Raw materials and technology of Medieval Glass from Venice: the Basilica of SS. Maria e Donato in Murano

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Abstract: Assemblages of medieval glass from Venice, the leading glassmaking centre in Europe, are rarely accessible for analysis. Here we present electron microprobe analyses of sixty-one glass vessels dated to between the 12th and 15th centuries from the island of Murano, which from the late 13th century was the centre of glass production in the city. All appear to have used the same type of soda ash, with similar levels of soda, magnesia, potash and phosphate and this is likely to have originated in the Levant. The alumina, iron and titanium contents suggest that three different silica sources have been used for the glass. Comparison with the available data from Venice and elsewhere in northern Italy suggests that the assemblage may include material made on the island. Furthermore, there are similarities with glass from the Levant and Egypt raising the possibility that raw glass from several regions may be represented. However, records indicate that Venice imported sand as well as raw glass from the Levant, which remains a possibility in the present case.

Keywords: Medieval glass technology; Venetian glass; Levantine plant ash glass; Egyptian plant ash glass

1. Introduction

The city of Venice rose to become the leading producer of glass in the European Renaissance (15th-17th centuries) and its products were exported across the world (Tait 1979). Documentary evidence in the Venetian Archives suggests a more-or-less uninterrupted tradition of glassworking from at least the tenth century, and certainly by the mid-thirteenth century Venice was importing raw materials such as sand and ash from the eastern Mediterranean, indicating that her artisans were manufacturing raw glass at that time (Zecchin, 1990:175, 1987:5). However, the origins of this industry are still not fully understood. The remains of a glass workshop on the nearby island of Torcello in the seventh century has been considered as early evidence of a Venetian glass industry (Leciejewicz, 2002, 2000; Leciejewicz *et al.*, 1977; Tait, 1979) but the presence of mosaic tesserae in the workshop (Tabaczinska, 1968) places it with workshops excavated elsewhere in Italy where the activity was based upon the recycling of old Roman natron glass (Bertini *et al.*, 2020; Schibille and Freestone, 2013; Silvestri and Marcante, 2011). The comment by Tait (op. cit.: 9) that "distressingly little has survived to support....an unbroken history [of Venetian glassmaking] from Roman times" remains true.

Venetian glass was a soda-lime-silica type, based upon fusing the ashes of halophytic plants with silica. This is the technology adopted across the Middle East following the demise of the natron tradition in the 9th century (Phelps *et al.*, 2016; Schibille *et al.*, 2019). Venice was an important trading nation and it has been suggested that Near Eastern plant ash glass technology was directly transferred to the city through its trading network (Jacoby, 1993; Whitehouse, 2014). Furthermore, in 1124 Venice laid siege to and conquered the city of Tyre, where it maintained an enclave until its conquest by the Mamluks in 1291. Literary and documentary evidence shows that Tyre was well known as a source of high-quality glass material (Carboni *et al.*, 2003) and it was the location of a major production site of raw glass (10th-11th century), excavated by Jennings et al. (2001) (Aldsworth *et al.*, 2002). Implicit in the documents is that raw glass was transported from Tyre to Venice and Whitehouse has suggested the possibility that Tyre played a role in the transmission of glassmaking know-how to Venice (in Carboni et al., op. cit.: 149). On the other hand, since plant ash glass was widely used in Italy during the medieval period (Cagno *et al.*, 2008, 2010, 2012a; Gallo and Silvestri, 2012; Posedi *et al.*, 2019), the technology might have come to Venice through some other Italian centre.

Both documentary and archaeological evidence (Carboni and Whitehouse, 2001; Krueger, 2018; Mack, 2002; Mathews, 2014; Zecchin, 1990, 1989, 1987) have shown that significant exchange of glass raw materials and entire objects between the Islamic world and Italy took place throughout the medieval period. The issues around the origin of Venetian glassmaking should therefore be amenable to investigation through the analysis of the glass materials. However, while decorative Venetian glass of the Renaissance has been subjected to intensive study (Biron and Verità, 2012; Janssens *et al.*, 2013; McCray, 1999, 1998; Šmit *et al.*, 2005, 2004; Thornton *et al.*, 2014; Verità, 1985; Verità and Zecchin, 2009b, 2008) the history of Venetian glass production prior to the 15th century, and its relationship with other glassmaking industries such as those in the Islamic World, have not been addressed in any detail.

The present paper is part of a larger project on the technology of medieval glass from Venice which addresses key questions related to the raw materials used and their provenance. It concerns the compositional investigation of glass retrieved from the Basilica of SS. Maria e Donato in Murano, dated between the 12th and 15th century. The results are used to investigate the raw materials employed, to assess compositional similarities with other medieval Venetian and Italian glass assemblages as well as to identify analogies with glass from the Eastern Mediterranean.

2. Archaeological context

The Basilica of SS. Maria e Donato is located in Murano, the island where all Venetian glassmaking was located from 1291 A.D, when a decree emitted by the State banned the presence of furnaces in Venice and relocated the production of glass to the island of Murano, mainly for safety reasons but also to have better ventilation and to provide more space for the workshops (Zecchin 1987:6). The church was probably founded in the 7th century A.D., restored in the 9th century A.D. then rebuilt in the first half of the 12th century (Gasparetto, 1977). A new external building, which comprised two sacristies, was added to the basilica and was probably built in the 16^{th} and 17^{th} centuries (ibid). Between the end of the 17th century and the first half of the 19th century, a series of haphazard building works altered the structure of the Basilica to the point that its stability was severely compromised. In 1858, the Austrian government, which was at the time ruling Venice, directed a series of restoration works in order to stabilise and conserve the church. During these works, in 1866, the small external building which served as a sacristy, adjacent to the south-east corner of the right nave of the basilica, was demolished. In 1973-6, a significant number of archaeological glass fragments were found in this area during consolidation works on the church foundations and floor (Gasparetto, 1977) The glass was found in a small brick-made cell, circa 30x30 cm, at the level of the church floor, which is lower than the external trampling floor. Its date and function are unclear. This cell might have been made during the demolition in 1866 for the workers to deposit the glass fragments found in the sacristy. Another possibility is that it was a sort of *sacrarium* (which is usually located underground) where broken and unused glasses were discarded together with the holy water employed in purification rituals. It could also have been a collection of broken ecclesiastical glass kept for recycling (Marii and Rehren, 2009). No evidence of a glass workshop was found.

3. Materials and methods

3.1 Glass finds

About 80 glass fragments were retrieved in the basilica of which 61 which presented indicative features have been analysed (Tab.1). The chrono-typological characterisation of the finds will not be discussed in detail here as it can be found in Gasparetto (1977). According to Gasparetto, (1977, 1979) the finds can be dated between the 12^{th} and the 15^{th} centuries; all were for common use and include, bottles, beakers, lamps, window glass and liturgical ampoules (Tabs.1 and 2, Figs.1 and 2). The bottles show varying typological features such as in the shape of the upper part of the neck and in the shape of the rims. All the bottles analysed here belong to the typical Venetian "inghistere": with a long neck and pot-bellied, mostly used to contain water and wine (Gasparetto, 1977) (Figs.1,2 and Tab 2). Beakers of the same type analysed here are known to have been produced in Murano and are the flat-based beaker called in the Venetian documents "moioli"(Gasparetto, 1979, 1958:87; Zecchin, 1990:133). Glass lamps of the type analysed were called "cesendelli", a term that appears in Venetian archives for the first time in 1313 (Zecchin 1990:137).

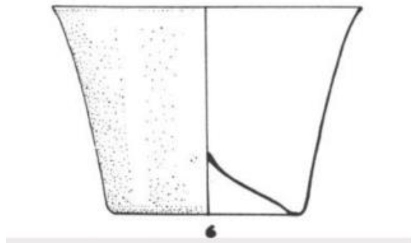
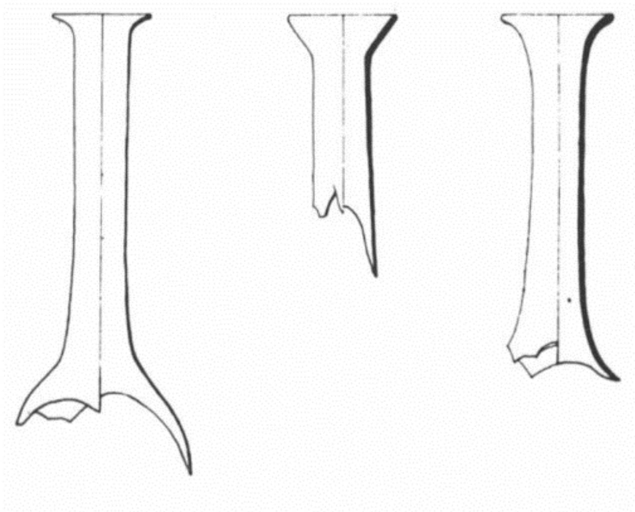
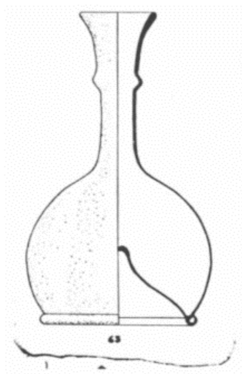
The finds are made of colourless, bluish-green, yellow and grey glass. No opaque glasses have been found. All the glasses are iridescent due to surface weathering.

Figure 1: Examples of the inghistere bottles analysed. The differences in shape of the bottle necks are clearly visible.

Table 1: Identified forms along with the number of samples analysed per type and colour of the samples.

Type	No. analysed	Colour
Inghistera or anghistera	30	Weak blue, weak grey
Flat-based beakers	3	Weak blue
Hanging lamps "cesendelli"	3	Weak blue
Ampoules	11	Weak blue, weak grey
Window glass	3	Weak grey
Unidentified Fragments	11	Weak blue, weak grey

Table 2: Profiles of the analysed types. Drawings from Gasparetto (1979).

	Example of a flat-based beaker, or “moioli”.
	The three hanging glass lamps, “cesendelli” from SS. Maria e Donato.
	Three necks of “inghistere” bottles from SS. Maria e Donato.
	Example of a complete “inghistera” type bottle (Corinth 11th-12th century).

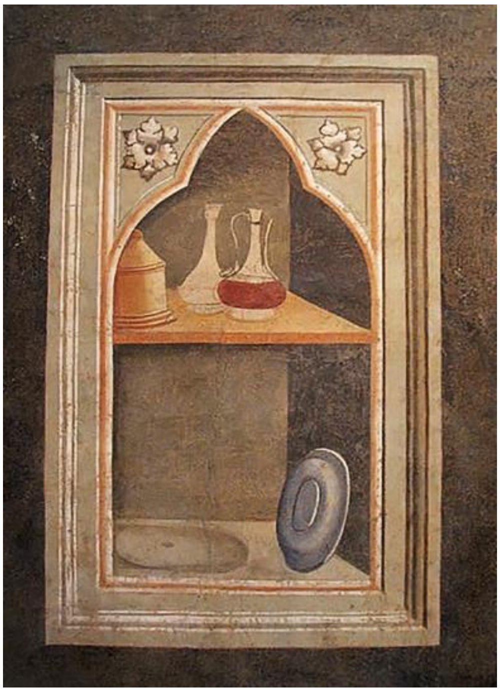


Figure 2:Representation of the typical medieval inghistera and liturgical ampoule in a 14th century fresco by Taddeo Gaddi in the Santa Croce Church, Florence. (Picture from: "Portale di Archeologia Medievale, Università di Siena, Dipartimento di Scienze Storiche).

Nonetheless, the finds cannot be securely attributed to Venetian production. Gasparetto (1977:79) highlighted the presence of motifs and stylistic features which were widely used in the Byzantine and Islamic world, such as the "inverted cone" shape of the mouths of some of the bottles (e.g. C9 in Table 2), typical of some Syrian and Egyptian medieval bottles; the similarity of the hanging lamps to those used in the Byzantine territories as well as later under Islamic administration. Given the location of the assemblage on Murano and given that Venetian glass production had already reached a substantial scale in the 13th century (Verità, 2013; Zecchin, 1987:6), some of these glasses may represent an attempt of the Venetian glassmakers to imitate these characteristics (Gasparetto 1977). Just as it has been assumed that glass fragments retrieved from the Venetian lagoon were made in local factories (Verità, 2013; Verità and Zecchin, 2009a), we assume that the vessels analysed here were blown in Venice, although the raw glass may not have been there.

3.2 Electron Probe Micro-analysis

61 samples were chosen for analysis, which included every form and typology identified in the assemblage, as well as some unidentified fragments that were available. Small fragments of glass of 2-3 mm^3 were removed from the samples, embedded in epoxy resin, ground, polished using a diamond paste up to 1 µm and then carbon coated. They were analysed using a JEOL EPMA JXA-8100 electron microprobe with three wavelength dispersive spectrometers, operated at 15 kV accelerating potential, beam current 50 nA, working distance of 11mm, and a magnification of 800x so that the areas analysed were of approximately 150x110 µm. Counting times were 20s for each peak

and 10s for each background for most elements, while for Al, Mg, Co, Zn, Ba, Fe, Ti, S, P, Cu, Sb, Sn, Sr counting times were 60s on peak and 30s off for the background. The standards used for calibration were a combination of pure elements, oxides and minerals of well-known composition. Every sample was analysed 5 times in different areas and a mean composition calculated. Corning Museum Glass Standards A and B (Brill, 1999) were measured several times at the beginning and at the end of the analytical run (end of Tab. 3). Relative standard deviations were better than 0.2% and 15% for the major and minor elements respectively. Relative accuracy was better than 2% for SiO_2, K_2O and Fe_2O_3, better than 5% for Na_2O, Al_2O_3, TiO_2, CaO, MnO, Sb_2O_3, SO_3, better than 10% for MgO and usually not worse than 20% for the other minor elements (Tab.3). Detection limits varied on the basis of the matrix of the samples, but they were about 0.03% for all elements for these operational conditions. The analyses were performed at the Wolfson Archaeological Science Laboratories, UCL Institute of Archaeology.

4. Results

The electron microprobe results are presented in Tab. 3. All samples are soda-lime-silica glass with relatively high levels of potash (K_2O) and magnesia (MgO) over 2%, consistent with the use of soda ash as a flux (Lilyquist and Brill, 1993). Alumina ranges from 0.73 to 1.76%, and iron oxide from 0.28 to 0.72%. Manganese is present in variable quantities between 0.04 % and 1.56%. In most of the glasses manganese was probably added intentionally as a glass decolouriser in order to counteract the colouring effect of the iron (Sayre, 1963) as it is high relative to the amount naturally present in soda plant ashes (<0.06%; Barkoudah and Henderson, 2006) and in glassmaking sands (around 0.02%; e.g. Schibille et al. 2017; Phelps et al. 2016).

The glasses analysed can be divided into three compositional groups, according to their differing amounts of alumina and titanium oxide (Fig. 3), which can be considered to represent the feldspar and heavy mineral contents of the glassmaking sand respectively (Freestone *et al.*, 2018; Schibille *et al.*, 2017). Mean group compositions are provided in Table 4. Differences between Groups 2 and 3 may be also observed in terms of iron oxide versus alumina (Fig.4); although Group 1 overlaps with the high iron glass of Group 2 in this figure, it is not identical and typically has a relatively high Fe_2O_3/Al_2O_3 ratio.

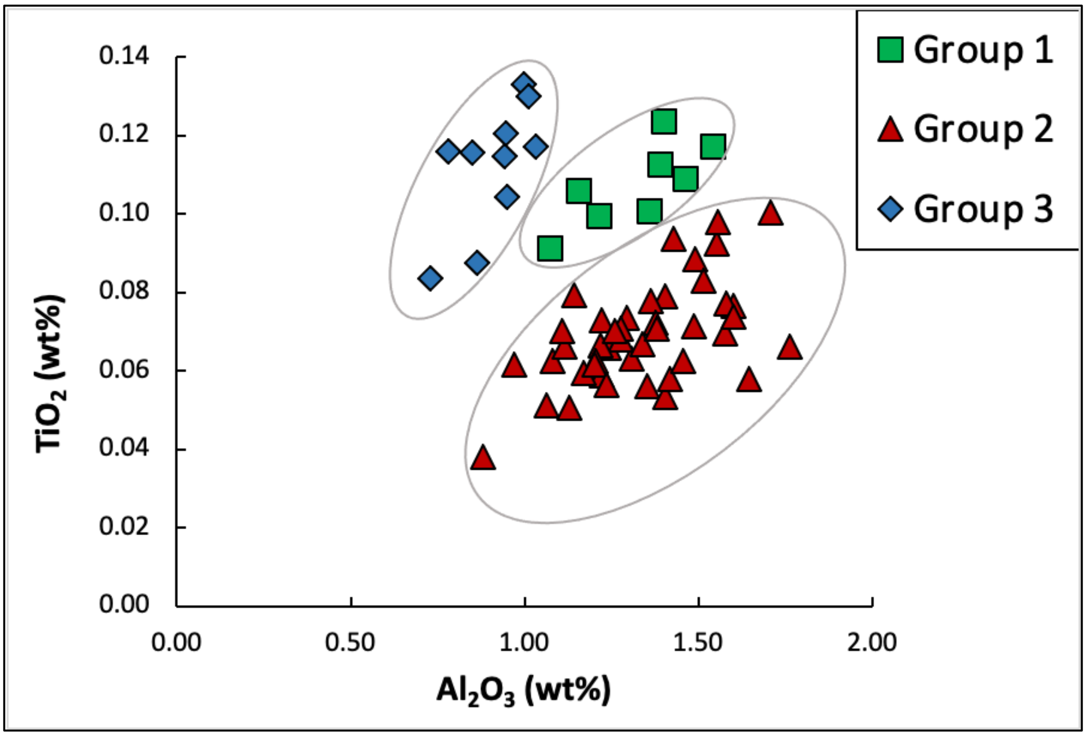


Figure 3: Compositional groups based on the mineralogy of the sand showing the subdivision into three groups.

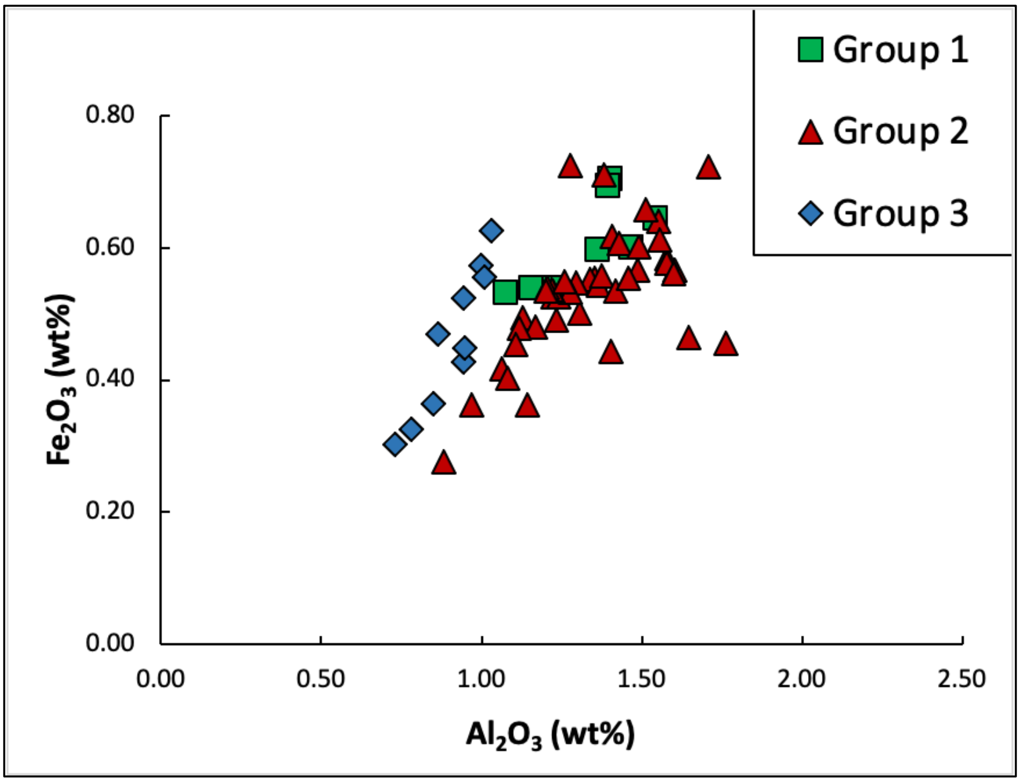


Figure 4: Biplot of iron oxide versus alumina for the groups identified. Differences mainly between group 3 and the other groups can be observed (colour in print).

In contrast to the concentrations of alumina, titanium and iron oxides, those of silica, soda, potash and magnesia are very similar across all three identified groups. The presence in ten samples of contamination by colourants and opacifiers such as lead, tin and copper oxides, in concentration between 100 ppm and 1000 ppm, are generally interpreted as an indication of recycling: these are incorporated to the glass when small amounts of coloured glass are included (Ceglia *et al.*, 2019; Freestone, 2015; Silvestri *et al.*, 2008).

Group 1 encompasses a small group of eight samples and comprises beakers, bottle bases and necks. It is characterised by relatively low contents of calcium oxide (mean 8.76%), moderate contents of alumina (mean 1.33%) and relatively high contents of titanium oxide (mean 0.11%) (Table 4). Iron oxide, introduced as an impurity with the sand, is present in moderate quantities of on average 0.61% (Fig.4).

Group 2 represents the majority of the glass fragments, encompassing 43 samples. This group includes a range of forms such as bottle necks, beakers and bottle bases, window sheets, ampoules and one lamp. The composition of this group resembles Group 1 in terms of both plant ash and sand related elements, but it has significantly less titania (mean 0.07%), suggesting different sands were used to make the glass (Table 4, Fig. 3).

Group 3 is made of 10 samples and comprises one window fragment, one lamp, and several beaker bases and bottle necks. It has the highest contents of lime with a mean content of 10.83%. Group 3 differs significantly from all the other groups in terms of the sand-related elements (Table 4), having significantly lower alumina (mean 0.91%), slightly lower iron yet relatively high titania (mean 0.11%). It is therefore clearly separated in terms of TiO_2/Al_2O_3 and Fe_2O_3/Al_2O_3 ratios (Figs. 3, 4).

Table 3: Chemical composition of all glasses analysed expressed in wt% (average) and standard deviations (sd). The data are not normalised. The type of glass and the compositional group are indicated for each sample. B.d.l stands for below detection limits (≤ 0.03).Values for Corning standards mainly from Brill, (1999) *with additional information from* Adlington, (2017).

Sample name	Glass type	Colour	Group	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	Na_2O	K_2O	MgO	CaO	MnO	CuO	SnO_2	ZnO	PbO	P_2O_5	Cl	SO_3	BaO	Total
GB 1	Beaker base	Weak blue	1	69.3	1.4	0.71	0.12	10.9	3.04	3.39	7.84	0.41	b.d.l.	b.d.l.	b.d.l.	b.d.l.	0.4	0.72	0.23	0.03	98.51
sd				*2.32*	*0.04*	*0.01*	*0.01*	*0.10*	*0.04*	*0.03*	*0.11*	*0.02*	-	-	-	-	*0.03*	*0.02*	*0.01*	*0.02*	
PMPI 2	Beaker wall	Weak blue	1	71.32	1.39	0.69	0.11	11.04	3.05	3.37	7.84	0.37	b.d.l.	b.d.l.	b.d.l.	b.d.l.	0.36	0.74	0.23	0.03	100.57
sd				*2.13*	*0.04*	*0.01*	*0.01*	*0.14*	*0.08*	*0.04*	*0.08*	*0.04*	-	-	-	-	*0.02*	*0.02*	*0.01*	*0.01*	
F 8	Vessel Fragment	Weak blue	1	73.02	1.36	0.6	0.1	10.72	2.27	3.29	8.65	0.49	b.d.l.	b.d.l.	b.d.l.	b.d.l.	0.27	0.63	0.24	0.03	101.76
sd				*0.34*	*0.04*	*0.02*	*0.01*	*0.07*	*0.04*	*0.08*	*0.07*	*0.02*	-	-	-	-	*0.02*	*0.02*	*0.01*	*0.03*	
F 10	Vessel Fragment	Weak blue	1	74.18	1.07	0.53	0.09	11.77	2.1	3.35	8.95	0.26	b.d.l.	0.04	0.04	0.06	0.27	0.72	0.31	0.04	103.83
sd				*0.46*	*0.01*	*0.01*	*0.02*	*0.16*	*0.02*	*0.02*	*0.12*	*0.03*	-	*0.02*	*0.02*	*0.02*	*0.01*	*0.02*	*0.02*	*0.02*	
GB 2	Beaker base	Weak blue	1	72.65	1.46	0.6	0.11	10.71	2.33	3.39	8.95	0.48	b.d.l.	b.d.l.	0.03	b.d.l.	0.27	0.67	0.23	0.04	101.93
sd				*0.49*	*0.04*	*0.01*	*0.01*	*0.08*	*0.05*	*0.03*	*0.08*	*0.02*	-	-	*0.00*	-	*0.02*	*0.01*	*0.02*	*0.02*	
C 12	Bottle neck	Weak blue	1	68.78	1.22	0.54	0.1	12.69	2.12	3.6	8.96	0.28	b.d.l.	0.04	0.04	0.05	0.27	0.7	0.31	0.03	99.74
sd				*1.89*	*0.03*	*0.02*	*0.01*	*0.11*	*0.02*	*0.02*	*0.06*	*0.03*	-	*0.01*	*0.01*	*0.03*	*0.01*	*0.01*	*0.01*	*0.01*	
PI11	Bottle base	Weak blue	1	67.34	1.15	0.54	0.11	11.8	2.08	3.45	9.05	0.26	b.d.l.	0.04	0.05	0.06	0.27	0.72	0.29	0.04	97.28
sd				*0.93*	*0.03*	*0.01*	*0.01*	*0.06*	*0.03*	*0.01*	*0.08*	*0.01*	-	*0.01*	*0.03*	*0.02*	*0.01*	*0.02*	*0.02*	*0.02*	
C 20	Bottle neck	Weak blue	1	70.26	1.54	0.65	0.12	11.6	2.35	3.01	9.88	0.54	b.d.l.	b.d.l.	b.d.l.	b.d.l.	0.28	0.74	0.17	b.d.l.	101.25
sd				*0.47*	*0.04*	*0.02*	*0.01*	*0.06*	*0.06*	*0.06*	*0.05*	*0.02*	-	-	-	-	*0.02*	*0.02*	*0.01*	-	
B 16	Ampoule	Weak blue	2	69.98	1.22	0.53	0.06	11.81	2.3	3.53	7.4	0.48	b.d.l.	b.d.l	b.d.l.	b.d.l.	0.34	0.7	0.26	0.04	98.69
sd				*0.87*	*0.02*	*0.02*	*0.01*	*0.04*	*0.03*	*0.03*	*0.13*	*0.01*	-	-	-	-	*0.02*	*0.02*	*0.02*	*0.01*	
C 16 tr	Bottle neck	Weak grey	2	72.85	1.13	0.5	0.05	13.09	2.45	3.1	8.52	0.53	b.d.l.	b.d.l.	b.d.l.	b.d.l.	0.24	0.73	0.27	0.03	103.55
sd				*1.28*	*0.02*	*0.02*	*0.01*	*0.18*	*0.05*	*0.04*	*0.14*	*0.03*	-	-	-	-	*0.02*	*0.01*	*0.02*	*0.01*	
PI12	Bottle base	Weak grey	2	74.48	0.97	0.36	0.06	11.74	2.33	3.33	8.55	0.34	b.d.l.	b.d.l.	b.d.l.	b.d.l.	0.22	0.75	0.27	0.02	103.47
sd				*2.69*	*0.01*	*0.01*	*0.01*	*0.07*	*0.04*	*0.03*	*0.13*	*0.02*	-	-	-	-	*0.03*	*0.01*	*0.02*	*0.02*	
F 3	Vessel Fragment	Weak blue	2	69.43	1.24	0.53	0.07	11.64	2.24	3.52	8.65	0.37	b.d.l.	b.d.l.	b.d.l.	b.d.l.	0.26	0.71	0.27	0.03	99.03
sd				*1.78*	*0.03*	*0.02*	*0.01*	*0.12*	*0.03*	*0.02*	*0.10*	*0.01*	-	-	-	-	*0.02*	*0.02*	*0.02*	*0.02*	
C 2	Bottle neck	Weak grey	2	65.57	1.6	0.57	0.08	13.38	2.47	3.98	8.66	0.18	b.d.l.	b.d.l.	b.d.l.	b.d.l.	0.29	0.71	0.3	0.01	97.87
sd				*1.73*	*0.04*	*0.01*	*0.01*	*0.12*	*0.02*	*0.03*	*0.10*	*0.01*	-	-	-	-	*0.01*	*0.02*	*0.01*	*0.01*	

Sample name	Glass type	Colour	Group	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	Na_2O	K_2O	MgO	CaO	MnO	CuO	SnO_2	ZnO	PbO	P_2O_5	Cl	SO_3	BaO	Total
VP4	Window fragment	Weak grey	2	68.47	1.14	0.36	0.08	12.88	2.44	3.63	8.67	0.76	b.d.l.	b.d.l.	0.03	b.d.l.	0.26	0.68	0.26	0.03	99.75
sd				*0.95*	*0.02*	*0.01*	*0.01*	*0.12*	*0.05*	*0.02*	*0.07*	*0.02*	-	-	*0.03*	-	*0.02*	*0.03*	*0.01*	*0.02*	
B6	Ampoule	Weak blue	2	68.77	1.58	0.58	0.08	13.77	2.52	4	8.72	0.17	b.d.l.	b.d.l.	b.d.l.	b.d.l.	0.3	0.72	0.31	bdl	101.56
sd				*0.93*	*0.02*	*0.02*	*0.01*	*0.03*	*0.01*	*0.03*	*0.04*	*0.01*	-	-	-	-	*0.01*	*0.01*	*0.00*	-	
C3	Bottle neck	Weak blue	2	67.17	1.35	0.55	0.06	12.55	2.25	4.06	8.72	0.53	b.d.l.	b.d.l.	0.03	b.d.l.	0.28	0.76	0.28	0.02	98.68
sd				*1.77*	*0.02*	*0.01*	*0.01*	*0.09*	*0.03*	*0.03*	*0.06*	*0.02*	-	-	*0.01*	-	*0.02*	*0.01*	*0.01*	*0.01*	
B 14	Ampoule	Weak grey	2	64.36	1.4	0.44	0.05	12.43	2.63	3.93	8.75	0.42	b.d.l.	b.d.l.	0.03	b.d.l.	0.25	0.62	0.29	b.d.l.	95.63
sd				*0.62*	*0.03*	*0.01*	*0.01*	*0.12*	*0.04*	*0.02*	*0.14*	*0.02*	-	-	*0.01*	-	*0.02*	*0.02*	*0.02*	-	
C 8	Bottle neck	Weak blue	2	71.26	1.31	0.5	0.06	11.19	2.37	3.6	8.76	0.48	b.d.l.	b.d.l.	0.05	b.d.l.	0.27	0.61	0.3	0.03	100.84
sd				*2.03*	*0.03*	*0.01*	*0.00*	*0.10*	*0.04*	*0.02*	*0.08*	*0.03*	-	-	*0.01*	-	*0.02*	*0.01*	*0.01*	*0.02*	
B1	Ampoule	Weak blue	2	67.9	1.34	0.55	0.07	12.55	2.35	3.67	8.86	0.38	b.d.l.	b.d.l.	0.03	b.d.l.	0.28	0.68	0.26	0.04	98.95
sd				*0.50*	*0.02*	*0.01*	*0.01*	*0.07*	*0.01*	*0.06*	*0.09*	*0.02*	-	-	*0.02*	-	*0.01*	*0.01*	*0.02*	*0.02*	
Co504	Vessel Fragment	Weak blue	2	69.76	0.88	0.28	0.04	12.95	2.37	3.21	8.88	0.17	b.d.l.	b.d.l.	b.d.l.	b.d.l.	0.23	0.74	0.31	b.d.l.	99.87
sd				*0.68*	*0.02*	*0.02*	*0.00*	*0.11*	*0.02*	*0.02*	*0.12*	*0.01*	-	-	-	-	*0.01*	*0.02*	*0.01*	-	
C7	Bottle neck	Weak blue	2	74.01	1.29	0.55	0.07	11.68	2.32	3.07	8.94	0.47	b.d.l.	b.d.l.	b.d.l.	b.d.l.	0.34	0.76	b.d.l.	b.d.l.	103.79
sd				*0.28*	*0.02*	*0.01*	*0.01*	*0.17*	*0.05*	*0.04*	*0.13*	*0.02*	-	-	-	-	*0.04*	*0.01*	-	-	
B 13	Ampoule	Weak grey	2	71.68	1.06	0.42	0.05	12.28	2.11	3.71	8.94	0.5	b.d.l.	b.d.l.	b.d.l.	b.d.l.	0.25	0.72	0.32	0.03	102.15
sd				*0.70*	*0.04*	*0.01*	*0.01*	*0.09*	*0.01*	*0.03*	*0.14*	*0.03*	-	-	-	-	*0.01*	*0.01*	*0.01*	*0.01*	
F 5	Vessel Fragment	Weak blue	2	70.72	1.28	0.53	0.07	11.78	2.29	3.49	9	0.38	b.d.l.	b.d.l.	b.d.l.	b.d.l.	0.3	0.69	0.31	0.03	100.88
sd				*1.41*	*0.04*	*0.01*	*0.01*	*0.04*	*0.03*	*0.05*	*0.12*	*0.01*	-	-	-	-	*0.02*	*0.02*	*0.01*	*0.01*	
F1	Vessel Fragment	Weak blue	2	64.82	1.58	0.58	0.07	12.09	2.33	4.18	9	0.65	b.d.l.	b.d.l.	b.d.l.	b.d.l.	0.29	0.67	0.32	b.d.l.	96.57
sd				*0.82*	*0.05*	*0.01*	*0.01*	*0.07*	*0.03*	*0.02*	*0.18*	*0.03*	-	-	-	-	*0.03*	*0.02*	*0.01*	-	
B8	Ampoule	Weak blue	2	69.6	1.22	0.54	0.07	11.54	2.23	2.95	9.07	0.43	b.d.l.	b.d.l.	b.d.l.	b.d.l.	0.4	0.77	b.d.l.	0.04	99.06
sd				*1.23*	*0.04*	*0.01*	*0.01*	*0.08*	*0.02*	*0.08*	*0.07*	*0.01*	-	-	-	-	*0.01*	*0.02*	-	*0.02*	
C 13	Bottle neck	Weak grey	2	70.43	1.08	0.4	0.06	12.43	2.29	3.71	9.13	0.71	b.d.l.	b.d.l.	b.d.l.	b.d.l.	0.26	0.71	0.32	0.03	101.65
sd				*0.51*	*0.01*	*0.01*	*0.01*	*0.12*	*0.02*	*0.02*	*0.07*	*0.03*	-	-	-	-	*0.01*	*0.02*	*0.01*	*0.02*	
F7	Vessel Fragment	Weak blue	2	68.24	1.41	0.62	0.08	12.67	2.06	3.5	9.15	0.21	b.d.l.	b.d.l.	0.05	b.d.l.	0.3	0.69	0.29	b.d.l.	99.32
sd				*0.92*	*0.05*	*0.01*	*0.01*	*0.07*	*0.03*	*0.02*	*0.04*	*0.01*	-	-	*0.03*	-	*0.01*	*0.03*	*0.02*	-	

Sample name	Glass type	Colour	Group	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	Na_2O	K_2O	MgO	CaO	MnO	CuO	SnO_2	ZnO	PbO	P_2O_5	Cl	SO_3	BaO	Total
C 10	Bottle neck	Weak grey	2	71.75	1.22	0.54	0.07	10.48	2.25	3.65	9.15	0.67	0.03	b.d.l.	0.04	b.d.l.	0.25	0.7	0.31	b.d.l.	101.14
sd				1.23	0.02	0.01	0.01	0.09	0.03	0.04	0.12	0.01	0.01	-	0.01	-	0.02	0.02	0.01	-	
F 4	Vessel Fragment	Weak blue	2	70.81	1.21	0.54	0.06	10.08	2.22	3.54	9.16	0.64	0.03	b.d.l.	0.04	b.d.l.	0.25	0.73	0.3	b.d.l.	99.65
sd				0.90	0.02	0.01	0.01	0.11	0.04	0.03	0.08	0.02	0.03	-	0.01	-	0.02	0.01	0.01	-	
PI15	Bottle base	Weak grey	2	62.49	1.64	0.47	0.06	13.04	2.53	3.97	9.22	0.4	b.d.l.	b.d.l.	0.03	b.d.l.	0.26	0.74	0.34	0.03	95.24
sd				0.60	0.04	0.00	0.01	0.05	0.04	0.03	0.09	0.02	-	-	0.01	-	0.01	0.04	0.01	0.01	
B 10	Ampoule	Weak blue	2	69.68	1.43	0.61	0.09	11.44	2.75	2.96	9.69	0.55	b.d.l.	b.d.l.	0.03	b.d.l.	0.43	0.76	0.21	0.05	100.7
sd				0.60	0.04	0.01	0.01	0.14	0.02	0.08	0.07	0.02	-	-	0.03	-	0.01	0.02	0.01	0.01	
C5	Bottle neck	Weak blue	2	72.33	1.49	0.6	0.09	11.52	2.75	3.09	9.54	0.56	b.d.l.	b.d.l.	0.04	b.d.l.	0.33	0.75	0.18	0.05	103.39
sd				0.62	0.02	0.02	0.01	0.10	0.03	0.01	0.08	0.02	-	-	0.01	-	0.02	0.01	0.01	0.02	
S1	Lamp	Weak blue	2	67.25	1.55	0.64	0.09	13.62	2.04	3.17	11.59	0.22	b.d.l.	b.d.l.	0.04	b.d.l.	0.3	0.79	0.24	b.d.l.	101.58
sd				2.54	0.02	0.01	0.02	0.14	0.05	0.04	0.06	0.01	-	-	0.01	-	0.02	0.02	0.01	-	
C9	Bottle neck	Weak blue	2	65.22	1.56	0.61	0.1	11.07	2.48	3.61	10.13	0.49	0.03	b.d.l.	0.03	0.05	0.33	0.61	0.23	0.03	96.6
sd				0.49	0.05	0.01	0.02	0.07	0.02	0.01	0.13	0.01	0.02	-	0.02	0.04	0.01	0.02	0.01	0.02	
LA	Lamp	Weak blue	2	69.3	1.71	0.72	0.1	11.74	2.62	3.51	11.78	0.92	0.03	b.d.l.	0.04	b.d.l.	0.33	0.63	0.23	0.04	103.74
sd				0.59	0.02	0.01	0.01	0.11	0.03	0.04	0.04	0.03	0.01	-	0.01	-	0.01	0.01	0.02	0.02	
S2	Bottle base	Weak blue	2	69.45	1.36	0.54	0.08	12.53	2.23	3.05	10.79	0.4	b.d.l.	b.d.l.	b.d.l.	b.d.l.	0.28	0.77	0.21	0.04	101.75
sd				0.84	0.03	0.01	0.01	0.10	0.03	0.05	0.09	0.02	-	-	-	-	0.01	0.01	0.01	0.02	
C 17	Bottle neck	Weak grey	2	66.89	1.51	0.66	0.08	12.89	2.7	3.14	10	0.71	b.d.l.	b.d.l.	0.03	b.d.l.	0.28	0.79	0.24	b.d.l.	99.94
sd				0.26	0.02	0.01	0.01	0.07	0.07	0.02	0.04	0.01	-	-	0.02	-	0.02	0.03	0.02	-	
Co3	Vessel Fragment	Weak blue	2	67.56	1.17	0.48	0.06	11.84	2.36	3.87	9.69	0.04	b.d.l.	b.d.l.	0.04	b.d.l.	0.28	0.57	0.34	b.d.l.	98.34
sd				1.08	0.03	0.01	0.01	0.13	0.03	0.04	0.11	0.01	-	-	0.02	-	0.01	0.02	0.01	-	
C 19	Bottle neck	Weak grey	2	66.59	1.6	0.56	0.07	14.29	2.36	3.65	9.71	1.18	0.04	b.d.l.	b.d.l.	b.d.l.	0.27	0.72	0.32	b.d.l.	101.48
sd				0.23	0.03	0.01	0.01	0.25	0.02	0.10	0.04	0.02	0.01	-	-	-	0.02	0.02	0.03	-	
VP1	Window fragment	Weak grey	2	64.16	1.28	0.72	0.07	11.22	2.38	4.3	9.93	0.46	b.d.l.	b.d.l.	0.05	0.03	0.27	0.72	0.38	0.05	96.07
sd				1.48	0.03	0.01	0.01	0.08	0.04	0.04	0.06	0.02	-	-	0.02	0.02	0.02	0.01	0.02	0.01	
B 7	Ampoule	Weak grey	2	69.42	1.38	0.56	0.07	13.03	2.45	3.86	9.93	0.35	b.d.l.	b.d.l.	0.03	0.03	0.26	0.7	0.3	b.d.l.	102.38
sd				0.50	0.03	0.01	0.01	0.18	0.02	0.05	0.08	0.02	-	-	0.02	0.02	0.02	0.02	0.02	-	

Sample name	Glass type	Colour	Group	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	Na_2O	K_2O	MgO	CaO	MnO	CuO	SnO_2	ZnO	PbO	P_2O_5	Cl	SO_3	BaO	Total
C6	Bottle neck	Weak blue	2	71.56	1.42	0.54	0.06	12.41	2.27	3.13	10.31	0.4	b.d.l.	b.d.l.	0.04	b.d.l.	0.22	0.74	b.d.l.	b.d.l.	103.37
sd				*0.36*	*0.01*	*0.01*	*0.04*	*0.11*	*0.03*	*0.02*	*0.03*	*0.02*	-	-	*0.02*	-	*0.01*	*0.02*	-	-	
C1 tr	Bottle neck	Weak grey	2	68.74	1.2	0.53	0.06	13.06	2.23	3.65	10.44	0.83	b.d.l.	b.d.l.	b.d.l.	b.d.l.	0.21	0.79	0.26	b.d.l.	102.14
sd				*0.17*	*0.01*	*0.02*	*0.01*	*0.13*	*0.04*	*0.03*	*0.14*	*0.01*	-	-	-	-	*0.01*	*0.03*	*0.02*	-	
B 15	Ampoule	Weak grey	2	62.99	1.49	0.57	0.07	11.13	2.21	4.12	10.45	1.56	b.d.l.	b.d.l.	0.03	b.d.l.	0.27	0.68	0.26	0.04	95.89
sd				*1.00*	*0.05*	*0.01*	*0.01*	*0.10*	*0.03*	*0.04*	*0.09*	*0.05*	-	-	*0.02*	-	*0.01*	*0.02*	*0.02*	*0.02*	
C4	Bottle neck	Weak grey	2	69.34	1.46	0.56	0.06	12.84	2.16	3.46	10.55	0.36	b.d.l.	b.d.l.	b.d.l.	b.d.l.	0.23	0.9	0.21	b.d.l.	102.21
sd				*0.40*	*0.02*	*0.01*	*0.01*	*0.09*	*0.03*	*0.03*	*0.04*	*0.01*	-	-	-	-	*0.03*	*0.01*	*0.02*	-	
B 11	Ampoule	Weak blue	2	68.97	1.23	0.49	0.06	12.72	2.23	3.05	10.6	1.24	b.d.l.	b.d.l.	b.d.l.	b.d.l.	0.26	0.85	b.d.l.	0.04	101.99
sd				*0.71*	*0.03*	*0.01*	*0.01*	*0.15*	*0.05*	*0.02*	*0.05*	*0.03*	-	-	-	-	*0.02*	*0.01*	-	*0.02*	
C 21	Bottle neck	Weak grey	2	67.25	1.76	0.46	0.07	14.12	2.45	3.6	10.64	0.37	b.d.l.	b.d.l.	b.d.l.	b.d.l.	0.23	0.78	0.26	b.d.l.	102.07
sd				*0.32*	*0.04*	*0.01*	*0.00*	*0.16*	*0.03*	*0.03*	*0.11*	*0.02*	-	-	-	-	*0.03*	*0.02*	*0.03*	-	
Pl 13	Bottle base	Weak blue	2	70.23	1.26	0.55	0.07	11.67	2.33	2.98	10.85	0.56	b.d.l.	b.d.l.	0.04	b.d.l.	0.3	0.68	0.26	0.04	101.84
sd				*0.52*	*0.01*	*0.01*	*0.01*	*0.13*	*0.02*	*0.04*	*0.10*	*0.03*	-	-	*0.02*	-	*0.02*	*0.01*	*0.02*	*0.01*	
Pl 1	Bottle base	Weak grey	2	70.4	1.12	0.48	0.07	11.59	2.11	2.99	10.95	1.03	b.d.l.	0.03	0.03	0.07	0.26	0.72	0.28	0.06	102.23
sd				*0.51*	*0.04*	*0.01*	*0.01*	*0.03*	*0.05*	*0.02*	*0.13*	*0.02*	-	*0.03*	*0.01*	*0.03*	*0.01*	*0.02*	*0.02*	*0.02*	
C	Bottle neck	Weak blue	2	67.95	1.38	0.71	0.07	11.86	2.28	3.49	11.03	1.07	b.d.l.	b.d.l.	0.03	b.d.l.	0.23	0.69	0.25	b.d.l.	101.14
sd				*0.21*	*0.03*	*0.00*	*0.01*	*0.03*	*0.05*	*0.01*	*0.19*	*0.03*	-	-	*0.01*	-	*0.02*	*0.02*	*0.01*	-	
Pl 3	Bottle base	Weak grey	2	69.19	1.11	0.45	0.07	12.06	2.17	3.03	11.25	0.68	b.d.l.	b.d.l.	b.d.l.	b.d.l.	0.3	0.75	0.24	b.d.l.	101.41
sd				*0.57*	*0.02*	*0.01*	*0.01*	*0.15*	*0.05*	*0.03*	*0.03*	*0.01*	-	-	-	-	*0.02*	*0.02*	*0.01*	-	
VP3	Window fragment	Weak grey	3	64.84	0.73	0.3	0.08	12	2.35	3.81	10.08	0.53	b.d.l.	b.d.l.	0.04	b.d.l.	0.31	0.78	0.45	0.03	96.39
sd				*1.91*	*0.04*	*0.02*	*0.01*	*0.21*	*0.07*	*0.05*	*0.17*	*0.01*	-	-	*0.03*	-	*0.03*	*0.04*	*0.02*	*0.02*	
C 14	Bottle neck	Weak grey	3	70.31	0.78	0.33	0.12	12.22	2.7	3.48	9.59	0.41	b.d.l.	b.d.l.	b.d.l.	b.d.l.	0.25	0.71	0.35	b.d.l.	101.3
sd				*1.27*	*0.01*	*0.01*	*0.01*	*0.07*	*0.04*	*0.04*	*0.08*	*0.04*	-	-	-	-	*0.02*	*0.01*	*0.01*	-	
B5	Ampoule	Weak grey	3	67.5	0.85	0.36	0.12	12.03	2.09	3.71	10.55	0.44	b.d.l.	b.d.l.	b.d.l.	b.d.l.	0.27	0.71	0.38	b.d.l.	99.06
sd				*1.28*	*0.03*	*0.01*	*0.01*	*0.14*	*0.02*	*0.03*	*0.07*	*0.01*	-	-	-	-	*0.02*	*0.03*	*0.02*	-	
Pl 8	Bottle base	Weak blue	3	70.27	0.86	0.47	0.09	11.99	2.02	2.82	11.06	0.44	b.d.l.	b.d.l.	0.03	b.d.l.	0.28	0.75	0.27	0.06	101.46
sd				*0.37*	*0.03*	*0.01*	*0.01*	*0.09*	*0.03*	*0.05*	*0.19*	*0.01*	-	-	*0.02*	-	*0.01*	*0.02*	*0.02*	*0.02*	

Sample name	Glass type	Colour	Group	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	Na_2O	K_2O	MgO	CaO	MnO	CuO	SnO_2	ZnO	PbO	P_2O_5	Cl	SO_3	BaO	Total
PI7	Bottle base	Weak grey	3	70.16	0.94	0.43	0.11	11.64	2.23	4.03	10.45	0.79	b.d.l.	b.d.l.	b.d.l.	b.d.l.	0.24	0.78	0.34	0.05	102.27
sd				*0.65*	*0.04*	*0.01*	*0.00*	*0.08*	*0.02*	*0.05*	*0.09*	*0.02*	-	-	-	-	*0.02*	*0.02*	*0.02*	*0.02*	
S3	Lamp	Weak blue	3	67.53	0.95	0.52	0.12	12.88	2.47	3.21	13.28	0.15	b.d.l.	b.d.l.	0.04	b.d.l.	0.3	0.82	0.24	0.04	102.57
sd				*1.37*	*0.03*	*0.01*	*0.01*	*0.10*	*0.06*	*0.04*	*0.07*	*0.01*	-	-	*0.02*	-	*0.01*	*0.02*	*0.02*	*0.01*	
C 11	Bottle neck	Weak grey	3	69.91	0.95	0.45	0.10	11.39	2.56	3.7	9.68	0.54	b.d.l.	b.d.l.	b.d.l.	b.d.l.	0.27	0.64	0.33	0.04	100.6
sd				*0.61*	*0.03*	*0.02*	*0.02*	*0.05*	*0.04*	*0.03*	*0.06*	*0.02*	-	-	-	-	*0.02*	*0.01*	*0.01*	*0.02*	
F9	Vessel Fragment	Weak blue	3	71.3	1	0.57	0.13	10.61	2.08	3.39	10.65	1.03	b.d.l.	b.d.l.	b.d.l.	0.03	0.26	0.66	0.34	0.08	102.18
sd				*0.25*	*0.03*	*0.01*	*0.01*	*0.05*	*0.02*	*0.02*	*0.11*	*0.03*	-	-	-	*0.02*	*0.02*	*0.02*	*0.01*	*0.01*	
F 6	Vessel Fragment	Weak blue	3	72.89	1.01	0.56	0.13	10.91	2.1	3.54	10.82	0.93	b.d.l.	b.d.l.	b.d.l.	b.d.l.	0.25	0.7	0.29	0.07	104.29
sd				*0.51*	*0.02*	*0.01*	*0.01*	*0.10*	*0.03*	*0.04*	*0.08*	*0.03*	-	-	-	-	*0.01*	*0.02*	*0.02*	*0.02*	
S4	Bottle base	Weak blue	3	68.28	1.03	0.63	0.12	12.12	2.3	2.94	12.18	0.4	b.d.l.	b.d.l.	0.04	b.d.l.	0.27	0.73	b.d.l.	b.d.l.	101.33
sd				*0.51*	*0.02*	*0.01*	*0.01*	*0.10*	*0.04*	*0.05*	*0.12*	*0.02*	-	-	*0.01*	-	*0.01*	*0.00*	-	-	
Corning A	Standard published	–	–	66.56	1	1.09	0.79	14.3	2.87	2.66	5.03	1	1.17	0.19	0.044	0.0725	0.0847	0.1	0.14	0.46	99.6
Corning A	Standard measured(n=5)	–	–	66.22	1.08	1.06	0.78	14.02	2.9	2.54	5.02	1.02	1.07	0.2	0.07	0.05	0.08	0.09	0.14	0.5	99.58
SD	–	–	–	0.21	0.05	0.01	0.01	0.42	0.02	0.05	0.02	0.03	0.03	0.03	0.03	0.02	0.01	0.01	0	0.03	0.014
Absolute error	–	–	–	-0.34	0.08	-0.03	-0.01	-0.28	0.03	-0.12	-0.01	0.02	0.9	0.01	0.026	-0.02	-0.01	-0.01	0	0.04	-0.02
Corning B	Standard published	–	–	61.55	4.36	0.34	0.09	17	1	1.03	8.56	0.25	2.66	0.0241	0.19	0.61	0.82	0.2	0.5	0.077	99.65
Corning B	Standard measured(n=5)	–	–	60.62	4.41	0.33	0.11	16.61	1.06	1.03	8.64	0.25	2.4	0.03	0.2	0.5	0.81	0.17	0.51	0.09	98.23
SD	–	–	–	0.1	0.02	0.02	0.02	0.67	0.01	0.02	0.1	0.01	0.03	0.01	0.01	0.02	0.08	0.01	0.03	0.02	1
Absolute error				-0.93	0.05	-0.01	0.02	-0.39	0.06	0	0.08	0	-0.26	0.01	0.01	-0.11	-0.01	-0.03	0.1	0.01	-1.42

Table 4: Mean compositions and standard deviations of the three groups identified.

	Group 1 (*n*=8)		Group 2 (*n*=43)		Group 3 (*n*=10)	
	Mean wt%	s.d.	**Mean wt%**	s.d.	**Mean wt%**	s.d.
SiO_2	70.86	*2.35*	68.81	*2.73*	69.30	*2.29*
Na_2O	11.40	*0.69*	12.25	*0.92*	11.78	*0.67*
CaO	8.76	*0.67*	9.62	*0.98*	10.83	*1.13*
K_2O	2.42	*0.40*	2.35	*0.17*	2.29	*0.23*
MgO	3.35	*0.17*	3.51	*0.38*	3.46	*0.38*
Al_2O_3	1.33	*0.16*	1.34	*0.20*	0.91	*0.10*
Fe_2O_3	0.61	*0.07*	0.53	*0.09*	0.46	*0.11*
BaO	0.03	*0.01*	0.03	*0.01*	0.05	*0.02*
TiO_2	0.11	*0.01*	0.07	*0.01*	0.11	*0.02*
MnO	0.39	*0.11*	0.56	*0.31*	0.57	*0.27*
PbO	0.05	0.01	0.03	0.02	0.03	*0.01*
Cl	0.71	*0.04*	0.72	*0.06*	0.73	*0.06*
SO_3	0.25	*0.05*	0.28	*0.04*	0.33	*0.06*
P_2O_5	0.30	*0.05*	0.28	*0.04*	0.27	*0.02*
Total	99.57		99.11		101.14	

5. Discussion

5.1 Raw materials and technology

Previous studies suggest that it is possible to distinguish the plant ashes used in glassmaking in different regions. The view put forward by Brill (1989) that soda plant ash glass from central Asia is particularly high in K_2O (>4%) has been generally accepted (Abduraskov, 2009; Gan, 2009; Henderson *et al.*, 2018), while Freestone (2006) distinguished between those used for “Syrian” plant ash glass and those used in Mesopotamia, where the latter had higher MgO (typically above 4%) . Similarly, *Barilla* originating from coastal regions in the western Mediterranean such as Spain, Sicily and Sardinia, is a type of soda plant ash with relatively high potash, resulting in glass with higher K_2O (Cagno *et al.*, 2010, 2008; Fernández Pérez, 1998; Tite *et al.*, 2006).

In this context, the remarkably consistent levels of the ash-related components across all glasses from SS. Maria and Donato are noteworthy. They are consistent with “Levantine” ash (used here as an umbrella term for the ash which appears to have been used in Syrian, Levantine and Egyptian glass) as shown in Fig. 5. Furthermore, the glass from all groups plots in a relatively limited area of the Levantine category, emphasising that these glasses are likely to have been exploiting a limited plant ash source with its own characteristics. Groups

1 and 2 from Raqqa, Syria (Henderson *et al.*, 2004) also lie in this region.

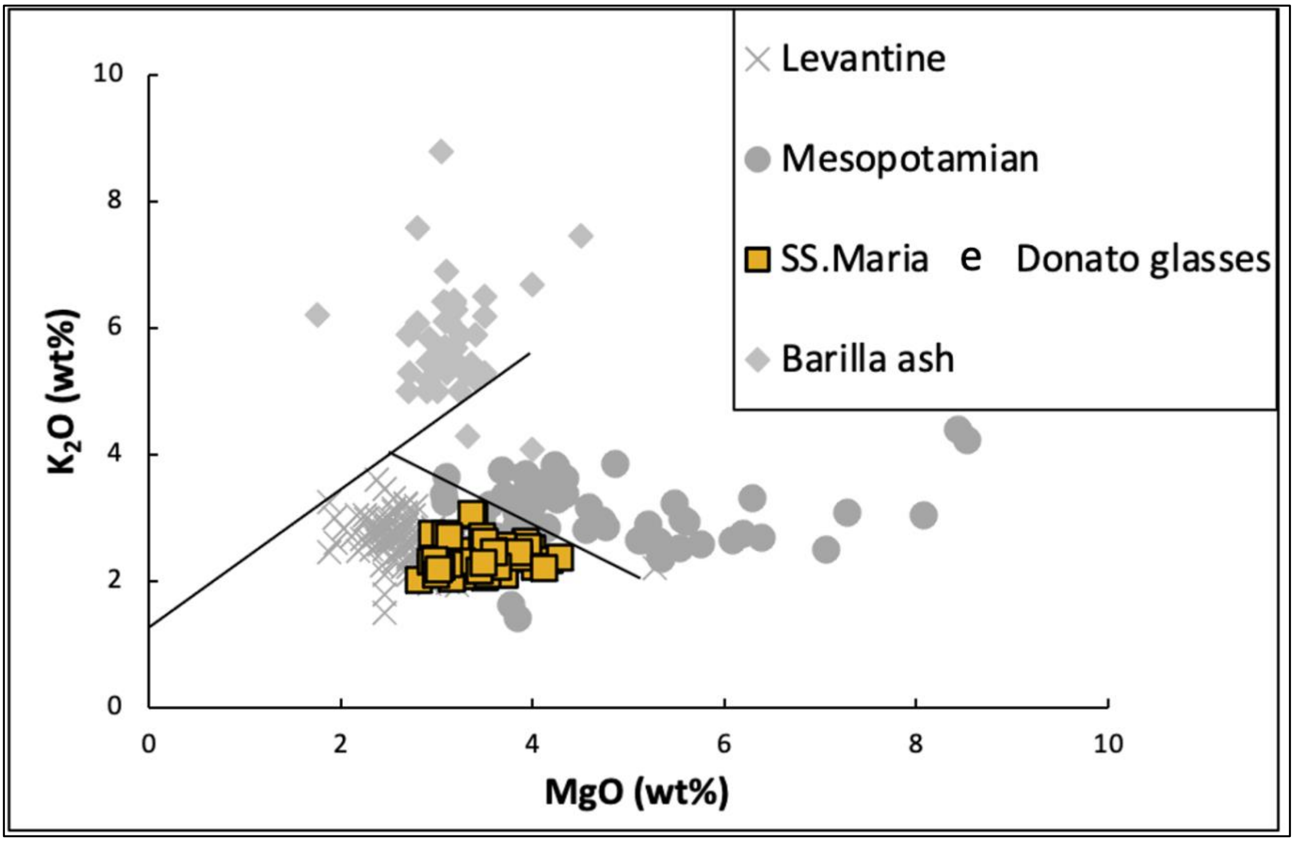


Figure 5: K_2O vs MgO concentrations identifies differences between plant ash glasses from the "Levantine" Islamic tradition (Brill, 1999; Freestone, 2002; Henderson et al., 2016, 2004; Phelps et al., 2016), the Mesopotamian Sasanian tradition (Mirti *et al.*, 2009, *Henderson et al. 2016*)*, and the "Barilla ash" tradition* (Cagno *et al.*, 2010, 2012a).

As noted, the glasses of SS. Maria and Donato appear to have been made using three different silica sources (Figs. 3, 4). The main sources of silica suitable for glassmaking are quartz sand, quarried siliceous minerals and rocks such as vein quartz, chert and quartzite, or pebbles composed of these materials. Legal texts found in the Archives of Venice indicate that Venetian glassmakers made use of both sand and quartz pebbles from at least as early as the late fourteenth century (Jacoby, 1993; Zecchin, 1987:17). Compositional criteria for the use of pebbles or sand in glassmaking are not well defined, as sand can be very pure, while pebbles may be impure. Late Bronze Age glass, generally accepted to have been made using pebbles, has Al_2O_3 typically below one percent, Fe_2O_3 below 0.5% and TiO_2 below 0.1% (Shortland and Eremin, 2006). Alumina contents significantly above one percent might be considered to indicate the use of a sand, rather than pebbles as a silica source (Brill, 1995). However, Henderson et al. (2005) considered glass from Raqqa with mean Al_2O_3 of 1.17% to have been made using quartz pebbles, which are common near the site.

Verità (2013) points out that sixteenth-seventeenth century Venetian *vitrum blanchum* was made using quartz pebbles and has around 1% Al_2O_3 with a fairly large dispersion, with around 0.35% Fe_2O_3 and 0.05% TiO_2. Groups 1 and 2 of the present study both contain higher concentrations of these components, with around 1.3% Al_2O_3 and 0.5-0.6% Fe_2O_3 (Table 4), so on balance are likely to have been made using sand. Group 3, however, has lower quantities and may have been made using quartz pebbles. Although Group 3 has high TiO_2 (c. 0.11%), the historic documents make clear that the glassmakers obtained quartz pebbles from different sources and their quality varied (Jacoby, 1993). Hence, we cannot be sure of the character of the silica source on the basis of our present data. However, irrespective of the precise origins of the silica, we are able to identify three potential sources on the basis of their TiO_2 and Al_2O_3 ratios (Fig. 3). All three silica sources were combined with the same Levantine ash, in about the same proportions, to make the glass (Fig.5).

It is noted that the compositional groups have broadly similar iron contents and do not differ in the visual appearance of the glass fabric. The broadly similar compositions indicate that their working properties would also have been similar. Hence, they have not been selected for technical reasons and it seems that that the raw glasses were either produced in different workshops that were supplied with different raw materials, or were produced at different times, or both.

5.2 Technological Affinities

The analysis of the samples from SS. Maria e Donato have been first compared with data of similar medieval assemblages believed to be of Venetian manufacture, looking at both their sand related elements and plant ash ones (Fig.6, Tab. 5), in order to investigate their production technology and to advance hypothesis on their provenance.

Group 2, which represents the majority of the glass fragments, reveals strong similarities in terms of both plant ash and sand related elements with the *low alumina Venetian glass* group of the 11^{th} to 14^{th} centuries A.D identified by Verità and Zecchin (2009b) (Tab. 5) as well as with group A/1 of Gallo and Silvestri (2005) from Asolo, located just 70 km northwest of Venice and which they dated to between the 12^{th} and the 15^{th} centuries (Fig. 6 and Tab. 5). The same group also has a chemical composition similar to the one of the 11^{th}-14^{th} century glass from S. Leonardo in Fossamala, an island northern the lagoon (Verità and Toninato, 1990) (Fig. 6 and Tab.5).

Glass from Ferrara (8^{th}-12^{th} century), a site in the Venetian hinterland located around 100 km from Venice, and two samples of 10^{th}-12th century glass from S. Arian, another small island in the lagoon (Verità and Toninato, 1990), also have a composition similar to Group 2 (Fig. 6) but given their early dating, they cannot be unquestionably attributed to a Venetian production (Verità, 2013).

Group 2 also presents some similarities with the 15th-16th century Venetian glass categorised as "vitrum blanchum" (Fig. 6 and Tab. 5) (Verità, 1985; Verità and Zecchin, 2009a, b) but our group contains slightly more aluminum, iron and titanium oxides, suggesting that a somewhat less pure silica source, but still of a very good quality, may have been used in earlier centuries. Indeed, documentary evidence reports that from at least the late 13^{th} -early 14th century Venetian glassmakers were producing glass of diverse qualities, to be used for different products and probably made using distinct raw materials. A distinction between white ("vitrum blanchum", colourless) and green glass (naturally coloured) is indicated in an article of the *Capitolare dei cristalleri* dated to the 14th century (Zecchin, 1990:137). Moreover, a sentence dated 1284 reports that it was forbidden to falsify rock crystal using the already mentioned "white glass", hence providing evidence that glass of a very high quality, to be mistaken for rock crystal, was already being produced in Venice in the 13th century (Monticolo, 1914).

In the light of this, it is interesting that the SS Maria and Donato assemblage appears to have contained no examples of an iron-rich, green low-quality glass. This is likely to reflect the use of the best quality glass for ecclesiastical purposes, but the possibility that Venice first produced high quality glass, and began producing cheaper "common glass" later, as market demand increased, cannot be dismissed at this stage.

Group 1 has a mean composition which is in many respects comparable to Group 2 (Fig.3, Tab.4) and, similarly, it might be a group of glasses produced in Venice. However, it should be noted that its higher levels of titanium, as previously highlighted, separate this group from Group 2, and clearly separate Group 1 from the other medieval Venetian glasses, while Group 2 plots with them in Fig. 6. Therefore, we regard Group 1 as likely to have an origin distinct from that of Group 2. Furthermore, to the authors' knowledge, no data on assemblages of medieval glass attributed to Venice match the compositional characteristics of Group 1. These differences, although dependent upon a single component, TiO_2, suggest a different provenance for the glasses of Group 1. We note that TiO_2 is a well-measured component and has proved a very useful indicator in provenance investigations of glass, for example it has been shown to separate most glass made in Egypt from that made on the Levantine coast (Foy *et al.*, 2003; Nenna, 2014) and can separate closely related groups from Egypt (Freestone, 2021).

Group 3 has on average lower levels of alumina and higher levels of titanium oxide than the other samples analysed (Fig. 3, Tab. 4). Comparison with other medieval Venetian glasses (Fig. 6) indicates that these higher levels of titanium, in combination with very low levels of alumina, are not commonly found in Venice (Verità, 2013; Verità and Zecchin, 2009a, 2009b). Nevertheless, fourteenth century soda-lime-silica stained glass windows from Santa Croce Basilica (Florence), were tentatively attributed to Venetian production by Verità *et al.*, (2019) , and also show high levels of titanium (on average 0.13%) and low levels of alumina (below 1%) (Fig.6).

All the samples analysed differ considerably in terms of their sand-related elements to another group of 11^{th}-14^{th} century glasses from Ferrara and S. Leonardo in Fossamala, (Verità and Toninato, 1990), as well as groups A/2 and A/3 from Asolo (Gallo and Silvestri, 2012), which correspond to the *high alumina* Venetian glass group identified by Verità and Zecchin,(2009b)(also dated 11^{th} - 14^{th} centuries) (enclosed in dotted line in Fig.6). and which appear equivalent to the naturally coloured "green glass" mentioned in the documentary evidence (in Cecchetti, 1874:224).

The restricted variation of our samples in terms of plant ash components and their similarities to other medieval glasses attributed to Venetian production (Tab.5) can be explained by the mandatory use in Venice, from at least 1255, of Levantine plant ash, "alume catino" as a flux (Zecchin, 1990:175, 1987:5, 1997), which was imported, together with raw glass to be remelted, from Syria and Egypt, the ash from the latter considered of poorer quality (Zecchin 1990:173). Use of other types of ash, such as the wood ash used in northern Europe and possibly in other Italian centres such as in Florence (Verità *et al.*, 2019), Pavia (Messiga and Riccardi, 2006) and Orvieto (Kunicki-Goldfinger *et al.*, 2013), was strictly forbidden by the Venetian State (Ashtor and Cevidalli, 1983; Jacoby, 1993; Zecchin, 1990:176).

Table 5: Mean chemical composition of Group 2 compared to group A/1 from Asolo (12^{th}-15^{th} century) (Gallo and Silvestri 2012), the group "low Alumina Venetian glass" identified by Verità and Zecchin 2009b (11^{th}-14^{th} century), Vitrum Blanchum from Fusina

(15th-16th century)(Verità, 1985) and the low-Al glass samples from the island northern the lagoon of S. Leonardo in Fossamala (11th-14th century) (Verità and Toninato, 1990).

	Group 2 (*n*=43)		**Venetian glass "low Al"**		**Asolo glass A/1**		**Vitrum Blanchum, Fusina**		**S. Leonardo in Fossamala**	
	Mean wt%	s.d.	**Mean wt%**	s.d.	**Mean wt%**	s.d.	**Mean wt%**	s.d.	**Mean wt%**	s.d.
SiO_2	68.81	*2.73*	67.26	*1.58*	67.36	*1.48*	67.3	*1.07*	69.03	*0.84*
Na_2O	12.25	*0.92*	12.75	*1.4*	12.49	*1.03*	13.14	*1.18*	12.23	*0.46*
CaO	9.62	*0.98*	8.97	*1.53*	10.1	*0.98*	10.14	*1.17*	9.75	*1.94*
K_2O	2.35	*0.17*	2.41	*0.22*	2.41	*0.22*	2.58	*0.59*	2.45	*0.87*
MgO	3.51	*0.38*	3.28	*0.57*	3.76	*0.44*	3.55	*0.61*	2.3	*1.01*
Fe_2O_3	0.53	*0.09*	0.51	*0.21*	0.6	*0.22*	0.36	*0.09*	0.38	*0.09*
Al_2O_3	1.34	*0.20*	1.47	*0.58*	1.59	*0.44*	1.01	*0.36*	1.75	*0.3*
TiO_2	0.07	*0.01*	0.11	*0.06*	0.08	*0.02*	0.04	*0.02*	0.06	*0.02*
MnO	0.56	*0.31*	0.97	*0.52*	1.24	*0.72*	0.5	*0.22*	0.58	*0.33*
P_2O_5	0.28	*0.04*	0.34	*0.09*	0.27	*0.04*	0.2	*0.22*	0.37	*0.02*

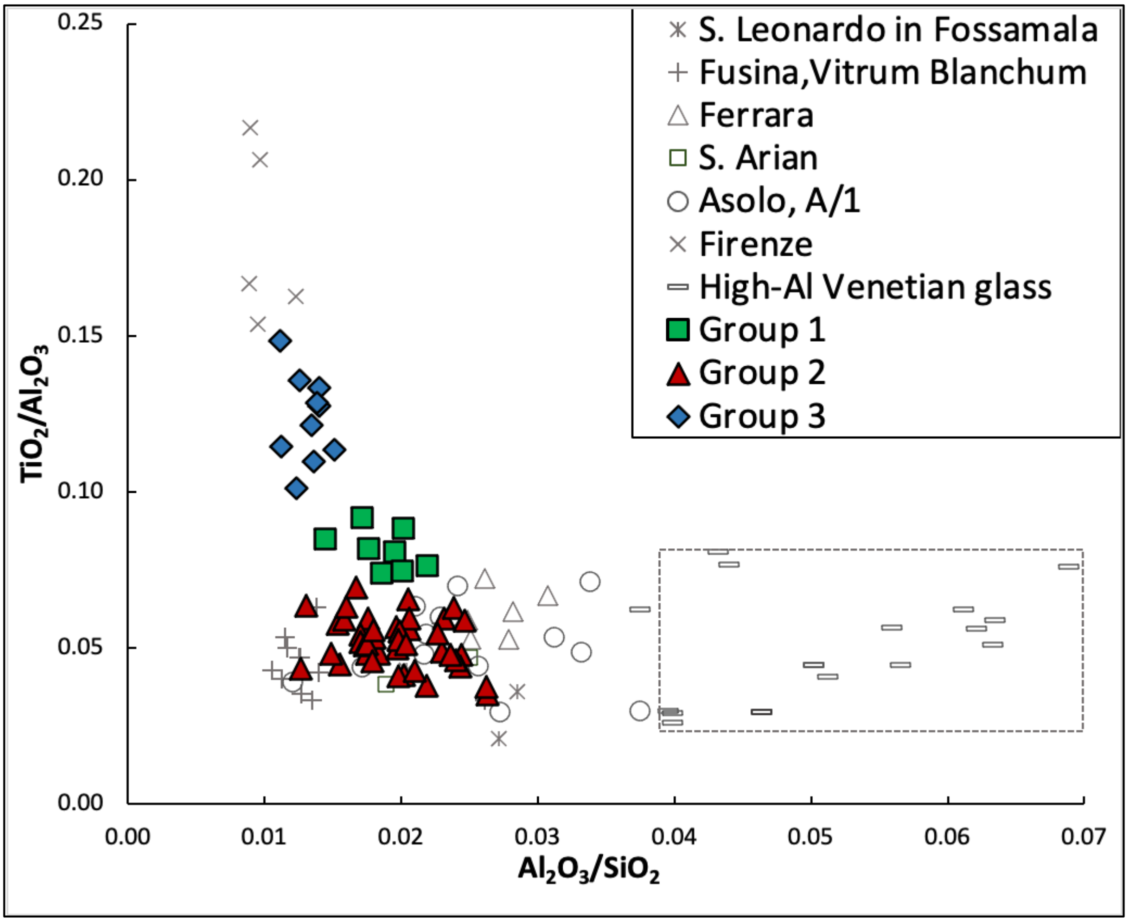


Figure 6: TiO_2/Al_2O_3 vs Al_2O_3/SiO_2 of SS. Maria e Donato groups and medieval Venetian glass from S.Leonardo in Fossamala (11th-14th century, Verità 1985), Fusina (15th-16th century, Verità 1985), Ferrara (8th-12th century, Verità and Toninato 1990), S. Arian (10th-12th century, Verità and Toninato 1990), Asolo A/1 (12th-15th century, Gallo and Silvestri 2012), Firenze (14th century, Verità et al. 2019). Similarities can be seen between Group 2 and medieval Venetian glass categorised as "low-Al Venetian glass", as opposed to the high-Al Venetian glass (enclosed in dotted line, data from: Verità and Toninato 1990, Gallo and. Silvestri 2012).

Comparison with other Italian medieval glass assemblages is shown in Fig.7. We recognise three main technological categories: LEV-Si glass made with Levantine ash and a relatively pure source of silica lower in Al_2O_3,(Cagno et al., 2012b, 2010, 2008) which has a composition broadly similar to Venetian glass (Verità and Zecchin, 2009a), LEV-Al comprising Levantine ash plus local sands richer in feldspars, with Al_2O_3 contents well above 3.5% (Cagno et al., 2012a, 2010, 2008;); and BAR-Al made with Barilla ash plus high Al_2O_3 local sands (Basso et al., 2008; Cagno et al., 2010, 2008). Combination BAR-Si was used less frequently (Cagno et al., 2010) presumably because the lower quality barilla ash was not used to make high quality glass with pure silica (Fig. 7). Similar combinations of raw materials has been recognised by Cagno *et al.*, (2010) for the production of medieval glass from Tuscany.

While glass from regions other than Venice in the LEV-Si category presents compositions that are similar to our samples and to medieval Venetian glass (Fig.7), the latter having levels of Al_2O_3 which generally do not exceed 3.5% (Verità and Zecchin, 2009a), it tends to have on average higher levels of alumina and iron oxides, pointing to the use of different silica sources than our samples (Fig.8).

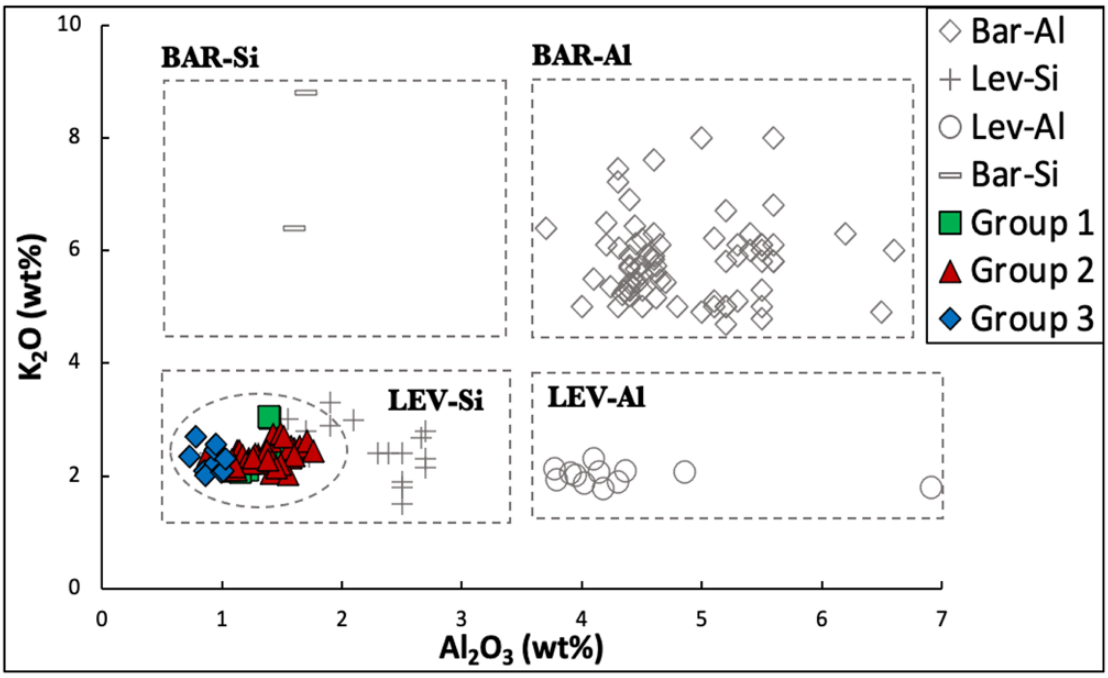


*Figure 7: K_2O and Al_2O_3 biplot (wt%) for SS. Maria e Donato glasses, and the technologies recognized, depending upon the combination of ash type and sand quality, here called LEV-Si (data from Verità 1985, Verità and Toninato 1990, Verità and Zecchin 2009, Gallo and Silvestri 2012, Verità et al. 2019, Cagno et al. 2010, 2012b,*Genga *et al.*, 2008; Posedi *et al.*, 2019; Vandini *et al.*, 2018) *LEV-Al* (Cagno *et al.*, 2010; Posedi *et al.*, 2019) *and BAR- Al* (Basso *et al.*, 2008; Bianchin *et al.*, 2005; Cagno *et al.*, 2012a, 2010), *BAR-Si (Cagno et al. 2010). Venetian low-Al glasses dated between the 9h and the 14th century (Verità 1985, Verità and Toninato 1990, Verità and Zecchin 2009, Gallo and Silvestri 2012, Verità et al. 2019) are also compared (dotted ellipse) and are part of the broader LEV-Si category.*

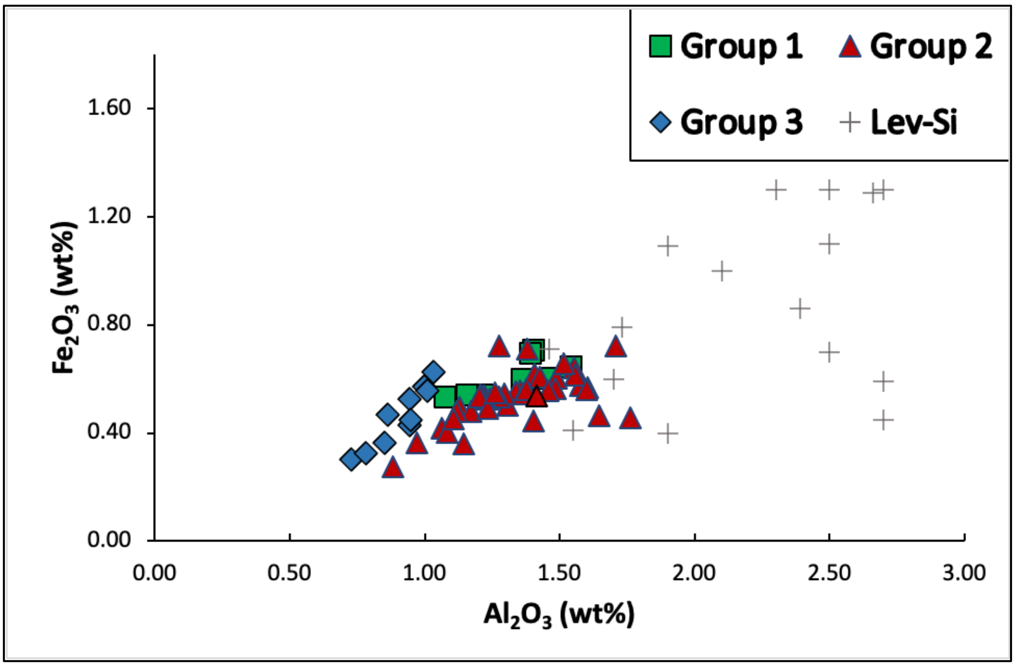


Figure 8: Fe_2O_3 vs Al_2O_3 contents of SS. Maria e Donato groups and the non-Venetian Italian glass of the LEV-Si category shown in Fig.7 (data from Cagno et al 2010, 2012b, Posedi et al. 2019, Vandini et al. 2018, Genga et al. 2008).

5.3 *Comparison with glass from the Eastern Mediterranean*

We have observed that the SS Maria e Donato glass was made using Levantine ash, and that this is consistent with historical records of Venetian glassmaking. However, it is documented that the Muranese glassmakers imported raw glass, as well as raw materials, from the Middle East (Zecchin 1987:5; Verità 2013). Therefore, we have compared our data with the compositions of medieval glass from Syria and the eastern Mediterranean. As discussed above, plant ash used in Venice at this time was imported from the Middle East, so that all three of our groups resemble middle eastern glasses in terms of their ash-related components impurities, while their sand-related components can serve for further comparisons with the eastern examples, shown in Fig. 9.

In particular, Group 2 resembles the composition of 11^{th} century glass from Tell Fukhkhar in Al Raqqa (Henderson *et al.*, 2004) and shows some similarities with a group of 13^{th} century glass from the Crusader castle at Montfort (Upper Galilee, Israel; Whitehouse *et al.*, 2017), whereas it differs from glass produced on the Levantine coast in Tyre, Lebanon (Freestone, 2002) and of "Tyre type" (Phelps, 2016) (Fig.9, Tab.6). It should be noted that the glass from Montfort has been divided in two groups by the present authors in order to highlight the different titania contents of the glasses, as well as different iron oxide and alumina contents (Fig. 9, Tab.6), which might denote different raw materials and hence different sources for the two groups of glass.

Group 1 resembles a group of six glasses from Khirbat-al Minya, Israel (Henderson *et al.*, 2016). On the other hand, Group 3 shows similarities to a group of glasses from Banias (11^{th}-13^{th} centuries) (Israel, Freestone *et al.*, 2000) and the "high-TiO_2" Montfort (Israel) group (Whitehouse *et al.*, 2017)(Fig.9, Tab.6). Group 3 also shares lower alumina to iron oxide ratios with the Banias and Montfort glasses (Tab.6). High TiO_2 contents are especially characteristic of sand of an Egyptian origin, as supported by several studies (e.g in Kato *et al.*, 2010; Nenna, 2014; Picon and Vichy, 2003; Schibille *et al.*, 2019), and there is a possibility that the glass from Banias, the "high TiO_2" glass group from Montfort and our Group 3 may represent an Egyptian glass type. Indeed, glass analysed by Kato et al. (2010) from the port of Raya on the Sinai Peninsula, (group PA-1b, 10th-11th centuries), and believed to have been produced in Egypt, show high levels of titanium and a broadly comparable TiO_2/Al_2O_3 ratio to Group 3 (Fig.9 and Tab.6).

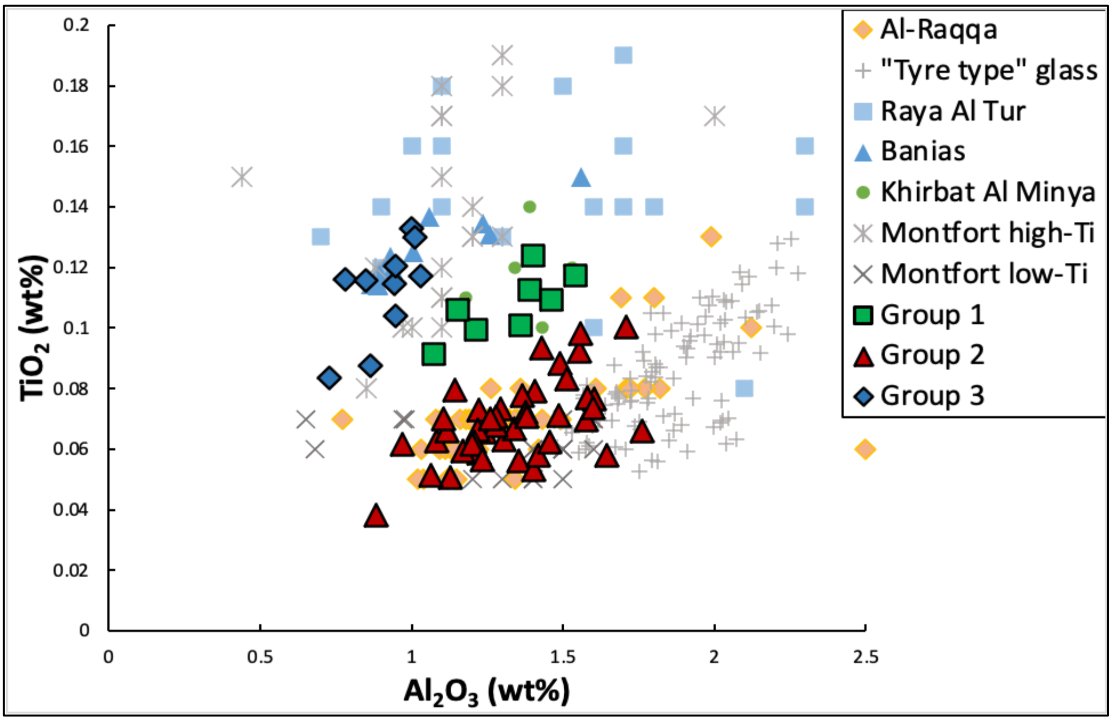


Figure 9: Similarities, according to the sand characteristics, between the groups identified and middle eastern glass assemblages from Al-Raqqa (Henderson et al. 2004), Raya Al Tur (Kato et al. 2010), Banias (Freestone unpublished), Khirbat Al Minya (Henderson et al. 2016), Montfort (Whitehouse et al. 2017) and "Tyre type glass" (Phelps 2016).

Table 6: Average chemical compositions of the SS. Maria e Donato groups, of glass from Raya al Tur (Kato et al. 2010), A-Raqqa (Henderson et al. 2004), Banias (Freestone unpublished), Montfort (divided in two groups by the present authors)(Whitehouse et al. 2017) and the "Tyre type" glass (Phelps 2016).

	Group 1 (*n*=8)		**Group 2 (*n*=43)**		**Group 3 (*n*=10)**		**Raya Al Tur, Egypt**		**Al-Raqqa, Tell Fukhkhar**		**Banias**		**Montfort "low TiO_2"**		**Montfort "high TiO_2"**		**Tyre type**	
	Mean wt%	s.d.	**Mean wt%**	s.d.	**Mean wt%**	s.d.	**Mean wt%**	s.d.	**Mean wt%**	s.d.	**Mean wt%**	s.d.	**Mean wt%**	s.d.	**Mean wt%**	s.d.	**Mean wt%**	s.d.
SiO_2	70.86	*2.35*	68.81	*2.73*	69.3	*2.29*	66.2	*2.6*	67.66	*1.49*	71.62	*1.18*	68.12	*2.32*	69.58	*1.3*	67.92	*1.69*
Na_2O	11.4	*0.69*	12.25	*0.92*	11.78	*0.67*	17.9	-	12.18	*0.95*	11.96	*0.58*	13.58	*1.67*	11.33	*1.79*	12.38	*1.07*
CaO	8.76	*0.67*	9.62	*0.98*	10.83	*1.13*	7.5	*0.8*	10.18	*1*	8.6	*0.98*	8.02	*0.91*	8.84	*1.01*	9.48	*1.17*
K_2O	2.42	*0.4*	2.35	*0.17*	2.29	*0.23*	2.2	*0.4*	2.48	*0.33*	1.51	*0.34*	2.64	*0.35*	2.55	*0.36*	2.35	*0.35*
MgO	3.35	*0.17*	3.51	*0.38*	3.46	*0.38*	2.1	*0.3*	3.38	*0.28*	2.4	*0.57*	3.26	*0.3*	3.3	*0.42*	3.02	*0.51*
Al_2O_3	1.33	*0.16*	1.34	*0.2*	0.91	*0.1*	1.8	*0.8*	1.24	*0.17*	1.22	*0.63*	1.30	*0.3*	1.16	*0.3*	1.86	*0.2*
Fe_2O_3	0.61	*0.07*	0.53	*0.09*	0.46	*0.11*	0.82	*0.15*	0.55	*0.25*	0.68	*0.49*	0.48	*0.25*	0.67	*0.29*	0.50	*0.12*
TiO_2	0.11	*0.01*	0.07	*0.01*	0.11	*0.02*	0.17	*0.06*	0.06	*0.01*	0.13	*0.12*	0.07	*0.01*	0.15	*0.03*	0.08	*0.02*
MnO	0.39	*0.11*	0.56	*0.31*	0.57	*0.27*	1.02	*0.28*	1.09	*0.51*	0.83	*0.28*	0.67	*0.34*	0.64	*0.22*	1.00	*0.38*
Cl	0.71	*0.04*	0.72	*0.06*	0.73	*0.06*	na	-	0.73	*0.08*	0.86	*0.07*	0.85	*0.08*	0.85	*0.07*	1.00	*0.38*
P_2O_5	0.3	*0.05*	0.28	*0.04*	0.27	*0.02*	na	-	0.27	*0.03*	0.24	*0.04*	0.31	*0.08*	0.41	*0.08*	0.30	*0.06*

6. Conclusions

This paper presents a new dataset for medieval glass retrieved from an archaeological context on the Island of Murano, where Venetian glassmaking was situated after 1291 A.D. (Zecchin 1987:6). The SS. Maria e Donato glasses were made using ash from the Levant and form three groups on the basis of the minor oxides contributed by their silica sources. They have relatively low K_2O and Al_2O_3 and are distinguished from much of the medieval glass made in central Italy which melted barilla ash from the western Mediterranean with an alumina-rich siliceous sand. Current evidence suggests that Levantine ashes were used elsewhere in medieval Italian glassmaking centres but, on the basis of the minor elements, the sands used appear to have differed from those of the SS Maria and Donato assemblage. This evidence is consistent with the understanding gleaned from contemporary sources on the Italian glass industry, particularly on the regulations imposed by the Venetian government on the exclusive use of Levantine ash. This imported soda ash was an indispensable raw material for the Venetian glassmaking industry and was a characteristic trait of virtually all the Venetian glass over the several centuries of its production.

The largest group identified, Group 2 closely resembles previous analyses of medieval glass believed to have been made by Venetian artisans between the 11th and 15th centuries and it also shows similarities with the later *vitrum blanchum* of the 15th-16th century, strongly suggesting that this group represents a rarely accessible assemblage of medieval Venetian glass made in the island. Group 1 has a composition similar to Group 2 but its average higher levels of titanium dioxide do not match precisely any Venetian glass groups similar to Group 2, and they might be suggestive of a different provenance.

Group 3, on the other hand, differs from the other Venetian medieval assemblages due to its considerably lower levels of Al_2O_3 and higher contents of TiO_2. Only a single northern Italian medieval assemblage shows similar levels of these elements and is a small group of windows glass from Florence which have been tentatively suggested to have been made in Venice (Verità *et al.*, 2019).

In spite of some similarities to Venetian products, particularly in the case of Group 2, the SS. Maria e Donato groups also resemble glass from the Eastern Mediterranean. In particular, Group 2 resembles Syrian glass (El Raqqa) and a lower TiO_2 group of glass from Montfort. While there is the possibility that Venetian glass was exported to Crusader Montfort, its use in Raqqa seems improbable. However, records indicate that raw glass, cullet and sand was exported from the Levant and worked in Venice and this assemblage might represent imported glass or glass made with imported sand. Group 1 resembles a group of glasses from Khirbat-al Minya, Israel and may therefore be a Levantine type. Group 3 on the other hand resembles a second group from Montfort (here named "high-TiO_2"), as well as glass from Banias, Israel and glass from the Raya port, on the Sinai Peninsula, Egypt. High TiO_2 is particularly characteristic of Egyptian glass and the high TiO_2 of this group of glasses might suggest an Egyptian origin.

These relationships leave a number of issues unclear. While it seems likely that the high-TiO_2 Group 3 reflects an imported raw material, Group 2 resembles other glass thought to be made in Venice, although it cannot be distinguished from some Syrian glass on the basis of the present analyses, while the origin of the intermediate Group 1 is also ambiguous. This is likely to be a reflection of the complex emergence of Venice as one of the major centres of glassmaking in the Middle Ages. In their search for high quality raw materials, not only ash but also raw glass and even sand was imported from the Levant and the Venetian State created a monopoly in their importation, sale and use, in this way ensuring Venice's supremacy in glassmaking (Jacoby, 1993, 1991; Zecchin, 1987:5). Information on the type of raw materials used and their provenance can be found in the written evidence. The Archives of State of Venice indicate that the Muranese glassmakers were importing both glass cullet and sand: glass cullet was imported from the Levant and from Tripoli (Lebanon) in the 13th century (Zecchin, 1990:173), while sand was imported from Crete (1293-1302) (Zecchin, 1997) and Sicily (1340)(Zecchin 1990:176) and silica pebbles were also imported from the Ticino river and Verona (1394) (Jacoby, 1993:73). However, local raw materials, such as local sand, called "sablone roseto" (red sand) or "sabbion" in the Archives, was probably used as well in Venice (Zecchin, 1987:7; Moretti and Hreglich, 2013; Verità, 2013, 1985; Zecchin, 1990:176) and further analysis are needed in order to be able to distinguish it from the other sources.

As a consequence, the chemical composition of medieval Venetian glass is likely to reflect a complex situation of trade in raw materials and glass as well as a probable transfer of technology and/or artisans, which is reflected in the very similar recipes apparently used by both Italian and Levantine glassmakers. clarification of these issues will clearly require further work with trace elements and possibly isotopes. It is clear, however, that we are able to achieve some discrimination between glass groups using minor elements such as Ti, Fe and Al and that these allow a preliminary sorting of the data and identification of the key issues to be addressed.

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