Multi-disciplinary Investigation of the Windows of John Thornton, focussing on the Great East Window of York Minster

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Abstract

27 samples of glass from panel 2e of John Thornton's Great East Window (1405 -1408) have been analysed by energy dispersive X-ray analysis in the scanning electron microscope. Inserts and replacements of early modern and medieval glass are identified. White and coloured medieval glasses differ significantly in composition, suggesting different sources. 11 samples of white glass original to the window are identical within analytical error, suggesting they were from the same batch, but the head of Christ is from another panel. Blue and flashed red glasses were each the product of more than one batch of melting. The condition of the glass is primarily dependant upon silica content. Further investigations of other panels from the Great East Window, and of other windows by Thornton, are ongoing.

Introduction

The general principles of the composition and decay of medieval window glass have been reasonably well understood for some time[1], but we lack detail. We still have a limited idea of how the composition of glass varies with time and place and we are therefore not able to predict which colours in which windows are likely to be the least stable. Furthermore, at least for stained glass in Britain, our understanding of the supply of glass material is very limited. The present project is predicated on the assumption that a programme of analysis of glass from carefully controlled art-historical contexts, where dating is relatively clear, and where we are aware of potential later insertions, will yield a database of compositions which can significantly improve our understanding over a range of areas, from decay through to procurement and supply.

A joint project between Cardiff University, where the compositional analyses are conducted, and the University of York, which is providing art-historical control, the present project also depends heavily on close cooperation with conservators who are actively working on glass panels. In particular, in the early stages we are working closely with the conservation team of the York Glaziers Trust. We recognised at an early stage that the best way to conduct the required analytical programme was if glass samples could be removed from known positions in panels which were more-or-less complete. This could only be achieved if they were under conservation and the leads removed. Thanks to the foresight and generosity of the YGT, this has proved possible and, as the present results will show, the approach is proving very productive.

The dismantling for conservation of the Great East Window of York Minster, one of the greatest expanses of medieval stained glass in Europe, lies at the heart of the project. The window[2] was probably made between 1405 and 1408 by John Thornton of Coventry, whose name is recorded in a contract of the former year. The contract specifies a three-year term and a completion date of 1408 is recorded in the window itself, although there is some question as to whether this is part of a restoration. The window comprises some 287 panels, each containing a range of original coloured glasses. We intend to analyse glass from a range of panels across the Great East Window, focussing in particular upon glass which we believe to be original fifteenth century material. Glass inserted during later restorations will be included on a limited scale, to test our assumptions and to inform future study.

The conservation of the East Window provides a unique opportunity. We will have a comprehensive sample from across a large expanse of glass, where a range of colours (and therefore compositions) have been exposed to a similar environmental history. The control of composition over decay in a real situation (as opposed to on model compositions or accelerated laboratory experiments) will therefore be apparent. In addition, we will gain information on the procurement of glass for single panels, for a whole window, and by comparison with other windows made by Thornton, for a specific glazier. Once we have grasped the principles of variability within a single monument, we will be able to compare more limited samples of windows through time and across the UK and Europe, to determine sources. This is an ambitious programme, but we believe it is feasible if the required collaboration between conservators, art-historians, scientists and custodians can be attained. We are grateful to the Leverhulme Trust which has provided support for the initial three-year period.

The present paper reports the analytical results for the first panel analysed from the East Window and discusses some of their implications.

The Great East Window: Panel 2e

Little is known of the history or condition of the window until the late seventeenth century when antiquarians began to describe the glass. It seems that, between this date and the nineteenth century, the window was repaired as required by the Minster's own workforce, sometimes with the help of outside craftsmen; and that relatively large-scale repair or re-leading projects took place between 1730 and 1762, and in the 1820s. In 1939-40, the glass was removed from the window for safety; re-leading, repair, rearrangement and reinsertion took place between 1943 and 1953 under Dean Milner-White.

The window's glass tells, ambitiously, the history of the world from the beginning to end, drawn from the first and last books of the Bible. Panel 2e, the subject of this report, represents the Judge at the Last Judgement. At the centre of the panel is a composite, interpolated figure of Christ (Fig. 1). He stands with arms raised, before a yellow and white rainbow, his body apparently twisted to dexter, his head turned to sinister; his rayed yellow nimb has a white, trefoil-cusped border, and his hair and beard are corkscrew-curled. He wears a murrey cloak over a patterned white robe. On each side of Christ, oriented towards him and behind the yellow and white rainbow, stands an angel. Each has ruby wings and curly golden hair, wears a long white gown with patterned yellow neck apparel, and carries instruments of the Passion. The 'seaweed' foliage background is blue. The scene is framed by a canopy and side-shafts, all in white glass and silver-stain.

The panel has been damaged at some period, especially the central part. Milner-White[3] suggested that the figure of Christ was an insertion and probably made up from several sources. According to medieval iconographic convention, the subject matter demands that Christ be shown as the Judge, full-faced and seated on a throne or rainbow, and displaying his wounds. The existing figure of Christ, however, is shown standing to dexter, and with his head turned to sinister; also, as noted by French[4], his head has semi-corkscrew hair of a type not used for Christ anywhere else in this window. The blue 'seaweed' ground is also heavily patched.

Analysis of glass from this panel therefore presents a number of issues, in particular the identification of replacement material, which might interfere with our overall aims.

Sampling and samples

Twenty seven pieces of glass from the several hundred in the panel have been selected for sampling - twelve white, eight blue, four red and single examples of pink and murrey[5] (Table 1). The relative numbers sampled reflect in a general sense the abundance of these colours in the panel. On the basis of their iconography and preservation, eleven samples were confidently considered components of the panel when it was originally made; a further four examples were considered likely to be from the panel and three further pieces were considered definitely medieval, although perhaps not from the panel. The eleven remaining items were described as unknown, although a significant number were likely to be medieval, as their states of preservation were typical. An example of murrey glass, although showing corrosion characteristics typical of medieval glass, may or may not have been inserted into its current position. The single pink glass appeared to have been inserted in the mid-twentieth century, when the panel was restored.

While the panel was unleaded in the conservation studio, samples of about 3x2 mm were removed from the edges of the pieces using a glass cutter[6]. The positions of the fragments were recorded on a plan of the panel and the state of preservation on inner and outer surfaces noted. Carefully oriented cross sections of the glass plates were embedded in epoxy resin (EpoFix, Struers), ground flat with silicon carbide and polished with diamond pastes down to 0.25 μm.

Experimental

Digital Photomicroscopy

A Nikon SMZ1000 zoom stereomicroscope with a CoolPix 4500 digital camera attachment was used to investigate the structure and morphology of the glass at magnifications top x40. The thicknesses of the fragments and dimensions of components such as flashed layers were measured using EclipseNet interactive image analysis software.

Scanning Electron Microscopy with Energy Dispersive X-Ray Analysis

The embedded and polished samples were coated with a thin layer of carbon and analysed using a CamScan Maxim 2040 scanning electron microscope equipped with an Oxford Instruments ISIS energy dispersive X-ray spectrometer. Back-scattered electron imaging was used to distinguish areas of fresh glass for analysis.

For elemental analysis, the electron beam was rastered at a magnification of 500x over an area of fresh glass for 100s, at 20 kV accelerating voltage. Count-rate on metallic cobalt was around 4000 cps. Standards were pure oxides and minerals and quantification was carried out using the ZAF method. Oxide weight percents were calculated stochiometrically. Analytical totals were typically between 98% and 102% and have been normalised to 100% for comparative purposes.

The results of repeated analyses of the reference glass Corning D are shown at the bottom of Table 1. Good agreement between recommended and analysed results[7] was obtained in the case of all components, except SO_3, which is close to the limits of detection. The departures from the accepted values for other elements fall below 6% relative and for CaO and SiO_2 below 1%.

Results

Morphology and colour

Almost all samples contain imperfections, such as bubbles and striae. The cross-sectional thicknesses of the medieval glasses (Table 1) fall into the range ~1.1 – ~ 2.9 mm, with blue flashed glass B9, a post-medieval insert, being of exceptional thickness, at ~ 4.1 mm. The average thickness of unflashed white is about 1.8 mm (range ~1.1-~ 2.4). Murrey and blues are typically thicker with an average value of ~2.4 mm. The thicknesses of medieval flashed reds R1, R2, R3 are of more-or-less similar thickness to the unflashed whites.

White glasses, including the supporting layers in the flashed glasses, usually have a greenish tint. W11 seemed to be more bluish and the base glass of modern insert B9 appeared to be almost perfectly colourless. The tints and intensities of all reds are very similar, while among blues B4 is paler than the rest and B2 resembles what is often termed "petrol blue".

State of preservation

For the purpose of this preliminary statement, a very general description of glass condition is used. Fragments which appear in good condition when assessed by the naked eye are indicated as 'good' in the last column of Table 1 and those which show any visible sign of corrosion in the form of pitting, crusting or losses, are marked as 'decay'. In general, white glasses have survived in better condition than coloured glasses and the white layers of flashed glasses. However there are several well-preserved pieces in the coloured group.

Chemical composition

The results of chemical analysis as weight percent oxides are shown in Table1. Almost all glasses are of the K_2O-CaO-SiO_2 type with significant amounts of MgO and P_2O_5 and are likely to be medieval. There are only three exceptions. Flashed red glass R4, which appeared to be an insert, is the only example of Na_2O-CaO-SiO_2 type and the extremely low MgO, MnO and P_2O_5 , as well as the high concentration of silica (72.9%) suggest that it dates to the nineteenth-twentieth centuries; a level of chlorine less than 0.2% suggests a manufacture after the mid-19th century. A medieval date can be certainly excluded for this fragment. Two other glasses - the white base layer of flashed blue B9 and pink glass P1 – are high lead glasses (~36 and ~30% of PbO respectively) and they are again characteristic of the eighteenth century or later. The modern red and pink both occur in the area between the left hand angel and Christ, while the blue is from the background beneath the scroll at the bottom of the panel. These three glasses are not included in the graphs, which show only potash-lime-silica glasses.

24 glasses are of the potash-lime-silica type and can be sub-divided into two main groups, easily distinguished from each other by CaO (lime) and MgO (magnesia) contents, shown in Fig 3. The group characterised by lower CaO values (14.7-15.4%) as well as by an elevated concentration of MgO (6.98-7.46%) consists exclusively of whites and all white glasses without flashed layers that were analysed are members of this group. It is very coherent with very narrow ranges of all components; a single outlier is W8 which has a slightly higher MgO concentration (Fig. 3). Fig. 4 demonstrates that glasses of this group also typically have higher Na_2O (>2.4%) and SiO_2 (57.9-58.8%) contents. W8 is again seen to be an outlier but is closely associated with the main group of whites (Fig 4).

The remaining samples comprise all coloured and flashed glasses and have significantly lower MgO (<5%) and higher CaO contents (>21%) than the whites (Fig 3). However they are not homogeneous and subgroups and outliers can be distinguished. The flashed reds (R1, R2, R3) and the blues (B1, B3, B5, B6, B7, and B8) are similar in most respects and in particular have similar concentrations of K_2O (~11%) and CaO (~24%) (Fig. 3, Table 1). Furthermore, on the basis of other constituents, particularly those associated with the colour technology, such as Fe_2O_3 and ZnO, the six blues can be sub-divided into two: B3, B5, B6 which have high Fe_2O_3 and B1, B7, B8 with high ZnO (Table 1, Fig. 5). Three outliers, blues B2, B4 and murrey M1, are clearly different from the main group (Figs. 4, 5).

Discussion

The potash-lime-silica glasses are typical of medieval woodash glass. The concentrations of minor components such as Al_2O_3, Na_2O, BaO and Fe_2O_3 as well the range of SiO_2 contents are broadly consistent with many previously published results[8]. It is notable that all medieval glasses analysed contain around 1-2% MnO, irrespective of their colour. This is consistent with current understanding, which attributes the presence of manganese in northern European glass to its presence in wood ash, rather than to deliberate addition by the glassmaker, as was the case in the soda-lime-silica glasses of the South. Blue glasses owe their colour to cobalt, although we could not measure this element in every case, as it was close to the detection limits of our spectrometer under the conditions of analysis we used (Table 1). The red flashed layers are due to copper, and a discussion of these glasses will follow in due course.

Panel 2e includes two very distinct compositional groups, one with low calcium and high magnesium oxides, which comprises the white glasses, and a high calcium and low magnesium type which comprises the other colours (Fig. 3). These groups appear to represent two distinct productions, differing significantly in technology and/or raw materials. If it is assumed that most of the potash, lime and magnesia were derived from woodash, then two significantly different ashes were used in the production of the two glass groups.

These results are consistent with the view that English glaziers obtained their glasses from a variety of sources[9]. In particular, in the present panel the origin of the white glasses is likely to differ from that of the coloured glasses. The source of coloured glass is generally assumed to have been continental. However, Brill and Pongracz[10] plotted the compositions of 296 medieval window glasses in terms of CaO vs K_2O and P_2O_5 vs MgO and a preliminary inspection suggests that the Great East window coloured glasses do not match any of the major continental groupings that these authors identified. The source of the white glass is also unclear, although documentary sources suggest that York Minster received glass from Staffordshire in the fifteenth century[11].

The extremely tight compositional distribution of the main group of eleven samples of white glass (neglecting outlier W8) is highly significant. The individual analyses of this group are all within two to three times the standard deviation of repeated analyses on the Corning D standard for every component (Table 1). Thus they are identical within experimental error. As discussed elsewhere[12] this suggests that these glasses were produced as a single batch of material. They represent glass gathered from a single pot, or several pots made from the same raw material batch. They may represent one or several sheets of white glass but in any case are likely to have been blown in relatively short succession. We can therefore be confident that all of these fragments are original to the window and probably to the panel. On the other hand, outlier W8 was made from a different batch of glass. In fact, this is the Head of Christ which, on art-historical grounds, has been suggested to be an insert to the original panel. Interestingly, the compositions of samples W7, Christ's right arm, and W9, Christ's body just below the head (Fig. 1) match the remaining white glasses very closely, and do not support the view that they are also inserts from a different panel (see above). However, to confirm this, we need to enlarge our sample of white glass from other panels in the window.

Fig. 5, which plots iron oxide and potash, emphasises the differences between the different subgroups of coloured glass. The high variation in iron oxide contents is likely to reflect the use of different batches of cobalt colourant in the blues, as iron is a well-known impurity in cobalt pigment. It is clear (Figs. 4 & 5) that there are several subgroups of blue in the panel, and these are likely to represent blue glasses cut from different sheets. While several of these blues may be inserts, it is not clear that all are, and it seems possible that the two larger groupings are original to the panel. The glasses forming the group with higher iron oxide, nos.B1, B7, B8, are from above or to the left of the cross held by the right hand angel. The samples in the group with higher zinc are from the area to the right of the right hand angel, above and below the rainbow (B5, B6) and from the region below the scroll, centre bottom (B3).

Samples B2 and B4 are blues which are of medieval composition but with distinctive tones, and which are compositional outliers with respect to other glasses in the panel, having significantly lower K_2O (potash) contents (Table 1; Figs. 4, 5). B4 is from the area below the scroll and was adjacent to modern insert B9, while B2 is from the area between Christ and his right arm, close to modern inserts R4 and P1. The close association of these two medieval outliers with demonstrably post-medieval glasses suggests that they represent the use of old medieval glass in one or more modern campaigns of repair.

Of the three flashed reds analysed, two are almost identical, and therefore likely to have been cut from a single sheet, while the remainder is from a different batch, having a higher soda content (Fig. 4). Samples R2 and R3 are respectively from the base and head of the right hand angel, and represent glass from a single batch, while the third red sample, R1, is from the base of the left hand angel. The murrey glass clearly differs in composition from the others, but we cannot comment on the significance of a single sample at this stage.

The disposition of blues and reds from the same batch in the panel suggests that each sheet of coloured glass was used to glaze a specific part of the window and that they are likely to record the progression of the glazing process. There are several possibilities to account for the apparent use of a single batch of white glass but more than one batch of blue and red glass in a single panel. It might be due to the production of coloured glasses in smaller sheets by the glassmakers, or alternatively a policy by the glazier of careful conservation of coloured glass and the careful matching of the desired shapes with the available sheets. The production of data on colourless and coloured glasses in other panels of the window will cast light on these practices.

A key aim of the present project is to compare the conditions of glasses of different composition from a single window, as they are likely to have been subjected to essentially the same environmental conditions for the same period of time. The present cohort indicates that corrosion is strongly dependent upon silica composition, as is widely understood. However, it also supports the view of Cox et al.[13] that the relative amounts of alkali to alkaline earth oxides have little effect, as glasses with weight percent SiO_2 below 55% appear to be corroded, and those with higher silica preserved, in spite of widely varying CaO, MgO and K_2O contents. In due course, we expect to be able to focus upon the character of this compositional boundary between weathered and unweathered glass in more detail.

Conclusions

The conclusions that we have been able to draw from the in-depth examination of a single window panel are of course provisional, but they show promise for future work. Multiple sampling of colours not only reveals gross differences in origins of glasses, but also allows us to engage with the working practices of glaziers and glassmakers, through the recognition of individual batches and sheets of glass. We are able to identify inserts and replacements not only of post-medieval glass, and medieval glass of a different origin or period, but even of medieval glass closely contemporary with the window. We are also able to focus on the relationship between corrosion and composition in much greater detail than has previously been the case, confident that different environmental histories are not responsible for the variations that we see.

This study would not be possible without the close cooperation of art historians, who are familiar with the history and iconography of the Great East Window, conservators who are intimately familiar with the materials, and scientists who have experience in the analysis of historical glass from other contexts.

Acknowledgements

We are extremely grateful to the Leverhulme Trust for funding our research, and to the Dean and Chapter of York Minster, who gave permission for the analyses to be undertaken. Nick Teed and his colleagues in the conservation studio of York Glaziers Trust have provided invaluable and enthusiastic help and advice. We would also like to thank the members of the East Window Advisory Committee at York, in particular Andrew Arrol, Sarah Brown and Christopher Norton for their strong interest and support. Finally we are very grateful to Lisa Pilosi, who in her inimitable way pointed IF and TA towards one another, and waited for something interesting to happen.

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Fig. 3. Magnesia versus lime for analysed medieval glasses. Note the clear separation of whites and other colours.

Fig. 4. Soda versus silica for analysed medieval glasses

Fig. 5 Iron oxide versus potash for medieval glasses analysed. Note that two blue samples in the upper group are superimposed.

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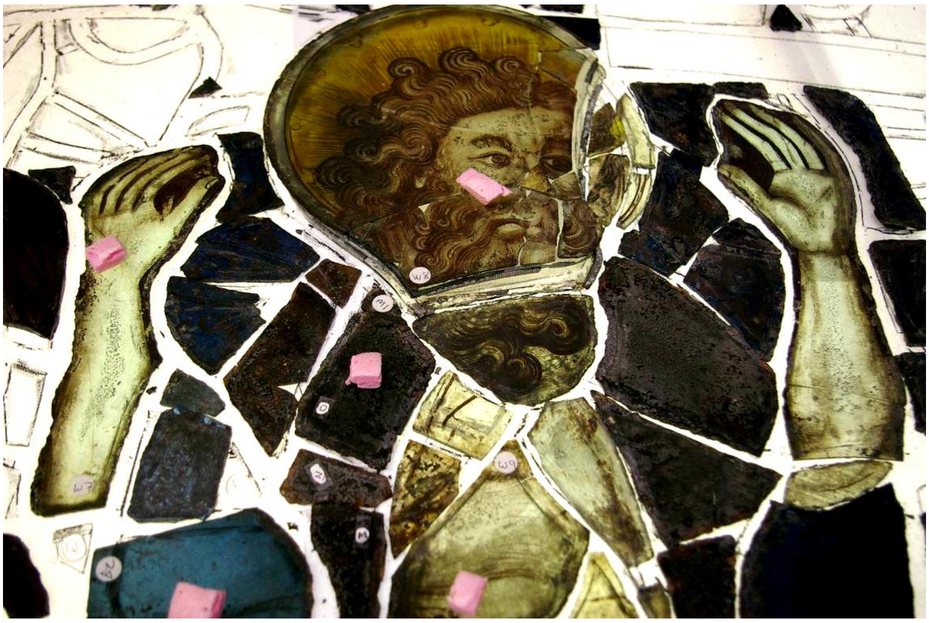

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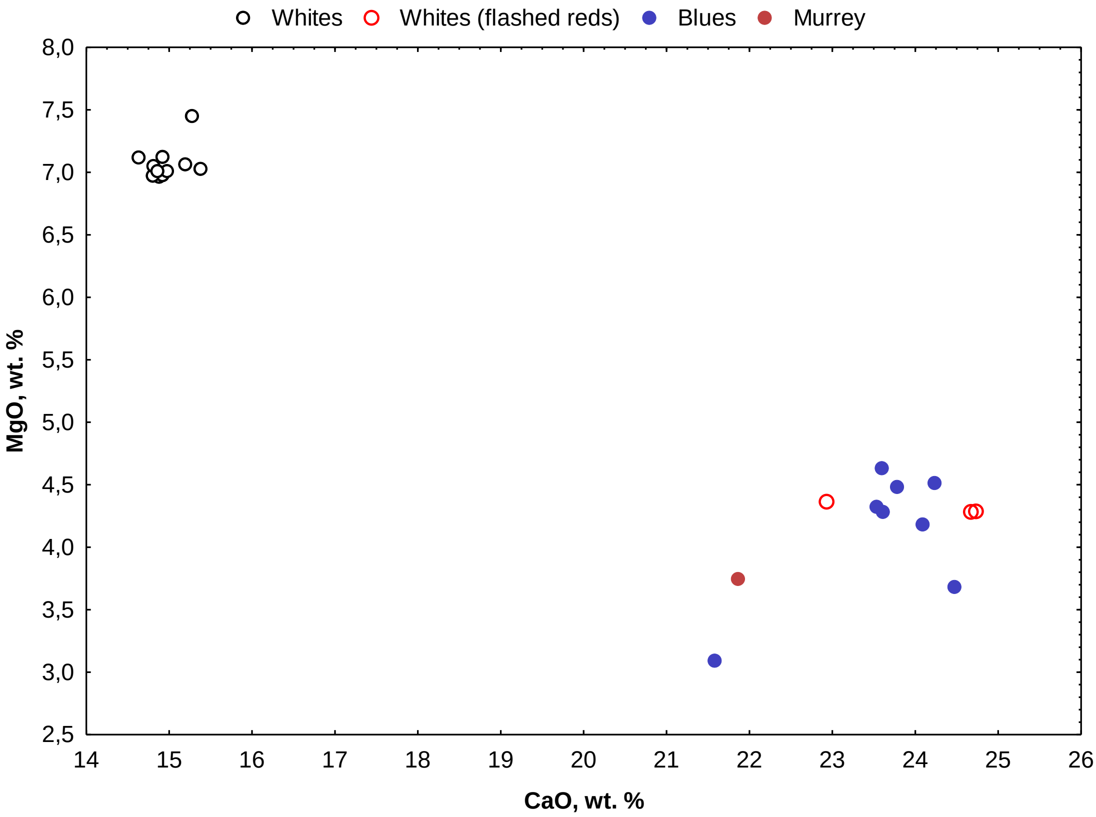
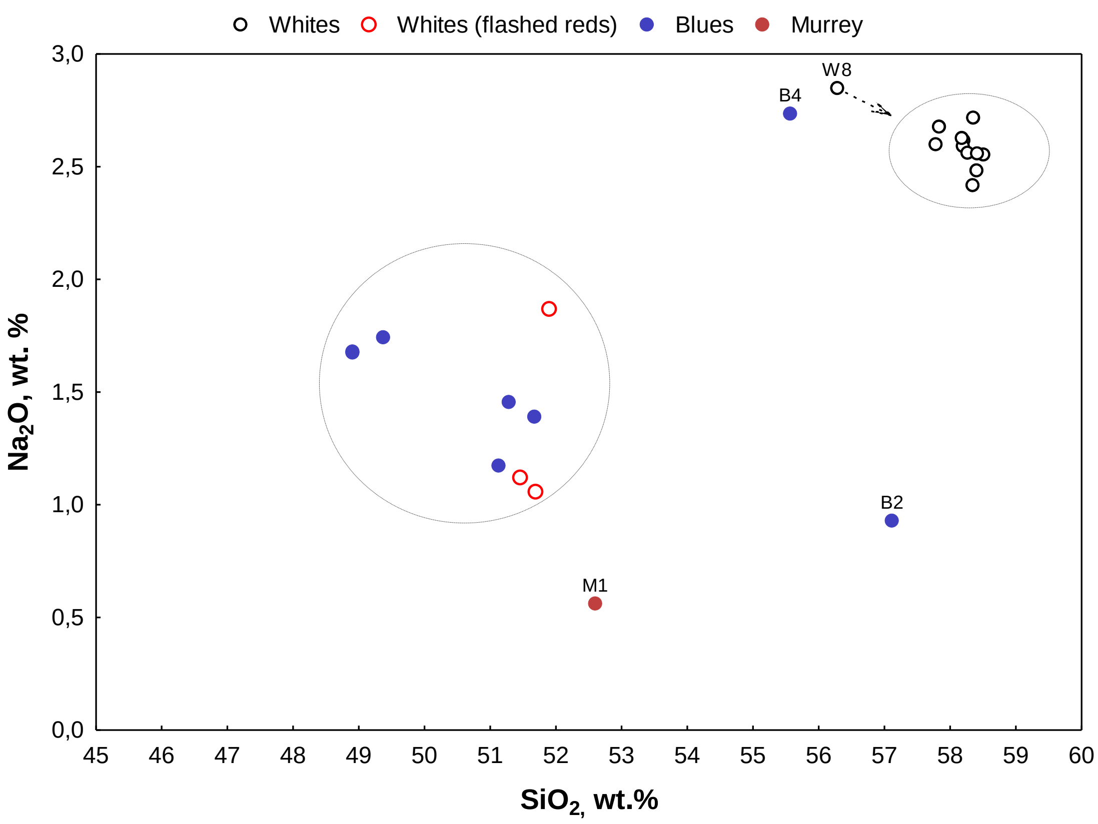


Fig. 3. Magnesia versus lime for analysed medieval glasses. Note the clear separation of whites and other colours.



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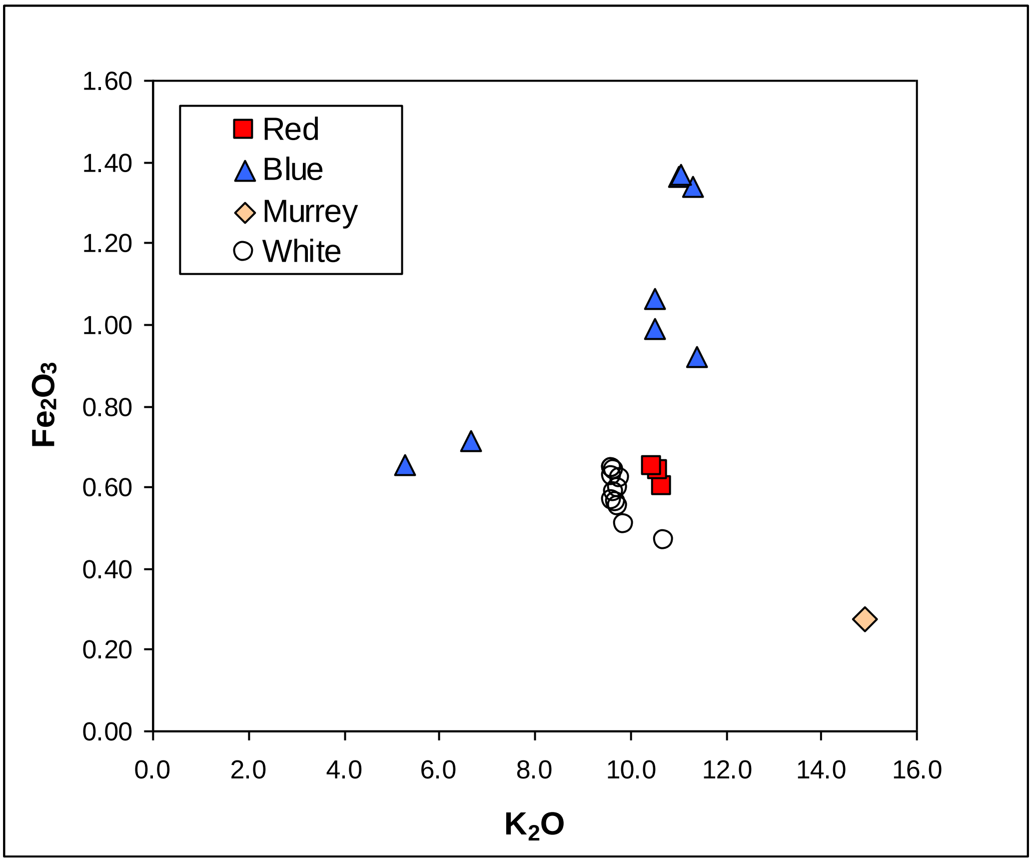

Fig. 5 Iron oxide versus potash for medieval glasses analysed. Note that two blue samples in the upper group are superimposed.

Table 1. EDXA Analyses of Glasses from panel 2e, Great East Window

Sample*	Colour of analysed layer*	K_2O	Na_2O	CaO	MgO	Al_2O_3	SiO_2	MnO	Fe_2O_3	P_2O_5	SO_3	Cl	BaO	TiO_2	CuO	ZnO	PbO	CoO	Thickness [mm]	Condition*
W1	White	9.68	2.63	14.9	7.00	1.27	58.5	1.43	0.64	3.09	0.28	0.34	0.23	<	<	<	<	<	>1.7	Good
W2	White	9.62	2.57	15.0	7.01	1.25	58.8	1.37	0.65	3.12	0.34	0.31	<	<	<	<	<	<	n.a.	Good
W3	White	9.66	2.59	14.9	7.13	1.36	58.2	1.47	0.58	3.15	0.30	0.28	0.31	<	<	<	<	<	1.5	Good
W4	White	9.79	2.69	15.3	7.10	1.29	58.1	1.41	0.62	3.14	0.28	0.33	<	<	<	<	<	<	2.3	Good
W5	White	9.88	2.61	15.4	7.04	1.31	57.9	1.55	0.50	3.16	0.15	0.31	<	0.19	<	<	<	<	n.a.	Good
W6	White	9.62	2.56	14.9	6.98	1.41	58.3	1.52	0.57	3.06	0.28	0.33	0.27	0.16	<	<	<	<	1.5	Good
W7	White	9.62	2.72	14.7	7.14	1.29	58.5	1.45	0.62	3.11	0.25	0.34	0.31	<	<	<	<	<	1.4	Good
W9	White	9.76	2.42	15.0	7.02	1.32	58.4	1.48	0.60	3.15	0.35	0.31	0.24	<	<	<	<	<	1.1	Good
W10	White	9.73	2.49	14.8	6.98	1.39	58.5	1.60	0.56	3.16	0.32	0.29	<	0.18	<	<	<	<	2.3	Good
W11	White	9.61	2.56	14.8	7.07	1.30	58.5	1.46	0.65	3.18	0.24	0.32	0.22	<	<	<	<	<	2.3	No data
W12	White	9.74	2.63	14.9	7.02	1.32	58.3	1.50	0.55	3.20	0.31	0.31	0.29	<	<	<	<	<	2.5	No data
W8	White	10.7	2.85	15.3	7.46	1.17	56.4	1.52	0.47	3.26	0.25	0.35	0.24	<	<	<	<	<	1.4	Good
R2	White, F (2)	10.7	1.13	24.8	4.31	1.61	51.7	1.35	0.60	3.27	0.27	<	0.31	<	<	<	<	<	1.9	Decay
R1	White, F (3)	10.6	1.87	23.0	4.38	1.48	52.0	1.06	0.64	4.18	0.38	0.11	0.26	<	<	<	<	<	1.7	Decay
R3	White, F (2)	10.5	1.06	24.8	4.31	1.54	52.0	1.41	0.65	3.11	0.24	0.10	<	<	<	<	0.33	<	2.0	Decay
R4	White, F (2)	0.11	11.21	14.0	0.15	0.40	72.9	<	0.26	<	0.74	0.17	<	<	<	<	<	<	2.1	Good
B9	White, F (2)	10.7	<	<	0.19	<	53.0	<	<	<	<	0.17	<	<	<	<	36.0	<	4.1	No data
B5	Blue	10.5	1.46	23.6	4.33	1.53	51.4	1.36	1.06	3.27	0.42	<	0.35	<	0.21	0.38	<	0.19	2.3	Decay
B3	Blue	11.4	1.18	24.2	4.19	1.46	51.3	1.16	0.92	3.17	0.26	<	0.48	<	<	0.32	<	<	n.a.	Decay
B6	Blue	10.5	1.40	23.7	4.30	1.63	51.9	1.24	0.99	3.28	0.28	<	<	0.19	0.24	0.36	<	<	2.9	Decay
B1	Blue	11.0	1.68	24.3	4.53	1.76	49.1	1.24	1.37	4.10	0.27	0.08	0.34	<	<	<	<	0.16	2.4	Decay
B8	Blue	11.3	1.69	23.9	4.50	1.93	49.1	1.12	1.34	4.23	0.26	0.10	0.29	0.19	<	<	<	<	2.2	Decay
B7	Blue	11.0	1.75	23.6	4.64	1.77	49.5	1.10	1.37	4.24	0.27	<	0.34	<	0.36	<	<	<	2.6	Decay
B4	Blue	5.26	2.74	24.5	3.68	1.25	55.6	1.22	0.65	3.90	0.17	0.54	0.35	0.18	<	<	<	<	2.0	Good
B2	Blue	6.65	0.93	21.6	3.10	3.84	57.2	2.12	0.71	3.00	0.20	0.27	0.38	<	<	<	<	<	2.1	Good
M1	Murrey	14.9	0.56	21.9	3.75	1.00	52.7	1.51	0.28	2.45	0.50	0.07	0.38	<	<	<	<	<	>2.8	Decay
P1	Pink	9.85	1.68	0.57	0.33	0.65	53.5	2.03	0.58	<	<	0.50	<	<	<	<	30.3	<	2.2	Good
Corn. D - recommended		11.3	1.20	14.8	3.94	5.30	55.24	0.55	0.52	3.93	0.19	0.16	0.30	0.38	0.38	0.10	0.25	0.023		
Corn. D - analysed, av. (n=13)		11.5	1.182	14.7	3.874	5.00	55.7	0.562	0.48	4.131	0.32	0.17	0.31	0.429	0.40	<	0.23	<		
	sd	0.1	0.08	0.2	0.06	0.08	0.5	0.06	0.06	0.10	0.04	0.02	0.09	0.06	0.08		0.07			

Colour of glass plate: W - white; R - red; B - blue; P - pink; M - murrey

F (x) - flashed glass (number of layers)

< - below detection limits, n.a. - not possible to measure

[1] For composition, see Karl Hans Wedepohl. *Glas in Antike und Mittelalter*. (Stuttgart: E. Schweizbart'sche Verlagsbuchhandlung, 2003). For decay, Hannelore Römich. (1999) "Historic glass and its interaction with the environment" In *The Conservation of Glass and Ceramics* ed. Norman H. Tennant (London: James & James 1999) pp. 5-15.

[2] T. French *York Minster: The Great East Window* (Oxford, 2003)

[3] Friends of York Minster *Annual Report for 1953*, p 37.

[4] T. French *York Minster: The Great East Window* unpublished ms. 1978.

[5] The terminology of glass colours has been intentionally simplified and refers to the colour seen through the glass panel in undecorated areas. Glasses that were not intentionally coloured and presumably should have been seen in a window as colourless are termed white irrespective of their true tint. This term is also used to describe the nearly-colourless supporting glass of flashed red or blue. The terms red, blue, pink and murrey refer to the general impression and neglect minor variations in hue or intensity. Glass with a surface yellow silver stain is also described as white.

[6] The sampling was carried out at the York Glaziers Trust Stained Glass Conservation Studio in York in conjunction with Mr Nick Teed, conservation manager of the Trust.

[7] Recommended values from Robert H. Brill *Chemical Analyses of Ancient Glass*. (New York: Corning Museum of Glass, 1999). Values for Cl, BaO, PbO and SO_3 from Edward P. Vicenzi, Stephen Eggins, Amelia Logan. and Richard Wysoczanski "Microbeam characterization of Corning archaeological reference standards: new additions to the Smithsonian Microbeam Standard Collection." *J. Res. Natl. Inst. Stand. Technol.* 107 (2002), pp.719-727.

[8] E.g. Wedepohl. *Glas in Antike und Mittelalter*; Brill *Chemical Analyses of Ancient Glass*.

[9] Richard Marks (1993) *Stained Glass in England in the Middle Ages* (London: Routledge)

[10] Robert H Brill and Patricia Pongracz "Stained glass from Saint-Jean-des-Vignes (Soissons) and comparisons with glass from other medieval sites. *J Glass Studies* 46 (2004), pp.115-144.

[11] Christopher Welch. (2003) York Minster glass from Staffordshire in the late fifteenth century. *Glass News*, Winter 2002/3. London: Association for the History of Glass.

[12] Jennifer Price, Ian C. Freestone and Caroline R. Cartwright "All in a day's work?' The colourless cylindrical glass cups found at Stonea revisited." In *Image, Craft and the Classical World. Essays in honour of Donald Bailey and Catherine Johns.* Ed. Nina Crummy. Collection 'Monographies Instrumentum' no 29. Montagnac, éditions Monique Mergoil, (2005) pp.163-169; Ian C. Freestone, Jennifer Price and Caroline R.

Cartwright “The batch: its recognition and significance.” *Annales 17th Congress AIHV*. (In press, Antwerp: Association Internationale pour l’Histoire du Verre)

[13] G. A. Cox, O. S. Heavens, R.G. Newton and A.M. Pollard “A study of the weathering behaviour of medieval glass from York Minster.” *J Glass Studies* 21, (1979) pp.54-75.