lime levels found in forest glasses (see section 3.3). Glass produced from the mid-16th century onwards is characterised by increasing lime contents and decreasing total alkali contents, more specifically potash contents (Mortimer 1997; 39). Mortimer (1997) refers to these glasses as high-lime low-alkali (HLLA) glass and Hartmann (1994) as woodash-lime glass. Hartmann suggests that this later glass type could have been produced using a mixture of 20% limestone, 20% beechwood ash and 60% quartz sand (ibid.; 118). Schalm et al. (2004; 1648) believes that in Germany it may even be possible to define a period of wood-ash and sand production from 1000-1400 and wood-ash, sand and lime from 1400-1800.

Smedley et al. (2001; 206) have shown that a glass produced using birch ash and sand can have a lime content in excess of 21 wt%. This is within the range of lime values for HLLA glasses, but it is not HLLA glass due to its high alkali content. The use of lime in forest glass production cannot therefore be completely discounted or proved at this stage. If lime was added it will not only affect the calcium oxide levels in the glass, but also the strontium concentration and isotope ratios. It must therefore be considered as a possibility when discussing the results of this study.

Freestone et al. (2003; 27) have demonstrated how natron based glasses deriving their lime from either coastal or limestone-bearing inland sands vary in terms of their strontium concentration and isotope ratios. This is a very different situation to that of forest glasses as all the lime in these natron glasses is derived from the silica source. However, the results of their study may still be useful when looking for evidence of the addition of lime to forest glasses, either as part of the sand source used, or as a separate addition.

The final issue which must be discussed is the possibility of two lime-rich sources being used and both contributing strontium to the glass. Freestone et al. (2005) and Degryse et al. (2009b) have been able to show, using strontium isotopes, that Roman high-iron, manganese and titanium (HIMT) glass was very likely produced by the mixing of two different lime-rich raw materials. Unlike the likely situation in forest glasses, i.e. two different ashes being mixed, these two sources are two types of lime-bearing sand. However, in principal their studies have shown that the mixing of lime, and therefore strontium, sources in ancient glass production can sometimes be identified using isotopic analysis.

1.2.4 Cullet

Cullet, or broken glass, was added to glass batches, not only for recycling, but also because it lowers the melting point of the batch. The glass breakages on site were seldom enough to provide the glassmakers with the quantities necessary for their recipes. Godfrey (1975; 159) believes that nearly all glassmakers had to buy broken glass. She states that it was sold commercially and was often shipped around the coast, and also at times exported or imported between countries (ibid.). At one stage the price of cullet went up sufficiently that the London glaziers could sell their cuttings to French glassmakers.

The possible recycling of glass is a notable problem when attempting scientific analysis in the hope of finding site-specific chemical or isotopic signatures. The composition of glass produced using cullet brought from another site will be a mixture of the raw materials used and that of the cullet. If these two types could be separated and characterised they could provide evidence of trade in cullet. However, in practice recycling generally obscures site-specific chemical compositions. When discussing the results of this study it will be important to bear this in mind. Even though the chemical compositions of the glass produced at a site may be influenced by the mixing of glasses, it may still be sufficiently different, in some respect, from glass produced at other sites and therefore still provide a useful means of identifying a site-specific composition.

Using isotopic analysis some previous studies have been able to show mixing where it has occurred in a variety of ancient glass production locations and periods. Henderson et al. (2009; 92) found evidence for the mixing of two plant ash glasses at the site of Raqqa in Syria. This evidence is based on mixing lines found in a bi-plot of neodymium isotope ratio vs. strontium isotope ratio. The results can even be used to suggest, very approximately, what the isotopic composition of the glasses that were mixed may have been. It is hoped, therefore, that the isotopic methodology used in this study may be able to identify where mixing of different glasses may have occurred at forest glass production sites.

1.2.5 Recipes and proportions of raw materials

It is important to understand the proportions of raw materials used by forest glassmakers to allow the production of accurate model glasses (see section 3.4). Work by Smedley, Jackson et al. (2000; 2001; 2002a; 2002b; 2004; 2006) has attempted to define the recipes used by forest glassmakers. The writers of medieval recipes (see section 1.2.1) tended to list an alkali, and the proportions of alkali and silica, but not how these proportions were measured. The most common proportions were 2 parts ash to 1 part sand/silica based on written accounts found in surviving manuscripts. Smedley and Jackson (2002a; 27) found that volumetrically measured batches of this proportion resulted in excess silica. It was therefore concluded that the ratio 2:1 was measured by weight and not volume. When observing ash and sand, it becomes clear that this would be the case as similar volumes of ash and sand would have a mass that differed by a factor of 50.

The compositions of the model glasses produced show similar trends to the compositions of the ashes from which they are formed (compare tables 1.2 and 1.3 with tables 1.6 and 1.7) (Jackson and Smedley, 2004). For example, the ash with the highest lime levels, oak, produces glass with the highest lime levels, and so on. The glasses were produced using beech, oak and bracken ashes mixed with Loch Aline silica sand, a very pure sand source, in varying ratios and fired at temperatures between 1100 and 1450°C. Slip cast mullite (aluminum silicate, $Al_6Si_2O_{13}$) crucibles were used for the melting experiments.

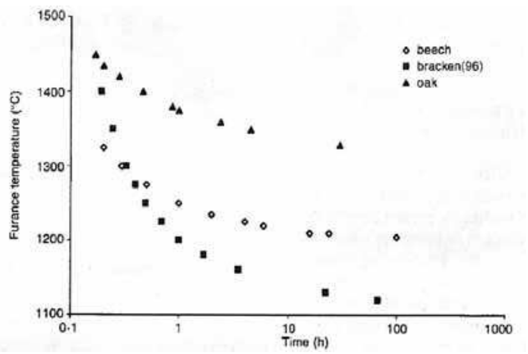

Figure 1.1: Melting behaviour of 2:1 (wt) beech, batch oak and bracken mixtures with sand (Jackson and Smedley 2004; 39, f1).

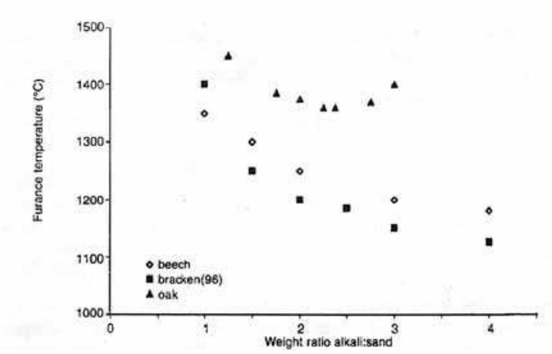

Figure 1.2: Temperature required to achieve batch- free melts after 1 hour melting time for ash sand mixtures (Jackson and Smedley 2004; 40, f2,).

Figures 1.1 and 1.2 show that the amount of time required to melt a batch is decreased by increasing the temperature and that the temperature required is related to quantity of alkali present. The total alkali ($Na_2O + K_2O$) present in the ashes is 20, 15 and 40% for beech, oak and bracken respectively (see tables 1.2 and 1.3). Figures 1.1 and 1.2 shows that these levels are directly related to the temperature and amount of time needed to produce a glass. Lime has the opposite effect, too much will increase the temperature and time required. However, it is a necessary component in the finished glass as a stabiliser (see section 1.2.3).

The temperatures required for melting a glass made with this particular oak ash are considerably higher than those for these beech or bracken ashes. The implications of this are that if oak was used as the alkali the process of glass making would have to be altered. The furnace itself would have to be able to achieve these high temperatures, perhaps with the use of a different fuel source (Jackson and Smedley 2004; 41). However, as discussed throughout this section the composition of the ashes of these tree species are highly variable and this single oak analysis cannot be taken as absolute proof of the properties of glass produced using any oak ashes.

Increasing the quantity of ash decreases the required temperature to a point and then its effect lessens, or in the case of oak starts to increase the required temperature. The ratio of 2:1 discussed above seems to be a sensible trade-off between conserving the ash resource and being able to achieve a batch-free melt at a reasonable temperature. This shows that the medieval glassmaker understood the behaviour of the different raw materials and chose a ratio of 2:1 based on this.

	SiO_2	Na_2O	K_2O	CaO	MgO	Al_2O_3*	Fe_2O_3	P_2O_5	TiO_2	MnO	SO_3	Σalkali
Beech	48.97	0.77	11.91	18.03	4.29	1.35	0.66	9.23	0.02	3.7	<0.01	12.68
Oak	46.41	0.42	5.63	35.53	2.35	6.25	1.08	1.75	0.07	0.2	<0.01	6.05
Bracken	62.03	0.83	21.33	6.38	3.58	0.59	0.26	4.01	0.01	0.35	<0.01	22.16

Table 1.6: Composition (wt%) of beech, oak and bracken glasses (2:1 ash:sand)
* Al_2O_3 is elevated in the finished glasses due to contamination from the sand during milling and the crucible body.
(Jackson and Smedley 2004; t.5, p.40).

Table 1.7: Chemical compositions of model glasses (wt%)
(Smedley et al. 2001; t.3, p.206).

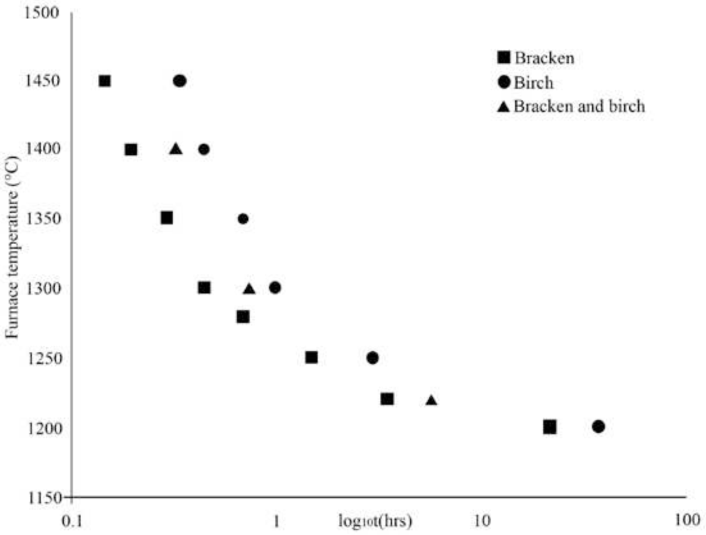

Figure 1.3: Melting curves for bracken and birch batches
(after Smedley et al. 2001; 205, f.3).

Figure 1.3 shows a similar trend to figures 1.1and 1.2, and also the effect of mixing two alkali sources. The curve for a mixture of birch and bracken lies between the two other mixing curves. It can therefore be seen from the results of Smedley et al. (2001) that it is possible to predict the temperature and batch free time when mixing two ash sources if these variables are known for the two separate sources.

Table 1.7 and figure 1.4 shows how the composition of the glass produced compares with the glass found at the site of Little Birches. On first inspection of the compositions it is clear that the closest model glass composition to that found at Little Birches is a mixture of birch and bracken (ibid.; 206). When CaO is plotted against total alkali (K_2O + Na_2O), this link becomes even clearer (figure 1.4).

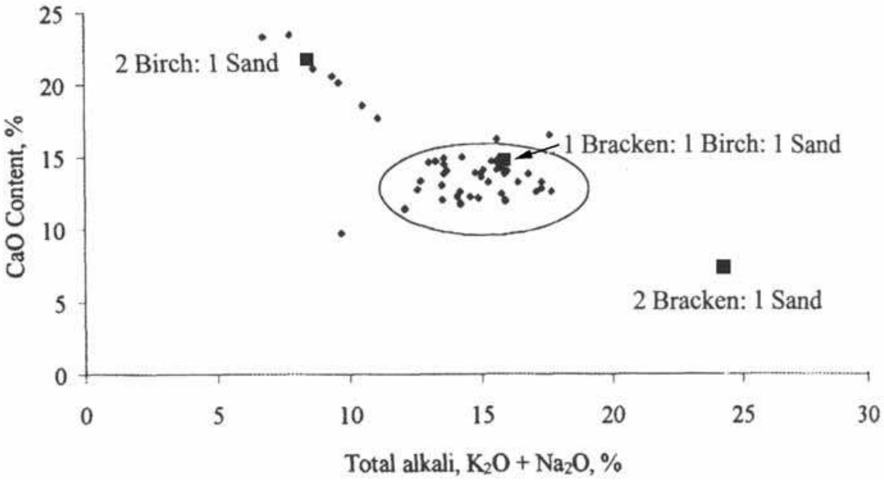

Figure 1.4: CaO vs. total alkali (wt%) for the three model glasses and some archaeological glasses from Little Birches (Smedley, Jackson and Welch, 2001; 206, f.4).

Due to the high variability in chemical compositions even within a specific plant species, the conclusions from this work are not definitive. However, the results suggest that a mixed-ash source consisting of bracken and birch ash may have been used in the forest glass produced at Little Birches. There are many oxides present at very different levels in the glasses from Little Birches compared to the model glasses, including sodium, magnesium and manganese oxide. These variations may be due to the use of different species of plants, or the use of bracken and birch ashes which simply have a different composition to those used to produce the model.

What can be learned from these informative studies, and those on alkali sources discussed above, is that the glassmaking recipe was a 2:1 ratio of ash:silica measured by weight. Also, that it is very difficult to distinguish between the ashes of different tree species due to their high levels of intra-species variability. However, it will be possible to discern the difference between the use of trees or plant ash, and may be possible to suggest where bracken ash was used rather than wood ash.

1.3 Furnaces

Three basic types of furnace are found at the sites in this study. They will be discussed in detail on a site-by-site basis in chapter 2. However, it is necessary to understand what, if any, effect their design will have on the types of glass produced at each site. The three types are; rectangular, winged and coal-fired. Table 2.1 summarises which types of furnace were located at each site. There are two ways in which the furnace design can indirectly and directly alter the types of glass produced.

Firstly, by increasing the achievable temperature and allowing glasses of higher melting points to be produced (see section 1.2.5). This is not a direct change brought about by the furnace design, but may have had an effect on the types of glass produced at a site. It would be necessary to experiment with the melting points of various glass recipes and temperatures achievable in furnaces to investigate this further.

Secondly, by altering the environment in the furnace and thereby altering the colour of glass produced. The main reason for alterations in colour in forest glasses is their iron content. Those with a higher iron level will be a darker green. However, it is possible to further affect this colouration by altering the oxygen levels in the furnace. By altering the oxygen levels it is possible to alter the equilibrium between iron (II) oxide (FeO) and iron (III) oxide (Fe_2O_3). Under oxidising conditions Fe_2O_3 predominates, which gives the glass a darker green or brown colour, and under reducing conditions FeO predominates, giving the glass a paler blue or green colour (Pollard and Heron 1999; 171). The alteration of furnace conditions may account for some of the differences in colour seen in the glasses sampled from each site. The colours of glass found at each site will be discussed further in section 2.7.

The three furnace types introduced above have many structural differences that alter their operation. The rectangular furnaces are simple structures with two sieges on either side of a fire trench, an arched roof and are heated with an external fire. The central portion of winged furnaces is fairly similar. The main differences are the wings on either side of the stoking area. In these wings some, or all, of the subsidiary glassmaking activities could take place, namely the fritting of the batch, prefiring of the crucibles, the reheating of the glass during blowing and working, and annealing (Wilmott 2005; 79).

The change to winged furnaces coincided with an apparent increase in efficiency in terms of the levels of fuel used by forest glassmakers. This is thought to have been brought about by increases in the price of wood at this time (Crossley 1991; 413). This increased efficiency was probably linked to an increase in the temperatures achievable in furnaces, allowing glass to be melted in a shorter time. One possible explanation for this is the introduction of an increased level of oxygen to the fire. These higher temperatures would allow glass types of differing compositions to be produced. It is also therefore likely that the glass made in a winged furnace may have been melted in a more oxidising environment than that found in rectangular furnaces. This would lead to a darker appearance in the finished products (see above).

Coal fired forest glass furnaces can be similar in plan to either the rectangular or winged furnaces. However, the major difference with furnace design was that the fire was placed at the centre of the furnace. The central location of the fire was due to the shorter flame travel of a coal fire and made it necessary to incorporate passages for the removal of ash (Crossley 1983; 152). Coal also needed more oxygen to burn successfully and so increasingly elaborate flue systems needed to be built under the furnaces (Vose 1980; 83). At some of these furnaces closed or lidded crucibles have been found, used to protect the glass melt from the smut and sulphurous fumes given off by the coal fire (Pilbin 1937; 301; Vose 1994; 45).

The environment in these furnaces is therefore likely to have been more highly oxidising than earlier wood-fired furnaces. However, where closed or lidded crucibles were used the levels of oxygen interacting with the glass will have been lower and therefore the environment more reducing. The glass produced in coal-fired furnaces may therefore have been produced in either an oxidising or reducing environment and could therefore be dark or light in colour.

1.4 Summary

The development of glassmaking in England from the Roman period to the 17th century is hard to trace at times and very well documented at others. Periods of foreign influence, political control and internal development have influenced the production of glass in myriad ways. Some of these factors, such as the arrival of new glassmakers, will have an impact on the types of glass produced, and therefore the results of this study.

The major focus of this project is on the chemical and isotopic analysis of glass and raw materials. From previous work it is understood that the results of this study will probably not be able to provide a means of defining the specific species of trees and plants used by forest glassmakers. However, the results of chemical analyses will be able to show general trends, such as the use of a soda-rich plant ash rather than a potash-rich wood ash.

The isotopic ratios present in the ashes will be independent of many of the factors discussed above, as they are independent of the species used. It is therefore expected that the isotopic analyses will provide the best means of discerning differences between the production sites.

The use of different furnaces will not directly alter the chemical or isotopic composition of the glasses produced. However, their development may have allowed the production of different glass types. It is therefore important to note the types of furnaces employed at each site when discussing the results of the analytical study.

Chapter 2: Production sites

2.1 Locations of forest glassmaking sites

2.1.1 Introduction

‘Different traditions of scholarship have increasingly located the pre-industrial countryside as a key arena of social and cultural transformation’
(Johnson, 1996; 38)

Glasshouses in medieval Europe operated in two types of locations, the forest and the town, and therefore worked in very different social and economic conditions (Polak 1975; 35). Glass-making was a rare urban industry in the medieval period and, in fact, a relatively rare industry anywhere in the British Isles until the end of this period (Schofield and Vince 2003; 126). Operating in the forest gave clear advantages as all the glassmakers’ raw materials necessary to produce forest glass could be found there: sand, (ferns), wood for ashes and fuel. However, the most important of the reasons for operating in woodland was the easy access to firewood.

Glassmakers working in towns would have a far greater problem obtaining this resource. Of course, the benefit of working in a town was the proximity of customers. If the town was large enough, the needs and demands from different social groups could stimulate specialised and sophisticated production (Polak 1975; 35). Transport links would also be better in the city and access to monetary loans and foreign exchange. In the 16th century and later, urban glassworks became more common and with the replacement of stoneware bottles by glass vessels in the mid-17th century (and thus the creation of a mass market for the products) the industry was usually associated with towns (Schofield and Vince 2003; 128). In this case the balance between production at source and production at the market was tipped by a change in the demand for glass and, perhaps, by changes in technology (ibid.). None of the glasshouses discussed in this study was located in an urban environment.

The environmental conditions for forest glassmaking were better north of the Alps, with larger forests, more navigable rivers. Production of glass in towns was less widespread in the north of Europe than in the south. Glasshouses continued to operate in forest environments until well into the modern industrial age.

2.1.2 Medieval environment and settlement patterns in England

Figure 2.1: Map of the distribution of wood-pasture, champion and upland landscape in England annotated with the sites discussed in this study (after Johnson 1996; 22, f.2.1).

Focussing on England it is possible to view how the differences in environment may have affected the locations of glasshouses. In terms of physical geography England varies between forests, fertile lowlands and more barren mountainous uplands and valleys. The ways in which these physical landscapes are used vary greatly, but can be divided into three types of rural landscape known as arable, wood-pasture and upland (see figure 2.1). Such a division is of course a huge oversimplification.

Johnson (ibid.) notes that recent work on English local history has stressed how different physical areas formed a complex interplay of different physical environments.

Nucleated settlements in arable landscapes consisted of more traditional, conservative communities with tighter social bonds and more emphasis on ‘neighbourliness’ than wood-pasture regions (Johnson 1996; 25). Their work was focussed more on arable rather than pastoral agriculture. Large nucleated settlements were much rarer in wood-pasture environments. Here settlements were generally clustered in small hamlets. In wood-pasture farming areas the ways of working were much more diverse and less community-based than in champion areas (ibid.; 26). Due to the wooded environment the fields were much smaller and laid out in strips, certainly not open to use by the whole community. In these areas manorial control was less strict and this allowed the scope for individuals to innovate new farming and other practices.

Therefore, was it the case that it was not only the proximity to raw materials that encouraged the growth of industry in wood pasture areas? The lack of manorial control may have played a part in this development. Johnson (1996; 27) believes that between the 14th and 16th centuries England saw a shift in the regional distribution of wealth away from arable towards wood-pasture areas. This must have been linked to a move to exploiting the woodlands for industrial activities.

2.1.3 Forests and the organisation of glassmakers

Forest glassmaking was practised over quite considerable areas of northern Continental Europe, in present-day Belgium, France and Germany, in many countries in central Europe including Bohemia, as well as England (Polak 1975; 37). There is a large quantity of archaeological and documentary evidence for these production sites from the 10th and 11th centuries onwards.

Where a good forested area for glass production was found and exploited by one glasshouse, it was often followed by many others. In the Thuringian forests, near Suhl, there were a large number of glasshouses that appear to have been established simultaneously (Polak 1975; 39). Documentary evidence shows that the glassmakers lived in villages on the edge of the forest and working in the glasshouses was part of their seigniorial duty (ibid.). Each furnace was probably in use until it became unusable, or the wood in the immediate vicinity was used up at which point another was built nearby. This pattern can also be seen in the Sussex Weald and Bagot’s Park, England, from the 14th to the 16th century (Willmott 2005; 48; Linford and Welch 2003; 37).

Some forest glass furnaces were temporary structures, and may have only existed for specific purposes. For example, in the northern region of Vendsyssel German glassmakers produced flat glass for the glazing of a manor house built between 1586 and 1591 (Polak 1975; 40). In different areas glasshouses became more permanently established at different times, usually linked to an increase in demand. In Lorraine, France, glasshouses were settled establishments by the mid-15th century, whereas itinerant glassmaking continues in England well into the 16th century, and in Denmark, into the 17th (ibid.). Glasshouses were often activated by landlords, as seen in Fehrenbach, and on a much larger scale in Bohemia-Silesia during the 16th and seventeenth centuries (ibid.).

Glassmakers operated beside potters in Lorraine, and ironworkers in northern Bohemia, the Ardennes, Sussex Weald and Småland (ibid.; Crossley 1998; 172). This is not surprising as these industries required the same fuels and means of communicating and sending products to markets.

Some contracts that survive from the 14th and 15th centuries show that glassmakers paid the landlords rent, payable twice a year. They were also bound to provide the landlord with a supply of glass, to both use himself, and sell on (Polak 1975; 41). They were allowed to use trees from the estate for fuel, plants for ashing, erect dwellings for workmen, grow corn and grass, set up mills etc. (ibid.). Early contracts worked very well in the glassmakers' favour. They were often granted freedom from certain taxes and from serving as soldiers. However, as the forest resources became more valuable, glass less rare and central governments stronger, the provisions became less common and useful.

2.2 The origins of the samples used in study

The sites described below are those from which samples have been taken for analysis in this study. They are discussed in chronological order and the important features of the discussion are summarised in table 2.1. Their locations can be seen in figure 2.2. Samples were taken from as many forest glass production sites in England as possible. They were sourced from museums and archaeological units across the country. The number of samples analysed by electron microprobe was only restricted by time. So, a large total number of samples were taken from a wide range of sites across England. A discussion of the types of glass sampled from each site can be found in table 3.1 and the results tables in the appendix.

There are of course various other glass production sites producing forest glass in this period, but it was decided to limit the discussion to those of most importance to this study. For a discussion of some of the other excavated sites, many of which are later, see: Wollaton, Nottinghamshire (Smith 1962), Bolsterstone, Yorkshire (Ashurst 1987), Silkstone, Yorkshire (Cromwell and Dungworth 2003), Gawber, Yorkshire (Ashurst 1970), Glasshouse Wood, Warwickshire (Ford 1971), Delamere Forest, Cheshire (Ridgway and Leach 1948; Newstead 1939).

The quantity and quality of evidence from the excavation of each site varies greatly. Interpretation of some of the features is therefore rather difficult. It was not within the scope of this study to be able to investigate each of the sites in great detail. So, for example, it is often not possible to say how much of the glass collected from each site by the investigators may have been imported cullet. However, the information presented below should give as detailed an introduction as possible to the sites.

A discussion of the various glass colours found at each sites follows the site descriptions in section 2.7.

Site	Location	Date	Products	Glass colour	Probable raw materials	Furnace type and fuel
Blunden’s Wood	The Weald	First half of 14th century	Vessel and window	Medium Blue-Green	Wood ash and sand[a]	Rectangular, wood fired
Knightons	The Weald	Mid-16th century	Vessel and window	Medium Green	Wood ash and sand[a]	Rectangular, wood fired
Bagot’s Park	Staffordshire	Mid-16th century	Vessel and window	Medium Green	Wood ash and quartz pebbles or sand[ab].	Rectangular, wood fired
Little Birches	Staffordshire	Mid-16th century	Window-crown (possibly some vessel)	Very Light Green	Wood ash and quartz pebbles or sand[ab].	Rectangular, wood fired
Buckholt	Hampshire	Late-16th century (*c* .1576-80?)	Vessel and window	Very Dark (Yellow-) Green	Unsure	Winged, wood fired
Buckholt West	Hampshire	Late-16th century (*c* .1576-80?)	Vessel and window	Very Dark (Yellow-) Green	Unsure	Insufficient excavated remains
Hutton	North Yorkshire	Late-16th century	Vessel	Dark Green	Wood ash/plant ash and sand[a]	Winged, wood fired
Rosedale	North Yorkshire	Late-16th century	Vessel	Dark Green	Wood ash/plant ash and sand[a]	Winged, wood fired
Glasshouse Farm	Herefordshire	Late-16th/Early-17th century	Vessel and window	Dark Green	Wood ash and sand[a]	Winged, wood fired
Bickerstaffe	Lancashire	Early-17th century	Vessel	Medium Blue-Green	Plant ash and sand[a]	Unsure, wood fired
Kimmeridge	Dorset	*c* .1617-1623	Vessel	Very Dark Green	Plant ash and sand[a]	Winged, coal fired
Haughton Green	Greater Manchester	*c* .1615-1653	Vessel and window	Very Dark Green	Plant ash and sand[a]	Rectangular, coal fired

Table 2.1 Summary table of production sites under discussion (see sections 2.3-2.6 for references for this information).

[a] See previous analytical work section in section 3.3

[b] See Welch 1997; 45

Figure 2.2: Locations of production sites discussed in this study.

2.3 Early (pre-1500AD)

2.3.1 Blunden’s Wood, Surrey (51°07’39 N 0°37’05 W)

Introduction

The Weald has long been identified as the major centre for glassmaking in medieval England (Dawson 1905; 8). The resources of the well-wooded western part of the Weald of Surrey and Sussex would have been very attractive to the medieval glassmaker. Glass was manufactured here from the 13th century until about 1620 (Crossley 1994; 64). After the mid-16th century Continental glassmakers were established in the Weald (Mortimer 1993; 1). The Wealden sites cease to exist following 1620, as coal became the only source of fuel for the furnaces and the foci of glassmaking moved elsewhere (Merchant et al. 1997; 31). 42 known or probable glassmaking sites in the Weald were listed in Kenyon’s *The Glass Industry of the Weald* (1967). Kenyon (1967) also divided the glass types found on Wealden sites into two groups: Early (pre-1567) and Late (post-1567).

A member of the Surrey Archaeological Society first discovered the site of Blunden’s Wood in 1959 virtually by chance. The site consisted of two mounds, one larger than the other, where pieces of crucible, glass waste and finished glass had been found. There is no documentary evidence for the use of this particular site.

Excavations

Blunden’s Wood was the first medieval glass furnace to be excavated in England (Crossley 1994; 66). The clay bank on top of which the furnace stood was to be removed as a source of clay by the brickworks that owned the site, so the discovery of the mound in 1959 was very lucky (Wood 1965; 57). Excavation took place very rapidly over three weekends in March and April 1960. The larger of the two mounds covered a sub-rectangular furnace (3.4 x 2.4m) with a straight central flue, fireplaces at both ends and sieges on either side (figure 2.3). The sieges (2.4 x 0.7m) each had two 38cm diameter circular depressions for crucibles. The flue was narrowed by glass scum that had poured over from the sieges, it would have been 61cm when first built. This glass scum seemed to have been deposited in two layers, possibly implying a break in the use of the furnace (ibid.; 58).

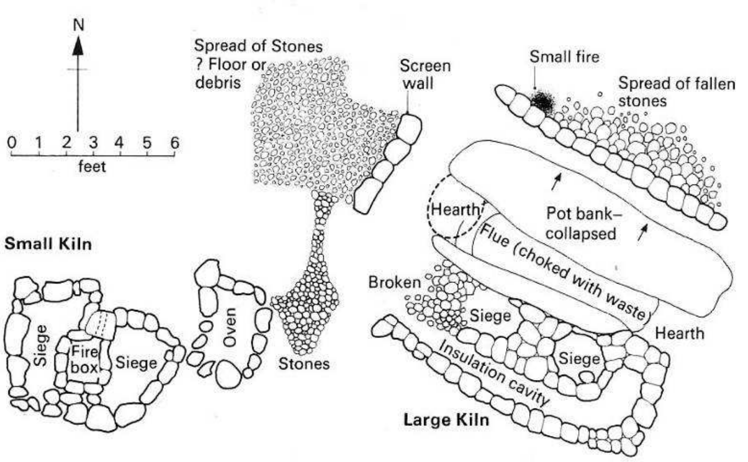

Figure 2.3: Plan of the medieval glasshouse at Blunden’s Wood (Vose 1980; 134, f.14).

The second smaller mound produced a number of features, which were more difficult to interpret. The main feature was an irregular heart-shaped furnace which measured 2.4 x 1.4m. This had a central clay-lined fireplace, a *tuyère* for the insertion of a bellows and cavities on either side, the one on the left was spattered with glass (Wood, 1965; 59). This was interpreted by Wood as a fritting oven, however, the splashes of glass and presence of a *tuyère* contradict this (Willmott 2005; 50). The presence of molten glass suggests that melting was taking place here; however its exact function remains unknown. The final structure consists of an oval of large stones, 0.75 x 0.45m, between the two furnaces. The small size of this ‘oven’ makes it difficult to interpret.

The glass

400 pieces of glass were recovered, although not all of the cullet was kept (Wood 1965; 65). Interpretation of the types of evidence found suggests that both vessels and windows were produced.

Wood (1965; 55) suggests that the sand used at this site may have been imported from Graffham , Sussex, however, there was a source nearby at Hambledon Common. He goes on to use analytical data to suggest that a local sand source was used, that wood, not bracken, ashes were the alkali source and that the levels of calcium oxide in the glass do not necessitate a separate addition of limestone (ibid.; 68; 61 note 7). This cannot be said with any certainty from the analytical data (Merchant et al. 1997). However, it is clear that potash glasses were produced at this site (see section 3.3).

Dating

It is not possible to date the site based on documentary evidence, as none exists. Archaeomagnetic dating was carried out on 16 samples taken from the furnace and this gave a date of *c*. 1330 (Wood 1965; 78). Pottery found during the excavation can be dated to the second half of the 14th century; however the stratigraphy of these finds is not recorded. Willmott (2005; 52) believes that this early use of archaeomagnetic dating, as with most dating techniques, is not without problems and leans towards the date from the pottery being more accurate.

2.4 Transitional (1500-1567AD)

2.4.1 Knightons, Surrey (51°05’51 N 0°32’57 W)

Introduction

The site of Knightons was accidentally discovered in May 1965 by the curator of the Guildford Museum. It is one of very few sites in the Weald that is thought to date to the first half of the 16th century.

Excavations

A series of excavations were undertaken at the site between October 1965 and May 1973 directed by Eric Wood. The excavation uncovered at least two phases of activity. The earliest furnace was of the traditional medieval rectangular design – rectangular, single-chambered, with a central flue running SW–NE and sieges on either side (figure 2.4). These sieges appear to have been able to take three crucibles each. It measured 4.5 x 3.2m externally and 3.4 x 2.3 m internally. This furnace had been heavily robbed and replaced by a second furnace. The second furnace was built overlapping the footprint of the northern corner of the first furnace. The only differences between the first and second furnaces were that the later of the two was slightly narrower, and its flue ran WSW–ENE. In a limited survey Scoville (1950; 37) notes that well-built 17th century furnaces generally lasted from between nine and 27 months. Also, there may have been a roof over the main furnace area, one large posthole was found 1.5m south-east of the first furnace and tiles were found in the area of the furnaces.

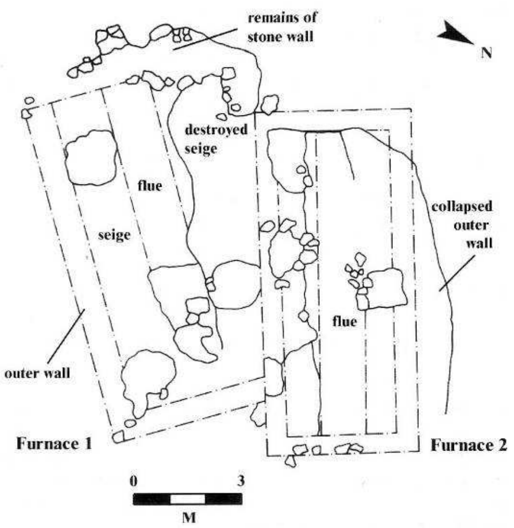

Figure 2.4: Furnaces 1 and 2 at Knightons (Willmott, 2005; 67, f.40).

A third furnace was found to the south of the first two (figure 2.5). This furnace had been more heavily robbed, but its layout is visibly similar to the two earlier furnaces. The excavation of the third furnace discovered lump glass, frit and scum, leading Wood (1982; 9) to believe that this may have been a fritting oven. However, the design of the furnace makes it much more likely to have been a third melting furnace.

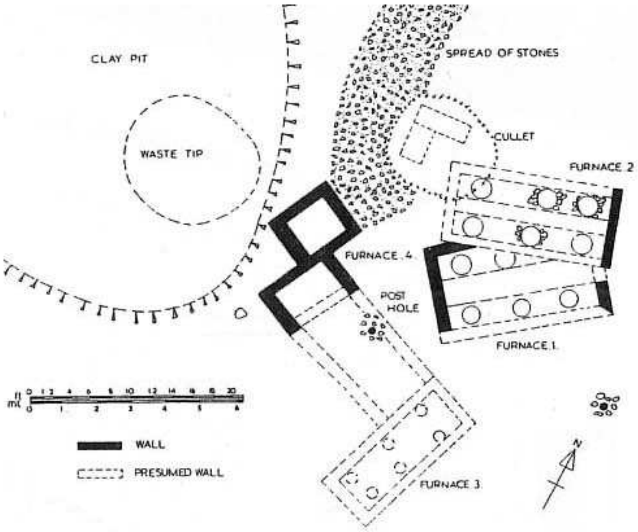

Figure 2.5: Knightons glasshouse. Plan of site (Wood, 1982; 9, f.3).

A possible fourth furnace was also found (figure 2.5). This structure consisted of two rectangular chambers (1.9x1.2m and 2.2x1.5m) set diagonally to each other sharing a common wall for one metre, within which was a gap of 60cm, representing a passage for hot gases to pass from one chamber to another (Wood 1982; 9). However, no evidence for how these furnaces were heated remains. The floors of these chambers were reddened from burning, but clean of ash, and had a thick layer made up of fragments of crown glass, bottlenecks and bases. These structures are interpreted as being annealing ovens similar to those illustrated in the French *Encyclopédie* of 1765.

The glass

The glass found at Knightons consists of window, vessel, drinking glasses, bottles, domestic ware, medical ware and distilling apparatus (Wood 1982; 19). 61.5 kg of glass was recovered from the site, including only a sample of the glass from the cullet store where 61 kilograms were found. Most of these 12,000 pieces were amorphous flat or curved, only 320 pieces were diagnostic of vessel types, or coloured. Almost all the glass was weathered and, apart from 46 pieces, all of the early Wealden type (i.e. probably pre-1567, see Kenyon 1967). Previous chemical analysis has shown the glass produced at Knightons to be of potash composition with relatively high calcium levels (Green and Hart 1987; see section 3.3). The alkali raw materials are therefore likely to have been some form of wood or bracken ash. As noted in section 1.2.2 there are two sand sources near the site which may have been exploited by the glassmakers.

Dating

Knightons has been dated archaeomagnetically to the 1550s. The best artefactual evidence for the dating of this site consists of a silver shilling of Edward VI dating to 1550, found in the east chamber of the ‘annealing’ oven (Wood 1982; 44). The majority of the pottery found at the site is of 16th century date, there are some 18th-19th century pieces but these are related to the nearby Basingstoke Canal, opened in

1796 (ibid.; 41). The presence of glassmakers in the Weald in the mid-16th century has been established through documentary research; however, none has been definitively linked with glassmaking at Knightons (Crossley 1994; 67). The large quantity of crown glass found at the site fits with the dating of the mid-16th century as the use of this technique becomes increasingly widespread in this period in England.

2.4.2 Bagot's Park (site 4), Staffordshire (52°50' 39 N 1°51'53 W)

Introduction

Glassmaking had begun in Staffordshire by the early years of the 14th century (Welch and Linford 2005; 210). Documentary evidence shows that pre-1585 glassmaking in this area was concentrated in three locations, two near Abbots Bromley, and one at Wolseley (Pape 1934; 75). Between the late-13th and 15th centuries there are references to this industry in terms of field and road names, and throughout the 14th and 15th centuries personal names occur which suggest the manufacture of glass (Crossley 1967; 44).

At Bagot's Park 15 glass furnaces have been uncovered in an area of approximately 1.5 square miles, each furnace presumably being abandoned either because its situation became uneconomical as the surrounding woodland was cut and the fuel had to be brought in; or because the furnace itself wore out (Charleston, 1984; 30). Documentary evidence linked the site with the manufacture of glass by Ambrose and Edward Hensey, from Lorraine, who were involved in setting up a furnace with Sir Richard Bagot in 1585 (Vose 1980; 110). However, the documentary research that followed the excavation was able to firmly date its use to the beginning of the 16th century. A charter of 1501 contains details of a croft on the excavation site granted to

Thomas Harvey of Abbots Bromley, glassmaker (Charleston 1984; 45). This makes Bagot's Park one of very few glasshouses dating to the first half of the 16th century.

Excavations

Figure 2.6: Main furnace at Bagot's Park (Willmott, 2005; plate 15).

The excavated site, site 4, is one of a large number of known glassmaking sites in Bagot's Park. Pre-excavation fieldwork and trial excavations were able to identify many of these sites where glass fragments were most commonly found (Crossley 1967; 51). The excavation took place over three weeks in August 1966. A large rectangular area was stripped and two furnace structures were identified. The first, to the north-east, was clearly the main melting furnace (see figure 2.6). It was a rectangular structure with a central flue and two sieges around 80cm wide, with space for three crucibles, 30-36cm in diameter on each (ibid.; 57). Its stone base was built on a pebble bank and it had a stone flue extension to the northeast and one made of brick to the south-west. The furnace was heated from two fires and the flames from these two fires met under a clay reverberatory roof (ibid.). Fragments of this roof were found, it was made of clay shaped with a stiffening of twigs, which burnt out as the clay hardened during the first firing (ibid.). One working hole cover was discovered and presumably, as there was space for six crucibles, there were six such holes in the furnace. As at Knightons, large postholes were found 1.5m from each end of the furnace with large stone packing. Part of the support for a tiled roof covering the whole furnace, found in the adjacent rubble, was similar to that seen in the Mandeville illumination (see front cover illustration).

The second furnace was more disturbed than the first. The excavated evidence was far less substantial; characterised by an oval patch of burning covered in places by stone slabs. There were also associated lines of brickwork and postholes. However, due to their disturbed nature, it was not possible to reconstruct their use. This was most likely an auxiliary furnace used for the annealing of vessels.

The glass

The majority of the glass found consisted of edges and bull's eyes from crown-glass sheets, and it seems probable that these were the main product of the furnace (Charleston 1984; 78). Fragments from a number of vessels including beakers, flasks and handled tankards were also found, many of these fragments were thought by Crossley (1967) to be imported cullet. However, much of the glass initially classed as vessel glass can now be identified as blowing waste from vessel manufacture, suggesting that many of these vessels were products and not cullet (Willmott 2005; 70). Therefore the proportions of vessel to window glass manufacture proposed by Crossley may have to be reconsidered.

A small number of glass samples have previously been analysed and these were all found to contain high levels of potash (Welch 1997; see section 3.3). This corresponds with the use of alkalis derived from bracken or wood ash. A few coloured glasses found at the site did contain more soda, however Crossley (1967; 62) believes that they were likely to have been imports due to their very small numbers.

Silica could have either come from sand or crushed pebbles. Sand deposits are present in the park, but none appear to be large enough to sustain glassmaking. In southern Derbyshire sand sources considered suitable for modern glassmaking occur in hollows in the carboniferous limestone. However, there are deposits of white pebbles in the marls of Bagot's Park itself that may have been used. Small fragments of these white pebbles occasionally found in waste glass from Bagot's Park provide evidence for this possibility (Welch 1997; 45).

Dating

Along with the documentary evidence discussed in the introduction there is a substantial amount of physical evidence to date this site to the first half of the 16th century. 38 burnt clay samples from the base of the main furnace provided an archaeomagnetic date of 1535 ± 35 years (Vose 1980; 177). This was also confirmed by the associated ceramics at the site, which all belong to the first half of the 16th century. So this glass furnace was in operation before the arrival of the Lorrainers who revived glass production here in 1585 (Godfrey 1975; 10).

Further archaeomagnetic dating of 22 glassmaking sites around Bagot's Park has shown that there were three phases of activity. An early phase with a few sites ending around 1300, a middle phase with many sites and possibly continuous production from the last few years of the 14th century until the middle of the 16th, and a late phase associated with the Lorrainers lasting 30 years from 1585 (Welch and Linford 2005; 211).

2.4.3 Little Birches, Staffordshire (52°46’03 N 1°59’55 W)

Introduction

During the 16th century glass production in Staffordshire was centred in the south-east of the county. There were two concentrations in this area, one at Abbots Bromley, around Bagot’s Park (see 2.4.2 Bagot’s Park), and another north-west of the town of Rugeley on the Wolseley estate, where Little Birches is situated (Welch 1997; 2). It was discovered in 1990 when earthmoving machinery disturbed a mound of debris on the edge of Rugeley Quarry (ibid.; 1). The material evidence found all dated to between 1300 and 1615. However, when a proper excavation of the site was carried out, two sites were revealed. One dating to the 14th century and the other to the mid-16th century. The earliest reference to the presence of a glassmaker in this area occurs in 1377, and more specifically to glassmaking in 1447 (ibid.; 2). However, none of this evidence can be directly related to glassmaking at Little Birches.

Excavations

The glass used in this study is from the later site, so the discussion of the excavations will focus on this site. The site took the form of a series of low mounds 30-40m south of the 14th century site. The largest of these mounds was found to be a large, well-preserved furnace, built of sandstone, measuring 4.3 x 2.2m (see Figure 2.7). It had a central fire trench, 50-54cm wide, and sieges approximately 1.6m long and 40cm wide. These sieges had the impressions of 30-35cm diameter crucibles on them, two on the north siege and one on the south. At either end of the furnace there were pairs of postholes. These may have contained posts that supported a roof structure (see Bagot’s Park and Knightons).

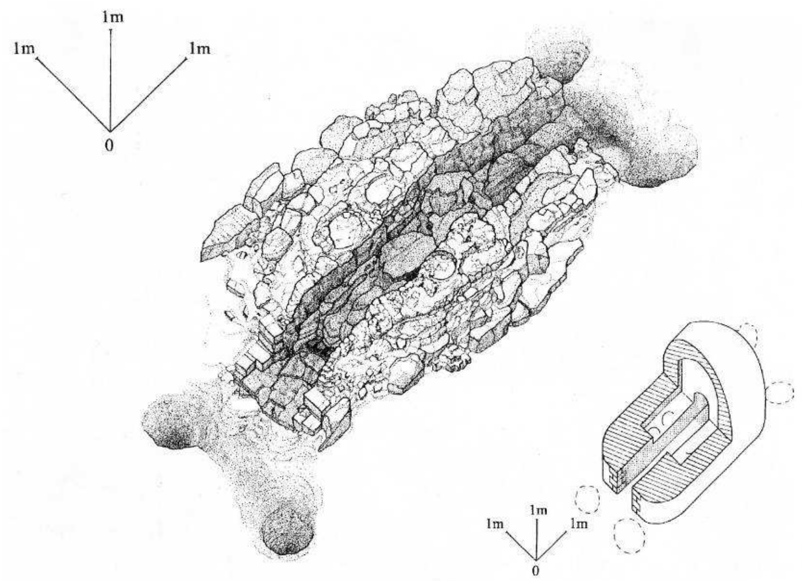

Figure 2.7: Axonometric view of the main furnace at Little Birches, with a speculative reconstruction (Welch 1997; 9, f.6).

A second furnace lay about 4m WSW of the first furnace consisting of two sides of what appears to have been a square structure. The south side was 1.6m long formed by a single course of sandstone blocks 10cm high either side of an opening 56cm wide that had been blocked at some stage with bricks. This gap may have been for the introduction of the glass produced and the structure may have been an annealing oven similar to that found at Knightons (see Figure 2.5).

A third furnace was located to the south of the first furnace. This had evidently been similar in design to the first furnace, but was more heavily disturbed. It was not possible to establish how this furnace related to the first chronologically. Three tips were also found nearby these furnaces, which all together contained almost 100m^3 of material.

Approximately 400 kg of crucible fragments were found at Little Birches, with 40% of that coming from the later site under discussion. There are no matches with the forms found at this site at any other site. Fragments of what are thought to be working hole covers were also found. These appear to have been around 22-23cm square, with a 3cm hole at their centres, suggesting that the working holes themselves were slightly smaller than 22-23cm.

The glass

A large quantity of waste glass was found at the site, especially in the tips. As at Bagot’s Park, a lot of the waste glass found contained small white chips, some of which were recognisable as small pebbles. Petrographic analysis was able to establish that these were quartzite pebbles, very similar to those found in local gravels (Welch 1997; 45). Generally these pebbles are quite resistant to destruction by impact, and it would have been difficult to crush them to a size suitable for the glass making process. One method that may have been employed by the glassmakers was to heat the pebbles then immerse them in cold water, leading to their disintegration. Previous scientific analysis has shown that the flux used was most likely derived from bracken or wood ash (Welch 1997; see section 3.3).

35 kg of blown glass was found at the site. However, only nine fragments of this total were found surrounding the earlier furnace. None of these were available for analysis in this study. Only 66 of the fragments found were recognisable as vessel glass, so it would seem that the major output of the furnace was window glass. However, what was found may not represent the total output, only what was left on the site when it was abandoned. Many of the window fragments had curved edges, suggesting that the type of window glass produced here was crown, which was also produced at the nearby site of Bagot’s Park, discussed above. The vessel fragments that were found are unlikely to have been produced on this site due to the diversity of the forms found and the presence of a number of well-attested continental imports (Welch 1997; 20).

Dating

As noted above there is no documentary evidence directly related to glass making at this site. Archaeomagnetic dating was carried out on samples from the clay in the south side of the main furnace. The dates obtained were 1533-1557 at 68% confidence and 1521-1565 at 95% confidence (Welch 1997; 16). These dates agree with the pottery found on the site.

2.5 Late (1567-1615AD)

2.5.1 Buckholt and Buckholt West, Hampshire (51°05’18 N 1°35’14 W and 51°05’36 N 1°35’55 W respectively)

Introduction

There are a number of documentary sources relating to glassmaking at Buckholt, most of which appear in the Walloon church register at Southampton. On the 7th October 1576 Jan du Tisac, Pierre Valliant and Claude Potier were described as ‘*ouvriers de verre a la verriere de Boucehaut*’ (‘glassworkers from the glasshouse at Buckholt’) (Charleston 1984; 83). There were several similar references, the last of which dates to the 4th of January 1579/80, when Monsieur du Hou ‘*verrieren a Bouquehaut*’ was admitted to communion (Willmott 2005; 79). It can therefore be accepted that, at a site near Buckholt, glass was being produced by immigrant glassmakers at least between 1576 and 1580. There are two sites near Buckholt, labelled on OS maps, which are probably related to these men.

Winbolt (1933; 18) believes that these immigrant glassmakers were forced out of the Weald by the English ironmakers with whom they were in competition for fuel supplies. Their contract with Jean Carré’s company ran out in 1576 and some time in this year they moved west along the Midhurst-Petersfield-Winchester road to

Hampshire. He (Winbolt 1933; 18) suggests that in 1580, once the fuel supplies of Buckholt had been exhausted, they moved further west to the Forest of Dean (see Glasshouse Farm section below), Newent and to Woodchester (see Baddeley 1920). The dating evidence for these sites is too imprecise to support this suggestion, but it is certainly a possible route the glassmakers may have taken. A resident of Worcestershire wrote in the 1590s 'as the woods about here decay so the glasshouses remove and follow the woods with small charge' (Godfrey 1975; 50).

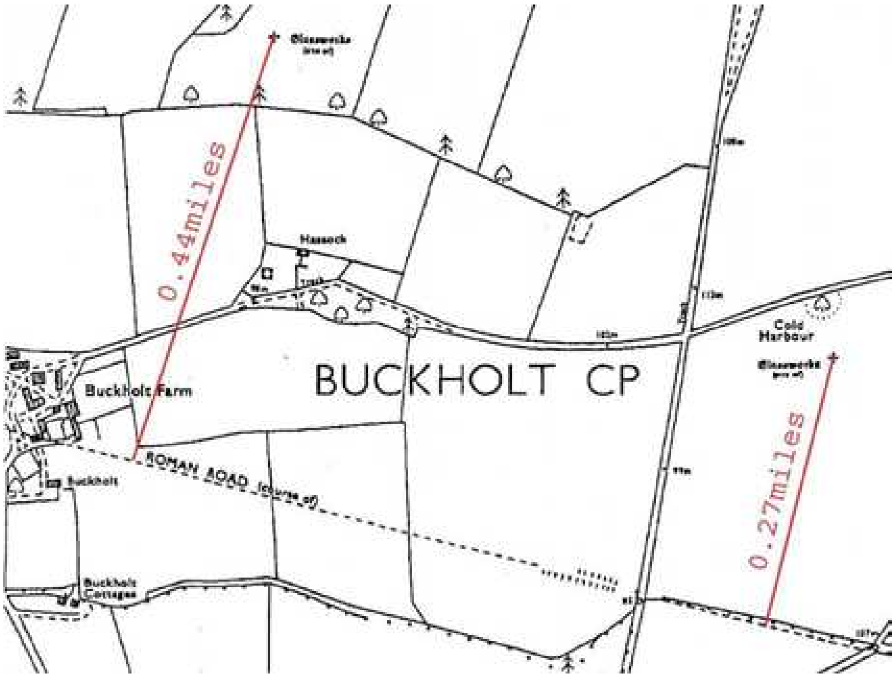

Figure 2.8: Map showing the location of the two glasshouses near Buckholt (after Ordinance Survey Map).

One of these sites was excavated in 1860 by the Reverend E. Kell (1861). However, due to his scant records it is difficult to say which one. His description of its location is "in a large field about a quarter of a mile from the Roman road" (Kell 1861; 55). Presuming that Kell could tell the difference between about a quarter of a mile (0.27miles) and about half a mile (0.44miles) it would seem that the site he excavated was that to the east (see figure 2.8). Therefore in this thesis this site shall be referred to as Buckholt and the other site as Buckholt West. In 1974 the Test Valley

Archaeological Committee re-excavated the site to assess plough damage (Russel 1985), however, they excavated the West site and the site at “Coldharbour Copse [was] not investigated”. However, this evidence is not conclusive and so it remains uncertain which site was excavated in 1860. The discussion below focuses on the 1860 excavation as the 1974 excavation was only a brief exploratory re-excavation. It is important to understand this earlier excavation as Kell was able to identify many features of the furnace which are important in terms of the dating of the site and suggesting who may have worked there.

Excavations

On the 21st of November 1860 Rev. Kell commenced digging at the site at its highest point. He found an oblong brick furnace with external dimensions of 1.25 x 1.8m (figure 2.9). This was surrounded by a number of irregular detached stone walls, the function of which Kell did not understand (Willmott 2005; 79). On further inspection, and with comparison to other excavated sites, it is possible to reconstruct this furnace as a central melting furnace with four attached wings for subsidiary glassmaking activities (see Rosedale, section 2.5.3). This winged construction is one that typifies later 16th and early 17th century furnaces and is generally acknowledged to be an indication of Huguenot workers.

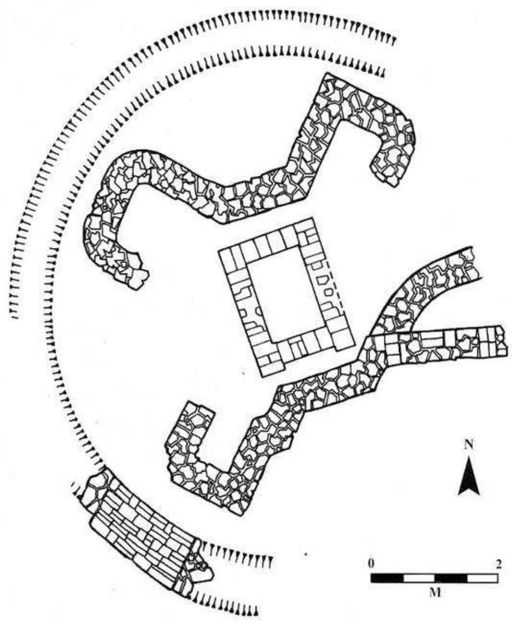

Figure 2.9: Plan of the furnace at Buckholt (Willmott 2005; 80, f.48).

The glass

Kell’s (1861; 56) description of the glass found is rather confusing. It does however seem that a large quantity of window and vessel glass was found. Some of the vessel glass found was decorated with white circles, dots and lines. His only mention of possible raw materials is to note that there is an abundance of wood nearby to produce wood ashes and flint could be found at the surface of this area to use as a silica source (ibid.). No previous chemical analyses have been carried out on glass from this site, so it is not possible to suggest probable raw materials. The glass is of a darker colour than that at most other sites (discussed further in section 2.7).

The glass analysed in this study originates from the 1974 excavation of the sites as none was available from the earlier excavation.

Dating

The dating evidence for this site consists of the documentary evidence for glassmakers in this area between 1576 and 1580 as discussed in the introduction. Also, the style of the furnace corresponds with this date. Unfortunately as there are two sites so close together, it is difficult to tell which site the documentary sources concern. It is quite likely that the glassmakers began at one of the sites, and at some time between 1576 and 1580 moved to the new site when the first became unusable.

2.5.2 Hutton, North Yorkshire (54°17’12 N 0°55’11 W)

Introduction

Evidence for glass production in northeast England in the later 16th century is very scarce. There are two sites dating to this period in North Yorkshire, both of which lie in the parish of Lastingham. The first site to be discussed is situated on Hutton Common, 1.5km south of Hutton-le-Hole. The only documentary evidence for either of these sites is a glassmaker referred to in the Lastingham parish register on the 2nd of March 1593 (Crossley and Aberg 1972; 107). This area contains all the natural resources necessary for glass production: timber, sand, fireclays and building stone, although it seems like rather an unlikely place for a glass furnace; on the open moorland of Yorkshire, very far from any large markets (Vose 1980; 155).

Excavations

The site was discovered in the late 1960s when clearance of bracken showed irregularities in the ground surface including stones covered with glass and wedge-shaped bricks from the flue arches (Crossley and Aberg 1972; 110). As this ground had never been ploughed the furnace remains survived above the modern ground level and resulted in a mound 0.1-0.6m high, and *c*.6 x 3m in size (figure 2.10). Two smaller mounds were found both of which had glass and burnt clay showing on their tops. There was also a small pit 20m to the north with a track leading from it back to the main mound. A magnetic survey of the site was able to confirm the visual observations with a strong anomaly at the main mound and weaker indications at the other two.

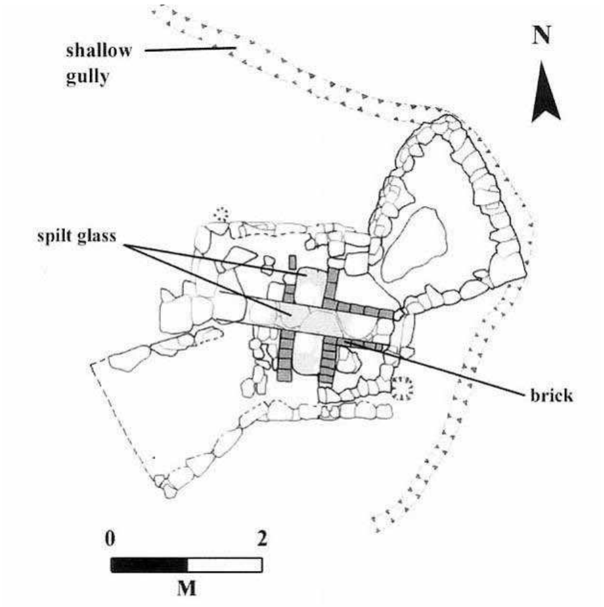

Figure 2.10: Plan of the Hutton furnace (*after* Crossley and Aberg 1972; 113).

Excavations took place in April 1971 in advance of the ploughing of the hillside. The main mound was found to be a glass furnace with two wings attached to the central furnace block. As the furnace was excavated it was found to have three periods of construction. In its first phase the furnace was relatively simple, around 3m by 5-6m with a central stone lined flue and a hearth at either end (Crossley and Aberg 1972; 111). The next period of construction resulted in a rebuilding of the furnace and the addition of two diagonally opposed wings to the furnace and the digging of a shallow gully to prevent groundwater from flowing into the furnace. The final phase of construction saw the central block of the furnace completely rebuilt, this time using brick in parts. The wings from the second phase were retained and a much larger ditch was cut. Five postholes were found to the north of the furnace, and eight to the south, the function of which was most likely to support a lightweight covering.

Another structure was found 3m west of the main furnace. The evidence was fragmentary and there was only a small quantity of glass waste associated with it. However, it was situated on severely reddened natural clay and surrounded by ash, so was used for some sort of heating. One explanation for this second structure is that it was an annealing oven and was destroyed when the addition of wings, used for annealing, made it superfluous (Crossley and Aberg 1972; 115). This structure was also surrounded by postholes and was therefore probably also covered by a roof.

The glass

A wide range of vessel forms including beakers and urinals were found at this site. Limited previous analysis has shown that some glass produced at this site is of a mixed alkali composition (Crossely and Aberg 1972; see section 3.3). This suggests that a plant ash was used, possibly along with wood ash, in glass production at this site. There is woodland and large quantities of bracken nearby which could have provided the necessary wood ashes. Sandstone outcrops in many areas in the vicinity, including Hutton-le-Hole Common, could have been prepared to give the silica necessary for glass production.

Dating

The single piece of documentary evidence shows there were glassmakers working in this area in 1593, but it does not mention this site specifically. A large quantity of pottery, including yellowy-green glazed coarse wares, common in the area during the late 16th century helped to confirm this date (Crossley and Aberg 1972; 152). Archaeomagnetic dating was also carried out at the site, and was able to suggest that the final firing of the furnace was during the last quarter of the 16th century.

In a waste heap to the south of the furnace a Groat of Elizabeth I was found. The exact date of this coin is not certain, but it was definitely struck in the first four years of Elizabeth’s reign (1558-1561) (Crossley and Aberg, 1972; 128). Two Nuremberg tokens were found in the western stokehole of the main furnace, most probably from the final phase of use. The common designs on these counters mean they could have been produced in the later 16th or early 17th centuries.

2.5.3 Rosedale, North Yorkshire (54°19’01 N 0°51’0 1 W)

Introduction

There is no documentary evidence specifically linked to this site. For a greater discussion of this please see the introduction to Hutton (section 2.5.2).

Excavations

This site was discovered in 1966 during a search for indications of iron smelting. Further investigation found that the locality had been known as ‘Glass holes’ and local people remembered finding glass fragments when digging for rabbits (Crossley and Aberg 1972; 116). Clearance of bracken in 1967 showed that the site consisted of two mounds, which would turn out to be the main furnace and an annealing furnace. Surveying by proton magnetometer confirmed significant anomalies at both these mounds.

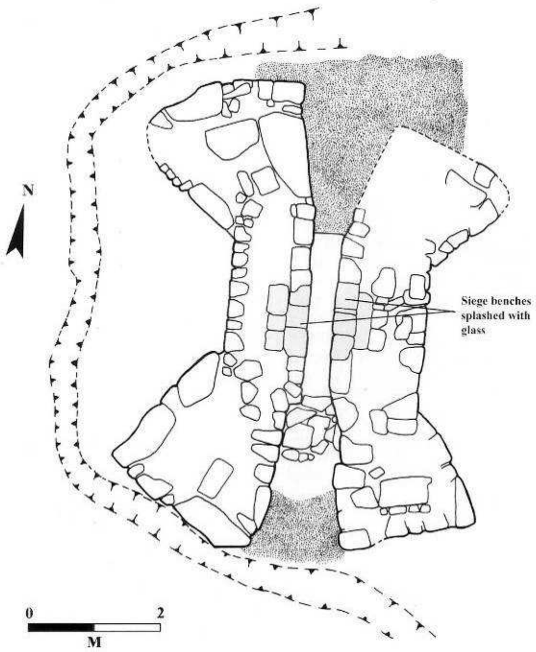

Figure 2.11: Plan of the Rosedale furnace (Willmott 2005; 92, f.57).

The main furnace was a single-period structure of the immigrant type, similar in width to that at Hutton, but longer (figure 2.11). The central flue ran north-south, the walls were constructed from dry stone and the sieges from clay and small stones. Each of these sieges only accommodated a single crucible, and traces of where the stone arches had sprung from the sieges were still visible. Three of the four wings attached to the furnace survived, the other had been dismantled during the working life of the furnace. None of the wings had evidence for fires being lit upon them. They would have been used for fritting, or pre-heating crucibles, drawing heat from the main furnace (Vose 1980; 142). Annealing would have required a fire to be built on the wings as a gradual reduction in temperature was necessary.

Post-holes cut into the working areas alongside the sieges suggest the presence of roofs. Within these working areas a large quantity of clipping fragments from the manufacture of glass items, and only very occasional and small pieces of flat glass, were found. Therefore the working of glass was carried out next to the furnaces beneath a lightweight roof.

To the north of this main furnace lay another structure, rectangular in form and constructed from clay with stone facings. Traces of a level patch of burned clay were found suggesting a hearth and fragments of vessel glass were found. All of this suggests that glass vessels were annealed here. The western part of the structure has a gap in its northern wall. This may have simply been eroded away or demolished, but it may also have been a walk-in loading point for glass. A second possible annealing furnace was found to the north-west of the main furnace. This one had a stone floored flue running westwards into it and consisted of a single square structure. As with the first structure this one had evidence of glass vessels, suggesting annealing. So it would seem the wings of the furnace were used for fritting or crucible heating and separate structures were still employed for annealing.

A small two-room cottage, contemporary with the glass furnace was also excavated. It was located about 25m away from the furnace, and may have been the residence of the glassmakers.

The glass

The glass found at Rosedale is surprisingly uniform in terms of colour and quality (Crossley and Aberg 1972; 128). The uniformity of the glass makes it easier to suggest that it was all produced here, rather than from cullet brought in from elsewhere. The composition of glass from this site is similar to that from Hutton (Crossely and Aberg 1972; see section 3.3). However, this similarity is based on a very limited data-set. Please see the above section on the glass from Hutton Common for probable raw materials.

Dating

As stated above, there is no documentary evidence specifically linked to this site. There is evidence for glassmaking in the area in 1593, however, this may apply to Hutton, Rosedale, or even an as yet undiscovered site. The main furnace has been archaeomagnetically dated to last quarter of the 16th century. This fits with the furnace design, i.e. after Huguenot glassmakers arrived in Britain in 1567. Pottery evidence at the site also adds support to this dating. The Rosedale furnace was superior in quality to the one at Hutton in every respect, it seems likely that the glassmakers operating in this area built this furnace after the Hutton furnace was established (Vose 1980; 142).

2.5.4 Glasshouse Farm, Herefordshire (51°54’09 N 2°45’50 W)

Introduction

It is well known that the immigrant glassmakers spread to many different areas around the country in the late-16th century. One of the most interesting yet under-researched of these areas is the south-west of England (Willmott 2005; 85). As noted in the discussion of Buckholt above, the glassmakers who began their work in the Weald moved first to Hampshire and then further north and west. Unlike the Weald and Staffordshire, this area has not been investigated so intensively and little documentary evidence of glass production here has been discovered.

The position of this site was originally indicated by the name of the farm; Glasshouse Farm. It was first located in 1922 by Basil Marmont who found specimens of glass and crucibles (Bridgewater 1963; 300).

Excavations

In 1959 the site was visited by N. Bridgewater who found large quantities of glass sticking out of the bank alongside the farm trackway. It was then decided to search for the remains of the furnace. Trial excavations later in 1959 were unable to find the furnace (Bridgewater 1963; 301). In 1961 a proton-magnetometer survey was carried out and this was able to very rapidly find a likely site for the furnace. Beneath the sub-soil the whole area was covered with a destruction layer. Below this layer all that was found was a large circular area of burning without any evidence of sieges or any other superstructure (Willmott 2005; 86). The only part of the furnace which survived was a surface of small stones running east-west which must have been the base of the flue (figure 2.12).

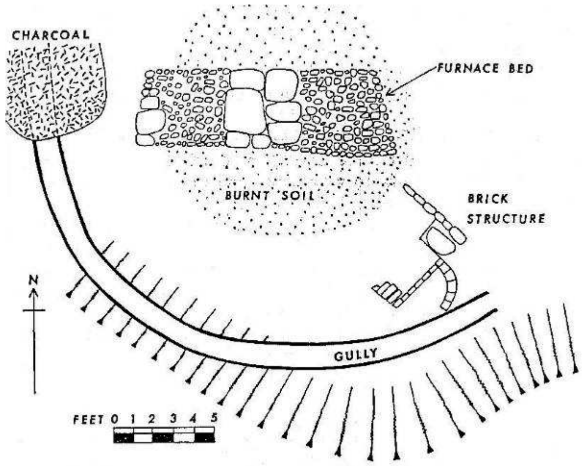

Figure 2.12: Plan of Glasshouse Farm furnace
(Bridgewater 1963; 303, f.3).

The distinct lack of evidence shows that the furnace was clearly destroyed before being abandoned. The gully to the south of the furnace would have been dug to prevent groundwater from getting into the furnace. The patch of charcoal and ash to the west of the furnace is very likely to be the raked out material from the flue. A brick-built structure found to the south-east of the furnace was interpreted by Bridgewater (1963; 303) as a free-standing annealing chamber. However, by comparison to other sites, like Buckholt and Rosedale, it may be better interpreted as an attached wing providing some evidence that this was an immigrant run furnace (cf. figures 2.9 and 2.11).

The glass

The glass objects found included parts of drinking vessels, window glass, bottles and linen smoothers, along with a large quantity of waste glass. Among the glass were examples of pedestal and cylindrical beakers, crown-window glass, which is consistent with the immigrant repertoire (Willmott 2005; 87).

Bridgewater (1963; 306) notes that there is a likely source of sand 10 miles away at Hangerberry Hill, Lydbrook, and that either burnt bracken or brushwood may have been used as a flux. However he also says that the alkali necessary was probably obtained from the ash already produced by the burning of wood in the furnace (ibid.). The composition of glass from this site suggests the use of a potash-rich wood or bracken ash (Bridgewater 1963; see section 3.3).

Dating

Unfortunately there is no documentary evidence to date this site. The only dating evidence presented in the report by Bridgewater (1963; 311) is based on the glass types found. By comparison with glass types and vessel forms the furnace is dated to between 1580 and 1620. If this furnace was operated by the immigrant glassmakers who had previous been operating furnace at the Weald (1567-1576) and then Buckholt (*c.*1576-1580), as Winbolt (1933; 18) suggests, it seems likely that the age of the furnace lies somewhere towards the first half of this timescale. However, his suggestion does not appear to be based on any firm data and as such this route from site to site must remain only a possibility.

2.5.5 Bickerstaffe, Lancashire (53°31’32 N 2°50’44 W)

Introduction

The only documentary background to the Bickerstaffe glasshouse so far found is a single entry in the Ormskirk Parish Register. This records on the 10th of December 1600: “A stranger slayne by one of the glassemen beinge A ffrenchman then working at Bycerstaff and bur(ied) 10 Dec 1600” (Vose 1970; 137). The 1841 Tithe Commutation and Award Map for Lancashire had only one field name suggesting glassmaking, which was Glass Hey Field adjacent to Hall Lane, and it was on this field that the glasshouse remains were found.

Excavations

In 1966 Mr David Pilkington of Pilkington Plc requested that the Pilkington Glass Museum of St Helens locate and excavate the glasshouse mentioned in the Ormskirk parish register (Vose 1995; 3). Research was focussed on Glass Hey Field, but aerial photographs revealed no crop marks or other indications of the presence of a glass furnace. Fieldwalking in 1968, after a hard frost, found crucible fragments, glazed sandstone and green cullet (Vose 1980; 156). The crucible fragments found were of an open bucket shape consistent with the technology of the period and indicating a wood fired furnace, hence in operation prior to the 1615 Royal Proclamation forbidding wood fuel to glassmakers, discussed further later in this chapter. A proton magnetometer survey was carried out on this area and was able to pinpoint a spot approximately 3m x 1.5m. Excavations of this area took place in 1968 and again in 1969.

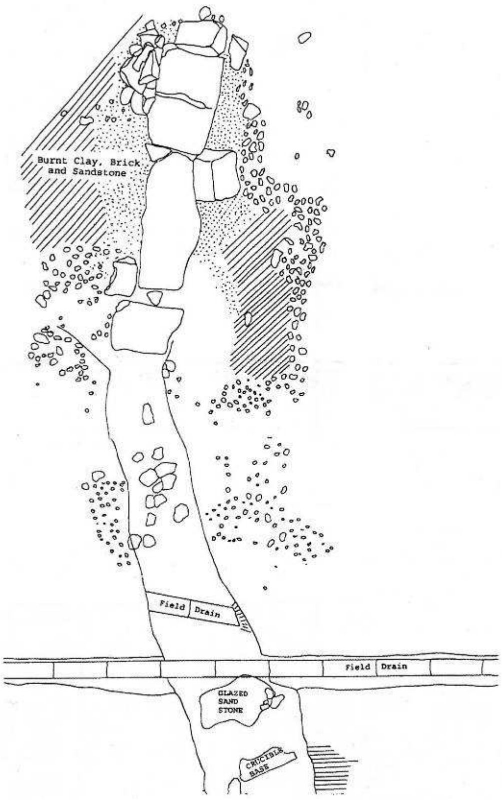

Figure 2.13: Bickerstaffe excavations. The excavation and line of destruction continue for approximately the same distance again further down. (Up is East and for scale the portion of the field drain shown is *c*. 3m across) (Vose 1995; 6).

The excavations in 1968 found a large number of crucible fragments, green glass fragments, burnt red soil and charcoal; however the only structure found was a field drain. Excavations carried out in 1969 were slightly more fortunate. The flat stone base of the furnace was found under burnt earth, sandstone and brick (figure 2.13). This represented the only in situ evidence of the furnace. The slightly higher burnt clay and rubble at either side of the depression containing the hearth stones suggest where the sieges were situated (Vose 1995; 4). Darker soil to the west of the furnace, that included a significant quantity of crucible and glass waste, gave the first indication of a demolition line coming from the furnace area (Willmott 2005; 85). This line tapered to the west and passed close to a circular dump containing broken red brick, sandstone, glass waste and crucible fragments, which lay 4.9m from the furnace. Apart from observing that sandstone blocks and red clay bricks formed part of the furnace, no further clues were found regarding its structure. It seems likely from the limited evidence that the furnace was of the common English rectangular design with parallel sieges. As the proton magnetometer survey was unable to discover any other structures in the vicinity it is likely that any subsidiary furnaces were attached to this main furnace.

The glass

Due to the disturbed nature of this site all of the glass found was from ploughed soil. This makes it very difficult to tell whether the glass found was produced on this site, or was imported from elsewhere as cullet. The great majority of the glass produced was green (93 %) and the remainder 'black' opaque. None of this black/amber glass was found adhering to crucible fragments, so its production at this site seems unlikely.

Another 1,216 glass sherds were found; 969 from clear green vessels, 184 flat glass sherds, 34 amber/black vessels and 29 modern pieces. The Bickerstaffe glasshouse was therefore primarily concerned with the production of vessels in a variety of forms including pedestal beakers and goblets, small flasks and jugs (Willmott 2005; 85). The vessel types found were those common to wood-fired glass furnace sites run by French immigrants in England from 1567. This may provide a link to the glassworkers. In 1615, 15 years after the murder by a Frenchman at Bickerstaffe was recorded, Issac du Houx was running the Haughton Green glasshouse only 30miles away, producing similar vessels (Charleston 1980; 82). This is the closest reference to French glassmakers nearby and it is possible that the du Houx family might have worked at Bickerstaffe prior to moving to Haughton Green.

The French glassmakers would have been attracted to this area not only because of the woodland as a source of fuel, but also the deposits of Shirdley Hill sand which run under much of Bickerstaffe soil (Vose 1995; 2). Two small ponds were found nearby the excavated site and it is possible that these were the pits from which the sand was taken.

Three species of wood were found as charcoal on the site; hazel, oak and birch (Vose 1970; 139). If these trees were used to fire the furnace then their ashes may also have been used in the production of glass here. Previous analysis of glass from this site suggests the use of a soda-containing plant ash, possibly in combination which a potash-rich wood ash (Vose 1995; see section 3.3).

Dating

The site was visited in 1969 for archaeomagnetic sampling. Unfortunately there was insufficient material present in situ due to the disturbed nature of the site for samples to be taken. The dating of the site therefore remains based on the documentary evidence (1600), the glass vessel forms found (post-1567) and that it was a wood-fired furnace (pre-1615).

2.6 Coal-Fired (post-1615)

2.6.1 Kimmeridge, Dorset (50°36’29 N 2°07’41 W)

Introduction

Unlike many of the earlier sites a large amount of documentary evidence concerning this site allows its operational history to be traced. The Dorset landowner Sir William Clavell (1568-1644) was involved in a number of industrial activities prompted by the availability of ‘Kimmeridge Coal’, more accurately oil shale, found on his estate at Kimmeridge (Crossley 1987; 340). The first piece of evidence concerning this site is a deal struck in 1617 between Clavell and Sir Robert Mansell, who then had sole control over the English glass industry, to produce glass here for sale in Dorset, Wiltshire, Hampshire, Devon and Cornwall (Willmott 2005; 101). Two years previous to this deal a window glass furnace was erected here, but this failed to be successful. A Lorrainer, Abraham Bigo, was brought from London to ensure this second attempt was more successful. He most likely first attempted to reuse the earlier furnace, but documentary evidence shows that in 1618 he entered into a partnership with Clavell; Bigo being in charge of the running of a new bigger four pot furnace (Godfrey 1975; 93).

The glass produced at Kimmeridge was to be sold, as stated above, in the south-western counties. In 1619 a complaint was made to the Privy Council that the glass was being sold in London, in contravention of the limitation agreed with Mansell (Crossley 1987; 347). Eventually Mansell’s attempts to persuade the Privy Council to uphold his monopoly position succeeded and in 1623 they ordered Clavell to enter into a new agreement with the monopoly over Kimmeridge. When he did not, the order was given to demolish the glasshouse.

Excavations

Excavations took place in 1980-1 to record the furnace, and identity its period of use. The demolition of the furnace in 1623 left little of the furnace standing above ground. Below the surface a stone lined passage was found extending beyond either end of the furnace, to bring air to the central block (Crossley, 1987; 350). This feature first appears in coal-fired furnaces of this period. Below this passage was a drain which ran under the whole furnace and eventually out to the sea. There were flights of steps at each end of the passage to allow access to the furnace for the removal of ash (see figure 2.14). This passage had been covered by vaults, although the evidence for these was limited to the lower courses, only found at the west flue.

Figure 2.14: Steps leading into the flue at Kimmeridge (Willmott 2005; 103, f.64).

Above ground the features were very different from other excavated glass furnaces where decay was the result of abandonment. Even the tops of the sieges, which usually survive, were missing. However, their size could be inferred and they were clearly designed to carry two crucibles each (Willmott 2005; 102). Examination of the crucible bases found that they may have been set overlapping the edge of the siege, exposing one side to temperatures likely to improve convection flows and thus the homogeneity of the melt (Crossley 1987; 366). The construction of the furnace roof, which would have sprung from the edges of the sieges could only be inferred by the discovery of three glass-splashed sandstone voussoirs. Even though the four triangular wings did not survive, their outline could be clearly seen (see Figure 2.15) and they greatly resembled those found on the earlier immigrant furnaces (see Rosedale section 2.5.3 for example).

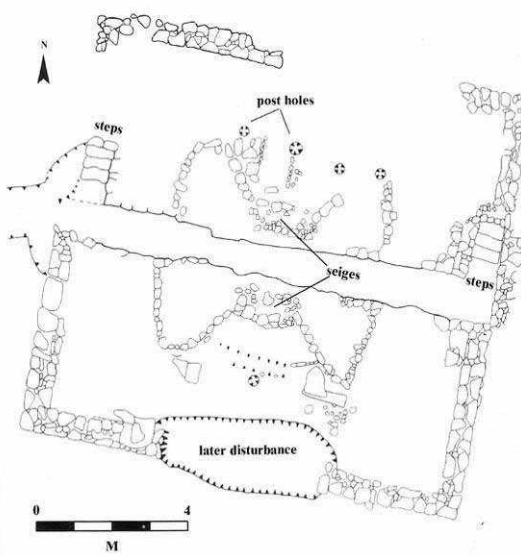

Figure 2.15: Plan of the furnace at Kimmeridge (Willmott 2005; 103, f.63).

Between the wings, on either side of the central furnace block, were the working areas. These consisted of a platform immediately outside the siege. The glass waste found on either side implied that gathering and blowing was carried out on both sides, but forming and annealing had taken place on the northern side, where far more vessel fragments were found. As there was no separate structure it seems likely that the annealing of the vessels was carried out in the wings, and more specifically in the northeast wing, based on the concentrations of fragments (Crossley 1987; 353). It is therefore likely that the pre-firing of crucibles and preparation of the batch were carried out on the southern wings. Some small pieces of mineral coal were found on the southwest wing, raising the possibility that some process had been thus fuelled here (ibid.).

The stone footings which surround the furnace are so far without parallel at any other forest glasshouse site. These are most likely the footings for the walls that made up the glasshouse itself. They are made from friable shale, which makes them unlikely to have been the foundation of a stone structure; rather it was probably a timber-framed structure. Fragments of shale slabs, each with a nail hole 1cm in diameter were found, and clearly made up part of a roof. A number of post holes found between the wings may have held supports for this roof, which would have been necessary as the span was 11m.

The reports of the furnace's demolition in 1623 appear to be correct. Excavations have shown that the demise of the furnace was the result of a thorough demolition and robbing, rather than gradual decay. The only substantial stones remaining were those of the underground air passages and stairways (Crossley 1987; 354).

The glass

A large quantity of crucibles and glass waste was found. In 1625 the glass found at the site was described by John Crase of Puddletown as 'only green glasses of very small value…not even worth the carrying away' (Crossley 1987; 345). In fact the glass is of a relatively good quality in comparison to that found at many other forest glass furnace sites. The green colouration, as with all these forest glasses, comes from the use of an impure sand source, most likely the Portland Sand which outcrops 1.2km northeast of Kimmeridge Bay.

As this was not a wood fired furnace there was no opportunity for the use of ashes from the furnace. The similar potash and soda levels found by Crossley (1987; 367-8) (2.5-4.4 wt%) show that a different alkali raw material was used here than that used to produce the high-potash composition glasses found at earlier furnaces (see section 3.3). The composition still suggests the use of a wood or plant ash, but of a mixed alkali (potash and soda) composition.

A wide range of plainwares were made here including small bottles, pedestal beakers, jugs and bowls. It had been suggested that the use of a cheap mineral fuel source reduced the cost of glass to a level where it became a worthwhile material for producing large quantities of utility containers (Crossley 1987; 357). The quantities of utility vessels found at Kimmeridge back up this view. Many of the forms found are in keeping with those made around the country by immigrant run glasshouses. This is unsurprising as Abraham Bigo had worked at Staffordshire, where French influences were strong.

Dating

The large quantity of documentary sources discussed in the introduction to this site provides the best evidence for the dating of the furnace at Kimmeridge. The first mention of a deal to produce glass here is from 1617, and the Privy Council records show its demolition was ordered in 1623. All of the pottery found during the excavation dates to the 17th century and in the southern working area a clay pipe stem of *c*.1620 was found. The vessel forms found are also contemporary with the date suggested by the documentary evidence.

2.6.2 Haughton Green, Greater Manchester (53°26’55 N 2°05’21 W)

Introduction

The earliest documentary evidence for glassmaking in this area comes from the Hyde parish record in 1615 when the daughter of Issac de Houx was baptised (Willmott 2005; 104). Mentions of the noble du Houx and Pilmey glassmaking families occasionally appear from this time and later they are documented as working at the Haughton Green glasshouse with English glassmakers. Puritanism was feature in the religious life of this area in the first half of the 17th century. The Huguenots would have therefore been moving into an area sympathetic to their views. This may have been why the glasshouse was built here rather than the heavily Roman Catholic south-western Lancashire plain where high-grade coal and vast quantities of sand suitable for glassmaking could be found (Vose 1994; 3).

As discussed above Sir Robert Mansell established his own coal-fired furnaces in widespread locations such as Kimmeridge, Milford Haven, Shropshire, Wollaton and Newcastle-upon-Tyne, but for the rest of the country he relied on furnaces licensed to burn coal to supply the more remote areas (ibid.; 2). Haughton Green was one of these. It is likely that the sales of glass from Haughton Green were limited to the local area, as was the case at other similar sites. There is a record in 1621 of a leasing agreement between Mansell and Issac de Houx (Godfrey 1975; 93).

The earliest documentary evidence from 1615 is significant as this is the year James I forbade the use of wood fuel to produce glass (Charleston 1984; 74). Evidence for the intermediary development of the English glass furnace at this innovative stage during the changeover to coal in the 17th century is very sparse (Vose 1994; 2). There is no evidence for glass production at this site after 1653. It is possible the Haughton Green glasshouse was destroyed during the many Civil War skirmishes that took place in the Manchester area between 1642 and 1659. Sir Robert Mansell was ordered to surrender his patent in 1642, the lessees working at Haughton Green probably may have continued to produce glass independently until the furnace's destruction.

Excavations

The glass furnace was first discovered in 1968 when a sewer line was being dug along the valley of the River Tame. Glass sherds were collected from this excavation and identified as high quality forest glass of the 16th or early-17th century. This coupled with the documentary evidence discussed above led to the Pilkington Glass Museum's decision to excavate the site. This excavation was carried out with the objective of excavating and dismantling the main furnace as a museum exhibit, which meant that some less important areas were not fully excavated. It was discovered that the main furnace was missed by the sewer diggings by only 1m.

Figure 2.16: Excavation of Haughton Green furnace (Anon 2006).

The first stage of the project was a proton magnetometer survey carried out in 1968. The results were inconclusive; however, in 1969 trial trenches were dropped on the areas with the most concentrated magnetic readings and what appeared to be the remains of three furnaces were found. The excavations were reopened and extended in 1970, and the main furnace was fully excavated (figure 2.16). Investigation of the main furnace concluded that it was a coal-fired furnace with a passage running approximately north-south underneath and between parallel sieges with dimensions of 1.3 x 0.6m (Vose 1994; 7). The furnace was constructed from sandstone blocks, and did not have the attached wings associated with immigrant-style furnaces. Instead it followed the design of previous wood-fired furnaces, but with large extending flues cut into the natural clay and lined with sandstone, one of which was curved. The flue, on the left of the figure 2.18, could be accessed by steps, presumably to allow workmen to enter the furnace and rake out ash and other production debris to keep the air moving freely.

The main melting area was around 3m square with two internal sieges, one of which had the fused remains of crucible bases in situ (Willmott 2005; 105). The most interesting feature was that portions of the furnace's barrel vaulted roof survived intact to a height of 1.2m above the hearth. The surviving arch was at the point where the flue leaves the main chamber creating the necessary entry for the prevailing winds which blow north-east up the river valley (Vose 1994; 12).

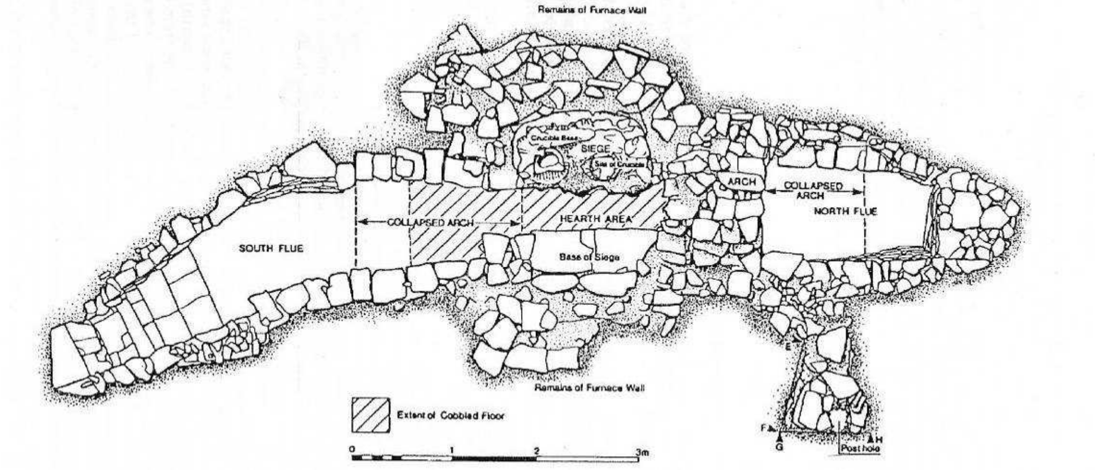

Figure 2.17: Haughton Green main furnace plan (Vose 1994; 10, f.4).

A rectangular building was found to the west of the main furnace. It showed no evidence of burning, but contained a large quantity of glass waste, so may have been the cullet store. Also, a series of three subsidiary rectangular ovens were discovered to the south of the furnace (see figure 2.18). These were constructed from sandstone blocks and with internal dimensions of around 1.75 x 2m. Their lack of flues implies that very high temperatures were not required. These were probably annealing ovens, heated to a reasonable temperature then allowed to cool with the finished glass inside (Willmott 2005; 105). Unfortunately, these ovens were not fully excavated as the Pilkington Glass Museum decided they did not want them dismantled, and therefore further excavation was unnecessary (Vose 1994; 16).

Figure 2.18: Haughton Green annealing ovens (Anon, 2006).

The fumes and particles circulating within the reverberatory roof of a coal-fired glass furnace would have a detrimental effect on the molten glass in open crucibles due to the smut and sulphurous fumes given off by the burning coal (Godfrey 1975; 150). The crucibles found at Haughton Green were mainly of a straight-sided bucket design (Willmott 2005; 106). There were some examples with v-shaped sections cut out of their rims. This, coupled with the discovery of three lid sherds, may imply that the crucibles were, once filled with charge, covered by a lid, and access to them could be gained through the cut-away at the rim (Vose 1994; 48). If this were the case, then this would be the earliest known use of covered crucibles.

The glass

The abundance of furnace waste and glass adhering to crucible sherds confirmed that clear green-tinted, opaque black and clear blue glass was made at the Haughton Green glasshouse approximately in the proportions 90% Green, 8% Black and 2% Blue. The green glass was used to make cylinder (broad) window glass, good quality vessels, bottles and chemical apparatus (Vose 1994; 20). The opaque black and clear blue glasses were limited to vessel production. Godfrey (1975; 151) believes that the dark coloured glass produced at Haughton Green was originally the accidental result of using open pots with coal as fuel (see above).

It is noted by Vose (1994; 57) that superficial sand deposits found locally were available for use, and a sample of sand found in the excavation was analysed and has the following composition: SiO_2 80.5 %, Al_2O_3 9.7 % and Fe_2O_3 2%. The iron content gives the glass produced here its green colour. Previous analysis has shown that the alkali used at this site, as at Kimmeridge, differs from that used at many of the earlier wood fired furnaces. The alkali content of the glass produced here is predominantly soda (green glass: Na_2O 6.5%, K_2O 0.8%).

Vose (1994; 21) notes that the glass produced at Haughton Green is different to the glass from earlier wood-fired sites. The styles of vessel produced are similar but the glass itself has a more robust and shiny appearance as it has not weathered as much as glass from earlier sites. Due to its distinct appearance, glass vessels produced at Haughton Green can more easily be said to have been made from glass produced here, rather than the result of imported cullet (ibid.).

Dating

The site was not considered suitable for archaeomagnetic dating, since the presence of an iron grill combined with the disturbed nature of the site would have made the results unusable (Vose 1980; 177). The main evidence for the dating of the furnace at Haughton Green comes from documentary evidence. As discussed above, this consists of evidence commencing around 1615 which continues until 1653, giving the glass furnace a life of at least 38 years. Fragments of a German Werra ware dish were also found dating to 1619, which adds to the validity of dating by documentary sources (Vose 1994; 1).

2.7 Appearance of sampled glasses

Figure 2.19 shows the glass found at each site. Due to problems in photographing the glasses subtle differences cannot be seen in these images. To complement the photos a discussion of the differences in colour follows. This is summarised in table 2.1.

The colours of glass vary by site and there is little intra-site variation in colour. Kenyon (1967; 17) describes the glass of the weald as fitting into three categories based on date and colour. His first category, Early, runs from the early-14th century to the mid-16th century. Wealden glass from this period he describes as semi-opaque and pale milky-green. The second category he discusses is Late, which runs from the mid-16th century until 1618 in the Weald. This glass he describes as fairly clear and dark blue-green. Finally he labels those glasses dating to the mid-16th century, which do not fit into either category, as Transitional.

The glasses investigated in this study show some similar trends. The glass from Little Birches (mid-16th century) is the lightest coloured. Those from Knightons and Bagot's Park (mid-16th century) are of a similar colour and darker than those from

Little Birches. The glass from Blunden's Wood (first half of 14th century) is of a similar darkness to those of Knightons and Bagot's Park, but has a slightly more aqua colour. The most similar glass to Blunden's Wood are those from Bickerstaffe (early 17th century), which have a stronger aqua colour. The glasses from Rosedale, Glasshouse Farm and Hutton (all late 16th century) are of a similar colour, but darker than those from Bagot's Park and Knightons.

The darkest coloured glasses are those from Buckholt, Buckholt West, Kimmeridge and Haughton Green. They can be very approximately differentiated by a slightly more olive colour in the glasses from the Buckholts (late 16th century), compared to Haughton Green and Kimmeridge (first half of 17th century). However, this difference is not sufficient to be used as a means of assigning the glasses to either group of sites.

Unlike Kenyon's (1967; 17) categories for glass from the Weald there is not a well defined chronology for the glasses studied here. The lightest glass is not found at the earliest site, and the darkest are found at the latest sites, and also some dating to an earlier period. Also, the aqua coloured glasses are found at both the earliest site and one of the latest. These findings show that using the colours to provenance or date the glasses would not be possible.

As was briefly discussed in chapter 1 the majority of differences in colour are due to the iron content of the glasses and also the oxygen levels in the furnace. The iron content of the glasses will be revealed by chemical analysis. However, the oxygen levels in the furnace can be discussed here. To summarise what is written in chapter 1, an increase in oxygen levels will result in the production of a darker green glass, and a reducing environment will lead to lighter and more blue-green colours. Some of the more extreme colours may have been caused by these alterations in environment in combination with the presence of iron.

As discussed above in the sections on Kimmeridge and Haughton Green, the introduction of coal as a fuel in glass furnaces required an increased level of oxygen to be introduced into the furnaces. This could explain these sites having the darker coloured glasses. The dark colours of glass produced at Buckholt and Buckholt West may also have been the result of an oxidising furnace environment, although the design of the furnace at Buckholt appears to be relatively similar to those of many of the other sites. The glass from Blunden's Wood and Bickerstaffe has a more blue-green colouring than those from other sites, and this may have been caused by a reducing environment.

These are just some possible causes of the colours. Of course, the levels of iron and possibly other components in the glass will also have had an effect on the colour (see section 1.2.2). These factors will be discussed later along with the other chemical analysis results.

a) Blunden's Wood (BW15)

b) Knightons (KN6)

c) Bagot's Park (BP15)

d) Little Birches (LBW6)

e) Buckholt (BH3)

f) Buckholt West (BHW8)

Figure 2.19a-f: Images of glasses from all furnace studies discussed in this study (numbers in brackets refer to the particular glass sample analysed).

g) Hutton (HN3)

h) Rosedale (RE12)

i) Glasshouse Farm (GF4)

j) Bickerstaffe (BS8)

k) Kimmeridge (KE4)

l) Haughton Green (HG20)

Figure 2.19g-l: Images of glasses from all furnace studies discussed in this study (numbers in brackets refer to the particular glass sample analysed).

2.8 Summary

It is important to understand the reasons for the location of glassmaking sites as they may affect the raw materials used. The interaction of glassmakers within glassmaking communities and between these communities is also important as it may have facilitated the transmission of glassmaking techniques and recipes. Changes in these recipes will hopefully be visible in the chemical composition of the glasses produced.

During the period of study the construction of glass furnaces and the raw materials used in them varies. How the influences discussed in chapter 1 affected production choices can be seen in alterations in furnace design and potentially glass recipes. The second of these points will be discussed further in chapters 3 and 4. While many of these changes will not directly alter the composition of the glass produced, they are very important to bear in mind when discussing any alterations in composition as they may be the key to understanding the reasons behind particular technological choices.

Chapter 3: Methodology and previous work

3.1 Methodology

3.1.1 Introduction

There are numerous problems involved in the study of archaeological artefacts by scientific means that require special attention (Ciliberto 2000; 1). There are a wide range of reasons to carry out an analytical programme, ranging from those which are necessary for the conservation of the artefact to those which are carried out to increase our knowledge of artefacts as a group. To complete a useful programme of analysis a number of steps must be taken to ensure that the 'correct' information is retrieved from the samples. Once the samples have been chosen, the first question is: what are we trying to discover about these samples? Is it as simple as: what is it? what is it made of? Or something more complicated like: how was it made? when was it made? where was it made? This project aims to answer the last of these more complicated questions, that of provenance.

Assigning provenance to archaeological artefacts allows us to discover more about the societies in which these objects were produced, distributed and used. Trading patterns can be established which can be used to study the relationships between different communities, regions, countries and cultures. Alterations in these patterns over time allow us to observe how these relationships altered and potentially link them to historical events, such as political changes.

The past success of chemical and isotopic analysis in provenancing archaeological artefacts has been useful in materials that remain relatively chemically unaltered from their geological sources, such as obsidian or amber (for example see Tykot 1997; Carter et al. 2006). As more ingredients or an increasing number of possible sources of a single material are combined the picture becomes increasingly blurred. Complex materials such as glass, and others with more than one ingredient such as metal alloys, will cause a greater problem for the archaeological scientist.

To assign a provenance to an archaeological glass it is necessary to understand a characteristic quality that can be linked to its place of manufacture. The choices of raw materials, their processing and mixing give glasses these characteristic qualities. In many cases, however, the same recipe was used for centuries and in a range of locations, so simply finding the types of raw materials used cannot be used to provide a provenance. The analysis of glass excavated at furnace sites can sometimes provide us with characteristic chemical compositions, but this is very rare. It is necessary to look for a characteristic of the glass which is more specific to its place of production than the recipe used in its production.

This project will strive to link a combination of chemical and isotopic data on archaeological glasses taken from production sites to their locations. These data can then be used to provenance finished glass items of unknown provenance. If successful this will allow the establishment of trading patterns, allowing conclusions to be drawn about the organisation of glass production in late- and early-post medieval England.

Raw materials collected from nearby production sites will also be analysed for strontium and neodymium isotopes. This will provide an isotopic signature for some local raw materials and can potentially be used to discover if local raw materials were being used. The raw materials will also be used to produce a model glass that will provide a means of studying how the isotopic ratios in raw materials combine during mixing and melting to provide an archaeological glass with its isotopic signature. This evidence will be very useful when attempting to link suspected raw materials to finished glasses.

3.1.2 Assumptions of scientific provenance

Often provenance studies have assumed that recycling does not take place. However, it seems clear that during many production processes it did. There are clearly a wide range of situations in which waste products of glass production/forming process (cullet) and raw materials imported from elsewhere would be incorporated into future batches (see section 1.2.4). A very simplistic study may see artefacts analysed, sources analysed, and if the analytical results overlap it is assumed the artefact comes from the source. However, source materials might have been available which are not now, or raw materials may have come from much further away than was expected in the study. How the boundaries of possible raw materials are defined is fundamentally important and will dictate any results or conclusions (Andrews and Doonan 2003; 107).

Provenance studies are generally better at working out where artefacts were not produced. Even when strong evidence for a raw material source is presented, the possibility of another matching source that has not been accounted for will always remain. Due to the compositional similarities in the different raw materials used for forest glass production, this is an important point to note for this study. Analysing the glass production waste and raw materials at a furnace site is a good source of information for making a link to the raw material sources used. However, many of these remains often do not survive in the archaeological record; for example sand and wood ashes. The glass production waste may have also been removed to be used as cullet at another site, or imported cullet may be present at the site of study.

A series of six assumptions have been proposed by Wilson and Pollard (2001; 507-8) that must be accounted for to produce a successful archaeological provenance study:

1. The prime requirement is that some chemical (or isotopic) characteristic of the geological raw material(s) is carried through (unchanged, or predictably relatable) into the finished object
2. That this ‘fingerprint’ varies between potential geological sources available in the past, and that this variation can be related to geographical (as opposed to perhaps a broad depositional environment) occurrences of the raw material. *Inter*-source variation must be greater than *intra*-source variation for successful source discrimination
3. That such characteristic ‘fingerprints’ can be measured with sufficient precision in the finished artifacts to enable discrimination between competing potential sources
4. That no ‘mixing’ of raw materials occurs (either before or during processing, or as a result of recycling of material), or that any such mixing can be adequately accounted for
5. That post-depositional processes either have negligible effect on the characteristic fingerprint, or that such alteration can either be detected (and the altered elements or sample be discounted), or that some satisfactory allowance can be made
6. That any observed patterns of trade or exchange of finished materials are interpretable in terms of human behaviour. This pre-supposes that the outcome of a scientific provenance study can be interfaced with an existing appropriate socio-economic model, so that such results do not exist *in vacuo*.

In particular point 4 above provides a problem for this study. It is known that raw materials and cullet were traded between forest glass production sites (see accounts in Lennard 1905 for example). It is therefore clear that there will be some cases in which the glasses analysed in this project will be the result of mixing of raw materials and/or glasses. It will therefore be necessary to take note of this when studying the analytical data produced. Where mixing has been used regularly, and from only one or two sources, it may be possible to identify this in these data (see Henderson et al. 2009; Degryse et al. 2009b; Freesone et al. 2005). As discussed in chapter 1, using a combination of chemical and isotopic analysis Freestone (2005; OO8.1.9-10) was able to show that Roman high iron, manganese and titanium (HIMT) glass was produced by the mixing of two end-members with differing compositions. This work has shown that when the mixing of raw materials or glasses has occurred it may still be possible to identify an elemental or isotopic signature for a set of glasses and suggest the types of end-members that may have been mixed to produce it. Mixing of a large number of sources will completely obscure any isotopic signature directly associated with the production location, however it may still be possible to characterise a mixed glass composition if it is sufficiently dissimilar from others that were produced at other locations.

3.2 Sampling of archaeological glasses

Table 2.1 lists the locations of glass production sites from which samples were taken and figure 3.1 illustrates their locations on a geological map. The glass samples selected were lumps of raw glass chosen from assemblages excavated at production sites (see table 3.1). Raw glass is defined in this thesis as glass production waste believed to have been produced from raw materials at the site from which they were excavated. These types of samples were chosen as they provide the best possibility to provide analytical results characteristic of the glass produced at these sites. There is the possibility of inadvertently collecting some samples which are imported cullet. However, where the glass is physically very similar this is unavoidable and may be identifiable in the analytical data.

All pieces of glass sampled, apart from two taken from crucibles (discussed below), were lumps of varying sizes. These lumps have no distinguishing features to suggest they were glass working, rather than glass making waste. However, where the lumps were very small this is still a possibility. The types of glass sampled are included in the results in appendix tables 1-13.

The results of Merchant et al. (1997; 35; 1998), amongst others, have shown that there is a reaction between forest glasses and the crucibles used in their production. The glass penetrates into the clay of the crucible and the composition of the crucible influences that of the glass close to the crucible wall. It is therefore important not to analyse glass from crucibles unless there is a sufficient thickness of glass present, and that any glass close to the crucible wall is discarded. This compositional alteration is only present in the first few millimetres of the glass, and it will therefore be acceptable to use glass of 5mm and more in thickness, as long as the first 3mm are discarded.

Site	Sample	No. of samples	Ownership
Buckholt	Production waste	3	Southampton City Council Archaeological Unit
Buckholt West	Production waste	19	Southampton City Council Archaeological Unit
Bagot's Park	Production waste	17	Stoke Potteries Museum
Blunden's Wood	Production waste	20	Guildford Museum
Bickerstaffe	Production waste	12	Liverpool World Museum
Glasshouse Farm	Production waste	9	Hereford Museum
Haughton Green	Production waste	21	Portland Basin Museum, Manchester
Hutton	Production waste	10	Hutton-le-Hole Folk Museum
Knightons	Production waste	9	Guildford Museum
Little Birches	Production waste	11	Stoke Potteries Museum
Rosedale	Production waste	27	Hutton-le-Hole Folk Museum
Kimmeridge	Production waste	21	Dorset County Museum

Table 3.1: No of samples prepared for electron microprobe analysis from each site.

One of the assumptions listed above in terms of the ability of provenancing objects is that the inter-source variation is greater than the intra-source variation in some characteristic of a raw material source. Previous writers have suggested that, due to the low value of many of the raw materials used in forest glass production, local sourcing of many of the necessary raw materials was a strong possibility (see Kenyon 1967; Godfrey 1975 etc.). It was therefore necessary to have samples from a wide range of geological surroundings, as it is this variable which dictates variation in isotopic signature. Figure 3.1 shows the locations of sites studied on a geological map, and variations in geology can easily be seen between many of the sites.

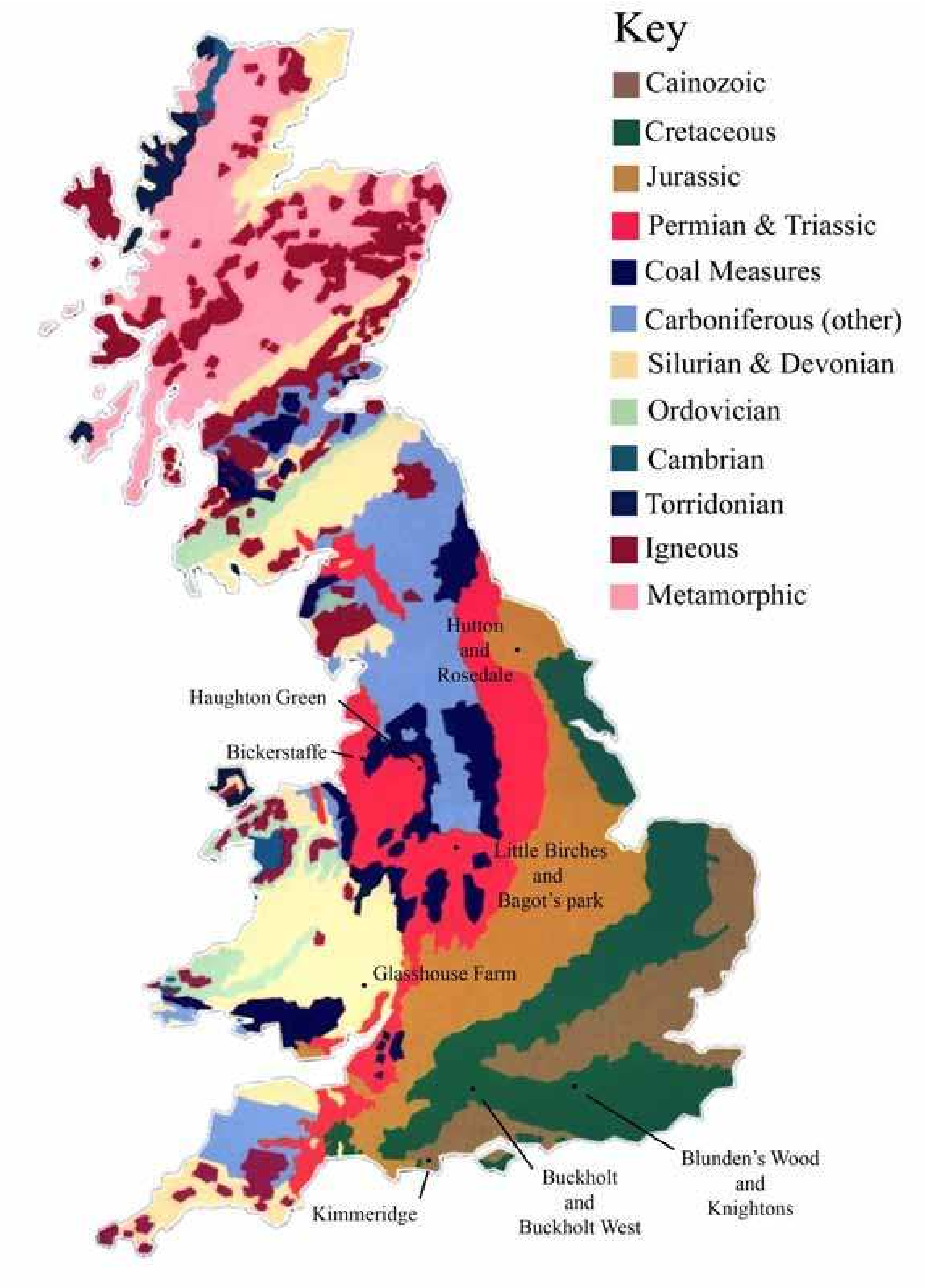

Figure 3.1: Geological map of Britain labelled with sites investigated in this study (after CoalPro).

3.3 Previous work

3.3.1 Chemical analysis

Many of the sites detailed in this study have been investigated previously by a variety of scientific means. Glass from Buckholt, Buckholt West and Kimmeridge has not been previously analysed. The following table summarises the previously published chemical analyses carried out on samples from the sites investigated in this project:

Site	Date	Technique	No. of samples	References
Blunden's Wood	First half of 14th century	SEM-EDX: Major, Minor	50	Merchant et al. 1997; 32
Knightons	Mid-16th century	SEM-EDX: Major, Minor	15	Green and Hart 1987; 280
Bagot's Park	Mid-16th century	SEM-EDX	8	Welch 1997; 43
Little Birches	Mid-16th century	SEM-EDX	54	Welch 1997; 41
Buckholt	Late-16th century	N/A	N/A	N/A
Buckholt West	Late-16th century	N/A	N/A	N/A
Hutton	Late-16th century	Unknown: Major, Minor NAA: Trace	1 6	Crossley and Aberg 1972; 151-2
Rosedale	Late-16th century	Unknown: Major, Minor NAA: Trace	1 6	Crossley and Aberg 1972; 151-2
Glasshouse Farm	Late-16th/Early-17th century	Unknown: Major, Minor	3	Bridgewater 1963; 310
Bickerstaffe	Early-17th century	SEM-EDX: Major, Minor	6	Vose 1995; 16, 20
Kimmeridge	*c*.1617-1623	N/A	N/A	N/A
Haughton Green	*c*.1615-1653	Unknown: Major, Minor, Trace	5	Vose 1994; 57

Table 3.2: Sites studied in this project with details of previously published analyses (N/A=no published analyses found).

The techniques used, number and types of samples analysed, and age of the studies varies greatly and therefore comparing these data will be problematic. None of the studies give any type of glass standard analysis data and so it is not possible to compare the techniques used. Separately the results, especially those from the more recent studies, may be considered useful. However, direct comparison between studies must be carried out with care. The data for some oxides is presented in different forms, for example in Crossley and Aberg's 1972 report on the excavations of Rosedale and Hutton Al_2O_3 is combined with TiO_2 and presented as a combined percentage. Problems such as these have led to the selection of only a few significant major elements for comparison in this study. These are presented in table 3.3 below. The sites are presented in order of date, see table 3.2 above for dates.

		Na_2O	MgO	SiO_2	K_2O	CaO	total alkali
Blunden's Wood	(n=50)	0.94	3.92	55.03	17.87	13.21	18.81
Knightons	(n=15)	1.16	4.26	58.39	8.50	18.50	9.66
Bagot's Park	(n=8)	2.78	6.91	59.90	10.05	12.53	12.83
Little Birches	(n=54)	2.33	7.16	56.80	11.71	14.55	14.04
Glasshouse Farm	(n=3)	2.00	3.95	58.08	9.06	19.59	11.06
Hutton	(n=1)	1.84	2.28	58.98	5.16	24.59	7.00
Rosedale	(n=1)	3.54	3.25	58.84	6.20	20.15	9.74
Bickerstaffe	(n=6)	5.20	4.60	58.48	2.30	20.12	7.50
Haughton Green	(n=5)	6.32	5.36	56.92	0.86	19.74	7.18

Table 3.3: Average values for a selection of oxides for previously analysed glasses from sites studied in this project (see table 3.2 for publication details).

The compositions vary greatly between sites. The main differences between the glasses from these sites are the alkali and lime levels. Earlier sites have more potash, and later sites more soda. This is a very approximate trend and in the case of some sites the results are based on very few samples. Blunden's Wood, Bagot's Park and Little Birches have the lowest calcium oxide levels, and the highest levels are found at the later sites. The glasses analysed from Bickerstaffe and Haughton Green have the lowest potash levels and highest soda levels. This compositional change was discussed in chapter 1 and is linked to a switch to the use of coal as fuel, necessitating the use of a different, apparently more soda-rich ash, rather than any of the wood ash produced in the furnace.

Very approximately the glasses fall into four compositional groups:

1. High potash, low calcium oxide: Blunden’s Wood, Bagot’s Park, Little Birches
2. High potash, high calcium oxide: Knightons, Glasshouse Farm
3. Mixed alkali, high calcium oxide: Hutton and Rosedale
4. Higher soda, high calcium oxide: Bickerstaffe and Haughton Green

These four groups are approximately chronologically ordered. Group 1 is 14th century to mid-16th century, Group 2 is mid- to late-16th century, Group 3 is late 16th century and Group 4 is early- to mid- 17th century. There may also be some geographical ordering of the Groups as, apart from Knightons and Blunden’s Wood, where any two sites are located in the same region of the UK they fall into the same compositional group.

These compositional trends have been noted for glass produced in England and abroad by other authors (Mortimer 1997; Hartmann 1994) and are discussed in terms of raw material uses in chapter 1. The small numbers of samples analysed do not allow these patterns to be confirmed with any confidence for the sites in this study. However, the results do suggest that they fit in with these previous trends.

Summary

These results, while limited in number, have shown that there is some compositional patterning which may be related to both the chronological and geographical location of the production sites. Compositional differences, which were expected from changes in raw materials at later sites, can be observed. In no case are there sufficient compositional differences to suggest a site-specific composition has been found. The patterning seen is still very useful and suggests that recipes altered over time. Also, glasshouses within a single region may have used a similar recipe showing that there may have been some communication between sites.

It must be noted here again that these conclusions are based on very limited sample numbers analysed by varying analytical techniques. The results of the analyses carried out in this study will be able shed more light on these emerging patterns. They will also allow more confidence to be given to conclusions as the analyses were all carried out using the same methodology.

3.3.2 Isotopic analysis

Only a very limited amount of isotopic analysis has been carried out on forest glasses, and none has been carried out previously on the samples from the sites studied in this thesis. Using strontium isotope ratio and concentration data Dungworth et al. (2009) (discussed in chapter 1) showed that seaweed was used in the production of forest glass at the site of Silkstone, located over 100km away from the coast. They also suggest that other alkali sources used at this site may have been grown in geologically very old regions of the UK, which only exist at least 130km from this site.

This evidence challenges the idea that many of the raw materials used in forest glass production were sourced locally. The use of seaweed, traded over such a long distance, suggests that it was in demand and that glassmakers must have considered it a very useful raw material. Their conclusions show that the isotopic analysis of glasses such as these can shed light on the types of raw materials used, and potentially a very approximate idea of possible source locations.

3.4 Raw materials and model glass production

3.4.1 Raw materials

The raw materials sampled were taken from nearby some of the production sites from which glass has been sampled (see table 3.4). Raw materials from these locations could have been used in the production of forest glasses at these sites. There is, of course, the possibility that raw materials have been imported, especially with the later sites where soda-rich plant ashes were used. The isotopic analysis of these raw materials may provide a means of establishing whether or not local materials will be used.

Site	Sample		Lat.	Long.
Sidney Wood	Ash	Bracken	51°6'26.64"N	0°32'5.41"W
Hutton	Ash	Bracken	54°18'0.65"N	0°55'5.70"W
Cannock Chase	Ash	Bracken	52°46'2.70"N	1°59'54.95"W
Cannock Chase	Silica	Pebbles	52°46'2.70"N	1°59'54.95"W
Hambledon Common	Silica	Sand	51°8'6.26"N	0°37'40.32"W
Hutton Common	Silica	Sandstone	54°17'11.54"N	0°55'10.62"W

Table 3.4: Type and location of raw materials collected for analysis.

Bracken was collected from these sites, not because it is believed that this is the sole alkali raw material used at these sites, but because it was the easiest to collect. No attempt was made to collect it at certain times of the year, as suggested in historical texts (see section 1.2.3). Therefore the chemical composition of the bracken will probably not relate to the raw materials used in the production of the archaeological glasses. The only useful data will be the isotopic ratios found. These will not have altered depending on the species or the time of year of its collection.

Sand, quartz or sandstone was also collected from some sites where it was easily discoverable. At these sites it is assumed these raw materials may have been used due to the easy access the ancient glassmakers would have had to them. This assumption will be tested with the results of the analytical study. A selection of these raw materials were used to produce model glasses, details of which are in section 3.4.2.

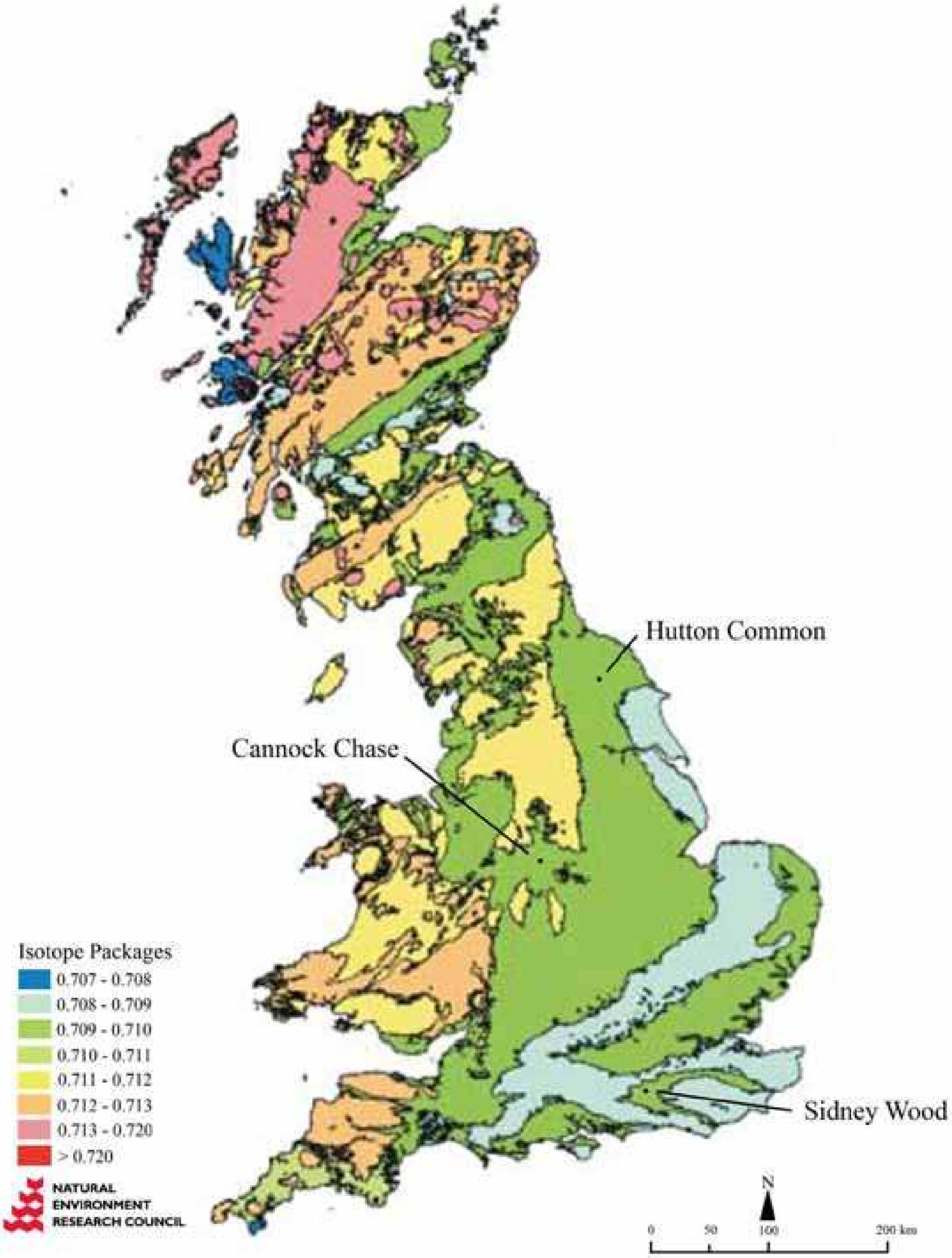

Figure 3.2: Raw material collection sites presented on a biosphere available Sr ratio map (after Evans et al. 2010; 2, f.1b).

As noted in chapter 1, the ^{87}Sr/^{86}Sr values should provide a means of provenancing the alkali sources dependent on the soil, and therefore geological surroundings, on which the plants grew. Evans et al. (2010) have produced a map of biosphere available strontium (Figure 3.2). This map is based on a limited data set and as such is only useful as an approximate guide to biosphere available strontium isotopes. It can be seen from the biosphere Sr ratio map (figure 3.2) that the samples of bracken taken for analysis in this study all originate from a single category of biosphere available Sr ratios; 0.709-0.710. However, it is clear from papers such as Chenery et al. (2010) that the biosphere strontium ratios can vary greatly over very small distances. The results of Sr isotope analysis of bracken ashes will be an interesting comparison with these data in this map.

Bracken

While there is certainly no definitive evidence to say that bracken was the main alkali raw material used in medieval glass production, it was chosen to be used in this study due to the ease of collection and that, in terms of the isotopic analysis, the type of plant collected should be irrelevant. The results of isotopic analysis are only intended to be used as an analogue for terrestrial plants local to the area of production.

Part of this area of this study is also to discover how the isotopic ratios in raw materials combine to give a glass its isotopic ratio. Therefore, even if the isotopic ratios of the model glass produced from the bracken and sand do not correspond to the archaeological glasses, the results will still be of use to future studies.

Bracken was collected from three locations near production sites. In Sidney Wood, near Blunden’s Wood and Knightons, on Hutton-le-Hole Common, near Hutton and Rosedale, and on Cannock Chase, near Bagot’s Park and Little Birches.

Silica

While bracken grows in abundance nearby all of the sites, it is slightly more difficult to find sources of silica that may have been exploited by the glassmakers.

Occasionally excavation reports define possible silica sources discovered by the excavators. Three samples of three different materials were taken for use in this study. In must be noted that there is no reason to expect these silica sources to be those used by the forest glassmakers. They have been collected due to their proximity to sites alone. As with the bracken ash the main use of the these samples is as an analogue for local raw materials and, in the case of those from the Weald, to observe how the isotopic ratios in them combine with those in the bracken to give the glass produced its isotopic signature.

Across Cannock Chase it is possible to find quartz pebbles. Around 10 pebbles were collected for use in this study. A single pebble was broken with repeated hammer impacts and prior to analysis the sample was powdered using a pestle and mortar.

Just below the topsoil on Hambledon Common is a layer of sand. This was very easily found in areas where rain had eroded the soil around trees. There was a high quantity of mud in these samples, but it was easily washed away, and resulted in a sand containing a large number of mineral impurities.

It was not possible to discover a sand source used at the sites of Hutton and Rosedale. However, at Hutton Common there is a large quantity of sandstone eroding from the side of the river. This may have been a silica raw material source used at this site and so was collected, crushed and washed.

3.4.2 Production of model glasses

A model glass was produced from raw materials collected from two sites in the Weald. Due to uncertainties about the actual raw materials used, in terms of specific sand sources and plant species, it was assumed that the chemical compositions of the model glasses produced would not relate to those from the site studied. As such, this model glass was not produced in an attempt to directly replicate the recipes and chemical composition of forest glasses. However, the strontium and neodymium isotope analysis should at least relate to the geological origins of the raw materials which would be the same in terms of the ash, independent of the species of plant. Using the data obtained by TIMS analysis it will be possible to investigate how the Sr and Nd isotope ratios and concentrations in these two raw materials combine in the glass production process. This information will be highly useful when attempting to relate the Sr and Nd composition of glasses to the raw materials used to produce them.

It was long thought that temperatures above 1200°C were difficult to achieve in medieval wood-fired furnaces. However, experimental observations have shown that model glasses produced from bracken and sand could not be melted at temperatures below 1350°C (Jackson et al. 2000; 338). The glasses from the 16th century site of Rosedale had liquidus temperatures of around 1350°C and that at Little Birches in excess of 1320°C (Welch 1997; 48).

The work of Caroline Jackson, Jim Smedley and others (discussed in detail in the section 1.2.5) has shown that there is a lot of information that can be found by producing glass from raw materials assumed to have been used by medieval glassmakers.

Glass was produced using sand and bracken ash from Hambledon Hill and Sidney Wood, respectively. The ratio used was that suggested by Smedley and Jackson (2002), that of 2 parts wood ash to 1 part sand, by weight (see section 1.2.5). The batch consisted of 12 grams of bracken ash and 6 grams of sand. The glass was made in a professionally produced refractory clay high sided crucible. It was slowly heated at a rate of 3°C per minute to 1300°C, held there for 10 hours, then slowly cooled to room temperature at the same rate. The whole process took 24.5 hours (see figure 3.3).

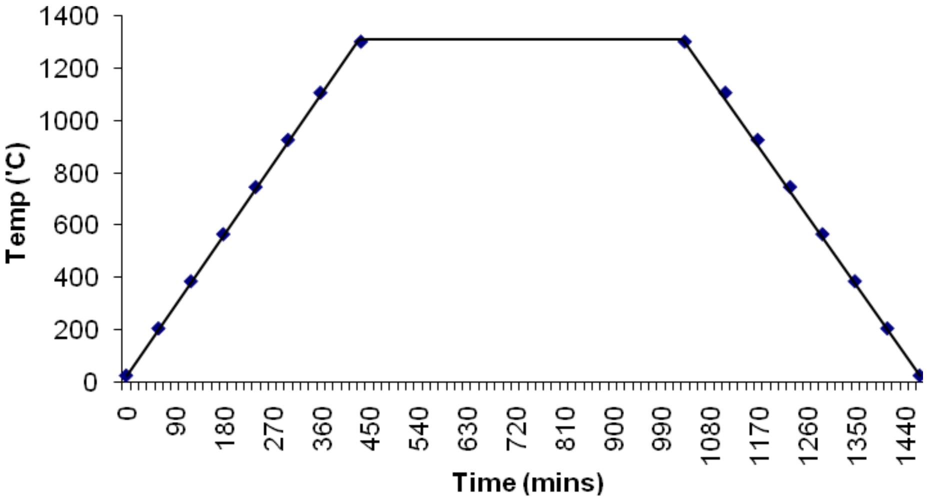

Figure 3.3: Time-chart for the furnace operation.

Figure 3.4: The glass produced using raw materials from The Weald (for scale, base of crucible is approximately 4cm in diameter).

	Crucible	Bracken ash	Sand	Total before firing	Total after firing	Loss
Mass/g	82	12	6	100	90	10

Table 3.5: Raw material weights for model glass production.

The glass produced was green most probably due to iron minerals in the sand used (figure 3.4). The loss in weight of 10 grams represents more than half the batch, and was probably all lost as volatile components were expelled from the bracken ash, which therefore went from 12 grams to 2 grams (see table 3.5). Some of the quartz was not fluxed and did not turn into glass, instead leaving a white *frothy* deposit on top of the green vitreous mass. This means that the proportions of ash and silica in the glass portion of what was produced may not actually be a 2:1 by weight ratio as was initially added to the batch. The analytical results of this model glass will be discussed below in section 3.8.

3.5 Compositional analysis

3.5.1 Introduction

The compositional analysis of archaeological glass samples was a very time consuming and expensive process up until the 1960s. There are now a wide range of techniques that can perform the task relatively quickly and inexpensively. ‘Elemental analysis, and each specific elemental analytical technique, is like a toolbox, designed for a specific purpose or set of purposes, but with its eventual usefulness based on the imagination and skill of its user’ (Hancock 2000; 11).

3.5.2 Preparation of samples for analysis by electron microprobe

Preparing samples for, and carrying out, electron microprobe analysis can be thought of as micro-destructive or destructive. The samples have to be mounted in epoxy resin. Small sub-samples will be broken from each glass sample ensuring that they included at least some unweathered glass. These samples will be set in 1” epoxy resin blocks, polished to a 0.25 μm diamond paste finish and carbon coated to prevent surface charging and distortion of the electron beam during analysis. Very small pieces of glass are needed and the technique itself will only destroy a microscopic area of 50μm and an even smaller depth. While the samples are then mounted in resin and will not be retrieved, they can be reanalysed at a later date again by electron microprobe or other techniques, including LA-ICP-MS.

Weathered samples are not good for compositional analysis. The crusty layers built up on the outside of glass samples are the result of alkali (sodium or potassium) leaching out of the glass during burial. They are made up of a hydrated residue with a high silica content (Frank 1982; 67). Analysis of these areas would therefore not produce data representative of the bulk composition of the glasses.

3.5.3 Electron microprobe

A JEOL JXA-8200 electron microprobe with four wavelength-dispersive spectrometers located in the Department of Archaeology at The University of Nottingham was used for analysis. An electron microprobe operates using X-rays to distinguish between elements. It can do this with two different techniques. Energy dispersive X-ray spectrometry is a very fast method of discovering the composition of an area of the sample. Wavelength dispersive X-ray spectrometry takes longer, but provides more accurate and precise compositional information on elements in far lower concentrations. This second technique was used for this project.

The electron beam can either be focussed on very small areas or larger spots to analyse either very specific areas of samples, or to allow an average composition of an area to be found. A defocused (to prevent affecting the volatiles present) electron beam with a diameter of 50μm employed at an accelerating voltage of 20 kV. Emitted X-rays were counted for 20 seconds for peaks (100s for magnesium) and 10 seconds for background (20s for magnesium). Calibration with mixed mineral and pure metal standards was carried out.

3.5.4 The significant elements

The compositional characterisation of the glasses relies on the differences found in the raw materials used, and their relative quantities. Below is a list of the elements which were analysed for in this study, although the results will be provided in terms of their oxide quantities:

Sodium, copper, titanium, zinc, aluminium, iron, calcium, tin, arsenic, manganese, antimony, nickel, magnesium, chlorine, potassium, cobalt, barium, lead, sulphur, chromium, vanadium, silicon, zirconium, phosphorus and strontium.

Some of these will be more relevant in characterising silica sources, others alkali sources. By characterising these sources, and their relative proportions, it is hoped that it will be possible to find characteristic compositional groupings for the sites. TIMS will also be used to discover the concentration of elements, but will be limited to the two of interest for the isotope analysis, strontium and neodymium. However, it will be able to accurately measure these elements at levels of less than 10 parts per million (ppm). The electron microprobe is unable to detect elements at these low levels, but the wide range of elements it is able to analyse accurately prove its usefulness in this project.

3.5.5 Analysis and standards

A total of 179 samples of glass were analysed using EPMA. Corning B was used as a sub-standard to check for accuracy and precision. Throughout the period of analysis this sub-standard was analysed at the beginning and end of each analytical run. In total it was analysed 89 times. The average results are presented in table 3.6 along with the quoted values for this standard, the standard deviations for these measurements and the percentage error of the measurements in comparison with the known values. These last two values are taken to represent the precision and accuracy of the measurements, respectively. The precision of the measurements is very good. The greatest standard deviations are found for the oxides present in the highest quantities.

The accuracy is rather more problematic. For the majority of oxides measured the measured value was within around 20%, most are much lower, of the known value for the standard and this is considered acceptable. For four oxides the error is in excess of this level and this must be taken into account when discussing the results. The two oxides are barium oxide and phosphorous oxide. The error for barium oxide can be greatly reduced when comparing with the results of Brill (1999). Brill measured the BaO content of Corning B as 0.12 %, and so using this value reduces the error to 14.29 %.

These revised values give a phosphorous oxide level of 0.82 % in Corning B and so this cannot account for the inaccuracy in measurement here. Values for this oxide must be considered semi-quantitative. The relatively low standard deviation allows for comparisons to be made between data-sets within this thesis. However, the values cannot be used to compare with values obtained by other authors.

Arsenic oxide, chromium oxide and strontium oxide were present at levels below the detection limit of this methodology. Values for these oxides must also therefore be considered as semi-quantitative where listed in this work.

	Na_2O	TiO_2	SiO_2	SnO_2	Al_2O_3	ZnO	SO_3	NiO	As_2O_5	CuO	Cl	CoO	MgO	K_2O	Sb_2O_5	FeO	BaO	MnO	CaO	ZrO_2	PbO	Cr_2O_3	P_2O_5	V_2O_3	SrO
Measured (89)	17.18	0.10	60.85	0.00	4.16	0.19	0.48	0.09	bdl	2.70	0.18	0.04	1.11	1.02	0.50	0.30	0.12	0.24	8.63	0.02	0.41	bdl	0.55	0.03	bdl
Known	17.26	0.1	61.55	0.04	4.22	0.2	0.54	0.09	nr	2.7	0.2	0.035	1.19	1.1	0.46	0.35	0.14	0.28	8.71	0.025	0.4	0.005	0.84	0.03	0.01
St.Dev.	0.29	0.01	0.66	n/a	0.10	0.02	0.03	0.01	n/a	0.04	0.01	0.01	0.06	0.02	0.03	0.01	0.05	0.02	0.22	0.01	0.03	n/a	0.04	0.02	n/a
Error (%)	0.45	0.54	1.14	n/a	1.38	4.76	11.32	5.26	n/a	<0.01	12.29	9.31	6.70	7.39	7.76	14.30	14.29	15.24	0.96	21.48	2.03	n/a	34.86	3.75	n/a

Table 3.6: Known and measured values for Corning B (wt.%), standard deviation of measured values and percentage error between known and measured values (nr=not reported, bdl=below detection limit, n/a=not applicable).

3.6 Isotopic analysis

3.6.1 Introduction

A smaller subset of samples were chosen for isotopic analysis. These samples were chosen to represent either the major compositional type found at a site, or a selection of the different types found. Time and quantity constraints led to fewer being analysed for each site, and occasionally only one compositional type has been chosen when two were in existence at a site. The compositional types of each glass isotopically analysed will be noted in the results tables in the appendix. The methodology used for strontium and neodymium analysis will be discussed first as they were carried out using a similar method. This is followed by a discussion of the oxygen isotope analysis methodology.

3.6.2 Strontium and neodymium isotope analysis

Introduction

The use of isotopic ratios in geology is a long established technique. They have been used to date rocks for many years. In archaeological studies the same isotopic ratios can also be employed. However, rather than dating they are used to link materials to their places of origin and in turn provenance the objects produced from them. It is important for archaeologists to understand the geochemical behaviour of isotopes as this will lead to a far greater appreciation of their significance in provenance studies (Li et al. 2006; 99). Compositional analysis has been used in archaeology for far longer and with far greater scope than isotopic studies, which are still in their infancy. The reasons for this are that the scientific techniques employed are time-consuming and expensive, and in the past required relatively large samples (Leslie et al. 2006; 254).

In recent years advancements in analytical techniques have brought isotopic analysis into the grasp of the archaeological scientist. While still more time consuming and expensive than compositional analysis, many studies have shown isotopic analysis to be far superior in some archaeological provenance studies. Even though major elements make up the largest proportion of a sample, their variation in composition across different locations and time periods is often limited. Isotopic analysis is not always a great success; for example many lead isotope studies of archaeological metals have not been able to find signatures which are specific to one source. It is important to combine isotope studies with chemical analysis so that an attempt can be made to link the raw materials used to the isotope systems employed.

Isotopic ratios depend on the composition and geological history of the source rock and are potentially more useful in fingerprinting artefacts made in different places (Li et al. 2006; 99). Britain has a highly variable geological history and therefore it is hoped that this will allow the discovery of signatures specific to regions, or even sites. However, the link between sites and local geology will only be possible where local raw materials were being used, and this is not likely to have been the case at many of the sites.

The process of analysing an archaeological sample isotopically involves a number of stages of preparation before it can even be introduced to the analytical equipment. The following discussion outlines these stages, the process of analysis and how this relates to the sources of the material analysed. Since this work concerns the use of thermal ionisation mass spectrometry (TIMS) to analyse for strontium and neodymium the following discussion will be limited to this technique and these elements.

Thermal ionisation mass spectrometry

The strontium and neodymium isotope compositions and concentrations were determined by TIMS using a Thermo Scientific Triton multi-collector mass spectrometer at the NERC Isotope Geosciences Laboratory. As the name suggests TIMS works by subjecting the analyte to high temperatures, resulting in its ionisation. The dried sample obtained by chemical separation is taken up as a salt solution, deposited on to a filament and evaporated (Platzner 1997; 153). For Sr analysis this filament is then inserted into the vacuum system and a current is passed through it. Raising this current induces resistive heating, eventually resulting in a temperature at which simultaneous volatilisation and ionisation of the sample occurs. The ions are accelerated through a high potential before passing through a uniform magnetic field. This field defects the ions by different angles depending on their mass. The ions are thus separated by this field and are measured by ion detectors. This technique is sensitive enough to distinguish between isotopes of the same element. The results are presented as ratios and concentrations in parts per million (ppm).

Strontium isotopes

Rubidium (Rb) is a group-1 alkali metal with two naturally occurring isotopes, ^{85}Rb and ^{87}Rb, whose abundance are 72.17% and 27.83% respectively (Dickin 2005; 42). Its ionic radius is sufficiently similar in size to that of potassium (K) to allow Rb to substitute for K in all K-bearing minerals (Faure 1986; 117). Rb is therefore present in detectable quantities in a large number of minerals. ^{87}Rb is radioactive and decays to the stable ^{87}Sr via beta decay by emission of a beta particle and anti neutrino, which share the decay energy (Q) as kinetic energy. It is this process which allows the measurement of Sr isotope ratios to be used to date rocks and minerals. It must be remembered, however, that the application of this method to archaeological glasses is in no way connected to dating them. Rather it is used to discern information about the geological environment upon which the plants used are growing (Henderson et al. 2005; 666). This will hopefully lead to the provenance of the raw materials. It is therefore important to understand the geological importance of this method before applying it to archaeological samples.

A certain proportion of the strontium will be included in the silica source used; e.g. in the form or shells or calcium-rich minerals present in sands. Based on previous analyses of plant and wood ashes, it seems likely that the majority will be in the alkali raw material (see tables 1.4 and 1.5). However, as discussed throughout chapter 1, the compositions of plant and wood ashes are highly variable. The calcium content of sands is also variable and will depend a great deal on the source used and also any processing, such as washing, that is carried out prior to the use of this material. It is therefore hard to state with any certainty that the strontium composition of forest glasses will be a reflection of only the plant or wood ash. This will be discussed further in section 3.7.

Neodymium isotopes

Samarium (Sm) and neodymium (Nd) are rare earth elements (REE) that occur in many rock-forming silicates, phosphate and carbonate minerals (Faure 1986; 200). The REE occur in trace amounts in common rock-forming minerals in which they replace major ions. Sm has seven naturally occurring isotopes, three of which are radioactive. ^{147}Sm is one of these and decays to ^{143}Nd by alpha emission. As with the Rb-Sr method it is possible to use this decay to date rocks and minerals. Again, this method will not be used to provide dates in this study, rather a means of characterising the silica sources used in the production of forest glasses. Previous work has assumed that this element will be present in far higher proportions in the silica source, rather than the wood or plant ash (see section 1.2.2).

Standards analysis

NBS 987 Sr standard gave an ^{87}Sr/^{86}Sr ratio of 0.710281 ±0.000005 (1s, n =16), the accepted value is 0.710250, to which these data collected were normalised. J&M Nd internal standard gave an ^{143}Nd/^{144}Nd ratio of 0.511108±0.000005 (1s, n =4), during the running of samples in this study, and these data were normalised to a value of 0.511123. Typical blanks are below 150 pg for Sr and 250 pg for Nd. A recent comparison between J&M and the La Jolla international standard was carried out and La Jolla gave an ^{143}Nd/^{144}Nd ratio 0.511846 ± 0.000003 (1s, n=6) (accepted value 0.511860) while J&M gave 0.511103 ± 0.000001, (1s, n=10).

3.6.3 Oxygen isotope analysis

Oxygen Isotope analysis has been used in archaeological glass studies for the past 40 years. There are two stable isotopes of interest ^{16}O and ^{18}O. The heavier ^{18}O isotope occurs naturally approximately at a ratio of 1:500 to the lighter isotope (Frank 1982; 64). The isotopic ratio of oxygen depends on where and the form in which it occurs in nature (Brill et al. 1999; 303).

The oxygen isotope method does not involve radioactive decay, like strontium and neodymium, it is physical and chemical fractionation processes that are responsible for the isotopic variations observed (Brill 1970; 143). Oxygen occurs in forms which readily interchange with one another, such as water, ice, water vapour and atmospheric oxygen (Faure 1986; 430-438). As it is particularly susceptible to fractionation during these interchanges the ^{18}O contents of various materials can be quite different (Brill 1970; 154).

By convention oxygen isotope ratios are reported in terms of δ which is a measure of the deviation in parts per thousand from a standard known as the standard mean ocean water (SMOW) (Brill 1970; 154). Thus the ^{18}O content of SMOW has by definition a value of zero on the δ scale. Those with a positive value have an excess of ^{18}O over SMOW and those with a negative value a deficiency (Brill et al. 1999; 304).

Brill et al. (1970; 1999) have noted that oxygen isotopes could be used to source silica because there is a natural range in isotope values which is dependent on the geology (see figure 3.5). They suggested that the oxygen isotope composition of archaeological glass is strongly dependent on the oxygen isotope composition of the raw ingredients, especially the silica, since silica is the predominant component (Henderson et al. 2005; 666). Experimentation has shown that varying the melting times and temperatures had no measurable effect on the final $\delta^{18}O$ of the glass, and therefore the geological ratios will remain in archaeological glasses.

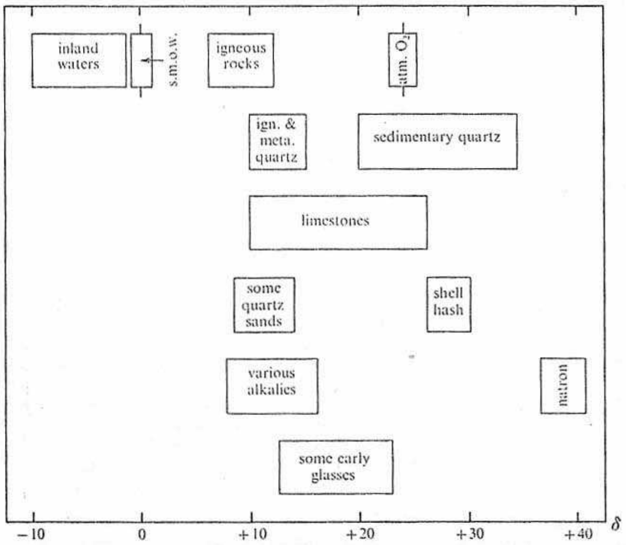

Figure 3.5: ^{18}O contents of some naturally occurring materials and glassmaking ingredients (Brill 1970; 155).

Due to the processes involved in the weathering of glasses, the ^{18}O levels in weathered glass are altered due to the exchange of ions with the surroundings. It is therefore particularly important to use unweathered glass when discerning oxygen isotope ratios. It is clear that weathering can have a drastic effect on the ^{18}O content of a glass (Brill 1970; 157). Weathered glass was avoided during all types of analysis carried out in this project.

The only factor determining a glass's oxygen isotope ratio is the raw materials. Brill (1970) and Brill et al. (1999) have stated that the oxygen isotope signature of a glass will be mainly dependent on the silica source, with a small effect from the flux and stabiliser. By experimenting with differing alkali and stabiliser sources Brill et al. (1999; 307) attempted to show this. Using a silica source with a δ^{18}O of 14 and sodium carbonates with δ^{18}O of 30 and 10 they produced glasses with δ^{18}O of 15.5 and 13.5. While this shows that the majority of the δ^{18}O value of a glass is based on the silica source, it is also clear that the other raw materials can have a noticeable effect on the oxygen isotope signature of the finished glass. Oxygen isotope data must therefore be considered as reflecting the silica source with some alteration due to the flux and stabiliser. None of the raw materials analysed in this study have been analysed for oxygen isotope ratios.

Preparation of samples

To carry out oxygen isotope analysis it is necessary to separate the oxygen from the glasses. Samples were subjected to laser fluorination to remove the oxygen. Preparation was initially carried out using glass powders; however the oxygen yields were low. Significantly higher yields were generally obtained using small chips of glass. Wherever a higher yield was obtained using powder, this result was used. After fluorination the oxygen was reacted with heated graphite rods to produce CO_2.

Analysis and standards

The oxygen isotope ratio was measured using mass spectrometry. The internal lab standard SES-1 was run, at least in triplicate, with each sample run (max 6 samples), and gave reproducibility of ±0.3‰ or better. The methodology used routinely obtains a result of 9.6±0.3‰ or better for the international quartz standard NBS 28.

3.7 Raw material analysis

The bracken ash and silica samples collected from The Weald, Staffordshire and North Yorkshire were subjected to analysis using TIMS. This gave concentrations and isotopic ratios for both strontium and neodymium. None of the raw material samples was analysed by electron microprobe.

3.7.1 Bracken ash

Sample	Material	Sr (ppm)	$^{87}Sr/^{86}Sr$	Nd (ppm)	$^{143}Nd/^{144}Nd$
Cannock Chase	Bracken ash	87.5	0.712562	1.084	0.512371
Hutton Common	Bracken ash	311	0.712815	7.315	0.511997
Sidney Wood	Bracken ash	235.3	0.713048	25.44	0.512095

Table 3.7: TIMS analysis results for bracken ashes.

The results of these analyses are of great importance to the interpretation of isotopic data for archaeological glasses. In previous studies neodymium has been associated with the silica source used in glass production. However, in the case of the particular bracken ashes analysed here the Nd content outweighs that found in all the silica sources in two out of three examples (see table 3.7). In one of these cases, that of the Wealden sample, the Nd content of the bracken ash is so much greater than that of the sand source that it will definitely influence the Nd isotope ratio. The concentration of Nd in the bracken may vary depending on ashing temperature, season of harvest (see section 1.2.3) and the composition of the soil on which it grew.

This discovery is rather limited in its actual implications due to the natural variability of source. However it is potentially very important in terms of the results of this study. It is no longer possible to be sure that $^{143}Nd/^{144}Nd$ results can be linked to the silica source alone. Rather, the Nd composition of the sample must be potentially considered a mixture of both the silica and alkali source. Further work on other raw material sources and locations must be carried out to discern the extent of the potential Nd contribution of wood and plant ashes, but this is beyond the scope of this thesis.

The $^{87}Sr/^{86}Sr$ values and Sr concentrations for the bracken ashes also vary greatly between source locations. As with the Nd concentrations there are many possible reasons for the differences in Sr concentrations. As discussed above the $^{87}Sr/^{86}Sr$ value should represent the biosphere available strontium in the environment in which it grew. Comparison with the map produced by Evans et al. (2010) shows that the measurements made on the three bracken ash samples do not represent the more widespread trend of $^{87}Sr/^{86}Sr$ values found in these areas (0.709-0.710). These results illustrate the difficulties with attempting to assign provenance to a material based on its source.

3.7.2 Silica

Sample	Material	Sr (ppm)	$^{87}Sr/^{86}Sr$	Nd (ppm)	$^{143}Nd/^{144}Nd$
Cannock Chase	Quartz	1.4	0.830912	0.35	0.512074
Hambledon Hill	Sand	7.5	0.720689	2.952	0.512018
Hutton Common	Sandstone	27.5	0.728206	6.752	0.511969

Table 3.8: TIMS analysis results for silica samples.

The three silica sources have very different strontium and neodymium compositions (see table 3.8). The quartz collected from Cannock Chase has the highest $^{87}Sr/^{86}Sr$ values, but a very low concentration and so would not greatly influence the $^{87}Sr/^{86}Sr$ values of a glass produced using it and a plant ash (see bracken ash Sr concentrations in table 3.7).

The $^{87}Sr/^{86}Sr$ values for the sand and sandstone are also much higher than those found for any of the bracken ashes. The concentration of Sr in these two silica sources may be enough to have a noticeable effect on a glass produced using them, depending on the Sr concentration of the plant or wood ash.

The Nd concentrations of all of the silica sources analysed are surprisingly low. All are lower than the corresponding bracken ashes for their areas of collection. The $^{143}Nd/^{144}Nd$ value of a glass produced using a combination of these sources would therefore be dominated by that of the bracken ash, rather than the silica.

3.7.3 Summary

It must be remembered that these are only three samples of each material, and that it is not possible to say that any of these sources were used by forest glassmakers. However, the results are still very important in terms of the findings of this study. Rather than expecting the strontium isotope signature of a glass to represent the plant or wood ash used, and the neodymium from the silica source, these results show that the $^{87}Sr/^{86}Sr$ value of a glass may be affected by strontium in the silica source, and the $^{143}Nd/^{144}Nd$ value may be affected, and even dominated, by that of the plant or wood ash used.

A further finding, which has already been noted by others, is that the $^{87}Sr/^{86}Sr$ varies within regions and an average biosphere available value for an area will certainly not represent the entire biosphere. This makes it very unlikely that it would ever be possible to provenance forest glasses using $^{87}Sr/^{86}Sr$ values, without first having analysed glass from a production site even if it were possible to be sure that local raw materials were used. Further to this complication, if a production site changed its raw material sources, even over a short distance the $^{87}Sr/^{86}Sr$ value of the glass produced could vary considerably (see Chenery et al. 2010).

3.8 Model glass analysis

3.8.1 Chemical composition

	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5*	K_2O	CaO	MnO	FeO	Sb_2O_5
Weald Model	0.66	3.43	1.33	57.76	1.74	8.18	16.77	1.59	0.35	0.44

Table 3.9: Selected oxide EPMA results for model glasses. All data is in weight % oxide. Phosphorus oxide value should be considered semi-quantitative (see section 3.5.5)

The chemical composition of the glass is listed in table 3.9. As noted above, the production of this glass was in no way intended to replicate the chemical composition of glasses found at sites in the Weald. Using this combination of raw materials it has been possible to produce a glass which, unsurprisingly, has a potash composition. The composition is not dissimilar to some forest glasses which have been analysed previously (see table 3.3). In particular those from Knightons, Bagot’s Park and Little Birches.

3.8.2 Isotopic composition

Sample	Material	Sr (ppm)	$^{87}Sr/^{86}Sr$	Nd (ppm)	$^{143}Nd/^{144}Nd$
Hambledon Hill	Sand	7.5	0.720689	2.952	0.512018
Sidney Wood	Bracken Ash	235.3	0.713048	25.44	0.512095
Wealden Model Glass	Model Glass	269.2	0.713177	29.61	0.512058

Table 3.10: Sr and Nd concentration and isotope ratios for model glass and raw materials.

The production of a model glass and analysis of its isotopic signature has illustrated many of the points noted above and added some more potential problems. The Sr and

Nd concentrations of the glass are higher than those of either of the raw materials (see table 3.10). Therefore, during the melting process other components of the mixture must be lost, causing the Sr and Nd concentrations to increase. The increase of Sr and Nd concentration will cause problems if this property of a glass is used as diagnostic of its production by a specific raw material by observing the concentration present in said raw material. Variation in Sr, Nd and other component concentrations during melting must be borne in mind when discussing possible raw materials.

The ^{87}Sr/^{86}Sr value is most similar to the bracken ash value, but it has been slightly elevated by the introduction of the sand with its higher ^{87}Sr/^{86}Sr value, but lower concentration. This illustrates what was expected from the raw material analysis; that silica sources can have a small, but noticeable effect on the ^{87}Sr/^{86}Sr of a glass produced from them. The elevated ^{87}Sr/^{86}Sr in the sand source is likely to be due to the presence of feldspars and other minerals in the sand which have high ^{87}Sr/^{86}Sr values.

The ^{143}Nd/^{144}Nd value for the model glass is almost exactly halfway between the values for the bracken ash and sand. Due to the high Nd concentration in the bracken ash, relative to the sand, and the recipe used it was expected that the ^{143}Nd/^{144}Nd of the glass would be closer to that of the bracken ash. The reasons for this difference from the expected effect are unknown at this stage in the research and will need to be investigated further, but this is beyond the scope of this project.

3.8.3 Summary

The production and analysis of a glass from raw materials previously analysed by TIMS proved very useful in identifying further discontinuities between the raw materials and finished glasses. The results have shown that there will be some alteration of the concentration of the components of a raw material as it is heated and some more volatile components are preferentially diminished in the melt.

3.9 Summary

The assignment of provenance to archaeological glasses is a very difficult process. It is very important to state the assumptions that have been made before an analytical project such as this one is begun. It is clear from previous analytical work by other authors, and the analysis of raw materials carried out in this study, that there will be many problems with finding compositional or isotopic signatures which will provide a link to the raw materials used in the production of forest glasses or their provenance.

Problems include the mixing of raw materials, potential use of cullet produced at other sites, the intra-species variation in plant and wood ashes, and the lack of elements or oxides that can be specifically connected to single raw materials. These problems are discussed both in this chapter and chapter 2. If these potential problems are known before the discussion of analytical results it is possible to attempt to account for them.

The glass samples taken for this study have been taken from as wide a range of sites as is possible to give the largest, and hopefully most variable, possible data-set. Previous analyses of glasses from many of these sites have shown variations that may be relatable to location and/or chronology of the sites. These compositions can be used to suggest the types of raw materials used at each site and how they may have altered. Even though the quantity of isotopic analyses carried out on forest glasses is very small, possible raw materials have been suggested and this single study has altered the perceived view of raw material use in forest glass production (see Dungworth et al. 2009).

The techniques employed in this study will provide a wide range of data which can be interpreted to answer many questions relating to the production of the glasses sampled. The electron microprobe data will be useful in characterising the glasses based on recipes and raw material use. While not specifying particular species, it should prove possible to suggest types, such as mixed-alkali, potash etc. The isotopic analysis data will provide a further means of characterising the raw materials used in the glasses' production. Previous work outlined in this chapter and the analysis of raw materials has shown that there will probably be many cases in which the isotope systems chosen cannot be tied directly to a single raw material. The discovery of a neodymium-rich plant ash is of particular importance to this study and will have ramifications for the results of archaeological glass analyses discussed in chapter 4.

The results outlined in this chapter will make the discussion of the results of this study far more complicated than was initially expected. In fact it will mean that many of the conclusions relating signatures to raw materials can only be suggested unless they have a very distinct quality. It is hoped that the analyses may still be able to produce site-specific isotopic signatures, even if they cannot be directly related to the provenance of the raw materials themselves.

Chapter 4: Results and discussion

4.1 Compositional analysis

4.1.1 Introduction

Samples from all of the sites discussed in chapter 2 were analysed by electron microprobe for 25 major, minor and trace elements. In total 179 samples from 12 sites were analysed. These ranged from three from Buckholt to over 20 from some of the sites. The number of samples analysed per site was dictated only by the amount that was made available for sampling and analysis.

This set of chemical compositions represents the largest study of English forest glass to date. Carrying out all the analyses using a single piece of equipment and methodology means they are all directly comparable. This alleviates many of the problems associated with looking at previous work, discussed in section 3.3.

Figure 4.1 is a plot of aluminium oxide (Al_2O_3) vs. magnesium oxide (MgO). It is a useful way of explaining compositional differences since the majority of the aluminium comes from the silica source and the magnesium from the alkali, in this case wood ash. They are both present in relatively large quantities (~1-8 wt.%) and therefore their variations can be easily and accurately detected by this means of chemical analysis. As a whole, the glasses all fall into a compositional grouping already established as that for wood and plant ash glasses. The samples do not generally fall into separate compositional groups, dependant on which sites they are from. However, the data from many of the sites does fall into a relatively small range of values: for example, the high alumina samples from Haughton Green and the low-alumina, high-magnesia samples from Blunden’s Wood.

Site and Period	n.	Na_2O	TiO_2	SiO_2	Al_2O_3	Cl	MgO	K_2O	Sb_2O_5	FeO	MnO	CaO	$P_2O_5^*$	∑Alkali	Type
Early															
Blunden's Wood	20	2.53	0.09	58.41	0.89	0.51	6.71	11.25	0.79	0.65	1.08	13.09	1.95	13.78	1
Transitional															
Knightons	9	2.38	0.22	56.48	1.96	0.35	6.6	10.72	0.71	0.73	0.94	13.43	2.43	13.1	1
Little Birches	11	2.27	0.13	60.3	2.16	0.17	6.31	11.93	0.79	0.61	1.24	10.9	1.7	14.2	1
Bagots Park	17	2.75	0.1	60.33	1.69	0.23	7.61	9.97	0.69	0.51	1.61	11.17	2.07	12.72	1
Late															
Buckholt 1	2	1.81	0.1	59.78	0.81	0.44	6.41	9.44	0.62	0.61	0.8	13.34	3.8	11.26	1
Buckholt 2	1	1.1	0.27	57.68	2.22	0.21	3.18	5.59	0.4	1.19	0.49	22.27	2.23	6.69	2b
Buckholt West	19	0.97	0.25	59.64	2.32	0.11	2.92	5.38	0.38	1.07	0.41	21.72	1.61	6.36	2b
Bickerstaffe	12	5.77	0.12	58.57	2.26	1.22	4.76	1.96	0.16	0.62	0.52	19.58	1.93	7.73	3b
Glasshouse Farm 1	3	1.6	0.25	56.55	3.35	0.36	3.75	9.41	0.66	1.29	0.57	18.52	1.76	11.01	2a
Glasshouse Farm 2	6	3.61	0.25	57.33	3.71	0.55	3.84	5.48	0.38	1.22	0.51	19.44	1.53	9.09	3a
Hutton	10	2.17	0.22	60.86	2.63	0.67	2.31	4.17	0.31	0.91	0.33	21.19	1.1	6.34	3a
Rosedale 1	2	1.63	0.2	58.05	2.6	0.43	2.7	8.2	0.57	0.98	0.4	19.84	1.52	9.83	2a
Rosedale 2	16	3.34	0.23	58.36	3.2	0.49	3.15	5.63	0.41	1.29	0.27	19.38	1.32	8.98	3a
Rosedale 3	9	6.7	0.24	56.43	3.45	0.59	5.89	4.71	0.33	1.55	0.29	15.1	1.45	11.42	3c
Coal Fired															
Haughton Green 1	5	4.32	0.29	51.74	5.5	0.39	4.12	5.4	0.38	2.54	0.53	19.31	2.03	9.72	3a
Haughton Green 2	16	5.7	0.25	55.89	4.69	1.21	4.27	2.21	0.16	2.14	0.45	18.29	1.79	7.91	3b
Kimmeridge	21	3.03	0.19	58.86	2.25	0.41	3.36	3.88	0.25	1.1	0.3	22.33	1.77	6.91	3a

Table 4.1: EPMA results for selected components ordered by site and chronological period (wt%).

Oxide	Type 1		Type 2a		Type 2b		Type 3a		Type 3b		Type 3c	
Wt%	Average (n=62)	SD	Average (n=5)	SD	Average (n=20)	SD	Average (n=61)	SD	Average (n=28)	SD	Average (n=9)	SD
Na_2O	**2.49**	***0.39***	**1.61**	***0.47***	**1**	***0.24***	**3.36**	***0.98***	**5.73**	***0.56***	**6.7**	***0.47***
TiO_2	0.12	*0.06*	0.23	*0.03*	0.24	*0.03*	0.22	*0.04*	0.19	*0.07*	0.24	*0.03*
SiO_2	58.94	*2.83*	57.15	*2.06*	59.6	*2.1*	58.37	*2.91*	57.04	*2.16*	56.43	*1.45*
SnO_2	nd	-	nd	-	nd	-	nd	-	nd	-	nd	-
Al_2O_3	**1.54**	***0.7***	**3.05**	***0.51***	**2.1**	***0.34***	**3.01**	***0.97***	**3.65**	***1.25***	**3.45**	***0.24***
ZnO	0.04	*0.01*	0.03	*0.01*	0.04	*0.01*	0.03	*0.01*	0.02	*0.01*	0.02	*0.01*
SO_3	0.17	*0.08*	0.15	*0.06*	0.29	*0.09*	0.26	*0.15*	0.06	*0.07*	0.24	*0.03*
NiO	<0.01	*n/a*	<0.01	-	<0.01	-	<0.01	-	<0.01	-	<0.01	-
As_2O_5*	0.07	*0.02*	0.02	*0.02*	0.02	*0.02*	0.02	*0.02*	0.02	*0.01*	0.07	*0.03*
CuO	0.01	*0.01*	<0.01	-	0.02	*0.01*	0.01	*0.01*	<0.01	-	<0.01	-
Cl	**0.34**	***0.16***	**0.39**	***0.1***	**0.12**	***0.05***	**0.53**	***0.17***	**1.22**	***0.14***	**0.59**	***0.11***
CoO	<0.01	-	<0.01	-	0.01	*0.01*	<0.01	-	<0.01	-	0.01	*0.01*
MgO	**6.86**	***0.94***	**3.33**	***0.6***	**2.95**	***0.63***	**3.34**	***0.73***	**4.48**	***0.35***	**5.89**	***0.47***
K_2O	**10.86**	***1.23***	**8.92**	***0.95***	**5.43**	***0.67***	**4.62**	***1.37***	**2.1**	***0.63***	**4.71**	***0.34***
Sb_2O_5	0.74	*0.09*	0.62	*0.07*	0.38	*0.05*	0.32	*0.1*	0.16	*0.04*	0.33	*0.02*
FeO	**0.62**	***0.14***	**1.17**	***0.22***	**1.07**	***0.17***	**1.26**	***0.51***	**1.49**	***0.8***	**1.55**	***0.17***
BaO	0.17	*0.07*	0.09	*0.05*	0.1	*0.04*	0.1	*0.07*	0.14	*0.04*	0.08	*0.02*
MnO	**1.22**	***0.29***	**0.5**	***0.11***	**0.42**	***0.1***	**0.34**	***0.11***	**0.48**	***0.06***	**0.29**	***0.09***
CaO	**12.25**	***1.8***	**19.04**	***1.3***	**21.79**	***1.64***	**20.4**	***2.19***	**18.84**	***1.53***	**15.1**	***1.57***
ZrO_2	0.01	*0.01*	0.03	*0.01*	0.03	*0.01*	0.03	*0.01*	0.02	*0.01*	0.02	*0.01*
PbO	0.03	*0.04*	<0.01	-	0.02	*0.01*	0.02	*0.02*	0.02	*0.01*	<0.01	-
Cr_2O_3*	nd	-	nd	-	nd	-	<0.01	-	nd	-	nd	-
P_2O_5*	2.09	*0.51*	1.66	*0.15*	1.67	*0.25*	1.51	*0.35*	1.85	*0.15*	1.45	*0.08*
V_2O_3*	<0.01	-	<0.01	-	<0.01	-	<0.01	-	<0.01	-	<0.01	-
*SrO**	nd	-	nd	-	nd	-	nd	-	nd	-	0.02	*0.03*
Total Alkali	**13.35**	***1.29***	**10.54**	***0.75***	**6.43**	***0.82***	**7.98**	***1.68***	**7.84**	***0.39***	**11.42**	***0.36***

Table 4.2: Average and standard deviation values composition of glass types found in the samples studied (wt%).

Notes for tables 4.1 and 4.2: There are two samples from Buckholt West WG11 and 21 which are not included in the average tables above due to anomalously high aluminium values, apart from these values they are group 2b glasses. WG11 also contains anomalously low lime levels.

There are four samples (C2-WG1, C3-WG1, C1-WG2, C1-WG3) from Glasshouse Farm which have Type 3 compositions, but also differ due to highly elevated alumina levels. They were all samples taken from crucible fragments. They have not been included in the average values in this table. One further sample (C2-WG2) was also taken from a crucible fragment was not included due to highly elevated calcium oxide levels.

Two pieces from Bagots Park C2 and C3 which were taken from crucibles and are Type 1 apart from high aluminium levels, are not included in the averages.

nd=not detected, <0.01=detected at levels below 0.01 wt%.

* Values for these oxides should be considered semi-quantitative. Please see section 3.5.5 for further details.

Type 1	Low Lime-Potash
Type 2a	High Lime-Low Soda-High Potash
Type 2b	High Lime-Low Alkali-Low Chlorine
Type 3a	Mixed Alkali-Low Soda
Type 3b	Mixed Alkali-High Soda-High Chlorine
Type 3c	Mixed Alkali-High Soda

Table 4.3: Descriptions of glass types.

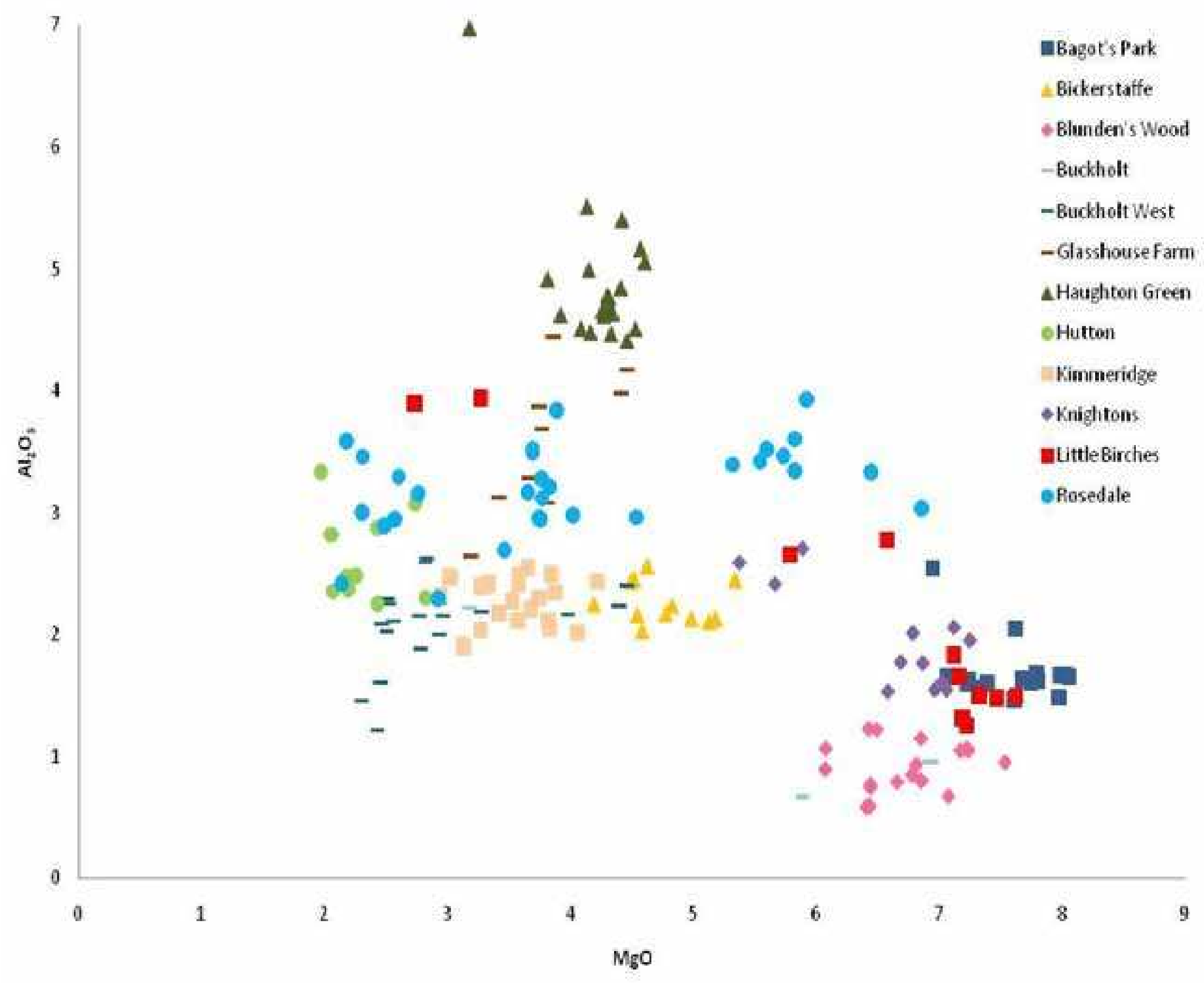

Figure 4.1: EPMA results for alumina vs. magnesia for all sites in this study (wt%).

4.1.2 Comparison with previously published work

There are a number of differences between the results found in this study and those found by previous workers. However, in terms of compositional types there are also many similarities. The earlier sites are higher in potash that later sites, and the chronological trend still seems to be towards an increasing use of soda-rich plant ashes at later sites. Green and Hart (1982) found glasses at Knightons that were higher in calcium than any of those found in this study. The glass produced here may therefore not only be of type 1 composition, but also of type 2a. However, no type 2a glass from Knightons was found in this study.

4.1.3 Discussion by compositional types

Three major compositional types were found in the glasses analysed in this study. They can be found in the table 4.2. In general these types, and the sub-types they are divided into, are not completely compositionally distinct based on any single component. It is only when a number of oxides are taken into account that the differences become clear. However, they are still useful ways of dividing the glasses into compositional types. The differences may be the result of gradual or sudden changes in recipes depending on chronological or geographical factors. The types will be described here and then possible reasons for their compositional differences will be discussed. Then how the types vary between sites and how this relates to chronology and geography will also be discussed.

Division of types

The compositional differences between types can be seen in table 4.2. Type 1 is a high potash, low lime composition commonly known at potash glass. Type 2 glasses are high lime, low soda glasses with varying potassium levels. Type 3 are mixed alkali glasses with varying soda and potash levels and high lime levels. Types 2 and 3 can be further divided into another two and three subgroups, respectively.

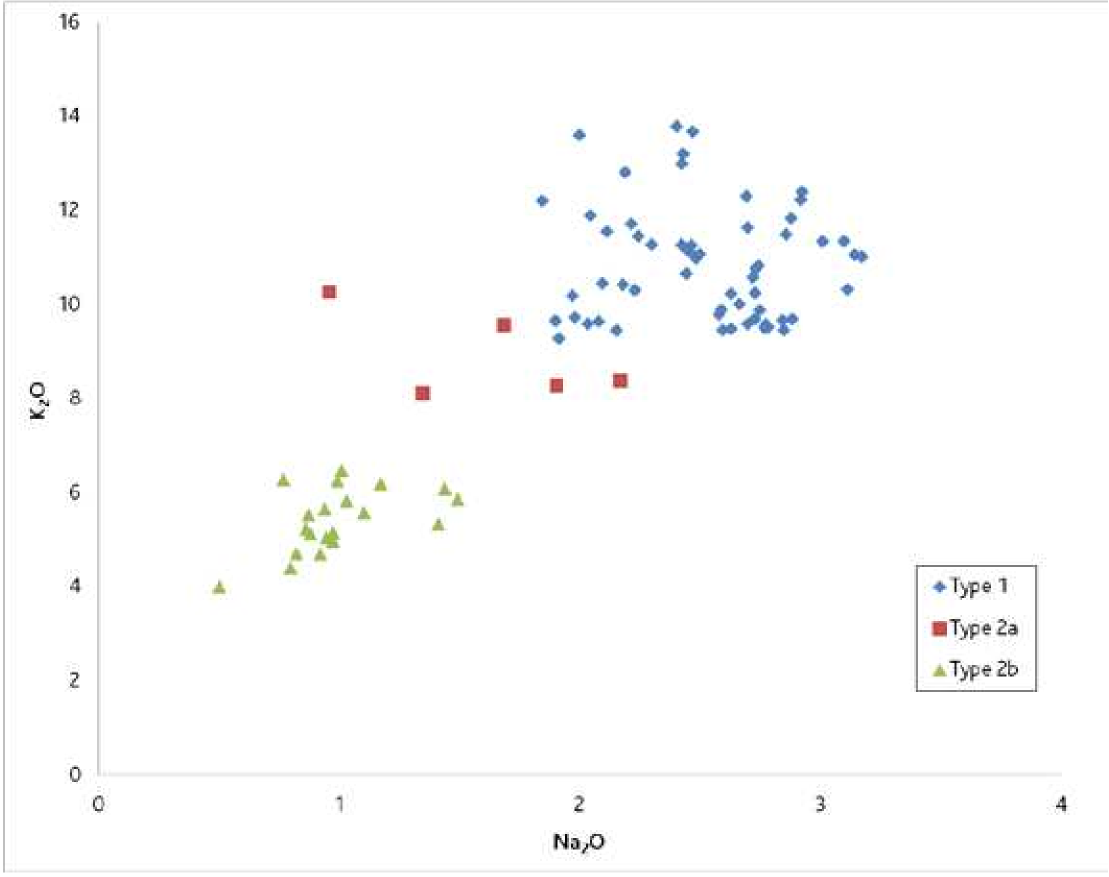

Figure 4.2: EPMA results for potash vs. soda for types 1 and 2 glasses (wt%).

Type 2a glasses have a high potash level comparable with some glasses from type 1. However they differ from type 1 glass due to their higher lime, low magnesia, low alumina and low soda composition. Type 2b share these four compositional characteristics with type 2a, but have much lower potash, and therefore total alkali levels (see figure 4.2).

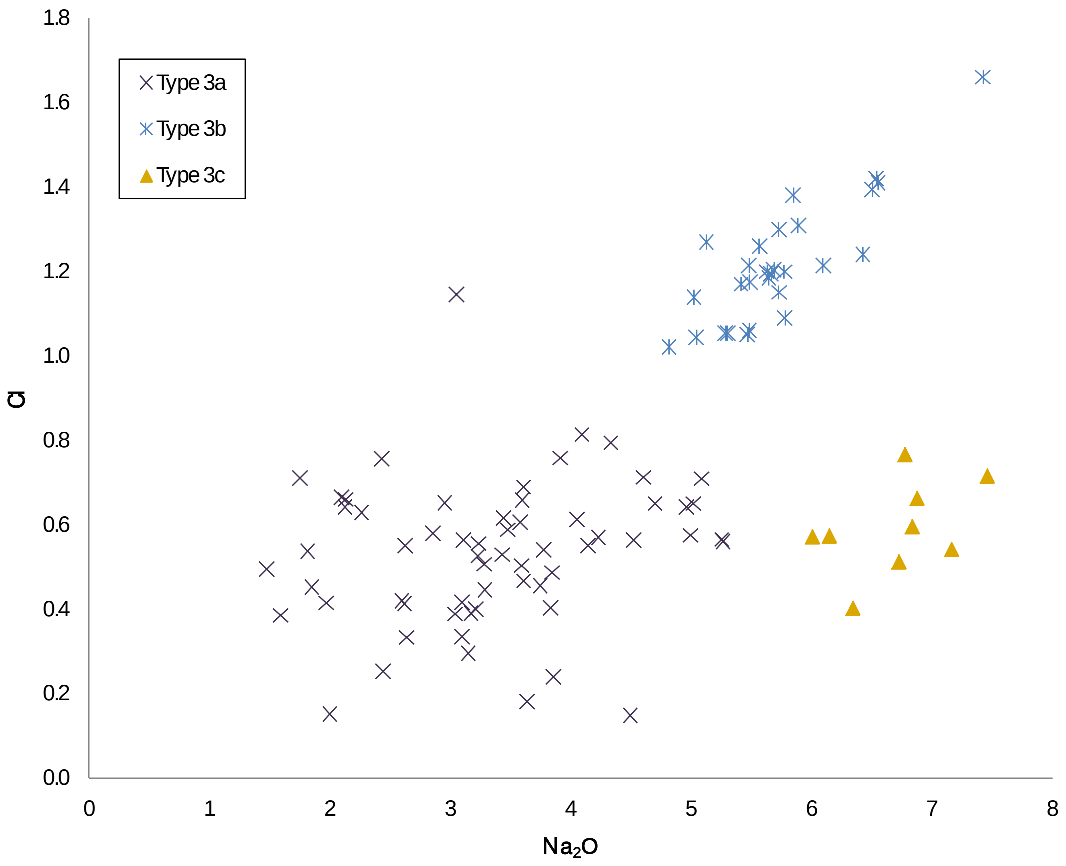

Figure 4.3: EPMA results for chlorine vs. soda for type 3 glasses.

Type 3a glasses have generally higher soda and lower potash contents than type 2 glasses (see table 4.2). Type 3b glasses differ from type 3a due to their higher soda, lower potash levels, and their high chlorine content. It is this third component which makes them distinct from all other glass types discussed here. The final type, type 3c, shares some compositional characteristics with both type 3b and 3a. Its soda levels are similar to type 3b, and its chlorine and potash levels are closer to type 3a (see figure 4.3 and table 4.2). It is distinct from both of these other type 3 glasses due to its elevated magnesia levels.

Reasons for compositional differences

Previous analytical work on raw materials carried out by archaeological scientists in attempts to discover the reasons for compositional similarities and differences in forest glasses has been discussed in chapter 1. The results of these studies will be used here in an attempt to discover the reasons for the compositional differences between types found in this study.

Type 1

As noted above type 1 glasses are high potash, low lime. They are also compositionally different from the other types based on a variety of oxides (see in particular those in bold font in table 4.2). Bearing in mind the high levels of intra-species variation in alkali compositions discussed in chapter 1, type 1 glasses share a number of compositional similarities with glass produced by Smedley et al. (2001) from a mixture of 1 part bracken ash, 1 part birch ash and 1 part silica. This is therefore one possible recipe for this type. However, this does not explain the high magnesia levels in this type (the above study produced a glass with only 2.42 wt% MgO, compared to 6.86 wt% in this study). There must be a difference in the alkali sources used, probably a different species of plant or wood ash. However, which species was used is currently unknown. The high potash and relatively low soda levels in these glasses make the use of soda-rich plant ashes in their production very unlikely.

The average values for the oxides that are generally associated with impurities the silica source used (i.e. alumina, titania, iron oxide [see section 1.2.2]) are lower in this type than any other, apart from some type 3b glasses from Bickerstaffe. This may be related to the type of sand used, or possibly that the sand used at these sites was purified in some way. Theophilus prescribed that the sand used in glass production should be ‘taken from water’ (Dodwell, 1961; 39). This may mean that the sand was river sand, or that it was washed in water prior to its use. This is only one possible explanation for the levels of these oxides. As was shown in chapter 1 these three oxides are also present in varying quantities in wood/plant ashes and so a variation in the species used at these sites may explain the difference. The average lime levels in these glasses are also lower than those of any other glass type found in this study (see figure 4.4), however they do overlap with some type 3 glasses. There are at least three possible explanations for this.

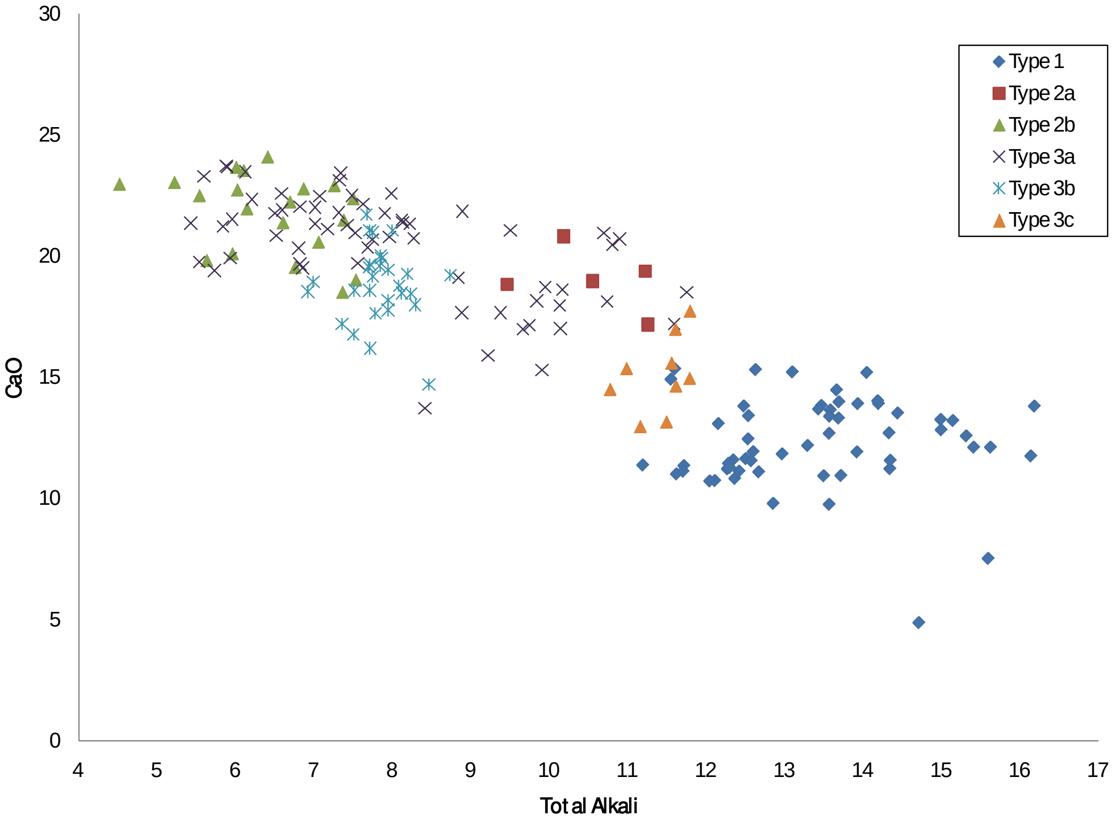

Figure 4.4: EPMA results for lime vs. total alkali levels divided by compositional type for all samples in this study (wt%).

Firstly, that a low lime sand source, either purified or selected for its lack of impurities, was used in the production of these glasses (see above). Smedley et al. (2001) found that using a refined sand source and bracken and birch ash a glass of 14.84 wt% CaO was produced (the average values for type 1 glass are 12.25 and a maximum of 15.3 wt% CaO). It is therefore possible to produce a glass with type 1 lime composition without the separate addition of lime as a separate raw material or as part of the silica source.

The second possible explanation for the low lime levels is simply the use of a different plant/wood ash at these sites. The high variability of calcium levels in different wood and plant ash, both inter- and intra-species, can be seen in the data reported in chapter 1. As shown by Wedepohl (1997, 2000) even the part of the tree used can greatly affect its lime content. Therefore choosing different parts of the tree to ash may alter the lime levels found in finished glasses significantly enough to cause the observed difference. The similarities between the compositions of glass produced at sites in The Weald and Staffordshire would seem to imply that the compositional variation is not due to differences in the growing environment and rather an ingredient or methodological choice made by the glassmakers at these sites.

The third explanation is that lime was added as a separate raw material in the production of types 2 and 3 glasses, but not in type 1 production. This possibility is discussed in detail in chapter 1 and has been suggested by a number of other authors (see Hartmann 1994; Schalm et al. 2004; etc.). From the current data available (see tables 1.2-5) it would seem that the addition of soda-rich plant ashes in type 3 glasses could not account for the increase in lime levels in the later glasses. This change in raw material choice can therefore not account for this change. As noted many times before, these compositions should not be considered definitive plant ash compositions. However, they suggest that a lime-rich raw material separate to the alkali sources may have been added.

It is not possible to discern from the compositional information presented here precisely which of these possibilities is the case. However, it seems very likely that the type 1 glasses were produced using a similar recipe and that similar choices of raw materials and recipes were being made by the glassmakers producing this glass type.

Type 2a

These glasses are also of a high-potash composition. They differ from type 1 glasses due to their elevated lime, alumina, iron oxide and titania levels and lower soda, magnesia and phosphorous oxide (see table 4.2). These changes imply different silica, alkali and, possibly, lime sources were used (see description of type 1). It is suggested here that these two changes are a switch to the use of a different wood ash alkali source, and the use of a higher impurity sand source than that used to produce type 1 glasses. However, as discussed above, these data do not discount the possibility that simply a different wood ash was used, perhaps with the addition of lime as a separate raw material.

Type 2b

These glasses share similar average lime levels and low average soda levels with type 2a. However, this type also has relatively low average potash and magnesia levels. The production of glass with this composition would have required a higher furnace temperature than types 1 and 2a due to the higher lime levels and lower total alkali levels. This high lime, low alkali composition would result in a more stable and durable glass, thereby making the effort to increase furnace temperature worthwhile. It is not possible to say for certain that this was the intention of the glassmakers, and they may have been forced into reducing the alkali levels due to problems sourcing raw materials, thereby necessitating the increase in furnace temperature (see section 4.1.4 for further discussion). The high lime levels in this low alkali sample results from a separate addition of lime, the use of a lime containing silica source, or the use of a high-lime low alkali ash.

Type 3a

This is the first of three sub-types with increased soda levels. As a single larger type they can be described as mixed-alkali glasses. This first sub-type is the largest of the three and describes glasses of highly variable soda and potash compositions (see figure 4.5). The lime levels in these glasses are comparable with glasses of type 2. The alkali composition of this type is due to the addition of a soda-containing alkali source. This source is probably a soda-rich plant ash, which may have been added in combination with a potash-rich wood ash, or alone, as it is possible to see from plant ash analyses they can contain approximately equal quantities of both alkalis, or more or less of either (see chapter 1 and Barkoudah and Henderson 2006).

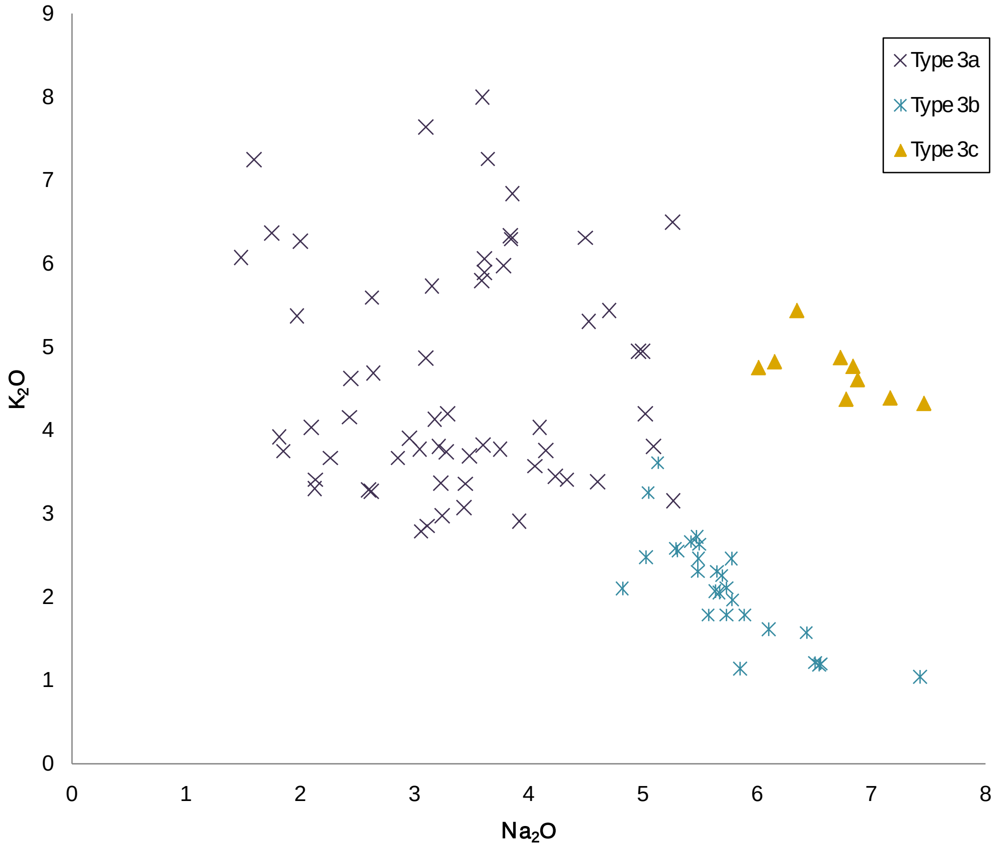

Figure 4.5 EPMA results for potash vs. soda for all type 3 glasses (wt%).

Type 3b

These glasses share some compositional characteristics with type 3a. However they differ due to elevated soda and chlorine contents and reduced potash (see figures 4.3 and 4.5). The total alkali and lime levels in type 3b glasses are very similar to those of type 3a composition. It has been shown by Tanimoto and Rehren (2008) that the quantity of chlorine present in glasses can be correlated with the alkali content of the glass; increasing the alkali content of a glass melt will allow more chlorine to be dissolved. However, as this glass has similar total alkali levels to those in type 3a it must be assumed that the elevated chlorine levels from one of the raw materials used in the production of type 3b glasses. It is suggested that type 3b glass is made using a different alkali raw material to type 3a, one that contains a higher proportion of soda relative to its potash levels, and chlorine. Hartmann (1994; 119) has suggested that the increased chlorine levels found in some German late-medieval glasses may be due to either the use of reed grass or salt (see chapter 1). The elevated zinc oxide levels he found in the high chlorine glasses from Germany are not found in this study. That rock salt would have been a relatively expensive commodity in the late medieval period would seem to suggest that it is more likely that a chlorine-rich plant ash was used to produce type 3b glasses (ibid.).

Type 3c

These glasses have some similarities with both type 3a and 3b glasses. They are mixed, and high total, alkali glasses with similar chlorine levels to type 3a glasses (see figures 4.3 and 4.5). They differ from both of the other type 3 subtypes due to their higher magnesia levels and lower average calcium levels (see table 4.2 and figures 4.1 and 4.4). These glasses seem to have been produced using a different alkali source to types 3a and 3b. They have similar soda levels to type 3b. However, if they were produced using an increased quantity of the same alkali source used for type 3b glasses an elevated chlorine content would also be expected, and is not seen.

4.1.4 Discussion by site and chronology

Table 4.1 shows the average compositions for each site. Where there was glass of more than one compositional type found at a site the average values for each type are listed. Below is a discussion of the analytical results in terms of chronology of the production sites.

Early

The only site dating to before the 16th century is Blunden's Wood (*c*.1330). All of the glass analysed from this site is of type 1 composition. The glass from Blunden's Wood has lower alumina values than the majority of other type 1 glasses (see figure 4.1). This may show some difference in the raw materials used here, most likely that a sand source with a lower feldspar content was used. This may not, therefore, have been a conscious choice, as this small variation (~1 wt.% Al_2O_3) would not noticeably alter the melting and working properties of the glass.

Transitional

There are three sites dating to between *c*.1500 and *c*.1567, Knightons, Bagot's Park and Little Birches. All of the samples analysed from these sites are also of type 1 composition. Without analysing samples from sites between the single 14th century site and these sites it is hard to say, but it would appear that there may be continuity in the recipe used during this two-hundred year period. There is no evidence for the suggestion by Welch (1997) that quartz pebbles may have been used at the Staffordshire sites. If this were the case a compositional difference would be expected compared to other sites in terms of lower impurities associated with the silica source used.

The compositional similarities between Knightons, Bagot's Park and Little Birches are very interesting. They show that in the mid-16th century there was a recipe which was used in both The Weald and Staffordshire. This implies there was some form of communication between these two areas at some time during or before this period.

These sites all have evidence for the production of windows, so an increased demand for window glass could have inspired glassmakers to move between these centres at some point during these periods and thereby transmit the recipe (see section 1.1.2). Perhaps there was an increase in demand in the Midlands, a decrease in demand in the South-east or vice versa. Further investigation into the consumption of glass in these two regions would assist with these assumptions, however this is beyond the scope of this thesis.

There are some glass samples from each of these three sites which do not conform entirely to type 1 composition. In general they have lower magnesia values and/or higher alumina values. However, due to their high potash and relatively low lime levels they are still considered type 1 glasses. The reason for the differences in their composition may be due to a lack of homogeneity in the glass crucible resulting in differences in composition in some samples, as these are the minority of samples from these sites. It probably does not represent the use of different recipes or raw materials, however this cannot be discounted.

Late

The glass produced in this period shows the greatest variation in compositional types. Every compositional type and subtype are represented in this chronological period. In terms of chemical composition, it is this period which is far more *transitional* than the one which precedes it.

The earliest sites in this group are those located in Hampshire, Buckholt and Buckholt West dating to the 1570s and 80s. There were only three samples from Buckholt: however, these three are of very important compositional types. Two are produced from type 1 glass, finding their closest analogies with the glass from Blunden’s Wood. The third sample is of type 2b composition, as are all the glasses from the nearby site of Buckholt West. It is particularly interesting to have found type 1 glass at Buckholt as this site was thought to have been run by glassmakers from The Weald who would have been working at sites like Knightons before moving to Hampshire (Winbolt 1933; 18). They may therefore have taken some glass with them from The Weald for use as cullet, or begun producing type 1 glass at Buckholt, before switching to producing type 2b glass at Buckholt and Buckholt West. The incredibly small quantity of data makes it impossible to prove this hypothesis, but this is one possible suggestion.

The production of type 2b glass at Buckholt and Buckholt West is also of great interest. The date of these two sites puts them after the arrival of immigrant glassmakers from north-western Europe. This influence can be seen in the winged design of the furnace at Buckholt (see chapter 2). In the discussion of glass types above it was noted that the melting of type 2b glass would require a higher temperature than type 1 (see section 1.2.5 for discussion of melting temperatures of glasses), and the winged furnace at Buckholt may have been more efficient at achieving higher temperatures than the rectangular furnaces producing type 1 glass in The Weald prior to this time. The low levels of alkali in type 2b glasses also fits rather well with the documented difficulties the glassmakers of this period were having in acquiring raw materials (see chapter 2). The glassmakers at the Buckholts may have been using less alkali, and the new furnaces, capable of achieving higher temperatures, allowed this to be possible. The darker colour of these glasses may also have been the result of a new furnace design which allowed a more oxygen-rich environment to be achieved (see sections 1.3 and 2.7).

The next site to be discussed is that of Glasshouse Farm, Herefordshire, dating to sometime between 1580 and 1620. The glass at this site is of two compositional types; 2a and 3a (see table 4.1). The first of these types shares its high potash levels with type 1 glass, but high lime levels with all of the other types. There are only three examples of this glass type found at this site. It may be the result of some form of experimentation in glass recipes, or have been produced elsewhere and brought to the site as cullet (see section 1.2.4). The type 3a glasses found here show that a soda-containing alkali source was being used at this site. If the dating of this site is towards the earlier end of the time period suggested by Bridgewater (1967; see section 2.5.4) this may be the first evidence found in this study of the use of this mixed-alkali composition in forest glass production in England.

The sites of Hutton and Rosedale are in close proximity to one another in both location and date. They are both located in North Yorkshire and date to the late 16th century. At Hutton the only glass type found was type 3a, this shows some similarity with some of the glass produced at Glasshouse Farm. However it cannot be suggested that precisely the same recipe was being used, merely that a similar raw material choice(s) appears to have been made.

The story at Rosedale is rather more interesting. Three compositional types were found in the glass at this site. Firstly, two samples of 2a glass, which is only also found at Glasshouse Farm, suggestions for its presence are the same as those laid out above. Secondly, 3a, which is found at a large number of sites and is a highly variable, mixed alkali compositional type and common to many of the sites in operation during the late 16th and early 17th centuries. The third is type 3c which is unique to this site. The discovery of this compositional group at this site shows that a different alkali source, or combination of sources, was used here and not at any of the other sites in this study.

The last site to be discussed from this time period is Bickerstaffe. The glass from this site is of an aqua blue-green colour, only similar in colour to that from Blunden's Wood. However, all of the glass analysed from this site is of a type 3b composition (see figure 4.3). This adds evidence to the possibility raised in section 1.3; i.e. that furnace environment, as well as the metal oxide contents, can control the colour of glasses produced. This type is a mixed alkali composition and is distinct from type 3a due to its higher soda and chlorine levels. This glass type is also found at Haughton Green, a site which is relatively nearby Bickerstaffe and may have been run by the same family of glass producers (see section 2.5.5). The discovery of this glass type at only these two sites lends further evidence to the suggestion that they may also be linked in terms of who was running them. Also, the glass produced at this site is therefore compositionally distinct from all other glass produced at other wood-fired furnaces studied in this project.

The influence of foreign glassmakers entering England from 1567 onwards has a clear and long lasting effect on the glass recipes used (see table 4.1). This influence does not come in the form of a *new recipe* which is rapidly adopted by all glass producers. In fact this period seems to be one of experimentation. It begins with a reduction in the levels of alkali used in glass production. This is followed by the use of a range of different alkali sources with higher soda levels than those exploited in the early and transitional periods. The use of the two types found in the largest numbers at these late sites, 3a and 3b, are continued in the following period.

Coal-fired

The final chronological group consists of two sites. At Haughton Green two compositional groups were found. Firstly, five samples of type 3a glass, the most common mixed-alkali glass type found in this study. Secondly type 3b glasses, as discussed above in terms of their discovery at Bickerstaffe. Both the type 3a and 3b glasses found at Haughton Green differ from those found at other sites due to their consistently high alumina levels. They also have the highest average iron oxide levels and some of the highest titania levels (see table 4.1). So it is suggested that the glass produced here was made using a higher impurity sand source. The high iron content of these glasses causes their very dark colour, perhaps in combination with an oxidising furnace environment. However, closed crucibles were found at this site, suggesting the glass may have been produced in a reducing environment (see section1.3). The high iron levels alone may be sufficient to explain these glasses' very dark colour.

The glass from Kimmeridge was all found to have a type 3a composition. It has no compositional characteristics which allow it to be distinguished from many other type 3a glasses. The discovery of type 3a glasses at these two sites shows a level of continuity of glass production between the Late and Coal Fired furnaces. The switch to coal therefore did not necessitate, or coincide for other reasons, a change in glass recipe. The dark colour of the glass from Kimmeridge must be due to differences in furnace environment compared to that of the wood-fired furnaces, as iron oxide is only present at around 1 wt% (cf. other sites producing type 3a glass in table 4.1). Closed crucibles were not found at this site, and therefore the high levels of oxygen present in the furnace in combination with these glasses' iron levels probably caused their dark colours (see section 1.3).

4.1.5 Summary

These analytical results confirm some of the trends observed in previous analytical studies carried out by other authors (see chapter 3). However, the generally larger number of samples analysed per site and use of the same analytical technique and conditions for each sample, allows far more secure conclusions to be drawn from the data.

The discovery of three compositional glass types, along with sub-types for two of these main types, is an important discovery as they can sometimes be linked to locations or time periods. There was only one site-specific composition and type, which was found at Rosedale. However, even in this case it was not the only compositional type found at this site. It is therefore not possible to state that all glass produced at this site will have this composition.

In terms of chronology the data suggests that there was a change from a single wood ash based recipe used from the early 14th until the mid-16th century. This was replaced with not a single new recipe, but a period of changing raw material use and experimentation. This period, Late, seems to have seen an increase in the use of plant ash alkali raw material rather than, or in combination with, wood ash. It might have been expected that the switch to the use of coal as a fuel might have required or prompted an alteration in glass recipes. This was not found in the data presented here. In fact plant ash appears to have been used long before the switch to coal. The use of varying new plant-based alkali sources increases the probability of the importation of raw materials. This will have ramifications for the interpretation of isotopic analysis, as will the possible use of limestone as a separate addition.

The single, or similar, recipe that was found to have been used at all early and transitional sites studied in this project was found regardless of geographical location. This implies a link between these sites, perhaps suggesting that there was a movement of glassmakers between The Weald and Staffordshire. There are also contemporary written texts describing the recipes for glass production (see section 1.2.1). However, it is highly unlikely that these would have been accessible by glassmakers. The documented arrival and movement of foreign glassmakers during the two later periods, Late and Coal-fired, explains how similar recipes might have been transmitted between regions (see section 1.1.3).

Similarities in composition between sites located near one another suggest that there was some contact between glassmakers working within a single region, such as at Bickerstaffe and Haughton Green or Little Birches and Bagot’s Park. However, due to the short lifespan of a glass furnace and the low resolution of dating techniques used on forest glass furnace sites it is possible that rather than being a matter of contact these sites were run by the same people, moving from one site to the next once a furnace became unusable or market unprofitable (see section 2.1.3; Linford and Welch 2003; 37).

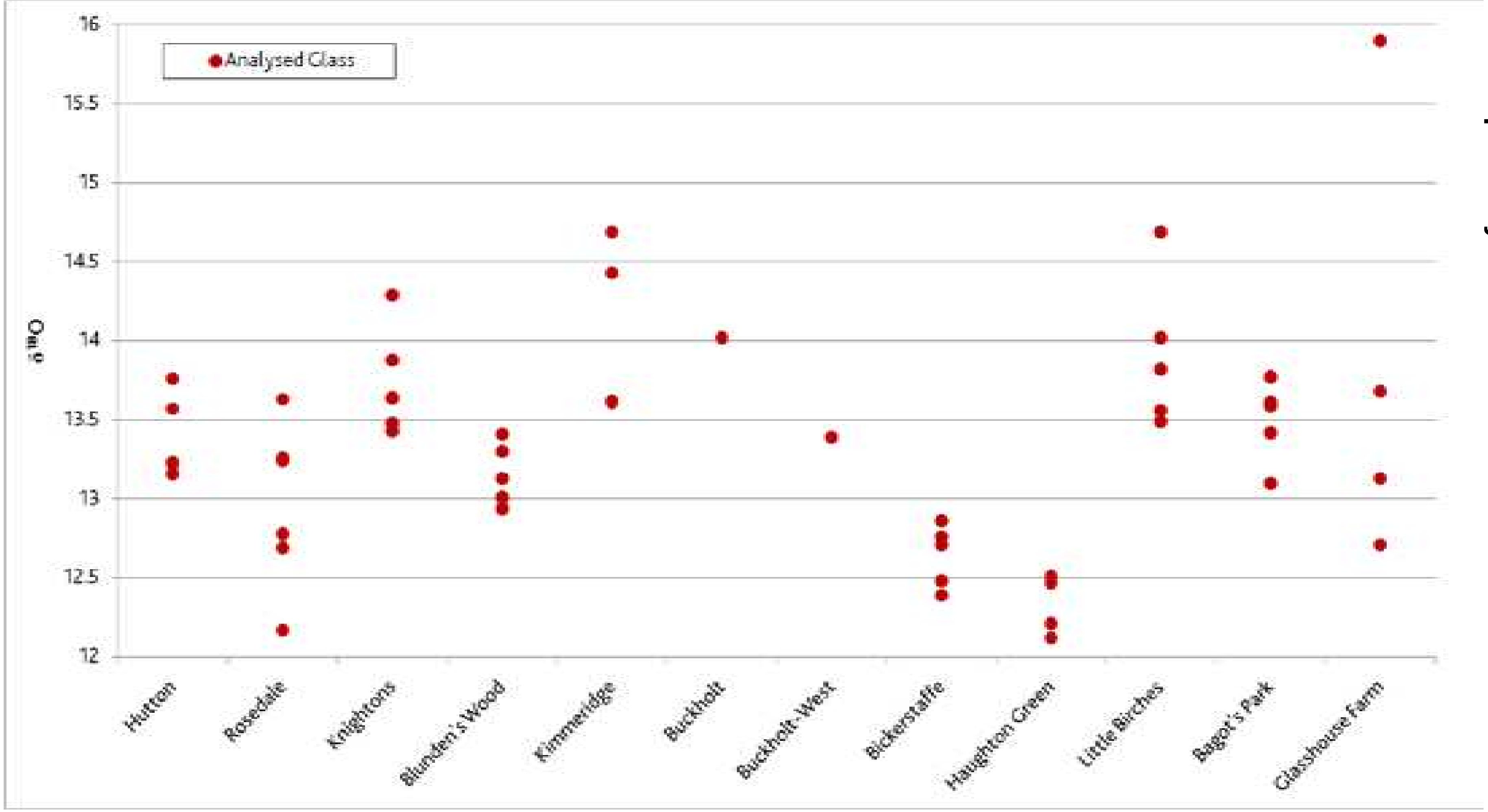

Figure 4.6: Oxygen isotope results organised by site and region.

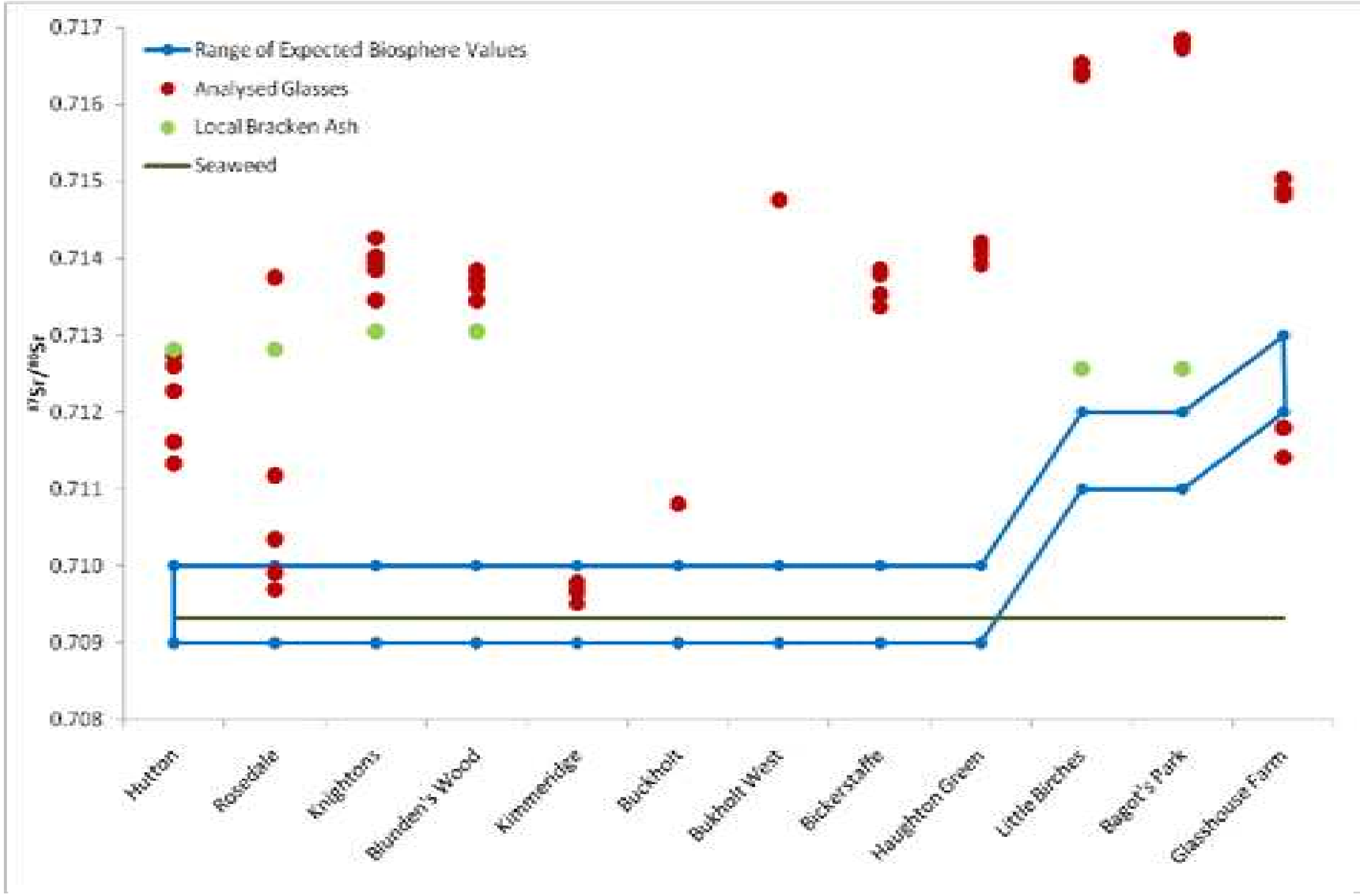

Figure 4.7: Strontium isotope results for all glasses and bracken ash TIMS analyses organised by site and region. Also included in this plot are expected biosphere values for regions from Evans et al. 2010 and seaweed values from Dungworth et al. 2009.

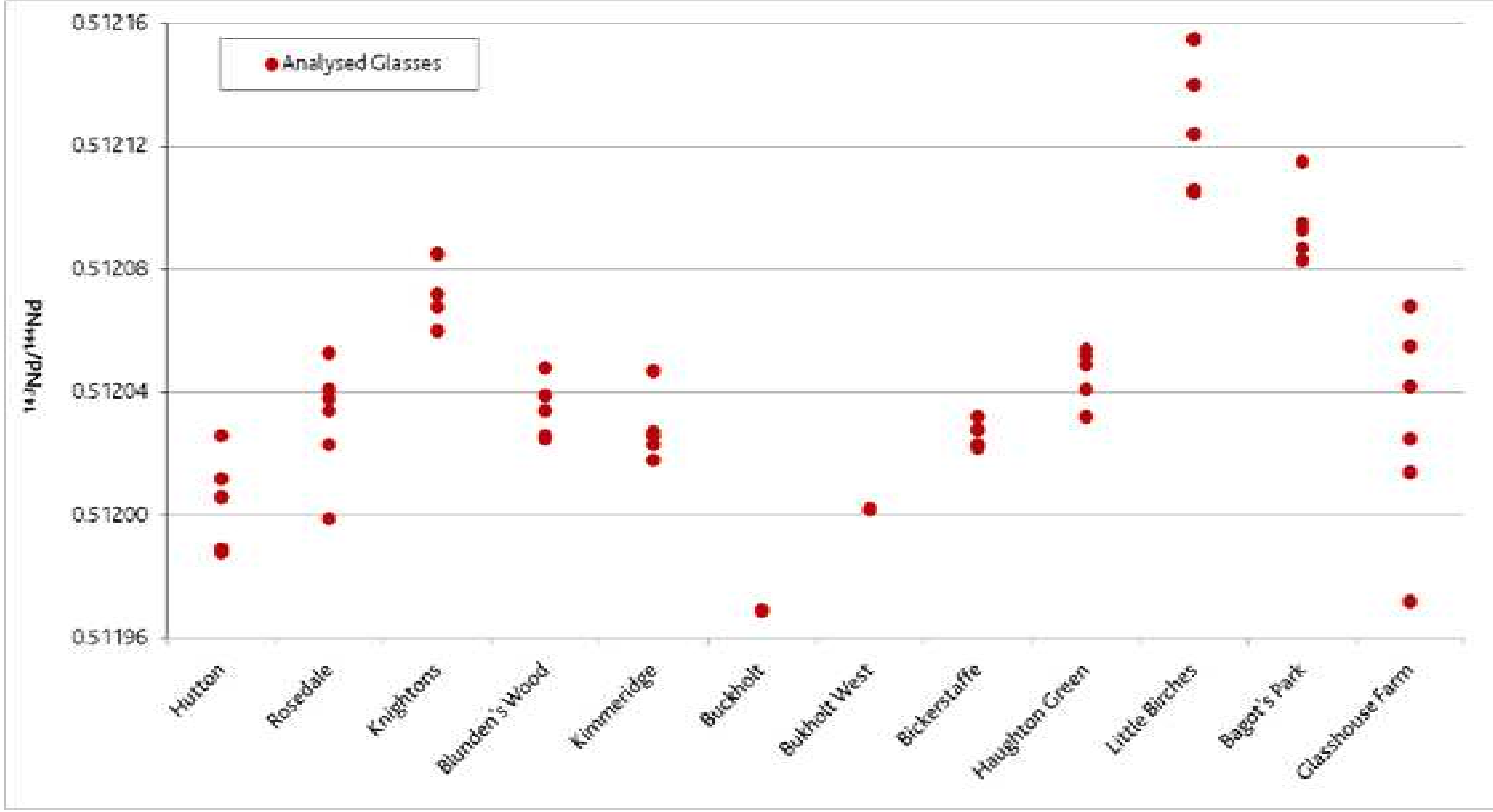

Figure 4.8: Neodymium isotope results organised by site and region for all glass samples analysed by TIMS.

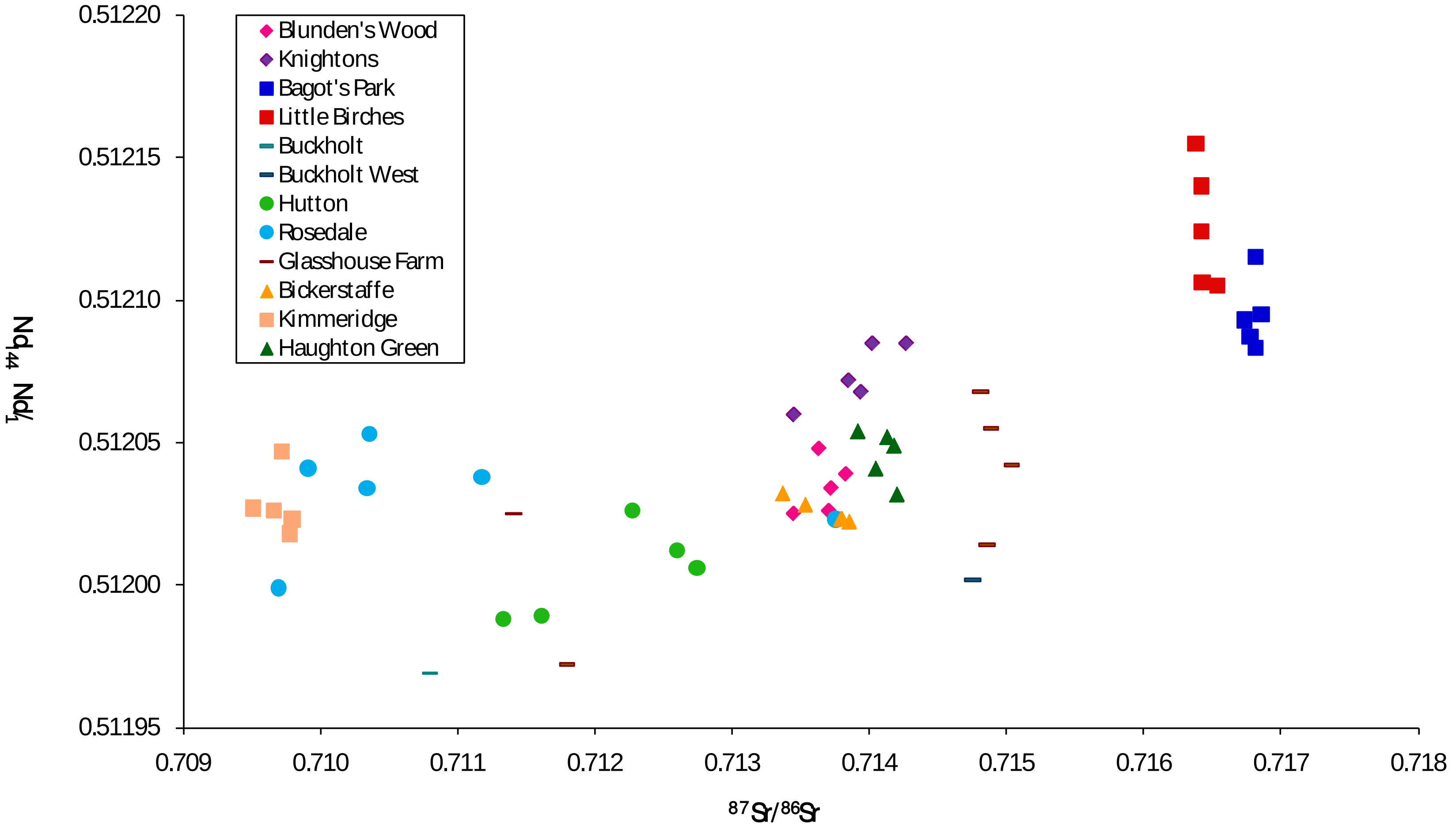

Figure 4.9: Neodymium isotope vs. strontium isotope ratios for all glass samples analysed by TIMS.

4.2.1 Introduction and general trends

Generally the isotopic results do not reflect any of the patterns seen in the compositional data. For example, the type 1 glasses which exhibited similar chemical compositions are split into two distinct isotopic groups based on both Sr and Nd isotope ratios. Where there are useful links between compositional and isotopic results they will be discussed below. Full results tables can be found in the Appendix. A brief description of each isotope system follows.

4.2.2 Oxygen isotopes

The O isotope analyses show a relatively small spread. The vast majority of the samples have $\delta^{18}O$ values of between 12 and 14 (see figure 4.6). Within this range there is a high degree of overlap between sites. Due to this small range and overlapping values there are no site-specific oxygen isotope signatures. However, there are some similarities between related sites which will be discussed in more detail below.

4.2.3 Strontium isotopes

The Sr isotope ratios and concentrations show a wide spread of values (see figure 4.7). A high level of variability is important in provenance studies (see section 3.6). This was expected from the high level of variability in the geology of England. The values often do not relate to those found for bracken collected from nearby production sites. This was expected due to reasons outlined in chapter 3. They also do not relate to the expected biosphere values recorded for regions by Evans et al. (2010).

Many of the sites related for geographic reasons exhibit similarities. The ranges of values for some sites are very small. The sites from Staffordshire may exhibit region-specific Sr isotope signatures. These results are therefore encouraging in terms of being able to use them to provenance glasses produced in these regions.

It is not possible to use these data to provide a means of characterising glasses in terms of whether or not lime has been added as a separate raw material. There is no correlation between the levels of lime and Sr in the glasses, which is possible, but not necessarily expected if limestone was added as a separate material as the mean strontium content of carbonate rocks is fairly similar to that of plant and wood ashes (*c*. 400 ppm Sr, but with a range of less than 100 up to over 10000 ppm) (Kahle 1965; 846). If beach shells were used, the Sr isotope ratios in the high lime glasses would reflect those of modern seawater (*c*. 0.709), this is not consistently observed. Where the ratio is similar to this value a separate explanation is presented and discussed below. Therefore the addition of lime in the form of a carbonate mineral cannot be proved, or disproved using these Sr isotope and concentration data, but the addition of lime in the form of shells is not observed in these glasses (see below).

4.2.4 Neodymium isotopes

The majority of sites have relatively small ranges of neodymium isotope ratios. As with the Sr and O data many of these ranges overlap with those of a number of other sites. However, as with the Sr data, there are similarities between many of the sites based on geographical location. The sites in Staffordshire again exhibit the highest neodymium isotope ratios.

Figures 4.6, 4.7 and 4.8 and the discussion above have shown that the Sr and Nd data provides the best hope of discovering useful isotope signatures for the glasses. Figure 4.9 has been produced to show how these two isotope systems might be combined to provide more distinct signatures for each site than those found by using each system alone.

There is a potentially positive correlation for these data, however this is not real. The appearance of a positive correlation is only due to of the results for glasses from Little Birches and Bagot’s Park which have abnormally high values for both Sr and Nd isotope ratios.

The Sr isotope data provides the widest spread of values and is the best discriminator for discerning differences between sites. However, combining it with Nd isotope ratios allows many sites to be separated, such as allowing a difference between the samples from Blunden’s Wood and Knightons to be seen.

The patterns seen in figures 4.6 to 4.9 will be discussed below. Sites have been grouped together in terms of their geographical location. The discussion aims to develop an understanding of similarities and differences between sites bringing together their location, date, and the isotope ratios and chemical composition found for their glasses.

4.2.5 Staffordshire

The glass from these two sites exhibit very distinct Sr and Nd isotope signatures. Figure 4.9 illustrates how different these glasses are from all those analysed in this study. Their O and Nd isotope signatures are much more variable than their Sr ratios, which are very discrete, and these may show some variation in silica sources used at these sites, or natural variation within a single source.

The Sr ratios, both of the bracken ash collected from nearby these sites and those found by Evans et al. (2010), are very different from the ratios found for glasses produced here. In fact, the Sr ratios for these samples are very much higher than those expected for the biosphere of much of the UK (see figure 3.2). It seems highly likely that the Sr ratios found at these sites may reflect a Sr source which is not the alkali raw material. One possibility is that the silica source used at these sites contained mineral impurities such as feldspars which contain Sr with a very high ratio and significant concentration (Deer et al. 2001; 130). The use of quartz pebbles, as suggested by Welch (1997; 45), would not explain the trend seen in these results. Although their Sr ratio is very high, their concentration is too low to affect the overall Sr ratio composition of the glasses (1.4 ppm Nd was found in pebbles collected from Cannock Chase, see chapter 3).

As discussed in chapter 3, Dungworth et al. (2009; 125) have stated that glasses from Silkstone, Yorkshire, which exhibit very high Sr ratios (0.714 and 0.718) are associated with geologically very old rocks found at least 130 km from Silkstone. They suggest that raw materials may have been traded over this distance. This seems very unlikely in terms of the raw materials used in the glasses from Staffordshire. These glasses are all type 1 composition, thought to have been produced using wood ash, or a combination of wood and bracken ash. It seems unlikely that these raw materials would have been traded to Staffordshire over very long distances. This is not to say that the glassmakers were not using imported ashes here, but that importing these particular raw materials over long distances seems futile.

If it is the case that the Sr component of these glasses originates from the silica source this shows that this isotope system cannot be reliably linked to a single raw material type. However, the results for samples from these sites are also evidence that this technique is still very useful in attempts to discern the provenance of these glasses. Figure 4.10 shows how Sr and Nd ratios can be used to discern the differences between all type 1 glasses from this study. While their chemical compositions were similar and overlapping, the combination of their Sr and Nd isotope ratios can be used to discern where they were produced.

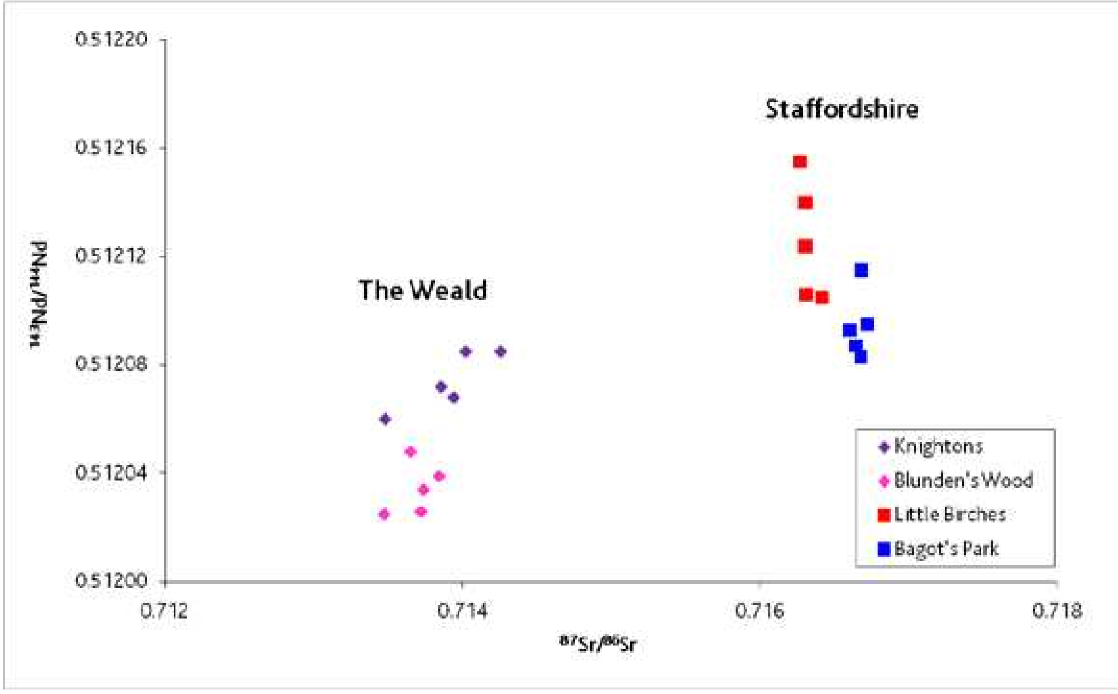

Figure 4.10: Neodymium isotope vs. strontium isotope ratios for glass samples from the Weald and Staffordshire.

4.2.6 The Weald

The samples from the Weald have relatively similar Sr isotope ratios and concentrations, but differing O isotope values and Nd ratios and concentrations. Prior to the work being carried out on raw materials it would be expected that this was due to the use of similar alkali raw materials and differing silica sources. However, as the Nd in these glasses may have come from the silica source it is not possible to state this with any certainty.

The high levels of Nd found in the bracken from Sidney Wood are reflected in the exceptionally high Nd levels found in the glasses produced at Knightons. This may show that the alkali raw material used at Knightons was sourced from this area. These high levels are not seen at Blunden’s Wood implying that a different source was used.

The Sr isotope ratios in all the glasses from the Weald are very similar to one another and are also fairly similar to those found in the bracken from Sidney Wood. The Sr source appears to have therefore been similar and, if it is the bracken ash, may have been local.

The results are useful in provenancing glasses from the Weald due to their similarities in Sr ratios and concentrations. As discussed above, the results for glasses from these sites are useful for discriminating between type 1 glasses in this study (see figure 4.10). The similarities between the model glass and the results for Knightons (see figure 4.11 and Nd concentrations in table 3.9 and appendix table 13) show that local raw materials may have been used at this site. The difference in Sr concentration may point to the use of a non-bracken local plant source.

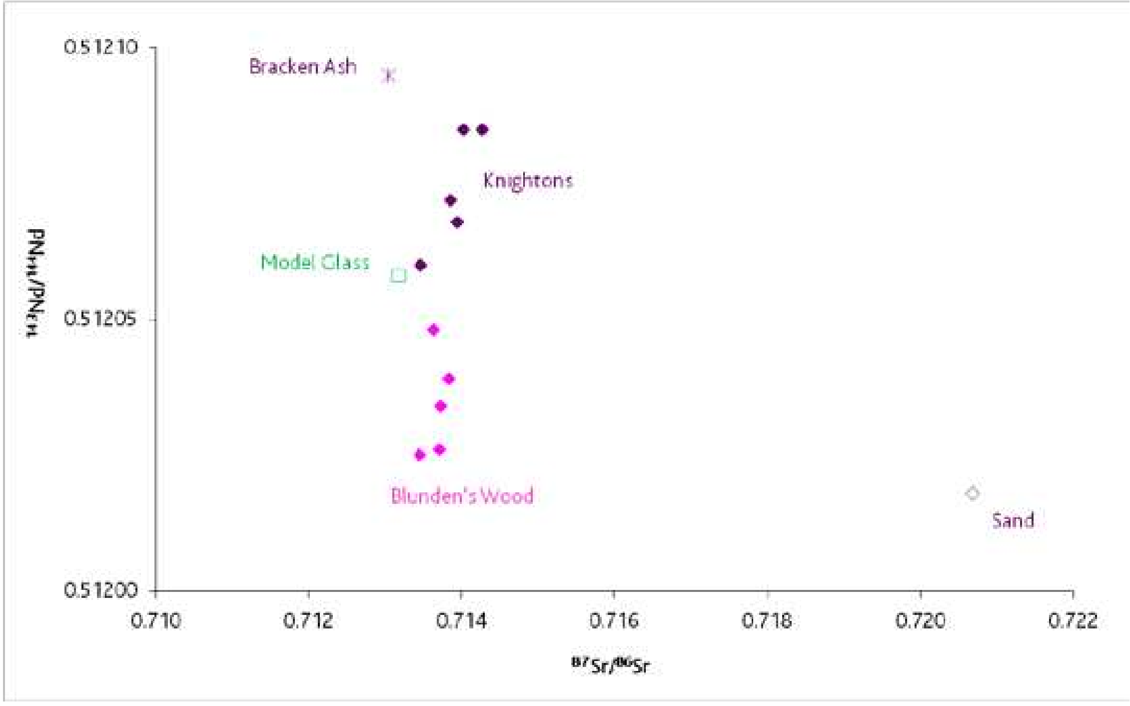

Figure 4.11: Neodymium isotope vs. strontium isotope ratios for glass, bracken ash, sand and model glass samples from the Weald.

4.2.7 North Yorkshire

The glasses from Hutton and Rosedale have a wide range of all three isotope ratios analysed in this study. The Nd and O isotope ratios suggest that a range of different silica sources were used at these sites. However, as the analytical work carried out on raw materials has shown, it is not possible to be entirely certain that the Nd values can be directly related to the silica source and were probably also influenced by the alkali used. Either way these data show that the Nd and O isotope composition of these glasses was variable. The wide spread of Sr isotope ratios and concentrations allows further conclusions to be made about the sourcing of raw materials and will be discussed in more detail below.

Glass samples Rosedale-WG4 and WG25 both have low $^{87}Sr/^{86}Sr$ values and high Sr concentrations (samples lie to middle-bottom of figure 4.12). These values are approaching those found by Dungworth et al. (2009) for glasses from Silkstone, Yorkshire. They concluded that these glasses were produced using seaweed (ibid. 124). As discussed in chapter 1, seaweed has a distinctively high strontium concentration and low $^{87}Sr/^{86}Sr$ values. The two glasses from Rosedale also have a distinct chemical composition; both are of type 3c composition. The high magnesia levels in these type 3c glasses are also seen in the seaweed glasses from Silkstone (see Dungworth et al. 2009; 124). The combination of these three factors suggests that type 3c glasses were produced using seaweed. The production of model glasses showed that the strontium levels found in an alkali source can be further concentrated during the production of glass. However, the production method used for the glasses at Rosedale does not appear to have been greatly different from that at many contemporary sites. This, coupled with the large difference between the concentrations found at most other sites suggests that these differences must be connected to the use of a different raw material.

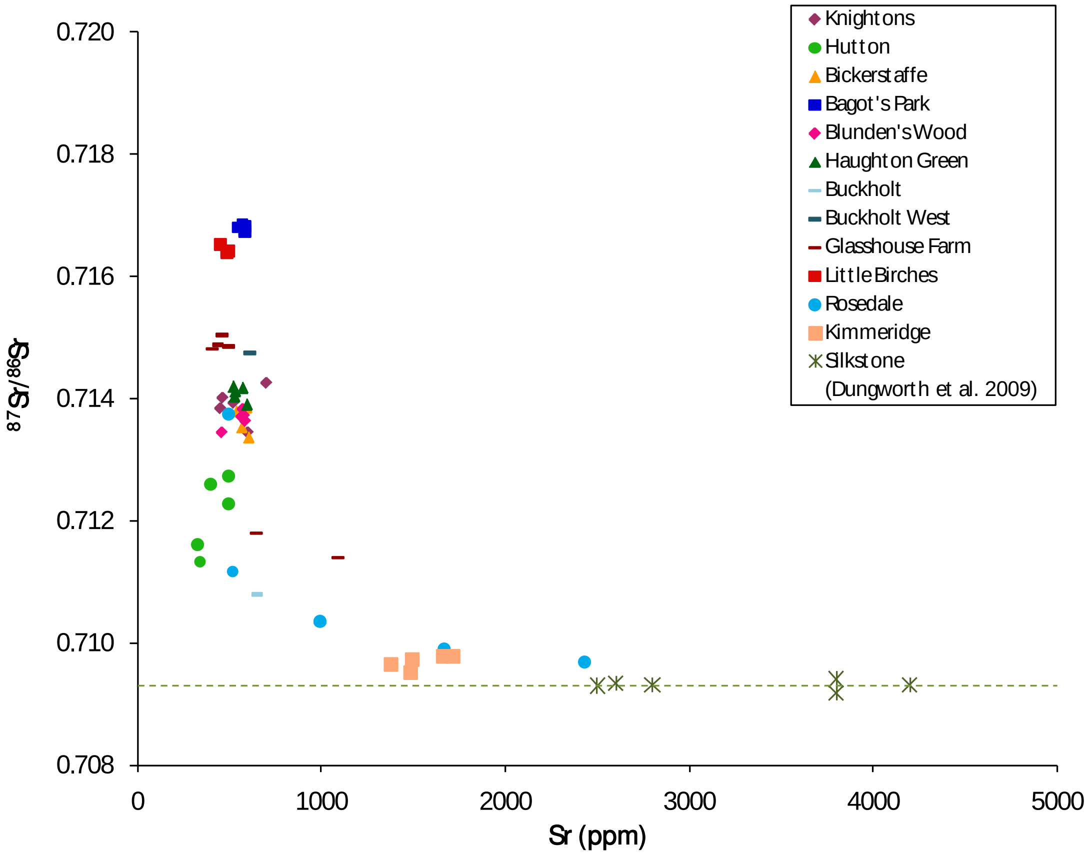

Figure 4.12: Strontium isotope ratio vs. strontium concentration for all glasses analysed by TIMS in this study and seaweed glasses from Dungworth et al. 2009. The dark green dotted line signifies the value found by Dungworth et al. (2009) for seaweed ash.

Many of the seaweed glasses from Silkstone have higher concentrations of strontium and lower $^{87}Sr/^{86}Sr$ values than those from Rosedale. It is therefore likely that another source of Sr was introduced into the Rosedale glasses. One explanation for this is the addition of another alkali source lower in Sr concentration and with higher $^{87}Sr/^{86}Sr$ value. Using the analytical data for bracken ash collected nearby Rosedale as an analogue for the use of a terrestrial plant alkali-source it is possible to investigate this further. Figure 4.13 shows that mixing a local terrestrial plant ash with a marine plant ash could explain the $^{87}Sr/^{86}Sr$ values of not only the type 3c glasses from Rosedale, but also three of the type 3a glasses from this site. At this site it would seem that a mixture of alkali sources were employed, one of which was seaweed.

Another possibility is that Sr in the silica source was affecting the overall Sr ratio of the glasses. This was presumed to be the case in the glasses from Staffordshire. However, the strong correlation seen in figure 4.13 makes the contribution of a local terrestrial plant ash source, rather than impurities in the silica source, more likely.

As at Silkstone, the long distance of Rosedale from the sea made the use of seaweed seem unlikely. However, this new data, along with that of Dungworth et al. (2009), have shown that seaweed ash was traded to glassmakers over long distances and therefore must have been known by glassmakers to be a useful alkali raw material.

One further sample from Rosedale, WG12, has a far higher ^{87}Sr/^{86}Sr value, but it is not chemically distinct from the other type 3a glasses. It is therefore suggested that this glass was made using a similar recipe to those other type 3a glasses, but using raw materials from a distinct source. It is not possible to discern where this source may be, however it adds to evidence to the theory that different alkali sources were in use at this site, some of which were traded over long distances.

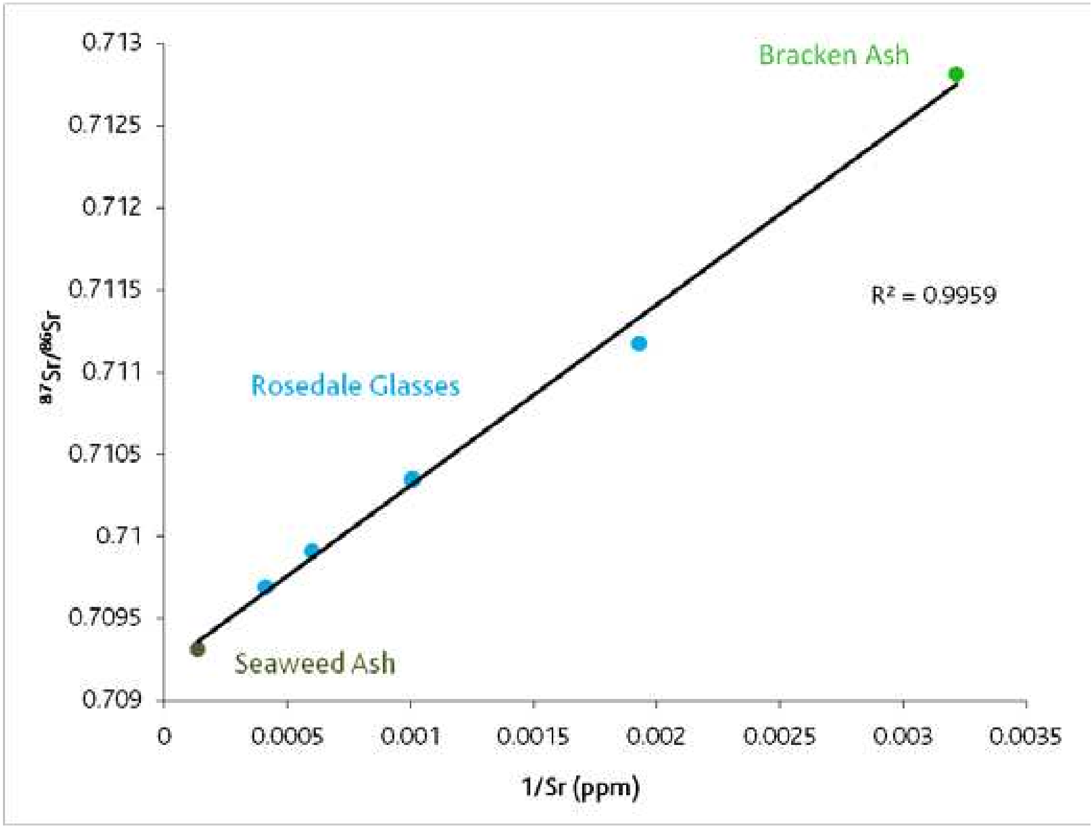

Figure 4.13: Strontium isotope ratio vs. 1/strontium concentration for selected glasses from Rosedale, bracken ash from Hutton Common and seaweed ash (Dungworth et al., 2009). As this plot is dealing with an isotope ratio it is necessary to plot against another ratio, 1/Sr concentration, to give a straight line rather than a curve. A straight line can then be used to give R^2 values.
The closer an R^2 value is to 1 the better the line fits the data.

The glasses from Hutton do not appear to have been produced using seaweed. They do not have particularly high Sr concentrations and their $^{87}Sr/^{86}Sr$ values are not as low are the majority of those from Rosedale. The spread of $^{87}Sr/^{86}Sr$ values found for glass at this site, while not as large as that from of Rosedale glasses, is relatively wide. It seems that at this site raw materials have been procured from a variety of sources. The results for samples Hutton-WG2, 3 and 7 are fairly similar to that found for local bracken analysed in this study. Therefore some of the glasses produced here may have been made using local raw materials. Samples Hutton-WG6 and 10 have lower $^{87}Sr/^{86}Sr$ values and concentrations and were probably produced using a different alkali source. Their lower Sr concentrations compared to those found for seaweed glasses from Rosedale discount the use of seaweed in their production.

4.2.8 Kimmeridge

The glasses analysed from Kimmeridge have relatively narrowly constrained Sr and Nd ratios, but variable $\delta^{18}O$ (see figure 4.6). The $\delta^{18}O$ values fall into two groups around 14.5 and 13.6. This difference may suggests some variation in the silica source used; however this is not reflected in the Nd ratios, or quantity or type of alkali raw material used (see table 4.1 and section 3.6.3). The Nd ratios and concentrations are similar to those found for the majority of other sites studied (see figure 4.8).

The Sr ratios are more useful for characterising the glass from this site. They are similar to those found for type 3c glasses from Rosedale. Their high Sr concentration and low Sr ratio suggest that these glasses were also produced using seaweed, possibly in combination with another alkali source (see figure 4.12). This is rather less surprising at this site as it is located approximately 150 metres from the sea.

The chemical composition of these glasses has shown that seaweed glasses are not necessarily of type 3c composition. It is necessary to analyse a glass for both its Sr concentration and isotope ratio to convincingly suggest that it is produced using seaweed as at least part of its alkali source.

4.2.9 The North-west

The sites of Bickerstaffe and Haughton Green are related by their proximity and also that they may have been run by the same family (see section 2.5.5). The chemical compositions of these two sites are also related. The major difference in composition between these two sites was the alumina levels which are much higher at Haughton Green than at Bickerstaffe.

The glasses from these two sites that were analysed isotopically are all of type 3b composition, a type specific to these sites. This type appears to have been associated with the use of a chlorine-rich plant ash. The use of related raw materials at these sites can be backed up by the isotopic analyses. For all three isotope systems these glasses show very similar compositions. The difference in alumina and iron oxide levels is therefore not directly linked to any differences in the isotope analyses (see section 4.1.4).

The Sr ratios of these glasses are much higher than those found for this region by Evans et al. (2010). There are multiple possible reasons for this. The low resolution of this mapping, the probable importation of chlorine-rich plant ash to this site, which was grown elsewhere, or the influence of a Sr-rich silica source. However, what is most important to note about these results are the similarities between them for two sites located in the same region.

A further point to note about the glass from Bickerstaffe is the relationship between the Sr and Nd isotope ratios for this site. They are strongly negatively correlated (see figure 4.14). One likely explanation for this is that the two raw materials used at this site were both contributing Sr and Nd. The compositional similarity of these samples and this distinctive correlation may imply that these glasses were all produced in the same single melt. Perhaps this melt was not entirely homogenised and therefore some small differences in ratios of the two raw materials were present producing this mixing line. It would seem unlikely that the raw materials used to produce this glass could be tightly controlled enough to produce this type of correlation over several melts by any other means. Alternatively, this mixing line could be the result of cullet use in a single melt (see section 1.2.4).

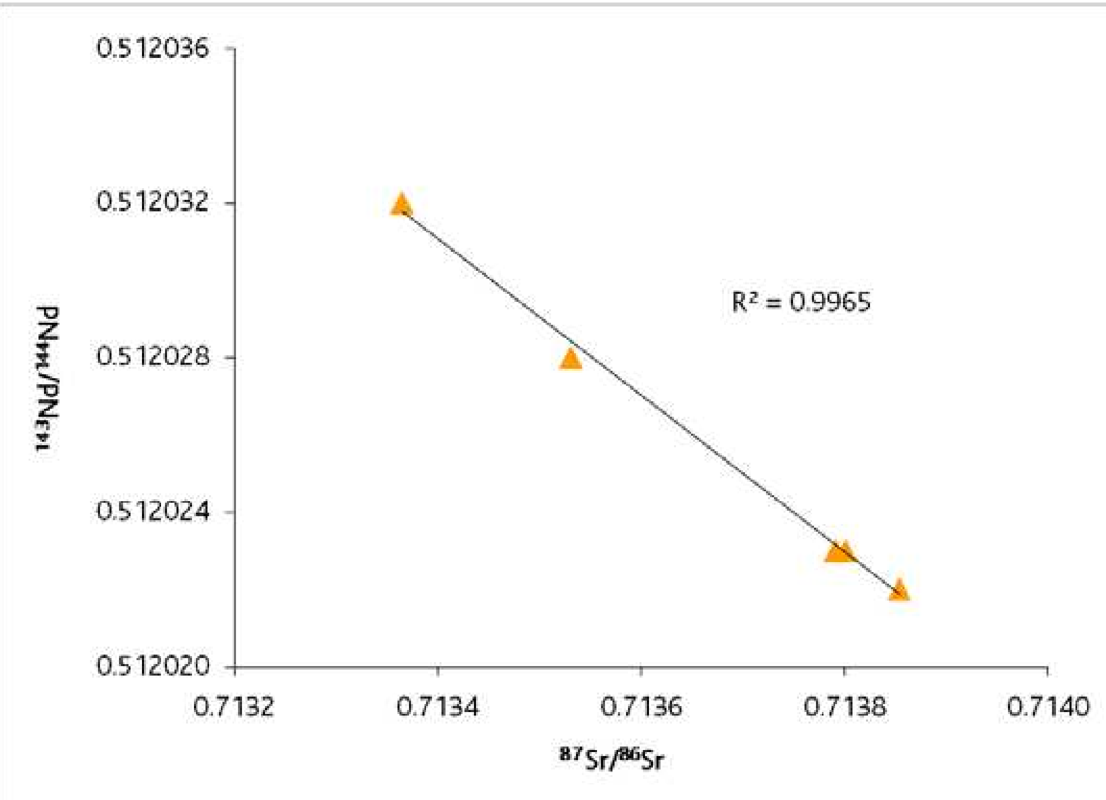

Figure 4.14: Neodymium isotope vs. strontium isotope ratios for all glasses from Bickerstaffe analysed by TIMS. See figure 4.13 for description of R^2 values.

4.2.10 Hampshire

Only two samples were analysed from the sites of Buckholt and Buckholt West, one from each. It is therefore very difficult to draw any meaningful conclusions from their results. These two samples have similar chemical compositions, but very different isotope signatures for Sr, Nd and O. It appears that they were using a similar recipe to produce the glass, but sourcing raw materials from different locations. The glass from Buckholt West may have been produced using a sand source with a higher accessory mineral content than that from Buckholt (see Staffordshire, section 4.2.5). Or the glass from Buckholt may have been made using a local alkali source (cf. biosphere values from Evans et al. 2010) and the glass from Buckholt West using a source acquired from elsewhere. The low Sr ratio of glass from Buckholt suggests the possible use of seaweed. However, the relatively average Sr concentration negates this possibility (see Dungworth et al. 2009, section 4.2.7 and figure 4.12).

Due to the limited data set it is not possible to say which, if any, of these possibilities is correct. The only conclusions that can be drawn are that there were differences in the source of raw materials, and probably not recipe, used at these sites.

4.2.11 Herefordshire

The glass produced at Glasshouse Farm has variable chemical compositions. The glasses from this site can be described as type 2a and 3a, however this does not quite illustrate how variable the compositions are. The isotope analyses show similarly high levels of variability. Overall these glasses have the highest spread of isotope values for any site analysed in this study.

Glass of both type 2a and 3a composition were analysed isotopically, however the same split was not observed in the isotope analysis. It would appear that at this site glass was being produced from varying raw materials which were sourced from varying locations. Where some similarities are seen for some elements they are contradicted by others. For example, the similarities between samples GF3 and GF5 in terms of Sr and Nd values, these are contradicted by radically different O values.

The large spread of values may imply that the glassmakers at this site had some trouble in sourcing raw materials. The lack of access to a steady supply of raw materials would result in these differences in composition. In fact it is a testament to the glassmakers if they were able to produce a useable glass when their raw material sources were so variable. This variability in composition makes it very hard to see any distinction between the glass produced at this site and many others. Deciphering the provenance of glass from this site will prove particularly difficult.

4.2.12 Summary of isotopic analyses

The isotopic analyses have shown that it is not possible to link the Sr isotopic ratios found in glasses to the local biosphere values. This is not necessarily because they were not made using local raw materials. The biosphere available Sr isotope ratios can vary by large amounts within geological regions (cf. bracken collected in Sidney wood with values from Evans et al. (2010)) and over fairly short distances (see Chenery et al. 2010). It is also clear that many of the raw materials are likely to have been imported.

The results of raw material and glass analysis have shown that the Sr and Nd isotope values are definitely not representative of single raw materials each. Sr can be introduced to the glass melt with the silica raw material, possibly in quantities which will greatly influence the overall ratio in the glass (see Staffordshire sites) and Nd can come from the wood ash (see concentration of Nd in bracken ash from Sidney wood, section 3.7.1). So there is no reason to expect the Sr or Nd values to definitely represent those found in local raw materials, even if the raw materials were used. It would prove impossible to analyse all the possible raw material sources to produce a comparative dataset as their variability makes them too numerous.

However, in spite of this, the isotopic analyses will be useful in provenancing forest glass samples. It is very clear, for example, that differences can be seen between the samples analysed from the two major production centres active in the 14th-16th centuries, Staffordshire and the Weald. These differences may extend to other sites in these locations, but as the current data stands it is quite convincing evidence that useful differences have been found.

Evidence for the use of seaweed as a raw material has been found at one site very close to the sea, Kimmeridge, and another much further away, Rosedale. The evidence for this raw material use was only found using the combination of discerning the Sr isotope ratios and concentrations for these samples. Apart from the elevated MgO levels in these glasses from Rosedale, their chemical composition is fairly similar to that of other mixed alkali glasses. It has also been possible to suggest that the ash of seaweed and local terrestrial plants may have been mixed at Rosedale.

These analyses have not been able to prove or disprove the addition of lime to high-lime forest glasses as a separate raw material. It may be possible to determine what effect the addition of limestone as a separate raw material has on forest glass compositions through the production of further model glasses. However, due to the highly variable nature of carbonate mineral compositions, conclusive proof may still prove unattainable with this methodology.

The glasses from Buckholt, Buckholt West and Glasshouse farm have shown that even when similar chemical compositions, and therefore probably recipes, are found the isotopic ratios can be very different. This shows that similar raw materials were sourced from differing locations at some sites.

The analyses of samples from Bickerstaffe have shown that the mixing of Sr and Nd can be identified. Due to the issues surrounding the sources of these raw materials it is not possible to identify how this mixing occurred and which raw materials were responsible. Similarities between the samples from Bickerstaffe and those from Haughton Green show that the alkali raw material used at each of these sites may have been sourced from the same place/places. This adds evidence to the idea that the people running these glasshouses may have been in contact, or even the same family.

Chapter 5: Conclusions and further work

The results of this study have shown that it is possible to discriminate between some of the forest glasshouses active in England between the early-14th century and mid-17th century based on a combination of the chemical and isotopic composition of the glasses they produced. While it has not been possible to identify the contributing factor in many cases, these differences often provide a useful means of differentiating between sites, regions or chronological periods.

The use of a single analytical technique and methodology to analyse such a wide range of samples allows them to be compared directly for the first time. The findings of some previous studies have been confirmed by this more solid methodology. The glasses from many of the sites form tight clusters based on some chemical components; however there is generally not sufficient inter-site variation to allow these to be used as discriminators. Other sites, such as Rosedale have varying compositions and appear to have been producing glass using a variety of raw materials or recipes.

The chemical compositions of the glasses can be divided into compositional types. These types can be used to discern possible raw material categories which may have been used to produce them. The specific raw materials used cannot be identified based on these analyses, however overall trends can be viewed. Some subtypes are limited to one or a small number of sites, and therefore can be used as an approximate means of discovering if glass could have been produced at them. During the four time periods used to divide the sites chronologically alterations in the types produced suggest periods of continuity, experimentation and change. Some reasons for these changes have been suggested in the preceding chapter.

The use of strontium and neodymium isotopes and concentrations have proved to be better at providing methods of discriminating between forest glass producing sites than oxygen isotope ratios. It is therefore suggested that any future isotopic analysis of forest glasses focuses on the first two isotope systems. Of these two isotope systems strontium has proved the most useful, but many differences between sites would not be visible without the use of both systems in combination with one another.

One of the most important findings of this study involves the particular elements chosen for isotopic analysis in archaeological glass studies. The discovery of high concentrations of neodymium in bracken ashes from Sidney Wood and the probable high strontium concentration and isotope ratios of sand sources exploited in Staffordshire have shown that it is not possible to assign a specific isotope system to a single raw material.

In fact the isotopic signature of forest glasses must be considered to be a combination of both raw materials. It is only in some special and extreme cases, such as the use of seaweed, that they can be discriminated and assigned to specific raw material use. This finding will have ramifications for similar research using these elements in an attempt to provenance archaeological glasses. Without the prior analysis of a range of raw materials it is not possible to presume that an element originates from a single source. In fact, the raw materials used in forest glass production have proved so variable in composition and to be sourced over such a wide area that even a major programme of analysis would probably only succeed in confusing the subject further.

However, none of the above means that the findings of this study, or this methodology, are without use. Some site specific signatures have been found, and it is possible, using a combination of strontium and neodymium isotopes, to discern between the two major centres of forest glass operating between the 14th and 16th centuries. The results of this study will therefore be useful for future work on finished archaeological glasses and the methodology can continue to be used as long as the users have an understanding of what the results actually mean.

The next stage in this work has three important strands. Firstly to analyse glass from further forest glass production sites to provide more information from a wider range of locations and time periods. Secondly, the analysis of many more raw materials and the production of model glasses with a range of raw material combinations in varying quantities. This is the most important strand as it may allow the development of a model to actually link the isotopic composition of archaeological glasses to geographical locations. Even with a large quantity of further work this may prove impossible, but the work will not be without its uses. Any further analyses will help archaeological scientists to better understand the reasons for isotopic signatures found in archaeological glasses.

The final strand is the analysis of finished glasses. There is an enormous quantity of glass from archaeological excavations from across north-western Europe, both window and vessel. There are myriad research topics that are in need of investigation by a means of provenancing. For example, discovering the provenance of the enormous quantity of glass produced to replace church windows destroyed during the dissolution of the monasteries. Also, future work on sites in France, for example, with a concentration on those which are known to have been worked by Huguenot glassmakers prior to 1567 would help in the understanding of their influence.

Further investigation using a technique such as ICP-MS to provide a wider range of trace element analysis may be able to come up with usable fingerprints for production sites. If raw materials were also analysed for trace elements it may even become possible to link them to the glasses analysed. However, it is more likely that it would only be possible to find ways of discerning possible raw material sources for sites, rather than definitive sourcing.

This project has provided the evidence that this methodology can provide novel and highly useful information. Future work building on the results of this project will be able to solve many of the questions about the organisation of glass production and trade in this period.

Bibliography

ANON. 2006. 'Tameside Image Archive' *Tameside Metropolitan Borough Council Website*. Ashton-Under-Lyne: Tameside MBC.
Available at:
http://www.tameside.gov.uk/history/archive.php3
[27 April 2007]

ANDREWS, Kevin and Doonan, Roger. 2003. *Test Tubes & Trowels: Using Science in Archaeology*. Stroud: Tempus.

ASHURST, Denis. 1970. 'Excavations at Gawber Glasshouse, near Barnsley, Yorkshire' *Post-Medieval Archaeology*, 1970, **4**, pp. 92-140.

________________. 1987. 'Excavations at the 17th-18th century Glasshouse at Bolsterstone and the 18th Bolsterstone Pothouse, Stocksbridge, Yorkshire' *Post-Medieval Archaeology*, 1987, **21**, pp. 147-226.

BADDELEY, W.S.C. 1920. 'A Glass House at Nailsworth (16th and 17th century)' *Transactions of the Bristol and Gloucestershire Archaeological Society*, **42**, 1920, pp. 89-95.

BARBASTE, Mireille, Robinson, Keith, Guilfoyle, Stephen, Medina, Bernard and Lobinski, Ryszard. 2002. 'Precise determination of the strontium isotope ratios in wine by inductively coupled plasma sector field multicollector mass spectrometry (ICP-SF-MC-MS)' *Journal of Analytical Atomic Spectrometry*, **17**, pp. 135-137.

BARKOUDAH, Youssef and Henderson, Julian. 'Plant Ashes from Syria and the Manufacture of Ancient Glass: Ethnographic and Scientific Aspects' *Journal of Glass Studies*, **48**, pp. 297-321.

BAYLEY, Justine. 2000. 'Saxon Glass Working at Glastonbury Abbey' *In*: Price, Jennifer (ed.) *Glass in Britain and Ireland AD 350-1100*. London: The British Museum, pp. 161-186.

BRIDGEWATER, N.P. 1963. 'Glasshouse Farm, St. Weonards: A Small Glassworking Site' *Transactions Woolhope Naturalists Field Club*, **37**, 1963, pp. 300-315.

BRILL, R.H. 1970. 'Lead and oxygen isotopes in ancient objects' *Philosophical Transactions of the Royal Society of London A*, **269**, 1970, pp. 143-164.

___________. 1999 *Chemical Analysis of Early Glasses*, Two Volumes. New York: Corning Museum of Glass.

___________., Clayton, R.N., Mayeda, T.K. and Stapleton, C.P. 1999. 'Oxygen Isotope Analyses of Early Glasses' *In*: Brill, R.H. (ed.) *Chemical Analysis of Early Glasses*, Vol. 1. New York: Corning Museum of Glass, pp.303-322.

CARTER, T., Poupeau, G., Bressy, c. and Pearch, N.J.G. 2006. 'A new programme of obsidian characterisation at Catalhoyuk, Turkey' *Journal of Archaeological Science*, **33**, pp. 893-909.

CHARLESTON, R.J. 1980. '16th to 17th century English glass' *Bulletin de l'Association pour l'Histoire du Verre*, 1977-1980, **8**, pp. 77-99.

__________________. 1984. *English Glass*. London: George Allen and Unwin.

CHENERY, Carolyn, Müldner, Gundula, Evans, Jane, Eckardt, Hella and Lewis, Mary. 2010. 'Strontium and stable isotope evidence for diet and mobility in Roman Gloucester, UK.' *Journal of Archaeological Science*, **37**(1), 2010, pp. 150-163.

CILIBERTO, Enrico. 2000. 'Analytical Methods in Art and Archaeology' *In*: Ciliberto, Enrico and Spoto, Guiseppe (eds.) *Modern Analytical Methods in Art and Archaeology*. London: John Wiley and Sons Ltd, pp. 1-10.

COALPRO (Confederation of UK Coal Producers). Geological Map of Britain [online]. Available at:
http://www.coalpro.co.uk/images/map.jpg
[10 October 2010]

CRAMP, Rosemary. 2000. 'Anglo-Saxon Window Glass' *In*: Price, Jennifer (ed.) *Glass in Britain and Ireland AD 350-1100*. London: The British Museum, pp. 105-114.

CROMWELL, Tom and Dungworth, David. 2003. 'Silkstone, South Yorkshire. Excavation for evidence of glass working' *Council for Archaeology News*, Winter 2002-3.
Available at:
http://www.english-heritage.org.uk/upload/pdf/cfa_news_04.pdf
[08 March 2006]

CROSSLEY, D.W. 1967. 'Glassmaking in Bagot's Park, Staffordshire, in the Sixteenth Century' *Post-Medieval Archaeology*, 1967, **1**, pp. 44-83.

________________. and Aberg, F.A. 1972. 'Sixteenth-Century Glass-Making in Yorkshire: Excavations at Furnaces at Hutton and Rosedale, North Riding' *Post-Medieval Archaeology*, 1972, **6**, pp. 107-159.

________________. 1983. 'The Development of English Glass Furnaces in the Sixteenth and Seventeenth Centuries' *Journal of Glass Studies*, 1983, **25**, pp. 147-153.

________________. 1987. 'Sir William Clavell's Glasshouse at Kimmerage, Dorset: The Excavations of 1980-81' *The Archaeological Journal*, 1987, **144**, pp. 340-382.

________________. 1990. *Post-medieval archaeology in Britain*. Leicester: Leicester University Press

________________. 1991 'Current Research on English Glass Furnaces' *in*: M. Mendera (ed.), *Archeologia e storia della produz ione del vetro preindustriale* Firenze: University of Siena, pp. 411-422.

________________. 1994. 'The Wealden Glass Industry Re-visited' *Industrial Archaeology Review*, autumn 1994, **17**(1), pp. 64-74.

________________. 1998. 'The English Glassmaker and his search for raw materials in the 16th and 17th centuries' *In*: McCray, P. (ed.) *The Prehistory and History of Glassmaking* Technology. Westerville: The American Ceramics Society, pp. 167-179.

DAWSON, Charles. 1905. 'Old Sussex Glass: Its Origin and Decline' *Antiquary*, 1905, **41**, pp. 8-11.

DEER, William Alexander, Zussman, J. and Howie, Robert Andrew. 2001. *Rock-forming minerals: Framework silicates: feldspars, Volume 4*. London: Geological Society.

DEGRYSE, P. and Schneider, J. 2008. 'Pliny the Elder and Sr-Nd isotopes: tracing the provenance of raw materials for Roman glass production' *Journal of Archaeological Science*, 35(7), 2008**,** pp. 1993-2000.

_____________., Henderson, Julian and Hodgins, Greg. 2009a. 'Isotopes in vitreous materials, a state-of-the-art and perspectives' *In*: Degryse, Patrick, Henderson, Julian and Hodgins, Greg (Eds.) *Isotopes in Vitreous Materials*. Leuven: Leuven University Press, pp. 15-30.

_____________., Schneider, Jens, Lauwers, Veerle, Henderson, Julian, Van Daele, Bernard, Martens, Marleen, Huisman, Hans, De Muynck, David and Muchez, Philippe. 2009b. 'Neodymium and strontium isotopes in the provenance of primary natron glass production' *In*: Degryse, Patrick, Henderson, Julian and Hodgins, Greg (Eds.) *Isotopes in Vitreous Materials*. Leuven: Leuven University Press, pp. 53-72.

_____________., Henderson, Julian and Hodgins, Greg. 2009c. *Isotopes in Vitreous Materials*. Leuven: Leuven University Press.

DICKIN, Alan P. 2005. *Radiogenic Isotope Geology*. Cambridge: Cambridge University Press.

DODWELL, C.R. 1961. *Theophilus. The Various Arts*. London: Thomas Nelson and Sons Ltd.

DUNGWORTH, David, Degryse, Patrick and Schneider, Jens. 2009. ‘Kelp in historical glass: the application of strontium isotope analysis’ *In*: Degryse, Patrick, Henderson, Julian and Hodgins, Greg (Eds.) *Isotopes in Vitreous Materials*. Leuven: Leuven University Press, pp. 113-130.

EVANS, J. A., Montgomery, J., Wildman, G. and Boulton, N. 2010. ‘Spatial variations in biosphere 87Sr/86Sr in Britain’ *Journal of the Geological Society, London*, **167**, pp. 1-4.

EVISON, Vera I. 2000. ‘Glass Vessels in England AD 400-1100’ *In*: Price, Jennifer (ed.) *Glass in Britain and Ireland AD 350-1100*. London: The British Museum, pp. 47-104.

FAURE, Gunther. 1986. *Principles of Isotope Geology*. New York: Wiley.

FORD, W.J. 1971. ‘Glasshouse Wood, Warwickshire’ *West midlands Archaeological News Sheet*, 1971, **14**, p. 15.

FRANK, Susan. 1982. *Glass and Archaeology*. London: Academic Press.

FREESTONE, I.C., and Gorin-Rosen, Y., 1999, ‘The great glass slab at Bet Shearim: an early Islamic glass-making experiment?’ *Journal of Glass Studies*, **41**, pp. 105-16.

_________________., Gorin-Rosen, Yael and Hughes, Michael J. 2000. ‘Primary Glass from Israel and the Production of Glass in Late Antiquity’ *In*: Nenna, Marie-Dominique (ed.) *La route du verre : ateliers primaires et secondaires du second millénaire av. J.-C. au Moyen Âge*. Lyon: Maison de l'Orient Méditerranéen-Jean Pouilloux, pp. 65-83.

_________________., Leslie, K.A., Thirlwell, M., Gorin-Rosin, Y. 2003. ‘Strontium isotopes in the investigation of early glass production: Byzantine and Early Islamic glass from the Near East’, *Archaeometry*, **45**(1), pp. 19-32.

_________________. 2005. ‘The Provenance of Ancient Glass through Compositional Analysis’. *Materials Research Symposium Proceedings*, **852**, OO8.1.1-14.

_________________., Wolf, S. and Thirlwall, M. 2005. ‘The production of HIMT glass: elemental and isotopic evidence’ *Annales du 16e Congrès de l'Association Internationale pour l'Histoire du Verre*, London, 2003. Nottingham : A.I.H.V, pp. 153-7.

_________________., Hughes, Michael J. and Stapleton, Colleen P. 2008. ‘The Composition and Production of Anglo-Saxon Glass’ *In*: Evison, Vera I. *Catalogue of Anglo-Saxon Glass in the British Museum*. British Museum Research Publication 167, London: British Museum Press, pp. 29-46.

GODFREY, Eleanor S. 1975. *The Development of English Glassmaking*. Oxford: Clarendon Press

GREEN, Lorna R. and Hart, F. Alan. 1987. 'Colour and Chemical Composition in Ancient Glass: a Study of Roman and Wealden Glass by means of Ultraviolet-Visible-Infrared Spectrometry and Electron Microprobe Analysis' *Journal of Archaeological Science*, 1987, 14, pp. 271-282

HANCOCK, Ronald G.V. 2000. 'Elemental Analysis' *In*: Ciliberto, Enrico and Spoto,
Guiseppe (eds.) *Modern Analytical Methods in Art and Archaeology*. London: John Wiley and Sons Ltd, pp. 11-20.

HARRINGTON, J.C. 1952. *Glassmaking at Jamestown*. Richmond, VA: The Dietz Press, Inc.

HARTMANN, Gerald. 1994. 'Late-medieval Glass Manufacture in the Eichsfield Region (Thuringia, Germany)' *Chemie der Erde*, 1994, **54**, pp. 103-128.

HATCH, Charles E. 1941a. 'Glassmaking in Virginia, 1607-1625'. *William and Queen Mary College Quarterly Historical Magazine*, 2nd Series, April 1941, **21**(2), pp. 119-138.

_______________. 1941b. 'Glassmaking in Virginia, 1607-1625' Second instalment. *William and Queen Mary College Quarterly Historical Magazine*, 2nd Series, July 1941, **21**(3), pp. 227-238.

HENDERSON, Julian. 1989. 'The Scientific Analysis of Ancient Glass and its Archaeological Interpretation' *In*: Henderson, J. (ed.) *Scientific analysis in archaeology*, Oxford: Oxbow Books, Ch. 2, pp. 30-61.

_________________. 2000. *The Science and Archaeology of Materials.* London: Routledge.

_________________. 2005. 'Medieval and Post-Medieval Glass Finewares from Lincoln: an Investigation of the Relationships between Technology, Chemical Compositions, Typology and Value' *The Archaeological Journal*, **162**, 2005, pp. 256-322

_________________. Evans, J.A., Sloane, H.J., Leng, M.J. and Doherty, C. 2005. 'The use of oxygen, strontium and lead isotopes to provenance ancient glasses in the Middle East' *Journal of Archaeological Science*, 2005, **32**, pp. 665-673.

_________________., Evans, Jane and Barkoudah, Youssef. 2009. 'The provenance of Syrian plant ash glass: an isotopic approach' *In*: Degryse, Patrick, Henderson, Julian and Hodgins, Greg (Eds.) *Isotopes in Vitreous Materials*. Leuven: Leuven University Press, pp. 73-97.

HOOVER, Herbert and Hoover, Lou Henry. 1950. *Georgius Agricola De re metallica*. New York: Dover.

HORN, P., Holzl, S., Todt, W. and Matthies, D. 1993. '^{87}Sr/^{86}Sr from rock and soil into vine and wine' *Zeitschrift fur Lebensmittel Untersuschung und Forschung*, 1993, **196**(5), pp. 407-409.

JACKSON, C.M., Smedley, James. W., Booth, Carol A., and Lane, Beverley C. 2000. 'Biringuccio on 16th century glassmaking' *Annales du 14e Congrès de l'Association Internationale pour l'Histoire du Verre, Venezia-Milano, 1998,* Amsterdam : A.I.H.V, pp. 335-340.

_____________. and Smedley, J.W. 2004. 'Medieval and post-medieval glass technology: melting characteristics of some glasses melted from vegetable ash and sand mixtures' *Glass Technology*, 2004, **45**(1), pp. 36-42.

______________., Booth, C.A. and Smedley, J.W. 2005. 'Glass by design? Raw materials, recipes and compositional data' *Archaeometry*, 2005, **47**(4), pp. 781-795.

JOHNSON, Matthew. 1996. *An Archaeology of Capitalism.* Oxford: Blackwell.

KAHLE, Charles F. 1965. 'Strontium in oolitic limestones' *Journal of Sedimentary Research*; December 1965, **35**(4), pp. 846-85

KELL, E. 1861. 'On the Discovery of a Glass Factory at Buckholt' *Journal of the British Archaeological Association*, 1861, **17**, pp. 55-58.

KENYON, G.H. 1967. *The Glass Industry of the Weald*. Leicester: Leicester University Press.

KUISMA-KURSULA, Pirkko. 2000. 'Accuracy, precision and detection limits of SEM-WDS, SEM-EDS and PIXE in the multi-elemental analysis of medieval glass' X-Ray Spectrometry, 2000, 29(1), pp. 111-118.

LENNARD, T. Barrett. 1905. 'Glass-making at Knole, Kent' *Antiquary*, 1905, **41**, pp. 127-129.

LESLIE, K.A., Freestone, I.C., Lowry, D. and Thirlwall, M. 2006. 'The Provenance and Technology of Near Eastern Glass: Oxygen Isotopes by Laser Fluorination as a complement to Strontium' *Archaeometry*, **48**(2), pp. 253-270.

LI, Bao-Ping, Zhao, Jian-Xin, Greig, Alan, Collerson, Kenneth D., Feng, Yue-Xin, Sun, Xin-Min, Guo, Mu-Sen and Zhuo, Zhen-Xi. 2006. 'Characterisation of Chinese Tang sancai from Gongxian and Yaozhou kilns using ICP-MS trace element and TIMS Sr-Nd isotopic analysis' *Journal of Archaeological Science*, 2006, **33**, pp. 56-62.

LINFORD, Paul and Welch, Christopher. 2003. 'Archaeomagnetic dating: glassmaking sites at Bagot's Park, Staffordshire' *The Archaeologist*, 2003, **50**, p. 37.

MERCHANT, Ian. 1998 English Medieval glass-making technology: scientific analysis of the evidence. Unpublished PhD Thesis. The University of Sheffield.

________________, Henderson, Julian, Crossley, David and Cable, Michael. 1997. ‘Medieval Glass-making Technology: the Corrosive Nature of Glass’ *In*: Sinclair, Anthony, Slater, Elizabeth and Gowlett, John (eds.) *Archaeological Sciences 1995 Proceedings of a conference on the application of scientific techniques to the study of archaeology, Liverpool, July 1995*. Oxford: Oxbow Books, pp. 31-37.

MISRA, Mahendra K., Ragland, Kenneth W., Baker, Andrew J. 1993. ‘Wood ash composition as a function of furnace temperature’ *Biomass and Bioenergy*, **4**(2), pp. 103-116.

MONTGOMERY, Janet, Evans, Jane A. and Neighbour, Tim. 2003. ‘Sr isotope evidence for population movement within the Hebridean Norse community of NW Scotland’ *Journal of the Geological Society, London* **160**, 2003, pp. 649-653.

MORTIMER, Catherine. 1993. *Analysis of Glass and Glassworking Waste from the Collections of Guildford Museum*. English Heritage Ancient Monuments Report 106/93. London: English Heritage.

____________________. 1995. ‘Analysis of Post-Medieval glass from Old Broad Street, London, with reference to other contemporary glasses from London and Italy’ *In*: Hook, Duncan R. and Gaimster, David R.M. 1995. *Trade and Discovery: The Scientific Study of Artefacts from Post Medieval Europe and Beyond*. British Museum Occasional Paper 109. London: British Museum Press, pp. 135-144.

____________________. 1997. ‘Analysis of the Glass’ *In*: Welch, Christopher. ‘Glassmaking in Wolseley, Staffordshire’ *Post-Medieval Archaeology*, 1997, **31**, pp. 1-60.

NEWSTEAD, R. 1939. ‘Glasshouse in Delamere Forest, Cheshire’ *Journal of the Chester and North Wales Architectural, Archaeological and Historic Society*, 1939, **33**, pp. 32-39.

PAPE, T. 1934. ‘Medieval Glassworkers in North Staffordshire’ *Transactions of the North Staffordshire Field Club*, 1933-1934, **68**, pp. 74-121.

PILBIN, Preston. 1937. ‘External Relations of the Tyneside Glass Industry’ *Economic Geography*, 13(3), pp. 301-314.

PLATZNER, I.T. 1997. *Modern Isotope Ratio Mass Spectrometry*. Chichester: John Wiley & Sons.

POLAK, Ada. 1975. *Glass: its makers and its public*. London: Weidenfeld and Nicolson.

POLLARD, A.M. and Heron, C. 1996. *Archaeological Chemistry*. Letchworth: The Royal Society of Chemistry.

PRICE, Derk J. (ed.). 1959. *The pirotechnia of Vannoccio Biringuccio*. New York: Basic Books Inc.

REHREN, Th. 2008. 'A review of factors affecting the composition of early Egyptian glasses and faience: alkali and alkali earth oxides' *Journal of Archaeological Science*, **35**, pp. 1345-1354.

RIDGWAY, Maurice H. and Leach, Geo B. 1948. 'Further Notes on the Glasshouse Site at Kingswood, Delamere, Cheshire' *Chester Archaeological Society Journal*, **37**(1), 1948, pp. 133-140

RUSSEL, Andrew D. 1985. Buckholt Glassworks. Unpublished Site Assessment. Test Valley Archaeological Committee.

SANDERSON, D.C.W. and Hunter, J.R. 1981. 'Compositional variability in vegetable ash' *Science and Archaeology*, 1981, **23**, pp. 27-30.

SCHALM, O., Caluwé, D., Wouters, H., Janssens, K., Verhaeghe, F. and Pieters, M. 2004. 'Chemical composition and deterioration of glass excavated in the 15th-16th century fishermen town of Raversijde (Belgium)' *Spectrochimica Acta Part B*, 2004, **59**, pp. 1647-1656.

SCHOFIELD, John and Vince, Alan. 2003. *Medieval Towns*. Second Edition. London: Continuum

SCOVILLE, Warren C. 1950. *Capitalism and French Glassmaking, 1640-1789*. Berkeley: University of California Press

SMEDLEY, J.W., Jackson, C.M. and Welch, C. 2001. 'Unravelling glass compositions: Glassmaking raw materials at Little Birches, Staffordshire' *Annales du 15e Congrès de l'Association Internationale pour l'Histoire du Verre, New York 2001*. New York : A.I.H.V, pp. 203-207.

_____________., and Jackson, C.M. 2002a. 'Medieval and post-medieval glass technology: batch measuring practices' *Glass Technology*, 2002, **43**(1), pp. 22-27.

____________________________. 2002b. 'Medieval and post-medieval glass technology: a review of bracken in glassmaking' *Glass Technology*, 2002, **43**(6), pp. 221-224.

____________________________. 2006. 'Medieval and post-medieval glass technology: Bracken as a sustainable resource for glassmaking' *Glass Technology*, April 2006, **47**(2), pp. 39-47.

SMIT, Z., Janssens K., Schalm, O.,Kos, M. 2004. 'Spread of façon-de-Venise glassmaking through central and western Europe' *Nuclear Instruments and Methods in Physics Research B*, 2004, **213**, pp. 717–722.

SMITH, R.S. 1962. 'Glass-Making at Wollaton in the Early Seventeenth Century' *Transactions of the Thoroton Society*, 1962, **66**, pp. 24-34.

TANIMOTO, Satoko and Rehren, Thilo. 2008. 'Interactions between silicate and salt melts in LBA glassmaking' *Journal of Archaeological Science*, **35**(9), pp. 2566-2573.

VERHAEGHE, Frans. 1997. 'The Archaeology of Transition: a Continental view' *In*: Gaimster, David and Stamper, Paul (eds.). 1997. *The Age of Transition: The Archaeology of English Culture 1400-1600.* Oxford: Oxbow Books, pp. 25-44.

VERITÀ, M. 2005. 'Comments on W.B. Stern and Y. Gerber, 'Potassium-Calcium Glass: New Data and Experiments', *Archaeometry*, 46(1) (2004), 137-56' *Archaeometry,* **47**(3), 2005, pp. 667-669.

VOSE, Ruth Hurst. 1970. 'Bickerstaffe and Haughton Green Excavations' *Annales du 5e Congrès de l'Association Internationale pour l'Histoire du Verre*, pp. 137-144.

________________. 1980. *Glass*. London: Collins

________________. 1994. 'Excavations at the 17th-century glasshouse at Haughton Green, Denton, near Manchester' *Post-Medieval Archaeology*, 1994, **28**, pp. 1-71.

________________. 1995. 'Excavations at the *c*1600 Bickerstaffe glasshouse, Lancashire' *Journal of the Merseyside Archaeological Society*, 1995, **9**, pp. 1-24.

WEDEPOHL, K.H. 1997. 'Chemical composition of medieval glass from excavations in West Germany', *Glastechnische Berichte*, **70**, pp. 246-55

________________. 2000. 'The change in composition of medieval glass types occurring in excavated fragments from Germany' *Annales du 14e Congrès de l'Association Internationale pour l'Histoire du Verre, Venezia-Milano, 1998,* Amsterdam : A.I.H.V, pp. 253-257.

WELCH, Christopher. 1997. 'Glassmaking in Wolseley, Staffordshire' *Post-Medieval Archaeology*, 1997, **31**, pp. 1-60.

__________________. and Linford, Paul. 2005. 'Archaeomagnetic dating of Medieval and Tudor glassmaking sites in Staffordshire, England' *Annales du 16e Congrès de l'Association Internationale pour l'Histoire du Verre*, London, 2003. Nottingham : A.I.H.V, pp. 210-213.

WILLMOTT, Hugh. 2002. *Early Post-Medieval Vessel Glass in England, c. 1500 1670*. CBA Research Report 132. York: Council for British Archaeology.

_________________. 2005. *A History of English Glassmaking AD 43-1800*. Stroud: Tempus.

WILSON, L. and Pollard, A.M. 2001. ‘The Provenance Hypothesis’ *In*: Brothwell, D.R. and Pollard, A.M. (eds.). *Handbook of Archaeological Sciences*, New York: J.Wiley, Chap. 41, pp. 507-517.

WINBOLT, S.E. 1933. *Wealden Glass: The Surrey-Sussex Glass Industry*. Hove: Combridges.

WOOD, Eric S. 1965. ‘A Medieval Glasshouse at Blunden’s Wood, Hambledon, Surrey’ *Surrey Archaeological Collections*, 1965, **62**, pp. 54-79.

____________. 1982. ‘A 16th Century Glasshouse at Knightons, Alfold, Surrey’ *Surrey Archaeological Collections*, 1982, **73**, pp. 1-47.

Site	Sample	Type	Na_2O	TiO_2	SiO_2	SnO_2	Al_2O_3	ZnO	SO_3	NiO	As_2O_5*	CuO	Cl	CoO	MgO	K_2O	Sb_2O_5	FeO	BaO	MnO	CaO	ZrO_2	PbO	Cr_2O_3*	P_2O_5*	V_2O_3	SrO*	Total	Type
Blunden's Wood	WG1	Lump	2.12	0.08	57.21	nd	1.06	0.04	0.08	0.01	0.07	<0.01	0.57	0.01	6.08	11.56	0.81	0.57	0.23	1.11	14.46	0.04	0.02	nd	2.14	nd	nd	98.24	1
Blunden's Wood	WG2	Lump	2.92	0.08	56.90	nd	0.81	0.04	0.13	<0.01	0.07	<0.01	0.51	nd	6.85	12.24	0.85	0.63	0.14	1.08	13.20	0.02	0.04	nd	2.02	nd	nd	98.53	1
Blunden's Wood	WG3	Lump	2.70	0.07	56.27	nd	0.80	0.04	0.13	<0.01	0.06	<0.01	0.48	<0.01	6.86	12.31	0.84	0.64	0.12	1.09	13.25	0.01	<0.01	nd	2.08	<0.01	nd	97.76	1
Blunden's Wood	WG4	Lump	2.49	0.09	58.05	nd	0.93	0.04	0.12	<0.01	0.08	0.02	0.49	<0.01	6.82	10.99	0.81	0.63	0.17	1.14	13.82	<0.01	0.06	nd	1.83	<0.01	nd	98.57	1
Blunden's Wood	WG5	Lump	2.93	0.08	57.74	nd	0.79	0.04	0.11	<0.01	0.07	0.01	0.48	<0.01	6.66	12.40	0.88	0.64	0.02	1.06	12.57	<0.01	0.01	nd	1.86	0.01	nd	98.37	1
Blunden's Wood	WG6	Lump	2.25	0.09	57.32	nd	1.22	0.04	0.09	<0.01	0.06	0.02	0.44	<0.01	6.43	11.46	0.81	0.67	0.25	1.12	13.97	<0.01	0.06	nd	2.09	0.02	nd	98.39	1
Blunden's Wood	WG7	Lump	3.10	0.10	56.46	nd	1.04	0.03	0.18	<0.01	0.07	0.01	0.45	<0.01	7.18	11.35	0.76	0.62	0.17	1.08	13.51	0.02	0.02	nd	1.93	nd	nd	98.09	1
Blunden's Wood	WG8	Lump	2.43	0.10	59.19	nd	1.22	0.02	0.07	<0.01	0.04	<0.01	0.43	nd	6.49	11.27	0.80	0.76	0.21	1.08	13.30	<0.01	0.07	nd	1.82	nd	nd	99.29	1
Blunden's Wood	WG9	Lump	2.08	0.06	62.78	nd	0.59	0.04	0.16	<0.01	0.06	<0.01	0.64	<0.01	6.41	9.64	0.64	0.74	0.06	0.96	11.35	<0.01	nd	nd	1.74	<0.01	nd	97.95	1
Blunden's Wood	WG10	Lump	2.04	0.07	63.44	nd	0.60	0.04	0.18	<0.01	0.07	<0.01	0.57	nd	6.43	9.59	0.65	0.75	0.05	0.96	11.01	0.01	nd	nd	1.65	<0.01	nd	98.11	1
Blunden's Wood	WG11	Lump	3.12	0.10	57.47	nd	0.95	0.03	0.20	nd	0.10	nd	0.53	<0.01	7.54	10.33	0.74	0.59	0.17	1.16	13.68	<0.01	0.01	nd	1.79	<0.01	nd	98.51	1
Blunden's Wood	WG12	Lump	2.41	0.11	53.90	nd	1.14	0.03	0.13	<0.01	0.08	0.03	0.34	0.01	6.85	13.79	0.95	0.71	0.19	1.19	13.80	0.01	0.07	nd	2.75	<0.01	nd	98.49	1
Blunden's Wood	WG13	Lump	2.18	0.07	61.17	nd	0.75	0.05	0.10	<0.01	0.07	<0.01	0.56	nd	6.44	10.43	0.76	0.72	0.07	0.97	11.92	0.01	0.00	nd	1.73	<0.01	nd	98.02	1
Blunden's Wood	WG14	Lump	2.30	0.08	59.33	nd	0.77	0.05	0.20	<0.01	0.06	<0.01	0.43	0.01	6.44	11.28	0.78	0.61	0.05	1.05	12.68	0.01	0.02	nd	2.16	nd	nd	98.28	1
Blunden's Wood	WG15	Lump	2.46	0.08	58.14	nd	0.85	0.04	0.13	<0.01	0.11	nd	0.57	nd	6.78	11.14	0.79	0.63	0.11	1.12	13.64	0.02	0.06	nd	1.89	<0.01	nd	98.54	1
Blunden's Wood	WG16	Lump	3.15	0.12	56.64	nd	1.06	0.03	0.18	<0.01	0.08	0.01	0.47	nd	7.23	11.06	0.76	0.62	0.15	1.12	13.90	0.01	0.04	nd	1.86	0.02	nd	98.49	1
Blunden's Wood	WG17	Lump	2.70	0.07	58.44	nd	0.67	0.03	0.14	nd	0.07	<0.01	0.57	<0.01	7.08	11.64	0.82	0.55	0.13	1.13	12.70	0.01	<0.01	nd	1.83	0.01	nd	98.60	1
Blunden's Wood	WG18	Lump	2.05	0.08	57.01	nd	0.89	0.03	0.08	<0.01	0.04	0.02	0.49	nd	6.07	11.90	0.85	0.56	0.07	1.09	13.90	0.02	0.02	nd	2.26	<0.01	nd	97.43	1
Blunden's Wood	WG19	Lump	3.18	0.11	57.00	nd	1.05	0.04	0.22	nd	0.08	0.02	0.47	nd	7.24	11.02	0.78	0.61	0.12	1.12	14.02	0.01	0.06	nd	1.90	0.01	nd	99.04	1
Blunden's Wood	WG20	Lump	1.98	0.07	63.75	nd	0.59	0.02	0.16	<0.01	0.06	<0.01	0.60	nd	6.43	9.73	0.66	0.75	0.05	0.98	11.12	<0.01	0.01	nd	1.59	<0.01	nd	98.55	1

Appendix Table 1: EPMA results for glass from Blunden's Wood. Results are presented in weight per cent oxide/element (*=semi-quantitative, nd=not detected, <0.01=detected at levels below 0.01 wt%).

Site	Sample	Type	Na_2O	TiO_2	SiO_2	SnO_2	Al_2O_3	ZnO	SO_3	NiO	As_2O_5*	CuO	Cl	CoO	MgO	K_2O	Sb_2O_5	FeO	BaO	MnO	CaO	ZrO_2	PbO	Cr_2O_3*	P_2O_5*	V_2O_3	SrO*	Total	Type
Knightons	WG1	Lump	2.45	0.18	54.27	nd	1.96	0.06	0.31	<0.01	0.07	0.01	0.26	<0.01	7.25	10.66	0.70	0.70	0.24	1.12	15.20	0.02	0.08	nd	2.54	<0.01	nd	98.08	1
Knightons	WG2	Lump	2.19	0.24	54.78	nd	2.02	0.05	0.38	<0.01	0.08	0.01	0.18	<0.01	6.79	12.82	0.85	0.78	0.10	0.92	12.82	0.02	0.12	nd	2.76	0.02	nd	97.90	1
Knightons	WG3	Lump	2.75	0.17	56.44	nd	1.78	0.03	0.27	<0.01	0.10	0.02	0.43	nd	6.69	10.84	0.71	0.62	0.11	0.86	13.38	<0.01	0.04	nd	2.63	0.01	nd	97.81	1
Knightons	WG4	Lump	1.85	0.16	53.39	nd	1.55	0.05	0.24	<0.01	0.08	nd	0.34	<0.01	7.06	12.21	0.80	0.59	0.10	0.94	15.18	0.02	0.10	nd	2.93	0.02	nd	97.60	1
Knightons	WG5	Lump	2.72	0.21	57.04	nd	1.77	0.04	0.37	<0.01	0.09	0.02	0.43	nd	6.87	10.58	0.70	0.76	0.16	1.11	12.18	0.01	0.04	nd	2.46	0.02	nd	97.58	1
Knightons	WG6	Lump	2.16	0.18	55.41	nd	1.62	0.07	0.31	<0.01	0.06	0.01	0.37	<0.01	7.03	9.45	0.65	0.60	0.18	0.93	15.33	0.03	0.14	nd	2.53	0.01	nd	97.03	1
Knightons	WG9	Lump	2.59	0.16	56.25	nd	1.55	0.02	0.32	<0.01	0.07	0.03	0.44	nd	6.97	9.90	0.67	0.60	0.20	0.89	13.80	0.02	0.06	nd	2.67	<0.01	nd	97.21	1
Knightons	WG10	Lump	1.90	0.17	57.08	nd	1.54	0.06	0.38	<0.01	0.10	0.02	0.44	nd	6.58	9.66	0.64	0.59	0.14	0.92	14.90	0.03	0.07	nd	2.46	nd	nd	97.65	1
Knightons	WG11	Lump	2.75	0.19	54.63	nd	2.06	0.04	0.13	nd	0.06	0.02	0.28	nd	7.12	9.89	0.67	0.66	0.15	0.95	15.30	0.01	0.19	nd	2.49	nd	nd	97.59	1

Appendix Table 2: EPMA results for glass from Knightons. Results are presented in weight per cent oxide/element (*=semi-quantitative, nd=not detected, <0.01=detected at levels below 0.01 wt%).

Site	Sample	Type	Na_2O	TiO_2	SiO_2	SnO_2	Al_2O_3	ZnO	SO_3	NiO	As_2O_5*	CuO	Cl	CoO	MgO	K_2O	Sb_2O_5	FeO	BaO	MnO	CaO	ZrO_2	PbO	Cr_2O_3*	P_2O_5*	V_2O_3	SrO*	Total	Type
Bagots Park	WG1	Lump	2.58	0.09	60.70	nd	1.59	0.03	0.14	<0.01	0.06	<0.01	0.24	nd	7.23	9.79	0.68	0.47	0.15	1.50	10.82	<0.01	<0.01	nd	2.11	<0.01	nd	98.22	1
Bagots Park	WG2	Lump	2.78	0.11	60.01	nd	1.67	0.04	0.14	nd	0.12	<0.01	0.19	<0.01	7.98	9.58	0.67	0.51	0.24	1.78	11.58	0.01	0.01	nd	1.98	0.01	nd	99.40	1
Bagots Park	WG3	Lump	2.85	0.10	59.97	nd	1.66	0.04	0.11	<0.01	0.08	0.02	0.19	<0.01	8.05	9.67	0.66	0.51	0.24	1.78	11.64	0.02	nd	nd	2.05	0.01	nd	99.61	1
Bagots Park	WG4	Lump	2.73	0.10	60.97	nd	1.63	0.05	0.16	nd	0.08	<0.01	0.26	<0.01	7.67	9.70	0.68	0.48	0.17	1.50	11.12	0.01	<0.01	nd	1.96	<0.01	nd	99.28	1
Bagots Park	WG5	Lump	2.89	0.11	59.65	nd	1.67	0.06	0.14	0.01	0.11	0.02	0.20	<0.01	8.02	9.70	0.63	0.51	0.33	1.76	11.55	0.01	<0.01	nd	2.01	0.01	nd	99.38	1
Bagots Park	WG6	Lump	2.73	0.10	59.09	nd	1.49	0.04	0.10	<0.01	0.07	0.01	0.17	<0.01	7.97	10.25	0.77	0.49	0.22	1.70	11.83	0.01	nd	nd	2.20	<0.01	nd	99.24	1
Bagots Park	WG8	Lump	2.63	0.10	62.16	nd	1.66	0.03	0.16	nd	0.07	0.02	0.27	<0.01	7.07	10.23	0.70	0.49	0.15	1.48	9.80	0.01	nd	nd	2.03	nd	nd	99.05	1
Bagots Park	WG9	Lump	2.63	0.10	61.38	nd	1.60	0.04	0.14	<0.01	0.08	<0.01	0.26	<0.01	7.39	9.49	0.66	0.48	0.27	1.50	10.73	0.02	<0.01	nd	2.02	0.02	nd	98.81	1
Bagots Park	WG10	Lump	2.74	0.10	58.77	nd	2.05	0.04	0.18	<0.01	0.07	0.02	0.35	<0.01	7.62	10.77	0.74	0.50	0.20	1.54	10.93	0.01	0.04	nd	1.86	<0.01	nd	98.51	1
Bagots Park	WG11	Lump	2.85	0.11	60.16	nd	1.67	0.07	0.08	<0.01	0.10	0.02	0.18	<0.01	7.98	9.46	0.61	0.52	0.22	1.74	11.45	0.02	<0.01	nd	1.99	nd	nd	99.24	1
Bagots Park	WG12	Lump	2.86	0.15	59.06	nd	2.55	0.04	0.18	nd	0.08	0.03	0.19	<0.01	6.95	11.49	0.82	0.78	0.22	1.31	11.22	0.01	<0.01	nd	2.10	0.03	nd	100.06	1
Bagots Park	WG13	Lump	2.60	0.10	62.66	nd	1.62	0.03	0.16	<0.01	0.07	<0.01	0.23	nd	7.24	9.46	0.65	0.48	0.20	1.48	10.72	0.02	0.01	nd	2.17	<0.01	nd	99.87	1
Bagots Park	WG14	Lump	2.67	0.10	61.19	nd	1.55	0.03	0.13	<0.01	0.07	<0.01	0.21	nd	7.34	10.01	0.70	0.47	0.15	1.51	11.09	0.01	<0.01	nd	2.20	nd	nd	99.44	1
Bagots Park	WG15	Lump	2.77	0.11	60.22	nd	1.67	0.03	0.11	<0.01	0.12	0.01	0.16	<0.01	7.79	9.51	0.68	0.54	0.23	1.77	11.22	<0.01	nd	nd	2.06	0.01	nd	99.01	1
Bagots Park	WG16	Lump	3.01	0.10	58.44	nd	1.47	0.05	0.19	<0.01	0.07	<0.01	0.37	nd	7.61	11.35	0.75	0.47	0.11	1.46	11.57	0.02	nd	nd	2.22	nd	nd	99.26	1
Bagots Park	WG17	Lump	2.70	0.10	60.65	nd	1.62	0.05	0.11	nd	0.06	0.02	0.21	nd	7.80	9.59	0.65	0.50	0.19	1.73	11.45	<0.01	<0.01	nd	2.20	0.01	nd	99.62	1
Bagots Park	WG18	Lump	2.79	0.11	60.59	nd	1.60	0.05	0.12	<0.01	0.09	<0.01	0.16	<0.01	7.75	9.52	0.65	0.53	0.14	1.80	11.27	<0.01	<0.01	nd	1.99	nd	nd	99.16	1

Appendix Table 3: EPMA results for glass from Bagot’s Park. Results are presented in weight per cent oxide/element (*=semi-quantitative, nd=not detected, <0.01=detected at levels below 0.01 wt%).

Site	Sample	Type	Na_2O	TiO_2	SiO_2	SnO_2	Al_2O_3	ZnO	SO_3	NiO	As_2O_5*	CuO	Cl	CoO	MgO	K_2O	Sb_2O_5	FeO	BaO	MnO	CaO	ZrO_2	PbO	Cr_2O_3*	P_2O_5*	V_2O_3	SrO*	Total	Type
Little Birches	WG2	Lump	2.43	0.10	56.69	nd	1.50	0.04	0.19	<0.01	0.10	0.01	0.23	nd	7.62	13.21	0.90	0.49	0.16	1.33	12.11	nd	<0.01	nd	2.24	nd	nd	99.35	1
Little Birches	WG3	Lump	2.43	0.11	56.61	nd	1.50	0.03	0.16	<0.01	0.08	0.01	0.24	<0.01	7.32	13.00	0.88	0.52	0.20	1.32	12.11	0.02	<0.01	nd	2.08	nd	nd	98.62	1
Little Birches	WG4	Lump	1.97	0.09	60.29	nd	1.32	0.01	0.15	<0.01	0.06	<0.01	0.23	<0.01	7.19	10.19	0.68	0.45	0.20	1.35	13.08	0.02	nd	nd	1.99	<0.01	nd	99.25	1
Little Birches	WG6	Lump	2.10	0.08	59.52	nd	1.25	0.05	0.16	<0.01	0.06	<0.01	0.24	nd	7.22	10.45	0.71	0.42	0.16	1.41	13.40	0.01	0.01	nd	2.00	<0.01	nd	99.26	1
Little Birches	WG8	Lump	2.88	0.19	69.86	nd	3.90	0.08	0.06	<0.01	0.02	0.04	0.02	<0.01	2.73	11.84	0.76	0.90	0.10	0.73	4.89	<0.01	0.01	nd	0.53	0.02	nd	99.57	1
Little Birches	WG9	Lump	2.22	0.12	59.26	nd	1.66	0.04	0.15	<0.01	0.09	<0.01	0.32	nd	7.16	11.72	0.80	0.54	0.17	1.32	11.91	0.02	nd	nd	1.80	0.01	nd	99.29	1
Little Birches	WG11	Lump	2.00	0.21	63.98	nd	3.94	0.05	0.07	nd	0.02	0.04	0.06	<0.01	3.27	13.61	0.89	0.85	0.46	0.99	7.53	<0.01	nd	nd	1.42	<0.01	nd	99.38	1
Little Birches	WG12	Lump	2.47	0.11	56.05	nd	1.48	0.03	0.14	<0.01	0.08	0.05	0.26	nd	7.47	13.68	0.89	0.47	0.20	1.23	11.75	0.01	<0.01	nd	1.92	0.02	nd	98.32	1
Little Birches	C7	Crucible glass	1.92	0.12	62.15	nd	1.83	0.03	0.06	<0.01	0.06	0.01	0.09	<0.01	7.12	9.28	0.58	0.54	0.33	1.31	11.37	0.01	nd	nd	1.55	<0.01	nd	98.35	1

Appendix Table 4: EPMA results for glass from Little Birches. Results are presented in weight per cent oxide/element (*=semi-quantitative, nd=not detected, <0.01=detected at levels below 0.01 wt%).

Site	Sample	Type	Na_2O	TiO_2	SiO_2	SnO_2	Al_2O_3	ZnO	SO_3	NiO	As_2O_5*	CuO	Cl	CoO	MgO	K_2O	Sb_2O_5	FeO	BaO	MnO	CaO	ZrO_2	PbO	Cr_2O_3*	P_2O_5*	V_2O_3	SrO*	Total	Type
Buckholt	WG1	Lump	1.14	0.09	60.69	nd	0.67	0.02	0.19	<0.01	0.05	0.02	0.13	0.00	5.89	9.41	0.65	0.55	0.14	0.77	13.34	<0.01	<0.01	nd	4.63	<0.01	nd	98.37	1
Buckholt	WG2	Lump	2.49	0.11	58.87	nd	0.95	0.01	0.02	<0.01	0.06	0.01	0.75	0.00	6.93	9.48	0.59	0.67	0.09	0.84	13.35	0.01	<0.01	nd	2.96	nd	nd	98.18	1
Buckholt	WG3	Lump	1.10	0.27	57.68	nd	2.22	0.04	0.38	<0.01	0.01	0.04	0.21	0.02	3.18	5.59	0.40	1.19	0.19	0.49	22.27	0.05	0.03	nd	2.23	0.02	nd	97.59	2b

Appendix Table 5: EPMA results for glass from Buckholt. Results are presented in weight per cent oxide/element (*=semi-quantitative, nd=not detected, <0.01=detected at levels below 0.01 wt%).

Site	Sample	Type	Na_2O	TiO_2	SiO_2	SnO_2	Al_2O_3	ZnO	SO_3	NiO	As_2O_5*	CuO	Cl	CoO	MgO	K_2O	Sb_2O_5	FeO	BaO	MnO	CaO	ZrO_2	PbO	Cr_2O_3*	P_2O_5*	V_2O_3	SrO*	Total	Type
Buckholt West	WG1	Lump	1.44	0.27	61.76	nd	2.60	0.02	0.31	<0.01	0.01	<0.01	0.18	0.01	2.82	6.10	0.40	1.09	0.12	0.37	19.04	0.03	0.01	nd	1.47	<0.01	nd	98.06	2b
Buckholt West	WG2	Lump	0.86	0.27	58.89	nd	2.25	0.04	0.41	<0.01	nd	<0.01	0.09	0.01	2.52	5.24	0.39	1.09	0.12	0.36	23.57	0.03	<0.01	nd	1.73	<0.01	nd	97.89	2b
Buckholt West	WG3	Lump	0.77	0.25	59.70	nd	2.16	0.02	0.21	<0.01	nd	<0.01	0.07	<0.01	3.98	6.29	0.47	1.29	0.07	0.36	20.60	0.02	0.02	nd	1.56	0.03	nd	97.87	2b
Buckholt West	WG4	Lump	0.80	0.24	61.58	nd	1.61	0.03	0.28	<0.01	0.01	0.02	0.09	<0.01	2.45	4.42	0.31	0.92	0.05	0.43	23.08	0.04	<0.01	nd	1.46	<0.01	nd	97.82	2b
Buckholt West	WG5	Lump	0.94	0.24	60.20	nd	1.88	0.04	0.27	<0.01	0.02	0.02	0.13	<0.01	2.78	5.67	0.38	1.09	0.14	0.54	21.41	0.04	0.02	nd	1.71	<0.01	nd	97.52	2b
Buckholt West	WG6	Lump	1.03	0.26	56.49	nd	2.24	0.05	0.11	nd	0.02	0.03	0.11	nd	4.39	5.84	0.42	1.12	0.16	0.47	22.81	0.04	<0.01	nd	1.95	nd	nd	97.52	2b
Buckholt West	WG7	Lump	0.98	0.26	60.21	nd	2.03	0.05	0.36	0.01	0.02	0.01	0.13	0.02	2.51	5.17	0.36	1.22	0.12	0.47	21.98	0.03	0.02	nd	1.56	<0.01	nd	97.51	2b
Buckholt West	WG8	Lump	0.88	0.26	58.03	nd	2.11	0.03	0.35	nd	<0.01	0.02	0.12	nd	2.56	5.54	0.42	1.09	0.06	0.32	24.13	0.03	nd	nd	1.62	<0.01	nd	97.56	2b
Buckholt West	WG9	Lump	0.98	0.27	62.27	nd	2.15	0.05	0.36	<0.01	<0.01	<0.01	0.17	0.01	2.77	4.99	0.31	1.11	0.14	0.47	20.12	0.02	nd	nd	1.66	<0.01	nd	97.87	2b
Buckholt West	WG10	Lump	1.01	0.24	58.05	nd	2.00	0.03	0.35	<0.01	nd	0.01	0.13	nd	2.93	6.49	0.44	1.10	0.05	0.47	22.40	0.03	0.05	nd	1.82	0.01	nd	97.61	2b
Buckholt West	WG12	Lump	1.00	0.26	56.46	nd	2.40	0.04	0.15	<0.01	0.04	0.02	0.08	0.01	4.46	6.27	0.46	1.12	0.04	0.46	22.94	0.03	0.03	nd	2.04	nd	nd	98.30	2b
Buckholt West	WG13	Lump	0.95	0.25	58.92	nd	2.16	0.05	0.22	0.01	<0.01	0.02	0.11	0.02	2.96	5.06	0.35	1.12	0.12	0.50	23.70	0.03	0.01	nd	1.80	<0.01	nd	98.36	2b
Buckholt West	WG14	Lump	1.42	0.27	61.38	nd	2.27	0.02	0.30	0.02	0.08	<0.01	0.22	0.06	2.94	5.35	0.39	1.24	0.07	0.59	19.56	0.04	0.02	nd	1.82	<0.01	nd	98.05	2b
Buckholt West	WG15	Lump	0.82	0.17	62.60	nd	1.46	0.03	0.35	<0.01	nd	0.02	0.06	<0.01	2.30	4.72	0.34	0.66	0.03	0.24	22.53	0.01	nd	nd	1.39	<0.01	nd	97.72	2b
Buckholt West	WG16	Lump	0.88	0.25	59.71	nd	2.09	0.04	0.36	<0.01	0.02	0.01	0.11	0.02	2.47	5.14	0.36	1.14	0.10	0.45	22.77	0.04	0.01	nd	1.44	<0.01	nd	97.42	2b
Buckholt West	WG17	Lump	1.50	0.25	60.96	nd	2.62	0.03	0.29	<0.01	<0.01	<0.01	0.18	<0.01	2.83	5.87	0.39	1.03	0.07	0.35	18.53	0.03	0.02	nd	1.52	nd	nd	96.49	2b
Buckholt West	WG18	Lump	0.92	0.25	59.11	nd	2.29	0.04	0.31	<0.01	0.03	0.01	0.11	0.02	2.51	4.71	0.35	1.15	0.08	0.41	19.84	0.03	<0.01	nd	1.50	0.03	nd	93.71	2b
Buckholt West	WG19	Lump	1.18	0.24	55.59	nd	2.19	0.04	0.27	<0.01	<0.01	0.01	0.13	<0.01	3.28	6.21	0.42	1.02	0.11	0.47	21.52	0.02	0.03	nd	1.89	<0.01	nd	94.62	2b
Buckholt West	WG20	Lump	0.50	0.14	62.36	nd	1.21	nd	0.13	<0.01	<0.01	nd	0.03	<0.01	2.43	4.02	0.30	0.60	0.11	0.20	23.00	0.02	0.01	nd	1.20	0.01	nd	96.28	2b

Appendix Table 6: EPMA results for glass from Buckholt West. Results are presented in weight per cent oxide/element (*=semi-quantitative, nd=not detected, <0.01=detected at levels below 0.01 wt%).

Site	Sample	Type	Na_2O	TiO_2	SiO_2	SnO_2	Al_2O_3	ZnO	SO_3	NiO	As_2O_5*	CuO	Cl	CoO	MgO	K_2O	Sb_2O_5	FeO	BaO	MnO	CaO	ZrO_2	PbO	Cr_2O_3*	P_2O_5*	V_2O_3	SrO*	Total	Type
Hutton	WG1	Lump	1.85	0.25	58.22	nd	3.34	0.02	0.17	<0.01	nd	0.01	0.45	<0.01	1.97	3.75	0.28	1.28	0.10	0.26	23.31	0.02	0.03	nd	0.94	0.02	nd	96.28	3a
Hutton	WG2	Lump	2.10	0.24	58.01	nd	3.08	0.04	0.22	0.01	0.09	<0.01	0.67	0.01	2.74	4.04	0.31	1.12	0.16	0.45	23.49	0.03	<0.01	nd	1.34	<0.01	nd	98.15	3a
Hutton	WG3	Lump	2.43	0.23	59.65	nd	2.88	0.03	0.24	nd	0.02	nd	0.76	<0.01	2.43	4.16	0.30	1.20	0.13	0.35	22.59	0.03	<0.01	nd	1.02	<0.01	nd	98.43	3a
Hutton	WG4	Lump	2.96	0.29	62.91	nd	2.49	0.03	0.22	<0.01	nd	<0.01	0.65	<0.01	2.26	3.91	0.26	0.93	0.14	0.38	19.52	0.04	<0.01	nd	1.04	<0.01	nd	98.00	3a
Hutton	WG5	Lump	1.75	0.20	58.37	nd	2.30	0.04	0.19	<0.01	<0.01	<0.01	0.71	nd	2.82	6.38	0.46	0.74	0.07	0.36	21.51	0.03	<0.01	nd	1.41	<0.01	nd	97.34	3a
Hutton	WG6	Lump	2.13	0.19	62.43	nd	2.36	0.03	0.14	<0.01	<0.01	<0.01	0.64	nd	2.07	3.31	0.25	0.69	0.03	0.28	21.37	0.05	nd	nd	1.04	<0.01	nd	97.01	3a
Hutton	WG7	Lump	3.06	0.25	59.29	nd	2.82	0.01	0.25	<0.01	nd	<0.01	1.15	<0.01	2.05	2.79	0.22	0.98	0.06	0.26	21.23	0.04	nd	nd	0.90	0.01	nd	95.36	3a
Hutton	WG8	Lump	1.82	0.19	62.75	nd	2.38	0.03	0.06	<0.01	nd	0.01	0.54	<0.01	2.19	3.92	0.30	0.70	0.01	0.29	19.41	0.04	nd	nd	1.08	<0.01	nd	95.71	3a
Hutton	WG9	Lump	1.48	0.18	62.32	nd	2.26	0.03	0.22	<0.01	<0.01	<0.01	0.50	<0.01	2.43	6.08	0.47	0.70	0.05	0.38	19.70	0.03	<0.01	nd	1.22	<0.01	nd	98.06	3a
Hutton	WG10	Lump	2.13	0.21	64.68	nd	2.47	0.05	0.12	<0.01	nd	<0.01	0.66	<0.01	2.18	3.41	0.25	0.72	0.01	0.30	19.75	0.03	nd	nd	0.99	0.01	nd	97.98	3a

Appendix Table 7: EPMA results for glass from Hutton. Results are presented in weight per cent oxide/element (*=semi-quantitative, nd=not detected, <0.01=detected at levels below 0.01 wt%).

Site	Sample	Type	Na_2O	TiO_2	SiO_2	SnO_2	Al_2O_3	ZnO	SO_3	NiO	As_2O_5*	CuO	Cl	CoO	MgO	K_2O	Sb_2O_5	FeO	BaO	MnO	CaO	ZrO_2	PbO	Cr_2O_3*	P_2O_5*	V_2O_3	SrO*	Total	Type
Rosedale	WG1	Lump	1.35	0.18	60.14	nd	2.30	0.05	0.15	<0.01	0.01	nd	0.47	nd	2.92	8.12	0.58	0.78	0.09	0.47	18.85	0.04	nd	nd	1.47	0.02	nd	97.97	2a
Rosedale	WG2	Lump	2.27	0.21	63.49	nd	2.42	0.04	0.12	<0.01	nd	<0.01	0.63	<0.01	2.14	3.67	0.26	0.71	0.17	0.28	19.94	0.05	<0.01	nd	0.96	<0.01	nd	97.36	3a
Rosedale	WG3	Lump	6.15	0.23	56.58	nd	3.52	0.02	0.27	0.01	0.09	<0.01	0.57	0.01	5.59	4.83	0.32	1.68	0.07	0.28	15.36	0.02	<0.01	nd	1.48	0.01	nd	97.10	3c
Rosedale	WG4	Lump	6.01	0.24	57.31	nd	3.61	0.03	0.27	<0.01	0.09	nd	0.57	0.02	5.82	4.76	0.33	1.69	0.12	0.28	14.50	0.02	nd	nd	1.49	<0.01	nd	97.15	3c
Rosedale	WG5	Lump	6.88	0.26	57.80	nd	3.93	0.03	0.25	<0.01	0.09	nd	0.66	0.02	5.92	4.62	0.34	1.81	0.10	0.25	13.16	0.02	nd	nd	1.40	<0.01	nd	97.53	3c
Rosedale	WG6	Lump	4.96	0.22	61.49	nd	2.96	0.04	0.23	nd	0.04	nd	0.64	<0.01	3.74	4.95	0.35	1.15	0.15	0.21	15.30	0.01	nd	nd	1.21	0.01	nd	97.67	3a
Rosedale	WG7	Lump	7.46	0.21	56.04	nd	3.34	0.03	0.18	<0.01	0.07	0.01	0.72	<0.01	6.44	4.33	0.34	1.54	0.08	0.25	14.96	0.02	<0.01	nd	1.53	<0.01	0.02	97.57	3c
Rosedale	WG8	Lump	4.53	0.23	58.23	nd	2.95	0.02	0.23	<0.01	<0.01	<0.01	0.56	nd	3.75	5.32	0.42	1.23	0.07	0.19	18.17	0.04	0.02	nd	1.34	nd	nd	97.30	3a
Rosedale	WG9	Lump	3.60	0.23	58.87	nd	3.30	0.00	0.11	0.01	<0.01	nd	0.66	nd	2.60	3.83	0.30	1.26	0.06	0.27	21.28	0.02	<0.01	nd	1.10	<0.01	nd	97.51	3a
Rosedale	WG10	Lump	3.84	0.28	55.89	nd	3.84	0.03	0.28	<0.01	nd	nd	0.40	<0.01	3.89	6.34	0.47	1.60	0.09	0.29	18.64	0.03	<0.01	nd	1.34	<0.01	nd	97.24	3a
Rosedale	WG11	Lump	2.00	0.21	58.95	nd	2.95	0.04	0.30	nd	nd	<0.01	0.15	<0.01	2.57	6.27	0.50	1.24	0.16	0.20	20.76	0.04	nd	nd	1.14	0.01	nd	97.50	3a
Rosedale	WG12	Lump	1.97	0.20	57.09	nd	3.01	0.01	0.11	0.01	nd	<0.01	0.41	<0.01	2.30	5.38	0.40	1.17	0.14	0.40	23.43	0.01	0.07	nd	1.21	<0.01	nd	97.34	3a
Rosedale	WG13	Lump	1.60	0.21	59.00	nd	2.69	0.04	0.10	<0.01	<0.01	<0.01	0.39	nd	3.46	7.25	0.53	1.32	0.16	0.27	19.10	0.02	0.02	nd	1.48	0.02	nd	97.66	3a
Rosedale	WG14	Lump	3.48	0.25	59.57	nd	3.59	0.03	0.11	<0.01	nd	<0.01	0.59	<0.01	2.18	3.70	0.26	1.33	0.05	0.22	21.12	0.03	nd	nd	1.03	0.02	nd	97.55	3a
Rosedale	WG15	Lump	3.85	0.23	58.23	nd	3.12	0.02	0.19	0.01	0.03	nd	0.49	nd	3.77	6.30	0.47	1.38	0.12	0.28	17.97	0.02	<0.01	nd	1.52	<0.01	nd	97.99	3a
Rosedale	WG16	Lump	3.78	0.23	59.29	nd	3.17	0.03	0.15	<0.01	0.02	0.01	0.54	<0.01	3.65	5.98	0.43	1.36	0.03	0.26	17.14	0.02	nd	nd	1.44	nd	nd	97.53	3a
Rosedale	WG17	Lump	3.10	0.23	57.19	nd	3.50	<0.01	0.09	<0.01	<0.01	<0.01	0.42	<0.01	3.69	7.65	0.54	1.45	0.13	0.26	18.12	0.02	nd	nd	1.39	nd	nd	97.78	3a
Rosedale	WG18	Lump	5.02	0.23	59.17	nd	2.97	0.02	0.29	<0.01	0.05	nd	0.65	<0.01	4.54	4.20	0.32	1.42	0.05	0.32	15.90	0.02	0.02	nd	1.36	<0.01	nd	96.55	3a
Rosedale	WG19	Lump	6.78	0.21	58.55	nd	3.04	<0.01	0.23	<0.01	0.10	nd	0.77	<0.01	6.85	4.38	0.36	1.21	0.08	0.25	12.97	0.02	nd	nd	1.33	<0.01	0.05	97.16	3c
Rosedale	WG20	Lump	7.16	0.23	55.84	nd	3.47	0.02	0.26	<0.01	0.03	nd	0.54	0.01	5.73	4.40	0.29	1.53	0.09	0.23	15.59	0.02	nd	nd	1.38	<0.01	0.01	96.83	3c
Rosedale	WG21	Lump	2.86	0.24	59.54	nd	3.46	0.03	0.13	<0.01	nd	<0.01	0.58	<0.01	2.31	3.67	0.29	1.32	0.16	0.27	20.84	0.02	nd	nd	1.07	<0.01	nd	96.79	3a
Rosedale	WG22	Lump	5.00	0.23	57.27	nd	2.98	0.01	0.30	<0.01	0.02	<0.01	0.58	nd	4.02	4.96	0.37	1.29	0.01	0.22	18.74	0.04	0.02	nd	1.58	<0.01	nd	97.64	3a
Rosedale	WG23	Lump	4.71	0.29	58.06	nd	3.53	0.01	0.18	<0.01	0.02	nd	0.65	nd	3.69	5.44	0.38	1.33	0.12	0.31	17.02	0.02	nd	nd	1.30	0.03	nd	97.07	3a
Rosedale	WG24	Lump	3.10	0.22	58.58	nd	3.16	0.02	0.16	<0.01	nd	0.01	0.34	<0.01	2.76	4.87	0.33	1.21	0.14	0.28	20.79	0.03	nd	nd	1.36	0.01	nd	97.37	3a
Rosedale	WG25	Lump	6.84	0.29	57.04	nd	3.35	0.02	0.24	<0.01	0.07	nd	0.60	0.02	5.83	4.78	0.33	1.59	0.08	0.19	14.64	0.03	nd	nd	1.41	0.01	0.07	97.41	3c
Rosedale	WG26	Lump	5.26	0.23	55.14	nd	3.28	0.03	0.29	0.01	0.02	0.02	0.57	<0.01	3.76	6.50	0.44	1.32	0.09	0.19	18.52	0.03	<0.01	nd	1.77	nd	nd	97.45	3a
Rosedale	WG27	Lump	3.60	0.24	56.62	nd	3.21	0.02	0.28	<0.01	0.04	0.02	0.50	nd	3.83	8.00	0.53	1.37	0.07	0.32	17.21	0.04	nd	nd	1.59	0.01	nd	97.49	3a
Rosedale	WG28	Lump	6.35	0.27	54.04	nd	3.40	0.02	0.23	<0.01	0.02	<0.01	0.40	0.02	5.32	5.45	0.37	1.42	0.07	0.49	17.73	0.03	nd	nd	1.60	<0.01	nd	97.22	3c
Rosedale	WG29	Lump	6.73	0.27	54.67	nd	3.42	0.04	0.25	nd	0.05	<0.01	0.51	<0.01	5.54	4.88	0.32	1.48	0.05	0.35	16.98	0.03	nd	nd	1.44	0.03	nd	97.03	3c
Rosedale	WG30	Lump	1.91	0.22	55.96	nd	2.90	0.02	0.15	<0.01	nd	nd	0.39	<0.01	2.48	8.29	0.57	1.17	0.10	0.33	20.82	0.02	<0.01	nd	1.56	<0.01	nd	96.88	2a

Appendix Table 8: EPMA results for glass from Rosedale. Results are presented in weight per cent oxide/element (*=semi-quantitative, nd=not detected, <0.01=detected at levels below 0.01 wt%).

Site	Sample	Type	Na_2O	TiO_2	SiO_2	SnO_2	Al_2O_3	ZnO	SO_3	NiO	As_2O_5*	CuO	Cl	CoO	MgO	K_2O	Sb_2O_5	FeO	BaO	MnO	CaO	ZrO_2	PbO	Cr_2O_3*	P_2O_5*	V_2O_3	SrO*	Total	Type
Glasshouse Farm	WG1	Lump	3.61	0.23	56.59	nd	3.13	<0.01	0.10	<0.01	0.03	<0.01	0.69	0.01	3.42	5.90	0.40	1.22	0.17	0.50	21.08	0.01	<0.01	nd	1.44	nd	nd	98.53	3a
Glasshouse Farm	WG2	Lump	3.15	0.27	59.34	nd	3.87	0.02	0.37	<0.01	0.06	0.02	0.30	0.02	3.74	5.74	0.38	1.30	0.12	0.50	17.67	0.03	nd	nd	1.49	0.02	nd	98.40	3a
Glasshouse Farm	WG3	Lump	2.17	0.25	57.17	nd	3.08	<0.01	0.08	<0.01	0.01	0.02	0.46	<0.01	3.81	8.38	0.58	1.26	0.12	0.59	18.98	0.02	nd	nd	1.66	0.01	nd	98.68	2a
Glasshouse Farm	WG4	Lump	3.61	0.31	58.02	nd	4.45	<0.01	0.30	0.01	0.04	0.02	0.47	0.02	3.86	6.06	0.41	1.57	0.11	0.38	17.00	0.03	nd	nd	1.34	<0.01	nd	98.00	3a
Glasshouse Farm	WG5	Lump	1.69	0.24	57.79	nd	3.29	0.03	0.13	<0.01	0.03	0.01	0.40	<0.01	3.66	9.57	0.67	1.28	0.02	0.53	17.19	0.02	0.02	nd	1.76	<0.01	nd	98.33	2a
Glasshouse Farm	WG6	Lump	2.63	0.21	58.40	nd	2.65	0.03	0.10	<0.01	nd	0.02	0.55	<0.01	3.19	5.60	0.39	0.92	0.14	0.62	21.35	0.02	nd	nd	1.53	nd	nd	98.33	3a
Glasshouse Farm	WG9	Lump	3.59	0.27	57.52	nd	3.98	0.03	0.36	0.01	0.06	<0.01	0.61	0.03	4.41	5.80	0.40	1.34	0.13	0.40	17.68	0.03	0.12	nd	1.46	<0.01	nd	98.23	3a
Glasshouse Farm	WG10	Lump	0.96	0.26	54.68	nd	3.69	0.02	0.24	0.01	0.06	0.01	0.23	0.02	3.77	10.27	0.71	1.34	0.14	0.60	19.39	0.02	0.01	nd	1.86	0.02	nd	98.28	2a
Glasshouse Farm	C1-WG1	Crucible glass	5.09	0.20	54.13	nd	4.18	0.01	0.08	0.01	0.03	<0.01	0.71	<0.01	4.46	3.81	0.28	0.97	0.31	0.66	21.86	0.02	0.01	nd	1.93	<0.01	nd	98.75	3a

Appendix Table 9: EPMA results for glass from Glasshouse Farm. Results are presented in weight per cent oxide/element (*=semi-quantitative, nd=not detected, <0.01=detected at levels below 0.01 wt%).

Site	Sample	Type	Na_2O	TiO_2	SiO_2	SnO_2	Al_2O_3	ZnO	SO_3	NiO	As_2O_5*	CuO	Cl	CoO	MgO	K_2O	Sb_2O_5	FeO	BaO	MnO	CaO	ZrO_2	PbO	Cr_2O_3*	P_2O_5*	V_2O_3	SrO*	Total	Type
Bickerstaffe	WG1	Lump	5.03	0.12	62.88	nd	2.25	<0.01	0.02	<0.01	0.02	<0.01	1.14	nd	4.19	2.48	0.20	0.58	0.15	0.51	16.77	0.01	0.03	nd	1.69	0.01	nd	98.07	3b
Bickerstaffe	WG2	Lump	5.73	0.12	58.35	nd	2.14	0.02	0.04	<0.01	0.04	nd	1.15	nd	4.98	2.11	0.17	0.52	0.18	0.56	19.60	0.02	0.02	nd	1.95	nd	nd	97.68	3b
Bickerstaffe	WG3	Lump	6.43	0.12	56.92	nd	2.24	<0.01	0.03	<0.01	0.04	<0.01	1.24	<0.01	4.83	1.58	0.09	0.66	0.12	0.50	21.07	0.01	0.01	nd	1.95	0.01	nd	97.85	3b
Bickerstaffe	WG4	Lump	5.85	0.12	60.00	nd	2.57	<0.01	0.04	<0.01	0.01	<0.01	1.38	<0.01	4.62	1.14	0.10	0.61	0.16	0.46	18.96	<0.01	<0.01	nd	1.85	nd	nd	97.90	3b
Bickerstaffe	WG5	Lump	6.51	0.11	56.51	nd	2.11	<0.01	0.06	<0.01	0.02	nd	1.40	<0.01	5.13	1.21	0.12	0.60	0.13	0.56	21.06	<0.01	0.02	nd	2.10	<0.01	nd	97.64	3b
Bickerstaffe	WG6	Lump	5.78	0.11	59.27	nd	2.17	0.02	0.04	<0.01	0.03	<0.01	1.09	<0.01	4.54	1.97	0.15	0.58	0.12	0.47	19.16	0.02	0.03	nd	1.89	<0.01	nd	97.44	3b
Bickerstaffe	WG7	Lump	6.10	0.13	59.65	nd	2.44	<0.01	0.05	<0.01	0.01	<0.01	1.22	nd	4.49	1.62	0.13	0.66	0.07	0.47	18.60	<0.01	0.02	nd	1.87	<0.01	nd	97.55	3b
Bickerstaffe	WG8	Lump	5.47	0.11	58.44	nd	2.17	0.04	0.03	<0.01	0.02	<0.01	1.05	<0.01	4.77	2.73	0.23	0.58	0.16	0.53	19.28	0.02	0.06	nd	2.08	nd	nd	97.76	3b
Bickerstaffe	WG9	Lump	5.13	0.13	56.44	nd	2.45	0.03	0.10	nd	0.06	0.01	1.27	<0.01	5.34	3.61	0.25	0.79	0.15	0.62	19.23	0.01	<0.01	nd	2.00	<0.01	nd	97.62	3b
Bickerstaffe	WG10	Lump	5.89	0.13	56.03	nd	2.46	0.01	0.08	nd	<0.01	nd	1.31	<0.01	4.52	1.79	0.14	0.75	0.23	0.44	21.71	0.02	0.01	nd	1.65	<0.01	nd	97.17	3b
Bickerstaffe	WG11	Lump	6.56	0.10	56.85	nd	2.14	0.01	0.02	<0.01	0.04	0.01	1.41	<0.01	5.18	1.20	0.13	0.61	0.16	0.61	20.98	<0.01	<0.01	nd	2.18	<0.01	nd	98.20	3b
Bickerstaffe	WG12	Lump	4.82	0.10	61.56	nd	2.03	0.04	0.02	<0.01	0.03	<0.01	1.02	<0.01	4.58	2.11	0.17	0.52	0.07	0.51	18.54	<0.01	0.02	nd	1.97	nd	nd	98.13	3b

Appendix Table 10: EPMA results for glass from Bickerstaffe. Results are presented in weight per cent oxide/element (*=semi-quantitative, nd=not detected, <0.01=detected at levels below 0.01 wt%).

Site	Sample	Type	Na_2O	TiO_2	SiO_2	SnO_2	Al_2O_3	ZnO	SO_3	NiO	As_2O_5*	CuO	Cl	CoO	MgO	K_2O	Sb_2O_5	FeO	BaO	MnO	CaO	ZrO_2	PbO	Cr_2O_3*	P_2O_5*	V_2O_3	SrO*	Total	Type
Kimmeridge	WG1	Lump	3.18	0.19	59.26	nd	2.40	0.04	0.38	nd	0.02	0.02	0.39	nd	3.28	4.14	0.24	1.11	0.08	0.29	21.81	0.02	0.01	0.01	1.76	0.02	nd	98.65	3a
Kimmeridge	WG2	Lump	4.15	0.18	58.25	nd	2.41	0.04	0.47	<0.01	0.01	0.01	0.55	nd	3.58	3.76	0.23	1.14	0.06	0.31	21.77	nd	0.02	0.01	1.72	<0.01	nd	98.68	3a
Kimmeridge	WG3	Lump	3.45	0.14	61.44	nd	2.04	0.02	0.47	nd	<0.01	0.03	0.62	<0.01	3.27	3.36	0.22	0.96	0.02	0.28	20.33	0.02	nd	nd	1.71	<0.01	nd	98.38	3a
Kimmeridge	WG4	Lump	3.28	0.18	59.80	nd	2.18	0.04	0.35	nd	0.02	0.00	0.51	nd	3.42	3.74	0.27	1.09	0.04	0.31	22.03	0.02	0.05	nd	1.63	nd	nd	98.97	3a
Kimmeridge	WG5	Lump	2.64	0.21	57.75	nd	2.47	0.04	0.45	<0.01	nd	0.01	0.33	0.01	3.02	4.69	0.31	1.31	0.10	0.32	23.13	0.03	0.01	<0.01	1.90	<0.01	nd	98.74	3a
Kimmeridge	WG6	Lump	3.29	0.20	57.99	nd	2.28	0.04	0.45	nd	nd	0.02	0.45	<0.01	3.53	4.20	0.28	1.13	0.03	0.30	22.52	0.04	0.03	nd	1.81	nd	nd	98.57	3a
Kimmeridge	WG7	Lump	4.23	0.19	60.21	nd	2.12	0.03	0.36	nd	nd	0.01	0.57	nd	3.82	3.46	0.21	1.05	0.11	0.30	20.36	<0.01	nd	nd	1.58	0.01	nd	98.61	3a
Kimmeridge	WG8	Lump	3.11	0.15	60.27	nd	2.21	0.04	0.54	<0.01	nd	0.01	0.56	<0.01	3.67	2.86	0.16	1.13	0.09	0.34	21.53	0.01	<0.01	nd	1.66	<0.01	nd	98.35	3a
Kimmeridge	WG9	Lump	3.05	0.19	59.28	nd	2.12	0.03	0.49	nd	0.02	0.01	0.39	nd	3.57	3.78	0.25	1.07	nd	0.30	22.04	0.02	0.02	nd	1.60	<0.01	nd	98.24	3a
Kimmeridge	WG10	Lump	4.10	0.17	58.46	nd	2.05	0.04	0.22	<0.01	0.02	0.01	0.81	nd	3.83	4.04	0.26	1.05	<0.01	0.26	21.40	0.03	0.02	nd	1.78	nd	nd	98.55	3a
Kimmeridge	WG15	Lump	4.61	0.21	56.16	nd	2.44	0.03	0.37	nd	0.02	0.01	0.71	nd	4.22	3.39	0.24	1.15	0.04	0.33	22.61	0.04	0.04	nd	1.82	<0.01	nd	98.45	3a
Kimmeridge	WG16	Lump	4.06	0.18	57.30	nd	2.55	0.04	0.41	nd	nd	0.02	0.61	nd	3.65	3.58	0.19	1.25	0.10	0.38	22.17	nd	0.02	0.01	1.73	<0.01	nd	98.25	3a
Kimmeridge	WG17	Lump	3.44	0.20	58.83	nd	2.48	0.03	0.45	nd	<0.01	0.01	0.53	<0.01	3.58	3.07	0.20	1.17	0.07	0.34	21.77	0.02	0.02	<0.01	1.90	<0.01	nd	98.11	3a
Kimmeridge	WG18	Lump	3.24	0.19	58.47	nd	2.35	0.03	0.54	nd	nd	0.04	0.56	<0.01	3.88	2.98	0.18	1.08	0.01	0.38	22.35	0.02	<0.01	nd	1.84	<0.01	nd	98.14	3a
Kimmeridge	WG19	Lump	3.75	0.17	58.23	nd	2.50	0.04	0.50	nd	<0.01	0.01	0.46	nd	3.84	3.78	0.23	1.15	<0.01	0.27	20.96	nd	0.02	<0.01	1.98	0.01	nd	97.92	3a
Kimmeridge	WG20	Lump	2.60	0.16	59.14	nd	1.91	0.02	0.42	nd	0.01	0.02	0.42	0.01	3.13	3.29	0.20	0.80	nd	0.26	23.72	0.03	0.03	nd	1.85	0.03	nd	98.06	3a
Kimmeridge	WG21	Lump	2.62	0.19	59.07	nd	1.90	0.03	0.44	0.01	0.01	0.02	0.41	<0.01	3.13	3.27	0.22	0.81	<0.01	0.26	23.67	0.02	0.03	<0.01	1.80	0.02	nd	97.95	3a
Kimmeridge	WG22	Lump	3.92	0.15	61.02	nd	2.02	0.03	0.34	<0.01	0.01	0.01	0.76	nd	4.06	2.91	0.22	1.01	0.08	0.31	19.69	0.02	0.02	nd	1.51	nd	nd	98.07	3a
Kimmeridge	WG23	Lump	3.23	0.18	58.90	nd	2.30	0.03	0.55	<0.01	<0.01	0.02	0.53	<0.01	3.74	3.37	0.21	1.15	0.06	0.36	21.92	0.01	0.03	nd	1.75	nd	nd	98.35	3a
Kimmeridge	WG24	Lump	3.21	0.20	59.25	nd	2.42	0.04	0.47	<0.01	0.01	0.02	0.40	nd	3.33	3.81	0.23	1.22	<0.01	0.29	21.34	nd	0.04	<0.01	1.68	<0.01	nd	98.00	3a
Kimmeridge	WG25	Lump	2.45	0.21	58.82	nd	2.33	0.04	0.36	<0.01	0.02	0.01	0.25	0.01	2.95	4.63	0.31	1.24	0.08	0.31	22.49	0.02	0.02	0.01	1.72	<0.01	nd	98.27	3a

Appendix Table 11: EPMA results for glass from Kimmeridge. Results are presented in weight per cent oxide/element (*=semi-quantitative, nd=not detected, <0.01=detected at levels below 0.01 wt%).

Site	Sample	Type	Na_2O	TiO_2	SiO_2	SnO_2	Al_2O_3	ZnO	SO_3	NiO	As_2O_5*	CuO	Cl	CoO	MgO	K_2O	Sb_2O_5	FeO	BaO	MnO	CaO	ZrO_2	PbO	Cr_2O_3*	P_2O_5*	V_2O_3	SrO*	Total	Type
Haughton Green	WG1	Lump	5.05	0.24	56.28	nd	4.51	0.05	0.36	<0.01	0.02	0.01	1.05	<0.01	4.09	3.25	0.24	1.83	0.23	0.44	17.99	0.02	<0.01	nd	1.96	<0.01	nd	97.62	3b
Haughton Green	WG2	Lump	5.48	0.25	56.00	nd	4.66	0.03	0.03	0.01	0.03	0.01	1.22	nd	4.26	2.31	0.14	2.14	0.16	0.44	17.63	0.03	0.03	nd	1.91	0.03	nd	96.79	3b
Haughton Green	WG3	Lump	6.54	0.26	57.94	nd	4.99	0.03	0.04	<0.01	0.02	<0.01	1.42	nd	4.15	1.18	0.10	2.01	0.11	0.41	16.21	<0.01	0.03	nd	1.75	nd	nd	97.18	3b
Haughton Green	WG4	Lump	5.67	0.23	55.09	nd	4.51	0.02	0.05	<0.01	0.02	<0.01	1.20	<0.01	4.53	2.06	0.15	2.13	0.18	0.54	19.66	<0.01	0.04	nd	1.93	0.02	nd	98.03	3b
Haughton Green	WG5	Lump	5.65	0.25	56.03	nd	4.64	0.03	0.05	<0.01	0.01	<0.01	1.19	<0.01	4.29	2.31	0.17	2.10	0.16	0.45	17.78	0.02	0.03	nd	1.91	0.01	nd	97.07	3b
Haughton Green	WG6	Lump	5.63	0.23	54.49	nd	4.41	0.02	0.06	<0.01	<0.01	0.01	1.20	nd	4.46	2.07	0.15	2.12	0.13	0.50	19.55	0.02	0.04	nd	1.87	<0.01	nd	96.98	3b
Haughton Green	WG7	Lump	4.34	0.26	53.57	nd	4.92	0.03	0.10	<0.01	0.02	<0.01	0.79	<0.01	3.82	3.41	0.25	2.31	0.22	0.44	20.68	<0.01	0.03	nd	1.70	0.03	nd	96.92	3a
Haughton Green	WG8	Lump	7.43	0.28	56.84	nd	5.51	0.02	0.02	0.01	0.02	nd	1.66	<0.01	4.14	1.04	0.09	3.11	0.07	0.32	14.72	0.01	nd	nd	1.80	0.01	nd	97.11	3b
Haughton Green	WG9	Lump	5.27	0.35	57.16	nd	6.98	0.02	0.05	<0.01	0.03	0.02	0.56	<0.01	3.18	3.16	0.24	4.35	0.20	0.33	13.73	0.03	0.03	nd	1.35	0.02	nd	97.04	3a
Haughton Green	WG10	Lump	3.86	0.29	49.10	nd	5.40	0.05	0.09	<0.01	<0.01	<0.01	0.24	nd	4.42	6.85	0.51	2.12	0.22	0.67	20.98	0.02	<0.01	nd	2.37	<0.01	nd	97.19	3a
Haughton Green	WG11	Lump	4.50	0.28	49.56	nd	5.16	0.04	0.06	<0.01	<0.01	<0.01	0.15	<0.01	4.57	6.32	0.43	1.96	0.19	0.61	20.47	0.02	0.02	nd	2.37	<0.01	nd	96.70	3a
Haughton Green	WG12	Lump	3.64	0.27	49.32	nd	5.06	0.05	0.06	0.02	0.02	0.02	0.18	<0.01	4.61	7.26	0.47	1.96	0.23	0.63	20.72	0.02	nd	nd	2.38	0.02	nd	96.91	3a
Haughton Green	WG13	Lump	5.49	0.25	55.32	nd	4.48	0.03	0.07	nd	<0.01	<0.01	1.18	<0.01	4.17	2.63	0.19	1.96	0.12	0.44	18.49	0.03	0.03	nd	1.89	<0.01	nd	96.77	3b
Haughton Green	WG14	Lump	5.57	0.24	58.99	nd	4.62	0.00	0.03	<0.01	0.02	0.02	1.26	<0.01	3.92	1.79	0.14	1.91	0.15	0.42	17.23	0.04	0.02	nd	1.60	0.01	nd	97.97	3b
Haughton Green	WG15	Lump	5.49	0.25	55.25	nd	4.67	0.03	0.04	<0.01	<0.01	nd	1.06	<0.01	4.33	2.47	0.14	2.11	0.17	0.48	19.43	0.02	0.02	nd	1.82	0.02	nd	97.79	3b
Haughton Green	WG16	Lump	5.73	0.25	56.45	nd	4.78	0.03	0.07	<0.01	0.04	<0.01	1.30	<0.01	4.30	1.79	0.14	2.03	0.18	0.43	18.59	0.02	<0.01	nd	1.65	0.02	nd	97.81	3b
Haughton Green	WG17	Lump	5.69	0.27	55.91	nd	4.84	0.04	0.04	<0.01	0.03	0.02	1.21	<0.01	4.41	2.26	0.15	2.12	0.05	0.43	18.20	0.02	0.04	nd	1.67	<0.01	nd	97.41	3b
Haughton Green	WG18	Lump	5.78	0.25	55.71	nd	4.76	0.03	0.04	<0.01	0.01	<0.01	1.20	<0.01	4.32	2.47	0.20	2.03	0.18	0.43	18.48	0.01	0.04	nd	1.87	0.01	nd	97.81	3b
Haughton Green	WG19	Lump	5.31	0.23	54.09	nd	4.47	0.04	0.13	<0.01	0.02	<0.01	1.06	<0.01	4.33	2.55	0.18	2.40	0.15	0.49	20.04	0.01	0.03	nd	1.65	<0.01	nd	97.17	3b
Haughton Green	WG20	Lump	5.29	0.24	54.10	nd	4.64	0.04	0.14	<0.01	0.03	0.02	1.06	<0.01	4.35	2.58	0.17	2.37	0.18	0.51	19.93	<0.01	0.02	nd	1.72	0.01	nd	97.39	3b
Haughton Green	WG21	Lump	5.42	0.25	55.86	nd	4.62	0.04	0.07	nd	<0.01	0.00	1.17	<0.01	4.27	2.67	0.17	1.91	0.15	0.43	18.80	0.02	0.03	nd	1.67	nd	nd	97.53	3b

Appendix Table 12: EPMA results for glass from Haughton Green. Results are presented in weight per cent oxide/element (*=semi-quantitative, nd=not detected, <0.01=detected at levels below 0.01 wt%).

Site	Sample	Type	Sr (ppm)	$^{87}Sr/^{86}Sr$	Nd (ppm)	$^{143}Nd/^{144}Nd$	$\delta^{18}O_{V-SMOW}$	Type
Blunden's Wood	WG4	Lump	567	0.713708	13.7	0.5120260	13.13	1
Blunden's Wood	WG6	Lump	588	0.713635	12.5	0.5120480	13.30	1
Blunden's Wood	WG8	Lump	574	0.713834	13.0	0.5120390	12.94	1
Blunden's Wood	WG14	Lump	459	0.713449	10.2	0.5120250	13.01	1
Blunden's Wood	WG15	Lump	581	0.713725	14.4	0.5120340	13.41	1
Knightons	WG1	Lump	699	0.714265	21.3	0.5120850	13.43	1
Knightons	WG5	Lump	600	0.713455	21.0	0.5120600	13.48	1
Knightons	WG6	Lump	524	0.713938	21.45	0.512068	13.64	1
Knightons	WG7	Lump	453	0.713849	20.3	0.5120720	14.29	1
Knightons	WG11	Lump	465	0.714021	19.7	0.5120850	14.66	1
Bagot's Park	WG2	Lump	582	0.716737	8.8	0.5120930	13.77	1
Bagot's Park	WG3	Lump	581	0.716777	8.5	0.5120870	13.61	1
Bagot's Park	WG5	Lump	570	0.716857	9.4	0.5120950	13.59	1
Bagot's Park	WG15	Lump	584	0.716814	9.7	0.5121150	13.42	1
Bagot's Park	WG17	Lump	551	0.716813	7.1	0.5120830	13.10	1
Little Birches	WG4	Lump	488	0.716419	10.06	0.512124	13.56	1
Little Birches	WG6	Lump	500	0.71642	10.3	0.51214	13.49	1
Little Birches	WG9	Lump	451	0.716537	10.9	0.512105	14.02	1
Little Birches	WG12	Lump	493	0.716426	10.68	0.512106	13.82	1
Little Birches	C7	Crucible Glass	485	0.716381	9.16	0.512155	14.61	1
Buckholt	WG3	Lump	652	0.710803	9.2	0.5119690	14.02	2b
Buckholt West	WG8	Lump	610	0.714756	9.347	0.512002	13.39	2b
Hutton	WG2	Lump	494	0.712274	11.809	0.512026	13.23	3a
Hutton	WG3	Lump	495	0.712744	10.5	0.5120060	13.76	3a
Hutton	WG6	Lump	341	0.711332	9.1	0.5119880	13.57	3a
Hutton	WG7	Lump	400	0.712599	10.7	0.5120120	13.16	3a
Hutton	WG10	Lump	327	0.711616	9.0	0.5119890	13.88	3a

Site	Sample	Type	Sr (ppm)	$^{87}Sr/^{86}Sr$	Nd (ppm)	$^{143}Nd/^{144}Nd$	$\delta^{18}O_{V\text{-}SMOW}$	Type
Rosedale	WG4	Lump	1667	0.709913	15.44	0.512041	13.63	3c
Rosedale	WG12	Lump	493	0.713754	10.21	0.512023	12.17	3a
Rosedale	WG14	Lump	519	0.711178	13.58	0.512038	13.26	3a
Rosedale	WG25	Lump	2431	0.709695	13.75	0.511999	12.78	3c
Rosedale	WG15	Lump	993	0.710356	13.89	0.512053	13.24	3a
Rosedale	WG16	Lump	994	0.710343	13.5	0.512034	12.69	3a
Glasshouse Farm	WG1	Lump	494	0.714858	10.29	0.512014	12.71	3a
Glasshouse Farm	WG3	Lump	438	0.714885	12.39	0.512055	13.68	2a
Glasshouse Farm	WG4	Lump	1090	0.711409	12.4	0.512025	13.22	3a
Glasshouse Farm	WG5	Lump	408	0.714814	12.9	0.5120680	15.90	2a
Glasshouse Farm	WG6	Lump	461	0.715042	9.56	0.512042	13.13	3a
Glasshouse Farm	C1-WG1	Crucible Glass	647	0.711796	13.9	0.511972	n/a	3a
Bickerstaffe	WG2	Lump	594	0.713854	4.7	0.5120220	12.48	3b
Bickerstaffe	WG3	Lump	605	0.713365	5.6	0.5120320	12.39	3b
Bickerstaffe	WG6	Lump	563	0.713801	5.1	0.5120230	12.86	3b
Bickerstaffe	WG7	Lump	537	0.713791	6.2	0.5120230	12.76	3b
Bickerstaffe	WG8	Lump	567	0.713531	4.9	0.5120280	12.71	3b
Kimmeridge	WG4	Lump	1667	0.709795	9.57	0.512023	13.62	3a
Kimmeridge	WG6	Lump	1484	0.709509	10.2	0.512027	14.43	3a
Kimmeridge	WG9	Lump	1720	0.709777	9.8	0.512018	13.62	3a
Kimmeridge	WG23	Lump	1493	0.709719	10	0.512047	13.61	3a
Kimmeridge	WG24	Lump	1380	0.709662	10.4	0.512026	14.69	3a
Haughton Green	WG5	Lump	528	0.714131	12.5	0.5120520	12.51	3b
Haughton Green	WG15	Lump	569	0.714181	12.0	0.5120490	12.47	3b
Haughton Green	WG18	Lump	524	0.714049	12.1	0.5120410	12.12	3b
Haughton Green	WG20	Lump	592	0.713920	11.9	0.5120540	12.21	3b
Haughton Green	WG21	Lump	518	0.714202	12.1	0.5120320	12.16	3b

Appendix Table 13: Mass spectrometry results for all archaeological glass samples analysed for Sr, Nd and O isotopes (n/a=not analysed).