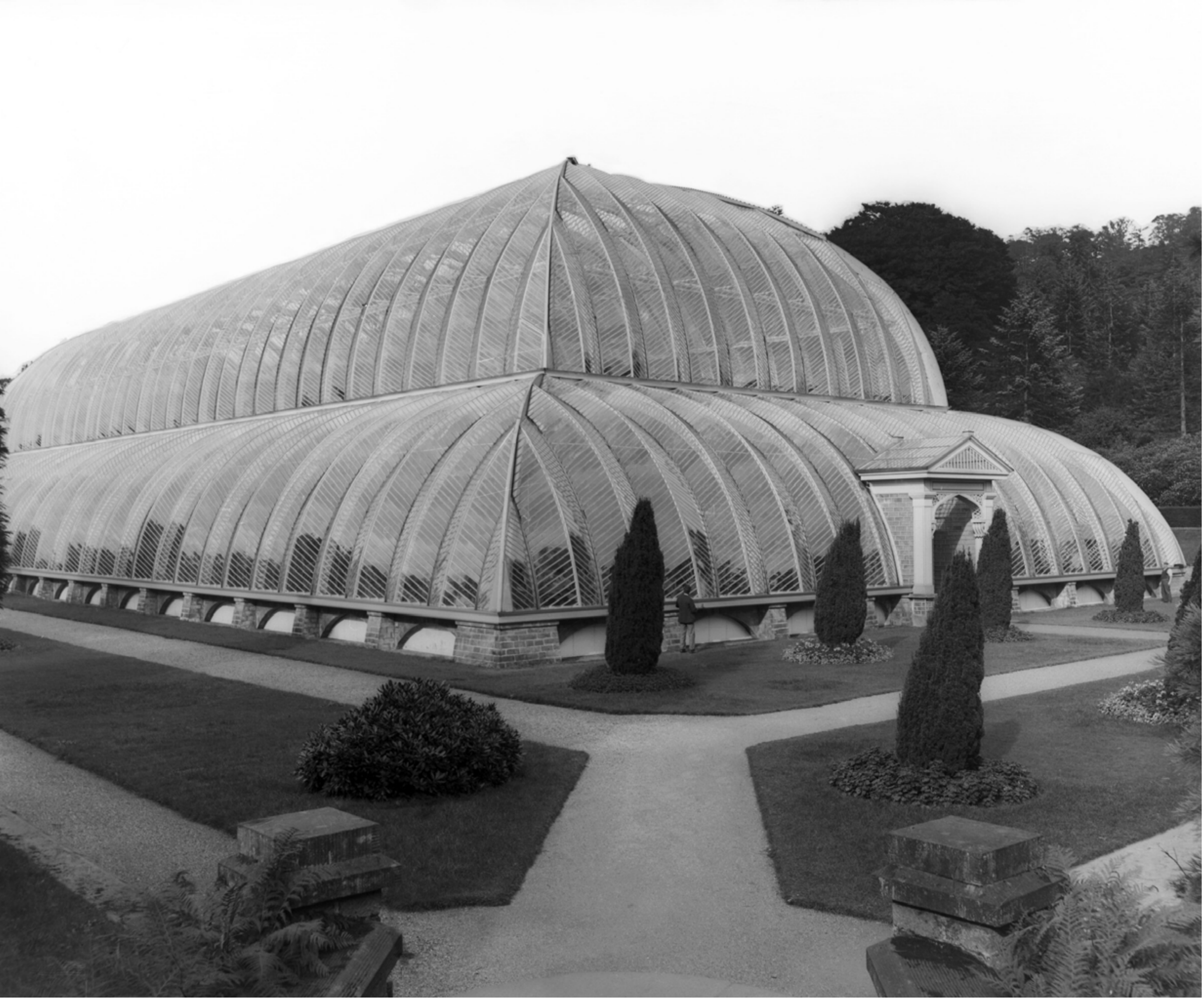
RESEARCH DEPARTMENT REPORT SERIES no. 90-2009

ISSN 1749-8775

CHATSWORTH CONSERVATORY, CHATSWORTH, DERBYSHIRE
AN INVESTIGATION OF THE FLAT GLASS

TECHNOLOGY REPORT

David Dungworth



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Research Department Report Series 90-2009

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NGR: SK 2622 6974

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ISSN 1749-8775

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SUMMARY

As part of a project to investigate changes in window glass manufacturing practice between 1500 and 1960, 187 samples of window glass from the site of the conservatory at Chatsworth were analysed to determine their chemical compositions. The conservatory was constructed between 1837 and 1840 under the supervision of Joseph Paxton who later designed the Crystal Palace for the Great Exhibition in 1851. The Chatsworth Conservatory was constructed using improved cylinder glass by Chance Brothers and Co of Birmingham. The forming technique had recently been introduced to Britain and also benefited from the use of synthetic alkalis (rather than more traditional alkalis based on plant ashes). The 187 samples have been assigned to four groups based on their chemical composition and Groups 3 and 4 have been tentatively identified as the glass originally installed between 1837 and 1840.

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DATE OF RESEARCH

2008–2009

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INTRODUCTION

The keeping of conservatories and greenhouses in the early 19th century was a largely aristocratic pursuit which allowed the production of a 'theatre of nature' (Kohlmaier and Sartory 1986, 1). The construction of greenhouses was to some degree to culminate in the Crystal Palace of the 1851 Great Exhibition. The ability to produce these large glass-walled buildings has often been linked to developments in the iron industry which from the beginning of the 19th century was able to provide large quantities of wrought iron (eg Kohlmaier and Sartory 1986). It may also be argued, however, that the success of greenhouses and similar structures was to a large extent due to changes in both the regulation of the glass industry and the technologies used to make flat glass (McGrath and Frost 1937).

One of the essential requirements of a successful greenhouse was that the flat glass used should allow the transmission of as much sunlight into the greenhouse as possible. At the turn of the 19th century most flat glass was made using kelp (the ash of various seaweeds) and sand, and the glass naturally had a marked blue-green tinge which would reduce slightly the transmission of light through it. The introduction of the Leblanc process into England in the 1820s (Clow and Clow 1952, 110–112) allowed the relatively cheap production of glass with a low iron content and so with little or no colour to reduce the transmission of light.

The nature of the taxation on glass production in England traditionally favoured the crown technique but there were limits on the size of panes that could be produced. Cooper's (1835) manual indicates that the largest panes of glass that could be obtained using the crown forming techniques were 22 by 14.5 inches (0.2m^2). Such small panes were not well suited to the glazing of large areas as the joins between so many individual panes would reduce the light inside the greenhouse.

The 1830s saw the introduction of improved methods for the production of cylinder glass which had far-reaching effects on the architectural use of flat glass. Cylinder (or broad glass) had long been produced in Britain but was not highly regarded: in part because it was traditionally made with relatively coarse raw materials which gave the glass a green tinge, and in part because the forming technique left the glass with a rather dull surface. In the early 1830s Chance and Hartley of Birmingham began to produce an improved cylinder glass using the more skilled forming techniques of continental workers (Chance 1919, 5–8; Douglas and Frank 1972, 149). In addition, from 1833 Chance and Hartley abandoned the use of kelp in favour of sodium carbonate or sulphate; experiments with the latter salt were carried out by Chance and Hartley as early as 1832 (Chance 1919, 9).

While the improved cylinder technique quickly became established, some of the initial motivation for Chance and Hartley to produce cylinder glass was due to the complications of the taxation of window glass production. In the early years of production they were able to claim a rebate (drawback) on exported cylinder glass which *exceeded* the initial tax by £1 4s. 6d per hundredweight of glass produced (Chance 1919, 6).

One of the earliest large-scale uses of Chance Brothers and Company's (Hartley left the partnership in 1836) improved cylinder glass in England was for the Duke of Devonshire's conservatory at Chatsworth which was constructed between 1837 and 1840 (Figure 1). The usage of the terms greenhouse and conservatory have changed somewhat over the last 180 years. In modern usage, a greenhouse is a glass-walled building for growing plants out of their normal season and/or climate, while a conservatory is now a glass-walled extension to a house which may not contain any plants. The modern usage of the term greenhouse better fits the purpose of the Chatsworth structure in question, however, it appears to have always been referred to as a conservatory.

The Chatsworth Conservatory was designed by Joseph Paxton who went on to design the Crystal Palace (also using Chance Brothers improved cylinder glass). Paxton encouraged Chance Brothers to increase the length of the sheets being produced — initially these were 0.9m long (and 0.25m wide) — but Chance Brothers quickly managed to produce longer cylinders which yielded glass sheets 1.2m long (Chance 1919, 7; McGrath and Frost 1937, 119).

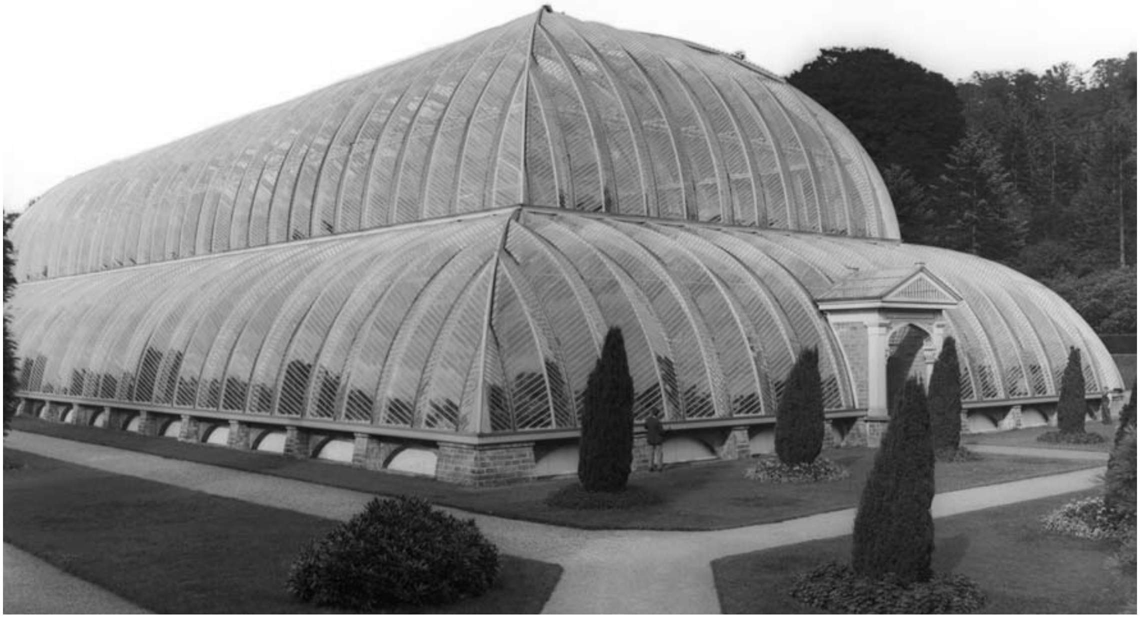

Figure 1. Chatsworth Conservatory in 1900 (© Country Life)

When completed in 1840, the Chatsworth Conservatory was the largest glass structure ever erected — it was 277 feet (84m) long, 132 feet (40m) wide and 67 feet (20m) high. The Palm House of Kew (built in 1842) which was slightly larger required 360,000 square feet of glass. Comparing the dimensions of these two structures it can be estimated that 338,500 square feet (31,400m^2) of glass were required for the Chatsworth Conservatory. The cylinder glass used for the construction of the Chatsworth Conservatory was not allowed to exceed 1/9th of an inch (2.8mm) as glass produced in excess of this thickness would have been deemed to be plate glass and taxed at a higher rate (Barker 1977, 63). Most of the glass recovered from the site of the glasshouse has a thickness of 2.4mm (see below). From the estimate of the area of glass required and the average thickness of the glass used it is possible to suggest that 75.4m^3 or 188.5 tons of glass were required. In the late 1830s Chances were producing around 15,000 pounds (6.6 tons) of sheet glass per week (Chance 1919, 14), therefore, providing the glass for the Chatsworth Conservatory would equate to about 28 weeks work. The glass for this one building represents about a quarter of all the improved cylinder glass produced in Britain during this period (35t in 1837, 112t in 1838, 255t in 1839 and 390t in 1840, Barker 1977, 62). The 1923 6-inch Ordnance Survey map shows the Conservatory survived until at least 1923, but McGrath and Frost report that the Conservatory was 'demolished only a few years ago, the only solution to the problem of upkeep being found in dynamite' (McGrath and Frost 1937, 211).

THE GLASS

The site of the Conservatory is now occupied by a maze (Figure 2). 187 samples of glass (1–5g in weight each) were collected by staff of the Gardens Department of Chatsworth House in 2008 from the Maze. The samples were presented to the author by the Head Gardener, Ian Webster, with the permission of Matthew Hirst, Head of Art and Historic Collections.

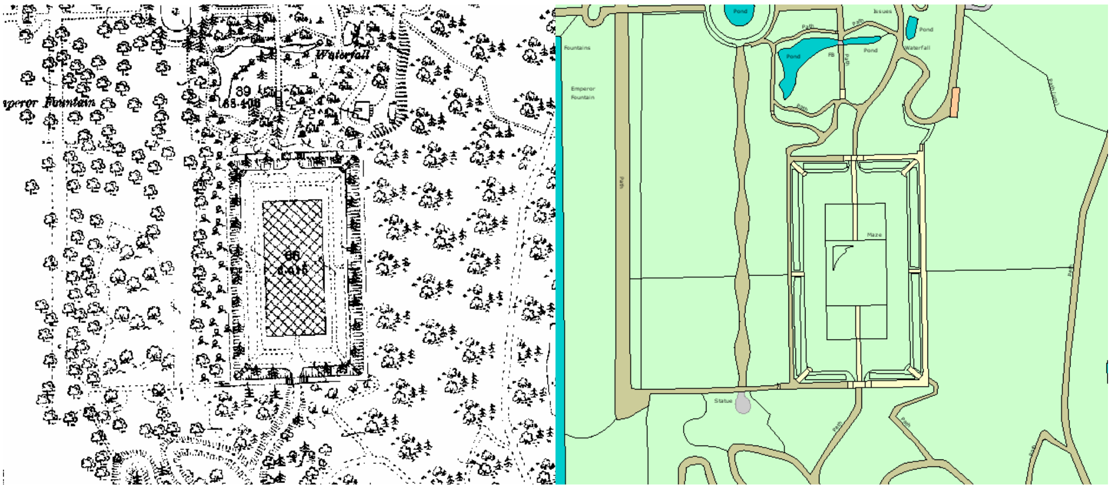

Figure 2. Chatsworth, left in 1879 showing the Conservatory, and 2009 showing the maze © English Heritage. Ordnance Survey mapping: © Crown Copyright and database right 2009. All rights reserved. Ordnance Survey licence number 100019088. Historic OS Mapping: © and database right Crown Copyright and Landmark Information Group Ltd (All rights reserved) Licence numbers 000394 and TP0024.

The thicknesses of each glass fragment was measured to within 0.1mm and an attempt made to evaluate the colour of the glass. 181 of the 187 glass fragments are between 1.5 and 3.2mm in thickness and show a normal distribution about an average of 2.4mm. Six samples were thicker (between 3.3 and 3.6mm). In most cases the glass was almost perfectly colourless with some very pale green or very pale blue-green tints detectable.

The 187 fragments of window glass available for analysis represent a tiny fraction of all of the glass which was used in the Conservatory. Given the above estimate of the total area of glass used it is likely around 14,000 panes of glass were used. Assuming that each of the 187 fragments analysed derive from a different pane, then the analysed fragments are a 1.3% sample. If considered from the point of view of the weight of glass, the analysed fragments are a 0.0003% sample, but this reflects the small size of available fragments of glass.

METHODS

Samples of each of the fragments of glass were mounted in epoxy resin, then ground and polished to a 3-micron finish to expose a cross-section through the glass. The samples were inspected using an optical microscope (brightfield and darkfield illumination) to identify corroded and uncorroded regions. None of the Chatsworth Conservatory samples exhibited any substantial corroded surfaces. The samples were analysed using two techniques to determine chemical composition: SEM-EDS and EDXRF. The energy dispersive X-ray spectrometer (EDS) attached to a scanning electron microscope (SEM) provided accurate analyses of a range of elements while the energy dispersive X-ray fluorescence (EDXRF) spectrometer provided improved sensitivity and accuracy for some minor elements (in particular manganese, iron, arsenic, strontium and zirconium) due to improved peak to background ratios (Table 1).

Table 1. Minimum Detection limits (MDL) and analytical errors for each oxide

	SEM-EDS			EDXRF	
	MDL	Error		MDL	Error
Na_2O	0.1	0.1	V_2O_5	0.02	0.03
MgO	0.1	0.1	Cr_2O_3	0.02	0.03
Al_2O_3	0.1	0.1	NiO	0.02	0.03
SiO_2	0.5	0.2	MnO	0.02	0.03
P_2O_5	0.2	0.1	Fe_2O_3	0.02	0.03
SO_3	0.2	0.1	CoO	0.02	0.02
Cl	0.1	0.1	CuO	0.02	0.01
K_2O	0.1	0.1	ZnO	0.02	0.01
CaO	0.1	0.1	As_2O_3	0.02	0.01
TiO_2	0.1	0.1	SnO_2	0.1	0.05
BaO	0.2	0.1	Sb_2O_5	0.15	0.07
			Rb_2O	0.005	0.005
			SrO	0.005	0.005
			ZrO_2	0.002	0.002
			PbO	0.05	0.02

The SEM used was a FEI Inspect F which was operated at 25kV with a beam current of approximately 1nA. The X-ray spectra generated by the electron beam were detected using an Oxford Instruments X-act SDD detector. The quantification of detected elements was achieved using the Oxford Instruments INCA software. The EDS spectra were calibrated (optimised) using a cobalt standard. Deconvolution of the X-ray spectra and quantification of elements was improved by profile optimisation and element standardisation using pure elements and compounds (MAC standards). The chemical composition of the samples is presented in this report as stochiometric oxides with oxide weight percent concentrations based on likely valence states (the exception being chlorine which is expressed as element wt%). The accuracy of the quantification of all oxides was checked by analysing a wide range reference materials (Corning, NIST, DGG and Newton/Pilkington, see Table 1). A number of elements were sought but not detected (eg cobalt, nickel, copper, and zinc).

RESULTS

The analysis of the 187 fragments of glass from the Chatsworth Conservatory shows that they are all soda-lime-silica glasses (Figure 3). Full analytical results are given in the Appendix. All of these samples contain 11–15wt% sodium oxide, 12–15wt% lime and 69–73wt% silica, while all the other oxides combined make up on average just over 2wt%. The composition of all of the analysed glass suggests that it was made using good quality sand, synthetic soda and good quality limestone or chalk. None of the glass appears to have been made using alkali obtained from plant ashes. In particular, the low concentrations of strontium oxide rule out the possibility that seaweed (kelp) ash was used as a source of alkali. Within the compositional limits already described, the glass samples show some variation and the existence of probable compositional groups (Figures 4 and 5). Four major Groups and three Sub-Groups have been recognised leaving nine samples with compositions which do not match any of the other groups. These Groups (and Sub-Groups) are described in more detail below.

Table 2. Average chemical compositions of the main groups of Chatsworth Conservatory glass.

Group	No.	Na_2O	Al_2O_3	SiO_2	SO_3	K_2O	CaO	MnO	Fe_2O_3	As_2O_3	SrO
1a	14	11.9	1.3	72.6	0.3	0.5	13.2	<0.02	0.26	<0.02	0.019
1b	4	12.0	1.5	73.2	0.2	0.6	12.3	<0.02	0.21	<0.02	0.022
2	61	13.8	0.5	72.3	0.4	<0.1	12.7	0.10	0.23	0.18	0.029
3a	56	13.8	0.8	70.6	0.3	<0.1	14.0	<0.02	0.21	0.38	0.015
3b	6	14.1	0.8	69.8	0.4	<0.1	14.4	<0.02	0.20	0.38	0.014
4a	28	14.5	0.6	69.6	0.4	<0.1	14.3	<0.02	0.19	0.46	0.016
4b	9	13.8	0.6	70.4	0.4	<0.1	14.2	<0.02	0.19	0.46	0.015

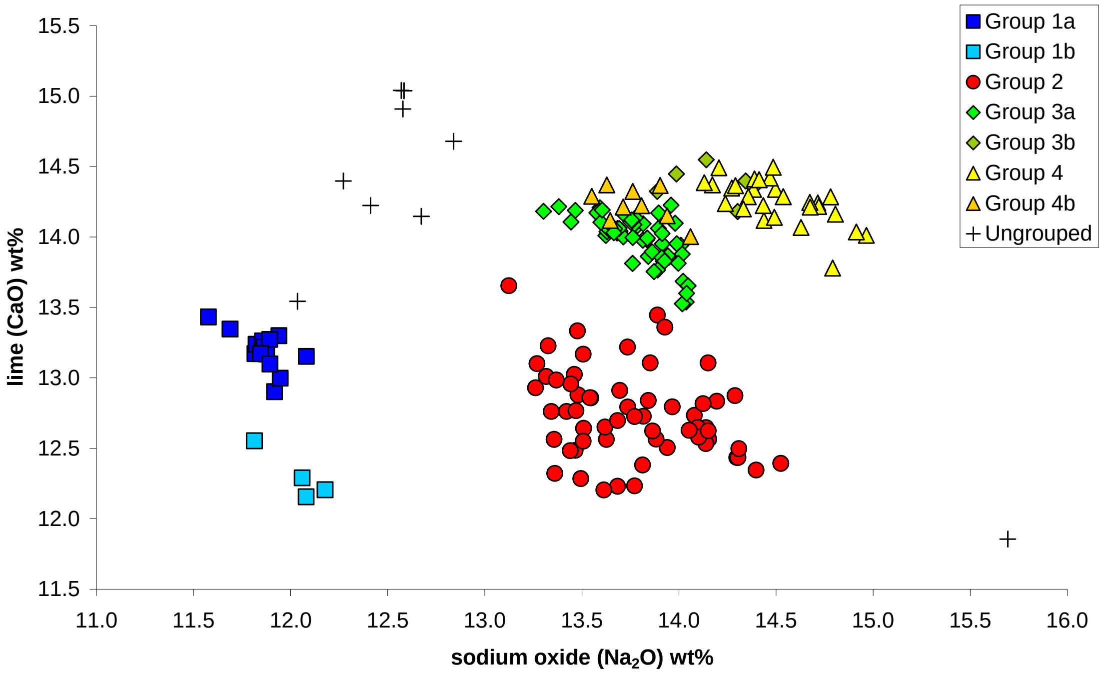

Figure 3. Sodium oxide and lime content of the Chatsworth Conservatory glass

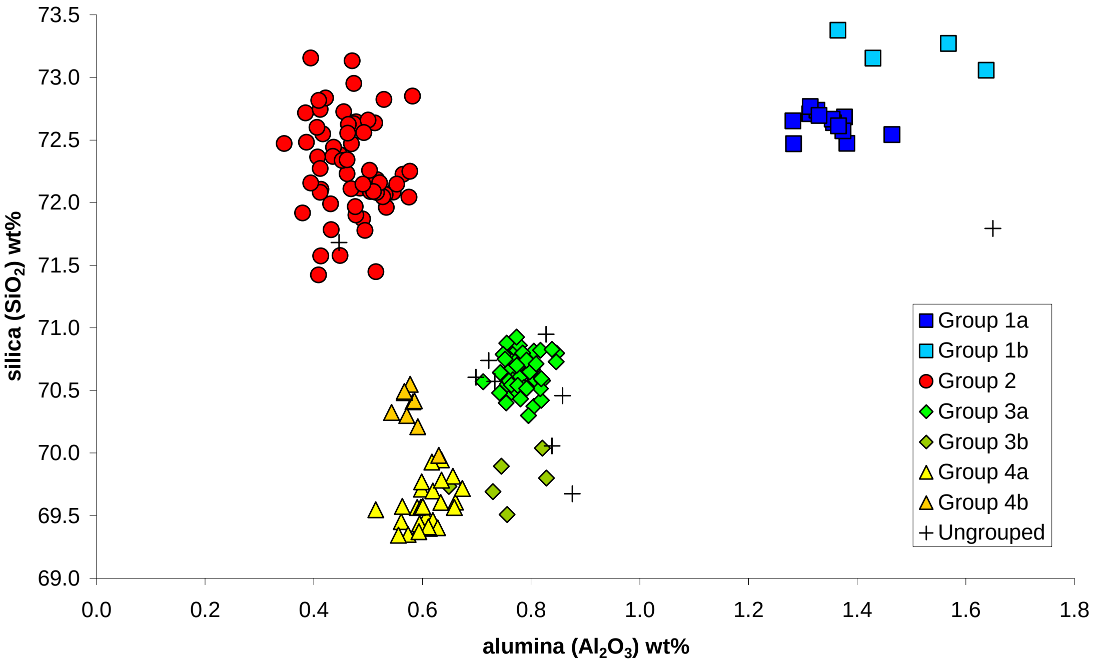

Figure 4. Alumina and silica content of the Chatsworth Conservatory glass

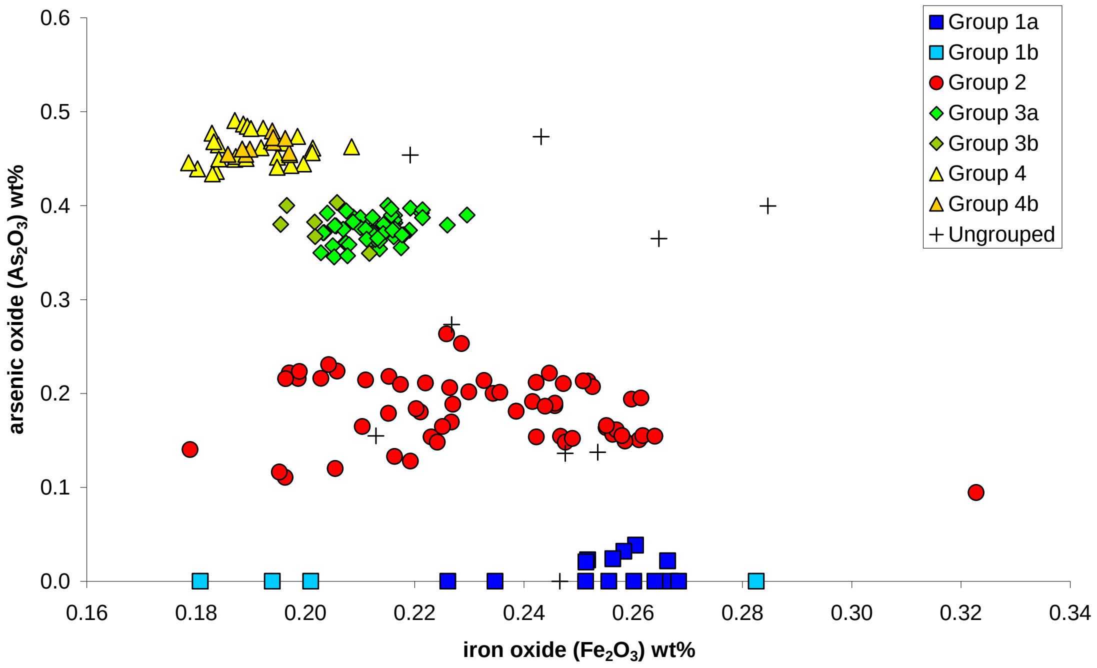

Figure 5. Iron oxide and arsenic oxide content of the Chatsworth Conservatory glass

Group 1

Group 1 is the smallest group and includes only 18 samples but is the most chemically distinct: it has a higher potassium oxide and alumina content and is easily distinguishable from all the other groups by the very low concentrations of arsenic. Group 1 can be divided into Sub-Group 1a and Sub-Group 1b based on differences silica and lime content. Group 1 samples are 2.46±0.30mm thick and mostly have a very pale blue-green colour.

Group 2

Group 2 comprises 61 samples and is distinguished from Groups 3 and 4 by its relatively low arsenic content and by the presence in this group of small proportions of manganese. Group 2 glasses also contain higher levels of strontium oxide than the other glass groups, although none contain more than 0.035wt% SrO. A very small possible Sub-Group with slightly elevated levels of potassium may be identified. Group 2 samples are 2.54±0.33mm thick (excludes one fragment >3.2mm thick) and mostly have a very pale blue-green or very pale green colour.

Group 3

Group 3 comprises 62 samples that are distinguishable by the fact that they contain more arsenic that Group 2 and less than Group 4. These samples also tend to have less sodium oxide than Group 4 but more lime than Group 2. The alumina content of Group 3 glasses is less than Group 1 but greater than Groups 2 and 4. A small Sub-Group (3b) can be distinguished from the main group by its higher sodium oxide and lime content and lower silica content. Thus, in some respects the Sub-Group 3b glasses have a composition which resembles Group 4a. The Group 3 samples are 2.38±0.35mm thick (excludes two fragments >3.2mm thick) and, where any colour could be detected, are generally a very pale green colour.

Group 4

Group 4 comprises 37 samples that are distinguishable by the fact that they have the highest arsenic content of all the glass samples analysed. In addition, their silica content is lower than that of Groups 1 and 2 but the alumina content is lower that Group 3. A small Sub-Group (4b) can be distinguished from the main group by its lower sodium oxide and lime content and higher silica content. Thus, in some respects the Group 4b glasses have a average composition which resembles Group 3. The Group 4 samples are 2.35±0.29mm thick (excludes two fragments >3.2mm thick) and, where any colour could be detected, are generally a very pale green colour.

Ungrouped

Nine glass samples have compositions which do not match any of the four groups described above and which display a wide range of compositions and so do not form a compositional group of their own. Nevertheless, all of these samples are soda-lime-silica glasses. Sample 91 shares many of the chemical characteristics of the group 1 glasses, such as high potassium oxide and alumina content, but its silica content is lower than any of the group 1 glasses. Several samples show some similarities with group 2 glass, namely they contain detectable levels of manganese and slightly elevated levels of strontium oxide. However, these samples contain more manganese than the group 2 glasses and are usually a pale purple or a pale grey tint.

Glass defects

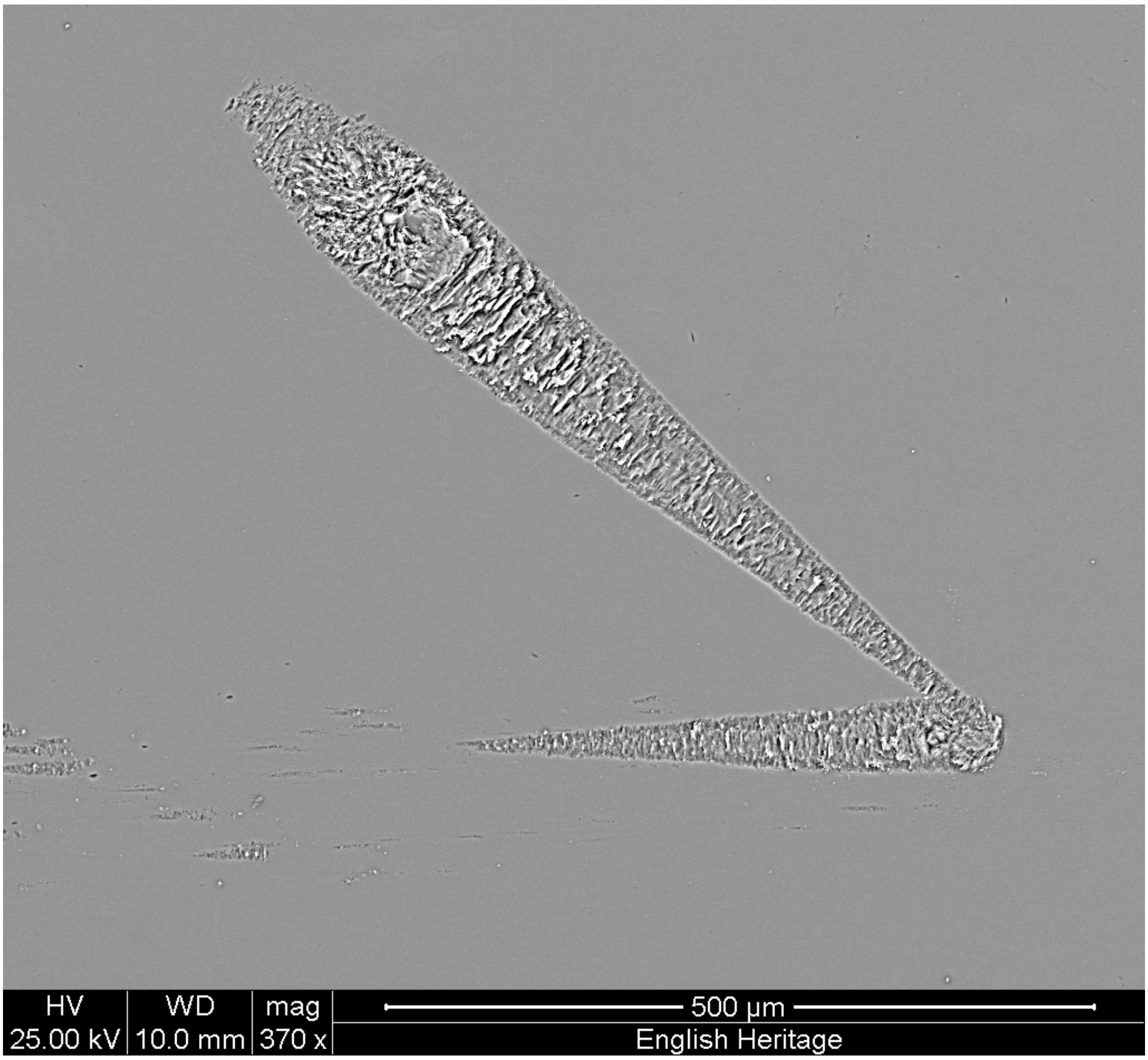

Figure 6. Scanning Electron Microscope image (back-scattered electron detector) of part of sample 102 showing glass defects

While the fragments of flat glass from Chatsworth were all chemically homogeneous and showed little or no surface corrosion at their surfaces, SEM examination showed that many had small features which are assumed to be glass defects of some sort (Figure 6). These defects were only visible in this way and were not visible when the glass was examined by eye. The defects were not restricted to just one of the compositional groups but were observed in examples of glass from each Group. The defects, which are tear-shaped, are usually less than 0.1mm across and up to 1mm in length. They appeared to show no particular orientation; they were not parallel to the length of glass or perpendicular to it, and in many cases several tear-shaped defects in the same sample had different orientations (Figure 6). The defects are distinguished from the surrounding glass by their 'flakey' texture (Figure 6). SEM-EDS analyses of the tear-shaped defects failed to reveal any chemical differences between them and the surrounding glass.

Contemporary sources mention many different types of defect in glass (Cable 2008, 141–148; Chance 1856, 226) These include bubbles, which are referred to as blister or seed depending on their size; tear drops and threads, which comprise vitrified droplets of the furnace roof that have fallen into the pot; knots and stones, which are fragments of unreacted batch or fragments; and ream and striae which are inhomogeneities in the glass caused by poor mixing of melted batch or dissolution of alumina from the pots. Bontemps' description of tears, as 'having behind them long tails' (Cable 2008, 144), echoes some of the features of the Chatsworth glass, however, he regards tears as deriving from the vitrification of the furnace roof so they should have a low lime content. In addition, Bontemps suggests that tears 'completely spoil the piece that is being made' (Cable 2008, 144) but in the Chatsworth glass they were only visible with a SEM. The true nature and cause of these tear-shaped, 'flakey' defects remain unclear for the moment.

DISCUSSION

One of the most significant changes in the manufacture of flat glass in the post-medieval period occurred around 1830. Traditionally most window glass had been manufactured using seaweed ash (kelp) and sand (Cooper 1835; Muspratt 1860; Ure 1844) but the introduction of the Leblanc process for the manufacture of sodium carbonate or sodium sulphate in the 1820s led to the abandonment of kelp in favour of synthetic soda (Muspratt 1860). Kelp had provided all of the alkali and all of the lime that was needed for the successful manufacture of a durable glass and the switch to synthetic soda was accompanied by the deliberate addition of limestone or chalk to the batch of raw materials. Chance Brothers made the switch to synthetic soda and limestone in 1832 — the identification of original Chatsworth Conservatory glass provides information on some of the earliest such glass produced in Britain.

Was any of the analysed glass original?

Similar projects have often shown that a majority of glass fragments from a single building often share a virtually identical composition and this is taken as representing the original glazing, while the remaining samples display a wide range of compositions and probably represent later repairs (eg Dungworth 2009). The Chatsworth Conservatory glass, however, shows the presence of four compositional groups (plus nine ungrouped samples), none of which form a clear majority on their own. Groups 2 and 3 each contain 33% of the samples, Group 4 20% and Group 1 10% (Figure 7).

The difficulty in identifying a single compositional group among the Chatsworth samples which constitutes a majority of the analysed glass samples may reflect the nature of the structure in which the glass was installed. The conservatory at Chatsworth was of such a size that the quantity of glass required would of necessity been produced over at least six months. Raw materials and batch mixing practices are likely to have varied slightly over such a long period of time and it is unlikely that all of the glass supplied by Chances would have had an identical composition. Indeed Henry Chance himself suggested that 'to lay down any standard proportions is almost impossible, as no two manufacturers use the same, and even in the same works the melting powers of the furnaces may so far differ as to render necessary . . . variations in the proportions of its elements.' (Chance 1856). Indeed Chance Brothers operated two furnaces for the production of sheet glass in the 1830s (Chance 1919, 14).

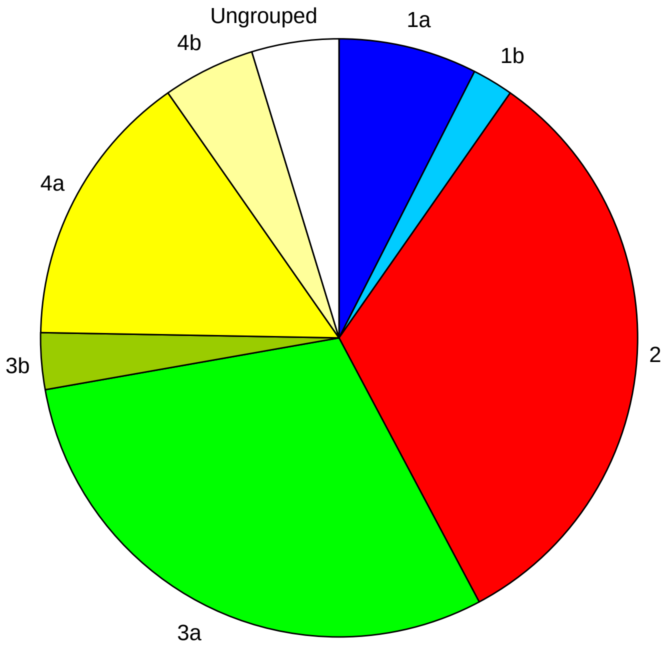

Figure 7. Proportions of the compositional groups

Few of the analysed samples have a sufficiently distinctive composition that would rule out manufacture in the late 1830s; for example, none have a high magnesia content that would indicate that they were produced after the introduction of mechanical techniques for the forming of window glass *c*1929 (Smrcek 2005). Nevertheless, Group 1 glass contains more alumina and potassium oxide than any of the other groups and it contains very low concentrations of arsenic. The low levels of arsenic in Group 1 glass are similar to the window glass from Welch Road (1894–95, Dungworth in preparation a) and Fort Cumberland (1940, Dungworth in preparation b). Arsenic is mentioned by most 19th-century sources (eg Cable 2008; Powell *et al* 1883; Ure 1844) as well as some early 20th-century sources (Marson 1918; Rosenhain 1919), however, the proportion added to 19th-century glass appears to be much higher. Therefore, Group 1 was probably produced during the early 20th century. Group 2 glass is in one minor aspect qualitatively different from the other groups (the presence of manganese) and probably reflects manufacture at a different production site (and possibly at a different time), though its arsenic content suggests it was probably produced in the 19th century.

Groups 3 and 4 are chemically very similar and show a degree of compositional overlap. Therefore, it is proposed that they were produced at the same site. Groups 3 and 4 contain 53% of all of the analysed glass fragments. While at this stage there can be no certainty, it is tentatively suggested that Groups 3 and 4 represent the glass produced by Chance Brothers and used in the original construction of the conservatory at Chatsworth. The compositional variation in the glass may reflect the fact that it would have been produced over a period of at least six months. It is possible that glass was manufactured in several phases, perhaps with intervals between each phase.

The nature of the glass manufactured by Chance Brothers, 1837–1840

It has been argued above that compositional Groups 3 and 4 probably represent the glass manufactured by Chance Brothers for the construction of the Chatsworth Conservatory between 1837 and 1840. The Chatsworth Group 3 and 4 glasses have compositions which are broadly similar to contemporary analyses and batch recipes for window glass. Muspratt (1860) provides three analyses of window glass of English manufacture (Table 3), one of which (Muspratt no. 9) is reported as having been carried out by Mr Cowper on glass manufactured by Chance Brothers. Charles Cowper was employed by Chance Brothers as a chemist between 1848 and 1860 (the year of his death).

Table 3. 19th-century analyses of window glass from Muspratt (1860) compared with Chatsworth Groups 3 and 4. (nr = not reported)

Source	Ref No.	Na_2O	Al_2O_3	SiO_2	CaO	MnO	Fe_2O_3
Muspratt	7	11.1	7.4	69.0	12.5	nr	nr
Muspratt	8	14.23	8.16	66.37	11.86	nr	nr
Muspratt	9	15.0	0.6	71.4	12.4	0.3	0.3
Chatsworth 3/4		14.0	0.7	70.3	14.1	<0.02	0.2

The contemporary analyses display a measure of variation in chemical composition which may reflect inherent variations in the early 19th-century glass industry (in particular the variability of the raw materials used). It is possible, however, that this variation reflects the limitations of the techniques used for the chemical analysis of glass in the early 19th century. This is particularly striking for the alumina content. Cowper's analysis shows 0.6wt% which compares very well with the Chatsworth Group 3 and 4 glass. The other analyses, however, indicate very high levels of alumina that are not paralleled by any modern analyses of contemporary glass. The Cowper analysis indicates rather higher iron concentration compared to the Chatsworth samples. It also indicates that manganese was used as a decolouriser, while the Chatsworth samples indicate that arsenic rather than manganese was used. Chance (1856, 223) reports that both arsenic and manganese were used to help reduce the effects of iron oxide on the colour of the glass.

Documentary sources provide data on contemporary glassmaking (including raw materials and recipes as well as occasional analyses of finished glass) which can be compared with the analytical data obtained from the Chatsworth Conservatory. This data can be used to shed some light on the nature of the raw materials used by Chance Brothers: the sand, alkali and lime.

Alkali used to make the Chatsworth Conservatory Glass

The chemical composition of the Chatsworth Conservatory glass indicates that a synthetic alkali was used. While glass made with kelp contains elevated concentrations of potassium, magnesium, phosphorus and chlorine (Dungworth *et al* 2009), these elements are virtually absent from the Chatsworth glass. The high sodium concentrations leaves little doubt that this glass was made using a synthetic soda produced using the Leblanc process. It remains unclear, however, whether this synthetic soda was in the form of sodium carbonate or sodium sulphate.

The process invented by Nicholas Leblanc in the late 18th century for converting common salt (sodium chloride, NaCl) into sodium carbonate comprised two steps. In the first of these steps, salt was heated with sulphuric acid to yield saltcake (sodium sulphate, Na_2SO_4), however, this compound reacts with silica very slowly and was not initially used in the glass industry. Therefore, in a second stage, the saltcake was heated with lime and charcoal or coal to produce soda ash (sodium carbonate, Na_2CO_3), which would react readily with silica.

Various historical sources indicate that after some time glassmakers found they could substitute some or all of the soda ash with saltcake, so long as a proportion of coal was added to the batch (Chance 1856). In France, the change from soda ash to saltcake for the manufacture of window glass appears to have started by 1825 (Cable 2008, 47). Bontemps describes how 'for a long time a mixture of half carbonate and half sulphate was used for window glass' (Cable 2008, 184–5) but suggests that by the end of the 1830s the carbonate was no longer used in France.

From 1831 sodium carbonate began to be used in glassmaking in England (Muspratt 1860) and English glassmakers also gradually added more sulphate until eventually the carbonate was no longer used in the manufacture of ordinary window glass (Chance 1856). Ure (1844) suggests that while saltcake was used in the manufacture of window glass in France, only the carbonate was used in Britain at the end of the 1830s. Chance and Hartley appear to have experimented with the use of at least a proportion of sulphate as early as 1832 (Chance 1919, 9), although it is not clear how successful these experiments were. Pellatt (1849) provides a batch with equal proportion of carbonate and sulphate. Historical sources unfortunately do not indicate when the use of a proportion of carbonate for plain window glass ceased; it certainly remained popular with plate glass manufacturers long after it was phased out by plain glass manufacturers (Powell *et al* 1883).

The sulphur in the Chatsworth glass is likely to have derived from the use of at least a proportion of sodium sulphate as the alkali (a small proportion might also derive from the coal fuel used). The sulphur concentrations in the Chatsworth glass are, however, not remarkably high or low and show a range of values that are comparable with other 19th- and 20th-century glass (Dungworth in preparation a; in preparation b; Smrcek 2005). The sulphur in the Chatsworth glass could also derive from the use of Leblanc soda. The second stage of the Leblanc process was rarely 100% effective and much commercial Leblanc soda contained small proportions of sodium sulphate (Angus-Butterworth 1948, 34).

Lime used to make the Chatsworth Conservatory Glass

The adoption of synthetic soda necessitated the deliberate addition of sufficient calcium-bearing material to stabilise the glass. Contemporary sources (such as Pellatt 1849; Muspratt 1860) mention the use of a variety of such materials, including limestone, and chalk. For the manufacture of high-quality window glass, chalk was often preferred due to its low iron content (the traces of iron in the raw materials being responsible for the colour of the finished glass). For the best quality window glass, which needed to be completely free from colour, good quality chalk could be slaked to reduce its iron content. The virtual absence of magnesium from the Chatsworth glass suggests that chalk was probably used, and this may have been slaked to reduce the iron content.

Sand used to make the Chatsworth Conservatory Glass

Contemporary sources (such as Pellatt 1849; Muspratt 1860) suggest that the best glassmaking sands used in the manufacture of window glass were obtained from Alum Bay on the Isle of Wight, King's Lynn, Norfolk and Reigate, Surrey. Boswell (1918) provides analyses of these glassmaking sands which indicate that Alum Bay has 1.9wt% alumina and cannot have been used for any of the Chatsworth glass except possibly Group 1. The alumina content of the Chatsworth is comparable, however, with both Lynn (0.6wt% Al_2O_3) and Reigate (0.7wt% Al_2O_3) sands. Both the Lynn and Reigate sands have very low iron oxide contents (<0.05wt%) compared to the Chatsworth glass but sand is not the only source of iron oxide in a finished glass. Angus-Butterworth quotes iron concentrations of 0.08wt%, 0.5wt% and 0.09wt% Fe_2O_3 for Leblanc sodium sulphate, Leblanc sodium carbonate, and typical glassmaking calcium carbonate, respectively (Angus-Butterworth 1948, 34–35). Therefore, if the Chatsworth glass was made using equal parts of sodium carbonate and sodium sulphate the batch would contain approximately 0.12wt% Fe_2O_3 (0.03wt% from the sand, 0.01wt% from the sodium sulphate, 0.06wt% from the sodium carbonate, and 0.02wt% from the calcium carbonate). If just the sulphate was used than the batch would contain approximately 0.17wt% Fe_2O_3, however, this is still lower than the iron oxide concentration of the Chatsworth glass. An explanation for the relatively high iron oxide concentration of the Chatsworth glass is probably to be sought in the reactions between the batch and the crucibles in which it was melted. As a rough estimate, finished glass will derive 99% of its chemical composition from the batch ingredients and 1% from the corrosion of the crucible (Dungworth 2008, 166), which could easily contain 1–2wt% iron oxide.

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APPENDIX: Chemical composition of the glass

Key clls = colourless; vpgn = very pale green; vpbg = very pale blue-green;
vpgy = very pale grey; vpuc = very pale, uncertain colour; vpp = very pale purple

#	Gp	Colour	Th.	Na_2O	MgO	Al_2O_3	SiO_2	SO_3	Cl	K_2O	CaO	TiO_2	MnO	Fe_2O_3	As_2O_3	PbO	SrO	ZrO_2
1	ug	vpp	1.6	12.58	<0.1	0.88	69.68	0.59	<0.05	0.25	14.91	0.05	0.56	0.26	0.36	<0.05	0.034	0.008
2	ug	vpp	1.7	12.27	<0.1	0.83	70.95	0.50	<0.05	0.11	14.40	0.10	0.30	0.24	0.47	<0.05	0.033	0.010
3	ug	vpgy	1.9	12.67	0.12	0.86	70.46	0.57	<0.05	0.20	14.15	0.09	0.32	0.22	0.45	<0.05	0.031	0.008
4	ug	vpgy	1.6	12.58	<0.1	0.84	70.06	0.50	0.10	0.14	15.04	0.06	0.26	0.23	0.27	<0.05	0.034	0.010
5	4a	vpgn	2.0	14.44	<0.1	0.63	69.94	0.43	<0.05	<0.1	14.12	<0.05	<0.02	0.20	0.46	<0.05	0.018	0.003
6	3a	vpgn	2.7	13.69	<0.1	0.74	70.64	0.28	<0.05	<0.1	14.06	<0.05	<0.02	0.21	0.37	<0.05	0.016	0.004
7	ug	vpgn	3.3	12.57	0.48	0.73	70.57	0.25	<0.05	0.15	15.04	<0.05	<0.02	0.25	0.14	<0.05	0.027	0.004
8	4a	vpgn	3.4	14.29	<0.1	0.66	69.56	0.46	<0.05	<0.1	14.36	<0.05	<0.02	0.20	0.47	<0.05	0.016	0.004
9	4a	vpgn	2.2	14.81	<0.1	0.59	69.38	0.43	<0.05	<0.1	14.16	0.05	<0.02	0.19	0.47	<0.05	0.013	0.005
10	3a	vpgn	2.4	13.89	<0.1	0.71	70.57	0.29	<0.05	<0.1	14.06	0.08	<0.02	0.22	0.37	<0.05	0.015	0.003
11	2	vpgn	3.5	13.94	<0.1	0.48	72.11	0.42	<0.05	<0.1	12.51	<0.05	0.11	0.25	0.21	<0.05	0.030	0.004
12	4a	vpgn	2.5	14.49	<0.1	0.66	69.81	0.39	<0.05	<0.1	14.14	<0.05	<0.02	0.19	0.44	<0.05	0.017	0.004
13	3a	vpgn	3.6	14.04	0.15	0.75	70.75	0.28	<0.05	<0.1	13.60	0.05	<0.02	0.21	0.37	<0.05	0.012	0.003
14	4a	vpgn	2.9	14.27	0.11	0.51	69.55	0.58	<0.05	<0.1	14.35	0.06	<0.02	0.19	0.48	<0.05	0.024	0.004
15	3a	vpgn	3.0	13.93	0.12	0.79	70.52	0.31	<0.05	<0.1	13.83	0.07	<0.02	0.22	0.39	<0.05	0.013	0.004
16	3a	vpgn	3.3	13.76	<0.1	0.77	70.70	0.22	<0.05	<0.1	14.12	0.05	<0.02	0.21	0.38	<0.05	0.011	0.005
17	4b	vpgn	2.5	14.06	<0.1	0.58	70.41	0.44	<0.05	<0.1	14.00	<0.05	<0.02	0.19	0.45	<0.05	0.014	0.003
18	3a	vpgn	2.5	13.84	<0.1	0.76	70.76	0.27	<0.05	<0.1	13.86	0.05	<0.02	0.22	0.38	<0.05	0.016	0.003
19	4a	vpgn	2.4	14.41	0.11	0.56	69.57	0.42	<0.05	<0.1	14.41	<0.05	<0.02	0.19	0.48	<0.05	0.015	0.007
20	4a	vpgn	2.5	14.72	<0.1	0.63	69.40	0.43	<0.05	<0.1	14.22	0.07	<0.02	0.19	0.45	<0.05	0.016	0.006
21	4a	vpgn	3.4	14.21	0.12	0.56	69.34	0.58	<0.05	<0.1	14.49	0.05	<0.02	0.18	0.47	<0.05	0.023	0.003
22	3b	vpgn	2.8	14.38	<0.1	0.65	69.73	0.38	<0.05	<0.1	14.35	0.08	<0.02	0.20	0.40	<0.05	0.013	0.004
23	3a	vpgn	2.5	13.76	0.13	0.79	70.52	0.29	<0.05	<0.1	14.00	0.06	<0.02	0.21	0.37	<0.05	0.015	0.004
24	2	vpgn	3.0	14.15	<0.1	0.53	71.96	0.35	<0.05	<0.1	12.56	0.06	0.12	0.26	0.15	<0.05	0.031	0.005
25	3a	vpgn	3.1	13.75	0.15	0.74	70.48	0.28	<0.05	<0.1	14.11	<0.05	<0.02	0.20	0.39	<0.05	0.014	0.006
26	3a	vpgn	2.5	14.05	0.14	0.85	70.73	0.29	<0.05	<0.1	13.65	<0.05	<0.02	0.20	0.37	<0.05	0.016	0.004
27	3a	vpgn	2.2	13.47	0.11	0.76	70.68	0.28	<0.05	<0.1	14.19	0.07	<0.02	0.21	0.36	<0.05	0.014	0.004
28	2	vpgn	2.5	13.55	<0.1	0.42	72.55	0.35	<0.05	<0.1	12.86	<0.05	0.09	0.25	0.15	<0.05	0.027	0.006
29	4a	vpgn	3.0	14.68	<0.1	0.60	69.57	0.42	<0.05	<0.1	14.21	<0.05	<0.02	0.18	0.45	<0.05	0.016	0.008
30	3a	vpgn	2.5	14.04	0.12	0.82	70.82	0.27	<0.05	<0.1	13.54	0.06	<0.02	0.21	0.36	<0.05	0.013	0.004
31	3a	vpgn	2.6	13.91	0.12	0.76	70.54	0.30	<0.05	<0.1	13.85	0.09	<0.02	0.21	0.37	<0.05	0.017	0.005
32	3a	vpgn	2.3	13.87	0.14	0.77	70.82	0.28	<0.05	<0.1	13.75	0.06	<0.02	0.22	0.39	<0.05	0.017	0.005
33	3a	vpgn	2.5	13.63	<0.1	0.77	70.93	0.24	<0.05	<0.1	14.04	0.08	<0.02	0.21	0.35	<0.05	0.014	0.003
34	3a	vpgn	2.2	13.58	0.13	0.77	70.58	0.30	<0.05	<0.1	14.17	0.05	<0.02	0.22	0.37	<0.05	0.016	0.004
35	3a	vpgn	2.9	13.96	0.10	0.80	70.30	0.29	<0.05	<0.1	14.23	0.05	<0.02	0.21	0.35	<0.05	0.014	0.003
36	4b	vpgn	2.9	13.71	<0.1	0.59	70.42	0.46	<0.05	<0.1	14.21	<0.05	<0.02	0.19	0.48	<0.05	0.017	<0.002
37	3b	vpgn	2.7	13.89	<0.1	0.82	70.04	0.36	<0.05	<0.1	14.32	<0.05	<0.02	0.21	0.35	<0.05	0.015	0.006
38	3b	vpgn	2.4	13.99	<0.1	0.75	69.90	0.40	<0.05	<0.1	14.45	0.07	<0.02	0.20	0.38	<0.05	0.013	0.002
39	3a	vpgn	2.3	13.99	<0.1	0.82	70.42	0.32	<0.05	<0.1	13.95	0.06	<0.02	0.21	0.39	<0.05	0.017	0.004
40	3a	vpgn	2.6	13.60	<0.1	0.75	70.79	0.24	<0.05	<0.1	14.10	<0.05	<0.02	0.21	0.37	<0.05	0.015	0.005
41	2	vpgn	2.7	13.32	<0.1	0.56	72.23	0.34	0.06	0.17	13.01	0.05	0.07	0.22	0.13	0.2381	0.025	0.005
42	2	vpgn	2.6	13.46	<0.1	0.39	72.48	0.40	0.05	<0.1	13.02	<0.05	0.08	0.20	0.11	<0.05	0.019	0.003
43	3a	vpgn	2.5	13.86	0.11	0.77	70.73	0.24	<0.05	<0.1	13.89	0.05	<0.02	0.21	0.38	<0.05	0.017	0.004
44	3a	vpgn	2.0	13.70	<0.1	0.79	70.76	0.28	<0.05	<0.1	14.04	<0.05	<0.02	0.22	0.40	<0.05	0.020	0.006
45	4a	vpgn	2.5	14.67	0.10	0.57	69.35	0.44	<0.05	<0.1	14.24	<0.05	<0.02	0.18	0.44	<0.05	0.014	0.003
46	3a	vpgn	2.6	13.61	<0.1	0.82	70.51	0.25	<0.05	<0.1	14.19	0.08	<0.02	0.22	0.37	<0.05	0.013	0.005
47	3a	vpgn	1.8	13.68	0.18	0.79	70.72	0.26	<0.05	<0.1	14.03	<0.05	<0.02	0.21	0.38	<0.05	0.015	0.006
48	3a	vpgn	2.4	13.94	0.12	0.78	70.60	0.30	<0.05	<0.1	13.87	0.06	<0.02	0.22	0.40	<0.05	0.015	0.005

#	Group	Colour	Th.	Na_2O	MgO	Al_2O_3	SiO_2	SO_3	Cl	K_2O	CaO	TiO_2	MnO	Fe_2O_3	As_2O_3	PbO	SrO	ZrO_2
49	4a	vpgn	2.1	14.36	0.11	0.60	69.71	0.40	<0.05	<0.1	14.29	<0.05	<0.02	0.20	0.46	<0.05	0.013	0.004
50	3a	vpgn	2.8	13.67	<0.1	0.81	70.71	0.24	<0.05	<0.1	14.06	0.07	<0.02	0.23	0.39	<0.05	0.016	0.002
51	4b	vpgn	2.2	13.90	0.10	0.63	69.98	0.41	0.05	<0.1	14.37	<0.05	<0.02	0.19	0.46	<0.05	0.013	0.004
52	3a	vpgn	1.9	13.92	<0.1	0.77	70.79	0.28	<0.05	<0.1	13.83	<0.05	<0.02	0.22	0.37	<0.05	0.012	0.007
53	4a	vpgn	2.4	14.78	0.10	0.59	69.44	0.43	<0.05	<0.1	14.29	0.06	<0.02	0.18	0.44	<0.05	0.014	0.005
54	4a	vpgn	2.6	14.49	<0.1	0.59	69.37	0.45	<0.05	<0.1	14.50	0.06	<0.02	0.18	0.45	<0.05	0.012	0.007
55	3a	vpgn	2.9	14.00	0.12	0.78	70.54	0.29	<0.05	<0.1	13.81	0.05	<0.02	0.22	0.37	<0.05	0.016	0.003
56	4a	vpgn	2.1	14.47	<0.1	0.56	69.45	0.42	<0.05	<0.1	14.42	0.07	<0.02	0.18	0.48	<0.05	0.013	0.005
57	4a	vpgn	2.3	14.39	<0.1	0.60	69.57	0.44	<0.05	<0.1	14.41	0.06	<0.02	0.18	0.46	<0.05	0.018	0.004
58	ug	vpgn	1.9	15.69	<0.1	0.70	70.61	0.48	<0.05	<0.1	11.86	<0.05	0.03	0.28	0.40	<0.05	0.031	0.003
59	4a	vpgn	2.2	14.43	<0.1	0.66	69.61	0.42	0.05	<0.1	14.22	<0.05	<0.02	0.20	0.44	<0.05	0.012	0.006
60	3a	vpgn	2.4	13.76	0.12	0.77	70.79	0.26	<0.05	<0.1	13.81	0.06	<0.02	0.21	0.37	<0.05	0.016	0.008
61	3a	vpgn	2.7	14.02	0.14	0.84	70.83	0.20	<0.05	<0.1	13.53	<0.05	<0.02	0.21	0.36	<0.05	0.014	0.006
62	4a	vpgn	2.0	14.72	<0.1	0.61	69.40	0.39	<0.05	<0.1	14.24	<0.05	<0.02	0.19	0.49	<0.05	0.015	0.005
63	3a	vpgn	2.2	13.71	0.18	0.76	70.55	0.25	<0.05	<0.1	14.00	0.05	<0.02	0.21	0.38	<0.05	0.015	0.004
64	3a	vpgn	2.3	13.84	<0.1	0.76	70.58	0.36	<0.05	<0.1	13.99	0.07	<0.02	0.21	0.39	<0.05	0.015	0.004
65	3a	vpgn	2.4	13.44	<0.1	0.78	70.86	0.26	<0.05	<0.1	14.11	0.05	<0.02	0.21	0.36	<0.05	0.014	0.005
66	3a	vpgn	2.3	13.77	<0.1	0.79	70.50	0.31	<0.05	<0.1	14.09	0.06	<0.02	0.21	0.39	<0.05	0.014	0.004
67	3a	vpgn	2.5	13.91	<0.1	0.80	70.65	0.24	<0.05	<0.1	14.02	0.07	<0.02	0.21	0.36	<0.05	0.011	0.006
68	3a	vpgn	1.9	13.62	0.13	0.78	70.70	0.31	<0.05	<0.1	14.01	<0.05	<0.02	0.22	0.38	<0.05	0.016	0.003
69	2	vpgn	2.2	14.08	<0.1	0.49	71.87	0.34	<0.05	<0.1	12.73	<0.05	0.11	0.24	0.15	<0.05	0.024	0.008
70	3a	vpgn	2.3	13.30	<0.1	0.80	70.67	0.29	<0.05	<0.1	14.18	0.07	<0.02	0.21	0.35	<0.05	0.012	0.004
71	3a	vpgn	2.4	13.38	0.12	0.76	70.88	0.28	<0.05	<0.1	14.22	0.05	<0.02	0.21	0.38	<0.05	0.012	0.004
72	3a	vpgn	2.0	13.91	<0.1	0.76	70.49	0.30	<0.05	<0.1	13.95	0.09	<0.02	0.20	0.37	<0.05	0.019	0.004
73	3a	vpgn	2.6	13.64	<0.1	0.79	70.74	0.22	<0.05	<0.1	14.05	0.08	<0.02	0.21	0.36	<0.05	0.013	0.005
74	4a	clls	2.5	14.79	<0.1	0.63	69.78	0.43	<0.05	<0.1	13.78	0.07	<0.02	0.20	0.45	<0.05	0.016	0.003
75	2	clls	2.6	13.36	<0.1	0.39	73.16	0.36	<0.05	<0.1	12.32	<0.05	0.09	0.21	0.22	<0.05	0.029	0.005
76	2	clls	2.0	13.89	<0.1	0.41	71.57	0.36	0.05	<0.1	13.45	<0.05	0.10	0.20	0.23	<0.05	0.029	0.004
77	2	clls	1.9	13.33	<0.1	0.46	72.23	0.39	<0.05	<0.1	13.23	<0.05	0.07	0.22	0.18	<0.05	0.026	0.006
78	2	clls	2.6	13.68	<0.1	0.46	72.73	0.41	<0.05	<0.1	12.23	<0.05	0.10	0.21	0.21	<0.05	0.026	0.007
79	2	clls	2.1	13.48	<0.1	0.35	72.47	0.35	0.05	<0.1	12.88	<0.05	0.11	0.20	0.22	<0.05	0.031	0.005
80	ug	clls	1.6	12.41	<0.1	0.45	71.68	0.40	0.22	<0.1	14.22	<0.05	0.39	0.21	0.15	<0.05	0.031	0.008
81	2	clls	2.5	13.34	<0.1	0.38	72.72	0.37	<0.05	<0.1	12.76	<0.05	0.09	0.22	0.22	<0.05	0.030	0.006
82	2	clls	2.7	14.20	<0.1	0.43	71.99	0.38	<0.05	<0.1	12.83	0.06	0.09	0.20	0.22	<0.05	0.031	0.004
83	2	clls	2.4	13.63	<0.1	0.41	72.75	0.33	<0.05	<0.1	12.56	<0.05	0.10	0.23	0.21	<0.05	0.031	0.004
84	2	vpbg	2.4	14.29	<0.1	0.45	71.58	0.48	<0.05	<0.1	12.87	<0.05	0.11	0.22	0.15	<0.05	0.032	0.006
85	1b	vpbg	3.1	12.08	<0.1	1.36	73.38	0.28	<0.05	0.57	12.16	0.07	<0.02	0.18	<0.02	<0.05	0.026	0.003
86	2	vpbg	2.5	14.12	<0.1	0.55	72.08	0.34	<0.05	<0.1	12.64	<0.05	0.12	0.26	0.16	<0.05	0.026	0.006
87	1a	vpbg	2.1	11.82	<0.1	1.46	72.54	0.29	<0.05	0.57	13.17	<0.05	<0.02	0.23	<0.02	<0.05	0.019	0.007
88	2	vpbg	3.0	14.30	<0.1	0.53	72.06	0.37	<0.05	<0.1	12.43	0.06	0.11	0.26	0.16	<0.05	0.029	0.008
89	2	vpbg	1.9	13.61	<0.1	0.58	72.85	0.29	0.07	<0.1	12.20	0.08	0.14	0.32	0.09	<0.05	0.027	0.008
90	1b	vpbg	1.8	12.18	<0.1	1.57	73.27	0.19	<0.05	0.54	12.21	0.07	<0.02	0.20	<0.02	<0.05	0.021	0.009
91	ug	vpbg	2.5	12.04	<0.1	1.65	71.79	0.28	<0.05	0.59	13.54	0.06	<0.02	0.25	<0.02	<0.05	0.012	0.006
92	1b	vpbg	2.2	12.06	<0.1	1.43	73.15	0.34	<0.05	0.55	12.29	0.06	<0.02	0.19	<0.02	<0.05	0.024	0.008
93	2	vpbg	2.8	14.14	<0.1	0.53	72.05	0.34	<0.05	<0.1	12.53	<0.05	0.11	0.25	0.15	<0.05	0.029	0.005
94	2	vpbg	2.2	14.14	<0.1	0.52	72.18	0.27	<0.05	<0.1	12.65	<0.05	0.12	0.26	0.16	<0.05	0.029	0.005
95	2	vpbg	3.0	14.40	<0.1	0.50	72.09	0.32	<0.05	<0.1	12.34	<0.05	0.12	0.26	0.16	<0.05	0.030	0.006
96	1a	vpbg	2.5	11.94	<0.1	1.38	72.47	0.25	<0.05	0.51	13.30	0.08	<0.02	0.25	<0.02	<0.05	0.020	0.007
97	2	vpbg	2.0	14.30	<0.1	0.47	72.11	0.33	<0.05	<0.1	12.43	<0.05	0.12	0.26	0.15	<0.05	0.024	0.007
98	2	vpbg	3.2	14.31	<0.1	0.52	72.08	0.36	<0.05	<0.1	12.50	<0.05	0.12	0.26	0.16	<0.05	0.029	0.002
99	1a	vpbg	2.4	11.92	0.12	1.37	72.62	0.31	<0.05	0.55	12.90	0.05	<0.02	0.26	<0.02	<0.05	0.019	0.006
100	1a	vpbg	2.5	11.82	<0.1	1.38	72.68	0.24	<0.05	0.50	13.24	0.05	<0.02	0.23	<0.02	<0.05	0.017	0.010
101	1a	vpbg	2.2	11.69	<0.1	1.31	72.71	0.28	<0.05	0.52	13.35	0.06	<0.02	0.26	0.04	<0.05	0.018	0.006
102	1a	vpbg	2.6	11.86	<0.1	1.36	72.64	0.26	<0.05	0.50	13.26	0.05	<0.02	0.27	<0.02	<0.05	0.018	0.008

#	Group	Colour	Th.	Na_2O	MgO	Al_2O_3	SiO_2	SO_3	Cl	K_2O	CaO	TiO_2	MnO	Fe_2O_3	As_2O_3	PbO	SrO	ZrO_2
103	2	vpbg	2.7	14.53	<0.1	0.48	71.90	0.37	<0.05	<0.1	12.39	<0.05	0.13	0.25	0.15	<0.05	0.030	0.006
104	2	vpbg	2.7	14.10	<0.1	0.52	72.16	0.35	<0.05	<0.1	12.65	<0.05	0.12	0.26	0.17	<0.05	0.030	0.004
105	2	vpbg	2.7	14.10	<0.1	0.51	72.09	0.34	<0.05	<0.1	12.58	<0.05	0.12	0.26	0.15	<0.05	0.027	0.007
106	1a	vpbg	2.8	11.86	<0.1	1.35	72.67	0.25	<0.05	0.50	13.22	0.07	<0.02	0.25	0.02	<0.05	0.018	0.007
107	1a	vpbg	2.4	12.08	<0.1	1.28	72.47	0.28	<0.05	0.49	13.15	0.06	<0.02	0.26	0.03	<0.05	0.020	0.007
108	1a	vpbg	2.8	11.88	<0.1	1.33	72.74	0.25	<0.05	0.51	13.17	0.06	<0.02	0.25	0.02	<0.05	0.022	0.004
109	1a	vpbg	2.3	11.89	<0.1	1.28	72.65	0.24	<0.05	0.49	13.27	0.07	<0.02	0.27	<0.02	<0.05	0.020	0.009
110	1a	vpbg	2.5	11.84	<0.1	1.31	72.77	0.23	<0.05	0.50	13.17	0.08	<0.02	0.27	0.02	<0.05	0.018	0.004
111	1a	vpbg	2.8	11.58	0.11	1.37	72.57	0.30	<0.05	0.52	13.43	<0.05	<0.02	0.26	<0.02	<0.05	0.018	0.007
112	1b	vpbg	2.5	11.81	<0.1	1.64	73.06	0.15	<0.05	0.61	12.55	0.06	<0.02	0.28	<0.02	<0.05	0.016	0.008
113	1a	vpbg	2.3	11.95	<0.1	1.33	72.70	0.29	<0.05	0.51	13.00	0.06	<0.02	0.26	0.02	<0.05	0.019	0.006
114	1a	vpbg	2.5	11.89	0.10	1.37	72.61	0.27	<0.05	0.52	13.10	0.07	<0.02	0.26	<0.02	<0.05	0.017	0.009
115	2	vpuc	2.7	13.85	<0.1	0.49	71.78	0.43	<0.05	<0.1	13.11	<0.05	0.11	0.22	0.18	<0.05	0.030	<0.002
116	2	vpuc	2.0	13.88	<0.1	0.50	72.26	0.37	<0.05	<0.1	12.56	<0.05	0.11	0.25	0.21	<0.05	0.030	0.007
117	3a	vpuc	2.5	14.02	0.13	0.76	70.58	0.26	<0.05	<0.1	13.88	0.06	<0.02	0.21	0.37	<0.05	0.014	0.005
118	2	vpuc	2.8	13.27	<0.1	0.58	72.25	0.34	0.05	0.16	13.10	<0.05	0.07	0.22	0.15	0.2409	0.029	0.002
119	2	vpuc	2.3	13.36	<0.1	0.53	72.82	0.32	<0.05	<0.1	12.56	<0.05	0.08	0.23	0.17	<0.05	0.026	0.006
120	2	vpuc	2.5	13.51	<0.1	0.48	72.65	0.33	<0.05	<0.1	12.64	<0.05	0.10	0.23	0.21	<0.05	0.030	0.005
121	2	vpuc	2.5	13.44	<0.1	0.47	72.47	0.36	<0.05	<0.1	12.96	<0.05	0.10	0.24	0.19	<0.05	0.033	0.002
122	2	vpuc	2.5	14.05	<0.1	0.49	72.15	0.32	<0.05	<0.1	12.63	0.06	0.12	0.26	0.16	<0.05	0.028	0.010
123	3b	vpuc	2.1	14.30	<0.1	0.83	69.80	0.33	<0.05	<0.1	14.18	0.07	<0.02	0.20	0.37	<0.05	0.015	0.004
124	2	vpuc	2.9	13.84	<0.1	0.41	72.11	0.40	0.08	<0.1	12.84	<0.05	0.10	0.21	0.12	<0.05	0.021	0.005
125	2	vpuc	3.0	13.54	<0.1	0.45	72.38	0.31	<0.05	<0.1	12.86	<0.05	0.10	0.26	0.19	<0.05	0.034	0.005
126	2	vpuc	2.4	14.15	<0.1	0.41	71.42	0.42	<0.05	<0.1	13.11	0.07	0.09	0.20	0.22	<0.05	0.033	0.006
127	3a	vpuc	2.2	13.78	0.11	0.77	70.50	0.24	<0.05	<0.1	14.14	0.08	<0.02	0.22	0.38	<0.05	0.015	0.004
128	2	vpuc	3.1	13.47	<0.1	0.42	72.83	0.33	<0.05	<0.1	12.49	<0.05	0.11	0.23	0.25	<0.05	0.030	<0.002
129	4b	vpuc	2.9	13.81	<0.1	0.57	70.48	0.38	<0.05	<0.1	14.22	<0.05	<0.02	0.19	0.46	<0.05	0.014	0.006
130	3a	vpuc	2.0	13.83	0.14	0.77	70.57	0.29	<0.05	<0.1	13.98	<0.05	<0.02	0.22	0.39	<0.05	0.016	0.006
131	3a	vpuc	2.0	13.81	0.12	0.80	70.37	0.33	<0.05	<0.1	13.98	0.07	<0.02	0.21	0.36	<0.05	0.014	0.004
132	2	vpuc	2.7	13.42	<0.1	0.41	72.60	0.35	<0.05	<0.1	12.76	<0.05	0.10	0.23	0.26	<0.05	0.031	0.005
133	3a	vpuc	2.4	13.68	0.13	0.82	70.58	0.27	<0.05	<0.1	14.05	0.05	<0.02	0.22	0.36	<0.05	0.015	0.003
134	3a	vpuc	2.6	13.72	0.10	0.78	70.43	0.31	<0.05	<0.1	14.16	<0.05	<0.02	0.21	0.39	<0.05	0.013	0.008
135	2	vpuc	2.4	13.12	<0.1	0.48	71.97	0.37	<0.05	<0.1	13.65	<0.05	0.07	0.21	0.16	<0.05	0.027	0.006
136	3a	vpuc	2.4	13.98	<0.1	0.75	70.40	0.28	0.06	<0.1	14.10	0.07	<0.02	0.21	0.38	<0.05	0.013	0.004
137	2	vpuc	2.5	13.62	<0.1	0.47	72.63	0.33	<0.05	<0.1	12.65	<0.05	0.11	0.26	0.20	<0.05	0.031	0.005
138	4a	vpuc	2.2	14.24	<0.1	0.67	69.72	0.40	<0.05	<0.1	14.24	<0.05	<0.02	0.19	0.45	<0.05	0.015	0.006
139	3a	vpuc	2.4	13.68	<0.1	0.78	70.80	0.21	<0.05	<0.1	14.06	<0.05	<0.02	0.20	0.35	<0.05	0.012	0.005
140	2	vpuc	3.1	13.74	<0.1	0.44	72.44	0.31	<0.05	<0.1	12.79	0.05	0.10	0.25	0.21	<0.05	0.033	0.005
141	3a	vpuc	2.1	13.89	0.12	0.78	70.50	0.28	<0.05	<0.1	14.17	<0.05	<0.02	0.21	0.36	<0.05	0.018	0.006
142	2	vpuc	2.7	13.48	<0.1	0.41	72.08	0.40	<0.05	<0.1	13.33	<0.05	0.09	0.22	0.21	<0.04	0.034	0.005
143	2	vpuc	2.3	13.86	<0.1	0.44	72.37	0.36	<0.05	<0.1	12.62	0.05	0.10	0.25	0.19	<0.04	0.033	0.003
144	3a	vpuc	1.9	13.82	<0.1	0.79	70.54	0.30	<0.05	<0.1	14.09	<0.05	<0.02	0.21	0.38	<0.05	0.016	0.004
145	2	vpuc	2.8	14.15	<0.1	0.39	72.16	0.34	<0.05	<0.1	12.62	0.05	0.09	0.20	0.22	<0.05	0.030	0.008
146	3a	vpuc	2.1	13.59	<0.1	0.82	70.56	0.28	<0.05	<0.1	14.21	0.08	<0.02	0.22	0.38	<0.05	0.016	0.003
147	2	vpuc	2.8	13.51	<0.1	0.51	72.64	0.37	<0.05	<0.1	12.55	<0.05	0.06	0.22	0.18	<0.05	0.026	0.007
148	4b	vpuc	2.6	13.94	0.10	0.59	70.21	0.43	<0.05	<0.1	14.15	0.05	<0.02	0.19	0.45	<0.05	0.015	0.004
149	2	vpuc	2.5	13.70	<0.1	0.41	72.36	0.35	0.05	<0.1	12.91	0.05	0.08	0.20	0.12	<0.05	0.021	0.006
150	3a	vpuc	2.1	13.95	0.14	0.79	70.65	0.21	<0.05	<0.1	13.85	<0.05	<0.02	0.22	0.40	<0.05	0.015	0.006
151	3a	vpuc	2.2	13.65	0.13	0.75	70.79	0.21	<0.05	<0.1	14.07	0.12	<0.02	0.23	0.38	<0.05	0.017	0.004
152	3b	vpuc	2.2	14.14	0.12	0.76	69.51	0.45	<0.05	<0.1	14.55	0.05	<0.02	0.21	0.40	<0.05	0.015	0.003
153	2	vpuc	2.2	13.77	<0.1	0.50	72.66	0.37	<0.05	<0.1	12.23	<0.05	0.10	0.25	0.19	<0.05	0.029	0.002
154	ug	vpuc	2.4	12.84	0.47	0.72	70.74	0.27	<0.05	0.16	14.68	<0.05	<0.02	0.25	0.14	<0.05	0.024	0.002
155	4b	vpuc	2.0	13.65	<0.1	0.58	70.55	0.44	<0.05	<0.1	14.12	<0.05	<0.02	0.19	0.47	<0.05	0.013	0.003
156	4a	vpuc	2.4	14.33	0.12	0.62	69.93	0.38	<0.05	<0.1	14.20	<0.05	<0.02	0.20	0.44	<0.05	0.016	0.005

#	Group	Colour	Th.	Na_2O	MgO	Al_2O_3	SiO_2	SO_3	Cl	K_2O	CaO	TiO_2	MnO	Fe_2O_3	As_2O_3	PbO	SrO	ZrO_2
157	4a	vpuc	2.0	14.38	<0.1	0.62	69.46	0.49	<0.05	<0.1	14.34	<0.05	<0.02	0.19	0.49	<0.05	0.014	0.004
158	3a	vpuc	2.2	14.01	0.10	0.81	70.58	0.25	<0.05	<0.1	13.94	<0.05	<0.02	0.22	0.39	<0.05	0.015	0.007
159	2	vpuc	2.5	13.47	<0.1	0.41	72.82	0.32	<0.05	<0.1	12.77	<0.05	0.10	0.23	0.20	<0.05	0.029	0.005
160	3b	vpuc	2.4	14.34	<0.1	0.73	69.69	0.40	<0.05	<0.1	14.40	<0.05	<0.02	0.20	0.38	<0.05	0.013	0.008
161	2	vpuc	2.6	13.51	<0.1	0.41	72.27	0.37	<0.05	<0.1	13.17	<0.05	0.09	0.18	0.14	<0.05	0.017	0.007
162	3a	vpuc	2.9	13.67	0.11	0.82	70.59	0.27	<0.05	<0.1	14.03	<0.05	<0.02	0.22	0.40	<0.05	0.015	0.004
163	4b	vpuc	2.1	13.55	<0.1	0.57	70.49	0.44	<0.05	<0.1	14.29	0.05	<0.02	0.19	0.47	<0.05	0.017	0.004
164	3a	vpuc	1.8	13.79	<0.1	0.76	70.46	0.32	<0.05	<0.1	14.08	0.05	<0.02	0.22	0.39	<0.05	0.016	0.003
165	3a	vpuc	2.4	14.02	<0.1	0.85	70.80	0.25	0.05	<0.1	13.69	<0.05	<0.02	0.21	0.38	<0.05	0.015	0.003
166	4a	vpuc	1.9	14.50	<0.1	0.61	69.49	0.43	<0.05	<0.1	14.34	<0.05	<0.02	0.19	0.48	<0.05	0.013	0.006
167	2	vpuc	1.9	13.97	<0.1	0.58	72.04	0.34	<0.05	<0.1	12.79	<0.05	0.08	0.23	0.19	<0.05	0.032	0.006
168	4a	vpuc	2.2	14.17	<0.1	0.62	69.70	0.40	<0.05	<0.1	14.37	0.06	<0.02	0.21	0.46	<0.05	0.016	0.005
169	4a	vpuc	2.1	14.54	0.13	0.59	69.56	0.44	<0.05	<0.1	14.29	<0.05	<0.02	0.19	0.46	<0.05	0.016	0.004
170	2	vpuc	2.6	13.81	<0.1	0.49	72.56	0.35	<0.05	<0.1	12.38	<0.05	0.10	0.24	0.22	<0.05	0.032	0.005
171	2	vpuc	2.5	13.82	<0.1	0.45	72.34	0.33	0.05	<0.1	12.73	<0.05	0.10	0.24	0.18	<0.05	0.029	0.006
172	4b	vpuc	2.1	13.63	0.13	0.54	70.32	0.42	<0.05	<0.1	14.37	<0.05	<0.02	0.20	0.46	<0.05	0.017	<0.002
173	2	vpuc	2.5	13.93	<0.1	0.51	71.45	0.36	0.08	<0.1	13.36	<0.05	0.09	0.22	0.21	<0.05	0.026	<0.002
174	2	vpuc	2.9	13.49	<0.1	0.47	73.13	0.35	<0.05	<0.1	12.28	<0.05	0.10	0.23	0.20	<0.05	0.029	0.006
175	4a	vpuc	2.4	14.13	<0.1	0.60	69.77	0.43	<0.05	<0.1	14.39	0.06	<0.02	0.20	0.47	<0.05	0.015	0.006
176	2	vpuc	2.1	13.44	<0.1	0.47	72.95	0.31	<0.05	<0.1	12.48	0.05	0.10	0.24	0.20	<0.05	0.030	0.004
177	4b	vpuc	2.2	13.76	<0.1	0.57	70.30	0.44	<0.05	<0.1	14.32	0.05	<0.02	0.20	0.47	<0.05	0.014	0.004
178	2	vpuc	2.7	13.74	<0.1	0.38	71.92	0.38	<0.05	<0.1	13.22	<0.05	0.09	0.20	0.22	<0.05	0.030	0.006
179	4a	vpuc	2.3	14.97	<0.1	0.60	69.40	0.44	<0.05	<0.1	14.01	0.05	<0.02	0.19	0.45	<0.05	0.015	0.004
180	4a	vpuc	2.5	14.91	<0.1	0.61	69.41	0.47	<0.05	<0.1	14.04	<0.05	<0.02	0.18	0.43	<0.05	0.014	0.005
181	4a	vpuc	2.6	14.63	<0.1	0.63	69.61	0.43	<0.05	<0.1	14.07	<0.05	<0.02	0.19	0.45	<0.05	0.015	0.003
182	2	vpuc	2.3	14.12	<0.1	0.43	71.78	0.40	0.07	<0.1	12.82	<0.05	0.10	0.23	0.16	0.0897	0.028	0.004
183	2	vpuc	2.8	13.26	<0.1	0.46	72.62	0.38	<0.05	<0.1	12.93	<0.05	0.10	0.24	0.21	<0.05	0.029	0.007
184	2	vpuc	2.3	13.37	<0.1	0.46	72.55	0.30	<0.05	<0.1	12.98	<0.05	0.10	0.24	0.19	<0.05	0.031	0.006
185	2	vpuc	2.0	13.68	<0.1	0.55	72.15	0.34	0.07	0.17	12.70	<0.05	0.07	0.22	0.13	0.245	0.025	0.003
186	2	vpuc	2.8	13.77	<0.1	0.46	72.34	0.36	<0.05	<0.1	12.73	<0.05	0.11	0.25	0.21	<0.05	0.030	0.006
187	3a	vpuc	2.2	13.89	<0.1	0.80	70.81	0.29	<0.05	<0.1	13.77	0.06	<0.02	0.22	0.38	<0.05	0.015	0.007

ENGLISH HERITAGE RESEARCH DEPARTMENT

English Heritage undertakes and commissions research into the historic environment, and the issues that affect its condition and survival, in order to provide the understanding necessary for informed policy and decision making, for sustainable management, and to promote the widest access, appreciation and enjoyment of our heritage.

The Research Department provides English Heritage with this capacity in the fields of buildings history, archaeology, and landscape history. It brings together seven teams with complementary investigative and analytical skills to provide integrated research expertise across the range of the historic environment. These are:

* *Aerial Survey and Investigation*
* *Archaeological Projects (excavation)*
* *Archaeological Science*
* *Archaeological Survey and Investigation (landscape analysis)*
* *Architectural Investigation*
* *Imaging, Graphics and Survey (including measured and metric survey, and photography)*
* *Survey of London*

The Research Department undertakes a wide range of investigative and analytical projects, and provides quality assurance and management support for externally-commissioned research. We aim for innovative work of the highest quality which will set agendas and standards for the historic environment sector. In support of this, and to build capacity and promote best practice in the sector, we also publish guidance and provide advice and training. We support outreach and education activities and build these in to our projects and programmes wherever possible.

We make the results of our work available through the Research Department Report Series, and through journal publications and monographs. Our publication Research News, which appears three times a year, aims to keep our partners within and outside English Heritage up-to-date with our projects and activities. A full list of Research Department Reports, with abstracts and information on how to obtain copies, may be found on www.english-heritage.org.uk/researchreports

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