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Craig J. Kennedy & the late K. Robin Murdoch

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Composition of late seventeenth century window glass from Scotland

By CRAIG J. KENNEDY[1] *and* THE LATE K. ROBIN MURDOCH[2]
[1]*School of Energy, Geoscience, Infrastructure and Society, Heriot-Watt University, Edinburgh, UK;* [2]*Harlaw Heritage, Balerno, UK*

SUMMARY: Samples of glass from four sites in Scotland were analysed using portable X-ray fluorescence. Three of the sites were archaeological excavations in Ullapool, Stirling and Hume Castle, where glass shards were recovered; the fourth site was a historic building, Traquair House, with original window glass in situ. Each of the sites yielded a chemically distinct type of glass that is remarkably consistent across all four locations. Chemically, the glass recovered shares some characteristics with high lime low alkali (HLLA) glass, used throughout the seventeenth century, and some with kelp fluxed glass, used from the late seventeenth century to the 1840s. The glass appears to be a hybrid of both, representing a late seventeenth century transitional phase from one form of alkali flux to another. Possible sources of this glass type are discussed.

KEYWORDS: Glass; kelp; flux; Scotland

INTRODUCTION

Windows are an integral part of any building. As well as being functional, by allowing in light and acting as a barrier to the external environment, they can have aesthetic benefits for a building also. Prior to the manufacturing techniques (Pilkington 1969) that allow for the creation of flawless, perfectly clear glass, windows installed in historic buildings were often characterised by imperfections such as bubbles, tinting and striations. In recent years, advances in scientific techniques have allowed for chemical analysis of window glass from historic buildings including clear 'white' window glass and stained glass (Dungworth and Girbal 2011; Kennedy, Murdoch, and Kirk 2013; Adlington and Freestone 2017). The portable nature of, for example, X-ray fluorescence allows for scientific analysis to take place on-site, as well as in a laboratory setting.

Utilising these technologies, and through comparisons with historic glasses of known composition and historical sources, Dungworth and Girbal (2011) developed a model for 'white' window glass manufactured in England (Table 1). This model identified the key elemental profiles of glass from various stages of development. The primary ingredients of glass are silica, sourced from sand, an alkali flux used to reduce the melting temperature of the sand, and other chemical additives used, for instance, to decolour the glass. These ingredients evolved over time and as such the phases of glassmaking are chemically distinct; for example, kelp glass, manufactured with the ashes of seaweed as an alkali flux to reduce the melting temperature of glass, can be identified by the presence of ~0.45% strontium oxide.

The model, coupled with the advent of hand-held portable X-ray fluorescence which allows

CONTACT Craig J. Kennedy, Email: craig.kennedy@hw.ac.uk

TABLE 1.
Simplified version of the Dungworth and Girbal (2011) model of the phases of development of window glass in England.

Glass type	Year
Forest Glass	Before c. 1567
High Lime Low Alkali	c. 1567 to c. 1700
Kelp	c. 1700 to c. 1835
Leblanc Soda Glass	c. 1835 to c. 1930
Mechanised Glass	From c. 1930

the chemical composition of window glass to be analysed *in situ*, is extremely beneficial in terms of understanding how much historic fabric remains in an historic building; for example, in understanding how many original panes of glass survive in a building relative to the number of new panes. This information could play a significant role in decisions made regarding alterations and developments to a historic site (Kennedy, Murdoch, and Forster 2015).

However, in Scotland the development of the glass industry did not occur at exactly the same time or the same speed as that in England (Turnbull 2001). The native Scottish glass industry, where glass was manufactured from raw materials, began in small scale from 1610 AD with a patent awarded to Sir John Hay; in England a glass patent was awarded to Jean Carré in 1567 and there had been glass production in forested areas of England during the Medieval period. The Scottish glass industry initially focused on bottle and vessel glass, with window glass making up a relatively minor component (Turnbull 2001). Prior to the development of the native glass industry in the 17th century, window glass was entirely imported into Scotland. Given the different beginnings to the industries in Scotland and England, the question has therefore to be asked: how applicable is the Dungworth and Girbal model to Scottish window glass?

Over time, the general trends in glass manufacture in Scotland followed that of England, with various developments in manufacturing techniques and ingredients (Kennedy 2017) being adopted in both countries. Taking kelp fluxed glass as an example, Dungworth's model gives a tentative start date of c. 1700 AD for its use, though in that paper he states that historical sources show kelp becoming more established in the middle of the 18th century as the primary flux. This corresponds with the development in Scotland where kelp was used in the late 17th century and established regularly on the Forth from around 1720 (Turnbull 2001) before undergoing a long period of market dominance (Thompson 1983). This suggests that in both Scotland and England there was a gradual change of materials used to manufacture window glass, from the high lime low alkali (HLLA) glass of the 17th century to the kelp fluxed glass of the 18th century.

Likewise, when economic and technological factors in the 1830s converged, the kelp industry for glassmaking effectively collapsed in that decade; Dungworth and Girbal (2011) indicated that English transition from kelp to synthetic soda took place over a period from the late 1820s to 1837. However, in Scotland there is evidence that glass manufacturers were still using kelp as a primary flux into the 1840s (Kennedy 2017). Although a relatively minor difference, it appears that Scottish glass manufacturers took longer to switch to synthetic soda than their English counterparts.

Understanding the transition from one phase of glass is an important consideration when attempting to date window glass. For instance, glass manufactured in the early 18th century could have been produced using either HLLA or kelp as the main flux. Accurately defining the phases and, importantly, periods of overlap between one glass type and another can help accurately put a building into context, and invites study beyond the scientific analysis alone.

Here we present findings from a series of experiments that indicate the presence of an additional phase of glass from Scottish buildings, not previously observed and not defined in the Dungworth and Girbal model.

MATERIALS AND METHODS

GLASS SAMPLES

Shards of archaeologically excavated glass were analysed from Hume Castle, Stirling and Ullapool; *in situ* window glass was analysed at Traquair House (Fig. 1, Table 1).

Hume Castle and surrounding settlement was subject to a 3-year long archaeological project. Excavations took place in the castle grounds, the Glebe, and in the garden of the West End

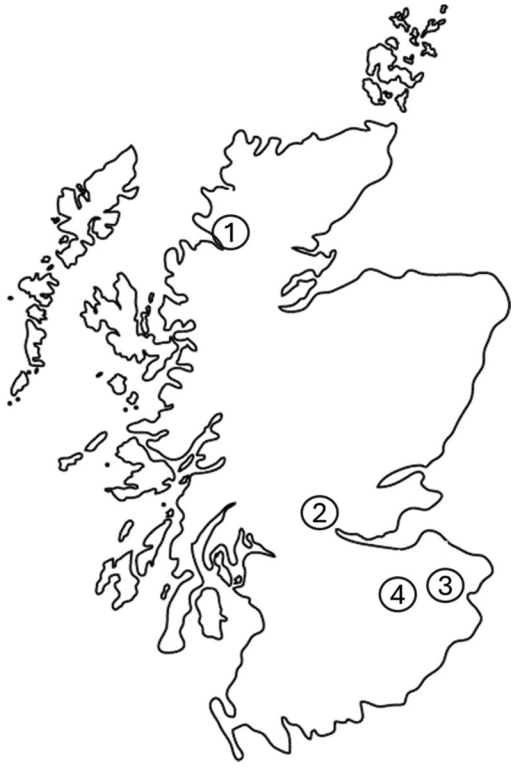

FIG. 1
Outline map of Scotland highlighting the locations where the samples analysed came from. The sites are Ullapool (1), Stirling (2), Hume Castle (3) and Traquair House (4).

Cottage in Hume Village. Window glass was recovered from the grounds of Hume Castle itself. Samples were selected for study here based on classification (Hill et al. 2023).

Archaeological excavations took place across an area scheduled for housing development at Goosecroft Road, Stirling, central Scotland (Hill 2018). The site underwent various changes over the centuries, as it resided in one of Scotland's most historically significant cities. Originally the site of a 13th century friary, the site was developed over subsequent centuries to include a church and, latterly, housing.

Archaeological investigations as part of the Lost Inverlael project were undertake from 2021 to 2022, co-ordinated by Ullapool Museum (McKeggie 2024). Excavations were undertaken by local community members under the supervision of Highland Archaeology Services staff, and focused on the Inverlael Township located at the south end of Loch Broom. 33 shards of window glass were excavated and visually categorised, with samples selected for analysis by X-ray fluorescence.

Traquair House, Innerleithen, dates to 1107 AD and is Scotland's oldest continually habited house. It is currently a tourist attraction in the Scottish borders. Glass was analysed and examined *in situ* rather than as the result of an archaeological excavation.

X-RAY FLUORESCENCE

Portable X-ray fluorescence (pXRF) analysis of the samples was undertaken using a Niton XL3t portable XRF system with 'GOLDD' detector. For analysis of glass shards, the XL3t is placed in a radiation-proof Tungsten-lined test stand and X-rays generated when the nosecone was in direct contact with the surface. For analysis of window panes *in situ*, the nosecone is pressed against the glass surface and X-rays generated using a trigger.

The Cu/Zn Mining mode was selected for use, which allowed the simultaneous detection of over twenty elements, including those of interest in the analysis of historical glass (P, A, K, Mg, Sr, Ca, Mn). The Cu/Zn Mining mode utilises four separate conditions to determine the concentrations in parts per million of selected elements. The on-board software for the XL3t uses a Fundamental Parameters algorithm to determine concentrations of each element within the range of those analysed. Of the four conditions, all were needed to gain readings of the elements needed for windows analysis: Main (15 seconds), low (15 seconds) high (15 seconds) and light (30 seconds), making a total sample time of 75 seconds 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, then multiplied according to a standard element oxide conversion table to produce a percentage by weight of each oxide.

It should be noted that this system is accurate for heavier elements but becomes increasingly inaccurate for lighter elements (Kennedy, Murdoch, and Kirk 2013). As such, although figures for light elements such as silicon, magnesium and aluminium were produced by the XL3t, they are not presented here.

RESULTS

ULLAPOOL

Ten shards of window glass were analysed from Ullapool, in addition to other glassware items. Of these three appear to be kelp fluxed glass, and seven could not be classified distinctly by the Dungworth and Girbal model.

STIRLING

Ten shards of window glass were analysed from Goosecroft Road, Stirling. Of these, eight appear to be standard kelp fluxed window glass and two could not be classified using the Dungworth and Girbal model.

HUME CASTLE

15 shards of glass recovered from Hume Castle were analysed, of which four could not be readily classified using the Dungworth & Girbal model. Of the remainder, one was a HLLA glass, one was kelp fluxed and six were synthetic soda glass. This range of glass typologies suggests a broad range in the age of glass found on site.

TRAQUAIR HOUSE

144 panes of glass from various locations around the house were analysed using X-ray fluorescence. The vast majority of these neatly fitted into Dungworth & Girbal's dating model as either kelp fluxed glass or synthetic soda glass dating from ~1700 or later. However three panes from a wing dating to 1690, and where the fenestration appears to be original, could not be classified by the model.

UNCLASSIFIED GLASS SHARDS

In each of the sites listed, a number of shards of glass did not fit easily into the Dungworth & Girbal model of window glass dating and chemical composition. However, there was a strong similarity between these shards to each other, as shown in Table 2.

DISCUSSION

CHEMICAL COMPOSITION OF UNCLASSIFIED GLASS SHARDS

Shards of glass from three archaeological excavations in Scotland as well as one site where glass remains *in situ* appear to show a strong consistency in terms of chemical composition. The sites – Ullapool, in the highlands of Scotland, Barnton, a suburb of Edinburgh in central Scotland, and Hume Castle and Traquair House in the Scottish borders, are geographically spread out.

TABLE 2.
Chemical composition (%) of the unknown glass shards from Ullapool, Barnton, Hume Castle and Traquair House.

Site	P_2O_5	SO_3	Cl	K_2O	CaO	TiO_2	MnO	Fe_2O_3	CoO	NiO	CuO	ZnO	As_2O_3	BaO	PbO	ZrO_2	SrO
Ullapool	0.86	0.35	0.29	2.75	19.44	0.13	0.02	0.86							0.03		0.38
	1.43	0.52	0.52	2.86	22.48	0.15	0.08	0.93						0.02			0.31
	1.20	0.58	0.29	2.83	20.39	0.15	0.06	1.15						0.02			0.36
	1.46	0.49	0.52	2.91	22.93	0.14	0.07	0.92						0.02			0.31
	1.39	0.49	0.55	2.89	22.92	0.14	0.08	0.94						0.02			0.32
	1.26	0.06	0.09	4.93	21.89	0.11	0.57	0.39						0.17			0.06
	1.33	0.54	0.40	2.87	21.66	0.14	0.07	1.04						0.02			0.34
Stirling	0.93	0.22	0.78	0.77	22.66	0.16	0.05	0.99					0.01	0.01	0.03	0.01	0.44
	0.29	0.17	0.08	1.71	17.24	0.17	0.08	1.38				0.01		0.03		0.01	0.24
Hume Castle	0.51	0.23	0.44	1.28	21.49	0.12	0.03	0.75							0.09		0.23
	1.08	0.53	0.28	2.42	23.46	0.15	0.10	1.71						0.02			0.20
	1.14	0.57	0.32	2.51	24.57	0.17	0.11	1.84									0.22
	0.56	0.44	0.39	1.96	22.78	0.13		0.77						0.02	0.02		0.20
Traquair House	1.32	0.96	0.74	3.43	22.42	0.13	0.16	0.99				0.01			0.01		0.23
	1.18	0.84	0.61	3.39	21.86	0.12	0.14	0.90				0.01			0.01		0.22
	1.36	1.17	0.69	3.40	21.73	0.12	0.14	0.93				0.01			0.02		0.22

Light elements such as the oxides of Magnesium, Aluminium and Silicon have been excluded given the inaccuracy of the XRF system for these elements (Kennedy, Murdoch, and Kirk 2013).

Despite the variations in location there is a high degree of consistency between these unknown samples, particularly in terms of key element oxides such as calcium, potassium and strontium.

According to Dungworth and Girbal (2011) high lime low alkali (c. 1567 to c. 1700) glass is characterized by CaO at ~21.5%, K_2O at ~5.6% and MnO at ~1%. This was followed by kelp fluxed glass (c. 1700 to c. 1835) that is characterised largely by the presence of strontium oxide at ~0.45%. In addition kelp glass was shown to consist of CaO at ~10.4%, K_2O at ~4.2%, with MnO absent.

The unknown samples of glass appear chemically to be a hybrid of both HLLA and kelp fluxed glass. The CaO level of the hybrid glass is approximately 21.5%, the same as HLLA glass, and levels of Fe_2O_3 (~1.1%), SO_3 (~0.35%) are also consistent with this glass type. The hybrid glass also displays a lower level of MnO (~0.1%) and K_2O (~2.2%) than HLLA. What is interesting is the presence of SrO (~0.28%) in the hybrid glass. Kelp fluxed glass is the only glass type to display strontium oxide at any significant level (~0.45%).

The hybrid glass, as it is termed here, appears to display some characteristics of both HLLA and kelp fluxed glass.

Post-medieval glass containing levels of SrO at ~0.25% have been observed previously by Dungworth et al. (2006). However, in those instances the level of CaO was around 9%, significantly lower than the hybrid glass observed here, and the level of K_2O was around 5.9%, around double that observed in the hybrid glass.

TIMESCALE OF THE HYBRID GLASS

Given that this type of glass appears to be a mix of HLLA and kelp glass, it can be speculated that this type of glass was manufactured between these phases. Interestingly, two English sites have shown glass samples of similar chemical composition and ages: Shortlands Lane, Cullompton, Devon, and Apethorpe Hall, Apethorpe, Northamptonshire. In both cases the authors summarized that these glasses were made with a mixture of kelp and non-kelp alkali fluxes (Girbal and Ford 2011; Dunster 2011).

Turnbull (2001) noted that kelp was used in glassmaking in Scotland in the second half of the 17th century; in 1661, botanist John Ray visited a glassworks on his journey between Bass Rock and Leith, most likely at Westpans, and saw kelp and sand mixed together (Ray 1760). At Leith itself, a legal dispute at the glassworks there was resolved in 1664 with Edward Dagnia ordered to pay Robert Pape 5s 4d for kelp. Turnbull suggests that the kelp was available through a local coastal trade and as such, relatively inexpensive.

Further, in 1678 Sir James Stanfield and partners established another glassworks in Leith, Edinburgh. Stansfield's papers show that he purchased raw materials for use in the glassworks including barilla from London, and kelp from Borrowstoneness, near Linlithgow (Turnbull 2001). Of interest to this research is the procurement of two different fluxes for use at the same site, at the same time.

There is evidence that kelp was used as an alkali flux for glassmaking in England and Wales from the 1660s (Dungworth 2009). Dungworth et al. (2006) noted the presence of strontium oxide in glass manufactured in Yorkshire, England, from 1680, though this was at the time restricted to tableware and not window glass.

Some clue regarding the dates of manufacture can be given by the sites themselves. Hume Village dates to the mid-12th century. Hume Castle itself was originally a medieval stronghold dating back to the 13th century. It was destroyed in 1651 before being rebuilt as a folly in the late 18th century. Interestingly, this means that the only time Hume Castle was not in operation as a castle was during the period when kelp was used as an alkali flux; Hill et al. (2023) suggest that another building or buildings, built on top earlier structures, were in use for many years following the destruction of the castle, with the presence of the window glass suggesting that these buildings may have held a high status in the remaining village during this period. These buildings, constructed between the destruction of the castle and the construction of the folly, are the most likely source of the presence of the hybrid glass.

The Inverlael site at Ullapool was a thriving community from the 14th century, until it was cleared by court order in 1819/20. The archaeological excavations date back to the 1600s, covering glass manufacture periods of High Lime Low Alkali, and kelp fluxing (McKeggie 2024).

Perhaps a key indicator of date comes from Traquair House where the panes of glass were examined in situ. The wing that contained the three panes showing the hybrid glass was constructed in 1690. Assuming the glass is original to this time, and there is no indication

that the glass is not, then this could clearly indicate a late 17th century date for the hybrid glass type.

ORIGINS OF THE HYBRID GLASS

Given the lack of information available on where the glass was manufactured, it is not possible to give a detailed account of its origins. In terms of chemical composition however, this type of glass bears the hallmarks of both HLLA and kelp fluxed glass. It would be a reasonable assumption therefore that this glass type represents a transition between the two. Glassmakers perhaps incorporated a smaller amount of kelp into the melts initially, before using it exclusively.

There is also no way at present to know categorically if the glass analysed here was manufactured in Scotland, say at Leith, or if it was imported from elsewhere.

One other prospect is that this glass type is representative of cullet, where broken glass of one type (say, HLLA) was added to the melt of another type of glass (kelp). This however is unlikely as the consistency of the chemical compositions of the glass found in disparate locations suggests that this was manufactured in this way over a period of time, rather than in a single melt.

CONTEXT AND SIGNIFICANCE

The Scottish glass industry of the late 17th century was relatively small in comparison with the English industry at the time (Turnbull 2001). Few glassworks were operating and manufacturing window glass at this time; Leith was perhaps the most significant of this time, being the only site manufacturing bottle and window glass in Scotland between 1661 and 1698. Window glass was both manufactured in Scotland and imported from England during the late 17th century.

Further, in the 1690s, the English parliament introduced excise duty on glass to help pay for the war with France. This tax caused significant issues for the English glass industry in that decade; two new glasshouses were formed in Scotland following this, in Glasgow and at Morison's Haven. Turnbull (2001) speculates that skilled English glassmakers who were lacking employment were brought to Scotland to augment and expand the existing workforce.

Given that similar glass was found in England, this suggests several possibilities for the creation of hybrid glass. Firstly, hybrid glass may have been manufactured at Leith in the late 17th century and also manufactured in England in parallel. Secondly, the hybrid glass may be English in origin, having been imported to Scotland from the 1660s to the 1680s during periods when Leith could not meet Scottish demand. Finally, it may be the case that skilled English glassmakers coming to Scotland in the 1690s brought the technology of the hybrid glass with them.

In any case, the existence of the hybrid glass offers a significant opportunity for the dating of window glass using pXRF. When the hybrid HLLA/kelp glass is observed chemically, it can be assumed that this glass was manufactured between the phases of glass manufacturing using HLLA and kelp, in the late 17th century. Whilst specific dates cannot be ascribed to this glass type as yet, as per the Dungworth and Girbal model, it does offer a clear indication of the age of the glass under analysis. When assessing samples of glass either from archaeological sites or *in situ*, the presence of hybrid glass can give a strong indication of the context of the site.

CONCLUSION

From a range of Scottish sites, a chemically distinct form of glass has been found. This glass appears to represent a transitional form of glass, with characteristics of both high lime low alkali (HLLA) and kelp fluxed glass. This glass is likely to have been manufactured in the late seventeenth century, before kelp became the dominant flux in the glass industry in both Scotland and England.

Given that this glass was found in a geographically spread out set of locations, from both archaeological excavations and also *in situ*, and that the chemical composition is very consistent, it is likely that for a period of time at least one glassworks, possibly in Leith, was manufacturing this 'hybrid' glass type. The Leith glassworks have very recently been excavated; future chemical analysis of any glass recovered from that site may yield more answers.

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DECLARATION OF INTEREST

No potential conflict of interest was reported by author(s).

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