The British Museum

New Light on Old Glass: Recent Research on Byzantine Mosaics and Glass

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Chapter 1 Glass Mosaic Tesserae from the 5th to 6th Century Baptistery of San Giovanni alle Fonti, Milan, Italy Analytical Investigations

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Introduction

During the period in which Milan was the capital city of the western Roman Empire (AD 286–402), many new buildings were erected as a result of imperial patronage. These buildings followed contemporary aesthetic criteria, not only architecturally but through interior decoration as well.[2] This new style of decoration can also be found in a number of Milan's Early Christian buildings, such as the mausoleum and the basilica of San Lorenzo.[3] Within this historical-archaeological framework, which is still unclear because of the poor preservation state of the buildings, it is likely that mosaics played a significant role. This raises a number of questions. Which artisans made the wall inlays where glass pastes and marble coexisted? Were glass tesserae produced locally or were they imported? Were they newly made or reused?

Previous hypotheses have argued for the presence of a workshop in Milan that produced coloured glass for tesserae made in the 4th to 12th century. Though not an unreasonable proposition, this hypothesis still lacks sound evidence from an archaeological point of view and an accurate definition of historical and stylistic contexts. As a result, differing conclusions have been formulated as to the origins and dating of the workshops and their products.[4]

In the course of the present investigation, the materials uncovered in the collapsed layers of the Baptistery of San Giovanni alle Fonti in Milan have been examined. X-ray microanalysis and scanning electron microscopy have been used to identify the nature of the glass, colourants, pigments and opacifiers of coloured and gold leaf tesserae, and to point out similarities with and differences to contemporary tesserae recovered from other sites.

Samples

A recent archaeological investigation has demonstrated that the baptistery of the Milanese episcopal building complex was built in the second half of the 4th century and sponsored by Bishop Ambrose. Parts that had been destroyed were later rebuilt by Bishop Laurence between the late 5th and early 6th centuries.[5] It is most likely that the mosaics date to this later period, and Magnus Felix Ennodius mentions these wall decorations in his celebration of Bishop Laurence's involvement in the rebuilding of the baptistery. In 1355, a systematic dismantling of the mosaics was ordered.[6]

The majority of the materials of the mosaic decoration were found in the demolition layers of the building during excavations carried out by Bignami towards the end of the 19th century and Mirabella Roberti in the 1960s. Their finds include 271 pieces of mosaic fragments and loose tesserae, which was slightly less than 1% of the supposed original mosaic surface.[8] Some fragments are actually conserved in the baptistery's 'antiquarium'.

According to the colour percentages of the excavated tesserae, the mosaic must have had a gold ground, while green-blue tesserae were most prominent in the decoration. Up to five or six colours were used, each one in a variety of hues, sometimes both translucent and opaque. Several slab edge pieces have been found of both coloured and gold leaf tesserae (the latter amount to approximately 20% of the preserved tesserae). This allows the suggestion that the glass cakes were cut *in situ*, though it cannot be conclusively excluded that these were reused materials.

Because of the severe deterioration of most of the tesserae, which were completely covered with yellowish and white weathered glass, a soft abrasion treatment and observation under the optical microscope was necessary in order to identify their real aspect and chromatic hue. As far as possible, all the colours were sampled for all different hues, including both opaque and translucent types, as well as the different kinds of gold leaf tesserae.

The analyzed tesserae comprised: four opaque blue tesserae (F5, BL.op1,2,3), two translucent ones with many bubbles (BL.b1,b2) and a transparent one (A1); three opaque yellow tesserae (F1, F2 and B4) and two translucent yellow ones crossed by micro-fractures (Gi1a, Gi1b); five green-yellow tesserae with yellow pigments, two opaque (E1, Ve.Gi1) and three semi-opaque (F3, F4 and Ve1a) ones; one light green tessera with white particles (A2), a set of five tesserae of an unusual anise green colour (from Ve1 to Ve5; with increasing colour intensity) and one emerald green tessera (Ve6); two red tesserae (C2 and D1), one red-brown (Br1), and two orange tesserae with dark veins (F6, Ar.d); and, finally, two tesserae of a particular purple-brown colour (Vi.b weathered, Vi.c well preserved); one black tessera (Ne1) and an opaque white one (Bi1) (see **Table 1**).

With regard to the gold leaf tesserae, these were classified into two groups according to the aspect of the transparent glass: yellow-green hues in the first group (analyzed: B1c, B2s, B3c, C1s, D2s, E2s, Au.as; the final s or c indicate respectively the glass of the support or of the cartellina) and well decolourized glass in the second group (sample Au1s). In many cases the cartellina was absent or completely weathered. Small fragments of the gold leaf were sampled and set on a suitable sample holder to determine their composition.

Analytical techniques

Glass fragments requiring analysis were dry cut from the tesserae and embedded in cross-section in acrylic resin in a teflon mould. The discs containing up to six fragments were ground and polished with diamond pastes down to a 3μm grain size.[9]

The polished sections were observed by optical microscopy in reflected light (Leika MZ12) and by scanning electron microscopy (Philips XL 30) in backscattered mode, where the grey levels indicated areas with different chemical compositions. Semi-quantitative identification of the opacifiers and pigments was performed by energy dispersive X-ray microanalysis (EDAX). The quantitative X-ray microanalysis was undertaken using a Cameca SX-50.[10] Various reference glasses of certified composition were employed to improve the accuracy of the analyses. The EPMA setting used in this work allows most of the oxides to be analyzed in concentrations as low as 0.02–0.05%. Before SEM and X-ray analysis, the surface of the samples was carbon coated.

Results

The quantitative chemical compositions of the tesserae are reported in **Table 1**. Average values are reported for the coloured tesserae, which also include the glassy phase and opacifying or colouring particles. Hereafter, the base glass composition (composition of the transparent glass to which colourants and opacifiers were added) is discussed separately from colourants, pigments and opacifiers.

Base glass

The composition of the base glass was calculated by subtracting from the composition of the 'coloured glass' the content of colourants, decolourants and opacifiers and then normalising to 100 wt%. The differences in the content of some oxides in the base glass allow a few compositional groups to be established.

The composition of most of the tesserae is in agreement with the dominant glass type from the Roman period until the 8th to 9th century and is composed mainly of sodium, calcium and silicon oxides (soda-lime-silica glass), with potassium and magnesium oxides each below about 1.5% and phosphorous below 0.2%. Natron, a sodium carbonate mineral associated with lower amounts of chlorides and sulphates from Egypt,[11] was the flux used to produce this glass. It was mixed and fused together with a silica-lime sand in which quartz and calcium carbonate were present in suitable ratios to make glass. According to Pliny (*Nat. Hist.* XXXVI. 192),[12] this type of sand was quarried in a few sites such as the mouth of the River Belus (presently Na'aman, between Haifa and Acre in northern Israel) and the River Volturno (north of Naples, Italy). Archaeological evidence and analytical investigation suggest that in this period the practice of making glass was carried out in a limited number of places located near the sources of these raw materials in tank furnaces where several tons of glass could be melted. Once the glass had melted, the furnace was left to cool and then demolished. Large blocks of transparent glass, slightly coloured in natural hues ranging from green, yellow to light blue, were then broken up into chunks of raw glass that were traded throughout the Mediterranean and Europe and distributed to workshops where they were remelted and made into artefacts.[13] In the case of mosaic tesserae, once the raw glass had been remelted, it was coloured, opacified and then shaped into cakes from which the tesserae were subsequently cut. However, no secondary centres for the production of glass cakes for mosaic tesserae have been identified up to now.

Analyses of the gold leaf tesserae from Milan reveal that the yellow green glass was obtained by using sand with high amounts of iron (high titanium and alumina concentrations are also present) and only partially decolourizing the glass with manganese. In contrast, the perfectly colourless glass of sample Au.1s was obtained from purer sand (the iron content is about 50% less than that of the yellow green gold tesserae), and antimony was used together with manganese for the decolouration. In both types of tesserae the metal leaf is less than half a micrometre thick and is of pure gold (Au 100%). The composition of the cartellina (a thin layer of blown glass 0.5 to 0.7mm in thickness covering the metal leaf thickness) is practically the same as that of the support glass. The optical quality, however, is different, for the cartellina glass is homogeneous, while the support glass is heterogeneous and contains many bubbles.

The orange tesserae and two of the red tesserae (C2 and D1, not the Br1) are made with a soda-lime-silica glass

Table 1 Quantitative chemical composition in wt% of the oxides of the analyzed tesserae (OP = opaque; TR = transparent; transl = semi-opaque)

			SiO_2	Al_2O_3	Na_2O	K_2O	CaO	MgO	SO_3	P_2O_5	Cl	TiO_2	Fe_2O_3	MnO	Sb_2O_3	CuO	PbO	SnO_2	CoO	As_2O_3	ZnO
F5	blue	OP	68.0	2.60	15.0	0.45	7.70	0.70	0.25	0.13	0.65	0.07	0.90	0.85	1.50	0.10	1.00		0.05	0.08	
Bl.op1	blue	OP	66.7	2.40	14.5	0.60	7.90	0.53	0.33	0.15	0.60	0.08	0.70	0.95	3.00	0.15	1.30		0.06		
Bl.op2	blue	OP	65.8	2.40	15.5	0.63	7.50	0.45	0.32	0.16	0.60	0.05	0.75	0.90	3.50	0.12	1.15		0.05		
Bl.op3	blue	OP	66.6	2.18	14.2	0.50	6.90	0.51	0.40	0.17	0.55	0.05	1.45	0.95	3.70	0.34	1.15		0.25	0.05	
Bl.b1	blue	transl	67.6	2.40	17.5	0.52	6.65	0.85	0.26	0.07	0.85	0.18	1.10	0.85	0.70	0.15	0.18		0.05	0.08	
Bl.b2	blue	transl	67.0	2.50	17.0	0.63	6.90	0.90	0.13	0.07	0.78	0.20	1.45	1.40	0.25	0.20	0.37	0.08	0.06	0.07	
A1	blue	TR	66.8	1.88	20.7	0.30	5.70	0.80	0.25	0.02	1.40	0.07	1.40	0.08		0.18	0.40		0.04		
F1	yellow	transl	64.2	2.40	20.0	0.43	5.50	0.78	0.33	0.05	0.95	0.26	1.20	0.50		0.50	2.50	0.30		0.10	
F2	yellow	transl	64.7	2.30	20.3	0.35	5.40	0.73	0.36	0.05	0.95	0.24	1.15	0.45		0.50	2.00	0.45		0.10	
B4	yellow	transl	64.4	2.25	20.0	0.50	5.60	0.80	0.43	0.06	1.20	0.23	1.20	0.45		0.40	2.20	0.30			
Gi1-a	yellow	OP	63.4	1.50	16.8	0.31	5.05	0.38	0.18	0.03	0.80	0.05	0.35	0.03			9.30	1.70		0.09	
Gi1-b	yellow	OP	67.0	1.70	17.3	0.33	5.40	0.45	0.18	0.03	0.90	0.10	0.35				5.70	0.50		0.10	
E1	green-yellow	OP	62.3	2.27	18.2	0.48	5.90	1.05	0.25	0.07	1.00	0.21	1.10	1.10	0.25	0.45	4.70	0.65			
Ve.Gi1	green-yellow	OP	62.4	2.60	18.8	0.36	6.30	1.25	0.27	0.07	0.65	0.55	1.75	1.95			2.80	0.15		0.04	
F3	green-yellow	transl	65.0	2.20	19.0	0.48	6.70	0.80	0.20	0.10	1.00	0.13	0.90	0.30		1.10	1.80	0.20		0.10	
F4	green-yellow	transl	64.5	2.30	19.2	0.53	6.70	0.85	0.24	0.08	0.90	0.13	0.80	0.40		1.10	1.90	0.25		0.12	
VE.1a	green-yellow	transl	62.5	2.15	20.0	0.25	6.60	1.15	0.22	0.05	1.00	0.13	1.30	0.10		2.10	1.00	1.00		0.08	0.40
A2	light green	transl	65.6	2.30	19.6	0.56	6.25	0.92	0.28	0.08	1.05	0.14	0.85	0.88	0.55	0.70	0.13	0.05			
Ve1	anise green	OP	64.0	2.40	18.0	0.52	7.00	1.00	0.27	0.06	0.75	0.28	1.10	1.55		0.05	1.05	2.00		0.04	
Ve2	anise green	OP	66.5	2.35	18.0	0.52	6.20	0.88	0.30	0.09	0.80	0.16	0.80	0.90	1.15	0.38	0.40	0.40		0.03	
Ve3	anise green	OP	66.5	2.35	18.2	0.52	6.30	0.87	0.28	0.08	0.78	0.15	0.82	0.90	1.10	0.35	0.40	0.40		0.04	
Ve4	anise green	OP	66.0	2.40	18.2	0.60	7.00	0.90	0.25	0.08	0.85	0.15	0.90	0.85	0.45	0.67	0.55	0.10		0.05	
Ve5	anise green	OP	65.5	2.25	18.3	0.45	6.00	0.90	0.25	0.05	0.90	0.22	0.85	1.00	0.43	0.70	0.57	1.50		0.04	
Ve6	emerald green	OP	60.4	2.50	15.5	0.69	6.80	0.80	0.23	0.15	0.75	0.09	0.94	0.53	0.55	2.00	7.00	1.00		0.03	

Table 1 (continued) Quantitative chemical composition in wt% of the oxides of the analyzed tesserae

			SiO_2	Al_2O_3	Na_2O	K_2O	CaO	MgO	SO_3	P_2O_5	Cl	TiO_2	Fe_2O_3	MnO	Sb_2O_3	CuO	PbO	SnO_2	CoO	As_2O_3	ZnO
C2	red	OP	55.8	3.40	13.3	1.21	6.45	1.80	0.20	0.50	0.70	0.54	3.40	0.38		1.60	8.00	1.10			1.60
D1	red	OP	50.5	2.90	11.5	1.11	5.70	1.30	0.15	0.40	0.70	0.34	3.00	0.15		1.90	18.0	1.50			0.80
Br1	red brown	OP	61.5	2.13	16.8	0.66	5.90	0.76	0.17	0.12	0.88	0.12	5.00	1.05		0.50	3.30	0.55		0.10	0.35
F6	orange	OP	41.5	3.00	8.2	1.30	5.20	1.20	0.17	0.47	0.47	0.30	3.00	0.55	0.07	5.00	27.0	1.50		0.25	0.40
Ar.d	orange	OP	41.2	2.70	10.8	1.35	4.95	1.25	0.25	0.45	0.55	0.35	2.20	0.65	0.09	4.40	27.0	1.15		0.20	0.45
Vi.b	purple-brown	transl	66.3	2.25	19.8	0.46	6.40	0.93	0.28	0.06	0.83	0.20	0.75	1.60						0.05	
Vi.c	purple-brown	transl	66.7	2.30	19.5	0.40	6.40	0.90	0.30	0.07	0.81	0.13	0.78	1.55						0.07	
Ne1	black	TR	63.8	2.05	19.5	0.33	5.75	0.74	0.21	0.05	1.15	0.13	6.00	0.05		0.05				0.11	
Bi1	white	OP	65.3	2.30	16.9	0.45	6.40	0.90	0.24	0.08	0.70	0.30	1.15	1.70			1.10	2.50			
B1c	gold yellow-gr.	TR	64.0	2.55	20.4	0.39	6.00	1.47	0.25	0.05	1.25	0.30	1.60	1.70							
B2s	gold yellow-gr.	TR	64.3	2.50	20.0	0.42	6.25	1.40	0.32	0.06	1.10	0.26	1.50	1.85							
B3c	gold yellow-gr.	TR	63.7	2.53	21.0	0.41	6.40	1.20	0.35	0.06	1.15	0.25	1.40	1.50							
C1s	gold yellow-gr.	TR	62.8	2.60	21.5	0.40	5.60	1.40	0.32	0.08	1.15	0.40	1.75	2.00							
D2s	gold yellow-gr.	TR	61.7	2.60	21.8	0.38	5.10	1.35	0.30	0.06	1.15	0.40	3.15	2.00							
E2s	gold yellow-gr.	TR	62.3	2.75	21.5	0.37	5.10	1.40	0.38	0.05	1.20	0.41	1.50	3.00							
Au.as	gold yellow-gr.	TR	65.8	2.55	19.3	0.38	5.90	1.15	0.25	0.08	0.80	0.50	1.25	1.90							
Au.1s	gold colourless	TR	69.0	2.15	19.0	0.64	4.90	0.60	0.30	0.12	0.70	0.10	0.60	0.42	1.20		0.20				

Plate 1 Polished section of fragments of the anise green tesserae (from left to right: Ve3, Ve4 and Ve5). Long side of the optical micrograph: 18mm

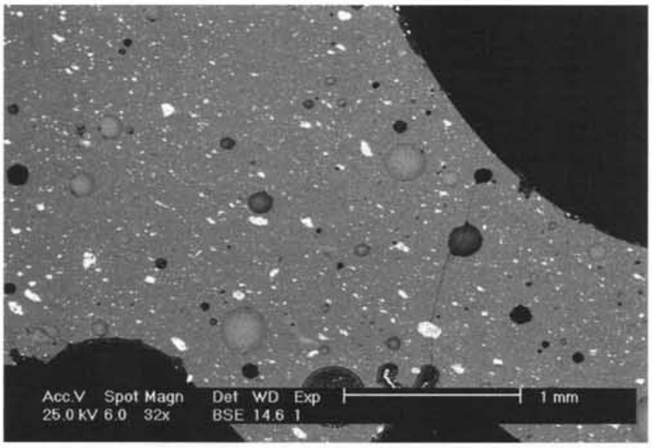


Plate 2 SEM micrograph of the polished section of a fragment of the green tessera Ve1. Bubbles and aggregates of tin oxide crystals (white areas) are randomly dispersed in the glassy phase

different from the natron type. In these samples the higher Mg, K and P contents indicate the use of a soda plant ash glass. The use of a different base glass melted from a batch of soda ash and silica sand is commonly found for orange and red Roman glass.[14]

Colourants and opacifiers

The colourant of the blue tesserae is cobalt. In these tesserae, traces of copper (its concentration is too low to modify the intense colour given by cobalt), lead and iron (in higher concentrations as compared with other glasses) were detected. These elements were introduced unintentionally with the cobalt ore which was added to a glass previously decolourized with manganese (except for sample A1). A number of these tesserae are translucent owing to the presence of bubbles and rare aggregates of white crystals (Bl. bo1 and Bl.bo2). Unexpectedly, in sample Bl.bo1 these aggregates consist of calcium antimonate, while in sample Bl.bo2 they are of tin oxide. Even more surprising is the presence of antimony in the glass of this last sample (Sb_2O_3 0.25%), while tin was found only in sample Bl.bo2. To intensely opacify the blue tesserae, calcium antimonate crystals were used.

The 'black' colour of sample Ne1 is due to the intense green-yellow colour of the transparent glass obtained by adding iron and keeping the melt in reduced conditions (with low oxygen) so as to favour the formation of the iron-sulphur amber chromophore.

The five anise green tesserae show increasingly darker hues from sample Ve1 (lightest colour) to Ve5 (darkest colour); this colour is peculiar and infrequent in mosaic tesserae (**Pl. 1**). The transparent glass of these tesserae is coloured with copper and iron; the colour of the first three tesserae changes to a more marked light blue hue in samples Ve4 and Ve5. The compositions of the five tesserae are fairly similar. The observation of the polished sections under the electron scanning microscope reveals the presence of tin oxide (SnO_2, cassiterite) particles up to 150 micrometres in size, more abundant in tesserae Ve1 and Ve5, which were used to clarify the colour (**Pl. 2**). Unexpectedly, some isolated particles of calcium antimonate are also present in sample Ve2. In all these tesserae (except Ve1), a certain amount of antimony was also found dissolved in the glass, though no calcium antimonate crystals were identified. As

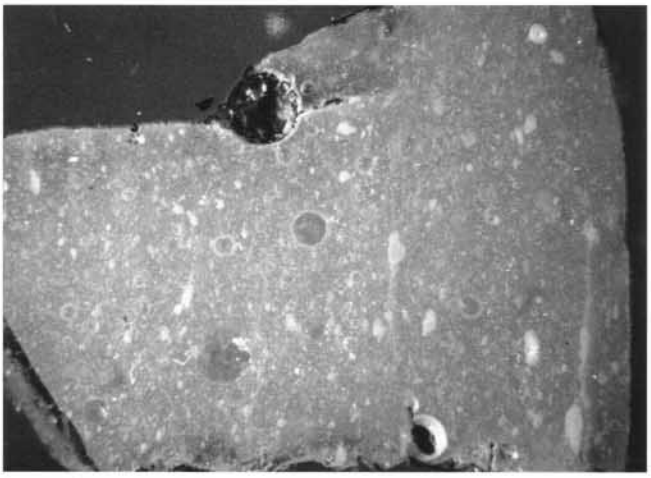


Plate 3 Polished section of a fragment of the white tessera Bi1 opacified with tin oxide. The optical micrograph (long side of the micrograph: 2.3mm) shows the heterogeneity of the tessera

previously illustrated, a similar result of glass containing antimony opacified with tin oxide was observed for some blue tesserae, whilst it was used in Islamic and Venetian red enamels on glass in the 13th century.[15]

Sample Ve6 exhibits a peculiar intense emerald green colour due to a high copper and lead concentration (the lead content is probably related to the use of a copper-lead metal slag as a colourant). In the section examined under the optical microscope, some isolated yellow particles were observed alongside numerous white particles. X-ray microanalysis revealed that the yellow particles were composed of lead and tin and the white particles were tin oxide. Antimony was also detected in this tessera, but no crystals containing this element were found. The dark green colour of the transparent glass of sample Ve.Gi.1 (coloured with iron and copper) was modified by adding lead stannate yellow particles. Rare tin oxide white particles were identified, maybe as a result of the decomposition of yellow pigment particles.

Sample Bi1 is an opaque ivory-white tessera with very interesting analytical features. When examined under the optical microscope it appears to be a rough, heterogeneous tessera with white particles (**Pl. 3**). When examined under the SEM the particles are distinguished in large geometric

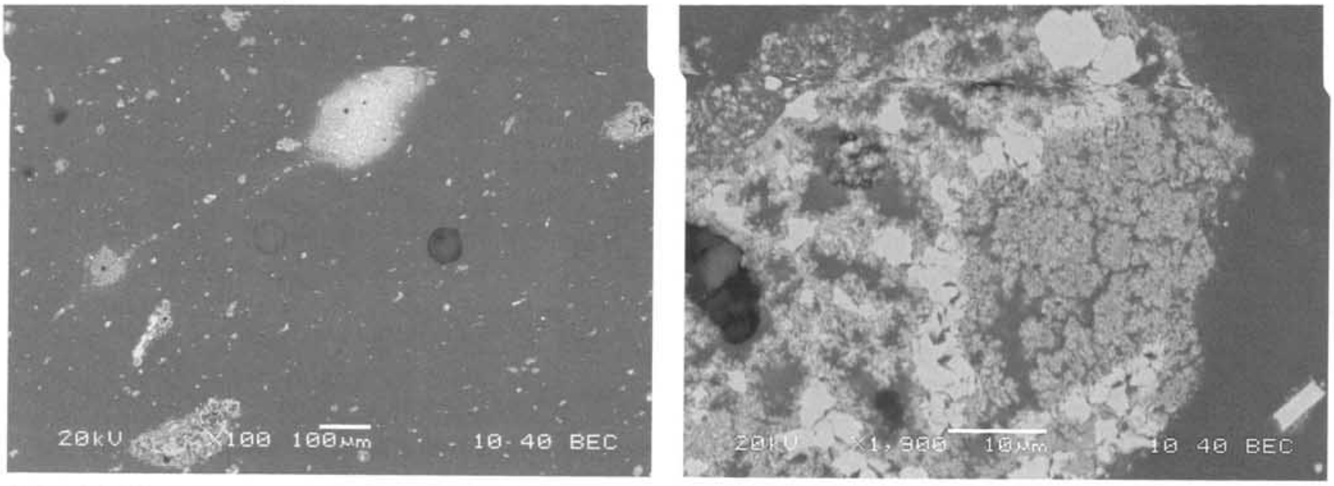


Plate 4–b SEM micrographs of the polished section of the white tessera Bi1. White areas correspond to tin oxide crystals and aggregates

crystals and micro-crystals often grouped in clusters (**Pl. 4a**). Both geometric and micro-crystals are made of tin oxide. The clusters show an elongated form, which indicates a rapid stirring of the melt and pouring into slabs (**Pl. 4b**).

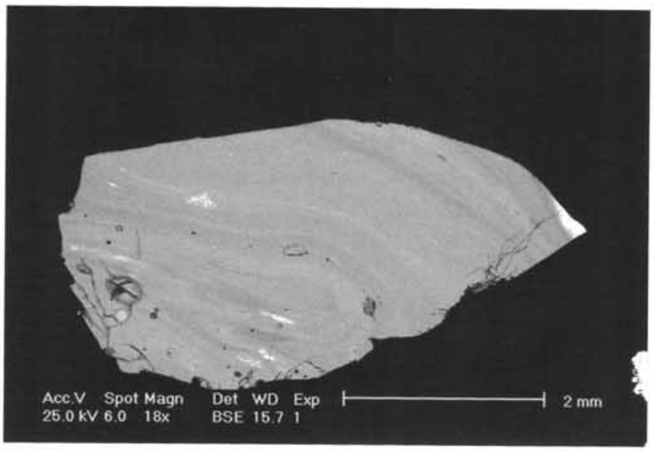
Pigments

Among the mosaic tesserae of the Baptistery of San Giovanni alle Fonti, yellow and green-yellow tesserae are most abundant. Minute yellow crystals (in the order of a micrometre in size) are dispersed in the colourless or green glass, individually or aggregated in particles a few tens of micrometres in size. The crystals and aggregates are arranged in layers, which indicates that they were added to the molten glass and roughly mixed. X-ray microanalysis revealed the fairly homogeneous composition of these pigments, which consist mainly of lead and tin (PbO 58–62%; SnO_2 28–32%), beside silica (SiO_2 around 5%) and iron (Fe_2O_3 1%). This composition corresponds to lead stannate yellow crystals.

The orange samples F6 and Ar.d were obtained from a transparent glass of the soda ash type to which considerable amounts of lead (PbO 27%) were added, together with copper, iron and lower amounts of tin and zinc. The colouring element is the copper, which forms very tiny cuprite crystals (Cu_2O), orange in colour. The dark layers correspond to transparent green zones free of pigments or to opaque red zones coloured by large dendritic crystals of cuprite. Lead, iron and zinc, which are commonly found in orange glass of the Roman period, are elements that favour the separation of the pigments from the melt during cooling (this phenomenon occurs only with suitable redox conditions). As for red glass (see below), it is probable that these elements were introduced through copper slag.[16]

In the red tesserae C2 and D1, the base glass is of the soda ash type, coloured by minute spheres of metallic copper and less abundant, but larger dendritic crystals of cuprite. The separation of the colouring compounds from the melt was favoured by the addition of iron, probably as ferrous oxide. This compound also modifies the colour, shifting it progressively to a red-brown hue. High concentrations of lead, tin and zinc were found, probably added as a metallic slag of copper. The red brown tessera (Br1: natron-type glass) shows opaque dark red streaks alternated with transparent green ones. The red colour is achieved by metallic copper particles; the concentrations of lead and tin are lower than those of the other red tesserae, but the iron content is higher. The chemical compositions of the red and transparent green streaks are similar. In the latter, the pigment has dissolved and the copper ion determines the dark green colour. The SEM analysis reveals a heterogeneous situation, showing the presence of tin oxide particles or aggregates and glassy streaks rich in lead (**Pl. 5**).

Plate 5 SEM micrograph of the polished section of a fragment of the red-brown tessera Br1



A group of tesserae with peculiar colours were obtained through specific techniques. In order to obtain the green-yellow colour of tessera (VE.1a), yellow (lead stannate), white (cassiterite), black (not identified) pigments and fragments of terracotta were added to a green bubble-rich transparent glass coloured with copper and iron (lead, tin and zinc are present also in this case) (**Pl. 6**). Another sophisticated technique was used to prepare the purple-brown tesserae (Vi.b e Vi.c), obtained from a transparent purple glass coloured with manganese, to which lamellar reddish iron particles (probably haematite, ferric oxide) were added. The lamellae are often aggregated in larger particles (**Pl. 7**); their irregular dispersion in the glass and the presence of bubbles suggest that this colourant was prepared separately, added to the molten glass, quickly

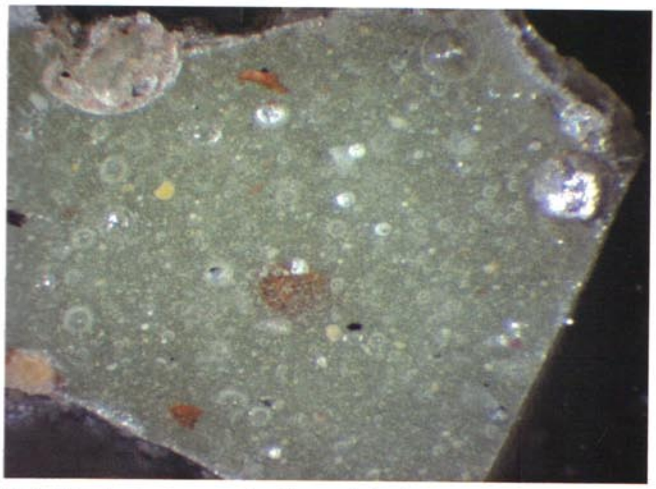


Plate 6 Optical micrograph of the polished section of a fragment of the green-yellow tessera VE.1a. Long side of the micrograph: 2.3mm

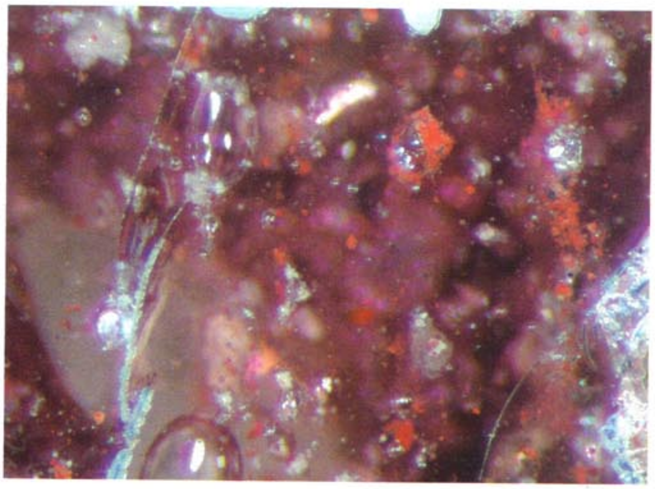


Plate 7 Optical micrograph of the polished section of a fragment of the purple-brown tessera Vi.b. Long side of the micrograph: 1.8mm

stirred and poured into slabs to avoid dissolution of the pigment. As far as the authors know, this colouring technique has never been found in mosaic tesserae.

Devitrification crystals

Needle-like or geometrically shaped, sometimes aggregated crystals are present in many tesserae in varying amounts, particularly in red, yellow and black tesserae. These crystals are made of calcium and silica, two of the major components of glass, and separate from the molten glass when it is kept at around 900°C (this is the temperature at which the molten glass was apparently kept before being poured into slabs). In some the 'devitrified crystals' reached a considerable size (for instance in the black tessera), thus increasing glass fragility and causing serious problems in cutting the tesserae.

Discussion

The picture resulting from the analyses is fairly complex. Some distinctive features emerged when the tesserae from the baptistery were compared with tesserae from the basilicas in Rome and Ravenna. Green and yellow tesserae were opacified with lead stannate particles and show a refined modification of the hue obtained by sometimes adding terracotta fragments and black pigments. The unusual anise green colour was obtained through the introduction of copper and iron, and lighter hues were achieved through increasing amounts of tin oxide crystals. These crystals were used to colour the white tessera. The purple-brown colour was achieved through a transparent purple glass coloured with manganese to which red flakes of iron oxide were added. In contrast, red and orange colours were made following the Roman tradition of glassmaking, with some idiosyncrasies that bring them more in line with practices in the Ravenna region.

The blue tesserae opacified with antimony (Bl.bo1) may be reused ones following the Roman tradition or imported from other production sites (for example Rome). The lighter blue translucent tesserae, containing some antimony dissolved in the glass (indicative of the remelting of glass cullet), were clarified with tin oxide crystals. It is well known that in several periods the production of the blue colour was difficult not only for technological reasons but mainly as a result of the difficulties in acquiring the cobalt ore. This shortage was compensated for by remelting recycled blue glass.[17]

Base glass

The majority of the analyzed tesserae show a typical Roman glass composition. Some sub-groups can be distinguished, following a classification of the Roman glass.

A first sub-group includes the gold leaf tesserae characterized by a yellow-green hue, some yellow tesserae (F1, F2, B4) and the green-yellow tessera Ve.Gi1, all of which display high Na, Mg, Al, Fe and Ti contents with low Si and Ca contents. These compositional characteristics are compatible with a natron glass termed HIMT (high iron, manganese and titanium), which was widespread in Europe and the Mediterranean area between the 4th and 7th centuries.[18] The geographical source of this glass has not yet been identified although some authors suggest an Egyptian origin. However, the provenance of the raw glass is not significant enough to establish the production site of the mosaic tesserae. In the present case, it was remelted to obtain glass cakes in secondary sites, which were probably far from the primary glassmaking centres. Identifying the provenance of raw glass is of great help in establishing trade routes and, consequently, the contacts that existed between different towns.[19]

A second natron sub-group characterized by low Ca, Mg, Ti, Fe and Al contents and high Na content includes the two yellow tesserae Gi1a and b, one blue A1 as well as the gold leaf tessera Au1s. This type of glass is characterized by the use of antimony in association with manganese as a decolourant in the production of clear glass.[20]

The analysis of the orange tesserae reveals that the chemical composition is comparable to those of coeval mosaics in Rome and Ravenna. In contrast, the composition of the red tesserae differs from the Roman ones in the presence of high concentrations of tin and zinc (generally absent or less than 0.1% in Roman tesserae). Compositional similarities found in a red tessera of the Neonian Baptistery in Ravenna,[21] suggest that both the Milanese and Ravenna mosaic tesserae, or at least a proportion of them, were made at the same site. It is interesting to observe that the red colour was widely used in Milanese mosaics, as if it was a readily available material.[22] However, it must be remembered that analyses of the mosaics in the Neonian Baptistery reveal a complex situation, in which important compositional differences indicate different provenances, and the presence of reused tesserae remains a possibility.[23] This issue deserves further investigation and represents another peculiarity of the Milanese tesserae in comparison with contemporary Roman ones.

Opacifiers

In this complex picture the most important innovative feature of the tesserae of the mosaics of San Giovanni alle Fonti is the use of tin as an opacifier and clarifier as an alternative to antimony. Most tesserae were opacified with tin oxide, except for some blue ones opacified with calcium antimonate. As mentioned before, tin is a novelty among the opacifiers used in mosaic glass tesserae. In contemporary Roman examples, antimony was used following a century-long tradition that would continue in later ages. In contrast, some of the tesserae in Ravenna were opacified with calcium antimonate, while calcium phosphate (bone ash) was used in others. This is a new technique that probably originated from the Byzantine Middle East.[24] In a number of blue and green tesserae opacified with tin, antimony dissolved in the glass or in the form of sporadic antimonate crystals was also found. The coexistence of tin and antimony in this kind of tesserae has no technological explanation. It is reasonable to suppose that they were prepared by remelting earlier glass containing antimony, which was then opacified by adding tin oxide. The use of tin in the tesserae of San Giovanni alle Fonti seems to indicate an influence of north European glass technology.[25] Unlike later opaque glass in which tin was introduced as a lead-tin calx, no lead was detected in these tesserae. It is likely that this was still an imperfect technique (the presence of lead helps the dispersion of the cassiterite crystals in the melt) that explains the heterogeneity of these tesserae and the presence of tin crystal aggregates. Because this technique had never been adopted before for mosaic glass tesserae, the analyses exclude the possibility that they are reused materials.

Gold leaf tesserae

The use in the same mosaic of gold leaf tesserae made from a transparent colourless glass or a yellow-green glass seems to have been a deliberate choice intended to give the gold leaf (pure gold in both cases) a different luminosity: a silvery effect on a colourless support and a warmer one on a yellow-green glass. In fact with the gold leaf being beaten into thin layers and partially torn, the colour of the support glass affects the hue of the tessera. This optical effect has also been observed in experimental tests on modern cakes. The supposed deliberate choice is supported also by the presence of both types of gold leaf tesserae, which can be distinguished by the naked eye, in all the Milanese examples examined up to now. This mixture can be observed in the gold background of the mosaics in the niches of Sant'Aquilino and in the gold sky of the vault of San Vittore. In these buildings, gold leaf tesserae seem to be mixed according to an aesthetic principle of imparting movement and avoiding excessive flattening of the background, and also by arranging the tesserae in an uneven way. One can also observe in the religious buildings of Ravenna the use of different types of gold, with the support made of a stronger or lighter coloured glass.[26] It has not so far been ascertained whether the two kinds of gold leaf tesserae used in Milan and in Ravenna were imported from different workshops, or locally produced with different types of glass.

Though it has been poorly studied, the use of different types of mosaic gold seems to have been a widespread practice in the Late Antique and Byzantine periods, to enhance both the gleam and brilliance so persistently pursued by contemporary aesthetic principles, mixing beauty and ostentation.[27]

Conclusion

The analyses of the glass tesserae belonging to the 5th to 6th century mosaics of the Baptistery of San Giovanni alle Fonti in Milan provide a complex picture that suggests more than one possible provenance for these materials.

Some tesserae are similar to those of the Roman and Early Christian mosaics in Rome. A characteristic of these tesserae is the use of natron type glass opacified with calcium antimonate. Some of the blue tesserae from Milan as well as some green ones fall into this group. The orange tesserae also belong to the Roman glassmaking tradition. It is not possible to establish whether the cakes were imported and then cut in the yard, or the tesserae were reused materials from previously dismantled mosaics, such as those from Milan. It is possible that the mosaic tesserae used in the imperial buildings in Milan had been made according to Roman glass making traditions. For historical reasons, trading contacts between Gothic Milan and Rome in this period are improbable, although they cannot be completely excluded.

The red tesserae from the Baptistery of San Giovanni show some peculiarities, such as unusual tin and zinc concentrations that can be also found in some of the red tesserae of the Neonian Baptistery in Ravenna. Further investigation is necessary to confirm these features and ascertain production areas.

The purple-brown tesserae coloured with flakes of iron oxide are a unique example of this technique. The remaining coloured tesserae were made with natron type glass, with tin-based white (tin oxide) and yellow (lead stannate) pigments. While lead stannate was commonly used in Late Roman and Byzantine glass making technology,[28] no evidence has been found for the use of white tin oxide. In contrast, tin oxide was already used in northern Europe for the production of opaque glass artefacts, such as enamels and glass beads, between the end of the 1st century BC and the early 1st century AD. It also appears in some Merovingian glassware (5th to 6th century). With regards to the production of glass tesserae, the mosaic in San Giovanni alle Fonti seems to be the earliest example of this technique. It is interesting to remember that the glass used for these tin opacified tesserae was most probably remelted glass cullet.

The divergences from the Roman glass making tradition might be associated with the presence of the Goths in Milan between the 5th and 6th centuries. It was the intention of the newcomers to maintain a cultural and, at first, a political continuity with Constantinople, although their presence inevitably introduced new elements to the already existing practices. To support this hypothesis, it would be necessary to extend the analyses to glass mosaic tesserae from extant mosaics of the Gothic period in northern Italy.[29] On the other hand, it is not unlikely that barbarian populations with metallurgical skills may have introduced novel details in glass making. The abundance of yellow colours, peculiar red colours and the use of tin are all possible indicators of this. These results reveal a complex picture for the 5th to 6th century mosaics of San Giovanni alle Fonti, and substantiate the hypothesis of a local production centre which has previously been formulated only on the basis of the presence of a large number of buildings with mosaics in Milan.

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Notes

1 This paper is the result of close collaboration between the authors. The analyses have been carried out by A. Conventi and M. Verità and the text has been edited by E. Neri.

2 For a summary on the historical-archaeological background see A. Salvioni (ed.), *Milano capitale dell'impero romano (286–402 d.C.)* (exh. cat., Milan, 24 January–22 April 1990), Milan, 1990; G. Sena Chiesa and E.A. Arslan (eds), *Felix temporis reparatio* (Atti del Convegno archeologico internazionale *Milano capitale dell'impero romano*, Milan, 8–11 March 1990), Milan, 1992; D. Caporusso, *Scavi MM3. Ricerche di archeologia urbana a Milano durante la costruzione della linea 3 della metropolitana*, Milan, 1991; D. Caporusso, M.T. Donati, S. Masseroli and T. Tibiletti, *Immagini di Mediolanum. Archeologia e storia di Milano dal V sec. a.C. al V sec. d.C.*, Milan, 2007; D. Caporusso and A. Ceresa Mori, 'C'era una volta Mediolanum', *Archeo. Attualità dal Passato* 307 (2010), 70–105.

3 S. Lusuardi Siena, 'Committenza laica ed ecclesiastica in Italia settentrionale nel regno goto', in *Committenti e produzione artistico-letteraria nell'alto Medioevo occidentale. Atti delle Settimane di Studio 4–10 Aprile* (Settimane de Studi de Centro Italiano di Studi sull'Alto Medioevo 39), Spoleto, 1992, 199–242; E. Neri, S. Lusuardi Siena and M. Verità, 'La produzione di tessellata vitrea trado antichi e altomedievali a Milano: un progetto archeologico-archeometrico', *AISCOM* XVI, Tivoli, 2011, 293–306.

4 M. Mendera, 'Produzione vitrea medievale in Italia e fabbricazione di tesserae musive', in E. Borsook, F. Gioffredi Superbi and G. Paliarulo (eds), *Medieval Mosaics: Light, Colour, Materials*, Milan, 2000, 97–138; J. Nordhagen, 'Mosaici di Sant'Aquilino: originali e rifacimenti', in C. Bertelli (ed.), *Il Millenio ambrosiano: Milano una capitale da Ambrogio ai Carolingi*, Milan, 1987, 162–7; C. Bertelli, 'Mosaici a Milano', in *Milano e i milanesi prima del Mille (VIII–X secolo). Atti del 10° Congresso Internazionale di Studi sull'Alto Medioevo, Milan 1983*, Spoleto, 1986, 333–49.

5 The excavation data was published in S. Lusuardi Siena, B. Bruno, L. Villa *et al.*, 'Le nuove indagini archeologiche nell'area del Duomo', in M. Rizzi (ed.), *La città e la sua memoria. Milano e la tradizione di Sant'Ambrogio*, Milan, 1997, 40–52; an overview of the episcopal building complex is in S. Lusuardi Siena, *Piazza Duomo prima del Duomo*, Milan, 2009, and. S. Lusuardi Siena and F. Sacchi, 'Gli edifici battesimali di Milano e di Albenga', in M. Marcenaro (ed.), *Atti del Convegno "Albenga città episcopale. Tempi e dinamiche della cristianizzazione tra Liguria di Ponente e Provenza" (Albenga, 21–3 settembre 2006)*, Albenga, 2007, 677–702; the discovery context of the decorations is detailed in S. Lusuardi Siena and F. Sacchi, 'Per un riesame dei sectilia parietali paleocristiani del Battistero di S. Giovanni alle Fonti a Milano', *AISCOM* X (2004), 81–96.

6 Ennodio, *Carmina*, 2, 56 (F. Vogel (ed.), Berlin, 1885, 157); for the English translation see S.A.H. Kennell, *Magnus Felix Ennodius: a Gentleman of the Church*, Ann Arbor, 2000.

7 Only vitreous materials were used. Despite the wide chromatic palette, stone was not used.

8 According to the reconstruction suggested in Lusuardi Siena and Sacchi 2007 (n. 5), the area of the dome should have been 108.73m^2. The basins of each circular niche have been estimated at 5.07m^2 and the lunette and soffit of the arch 6.6m^2.

9 M. Verità, 'Technology and deterioration of vitreous mosaic tesserae', *Reviews in Conservation* 1 (2000), 65–76.

10 The microprobe was equipped with three wavelength dispersive spectrometers (PET, LiF and TAP crystals). Twenty elements were quantified: X-ray Kα lines were analyzed except for Pb and Bi (Mα lines), Sb, As and Sn (Lα lines). Operating conditions were: accelerating potential 15kV, beam current 20 nA (major and minor components) or 100 nA (trace elements) respectively. A 40 x 50µm scanning electron beam and limited counting time (10s for major and minor elements, 20 to 30s for traces) were employed to ensure that no significant alkali drift (ion migration) occurred during the irradiation. The net X-ray intensities (peak minus background) were quantified by means of a PAP correction programme supplied by CAMECA.

11 According to Pliny (*Nat. Hist.* XXXI.107), Macedonia, Media and Thrace were also rich in natron. E. Dotsika, Y. Maniatis and D. Ignatiadou, 'A natron source for glass making in Greece? Preliminary results', in *Proceedings of the 4th Symposium of the Hellenic Society for Archaeometry, National Hellenic Research Foundation, Athens 28–31 May 2003*, Oxford, 2003, 359–61, have identified possible natron sources in Macedonia.

12 M. Vallotto and M. Verità, 'Glasses from Pompeii and Herculaneum and the sands of the River Belus and Volturno', in J. Renn and G. Castagnetti (eds), *Homo Faber: Studies on Nature, Technology, and Science at the time of Pompeii*, Munich, 2000, 63–74.

13 I.C. Freestone, 'The provenance of ancient glass through compositional analysis', in P.B. Vandiver, J.L. Mass and A. Murray (eds), *Materials Issues in Art and Archaeology VII* (Mater. Res. Soc. Symp. Proc. 852), Warrendale, PA, 2005, 008.1–008.14.

14 I.C. Freestone, C.P. Stapleton and V. Rigby, 'The production of red glass and enamel in the Late Iron Age, Roman and Byzantine periods', in C. Entwistle (ed.), *Through a Glass Brightly: Studies in Byzantine and Medieval Art and Archaeology Presented to David Buckton*, Exeter, 2003, 142–54.

15 M. Verità, 'Analyses of early enamelled Venetian glass: a comparison with Islamic glass', in R. Ward (ed.), *Gilded and Enamelled Glass from the Middle East*, London, 1998, 129–34; I.C. Freestone and C.P. Stapleton, 'Composition and technology of Islamic enamelled glass of the thirteenth and fourteenth centuries', in Ward ibid., 122–8.

16 I.C. Freestone, S. Wolf and M. Thirlwall, 'The production of HIMT glass: elemental and isotopic evidence', in *Annales du 16e Congrès de l'Association Internationale pour l'Histoire du Verre, London 2003*, Nottingham, 2005, 153–7, suggest the use of metallurgical by-products (from silver-refining in particular) to assist with the preparation of the red glass; B. Gratuze, D. Foy, J. Lancelot and F. Tereygeol, 'Les "lissoirs" carolingiens en verre au plomb: mise en évidence de la valorisation des scories issues du traitement des galènes argentifères de Melle (Deux-Sèvres)', in D. Foy and M.-D. Nenna (eds), *Echange et commerce du verre dans le monde antique* (Actes du colloque de l'Association Française pour l'archéologie du verre, Aix en Provence-Marseille, 7–9 June 2001), Montagnac, 2003, 101–7, suggest the use of slags to colour the red glass of the *lissoirs* of the Carolingian period.

17 B. Gratuze, I. Soulier, J.N. Barrandon and D. Foy, 'De l'origine du cobalt dans le verres', *Revue d'Archéometrie* 16 (1992), 97–108.

18 Freestone (n. 13).

19 It is interesting to observe that C. Fiori, M. Vandini and V. Mazzotti identified a lower percentage of HIMT type glass in the mosaics in San Vitale in comparison with the amount found in the Milanese mosaics (C. Fiori, M. Vandini and V. Mazzotti, *I colori del vetro antico. Il vetro musivo bizantino*, Vicenza, 2004).

20 C. Jackson, 'Making colourless glass in the Roman period', *Archaeometry* 47 (2005), 763–80.

21 M. Verità, 'Glass mosaic tesserae of the Neonian Baptistry in Ravenna: nature, origin, weathering causes and processes', *Proceedings of the Conference: Ravenna Musiva, 22–4 October 2009*, 2010, 89–103.

22 Red hues in Milanese mosaics are most prominent in the niches of Sant'Aquilino (4th to 5th century), the wall sectilia in Sant'Ambrogio, and in San Lorenzo.

23 See Verità (n. 21).

24 F. Marii and T. Rehren, 'Archaeological coloured glass cakes and tesserae from Petra church', in K. Janssens, P. Degryse, P. Cosyns, J. Caen and L. Van't dack (eds), *Proceedings of the 17th AIHV Congress, 2006, Antwerp*, Antwerp, 2009, 295–300; Verità (n. 21); M.T. Wypyski, 'Technical analysis of glass mosaic tesserae from Amorium', *Dumbarton Oaks Papers* 59 (2005), 183–92; A. Silvestri, S. Tonietto, G. Molin and P. Guerriero, 'The palaeo-Christian glass mosaic of St. Prosdocimus (Padova, Italy): archaeometric characterisation of tesserae with antimony- or phosphorus-based opacifiers', *Journal of Archaeological Science* 39 (2012), 2177–90.

25 M. Tite, T. Pradell and A. Shortland, 'Discovery, production and use of tin-based opacifiers in glasses, enamels and glazes from the late Iron Age onwards: a reassessment', *Archaeometry* 50 (1) (2008), 67–84, supplies documentary evidence for the use of tin in England, France and Czechoslovakia in the 2nd to 1st century BC and in Scotland in the 1st to 2nd century AD. For the use of tin in the Merovingian world (5th to 6th century) see M. Heck and P. Hoffman, 'Coloured opaque glass beads of the Merovingians', *Archaeometry* 42 (2000), 341–57; P. Hoffmann, S. Bichlmeier, M. Heck, C. Theune and J. Callmer, 'Chemical composition of glass beads of the Merovingian period from graveyards in the Black Forest, Germany', *X-Ray Spectrometry* 29 (2000), 92–100.

26 Warmer green glass tesserae were used in the more important parts, such as the absidal basin and around the main figures: E. Carbonara, C. Muscolino and C. Tedeschi, 'La luce del mosaico: le tesserae d'oro di Ravenna. Tecniche di fabbricazione e utilizzo', *AISCOM* VI (1999), 709–18.

27 For the role of light in Byzantine art and particularly in mosaics, see L. James, *Light and Colour in Byzantine Art*, Oxford, 1996.

28 R.H. Brill, *Chemical Analyses of Early Glasses: Volume 1 (tables) and 2 (catalogue)*, Corning, 1999; M. Verità, M. Maggetti, L. Saguì, and P. Santopadre, 'Colors of Roman glass: an investigation of the yellow *sectilia* in the Gorga Collection', *Journal of Glass Studies*, accepted for publication in issue 55, 2013.

29 However the glass tesserae of the mausoleum of the prefect Opilio in Santa Giustina in Padua (5th to 6th century) are opacified with antimoniate or calcium phosphate (Silvestri *et al.* [n. 24]). These tesserae are similar to tesserae from Ravenna (Verità [n. 21]).