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Blue decoration on glass Objects: Unravelling origins and Significance in late medieval – Early modern Portugal

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ABSTRACT

Late medieval and Early modern Portuguese archaeological contexts have brought to light several colourless objects with blue thread application. Usually related to cylindrical glasses and pedestal goblets, this decoration can be found in several features: one or more lines applied horizontally or in a spiral, frills forming festoons or blue lines combined with a ribbed decoration. The presence of these objects reveals a connection with the upper strata of society, as they were considered luxurious and could be identified as imported, raising questions about their provenance. This study examines 20 glass objects adorned with blue decoration from five Portuguese archaeological sites in Lisbon, Almada, and Setúbal, dating from the 14th to 16th centuries. Through a combination of micro particle-induced X-ray emission (μ-PIXE) and inductively coupled plasma mass spectrometry with laser ablation (LA-ICP-MS), the chemical composition of the glass was examined. Stylistic investigations and analytical techniques shed light on how the raw materials used in objects with this type of decoration differ between older and more recent artefacts, indicating changes in society's taste and the raw materials used, hence the place of production. The chemical composition of the analysed fragments, which falls within the soda-silica-lime group, gives clues to their origin and leads to a debate about whether these objects are imported or locally produced. This interdisciplinary approach combining archaeological findings, stylistic analysis and chemical analysis, offers an understanding of the cultural and technological dynamics that shaped glass production in medieval and Renaissance Europe.

1. Introduction

Recent studies of late medieval and early modern materials from archaeological excavations in Portugal have uncovered several glass objects characterised by shared features: a colourless body adorned with one or more applied blue threads. This group of 20 objects dated between the 14th and 16th centuries, stands out within the broader context of their assemblages of origin, which are predominantly composed of undecorated, utilitarian vessels. Moreover, the association of the colour blue with prestige during the Middle Ages (Pastoureau, 2002) suggests that these objects may have been linked to a certain degree of luxury. Nevertheless, their stylistic parallels with European productions raise questions regarding their provenance, specifically whether they represent imported objects. Blue applied decoration on vessels with colourless

body has been documented in France as early as the 13th century (Foy & Sennequier, 1989), and in the following century in Spain (Galmés, 2015). By the late 14th century, the production of beakers and goblets with applied blue decoration was in use in Italy, in Monte Lecco in the Genoese Apennines (Fossati & Mannoni, 1975) and in the Venetian lagoon (Pause, 2000; Gallo & Silvestri, 2012). Venetian innovations in technology and manufacturing were appreciated throughout Europe for the refinement of their products, which were exported to various courts. In several countries, glass began to be produced *à la façon de Venise* from the 16th century onwards, using local raw materials, often employing expatriate Venetian glassmakers (see, for example: de Rochebrune, 2004; Doménech, 2004; Henkes, 1994).

It cannot be excluded that the objects unearthed in Portugal with blue decoration may be part of a local production. Existing documentary

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evidence (Valente, 1950) and preliminary archaeometric studies on early modern glass fragments suggest that a tradition of local production *à la façon de Venise*, utilizing local raw materials while emulating Venetian craftsmanship, may have existed in Portugal starting from the 16th century (Coutinho, Medici, Alves, et al., 2016; Lima et al., 2012). However, confirming this hypothesis is particularly challenging due to the absence of direct archaeological evidence, such as glass workshops or furnaces, that could definitively support local manufacturing.

Through the study of these objects, this work aims to explore the stylistic evolution of the blue decoration applied on colourless glassware and examine whether and how the chemical composition of the glass used in their production changed between the 14th and 16th centuries. This research will combine the study of the archaeological context with the stylistic analysis of the glasses and their chemical characterisation, to use them as a basis for the discussion on provenance.

2. Archaeological contexts and materials

The study focuses on 20 glass objects (Fig. 2, Table 1), from different archaeological excavations across Portugal (Fig. 1), that share a

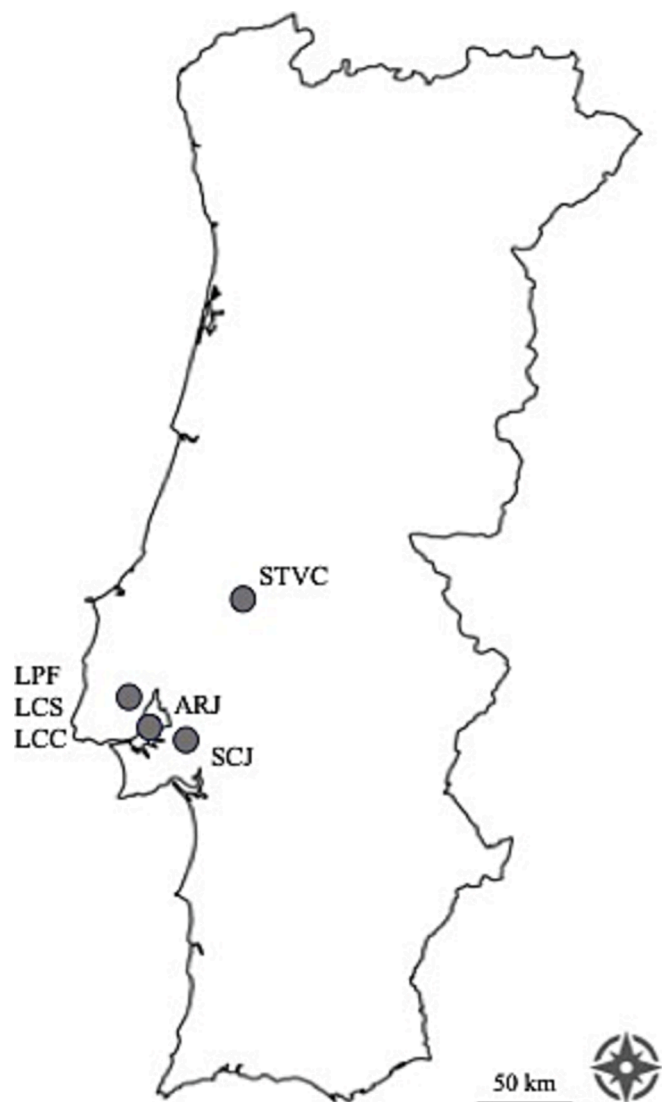


Fig. 1. Location of archaeological excavations: Travessa das Capuchas in Santarém (STVCC); Rua da Judiaria in Almada (ARJ); Praça da Figueira (LPF), Campo das Cebolas (LCC), Largo do Corpo Santo (LCS) in Lisbon; Convento de Jesus in Setúbal (SCJ).

common characteristic: the presence of blue decorations applied to colourless bodies. Overall, the stylistic analysis identified these vessels as related to the consumption of liquids, belonging to beakers, pedestal beakers and goblets.

Among the oldest finds, three fragments dating from the 14th-15th centuries were excavated in Travessa das Capuchas in Santarém (STCV) and Rua da Judiaria in Almada (ARJ). These sites revealed silos reused as cesspits filled with various materials and, among the others, fragments of glass objects (Boavida et al., 2013; Barros & Henriques, 2003). Furthermore, in Praça da Figueira in Lisbon (LPF), a fragment of colourless glass with an opaque blue frill was uncovered in layers associated with a domestic dwelling in Rua da Betesga (Banha da Silva, 2018). It is also dated to the 14th-15th century and probably belonged to a high-ranking residence, a hypothesis put forward on the basis of the other materials found in the excavation (Cámara del Río, 2015).

Most of the fragments (=16) date back to the 16th century. One (LPF0038) was found during the excavation of the Hospital Real de Todos-Os-Santos in Praça da Figueira (LPF) in a layer associated with the reconstruction of a section of the hospital that occurred at the end of the 16th century (Bargão et al., 2018). A group of objects was unearthed during excavations along the riverbank of the Tagus River in Lisbon, in the areas of Largo do Corpo Santo (LCS) and Campo das Cebolas (LCC). These finds are connected to a large dump site formed by accumulating debris from demolitions caused by the earthquakes of 1531 or 1551 (Alves et al., 2001, Manso & Abrantes Garcia, 2019). This area, known as *Ribeira Velha*, located near the banks of the Tagus River, was an intermediate space between the city and the waterways for communication and trade. The objects recovered likely provide insight the daily life of the noble palaces built nearby, as well as Lisbon's commercial activities with Europe and the rest of the world (Manso & Abrantes Garcia, 2019). Additionally, four colourless fragments with blue decorations, dated to the late 16th to early 17th century, were found in a dump area outside the Convento de Jesus in Setúbal (SCJ) (Cândido, 2009).

Among the objects analysed in this study (Fig. 2, Tab. 1), the most prevalent decorative feature is the application of horizontal blue threads on the body of the vessel ($n = 10$). This decorative feature is identified in items dating to the 14th century (STCV0005) and continues to appear in fragments from the 15th (ARJ0999) and 16th centuries (LPF0038, SCJ0060, LCS1027, LCS0924, LCS1059, LCS0286, LCC0029, LCC0013). This continuity highlights the enduring appreciation for this adornment across these centuries. Objects with the same decorations are found in the production of Altare glassblowers, present in the south of France between the 15th and 16th centuries (Foy & Sennequier, 1989), and in Majorca (Galmés, 2015) and Italy, on vessels dated between the late 14th and early 15th century from Savona (Ventura, 2001) and Monte Lecco, Liguria (Fossati & Mannoni, 1975), and in the south, in Apulia (Catacchio, 2020).

ARJ0452 and LPF0006, dated to the 15th century, show a frill decoration applied on a colourless wall adorned with regularly spaced vertical ribs. ARJ0452 conserves a complete profile of a goblet with a pedestal made from a single gather of glass, with a truncated conical bowl and a pushed-in base (Medici, 2005). Given the presence of the same decorations and its curvature, it is proposed that LPF0006 belonged to the same shape. This applied blue festoon decoration is recognisable in the base of a colourless goblet dated to the 14th century, decorated with an applied blue frill, of Majorcan production or under the crown of Aragon (Galmés, 2015). SCJ0058 is characterised by a blue thread decoration applied to the rim and an undecorated body. A similar fragment, the dating or provenance of which are unknown, was found in Beja (Praça Miguel Fernandes) (Medici, 2014). This type of decoration is documented in Spain, dated to the 14th-15th centuries (Medici et al., 2009) and in Italy between the 14th and 16th centuries in Pavia (Corpus Pavia, 2004), Venice (Gallo & Silvestri, 2012; Pause, 2000) and Altare (Ventura, 2001). Furthermore, the production of objects with this decoration is attested in France from the 14th century onwards (Foy & Sennequier 1989), and in Austria in the first half of the 16th century

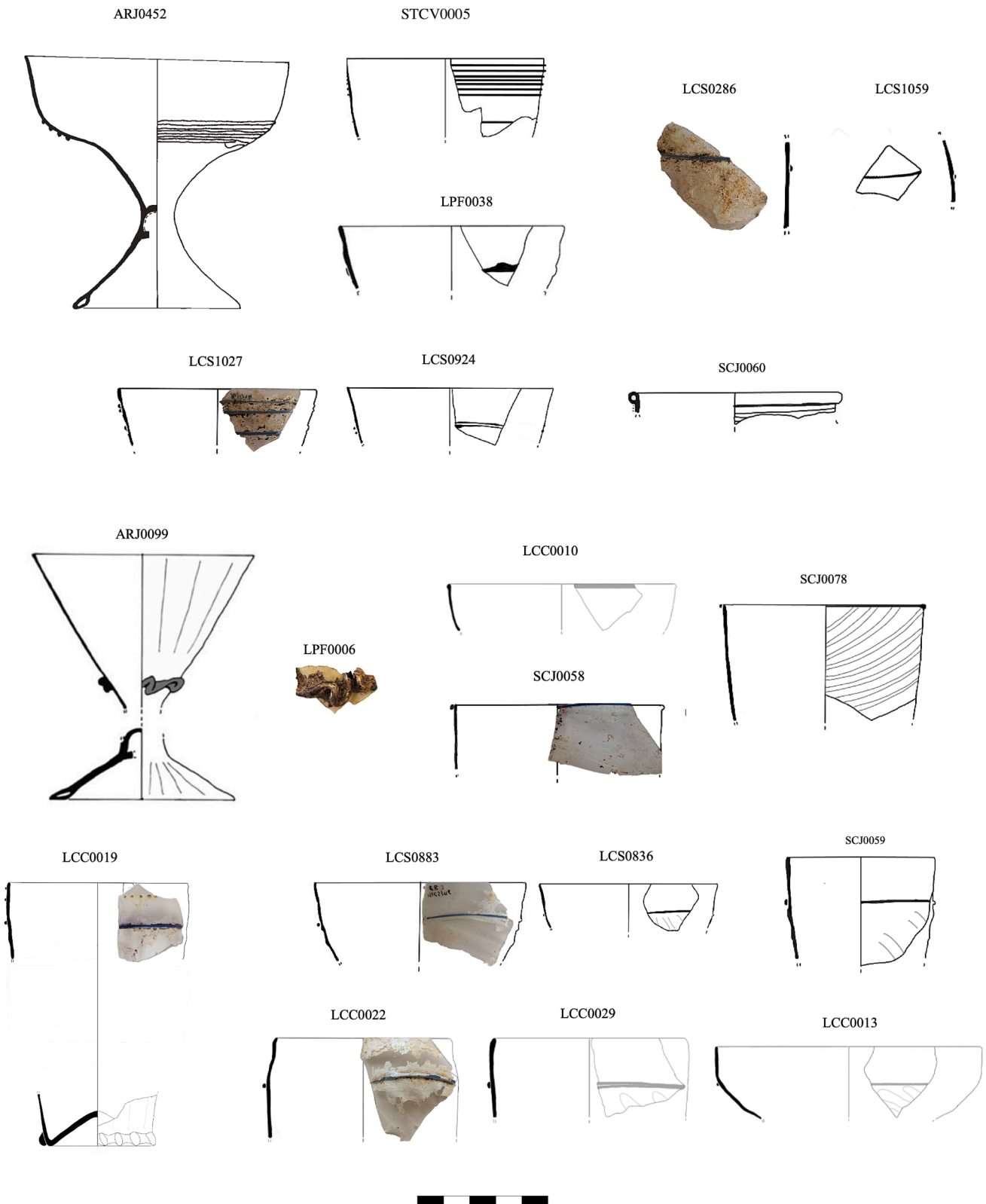


Fig. 2. Objects considered in this work (Drawings: ARJ © T. Medici; STCV, LPF, LCS and SCJ © A. Cristoforetti; LCC © B. Farinha).

(Tarcsey, 2018). SCJ0078 belongs to a colourless cylindrical beaker with blue thread applied to the rim and a body decorated with densely spaced twisted ribs, resulting from mould-blowing. Notably, two direct comparisons from Beja, Portugal, dated between the 14th and 15th centuries, exhibit similar characteristics (Coutinho et al., 2016a).

LCS0883, LCS0836, and SCJ0059 have, in addition to a blue thread applied to the wall approximately one centimetre below the rim, an oblique ribbed decoration probably obtained using *mezza stampatura*, invented in Murano in the 16th century (Mentasti Barovier & Tonini, 2019) and widespread in several European *façon de Venise* productions

Table 1
Objects under study, divided based on their decoration.

Fragment	Part preserved	Shape	Decoration	Age Century (CE)
ARJ0452	Wall with rim and pedestal base with tubular ring base	Pedestal goblet	Horizontal threads applied on the body	15th cent.
STCV0005	Part of wall with rim	Beaker		
LPF0038	Part of wall with rim	Beaker		16th cent.
LCS0286	Wall			
LCS1059	Wall			
LCS1027	Part of wall with rim	Beaker		
LCS0924	Wall	Beaker (?)		
SCJ0060	Part of wall with rim	Beaker		
ARJ0099	Part of wall with rim and pedestal base with tubular ring base	Pedestal goblet	Horizontal frill applied on the body	15th cent.
LPF0006	Part of wall with blue frill applied	Pedestal goblet (?)		14th-15th cent.
LCC0010	Part of wall with rim	Beaker	Horizontal thread applied on the rim	16th cent.
SCJ0078	Part of wall with rim	Beaker	Horizontal thread applied on the rim and oblique pattern of ribs	16th cent.
LCC0019	Part of rim with wall and base	Beaker	Horizontal thread applied on the body and vertical pattern of ribs	16th cent.
LCS0883	Part of wall with rim	Beaker (?)	Horizontal threads applied on the wall and oblique pattern of ribs	16th cent.
LCS0836				
SCJ0059				
LCC0022				
LCC0029				
LCC0013		Goblet		

(Philippart & Mergenthaler, 2011; Liefkes, 2004; Doménech, 2004). In Portugal, an example of goblets (16th century) with this same decoration was found in Carnide, in Largo do Coreto (Boavida & Medici, 2018). LCC0019 is part of a beaker with a truncated conical body and pushed-in base, decorated with a pinched thread applied. The body is adorned with a blue thread applied to the body of the vessel, enamelled spots near the rim and vertical ribs alternating with regular spaces, made using the *mezza stampatura* technique. Objects with similar features have been found in Venetian production starting from the 14th century (Pause, 2000) and in *façon de Venise* glass produced in Antwerp in the second half of the 16th century (Veeckman, 2002). Beakers with comparable decorative motifs, identified as Venetian imports dated between the 15th and 16th centuries, have been unearthed in the Tyrol region (Tarcsey, 2024).

3. Experimental

To determine the chemical composition of the glass under investigation, evaluate the raw materials used, and propose hypotheses regarding their origin, all the fragments described (Tab. 1; Fig. 2) were analysed using micro particle-induced X-ray emission (μ -PIXE). Based on their composition, a selection of samples was then subjected to laser ablation inductively-coupled-plasma-mass spectrometry (LA-ICP-MS) to obtain trace and rare-earth elements (REE). Small samples, ranging from 2 to 4 mm², were dry-cut from the fragments using a diamond wire, then embedded in epoxy resin and polished with SiC sandpapers down to a 4000 mesh. This procedure avoids obtaining information on the surface corroded layer then allowing accurate analysis of the bulk glass.

Sampling focused on both the body glass and the decoration. However, in some cases, sampling the applied thread would have compromised the integrity of the fragment, being then avoided. Quantitative results were obtained via μ -PIXE, an ion-beam technique based on detecting X-ray radiation induced by a particle beam with energy in the range of a few MeV and typically generated by an electrostatic accelerator. The analyses were conducted in collaboration with the Instituto Superior Técnico, Universidade de Lisboa (C2TN-IST/UL), using an Oxford Microbeams OM150 scanning nuclear microprobe setup for sample irradiation and the GUPIXWIN v3.0 software code (Campbell et al., 2021) for spectra deconvolution and quantitative analysis. Based on a fundamental parameters approach the program determined elemental concentrations, converted to their oxide form, with the total amount normalized to 100 wt%. All samples were initially irradiated with a low-energy 0.7 MeV proton beam to detect lighter elements such as Na, Mg and Al. For quantifying elements with high atomic numbers, higher than the one of Fe, a 2 MeV proton beam was employed. To validate the obtained results (Table 2, Supplementary Tab. 1), Corning Museum of Glass standard CMOG B was also analysed.

LA-ICP-MS was performed at the National Centre of Scientific Research (CNRS) in Orleans, France. This technique is frequently used in the analysis of archaeological glass, allowing to quantify the major, minor, trace and rare-earth elements (REE), important indicators of the provenance of sediments and sedimentary rocks (Gratuze, 2013; Brems & Degryse, 2014). LA-ICP-MS set-up consists of a Resonetics M50E excimer laser working at 193 nm coupled with a Thermo Fisher Scientific ELEMENT XR mass spectrometer. The excimer laser was operated at 5 mJ with a repetition rate of 10 Hz. The beam diameter can be adjusted from 20 μ m to 100 μ m. A pre-ablation time of 15 s is set in order to eliminate the transient part of the signal which is then acquired for 27 s corresponding to 9 mass scans from lithium to uranium. Calibration for glass was carried out using NIST610 and Corning B, C, and D reference materials (Gratuze, 2013). The detection limits range from 0.1 % to 0.01 % for major elements and from 20 to 500 ng/g for others. The composition is calculated as the average of two ablations performed in different sample areas, and the results are reported in (Table 2 and Supplementary Tab. 2). To ensure accuracy, glass reference standards Corning A, and NIST SRM 612 were regularly analysed as unknown samples throughout the analytical sequence (Table 2, Supplementary Tab. 2).

To validate the compositions obtained by μ -PIXE and LA-ICP-MS, the results of each element were compared. This comparison demonstrates the compatibility of the two methods, highlighting their potential as complementary analytical approaches. The correlation coefficients for all measured elements range from 0.96 to 0.82, confirming a strong agreement between the datasets. As examples, in Fig. 3 the three plots comparing the alumina (Fig. 3a), sodium (Fig. 3b) and magnesium (Fig. 3c) measured by the two different analytical methods are reported.

4. Results

The results of the analytical study reported in Table 2 show that the largest component, silica, ranges from 59.9 % to 72.4 %. The presence of high contents of Na₂O (12.9–19.6 wt%), in combination with MgO (1.4–4.3 wt%), K₂O (1.4–5.2 wt%) and relatively low P₂O₅ (0.2–0.4 wt%), and approximately 1 wt% of chlorine, suggests the use of soda-rich coastal plant ashes, commonly employed as fluxing agents in Mediterranean glassmaking in the time period considered (Šmit et al., 2009). Almost all blue decorations analysed have a composition similar to that of the body glass in terms of silica sources and flux. Minor differences are probably due to colouration, indicating that the same glass was used for both the vessel body and the decoration. However, there are exceptions for fragments LCS0286, LCC0029, LCS0883 that will be discussed below.

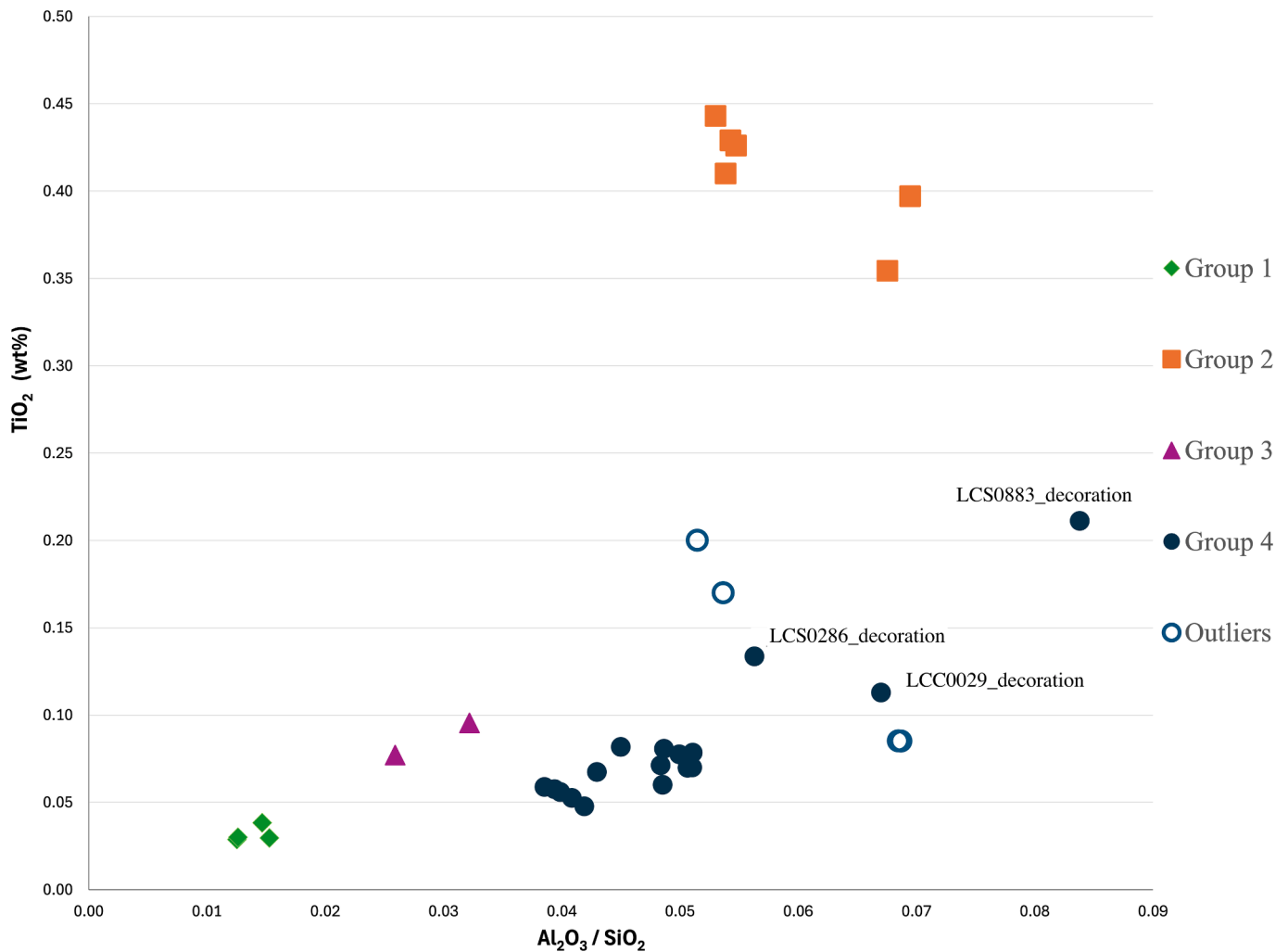


Fig. 4. Binary plot of $\text{Al}_2\text{O}_3 / \text{SiO}_2$ vs. TiO_2 .

This cluster also includes LCC0010 with a blue line applied on the rim and SCJ0078, which features an oblique rib motif impressed on the body, along with the rim decoration. Although the blue threads LCC0029, LCS0286 and LCS0883 show different concentrations compared to the body glass, they have been included in the same group and identified in Fig. 4, as they belong to the same object.

Fig. 5 shows the average of each previously identified group within a normalised plot of trace element to earth crust (Wedepohl, 1995). It can be observed that the groups present distinct trace element patterns. Notably, Group 2 stands out as different from the other groups, a difference already evident in Fig. 4. Interestingly, while Groups 1, 3, and 4 consist of objects dated to the 16th century, Group 2 comprises fragments from the 14th to 15th centuries. This indicates a shift in the sourcing of silica over the studied time frame.

Groups 1, 3, and 4, which include only fragments dated to the 16th century, display a similar overall trend in trace element patterns despite variations in impurity levels observed in Fig. 4. This suggests that the impurities across these groups may share comparable characteristics or quality.

In particular, Groups 3 and 4 are very close except for Al and Rb, this variation could be attributed to the use of feldspar sources with different chemical compositions. The significant discrepancy in Al, as well as the differing Al/Ti ratios highlighted in Fig. 4, suggests that the objects in these groups originated from different silica sources, geochemically related. Group 1 has the highest strontium value and lesser amounts of the other trace elements. This can be related to the use of a purer silica

source containing Sr-bearing aragonite from seashells (Cagno et al., 2012). The geochemical pattern of Group 1 was compared with the average trace element profile of three glass objects from the Monastery of Santa Clara-a-Velha (17th century), previously identified as authentic Venetian imports (Coutinho, Medici, Alves, et al., 2016). The near-complete overlap between the patterns suggests that the objects in Group 1 were likely produced using quartz pebbles from the Ticino River or an equally pure silica source.

4.2. Flux agents

All fragments fall under the soda-silica-lime type, thus with the use of plant ash as a fluxing agent. To differentiate the types of fluxes used in glass production, Fig. 6 compares the soda and potash values obtained by dividing the respective oxides with the sum of all components introduced into the ash. Two correlation lines are considered in medieval and post-medieval glass: $\text{Na}_2\text{O}^* + \text{K}_2\text{O}^* = 0.6$ for the use of natural ash and $\text{Na}_2\text{O}^* + \text{K}_2\text{O}^* = 0.75$ for purified ash (Cagno et al., 2012). Plant ash purification, introduced into the Murano glass production process in the 15th century, comprises several steps to remove water-insoluble substances, including iron, calcium and magnesium. This meticulous process was conducted on ashes imported from the Levant, which were utilized in the production of Venetian *crystallo* glass (Moretti & Hreglich, 2013). On the other hand, unpurified ashes refer to those that have not undergone this treatment.

All fragments belonging to Group 1 and 2 arrange themselves along

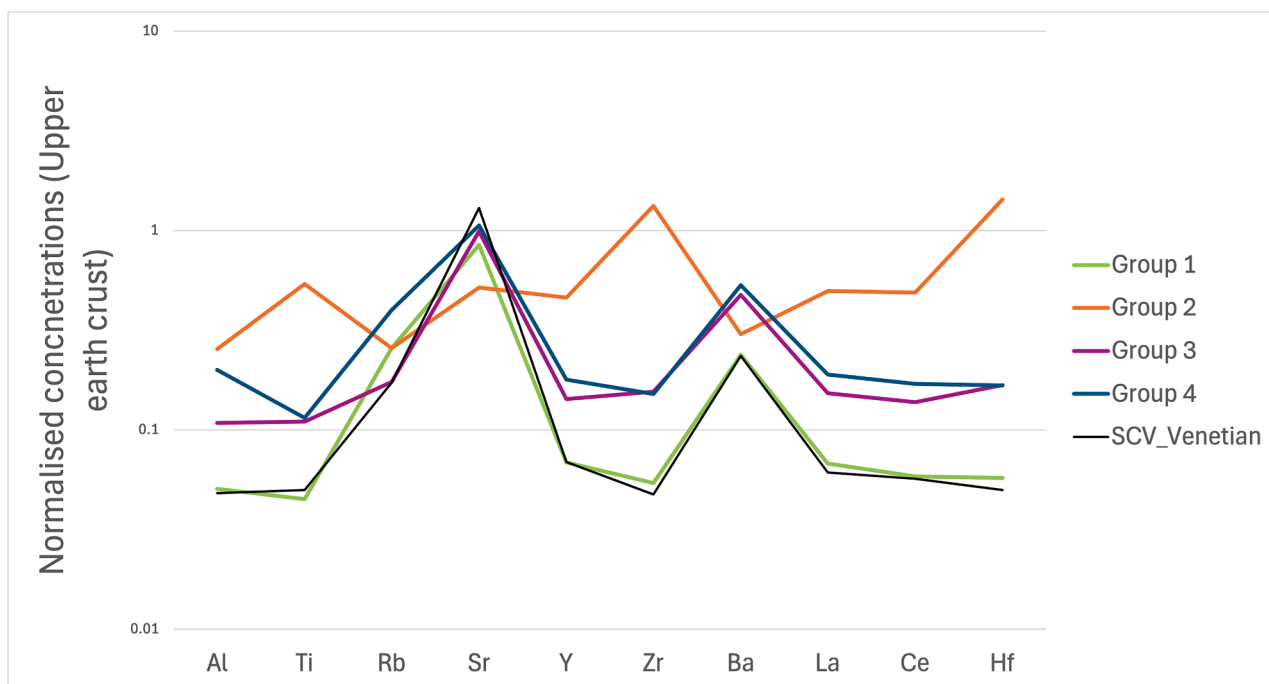


Fig. 5. Contents of selected trace and REE, normalized to Earth's upper crust, in logarithmic scale. Values for SCV are from Coutinho, Medici, Alves, et al., 2016.

the inverse correlation line of glass made using purified ashes and are close to the *crystallo* boundaries, which have a flux with low potassium concentrations and a higher soda content, comparable to that used in the Venetian glass production (Šmit et al., 2009; Verità, 2013). Fragments of Group 3 and 4 fall both in the *crystallo* area and close or inside the boundaries of *vitrum blanchum I* (Šmit et al., 2009). LCS1027 stands out as outlier, positioned on the line indicating a purified ash but with high potassium content.

4.3. Colourants and decolourants

The results reported in Table 2 for the decorations reveal that the blue glass was created by incorporating cobalt as a colouring agent into the base glass, with concentrations ranging from 0.07 to 0.26 wt%. Additionally, cobalt is found in correlation with copper (0.01 to 0.31 wt%) and iron oxides (0.66 to 2.14 wt%), elements naturally associated with the mineral ore used to produce the colourants, which were integrated into the glass batch. As mentioned earlier, the majority of the body glass and its associated blue decorative elements exhibit very close compositions, suggesting that they were likely produced using the same base glass to which a colouring agent was added. The blue decoration of LCS0286, LCC0029, and LCS0883, have higher levels of alumina and titanium indicating that the raw materials used for the blue glass were different and richer in impurities.

Examining the composition of the body glass in the analysed objects it can be observed that the MnO content in most samples, from approximately 0.3 % to 0.85 %, aligns with the typical range used for decolourising glass (Moretti & Hreglich, 2013). However, LCS1027 stands out with a higher concentration of 0.98 wt%, likely due to impurities in the silica source. In contrast, LCC0019 shows a rather lower concentration of 0.24 wt%, which may be attributed to the fact the decolouration process in Venice needed only small amounts of manganese added to the molten glass (Verità et al., 2024).

5. Discussion

The fragments analysed in this study were compared with results from literature regarding objects from the same period found in other

European contexts to identify potential compositional relationships (Fig. 7). Fragments SCJ0058 and LCC0019 (Group 1) align with 16th century Venetian *vitrum blanchum* productions, which involved the use of sands with low TiO_2 (< 0.07 wt%) and Al_2O_3 contents (< 1.5 wt%) (Verità, 2013). In Fig. 5 Group 1 stands out for its lowest trace elements, further highlighting the purity of the silica source. Specifically, the Zr and Hf content is often used in the literature to differentiate between Venetian and *façon de Venise* glass. Venetian glass typically exhibits low Zr levels, generally under 20 $\mu\text{g/g}$, and Hf concentrations below 1 $\mu\text{g/g}$ (Cagno et al., 2012; Coutinho, Medici, Alves, et al., 2016; De Raedt et al., 2001). The alkaline component of Group 1 indicates that these objects were made using purified ashes close to the *crystallo* type. It is proposed that objects in this group were produced using pure ashes similar to those brought to Venice from the Levantine region and with pure silica source, therefore advancing the hypothesis of a Venetian import. This idea is reinforced if considering the features of their decorations which as discussed above are in line with the Muranese production (Gallo & Silvestri, 2012; Pause, 2000).

Within Group 2, ARJ0099 and ARJ0452 exhibit overlapping characteristics with a fragment with blue decoration applied to the rim and an oblique ribbed pattern on a colourless body unearthed in Beja, Portugal, (15th century) with close titanium and alumina contents (Al_2O_3 3.4 wt%; TiO_2 : 0.45 wt%) (Coutinho et al., 2016a). Given the strong similarity in the values related to the silica sources and fluxing agents, it is suggested that these fragments were produced in the same production centre yet to be identified.

The ratios of $\text{Al}_2\text{O}_3/\text{SiO}_2$ versus $\text{TiO}_2/\text{Al}_2\text{O}_3$ of Group 3 and 4 align with *façon de Venise* objects from Portuguese excavations in Beja and the Monastery of São João de Tarouca (16th-17th centuries) (Coutinho et al., 2016b). When compared with other known European production centres such as Antwerp, Amsterdam and London (De Raedt et al., 2001; Hulst & Kunicki-Goldfinger, 2017; Janssens et al., 2013) the compositions show discrepancies, implying that the fragments here studied were not imported from these locations.

All fragments belonging to Group 3 and 4, except for the blue decorations, have iron oxide concentrations below 0.7 wt%, suggesting that the raw materials, rich in feldspars, were carefully selected (Coutinho et al., 2022). For these groups two production technologies have been

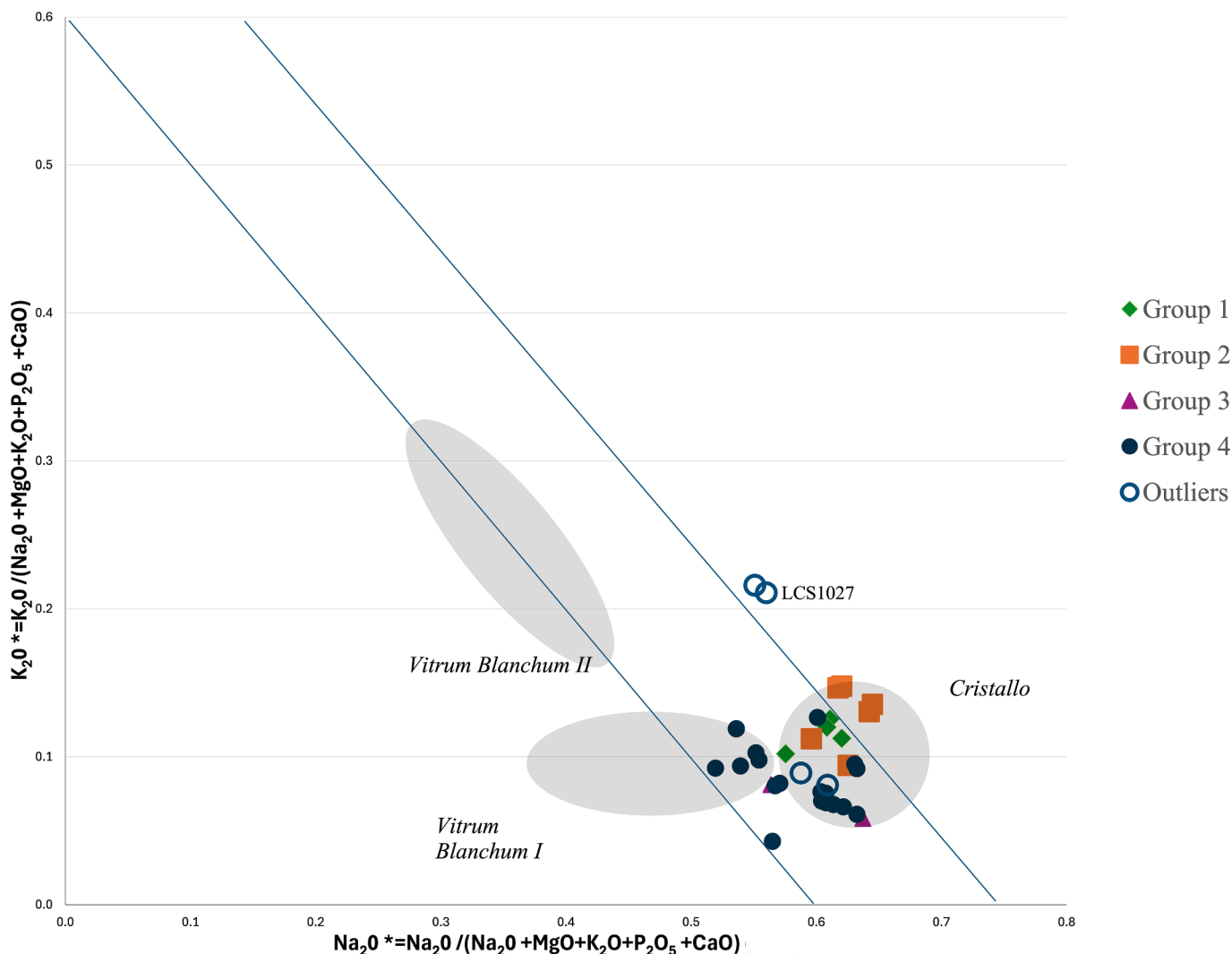


Fig. 6. Binary plot of Na_2O^* vs. K_2O^* . Na_2O^* and K_2O^* values are obtained through the division of the respective oxide by every component introduced by the ash (Na_2O , MgO , P_2O_5 , K_2O and CaO). The two correlation lines represent limit concentrations for the use of purified ash ($Na_2O^* + K_2O^* = 0.75$) or of unpurified ash ($Na_2O^* + K_2O^* = 0.6$) (Cagno et al., 2012).

identified using both unpurified and purified plant ashes (Fig. 6). These procedures may indicate an attempt to produce objects following Venetian techniques using locally available materials. Within these groups, objects originating from different contexts (LPF, LCC, LCS, SCJ) were identified, featuring blue decorations applied in various styles. This suggests the widespread use of a similar composition for producing objects with diverse decorative designs (i.e. horizontal thread applied on the body or on the rim; horizontal threads applied on the rim and a pattern of oblique ribs; horizontal threads applied on the body and a pattern of oblique ribs).

Considering the two outliers for LCS1027, both the body glass and decoration differ from the main group of fragments dated to the 16th century due to their higher alumina levels (4.30 wt%). Its impurity concentrations and the high potassium (5.15–5.25 wt%) align with analyses conducted on glass dated to the 15th century found in the glass-house of Monte Lecco, in the Genoese Apennines (Basso et al., 2008). Comparable sodium and potassium oxide levels have been identified in Granada, where it was suggested that local plants rich in sodium were purified and used in production (Coutinho et al., 2021). It cannot be excluded that the same process was used to produce this object. In Fig. 7, STCV0005 shows similarities in mineralogical characteristics with two objects from the production centre in Granada. Unlike the objects from the Spanish context, however, the fragment studied here was produced

using purified ashes.

Cobalt was identified as the element responsible for the colouring in all the blue glass analysed. A study on the mining locations used to obtain cobalt oxides enables the identification of possible areas of origin (Gratuze et al., 1996). To investigate the colouring technology, the elements in $\mu\text{g/g}$ related to the cobalt ore are plotted in Fig. 8. The co-presence of zinc, lead, and indium, suggests that STCV0005 dates between the 13th and 15th centuries, and that the cobalt ore used for its blue decoration is likely originating from the Erzgebirge mines near Freiberg, as outlined by Gratuze et al., 1996.

With reference to ARJ0452, ARJ0099 and LPF0006, Fig. 8 shows that the concentrations of cobalt-related elements have almost overlapping patterns. This similarity suggests a common origin for these objects and strengthens the hypothesis that they were produced in the same production centre, as the composition of the body glass is very similar as well.

Elements such as arsenic and bismuth help in more precise dating the objects. Their presence in the ore has been documented starting from 1520, when a shift occurred in the methodology of processing cobalt, which involves sorting and roasting the minerals in a reverberatory oven (Zucchiatti et al., 2006). The detection of larger amounts of these two elements in LPF0038 and SCJ0058 allows these objects to be dated to the second part of the 16th century. Furthermore, the presence of



Fig. 7. Binary plot of weight ratio of Al_2O_3/SiO_2 vs. weight ratio of TiO_2/Al_2O_3 for the samples considered in this work together with the concentrations of glass unearthed in Spain, in Granada (Coutinho et al., 2021), and in Portugal in Beja (14th-16th cent.) (Coutinho et al., 2016a; Coutinho et al., 2016b) and in Monastery of São João de Tarouca (16th-17th cent.) (Coutinho, Medici, Alves, et al., 2016). The areas marked as Venetian glass refers to the cristallo and vitrum blanchum groups, considering values reported in Verità, 2013.

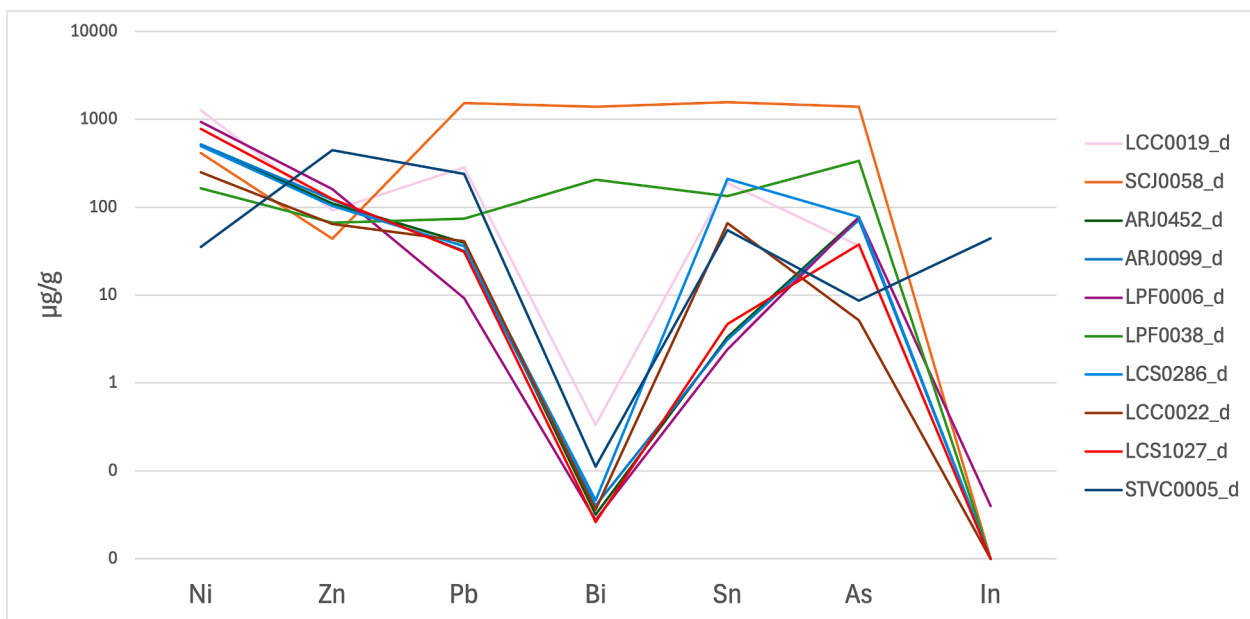


Fig. 8. Contents of elements related to cobalt ore, in $\mu g/g$.

arsenic, nickel, and bismuth is consistent with cobalt ore extracted from the Schneeberg mines in the Erzgebirge, Saxony (Gratuzze et al., 1996).

Additionally, LCC0019 and SCJ0058 exhibit relatively high levels of tin (188–1567 µg/g) and lead (283–1527 µg/g) in the blue decoration, compared to the other objects analysed. These elements were detected in Renaissance Venetian blue *crystallo* and *vitrum blanchum* samples (Verità et al., 2024; Verità & Biron, 2021), where their presence was believed to be due to the addition of unselected cullet which probably didn't affect the final blue colour of the glass (Verità & Biron, 2021). This comparison further reinforces the Venetian origin proposed for these two objects.

6. Conclusions

The study of glass objects featuring applied blue decoration, spanning from the 14th to the 16th century, provides significant insights into production techniques, raw material selection, and the origins of these items. From a stylistic perspective, the blue decoration was found in Portuguese excavations on tableware used for drinking, including beakers, goblets, and pedestal goblets, all with colourless bodies. Among the decorations observed, the applied blue horizontal thread stands out as the only consistent decorative element across the entire period. The perdurance of the use of these horizontally applied blue threads highlights their popularity across different time frames and production centres. On the other hand, it is noted that the pedestal goblets with applied blue festoon decoration, of which two examples with the same composition and dating (14th–15th century) have been found, disappear in the following century. Considering the results of µ-PIXE and LA-ICP-MS analysis, the objects dated to the 14th/15th centuries exhibit higher levels of impurities, which suggests the use of less refined silica sources. It is proposed that the objects belonging to Group 2 likely originate from the same production site. Specifically, fragments ARJ0099 and ARJ0452 share compositional characteristics, such as elevated titanium (around 0.4 wt%) and alumina (3.45–3.50 wt%), closely resembling a 15th-century beaker found in Beja, Portugal, which also features blue decoration applied to the rim. The strong similarities in the silica sources and flux agents suggest that they may have been produced within the same glassmaking workshop.

The fragments dated to the 16th century are identified as Venetian in origin (Group 1) or *façon de Venise* (Group 3 and 4). The presence of Venetian-imported goods indicates that Portuguese commercial activities were connected with the Venetian Lagoon during this period, reflecting the demand of the Portuguese high society for luxury items that were in fashion at the time. SCJ0058, from the excavation of the Convento de Jesus in Setúbal, provides further evidence that valuable and luxurious items, such as Venetian glass, were highly prized, acquired, and utilized within religious institutions. Moreover, the presence of such high-quality artifacts suggests that the women entering these convents were likely from noble families and became nuns while bringing with them their dowries. This is exemplified by the Convent of Santa Clara-a-Velha in Coimbra, where historical records documenting the names of the nuns have revealed that they originated from high-ranking social backgrounds (Coutinho et al., 2016b; Coutinho et al., 2019). Furthermore, it is well-documented that nuns, despite their vows of poverty and renunciation of material possessions, often brought objects from their family homes into the monastery to recreate aspects of their previous lives within the cloistered environment (Coutinho et al., 2019, 95). LCC0019, from the excavation of Campo das Cebolas in Lisbon, was unearthed from an area of the city, once peripheral and located at the margins of the urban centre, that progressively integrated into the urban fabric or the port system during the 15th and 16th centuries. Positioned along the river, it served as an intermediate zone between the city proper and the areas dedicated to trade and exchange and the ocean with the outside world. Nevertheless, unfortunately, the context of origin, a landfill to extend the river side of the Tagus river, does not provide conclusive evidence regarding the potential users or purchasers

of these objects.

The objects identified as *Façon de Venise* (Groups 3 and 4) include decorations influenced by the Murano tradition: decorations with threads applied to the rim, with a flat vessel or decorated with an oblique pattern of ribs. Additionally, there are objects with blue decoration applied under the rim and an oblique pattern of ribs, as well as, as mentioned, those with one or more blue threads applied. Their origin likely traces back to an unknown production centre shared with other *façon de Venise* objects dated between the 16th and 17th centuries, recovered from Portuguese excavations. The evidence suggests two distinct production technologies: one utilising unpurified plant ashes and the other using purified plant ashes, indicating efforts to replicate Venetian techniques with locally available materials.

Additionally, the fragment LCS1027, characterised by its higher alumina content and impurity profile, might be linked to the glass factory located in the Monte Lecco region. The compositional data is consistent with 14th/15th-century production remains from this region, indicating a potential exchange of goods with the area of Genoa, in Italy.

CRedit authorship contribution statement

Anna Cristoforetti: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Data curation. **Teresa Medici:** Writing – review & editing, Supervision, Conceptualization. **Catarina Villamariz:** Writing – review & editing, Supervision. **Luís C. Alves:** Writing – review & editing, Investigation, Formal analysis. **Nadine Schibille:** Writing – review & editing, Investigation, Formal analysis. **Inês Coutinho:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Data curation, Conceptualization.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jasrep.2025.105159>.

Data availability

Data will be made available on request.

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