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COMPOSITIONAL ANALYSIS BY P-XRF AND SEM-EDX OF MEDIEVAL WINDOW GLASS FROM  
ELGIN CATHEDRAL, NORTHERN SCOTLAND

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## ABSTRACT

Thirty shards of medieval window glass from Elgin Cathedral in North-East Scotland have been subjected to compositional analysis by portable-X-Ray Fluorescence and Scanning Electron Microscopy –Energy Dispersive X-ray Spectroscopy.

Comparison with previous analytical studies suggests the majority of the glass was probably produced in France, while a smaller group may have been made in Germany. Significant differences in base glass composition were observed between colours. Two distinct blue glasses compositions were identified.

The composition of the grisaille paint differs from paint on the continent providing the first evidence that it was made with local Scottish lead and iron pigments. This work represents the largest analytical study of Scottish medieval window glass yet undertaken and presents insights into the transfer of medieval materials, technologies and trade routes.

Keywords: Medieval, glass, SEM-EDX, p-XRF, Scotland, window, grisaille. Elgin

## RESEARCH AIM

The aim of this research was to examine the elemental characteristics of glass recovered from Elgin Cathedral, Scotland, in order to understand their chemical nature and determine similarities between the Elgin glass and samples recovered from other sites in Europe of a similar age.

## INTRODUCTION

### History of Elgin Cathedral

Elgin Cathedral is a historic ruin in Elgin, Moray in North-East Scotland (figure 1). A cathedral was first built on the present site in 1224 on land granted by King Alexander II on the outskirts of the historic burgh of Elgin, close to the River Lossie (Fawcett and Oram, 2014). The new cathedral was one of the earliest in Scotland to be built in a cruciform plan with a double-aisled nave and this new design is likely to have influenced the size and design of the window openings (Simpson, 1965). In 1270 there was an extensive rebuilding program after a fire and an octagonal chapter house, which is still mostly intact, dates from this major enlargement. Following an attack by King Robert III's brother the 'Wolf of Badenoch', further rebuilding took place in 1390 (Fawcett and Oram, 2014). The gable wall above the double-door entrance between the original west towers was rebuilt and within this wall still remains the outline and stone stub tracery work, of what was once a large rose window. The length of the choir was doubled and outer aisles added to the northern and southern walls of both the nave and choir.

A further attack in 1402 again resulted in partial destruction by fire. Following the Scottish Reformation in 1560, the cathedral was abandoned and there are records that the lead roof was removed in 1567, following which the cathedral fell into decay (Fawcett and Oram, 2014). Efforts were only made to halt the degradation of the building in the 19th century but by then the building was in a ruinous condition (Hall et al., 1998).

### Windows and Glass at Elgin Cathedral

At Elgin, as elsewhere in Scotland, window glass from this period only survives in the archaeological record (Spencer and Kennedy, 2015). The only historical information about the window glass at Elgin is that the See of Moray records that the glazier employed at the original building of the cathedral in the early 13th century was called 'Richard the Glazier' (MacGibbon and Ross, 1896) and the same Richard the Glazier is thought to appear as a witnesses in a charter of Bishop Andrew of Moray in 1237.

After each of the rebuilds it is likely that the glazing design will have changed to reflect the preferred designs of the day. For example, following the 1390 attack on the cathedral a great window was installed in the main west portal and the chapter house received narrow lancet windows (Simpson, 1965). New building techniques would also have allowed the enlargement of the windows, increasing the amount of glazing at each point the building was refurbished. MacGibbon and Ross (1896) and Simpson (1965) commented that the original cruciform design was predominantly influenced by a

French character, however the rebuilding after 1270, particularly of the chapterhouse, was clearly also influenced by English architecture (Fawcett and Oram, 2014).

The Cathedral site at Elgin has been excavated a number of times, but not all records survive. An assemblage of 1295 shards of glass is held in the collections of Elgin Museum and most of these were excavated in the mid to later 1970's from excavations close to the Cathedral, although some may have come from 19th century clearing of the cathedral itself (Murdoch, 2013). Further watching briefs and small trench excavation took place in 1989, 1996 and 2012 but no glass was recorded as being found (RCAHMS, 2015).

#### Appearance of glass recovered from Elgin Cathedral

Several investigators have studied the glass assemblage from Elgin Cathedral. Graves (1985) studied the typology and stylistic attributes of 241 shards of glass as part of a larger survey of Scottish medieval glass. Murdoch (2013) was commissioned by Historic Scotland (now Historic Environment Scotland) to undertake a visual examination of the collection of glass shards held in the care of the agency. The majority of the assemblage studied was of plain 'white' glass. This is glass where, although ranging in shade from pale blue to pale green, any colouring of the glass is not likely to have been intentional. 14.3% of the samples were painted (grisaille) and only 6% of the group was deliberately coloured 'pot-metal' glass. Figure 2 shows a selection of the grisaille fragments.

The presence of a significant number of plain rectangular, parallel sided fragments may suggest an arcade or framed window where the main panel is enclosed in a frame of glass or border.

The designs painted on the grisaille were generally foliate and can be compared with similar styles in England and France. Graves (1985) and Murdoch (2013) both stylistically attribute the majority of the grisaille glass recovered from Elgin to the 13th century. Graves (1985) comments that 'if the fashion in Scottish glass was similar to that in England, the Elgin glass would date from the period c 1224-1270'. Many of the pieces have cross hatched decoration which generally went out of fashion in English and French window glass in the second half of the 13th century with clear grounds being preferred (Marks, 1993). Graves (1985) considered the Elgin grisaille work to be even more detailed than similar cross-hatched grisaille work at Chartres and Troyes. An unusual pattern found, almost exclusively in Scotland, at Elgin is that of the double trefoil, with a smaller trefoil being painted inside a larger one on cross-hatched grounds (Murdoch, 2013). There are stylistic parallels with glass from nearby Spynie Palace of a similar date (Graves, 2002) and similar, but single, trefoils are found at both Lincoln Cathedral and York Minster dated to the first half of the 13th century (O'Connor and Haselock, 1977) and more recently noted at St Andrew's Cathedral. There is also the inclusion of berries, similar to a style found at Beverley Minster (Graves, 1996). A smaller number of shards lack the cross-hatched decoration, and may possibly be from the early 14th century. Murdoch (2013) who studied a greater number of samples from Elgin, considers some of the grisaille to be more naturalistic in form and therefore possibly from the early 14th century. Only 6% of the assemblage is of coloured glass, also pointing to an earlier date as during later periods there would likely have been more extensive use of colour (Brown and O'Connor, 1991). The lack of a published full excavation report and therefore details of the contexts and further dating evidence means this cannot be corroborated by the archaeological record at present.

There are many unanswered questions as to where the glass at Elgin originated and the forms in which it arrived on site. Here, a scientific investigation is undertaken in order to better understand the composition, technology of manufacture and the provenance of the Elgin glass.

## MATERIALS AND METHODS

### Samples

Although a large number of fragments were studied by Murdoch (2013) relatively few were deemed suitable for scientific analysis. The majority of the glass fragments had corroded in the ground, and although the shape and form of the shards was still intact, the original glass had been substituted by thick, opaque black and brown corrosion crusts. Some of the shards appeared to have been heat damaged as they are significantly distorted. This is unlikely to have occurred post deposition, suggesting that these fragments fell into the archaeological record following major fire damage.

Most were black and opaque and when sampled little 'heart glass' – intact glass in the centre of the sample - remained. The elemental composition of the heavily corroded glass would not have been consistent with the original compositions. Therefore 31 fragments of glass were selected, based primarily on their heavier weight which suggested that sufficient heart glass remained for examination. From the samples selected for analysis; 8 were coloured 'pot-metal', 5 were painted grisaille and the remainder was plain 'white' glass which ranged in hue from pale green to pale blue.

### Portable X-ray fluorescence (p-XRF)

Portable X-ray fluorescence is by its nature a surface technique. In order to analyse the 'heart glass' the heavily corroded surfaces were manually abraded. It was not possible to polish the surfaces prior to analysis and this will possibly lead to some discrepancy and errors in the analysis.

Portable X-ray fluorescence (p-XRF) analysis of the samples was undertaken using a Niton XL3t portable XRF system with a 'GOLDD' detector. The XL3t was placed against the glass and X-rays generated when the nosecone was in direct contact with the surface. The X-ray spot-size was 8 mm in diameter. The nosecone of the XL3t was flushed with helium to improve light element detection. The lightest detectable element for the XL3t, even under a helium flush, is Mg. The XL3t was controlled by hand. The Cu/Zn Mining mode was selected for use, which allowed the simultaneous detection of over 20 elements, including those of interest in the analysis of historical glass (P, S, K, Mg, Sr, Ca, As and Mn). The Cu/Zn Mining mode utilizes four separate conditions to determine the concentrations in parts per million of selected elements. The onboard software for the XL3t uses a Fundamental Parameters algorithm to determine concentrations of each element within the range of those analyzed. Of the four conditions, only three were needed to gain readings of the elements needed for windows analysis: main (15 s), low (15 s) and light (20 s), making a total sample time of 50 s for an elemental analysis. The spectra and values obtained from the XL3t (in parts per million) were downloaded to a computer for analysis. The values were divided by 10 000, and then multiplied according to a standard element oxide conversion table to produce a percentage by weight of each oxide and the values normalized to 100%. Only one analysis was taken for each sample due to the small area of glass exposed and the large spot size.

### Scanning Electron Microscopy and Energy Dispersive X-ray analysis (SEM-EDX)

Small samples of approximately 1-3 mm<sup>2</sup> were taken from each of the 31 samples to enable cross sections to be mounted for analysis. Samples were scribed with a diamond cutter and snipped with glass cutters. Each cross section was mounted in silicon moulds, using two-part Tiranti™ clear casting resin. The mounted samples were then ground and polished using a series of silicon-carbide papers and diamond polish to 3µm.

The samples were then analyzed using an XL30 LaB6/W ESEM equipped with Oxford Instruments X-max 80 EDX detector. The ESEM was operated in low vacuum, with water vapour utilized as the imaging gas. The samples were placed on a stage inside the chamber with the pressure set to 0.8 Torr. Samples were viewed using the Back-Scattered detector (BSE) to determine the most appropriate areas to analyse. Areas were selected to be analyzed that were in the centre of the samples and away from the visible corroded surfaces. The EDX was set at an operating voltage of 20 kV. The working distance was set to 10 mm and the spot size set to 4.2. The area was analyzed for 20 seconds. The area analyzed each time was approximately 100 µm<sup>2</sup>. Each sample was analyzed three times, choosing a different area for each analysis. Virtual standards were pure oxides and minerals and quantification was carried out using the ZAF correction software. Oxide weight percentages were calculated stoichiometrically. The average and standard deviations for the three measurements calculated.

The accuracy of the measurements by both methods was assessed by comparison with the measurement of glass standards of known elemental composition (Pilkington Glass Standards, and DDG). Table 1 shows the measurements recorded by p-XRF and SEM-EDX alongside the reported compositions of the standards.

## RESULTS AND DISCUSSION

The analyses made by P-XRF and by SEM-EDX are shown in table 2. SEM-EDX results are reported for all elements up to iron while the p-XRF results are reported for all elements identified heavier than potassium (percentages for calcium, manganese and iron oxides are reported for both methods, but the SEM-EDX results only considered in the discussion). The colours of the shards were determined according to Cramp (2005). The results of the analyses have been normalized for comparative purposes. They can only be classed as semi-quantitative due to the detection limits and the precision of the instruments.

As expected the EDX had better detection limits for the lighter atomic elements than the p-XRF, whereas the p-XRF demonstrated better detection limits of heavier atomic elements (Kennedy et al., 2013). EDX produced values for elements such as sodium, magnesium, phosphorous and silicon that can be treated with a level of confidence that the p-XRF could not. The p-XRF, in contrast, produced values for elements such as cobalt, copper, zinc, zirconium and titanium at a higher resolution than the EDX results. By undertaking both forms of analysis on the same samples, a fuller chemical profile can be gathered spanning a broad elemental range.

There was a degree of variation in the percentage of potassium and calcium detected by both methods. In some samples, the EDX detected a greater amount and in other samples the p-XRF produced the higher concentration. For example, sample B-O had a potassium composition of 18.09% using EDX and 15.56% when analyzed by p-XRF; while sample K-Z had a potassium composition of 18.77% when analyzed by EDX and 20.45% when analyzed by p-XRF. After consideration and comparison to the calibration standard data it was decided to use the SEM-EDX data for all elements to calcium and the p-XRF data for all heavier elements, starting with titanium.

The results of the analysis of Sample A-N by p-XRF were discounted from further study as it appeared that the corrosion products of the glass were analyzed rather than the heart glass as there

was a very low overall total, only 1.38% K<sub>2</sub>O (when the content with EDX was over 18%) and a high manganese concentration of 8.95%. Manganese has been shown to be enriched in corrosion crusts (Perez y Jorba and Bettembourg, 1991)

### Plain 'white' Glass

The 'white' glass fragments range from pale green to a pale aqua blue in colour. All are potash-lime-silica 'forest glass' composition. Potassium levels range from 11-20%, while calcium ranges from 12-28%. Most samples show between 1-3% of sodium present, 5-8% of magnesium and 1-3% of aluminium. This is broadly consistent with work by others analyzing European Medieval glass (Brill, 1992; Brill and Pongracz, 2004).

Figures 3 and 4 show that the white glasses appear to have been made using a wide range of recipes, many similar to the base glass recipes used for the coloured glass. This is unlike work on the John Thornton window at York Minster (dated to 1405-08) where the white glass is easily distinguished from coloured glass on similar plots (Freestone et al., 2014). At York it is therefore suggested that the white glass was made in England and the coloured glass on the continent. Although white glass was known to have been made in the Weald of England as early as the 13<sup>th</sup> century (Crossley, 1994) and in Staffordshire from the 14<sup>th</sup> century (Meek et al., 2012) the analysis suggests that the continent is a more likely origin of the Elgin glass.

A method of dating forest glass from Central Europe has been proposed by Wedepohl and Simon (2010). They studied the ratio of potassium and calcium in medieval and post-medieval German glass. They found that early Medieval (1000-1400) forest glass had a typical CaO:K<sub>2</sub>O ratio of 1, early wood-lime glass had a ratio of 1.9 and developed wood-lime glass from 1400-1600 A.D. had a ratio of 3.4. The lower ratio of the earlier glass suggests a higher quality of wood was used, but as the Medieval period progressed there was an increase in demand for wood, so more twigs and bark were used increasing the calcium content of the glass (Wedepohl and Simon, 2010). It is possible that lime may have been deliberately added to the recipe, which increased the calcium content further.

The CaO:K<sub>2</sub>O ratio for the white glass from Elgin generally ranges from 0.8 – 1.5 suggesting that the glass is of an earlier date and consistent with the hypothesis that the glass was from 13<sup>th</sup> century or early 14<sup>th</sup> century windows.

Brill and Pongracz (2004) analyzed glass from the French site of Saint-Jean-des-Vignes (Soissons) and compared the results with compositions of glass from other French, German and English sites. The glass from Soissons was dated archaeologically to the mid-13<sup>th</sup> century which means it could be of similar date to the Elgin assemblage. Three types of potash glass were identified (table 3). Type I is a low potassium glass with K<sub>2</sub>O levels of below 10%. There does not appear to be similar glass at Elgin. Type II and Type III glasses are separated by a comparison of CaO and K<sub>2</sub>O, and a further comparison by MgO and P<sub>2</sub>O<sub>5</sub>. Type II has lower K (12-16%), higher Ca (18-23%) and lower Mg (3.8-4.8), while Type III has higher Potassium (15-21%), lower calcium (13-17%) and higher magnesium (4.4-6.6%). Brill and Pongracz (2004) conclude that the various compositional types are long-lived and that 'differences in composition are more a matter of geography than date'.

When applying this categorization to the Elgin samples it appears that the majority (Group 1) fall into the Type III band with a CaO:K<sub>2</sub>O ratio of between 0.8 and 1.2. Based on the cluster analysis of glass from 32 sites in Europe, Brill and Pongracz (2004) contend that Type III glass are of a compositional type found in both English and French contexts between 1200-1400 A.D. Wedepohl (2010) states that glass from English and French glass houses often contained a greater proportion of phosphorous and

magnesium than wood ash glass produced in Germany. He attributes the greater amount of these elements to the use of fern and bracken or lower quality wood as the main alkali source. The high level of both these elements in Group 1 glass would support their production in France.

Group 2 has higher CaO:K<sub>2</sub>O ratio, greater than 2 and comparable with Brill and Pongracz Type II glass. This group also has lower phosphorus suggesting they were made from better quality or purified raw materials. Wedepohl (2010) suggests glass of this type was more likely made in Germany using beech or oak trees.

There is a further group of 'white' glass from Elgin (Group 3), that while being similar to Brill-Pongracz type III, being rich in potassium (>20%) they are different in having a very low CaO:K<sub>2</sub>O ratio of around only 0.7. The two brown glasses also fall into this group.

Previous analysis of nine fragments of glass from Elgin, alongside three fragments from Melrose, St Andrew's and Holyrood, by Tennent et al. (1984) using Atomic Absorption spectroscopy and subsequently included in statistical analysis by Rauret et al. (1987) showed that they did not form a compact group compositionally when interrogated by cluster analysis. Assemblages from Ulm (Germany), Avignon (France) and York (England) formed compact defined clusters when analyzed by principle component analysis suggesting the glass was made at a small number of sites. Hierarchical clustering analysis confirmed the inhomogeneity of the Scottish fragments. This is paralleled in the current analysis which suggests that the 'white' glass at Elgin came from a variety of sources and not from a single production site.

## Coloured Glass

A plot of calcium vs potassium highlights that the different colours of glass appear to form clusters (figure 3) with similar colours having a comparable base glass composition. This suggests that each colour was made with a different base glass recipe, rather than simply by the addition of colourants to a 'white' glass. Each colour will be discussed separately below.

## Blue Glass

The blue glass can be split into two groups; B1 comprising three shards and Group B2 comprising two shards. Visually B1 are a dark-blue colour, while Group B2 are light-blue. Early Medieval blue glass has often found to be made from sodic plant ash (O'Connor and Haselock, 1977), but the ones found at Elgin are all potassic glass suggesting they were made in Western Europe after 1168, when cobalt mines were first discovered in Germany and glass makers were not reliant on colourant sources from the east.

Group B1 has a CaO:K<sub>2</sub>O ratio of 1.2 whereas Group B2 has a higher CaO:K<sub>2</sub>O ratio of 2.5.

Group B1 has cobalt present in twice the amount of Group B2 (being 0.12-0.13% compared to 0.06-0.07%), which would produce the darker blue colour. The cobalt/copper ratio can also be used to separate the two groups with group B1 having a Co:Cu ratio of 0.35-0.45 while Group B2 has a ratio of 0.7. Zinc and lead are also present in twice the concentration in group B1. Group B2 appears to be made from an early wood-lime glass as classified by Wedepohl and Simon (2010) or with compositions similar to glass made in Germany. The B2 glass also has lower levels of magnesium and phosphorus than all the other glass samples analysed – again suggesting a German rather than

a French origin. The higher strontium and barium in group B2 is likely to originate from the copper source used as a colourant.

The difference in both the main glass composition and the proportions of colourants used suggest that the two different tones of blue were made in different locations, with both a different base glass and different colouring additives. Group B2 has a particularly distinct composition with a composition suggesting it was more likely made in Germany.

### Green

Three shards of mid/dark green glass were analysed. These had relatively low levels of both potassium and calcium compared to the other colours and form a clear compositional grouping on all three graphs despite varying in the tone of green. The predominant colouring agent was copper being present at between 3.64-4.97%. All three samples also have a significantly high percentage of lead of between 0.8-1.74%. It is probable that the lead is added alongside the copper in the form of leaded copper alloy filings which would be added to a glass melt to produce the strong green colour as in the recipes of Theophilus (Dodwell, 1961). Despite being different tones, the greens are likely to have been made in the same location as each other.

### Brown

The two brown glass shards both have lower calcium (<16%) and much higher potassium (> 18%) compared to the majority of other shards, indeed having a CaO:K<sub>2</sub>O ratio of only 0.7. The two brown glasses were also notable for their high concentration of both phosphorous (>5%) and magnesium (5-7%) probably linked to the ash source. This could suggest a French source and the use of bracken or fern as the main flux.

### Red

When studied under an optical microscope it can be seen that the red glass is made from a series of striated glass layers according to the description of Spitzer-Aronson (1986) and (2014). 'Flashed' glass, where a single (or sometimes double) layer of red glass is on top of a clear sheet, is thought to have been in use from the late 14<sup>th</sup> century while the use of the multi-layered glass technology, as seen in the Elgin glass, again suggests an earlier date for production. Copper is present at around 0.46%. Kunicki-Goldfinger et al. (2014) suggest that this type of glass was made by mixing a molten copper blue glass and a colourless glass in a crucible before blowing the glass into sheets. The red glass is not present in just flat layers but also concentrated with the red layers folded in on themselves, which would support this conclusion. Further heat treatment would cause the precipitation of copper nano-particles producing the red colour.

### GRISAILLE PAINT

The grisaille paint layer is a dark or chestnut brown colour and was analysed on 4 shards, all of which were stylistically dated to the 13<sup>th</sup> century. As the grisaille paint is heterogeneous in nature, it is more

problematic to determine a mean composition. Areas were chosen that were more 'glassy' to calculate the bulk composition, but individual grains and particles were also analysed for further study. The composition is similar to a potash glass but relatively high in lead (15-23%) and iron (2-7%). The ground iron oxide pigment, lead and scrap glass would have been ground together and mixed with an organic binder, such as egg white. It was then used as a paint and the decoration applied with brushes before being fired in a low temperature furnace as described by Theophilus (Dodwell, 1961). The lead-rich silica would melt at a much lower temperature than the body of the glass, allowing it to fuse and form a glassy phase that adheres to the surface. The Back Scattered Electron image (figure 5) shows the bright white lead rich paint layer sitting on top of the corrosion layer.

Although it is similar in composition to grisaille paint analysed on 13<sup>th</sup> – 14<sup>th</sup> century glass from Saint Chapelle in Paris, Saint-Urban at Troyes and Cologne Cathedral (Verita, 2009), the Elgin grisaille has significantly less lead (compared to 50-70% in the European examples) and a greater proportion of potash and silica. The Elgin grisaille is also richer in iron and elements associated with potash glass – such as aluminium, magnesium and calcium, suggesting it was made from different proportions of ingredients than the glass on the continent. This may be due to local Scottish production of the paint. It should be noted however, that few studies have been carried out on the corrosion of the grisaille paint in an archaeological context and the effect this would have on composition. It could be expected that the alkaline ions would be preferentially depleted, as in the glass itself and therefore depleted in potassium compared to the European examples which were still installed in windows. Verita (2009) studied the chemical weathering of lead-silica glass in the atmosphere and found that lead became depleted on the surface, and depletion of lead may also occur in more acidic burial environments, which may account for the lower lead composition.

The accepted method of production is that the sheet glass would be cut, painted and formed into the windows close to the site where the windows were to be installed. There is no archaeological evidence in Scotland of this activity but if this was the case the source of the pigment and the preparation of the paint layer may have been local to the site. Assessment of the painted decoration by Graves (1985) suggested that the glass was painted nearby by a local artist, but this analysis provides the first evidence that the paint itself was manufactured locally.

## CONCLUSIONS

Here we report on the scientific analysis of the largest assemblage of Scottish medieval window glass yet studied. The compositional analysis of the glass from Elgin Cathedral is consistent with the glass being of a 13<sup>th</sup> century date, as suggested by the decoration.

The results suggest that glass was imported from a number of different manufacturing locations in Europe in the 13<sup>th</sup> century. At least two compositional types of white glass could be distinguished. The majority of the glass is typical of Type III glass composition identified by Brill and Pongracz (2004), and also containing high levels of phosphorous which suggest it was made in 13<sup>th</sup>/14<sup>th</sup> century France. A second group of glass has composition more typical of German glass from this period.

Different colours of glass were not made from a single base glass composition, by adding independent colourants or changing the redox conditions, but were made using different base glass compositions, probably at different locations. For example, two distinct blue glasses have been identified, with different base glass compositions and different colourants used to produce different shades.

It is therefore concluded that the glass used to glaze the windows at Elgin Cathedral during the 13<sup>th</sup> century was sourced from a number of locations. Both white and coloured glass came from at least two continental suppliers and possibly more.

The Elgin grisaille paint composition shows significant differences from paint analysed in churches in France and Germany, to suggest that it could have been prepared in Scotland.

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Figure 1. Elgin Cathedral

Figure 2. A selection of grisaille painted window glass shards excavated from Elgin Cathedral

Figure 3. Calcium Oxide vs Potassium Oxide for the Elgin glass shards.

Figure 4. Graphs showing both Phosphorus Vs Calcium and Magnesium Vs Calcium. Note the separation of the colours on both graphs, but the broad range of composition of the white glass.

Figure 5. SEM image of a cross section of a glass shard, showing the grisaille paint

Table 1. Manufacturer's (Pilkington and DDG) guidance levels of elements in the glass standards alongside p-XRF and SEM-EDX measurements for comparison. Values listed as percentage of oxides.

Table 2. Composition of Elgin glass shards and grisaille paint shown as percentage of oxides (wt%) – Data of both SEM-EDX (Sodium to iron) and p-XRF analyses (Titanium and above) are shown normalised for comparison. All colours described as 'pale' are considered to be 'white' glass – i.e. the colour was unintentional

Table 3. Classification of glasses from St Saint-Jean-des-Vignes (Soissons) in comparison to Elgin glass adapted from Brill and Pongracz (2004)