ANALYSES OF EARLY MEDIEVAL STAINED WINDOW GLASS FROM THE MONASTERY OF BAUME-LES-MESSIEURS (JURA, FRANCE) *

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The collection of early medieval window glass found in the abbey of Baume-les-Messieurs (Jura, France) is exceptional because it dates to the end of the eighth century, and due to the number of fragments as well as their state of conservation. Different colours and forms have been identified. These pieces are a rare opportunity to address the glass craft, its recipes and techniques for a phase of its history that has remained little known. Analyses in PIXE–PIGE prove that, in addition to fragments from two soda glass items, the pieces are made from wood-ash glass. Most of them probably came from the same production and the raw material is present in the region. At this early stage of wood-ash glass production, the glassmakers had mastered the glass as well as the colour processes.

KEYWORDS: STAINED WINDOW GLASS, EARLY MIDDLE AGES, PIXE–PIGE, NATRON, WOOD ASH, COLOURING PROCESS

INTRODUCTION

At the end of the Merovingian period (AD 450–750), with the abandonment of burial gifts, scholars lose a valuable source of information for the history of glass. In north-western Europe, out of the graves, early medieval glass remained rare and, even if written sources confirm the use of window glass (Cramp 2000, 2006), these sources were long neglected by the archaeologists and glass specialists (Foy and Fontaine 2008). Fortunately, the increase in excavations has revealed the importance of glass in architecture (Foy 2005; Balcon-Berry et al. 2009). This material will certainly enlighten a phase of significant changes in glass technology.

Indeed, antique glass found in north-western Europe was made from a mixture of sand and natron (Henderson 1985). This latter material being unavailable in Europe, glassmakers had to

*Received 12 December 2014; accepted 13 May 2015
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import it from the eastern Mediterranean, most probably already fused with sand (Freestone et al. 2000, 2002; Freestone 2003; Foy et al. 2003). With the fall of the Western Roman Empire, the material supply could have become complex. If they could no longer import material, craftsmen would have had to recycle the existing stock of glass or to use new types of materials to shape fresh pieces of glass. This situation led to the development of glass based on the use of sand and wood ashes that were available locally, but the location, the conditions and the exact moment of the swing from one flux to the other remain unclear.

In order to retrace the evolution of glass at the beginning of the Middle Ages, several research papers have been written on vessels, mainly those of grave goods (Velde 1990; Wedepohl et al. 1997a; Mirti et al. 2000; Foy et al. 2003; Freestone et al. 2008; Motteau and Velde 2013). The composition of the glass found in north-western Europe seems to be at first quite homogeneous and recycling appears limited. Until the sixth century, glass was still imported from the eastern Mediterranean (Freestone et al. 2008). After that period, the compositions turned out to be much more varied and the sources of supply became less traceable. In the meantime, the increasing demand for glass in monumental architecture may have contributed to the development of a new type of material. The first traces of potash window glass were found in Germany at the Paderborn site, dating from the end of the eighth century (Wedepohl et al. 1997b). Later, it was also confirmed at the abbeys of Lorsch, Corvey, Brunshausen-Gendersheim and Fulda (Sanke et al. 2002; Kind et al. 2003; Wedepohl 2003), in Stavelot (Belgium) (Van Wersch et al. 2014) and at three French sites at least: Blois, Mousson and Saint-Benoît (Gratuze; 2005; Cuvelier and Herber-Suffrin 2009; Prysmicki and Velde 2009). Apart from these locations, research has been carried out on other important collections, such as those from Jarrow and Wearmouth in England (Brill 2006; Cramp 2006; Freestone and Hughes 2006), San Vincenzo al Volturno in Italy (Dell’Acqua 1997; Schibille and Freestone 2013), Rouen in France (Le Maho 2001), Sion and Müstair in Switzerland (Wolf et al. 2005; Wolf and Kessler 2010) and Zalavar in Hungary (Szöke et al. 2004), but the early medieval fragments remain soda glass.

In this context, the discoveries made at the abbey of Baume-les-Messieurs have brought important material to light. This collection gives us a rare opportunity to investigate the material and techniques used in glass production during an important phase of glass history, which lies at the root of stained glass window technology, for which the lack of data is obvious.

SITE AND CONTEXT

Thanks to a research programme at monasteries in Western Europe (5th–10th centuries), excavations took place at the site of Baume-les-Messieurs in winter 2011–12, in the choir of the present Saint-Pierre Abbey (Fig. 1). The oldest trace of occupation is a pit that goes back to the seventh century. Above that was a building made of stone, with a floor covered with a layer of charcoal. Corresponding to the same phase, a deposit (US 6.1212) made of heterogeneous material was found to contain masonry elements, strata with charcoal, ashes and a large amount of window glass fragments. $^{14}$C dating situates layer 6.1212 between AD 776 and AD 968, with the highest probability being AD 776 (sample Lyon-9504 (SacA 30373); age $^{14}$C BP, 1165 ± 30; calibrated time interval, from AD 776 to AD 968). The preparation layer of the floor of a Carolingian building sealed this stratigraphic unit. This floor is dated to the end of the eighth or the beginning of the ninth century by the archaeological material, as well as by a wall from the middle of the ninth century that tops off it. In addition,
a contemporaneous level of the floor is dated from the beginning of the ninth century by $^{14}$C (sample Lyon-9507 (SacA 30376); age $^{14}$C BP, 1155 ± 30; calibrated time interval, from AD 778 to AD 971, the highest probability being AD 800). Considering the $^{14}$C data, the archaeological material and the stratigraphy, the dating of layer 6.1212 at the end of the eighth or the beginning of the ninth century is reliable (Bully et al. forthcoming).

MATERIAL

A total of 1574 pieces equivalent to a total area of 1.89 m$^2$ were found in layer 6.1212. The set is in very good state of conservation (only 70 pieces are covered by alteration). Its visual homogeneity is significant. All the glass is of good quality, with few bubbles and almost no inclusions.
The main hues are light blue–green or naturally coloured glass (Figs. 2 (a) – 2 (c)), light green to olive-green (Figs. 2 (d) and 2 (e)), deep green (Figs. 2 (f) and 2 (g)), amber (Figs. 2 (h) – 2 (j)) and pink to purple (Figs. 2 (k) – 2 (m)). The naturally coloured pieces are the most numerous (621 pieces), comprising about 40% of the set. The amber (15%), pale green (13%) and dark green (11%) have close proportions, while the pink ones are somewhat more numerous (21%). A turquoise colour can also be distinguished, but there are only 17 such fragments (Fig. 2 (n)). Four of the turquoise pieces were decorated with a grisaille (Fig. 2 (n)). On 476 other fragments, red traces and lines were observed. The majority are short lines and spots on the edges.

Figure 2  Window glass fragments found at Baume-les-Messieurs.
or in the middle of the fragments (Fig. 2 (b)). Others are lines along the cut edges (on 106 pieces; Figs. 2 (f) and 2 (l)), and the third variation includes patterns and lines in the middle of the pieces (on about 40 fragments; Figs. 2 (b) and 2 (c)).

Outside of the set found in layer 6.1212, most of the glass windows discovered at the site of Baume-les-Messieurs are fragmentary altered pieces and neither the initial shape nor the colour can be observed. Only two small fragments are an exception (Figs. 2 (o) – 2 (p)). The first one is turquoise and comes from the filling of a Romanesque trench. The second one, which is amber and in the form of an arch, was found in a level floor preparation from the last third of the eighth century, which means that the fragment is earlier, probably Merovingian.

**METHOD**

All the glass fragments and their characteristics were registered in a database (general shape, shape of the edges, thickness, area, colour, bubbles and inclusions). Detailed macroscopic observations were made on most of the complete pieces in order to observe inclusions in the glass matrix and traces on the pieces due to the shaping, to the decoration, to their use and to alteration. Field records were also kept for description of the cleaning treatment done by the restorer. The records include references to the analyses.

For the chemical analyses, given the remarkable state of conservation, we wanted to preserve the intact fragments to the maximum possible extent. Two ion-beam analysis methods, particle-induced X-ray emission (PIXE) and particle-induced gamma-ray emission (PIGE) in external beam mode, were chosen. These have already proved to be efficient for glass analyses and are totally non-destructive methods (Šmit 2013).

The analyses were done on the ARCHEO line of the Institute of Nuclear, Atomic and Spectroscopy Physics (IPNAS) at Liège University. Produced due to a cyclotron with variable energies, a proton beam of 3 MeV, with a diameter of 0.8 mm², is extracted at the end of the line through a Si₃N₄ window that is 100 nm thick. The sample to be analysed is placed 6 mm from the window, with a continuous flux of helium in between to avoid the angular and energy dispersion of the particles.

For PIXE, X-ray spectra are recorded by two detectors placed at 45° to the extracted beam. The first one, a SiLi detector (30 mm², resolution 132 keV) equipped with an ultra-thin polymer window (AP3.7 Moxtek®) is used for detection of the low-energy X rays (Na, Mg, Al, Si, Ca, …). The second one, an UltraLeGe Camberra® germanium detector (50 mm², resolution 160 keV) is for the higher energies (6–35 keV). It is equipped with a beryllium window, and with an aluminium filter with a thickness of 50 μm in order to absorb the rays from the matrix and to be used for the detection of minor and trace elements (Mathis et al. 2010).

The spectra are recorded for 10 min with a current of 5 nA for a flux of 2 μC. The concentrations of Na₂O, MgO, Al₂O₃, SiO₂, P₂O₅, SO₃, K₂O, CaO, TiO₂, MnO, Fe₂O₃, CoO, NiO, Cu₂O, ZnO, As₂O₅, Rb₂O, SrO, ZrO₂, SnO₂, Sb₂O₅, BaO and PbO are calculated with the TRAUPIX program (Pichon et al. 2010), using the code GUPIXWIN (Campbell et al. 2010). The relative error is of the order of 10% for the majors and can go as high as 20% for trace and minor elements. The experimental conditions, such as the errors, are checked by means of regular measurements of the SRM 620, 610 and 612 glass standards from NIST and ROUX et MOUSTIER glass from Glaverbel.

PIGE is used for the detection of Na. The detector for gamma rays is a coaxial germanium device (XtRa HPGe Camberra®), equipped with a thin polymer window, placed at 60° to the
extracted beam. The sodium detection is carried out on the line at 440 keV. It is quantified due to the amount of sodium measured on the SRM 620 standard from NIST.

For the PIXE–PIGE analyses, we selected 39 fragments from layer 6.1212 and the 2 other unaltered pieces. All of them are in a very good state of conservation. On each selected object, three or four points were measured, if possible, on fresh breaks or on unaltered zones. These areas were cleaned with ethanol before the analysis. Note that even on zones that look unaltered, some discrepancies in light element concentrations can be present, especially for Al and Mg, as PIGE measures the Na bulk concentration. The results presented correspond to a mean and are expressed in wt% of oxides (Table 1). Their treatments were then processed using Statistica 0.7.

RESULTS

At first, it appears that two types of glass have been used (Table 1). The potash-ash glass fits with the glass from layer 6.1212. The soda glass corresponds to the amber and to the turquoise fragments from the other contexts.

Soda glass

The composition of the two fragments, the turquoise and the amber, is the one that is typical of natron glass. Sodium is high (18%), while the concentrations of potassium and magnesium remain low (MgO = 0.6% and 0.9%; K₂O = 0.84% and 0.42%). This glass is still produced in the Roman tradition.

In the late Roman period, two major chemical groups have been identified in north-western Europe (Foster and Jackson 2009). Even if subject to discussion, the HIMT group is the most common and was probably produced in Egypt (Freestone 2003; Foy et al. 2003; Foster and Jackson 2009; Nenna 2014), while the Levantine I group is supposed to have been made using sand from the Syro-Palestinian coast (Freestone et al. 2002; Foy et al. 2003). In addition to these, an older Roman glass, blue–green glass, was also available in large quantities for recycling—for the comparisons, we used results published by Jackson (1997), Velde and Sennequier (1985) and personal unpublished data. At the beginning of the early Middle Ages, glass, or at least a part of it, was still imported from the Mediterranean to Europe, as proven for the Saxon I group identified in England, and corresponding to contemporaneous glass found in Italy, Germany and France (Freestone et al. 2008). Alongside new types of glass, these could have been used and mixed to produce the fragments from Baume-les-Messieurs. Concerning the latter, the values for aluminium (2.68% and 2.87%) match the Levantine I glass. The percentage of calcium is also the same in Levantine I and in the turquoise fragment (7.92%), but it is lower in the amber shard (6.49%), which is closer to HIMT or Saxon I glass. The iron values of the two fragments (0.65 and 0.67%) are similar to those of the blue–green and Saxon I glasses. Looking at the components of the sands, these shards could correspond to recycling and/or a mix of different materials.

Some minor and trace elements, such as copper, lead, cobalt or nickel, can be indicative of recycling (Jackson 1997; Freestone et al. 2008), as well as manganese and antimony used as decolourisers (Jackson 2005). In the amber glass, most of the colouring elements are low, except for antimony and perhaps copper. These values, which are higher than the natural concentrations (Freestone and Hughes 2006; Foster and Jackson 2009), may be

due to recycling, because they are not linked with the amber colour. The turquoise glass has very low quantities of manganese and antimony. Of the components bond to its colour, the trace elements remain low and the turquoise glass fragment probably contains little recycled glass.

**Wood-ash glass**

This type of glass corresponds to the greater part of the analysed fragments (39 pieces) and most certainly to the whole set found in layer 6.1212. As indicated by the high percentages of potassium (8.79–16.70%), magnesium (1.69–4.39%) and phosphorus (1.23–3.43%), its composition can be identified with that of wood-ash glass made from a mixture of sand and wood ashes (Henderson 1985).

In this type of glass, the silica sources come from sand or quartz pebbles (Freestone 1992). Wedepohl et al. assume that, as they were established in the woods, medieval glassmakers avoided river sands and preferred to use tertiary sand available in the nearby area (Wedepohl et al. 2011). Few early medieval workshops are known and most of them seem to have been secondary workshops, first settled in the vicinity of abbeys, such as in San Vincenzo, Müstair, Fulda, Lorsch, Corvey and Zalavar or various urban locations (Dorestad, Aachen and Cologne) (Grünwald and Hartmann 2014). However, the silica sources are logically those available in the region, near the production area.

In addition to silica, quartz also incorporates minimal quantities of elements such as aluminium, titanium, iron, potassium, zirconium or barium, and the quartz that comes from sand is also contaminated with other material, adding more aluminium, titanium, iron or zirconium (Götze and Lewis 1994; Wedepohl et al. 2011). In the glass from Baume-les-Messieurs, the silica content varies between 55.44 and 65.51% and that of aluminium between 1.15 and 3.78%. Except for the glass that is coloured deep green, the values are between 0.44 and 1.35% for iron and between 0.13 and 0.25% for titanium. According to their homogeneous concentration and to the weak correlation of aluminium and titanium ($R^2=0.51$), the same source of sand could have been used. Tertiary sand deposits are available in the Jura (Bichet and Campy 2009) and are suitable for glass production, being used by the glassmakers of the 16th century (Marti 2006). More recently, Stern and Gerber (2004) fused Eocene quartz sand from the Jura in order to reproduce ancient glass recipes. In their experiment, sand containing 96.8% silica, 2.62% aluminium, 0.11% iron and 0.19% titanium, mixed with various types and quantities of wood ashes, gave glass with a silica content between 67.80 and 54.8%, aluminium between 1.43 and 4.97%, iron between 0.22 and 2.45% and titanium between 0.12 and 0.37% (Stern and Gerber 2004). Our glass fits within these parameters. Thus, sand from the Jura could have been used, although this composition is not sufficient to definitively reject other origins.

The glassmakers who made the glass of Baume-les-Messieurs added wood ash to the sand. This wood-ash material is responsible for the presence of lime and potash (Freestone 1992). Together with these elements, magnesium and phosphorus from the organic process, as well as silica, aluminium, iron, manganese, sodium and titanium are introduced into the glass (Stern and Gerber 2004). Trace elements such as copper, nickel, zinc, barium, strontium and rubidium are also linked to the composition of the soil where plants are grown (Wedepohl et al. 2011). In the wood-ash glass from Baume-les-Messieurs, the strongest positive correlation is the one between manganese and strontium ($R^2=0.93$), which is also correlated with
barium \( (r^2 = 0.83) \) (Fig. 3 (a)). These elements are weakly correlated with potassium. Outside of the pink fragments, two turquoise pieces and one amber piece, strontium and calcium are positively correlated (Fig. 3 (b)), as previously observed by Wedepohl et al. (2011) in wood-ash glass from Germany. Elements from the ash look homogeneous and these could come from the same initial material, at least for the amber, green and naturally coloured glass.

The glass compositions obtained with wood ash are much more variable than those made from natron (Wedepohl et al. 2011). The very large variability is due to different factors: the type of tree used, the soil where it had grown, the felling season (Stern and Gerber 2004) and the part of the tree that was burnt to make the ashes (Turner 1956; Jackson et al. 2005). Of course, in the process, plant species could also have been mixed (Henderson 2013). Suitable woods for glass production, such as oak, beech and pine, are available in the present-day forest around Baume-les-Messieurs and more generally in Jura, but it is currently impossible to re-create the type of ashes used in the glass recipes.
Looking at the composition and the K/Ca ratios (Table 1), we have supposed that the recipes reported by Stern and Gerber (2004), with potash added as an independent element, are unlikely for the glass of Baume-les-Messieurs and that wood ash was directly added to the sand. In his treatise, at the beginning of the 12th century, the monk Theophilus recommends two parts of ashes to one of sand (Bontemps 1876) and, as has been proven previously, the ‘parts’ probably referred to weight (Smedley and Jackson 2002). However, wood-ash glass compositions could change through time.

Based on research on medieval glass found in Germany, Wedepohl et al. (2011) subdivided the production into three periods: AD 780–1000, 1030–1300 and 1300–1500. During the first phase, the potassium level was low, around 9%, and NaCl was as high as 2.5%. For the early stage of the potash glass production (AD 780–1000), bulk trees were used. The low level of potassium (9.3%) was supplemented by the addition of NaCl (2.5%) and the Ca/K ratio was around 1.9. From AD 1030 to 1300, the concentration of potassium rose by 10%, and then fell during the last phase (Wedepohl et al. 2011). The Baume-les-Messieurs set is situated in the archaeological context of the end of the eighth century thus in the first phase. However, the composition varies substantially from the first group of Wedepohl et al. at first, concerning the potassium content. It is almost always above 9% and the highest Ca/K ratio is 1.81%. Second, the sodium concentration is lower than the one observed in Germany. Indeed, the composition of the fragments is closer to the glass from the second chronological phase of Wedepohl et al., but at this early stage of the production, and taking into account all the factors that influence the composition of wood-ash glass, we assume that different recipes already existed in the Carolingian Empire territory.

In this particular area, next to those of German glass, analyses of early medieval wood-ash glass are quite rare. Only some examples dated between the 9th and the 12th centuries can be compared to the fragments of Baume-les-Messieurs. Twelve pieces from Stavelot (Belgium) (Van Wersch et al. 2014) have higher phosphorus and magnesium values. They also contain more calcium and less sodium. Looking at the elements that could come from the sands, all of them are in smaller quantities in the glass from Stavelot. This certainly reveals the use of other types of materials and perhaps differences in the recipes. In France, nine samples of window glass from Blois (Gratuze 2005) as well as the two fragments from Mousson (Cuvelier and...

Figure 3  (a) A triplot of MnO, SrO and BaO. (b) A biplot of the SrO and CaO values in the wood-ash glass.
Herber-Suffrin 2009) show compositions that are very close to those of Baume-les-Messieurs. On the other hand, two fragments from Saint-Benoît (Vienne) are different and would result from a mix of Roman soda glass with wood-ash glass (Prysmicki and Velde 2009).

In order to have more data for French window glass made from wood ash, we have to look at examples dated between the 12th and the 14th centuries. The glass from Baume-les-Messieurs is quite close to 12th- and 13th-century glass from the Île de France (Lagabrielle and Velde 2005) and the north of France (Brill 1999; Brill and Pongracz 2004). However, its magnesium and phosphorus contents are slightly lower. For this period, the French glass compositions are different from one region to another (Barrera and Velde 1989; Brill and Pongracz 2004). As already noted for the vessel, the production of objects was adapted to local methods and available materials (Barrera and Velde 1989). The discovery of early medieval wood-ash glass and its study will allow us to trace the regional evolution of the production processes in order to underline their sustainability or to highlight innovations and external influences.

In the set from Baume-les-Messieurs, the light blue–green hue is the most common. This material may be considered to be the basic glass and certainly the easiest to obtain. In comparison with the other samples, naturally coloured material contains slightly lower potassium values. Phosphorus and sodium are more concentrated. The chlorine content also appears to be somewhat higher. As the latter remains less than 0.3%, it is considered as coming from the plant elements, rather than being added in form of NaCl (Gerth et al. 1998). The higher value of these elements in naturally coloured glass might be related to the firing time. According to Theophilus, colourless glass appeared first and coloured glass should spend more time in the furnace (Cannella 2006). During the production of wood-ash glass, Gerth et al. (1998) noticed the emission of H₂O, CO₂, Cl, Na and CH₄. We suppose that if glass was heated for a longer period, more gas could escape, but this should be confirmed by experimentation. The difference in compositions between naturally coloured and coloured glass is also due to the material used to obtain particular hues.

The colouring process

In order to colour the glass, craftsmen could add elements deliberately, and the use of metal oxides was common and widely practiced (Freestone 1992). On the other hand, Theophilus mentioned colours that appeared in some glass crucibles without pointing out the addition of colouring agents (Bontemps 1876). Indeed, wood-ash glass allows the production of various hues that natron glass does not, due to the iron and manganese contents of the ash, as well as to the melting procedure and the atmosphere (Sellner et al. 1979). This process has been demonstrated through experimental glass production (Gerth et al. 1998; Stern and Gerber 2004). In our results, we detected both processes.

Turquoise

In the only soda-glass fragment, the turquoise colour is clearly linked to the presence of copper (2.79%). It has been introduced into the batch in the form of bronze, because tin is also present in considerable amounts (0.42%) (Fig. 4 (a)). This is the case for most of the turquoise soda glasses from the early medieval period, such as those from Wearmouth and Jarrow, in which the alloy
contains 89.3% copper and 10.7% tin (Brill 2006). In Baume-les-Messieurs, the bronze used displays close ratios, with about 86% copper and 13% tin.

Despite the change of flux, copper alloys were still used to make wood-ash turquoise glass. The correlation of copper (1.2–2.4%) and tin (0.14–0.17%) indicates the addition of bronze to the batch (Fig. 4 (a)). The alloy also contained zinc (0.038–0.049% in turquoise glass, versus 0.023–0.033% in colourless samples).

In samples BLM 82 and 38, higher amounts of copper and arsenic were found, but less zinc and chlorine than in BLM 190 and 192. In BLM 82 and 38, lead was also present in higher quantities (0.21–0.026%), while it did not reach 0.1% in BLM 190 and 192. This could be due to the alloy composition, but researchers also noticed a thin layer with lead contamination from the alteration of the lead fixations and from the grisaille (Calligaro 2008). Even when we analysed clean surfaces and fresh breaks, we preferred to remain cautious about the lead concentrations of these pieces, which show evidence of both lead fixations and lead grisaille (Fig. 2 (n)).

Deep green

The addition of metallic elements is also responsible for the deep green colour. Iron is clearly present in higher quantities (≥3%) in these fragments than in the others (Fig. 4 (b)). The BLM 177 and 181 pieces display more antimony than BLM 163 and BLM 194.

In other medieval glass, copper was used to colour the glass green (Wedepohl et al. 2011). The addition of iron oxide has also been reported. It was introduced as crocus martis or Crocum-ferri, and sometimes as hematite (Lapis-ematitidis); Marcassite or Marchesita, iron and copper double sulphide and Armenian bole have also been mentioned (Moretti and Hreglich, 2013). Looking at the results, the iron introduced in the Baume-les-Messieurs glass was quite pure and the material contained no sulphur, copper or clayed minerals. It is possible that iron filings were added to the batch, also including antimony. However, it is quite a common material, certainly available in the region.

Pink to purple

In the pink and purple fragments, the colour is due to Mn$^{3+}$ (Sellner et al. 1979). The manganese content (0.8–2.06%) is clearly higher than in all the other colours (Fig. 4 (b)). According to Theophilus, the pink glass could appear in some crucibles and could be heated for a longer time.

Figure 4  Colouring elements in the glass from Baume-les-Messieurs: (a) a biplot of the Cu$_2$O and SnO$_2$ values; (b) a biplot of the Fe$_2$O$_3$ and MnO values.
in order to obtain a darker colour (Bontemps 1876). However, the increase in manganese cannot
be caused by the heating process; it must have been higher in the batch on purpose or
accidentally.

Manganese can be used to colour or discolour the material. In soda glass, in order to obtain
colourless material, glassmakers used mainly pyrolusite or psilomelane (Jackson 2005).
Manganese is also naturally present in wood ash and, in the glass, a quantity between 0.5%
and 3% can originate from it (Stern and Gerber 2004). In the pink fragments, strontium is high
and is correlated with barium and manganese (Fig. 3 (a)). These can come from plant elements.
The selection of specific plant species or perhaps a specific part of the tree could lead to these
compositions. In that regard, some authors have proved that beech is richer in manganese
(Royce-Roll 1994).

Amber and light green

The charge transfer between \( S^{2-} \) and \( Fe^{3+} \) must be responsible for the amber hue (Biron and
Chopinet 2013, 54–5). In the amber soda fragment, sulphur (0.21%) and iron (0.67%) are not
especially high. In wood-ash glass, sulphur (0.04–0.12%) and iron (0.94–1.06%) also remain
quite low. Yet 0.2% of \( Fe_2O_3 \) and 0.01% of \( SO_3 \) are enough to give an amber colour as long
as a reducing agent is present in the batch (Gerth et al. 1998).

As for pink, Theophilus does not mention any addition to create shades of yellow (Bontemps
1876), but other medieval and modern texts refer to olive trees or birch bark (Cannella 2006),
and carbon is added in modern glass (Gerth et al. 1998). The amber fragments of Baume-
les-Messieurs have slightly higher potassium, magnesium, aluminium and titanium values. Inten-
tionally or not, some kind of plant elements could have been present in higher quantities in order to
obtain this specific colour.

The sets of amber glass BLM 159 and 167 are different due to their magnesium content, which
is around 4%, while the others are around 2%. These samples are also higher in potassium and
lower in calcium and manganese. The concentrations of copper (0.033–0.034%) and rubidium
(0.031–0.033%) are significantly above those of the set. On the contrary, strontium, zirconium
and barium are lower. These two fragments, a rectangle and a trapezium, are the darkest of the
amber fragments.

In the light green glass, no distinctive chemical elements could be identified as having been
added for colouring purposes. The three light green samples show no real tendency and no clear
chemical difference from the light blue–green or amber glass. This colour is probably due to a
more oxidizing atmosphere during firing.

The use of the glass

According to the marks made with tools on the edges (Fig. 5 (a)) and to the presence of elongated
bubbles, the fragments were cut into glass sheets made by blowing (Foy 2005). The shapes are
varied: squares (about 10 pieces), rectangles (56), circles (11), quarters (13) and arches (50).
Some pieces even correspond to heads, feet, arms and/or legs (Figs. 2 (j) and 2 (m)). Some are
very close chemically. Looking at the composition and at their visual resemblance, it is tempting
to see elements from the same initial glass sheet. BLM 1 and BLM 2 are two heads in clear pink
glass. BLM 157 and BLM 169 correspond to the two dark amber pieces. BLM 160 and BLM 161
are two pink diamonds. BLM 82 and 38 also display the same turquoise colour as BLM 191 and
192, which could be reassembled.
In order to cut out the glass sheets, Theophilus refers to preparatory drawings made with chalk (Bontemps 1876). The red traces observed on pieces, especially those along the edge, could be the remains of these drawings (Figs. 2 (f) and 2 (l)). A first analysis made on this material reveals its heterogeneity and shows that it is mainly made of calcium (Table 1). It may correspond to the chalk described by Theophilus. However, this does not explain the presence of drawings in the middle of the pieces (Figs. 2 (b) and 2 (c)). Grisaille observed on the turquoise glass is mainly composed of lead and has nothing in common with the red traces (Table 1). The question persists as to why preparatory drawings would remain on the finished fragments. To solve this problem, more analyses were done in order to define this particular material and to observe its relation to the glass (Veronesi et al. 2014).

The presence of potential preparatory drawings on the fragments may lead to considering the glass fragments as the remains of a workshop. Yet, in addition to these, layer 6.1212 contained a keystone from a window and one small lead fragment. On two turquoise pieces, the white coating on the edges is indicative of the insertion of the fragments (Fig. 2 (n)). As shown by the traces left on the glass (Fig. 5 (b)), as well as by analysis, which proves a higher presence of PbO in these particular traces (Table 1, sample 167), the pieces of glass were set in lead. Moreover, some are impossible to insert because of distortion. They were deformed by heat and, in piece 519, sand inclusions were inlaid into the soft glass (Fig. 5 (c)). These deformations are due to fire. Indeed, the heat fused pieces together and smoke layers have been observed on some of them. The ash layers in US 6.1212 testify to a fire that certainly destroyed or damaged the building and the windows. At Jumiège Abbey, such pieces were found in a pit near the church. The glass fragments found may be due to the removal of a window (Le Maho 2013). At Baume-les-Messieurs, after a fire, the windows were certainly dismantled and the lead was gathered up, but—fortunately for us—the glass was left behind.

CONCLUSIONS

The stain glass windows from the Baume-les-Messieurs monastery are remarkable for the history of glass. The PIXE–PIGE analyses performed on 41 samples identified natron glass (2 pieces) and wood-ash glass (39 pieces) as existing before the end of the eighth century. Some of the wood-ash glass fragments are quite homogeneous in appearance and composition. At this early phase, the craftsmen had mastered recipes for making and colouring the glass by using local materials. Their compositions were different from those identified at contemporaneous German sites, but closer to French samples. To find out if a workshop existed in the Baume-les-Messieurs monastery, more extended archaeological excavations should be undertaken at the site.
ACKNOWLEDGEMENTS

The study was made possible thanks to a postdoctoral fellowship of the University of Burgundy (UMR 6298 Artehis), as part of a project directed by Dr Christian Sapin and financed by the Region de Bourgogne, as well as by the University of Liège. We would like to thank the DRAC Franche-Comté, who funded the restoration of the window glass, and Carine Bayol, who did the work. Finally, we are also grateful to the referees, who improved this paper through their comments and corrections.

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