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# Technical study of a rare Venetian turquoise glass goblet from the Waddesdon Bequest

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**SUMMARY** A Venetian enamelled and gilded goblet (WB.55) is part of the collection bequeathed to the British Museum by Baron Ferdinand Rothschild in 1898. Conservation treatment in 1994 provided the opportunity to remove a small sample containing some opaque white as well as rare turquoise glass. These fragments were analysed using scanning electron microscopy with energy dispersive X-ray spectrometry and by laser ablation inductively coupled plasma mass spectrometry. Further analyses were carried out on the enamels and blue glass knob of the goblet using surface X-ray fluorescence.

This contribution locates the object in the context of Venetian glass of the Renaissance as well as the history of collecting. The conservation history and the processes employed to conserve the object prior to its redisplay in the new Waddesdon Gallery at the British Museum in 2015 are described. Careful macroscopic and microscopic observations are combined with the chemical analyses to outline a comprehensive *chaîne opératoire* for the object. Technically, it is fully consistent with current understanding of glass production in Venice in the late fifteenth century.

## The goblet

The Venetian turquoise goblet (WB.55), which is the focus of this contribution, is one of the finest Renaissance glasses to be seen anywhere in the world, Figure 1. It came to the British Museum as part of the Waddesdon Bequest, a treasury collection formed over two generations by Baron Anselm de Rothschild of Frankfurt and Vienna, and his son Baron Ferdinand Rothschild, MP. Born in Frankfurt, Baron Ferdinand moved to England in the 1860s and became a British citizen, continuing to collect at his magnificent château, Waddesdon Manor in Buckinghamshire. He bequeathed this extraordinary treasury to the British Museum – of which he was a Trustee – at his death in 1898; his other collections remain at Waddesdon Manor.

The beautifully shaped goblet is widely accepted as having been made in Murano, the glassmaking island located off the main island of Venice, at the very end of the 1490s. It is enamelled with two pairs of lovers on the bowl, which suggests that it was possibly made to commemorate a betrothal or marriage [1; p. 160, 2; pp. 66–67, 3; pp. 95–97]. It was made in three separate parts: the opaque bright blue bowl and foot imitate the semi-precious stone, turquoise, while the darker blue stem imitates another semi-precious stone, lapis lazuli (this combination of different glasses is extremely rare; for comparative pieces see [4]). Trails of opaque white glass around the goblet and foot set off the brilliance of the colouring, along with touches of red, yellow and white enamel and gilding [1; cat. 21, 2; pp. 188 and 193, 5; cat. 208, 6; p. 66].

The hair and dress of the couples painted on the glass give valuable clues as to its status and date, Figure 2. They represent European aristocratic fashion of the very late 1490s [7; cat. 53].<sup>1</sup> A couple are shown as half-length figures in a landscape, lit in one scene by a sun with shining rays and in the other by a moon in a night sky streaked with cloud. In the sunlit scene, a couple stand close together with a fawn lying in front of them, Figure 2: left. A fawn or deer often appears beneath stylized sunrays on contemporary glass and maiolica, perhaps as an emblem of love and faithfulness [1; cat. 5, 7; cat. 309, 8]. The young man wears a cap over his long hair, while the woman wears a cloak and seems to hold up her hand to point at the heavens in emphasis as she speaks to him. On the moonlit side,



Figure 1. The Waddesdon goblet (British Museum WB.55: height 18.9 cm)



Figure 2. Details of the two roundels on the Waddesdon goblet

a different man, who is short-haired, clean-shaven and richly dressed in velvet brocade, faces the same woman in a low-cut gown with a belt and separate sleeves worn over a chemise, her flowing blonde hair picked out in yellow enamel and gilding, Figure 2: right. He gazes into her eyes and places his hand on her breast; they seem to be a betrothed or married couple in their wedding finery [2; pp. 55–56 and fig. 36]. The scenes appear to be part of a narrative – perhaps illustrating a poem or romance – as an allegory of love or chastity of the kind found on art made to commemorate marriage in Renaissance cities [2; pp. 66–67].

The decoration has been attributed to Giovanni Maria Obizzo, who was named in a glassmakers' legal dispute in Murano in 1490 as the painter of "more than a thousand pieces of opaque white glass (*lattimo*) and other colours, all gilt and enamelled", which he claimed had been illegally fired by a rival craftsman [1; p. 159]. Obizzo was a specialist at

a time when enamelled decoration came close to the work of Venice's finest painters. The portrait busts of men and women on about 20 surviving glasses of the opaque white glass mentioned in the dispute, which imitate Chinese porcelain, are close in style to the work of Vittore Carpaccio in the period 1495–1508 [9]. The enamelled bust of King Henry VII of England – copied from a coin portrait – on a *lattimo* flask in the British Museum is attributed to Obizzo and, if he decorated glasses of "other colours", he might also be the painter of the Waddesdon glass, Figure 3 [1; p. 106 and fig. 202, 9; p. 23]. Both sets of 'portraits' have a similar liveliness and sketchy quality, which might suggest the work of the same hand. Both are likely to have been special commissions from one of the leading workshops in Murano.

The turquoise body of the glass is striking and impressive. To the authors' knowledge, only three complete pieces made from Venetian turquoise glass survive and this is the



Figure 3. Vase made of opaque white *lattimo* glass painted with enamel colours (British Museum 1979,0401.1): left, the roundel on the front containing the bust of Henry VII; and right, roundel on the back containing a portcullis in blue and red



Figure 4. Comparative examples containing turquoise glass: left, enameled and gilded turquoise glass footed bowl (Victoria and Albert Museum 4319-1858); and right, the Fairfax cup, a turquoise glass beaker enamelled with three (possibly four) figures in green, blue, white and yellow in scenes from the story of Pyramus and Thisbe (Victoria and Albert Museum C.17 to D-1959). Images: © The Victoria and Albert Museum

most spectacular and sophisticated of the three. They imitate the effect of turquoise, a semi-precious stone that was highly prized in the Islamic world and was imported into Europe via Venice from Khurasan in eastern Iran. Turquoise had high curiosity value with European patrons in the Renaissance; Isabella d'Este, always a leader of fashion, commissioned a turquoise gem to be engraved with the figure of Orpheus by a Venetian craftsman in 1496 [2; p. 178, 10; pp. 99–100]. Muslim craftsmen had long made imitations of turquoise in glass and a fine bowl, made in Egypt in the 900s, was an established object in the Treasury of the Cathedral of San Marco in Venice and may have stimulated curiosity and ambition among Venetian craftsmen [1; p. 119 and fig. 147]. Copying precious and semi-precious stones in glass was a Venetian preoccupation, in which craftsmen experimented with creating the effect and colours of chalcedony, opal, amethyst, emerald and sapphire. But glass imitating turquoise was the rarest of the rare and there is only one reference in the Murano archives to “four little jugs of turquoise glass”, which appears in the record of a legal dispute in 1496 between two members of the same glassmaking family, Marietta Barovier

and her brother Giovanni [2; p. 188, 11; p. 20]. A further rare reference to turquoise glass appears in an inventory listing the possessions of the court painter to the Gonzaga of Mantua, Andrea Mantegna, who died in 1506 and had “a little flask of turquoise glass with the device of the sun upon it” [2; p. 195, 12; p. 112].<sup>2</sup> As described, it was enamelled with a sunburst, his personal device or *impresa*, which his patron the Marquis Ludovico Gonzaga had allowed him to use as a special privilege. As it was formerly a Gonzaga device, the artist was very proud of it and had it worked on his gold livery collar, blazoned on his dining silver and embroidered on the coverlet of his bed. The flask was obviously a treasured possession and was probably a gift from his patron.

The two other surviving examples of Venetian turquoise glass are a footed bowl enamelled with a sophisticated trellis design of twining tendrils (Figure 4: left), and a small beaker enamelled with the story of Pyramus and Thisbe (Figure 4: right), both in the collection of the Victoria and Albert Museum. The bowl shares several characteristics with the Waddesdon goblet, such as the white glass trails and superbly executed red, white and yellow enamelled decoration, and



Figure 5. The Waddesdon goblet dismantled prior to reconstruction in 2014

it was probably made in the same workshop and enamelled by Obizzo [13]. The beaker is however very different, as it is made of a dichroic glass that changes colour by transmitted light from turquoise to deep red [14]; it is also much more crudely enamelled. It was clearly prized by the English family that once owned it, the Fairfaxes, as one of them referred to it as “the Ancient Cup of our Familye” in 1694 [15; p. 49].

Other possible comparisons for WB.55 are four small rim fragments found in 2005–2006 in the French quarter of Southampton. Their light blue opaque glass, which shows no trace of enamelling or gilding, has been likened to the Waddesdon Bequest glass and dated to the late fifteenth century. The fragments were found in a pit with discarded household vessels in a large, important and well-documented property (Tenement 237), which had been inhabited by a series of wealthy Genoese merchants and a Venetian consul in the fifteenth century; in another pit a large quantity of good quality glass was found from the period 1500–1550 [16; pp. 28, 91, 106, 184, 190, 191 and cat. 30]. A further turquoise bowl or cup fragment with a white trail, similar to that of the Waddesdon Bequest glass, was recently excavated at the wealthy Convent of Santa Chiara in Padua.<sup>3</sup> This would seem to be the type of elite context in which Venetian glass of this rarity and finesse was used in the late fifteenth century.

All that is known of the history of the Waddesdon Bequest glass is that Baron Anselm acquired it before 1866, when it was included in the catalogue of his collection, which was published in Vienna by Franz Schestag. The fact that no previous references to it have yet been found, and that there are so few pieces with which to compare it, prompt a number of questions about the glass and its role in the technical evolution of Venetian glassmaking in the Renaissance.

This contribution sets out to answer some of these questions, and so allow the Waddesdon goblet to be properly compared with other surviving Venetian pieces of the highest quality in its composition, making and decoration.

### Conservation history

The goblet is damaged and in a fragmentary condition. At some time in the past it had been reconstructed using an adhesive, thought to be an animal glue, which had discoloured and attracted dust to the break edges. In 1994, at the instigation of the late Hugh Tait, the object was dismantled and reconstructed using HMG heatproof and waterproof adhesive (cellulose nitrate). This adhesive has been used successfully for more than 40 years at the British Museum to reconstruct vessels and other objects made from glass and ceramic, including cuneiform tablets. However, while the goblet was being

**Table 1. Colourants and opacifiers determined by XRF**

Colour	Significant elements
Turquoise body	Copper (Cu), lead (Pb) and tin (Sn)
White body decoration	Pb and Sn: almost identical to below, with a trace more manganese (Mn), potassium and calcium
White enamel	Pb and Sn: almost identical to above, with a trace more Cu
Brown enamel	Iron, Pb and Sn
Yellow enamel	Pb, Sn, antimony and zinc
Black enamel	Cobalt (Co), nickel (Ni), Mn, Pb and Sn
Blue knob	Co, Ni, Pb and Sn (no bismuth or arsenic detected)

re-examined in 2013 a fragment on the foot weakened and became detached. Although no further damage occurred to the vessel at the time, this unnerving incident drew attention to the need to examine the stability of the vessel in greater depth.

The currently preferred adhesive for the reconstruction of the majority of glass vessels is Paraloid B72 (methyl ethyl methacrylate), due to its documented stability. Because of the recent failure of the cellulose nitrate adhesive and for the long-term stability of the object, it was agreed that the goblet would be dismantled and reconstructed using Paraloid B72, Figure 5. The goblet was prepared for treatment by supporting and cushioning with tissue paper and Tyvek (spun bonded polyethylene). It was then placed into an atmosphere of acetone vapour to weaken the previous adhesive. Once dismantled the surface was lightly cleaned using cotton wool swabs moistened with a 1:1 mixture of distilled water and industrial methylated spirit. The break edges were then cleaned and degreased using acetone on cotton wool swabs. The fragments and a number of small glass flakes were incorporated into the reconstruction using HMG Paraloid B72 adhesive. During the reconstruction, Scotch® Magic™ Tape 810 (cellulose acetate carrier, acrylic adhesive) was applied to the inside of the vessel to secure the joints, avoiding the gilded decoration, while the solvent evaporated from the adhesive.

The intervention in 1994 provided a rare opportunity to remove a small fragment containing both turquoise and white glasses for scientific analysis from this complete and exceptional vessel.

### Scientific investigation

The vessel was analysed by surface X-ray fluorescence (XRF) to identify the colourants and opacifiers used in its production. The glass fragment was mounted and polished flat to reveal a cross-section showing both turquoise and white glasses and examined by scanning electron microscopy (SEM) in 1994. Major element compositions were determined with the attached energy dispersive X-ray spectrometer (SEM-EDX). The sample was recently re-analysed using the much more sensitive technique, laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS). This technique is particularly useful for the measurement of trace elements in low abundance, but also yielded additional data for the major and minor components. The data acquired for the elements that were measured using both techniques generally show good agreement once anticipated errors are taken into account.

The elements associated with colourants and opacifiers in the glasses and enamels, determined by XRF, are presented in Table 1. The characteristic opacifiers in Venetian glass,

enamels and ceramic glazes of this period are mainly tin based. Tin oxide was produced by the oxidation of tin metal, which was usually carried out in the presence of lead. It has been suggested that lead was added to lower the melting temperature of the tin oxide and to allow the tin oxidation to proceed to completion [17]. This lead-tin *calx* was added to the base glass to render it opaque. All of the colours analysed include significant quantities of lead and tin opacifier. The yellow enamel is an exception in that it also includes antimony oxide, which accords with the findings for yellow enamel reported by Biron and Verità in their study of Venetian enamelled glass [18]. It appears that by the late 1490s Venetian glassmakers had already increased the yellow palette by adding lead-antimonate yellow ('Naples yellow') and lead-tin-antimonate yellow to the lead-tin yellow used previously. This practice was also adopted in maiolica glazing, as indicated by Piccolpasso, writing in 1557 [19]. As noted by Rosi *et al.* [20], zinc could be added to deepen the tone of the yellow towards orange, a practice that may account for its detection here [21].

The presence of copper in the turquoise glass imparts the colouration, while cobalt (Co) provides the deep blue of the knob. A number of cobalt pigments were widely traded and the particular material employed can be characterized from the other metals associated with its ores. In their survey of French glass, Gratuze *et al.* identified a group of glasses that, like the goblet, are characterized by cobalt in association with nickel (Ni) but without arsenic (As) [22]. They dated this glass as from the end of the thirteenth to the beginning of the sixteenth century, just consistent with the dating of the goblet. However, more recent work dates the change from Co-Ni- to Co-As-bearing pigments to 1520–1530 [23, 24]. It is significant that in their survey of enamelled Venetian glass, Biron and Verità reported that only two of 10 cobalt-coloured glasses (nine blue, one black) contained significant nickel associated with the cobalt but no arsenic [18]. The presence of elevated cobalt, nickel and manganese in the black enamel of the goblet is again consistent with the single analysis of a black enamel by Biron and Verità [18]. The brown enamel has a high iron content and probably owes its colour to the presence of particles of the iron oxide hematite (Fe<sub>2</sub>O<sub>3</sub>).

The major and minor element compositions of the white and turquoise glasses are presented in Table 2, based mainly on EDX analysis but with LA-ICP-MS data for elements at low concentrations. Both glasses are soda-lime-silica types with high contents of lead and tin oxides. They are very close in composition, the main differences being the higher copper content of the turquoise glass and the higher levels of lead and tin in the white glass. This is reflected in the SEM

**Table 2. Compositions in wt% of the glasses, determined by SEM-EDX or by LA-ICP-MS (indicated by an \* and quoted to two decimal places)**

	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	MnO	MgO	CaO	Na <sub>2</sub> O	K <sub>2</sub> O	CuO	SnO <sub>2</sub>	PbO	P <sub>2</sub> O <sub>5</sub>	Cl	SO <sub>2</sub>	Total
White	47.3	0.6	0.19*	0.08*	0.7	3.0	13.2	1.7	0.02*	14.7	18.2	0.04*	0.6	<0.3	100.2
Turquoise	52.8	0.8	0.46*	0.07*	0.8	3.5	12.5	2.1	2.7	11.4	12.5	0.04*	0.6	0.3	100.3

**Table 3. Reduced compositions in wt% of the base glasses, produced using the data from Table 2 and renormalized to 100%**

	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	MgO	CaO	Na <sub>2</sub> O	K <sub>2</sub> O	Cl
White	70	0.89	0.28	1.0	4.5	20	2.5	0.89
Turquoise	72	1.1	0.63	1.1	4.8	17	2.9	0.82

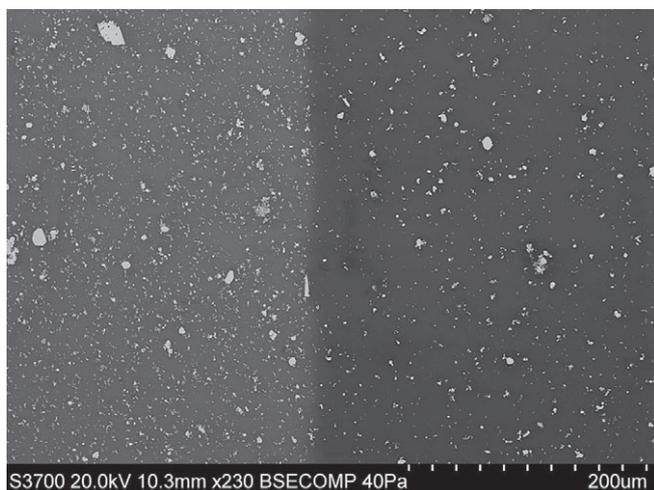
image of the sample (Figure 6), which shows a higher density of tin oxide particles in the white glass. It is clear that the turquoise glass was not simply a product of the addition of copper to the white. It would have been necessary to maintain a careful balance when producing the turquoise colour, as it required sufficient tin oxide to ensure it was opaque but not so much as to bleach out the rather weak blue imparted by the copper. To achieve this, a lower concentration of tin was required in the turquoise glass compared to the white. The tin oxide to lead oxide ratios are similar in the two glasses, indicating the addition of a similar lead-tin *calx*, but in different quantities.

The base glass compositions may be considered by subtracting the concentrations of lead, tin and copper oxides from the bulk compositions and renormalizing the remaining oxides to 100%, which produces a so-called ‘reduced’ composition, without added colourants, as shown in Table 3. Several characteristics are apparent. These are glasses produced using soda-rich plant ashes, which is characteristic of Venetian glass of the period. However, the low level of magnesia (MgO), at around 1%, along with relatively low lime (CaO) and high soda (Na<sub>2</sub>O) contents, clearly indicate that these were glasses of the *cristallo* type [25]. The secret of the production of *cristallo* glass was to remove the relatively insoluble impurities from the alkali plant ash by a process of dissolution, decantation and

evaporation. This reduced the amounts of undesirable colourants such as iron and titanium oxides but also, by incidentally reducing the oxides of calcium, magnesium and aluminium, produced a less stable glass. To counteract this effect it appears that a proportion of these latter insoluble salts was therefore returned to the glass mix [25].

In addition to the special characteristics of the glasses noted above, it was also observed that the amount of phosphate (P<sub>2</sub>O<sub>5</sub>) was exceptionally low for plant ash glass, at around 0.04 weight percent (wt%) (Table 2), again a reflection of the removal of insoluble components when the plant ash was purified. Transparent *cristallo* glass typically contains several tenths of one percent manganese, which was added as a decolourant [18, 25]. The quantities of manganese oxide (MnO) here are, however, much lower, at below 0.1 wt%. Glass without manganese was possibly used to avoid a pinkish colouration that can arise from the presence of oxidized Mn<sup>3+</sup>, which might tend to spoil the white and turquoise colours. The formation of Mn<sup>3+</sup> would have been likely in tin-opacified glasses as they would have been almost completely oxidized by the addition of calcined lead and tin oxides. Interestingly, opaque turquoise and white enamel glasses from the Roman and Romanesque periods display low manganese contents relative to other colours, suggesting a similar empirical approach to the production of pale opaque colours [26, 27].

The trace elements fall into two groups. Those typically associated with plant ash – lithium (Li), rubidium (Rb) and strontium (Sr) – and silica (other trace elements), the raw materials for the base glass, are presented in Table 4. These elements are similar in both the white and blue glasses, confirming that they were made using essentially the same base glass. However, a remarkable feature of these elements is their extremely low concentrations relative to most early glass. For example, in Roman colourless glass zirconium (Zr) is typically present at a level of 30–50 parts per million (ppm), chromium (Cr) at 10–20 ppm and titanium (Ti) at over 500 ppm. The concentrations of these elements are very much lower in Venetian *cristallo* because, rather than using sand as a source of silica, the glassmakers used pure quartz pebbles from the River Ticino that have very low levels of impurities [28]. Furthermore, the relatively low concentrations of Zr and Sr in the glasses in the Waddesdon goblet plainly demonstrate that the glass is indeed Venetian *cristallo*, and distinguish it very clearly from *façon de Venise ‘cristallo’* or *vitrum blanchum*, which were later made elsewhere in Europe, for example in Antwerp [29] and in London [30].



**Figure 6. Backscattered electron image of the boundary between the white (left) and turquoise (right) glasses. The lighter particles are tin oxide; a higher density of these particles can be seen in the white glass, which has a paler appearance due to the higher concentration of lead**

**Table 4. Compositions in ppm of the trace elements typically associated with the silica and ash sources, determined by LA-ICP-MS**

	Li	Be	B	Ti	V	Cr	Rb	Sr	Y	Zr	Cd	Ba	La	Ce	Th	U
White	2.86	0.0692	65.6	135	5.49	5.55	10.7	159	1.93	9.91	0.110	90.2	3.16	4.28	0.240	0.170
Turquoise	3.62	0.126	72.0	179	6.78	7.80	12.9	168	2.27	12.3	0.0763	98.2	3.66	5.12	0.344	0.216

**Table 5. Compositions of the elements (in ppm) and oxides (in wt%) typically associated with the addition of colourants and opacifiers, determined by LA-ICP-MS or SEM-EDX for those entries marked with an \***

	PbO	SnO <sub>2</sub>	CuO	Fe <sub>2</sub> O <sub>3</sub>	Co	Ni	Zn	As	Sb	W	Au	Bi	Ag
White	18.2*	14.7*	0.02	0.19	4.90	11.3	21.5	5.98	78.0	3.21	0.433	0.911	1.76
Turquoise	12.5*	11.4*	2.7*	0.46	43.7	34.9	46.6	52.7	153	8.80	1.09	5.90	11.9

The second group of trace elements comprises those that show marked differences between the white and turquoise glasses. On the whole these are higher in the turquoise glass (Table 5) and are transition metals that may derive from impurities in the copper-containing additive used to colour the glass. Although it was not possible to evaluate the tin and lead contents of the copper additive, because these elements were also added separately within the opacifier, it appears that, with the exception of iron, the copper was relatively pure, with concentrations of other components equivalent to less than 0.01 wt% of the copper. The origin of the higher iron level in the turquoise glass is less clear – this is not an alloying element of copper, but could reflect the addition of a copper mineral rather than a metal alloy, or indeed an addition of iron to enhance the colour in some way. The level of cobalt present in the turquoise glass is less than 50 ppm. This amount is enough to impart a light blue tint to a colourless glass and its presence in the glass may represent the deliberate addition of a cobalt-rich ore, which may have contained the iron and nickel impurities that were measured during this study. While its effect on the turquoise colour would probably have been small, it may be that the glassmakers believed that a small amount of cobalt was needed to achieve a good blue.

## The manufacturing and decorating processes

### Overview

The Waddesdon goblet was made in four distinct phases of manufacture by as many as four different groups of workers; these phases are summarized here and described in detail in the sections that follow.

- I. In a first step, the different coloured glasses needed for the goblet and the enamels required for its decoration were made in separate crucibles by glassmaking specialists.
- II. Next, a team of glassblowers created the goblet or ‘blank’ that was to serve as a canvas for enamelling and gilding.
- III. After the blank had been cooled to room temperature, gold was applied in leaf form and the enamels – suspended in a viscous medium – were painted on, operations that were probably undertaken by specialists, a view supported by archival evidence.
- IV. Once decorated, the blank was returned to the glassblowers for the crucial firing process, which would make the

decoration permanent. Finally, the decorated and fired goblet would be slowly annealed.

In total, up to about a dozen skilled specialists may have been involved in creating this object, not to mention the designers and entrepreneurs involved in its conception and the suppliers of the raw materials and fuel.

### Preparing the glasses and enamels

The required glasses – turquoise, ‘lapis blue’ and opaque white – were made in separate crucibles contained within a wood-fired glassmaking/glassworking furnace. High-quality *crystallo* glass was used as the base for each colour. This is likely to have been a special batch of *crystallo*, prepared without the usual addition of manganese and intended specifically for strongly coloured opaque glasses. According to Antonio Neri, the Florentine glassmaker and author of *The art of glass*, writing a century later in 1612, the base material for opaque enamels was a mixture of lead-tin *calx* and crystal glass [31; p. 204]. Alone, this would have produced an opaque white glass or enamel, to which copper or cobalt was added to produce turquoise or lapis blue. The present study suggests that the *calx* to *crystallo* ratio varied according to the colour, perhaps through the addition of extra *crystallo* at the colouration stage. This preparatory work might have been carried out by glassmaking specialists prior to the glassblowers beginning their work [31; p. 204]. The same glassmakers would also have made the enamels used later during the decorating process. At all times, one or more ‘stokers’ continually fed the furnace with thoroughly dried hardwood, carefully controlling both its temperature and atmosphere: oxidizing, reducing or neutral. In order to attain the strongest turquoise effect from the copper, it was probably necessary to maintain oxidizing conditions, as only oxidized copper(II) colours the glass blue.

### Making the goblet

The glassblowing steps used to make the blank are consistent with those believed to be typical of pre-seventeenth-century Venetian workshop practice: it was built by a continuous additive process that is sometimes called ‘building a goblet on the blowpipe’.

The bowl was begun by free blowing. A trail of opaque white glass was added to the lowermost edge of the bowl and immediately given a denticulate pattern using a fluted embossing wheel. Next, the stem was begun by carefully adding a

stubby section of lapis blue glass to the centre of the base of the bowl. To its end was added a thick-walled bubble of the same colour glass, only here it was first rolled over a strip of gold leaf, then inflated into a dip mould in order to produce the subtle ribbed pattern. After tooling to give the knob its three-element form, another stubby section of lapis blue glass was added, just as above. To its tip a small amount of molten opaque white glass was attached, which was immediately flattened to form a disc, and it can be seen that the disc was made slightly larger in diameter than the lowermost part of the stem.

The foot was made next. In a procedure identical to that used for making the knob (including the gilding and dip-moulding), a bubble of turquoise glass was carefully centred on the opaque white disc and cut free of its blowpipe. After the resulting hole had been enlarged, a thick trail of opaque white glass was applied adjacent to its edge, then flattened to form a band. After this, in a series of steps involving reheating and tooling, the foot was given its final trumpet-like shape. The remaining steps would give the upper half of the bowl its near-final shape and create the rim. To do this, the worker needed to attach a handle to the base and then break the partially formed bowl of the goblet from its blowpipe.

A pontil (sometimes called a 'punty') was attached to the interior of the foot at its apex. The pontil is a tool that functions as a handle with which the glassblower can hold a hot vessel at its base while finishing the upper, open end. In practice, the pontil is a rod of metal that is hot at only one end, this end having been coated thinly with molten glass. This soft glass adheres when touched to the bottom of a vessel, but only slightly, and can be broken free of the vessel upon completion of the manufacturing process. The use of a pontil can be detected from the small, rough scar left behind on the base of the object – the pontil mark.

Immediately after attaching the pontil, the vessel was broken free of its blowpipe. Through a series of reheating and tooling stages, the upper half of the bowl was given its almost final form, and the rim was expanded to close to the finished diameter. Finally, with a gentle tap on the metal rod, the blank was broken free of the pontil and placed into the annealing oven for gradual cooling to room temperature.

Although complicated, this carefully choreographed procedure would have required a mere 15 or so minutes to execute; for an experienced specialist, glassblowing can be stunningly quick. Sufficient annealing for an object of this modest thickness could have been achieved in as little as two to three hours.

### **Creating the decoration**

The decorators first applied an adhesive, such as a solution of water and gum arabic, to the surface of the glass in those areas where cold-applied gold was to complement the hot-applied gold that had been added earlier to the knob and foot during glassblowing. The gold leaf was laid on in strips to form bands near the top and bottom of the cup. After the adhesive had dried, some gold was scraped away to make the borders perfectly even and to create the fish-scale pattern.

Next, the enamels were applied as a mixture with a painting medium, such as water and gum arabic. The simplest consisted of finely powdered, intensely coloured glass mixed with a

painting medium. This seems to have been the procedure for most of the colours used on the goblet. Other enamels consisted of finely powdered, intensely coloured glasses and pulverized colouring agents. This appears to be the case for the brown enamel on the goblet, where red hematite pigment was mixed with either *cristallo* or opaque white glass, or a combination of the two. On close inspection, it can be seen that the enamel mixture used for the dots was very viscous: the dots stand proud and some appear rather granular. The enamel used for the portraits was more dilute and more finely ground.

### **Firing the decoration**

A fifteenth-century manuscript preserved in the Library of San Salvatore in Bologna describes the stages that followed in surprising detail:

put the glass upon the rim of the chamber in which glasses are cooled [the annealing oven], on the side from which the glasses are taken out cold, and gradually introduce it into the chamber towards the fire which comes out of the furnace and take care you do not push too fast lest the heat should split it, and when you see that it is thoroughly heated, take it up with the pontello [pontil] and fix it to the pontello and put it in the mouth of the furnace, heating it and introducing it gradually. When you see the smalti [enamels] shine and that they have flowed well, take the glass out and put it in the chamber to cool, and it is done [32; p. 26].

This procedure is difficult and fraught with peril. From the minute fractures of the gold leaf nearest the rim it can be seen that during firing the immediate area of the rim softened and the worker slightly increased its diameter. In contrast, elsewhere the gold is solid and unbroken, which indicates that no change of shape occurred after the gold was applied. Throughout this process the vessel would crack if it became too cool or, if it became too hot, it would collapse under its own weight without expert management.

When the firing was complete, the finished goblet was yet again broken free of the pontil and placed into an annealing oven for its final gradual cooling. Close examination of the inside of the foot reveals a double pontil mark, the first from the manufacture of the blank and the second, a remnant of the firing process, overlying the first.

### **Conclusions**

Through this interdisciplinary exploration it has been possible to investigate an important object from a variety of perspectives. Curatorial research has emphasized the importance and rarity of the goblet. Indeed, so few examples exist that an in-depth technical study was necessary to place the object in context and to confirm the presumed date and place of production.

The scientific investigation has shown that the composition of each part of the goblet and the enamelling is fairly typical of Renaissance Venetian glass production. There are some indications in the interpretation of the data, such as the use of a particular cobalt colourant, that corroborate the proposed production date at the end of the fifteenth century.

The major element composition and exceptionally low impurities, seen in the trace element analysis, indicate that the body glass is of the *cristallo* type, made from purified ash and quartz pebbles. Of particular interest is the early use of lead-antimonate yellow, modified by the addition of zinc, in the enamelling.

Certain aspects of the composition of the opaque turquoise glass could suggest why this colour is so rare. First, unlike colourless Venetian *cristallo* glass, the production of an opaque turquoise colouration required the use of a base glass low in manganese. The *cristallo* recipe therefore had to be modified to provide a base glass that could be used to produce this colour. Secondly, the glassmakers needed to achieve a perfect balance between the addition of a tin-based opacifier and copper colourant to produce the desired colour and this must surely have presented a considerable challenge.

The production of the goblet was a highly specialized process with many complex stages. The labour-intensive method, involving so many workers, would have added to the value of the object. Each of the production steps from the free blowing of the bowl to the firing of the enamels is consistent with Venetian production before the seventeenth century.

The combination of documentary and technical research, and the evidence of the goblet itself, has allowed the goblet to be placed into its correct context and has suggested some technological hypotheses to explain the rarity of this glass type.

## Experimental appendix

### *X-ray fluorescence (XRF)*

The unprepared surface of the goblet was analysed with a Bruker ARTAX spectrometer using a helium atmosphere, 50 kV X-ray tube voltage, 0.8 mA current, 0.6 mm diameter collimator and 200 s counting time.

The surface analysis of glass objects can provide results that are not consistent with the bulk composition. This is due to a process of weathering that occurs over time, which results in the leaching of alkali components from the surface and an associated enrichment in silica. However, the glasses and enamels analysed for this study were relatively free from weathering and the results are therefore believed to be a useful representation of the bulk glass.

Using this methodology, the XRF analysis was able to provide semi-quantitative results, i.e. to identify the presence or absence of elements and their relative proportions. Elements with an atomic number lower than silicon could not be quantifiably detected under the conditions used.

### *Scanning electron microscopy with energy dispersive X-ray spectrometry (SEM-EDX)*

The fragment was mounted in a block of epoxy resin and polished with diamond pastes down to 1  $\mu\text{m}$ . It was coated with a thin layer of carbon and examined in a JEOL JSM 840 scanning electron microscope (SEM). Elemental compositions were determined by energy dispersive X-ray spectrometry (EDX) using an Oxford Instruments Link Systems 860 spectrometer attached to the SEM. Precision and accuracy are believed to be better than 3% relative for  $\text{SiO}_2$ , 5% for other oxides

in excess of 5 wt% absolute and 10% for oxides in excess of 1 wt%. Backscattered electron (BSE) imaging was carried out using a Hitachi S3700 SEM.

### *Laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS)*

The analyses were carried out using the instrumental facilities at the London Centre for Ore Exploration (LODE). Data were collected using an Agilent 7700 quadrupole ICP-MS coupled to an ESI New Wave Research NWR 193 nm Ar:F excimer laser. The analyses were carried out using argon ( $\sim 1.1 \text{ L}\cdot\text{min}^{-1}$ ) and helium ( $\sim 0.5 \text{ L}\cdot\text{min}^{-1}$ ) as carrier gases. A gas blank was collected for 20 s prior to the start of each ablation. A short pre-ablation pass (typically a few individual bursts at a rate of 2 Hz) was performed before the start of each ablation in order to clean the surface of the specimen from the carbon coating applied during SEM analysis. Each spot was 70  $\mu\text{m}$  in diameter and was ablated for 50 s, with a repetition rate of 10 Hz and a fluence of approximately 3 to 3.5  $\text{J}\cdot\text{cm}^{-2}$ . The ICP-MS was tuned to achieve maximum sensitivity and stability at low oxide and doubly charged ion levels. To control elemental fractionation, the plasma operating conditions were adjusted so that the  $^{232}\text{Th}/^{238}\text{U}$  intensity ratio would be as close as possible to unity without sacrificing sensitivity.

The quantification of LA-ICP-MS data was performed using an Internal Standard Independent method with sum normalization. With this method compositional information, including major and minor components and trace elements, can be obtained in a single measurement and calculations can be performed without the need to measure an internal standard beforehand using a different technique [33]. The standards used for calibration were the National Institute of Standards and Technology (NIST) standard reference materials 610 and 612, and Corning Museum of Glass (CMG) glasses A, B, C and D. Calibration was performed for each element (whenever possible) using a six-point calibration curve based on all the analytical standards available. Each data point was assessed individually considering the response factors derived from each standard and regression residuals that would help exclude outliers. Those elements present in the sample at a concentration below that covered by the calibration curves were quantified using a one-point calibration curve based on the measurement of NIST 612. The nominal amount of trace elements in each standard was obtained from a collection of published values [33–37]. Accuracy and precision were calculated by repeated measurements of CMG A, which is the standard that most closely matches the matrix of the glass under investigation. Accuracy, calculated as the bias between measured and quoted values, was normally between 0.3 and 5% and generally below 10%. Precision was always better than 3%, except for those elements present at exceedingly low concentrations (ppb range), which suffered from heterogeneous distribution at the scale of sampling. Limits of Detection (LoD) were calculated as three times the standard deviation of the blank signal, quantified according to the methodology proposed by Longerich *et al.* [38]. The LoD was always in the ppb range, except in the cases of  $\text{Na}_2\text{O}$ ,  $\text{SiO}_2$ ,  $\text{CaO}$ ,  $\text{K}_2\text{O}$ , P and Fe, for which they were a few ppm.

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## Notes

1. The long hair and cap worn in the night scene are comparable with those of the youth on a maiolica vase in the British Museum, made in Naples around 1470–1500 (British Museum 1919,1114.1).
2. The objects in the inventory are not all Andrea Mantegna's but this glass flask, which is enamelled with his personal device, must have been his own possession.
3. This excavation remains to be published and the authors are grateful to Rosa Barovier for bringing it to their attention and to Marco Verità for discussing it with them.