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Ravenna, its mosaics and the contribution of archaeometry. A systematic reassessment on literature data related to glass tesserae and new considerations

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Ravenna, its **mosaics** **mosaic** **glass tesserae** and the contribution of archaeometry. A systematic reassessment on literature data related to glass tesserae and new considerations

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Abstract

Written about thirty years after the very first archaeometric analyses carried out on the mosaics of Ravenna, the paper provides a methodical and comprehensive review of data published so far in the literature on this topic. Aimed at reflecting upon what can, according to archaeometry, be actually stated on the provenance and the manufacturing technology of the multi-coloured glass tesserae found in the mosaics adorning the Ravenna monuments, the reassessment delivers a re-examination of published data from a critical thinking perspective. Almost all of the available analyses on Ravenna mosaics have been performed many years ago, when scientific investigations applied to mosaic glass tesserae were at an early stage and the knowledge of manufacturing technology of tesserae was more patchy than today. Data obtained by former investigations carried out on assemblages of tesserae from different monuments in Ravenna and its surrounding area will be, thus, framed in the current research scenario related to mosaic glass production and supply in the late antique Mediterranean world, in order to define an inclusive background to be used as a re-starting point for further investigation and research.

Keywords: Mosaic; Glass; Tesserae; Archaeometry; Ravenna

1 Introduction

Deep blue skies on which golden stars shine, luxuriant greenery where pure white sheep graze, precious jewels adorning elegant dresses and regal crowns: these are just some of the elements characterising the mesmerising mosaics adorning religious buildings erected in Ravenna between the 5th and the 6th century CE, where the tailored use of glass tesserae has donated an extremely realistic rendering of the depicted subjects.

Seat of the Western Roman Empire in the 5th century CE and, then, heart of Byzantine Italy, Ravenna boasts an outstanding collection of mosaics and monuments datable back to the early Christian period. The city centre and its surroundings are dotted with eight noteworthy historical monuments World Heritage, telling citizens and tourists the remarkable history of Ravenna: the Mausoleum of Galla Placidia, the Neonian Baptistery, the Basilica of Sant'Apollinare Nuovo, the Arian Baptistery, the Archiepiscopal Chapel, the Mausoleum of Theodericus, the Basilica of San Vitale and the Basilica of Sant'Apollinare in Classe, all inscribed to the UNESCO World Heritage List for their "outstanding significance, by virtue of the supreme artistry of the mosaic art they contain" (<https://whc.unesco.org/en/list/788>).

These places of worship witness the historical, political and religious events that happened in Ravenna after the city became, in 402 CE, *sedes imperii* of the Western Roman Empire, then known in Italy as the Ostrogothic and Byzantine capital. World Heritage monuments in Ravenna show extremely rich and sumptuous decorative apparatuses, characterised by an extensive use of mosaic as decorative and celebrative medium. Recent research on mosaic glass tesserae and their spread in the Mediterranean basin through centuries [1,2] clearly highlights how Italy was the area of the Western Empire where mosaics were most largely adopted between the 5th and the 6th century CE, Ravenna and Rome being the cities where newly built religious structures were extensively adorned with coloured tesserae.

Distinctive feature of Ravenna and its monuments, the sophisticated use of glass tesserae has long been and it still is an intriguing research topic. Though several studies have been undertaken, specific knowledge on the production technology of mosaic glass tesserae employed in Ravenna and information on where they were possibly made are still lacking; as a consequence, a thorough and informative scenario related to these issues has not been outlined yet. Moving from this premise, the present paper is aimed at providing a systematic literature review on archaeometric data so far achieved and published on mosaic glass tesserae from the Ravenna monuments, mainly

focusing on two key programmatic points for future research perspectives: define exactly what has been done and achieved up to now, and review data from a critical thinking viewpoint. This will allow re-framing compositional data on base glass, colourants and opacifiers in the current research scenario on production and supply of glass tesserae in the Late Antique period, paying specific attention to which analyses have been performed and to the actual information that we can obtain from the data.

2 A literature review on archaeometric data

Archaeometric investigations of Ravenna mosaics undoubtedly have a long tradition. Since 1988, especially on the occasion of conservative interventions, analyses have been carried out on assemblages of glass tesserae collected from the mosaic decorations of different UNESCO monuments in Ravenna.

Table 1 and related histograms (Fig. 1a and b) provide a summary of the literature related to archaeometric investigations carried out on glass tesserae from monuments located in Ravenna and its suburb, indicating, where reported, the sampling points, the number of investigated samples and the adopted analytical methods. The relative merits of various techniques will be discussed in sub-sections 3.1 and 3.2 Sections 3.1 and 3.2 aimed at laying the foundations for a critical thinking on what is, to date, possible to state about glass tesserae from Ravenna's mosaics based on archaeometric data. In Table 2 an overview on available data related to base glass and colourants/decolourants/opacifiers is also provided, with detailed references.

Table 1 Summary of the literature related to archaeometric investigations carried out on glass tesserae from monuments located in Ravenna and its suburb.

alt-text: Table 1

Site	Century	Sampling area	Samples	Coloured/colourless	Metal leaf	Analyses	References	Notes
Neonian Baptistery	5th AD		18	Coloured	No	SEM-EDS, EPMA	[5,6]	
			7	Coloured	No	XRF, ICP-AES	[3,4]	
Basilica of Santa Croce	5th AD		7	Coloured	No	XRF-WDS	[12]	
Basilica of Sant' Apollinare Nuovo	6th AD	Mosaics of the Theodorician period	3	Colourless	Gold	SEM-EDS, EPMA	[8,9] ^a	^{a,b} Same samples and data reported in [8]
	9th AD	Mosaics of the Agnellus period	1	Colourless	Silver	SEM-EDS, EPMA	[7]	
			4		Gold	SEM-EDS, EPMA	[6] ^b	
Basilica of San Vitale	6th AD	Presbytery arch	32	Both	Gold and silver	AAS	[10,11,13]	
		Presbytery - right side	9	Both	Gold	XRF	[12,13]	
		Presbytery - left side	8	Coloured	No	XRF, ICP-AES	[3,4,13]	
		Apse arch	31	Coloured	Gold	XRF, ICP-AES	[3,4,13]	
		Apse - left side	8	Coloured	No	XRF,	[3,4]	<u>There is a discrepancy in the number of analysed tesserae. The first publications [3,4] report a total of 33 analysed samples, without specifying the sampling areas and whether the tesserae belonged or not to the original decoration. In [12], a total of 47 analysed tesserae is reported, distinguishing sampling points.</u>

					ICP-AES		
	Giustinian mosaic panel	6	Coloured	Gold and silver	ICP-AES	[58 ^c ,13]	^c Same samples and data reported in [13]
	Theodora mosaic panel	40	Coloured	Gold and silver	XRF, ICP-AES	[58 ^c ,13]	
		7	Both	Gold	SEM-EDS, EPMA	[9]	
Monastic Complex of San Severo (Classe) 6th-10th AD		5	Coloured	Gold	XRF-WDS	[12]	
	Basilica (6th CE)	15	Both		XRF-WDS, AAS, ICP-OES	[24] ^d	^d Also reported in [22]
	Basilica (6th CE) and Monastery (9th-10th CE)	23	Both	No	SEM-WDS	[22]	
	Basilica (6th CE) and Monastery (9th-10th CE)	23	Both	No	XRF, EPMA	[23] ^e	^e Same samples and data reported in [22]
	<u>Monastery (9th-10th CE), sacellum (4th CE) and detached floore from the Basilica, 6th CE (now in Cripta Rasponi, RA)</u>	41	Both	No	EPMA, SEM-EDS, XRPD	[25]	
Basilica of Sant'Apollinare in Classe	6th AD	3	Coloured	No	XRF-WDS, AAS, ICP-OES	[12,24]	

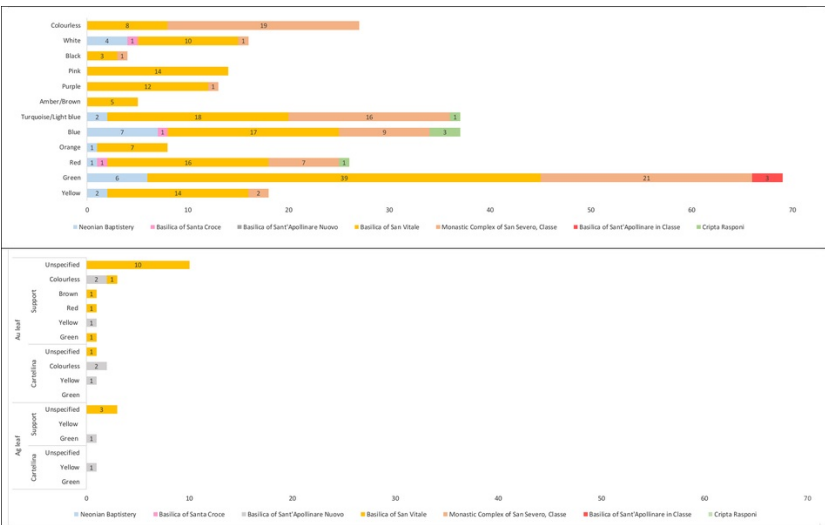


Fig. 1 Histograms showing, for each monument in Ravenna, the amounts of analysed ~~a) coloured and~~ (a) coloured and (b) metal leaf tesserae. Reference data from Tables 1 and 2.

Table 2 Summary of available data from the literature on base glass, colourants/decolourants and opacifiers detected in analysed tesserae from Ravenna and Classe. With reference to both the base glass and colourants/decolourants/opacifiers, the terminology adopted in the Table exactly reports the one that used in the cited references literature.

alt-text: Table 2

This section, organised by monument, following a chronological line and moving from Ravenna centre to its suburb, is aimed at delivering an exhaustive literature review on published archaeometric data, focusing upon the composition of the glass and the colouring/opacification technology.

2.1 The Neonian Baptistery (5th century CE)

The Neonian Baptistery, also known as Orthodox Baptistery to distinguish it from the Arian Baptistery, is one of the oldest monuments in Ravenna, probably built around the beginning of the 5th century CE under request of Bishop Ursus and concluded under his successor, Neon. Analyses performed on 25 opaque coloured tesserae from the Neonian Baptistery demonstrated the use of a silica-soda-lime natron-based glass, opacified and coloured by means of different materials [3-6]. In the white tesserae, either calcium antimonate or calcium phosphate was detected; turquoise shades were due to oxidised copper dissolved into the glass, while blue to cobalt and purple to manganese; green shades were ascribed to lead-antimonate and/or lead stannate crystals in the matrix, with a combined action of copper and iron to achieve darker shades; yellow tesserae with high lead contents (16.75–37 wt%) were coloured and opacified by either lead-antimonate or lead-stannate crystals. Relatively higher potash, magnesium and phosphorus oxides only detected in orange tessera G1 [5] suggested that it was made by using a different type of glass, presumably plant ash-based ($K_2O = 1.40$ wt%; $MgO = 1.10$ wt% and $P_2O_5 = 0.65$ wt%). The higher concentrations of lead ($PbO = 20.00$ wt%), in addition to the presence of tin ($SnO_2 = 6.00$ wt%), iron ($Fe_2O_3 = 5.00$ wt%) and zinc ($ZnO = 2.00$ wt%), were common features of this colour, whose particular composition could suggest that it was produced in a specialised centre. A single red tessera was, conversely, made by using a natron-based glass, with its dullish red colour due to the presence of copper nanoparticles and cuprite in the matrix.

Results from archaeometric analyses also led to some preliminary hypotheses on the use of two different types of tesserae [6]: some of them, produced according to traditional Roman technology, with natron-based glass and antimony-based compounds, could be of Italian origin, whilst for natron-based tesserae where either calcium phosphate had been detected as opacifier or lead and tin-based crystals were used as pigments to achieve yellow and green hues, a second production centre, located in the Levantine area, had been proposed.

2.2 The Basilica of Sant'Apollinare Nuovo (6th century CE)

Alongside with that decorating the Arian Baptistery, the mosaic programme from the Basilica of Sant'Apollinare Nuovo is the only surviving from Theoderic's Ravenna (r. 493–526). This basilica was erected at the behest of the Ostrogothic king, Theoderic the Great, of Arian faith, as palace chapel: the church, originally dedicated to Christ the Redeemer, was located within the imperial district. In 561, it was converted to the Catholic worship and renamed *Sanctus Martinus in Coelo Aureo*, taking on the name of Sant'Apollinare Nuovo only in 856, when the relics of Saint Apollinaris were transferred here from the homonymous basilica in Classe (in the suburb of Ravenna).

Unfortunately, available archaeometric data in the literature for mosaic glass tesserae from Sant'Apollinare Nuovo are quite limited (~~Table S1). Only four transparent tesserae-Table S1~~). Only four transparent tesserae - three with gold leaf from mosaics of the original decorative programme and one with silver leaf from mosaics ascribable to the 9th-century CE - ~~th century CE~~ - were collected and analysed during the recent restoration of the mosaics adorning the Basilica [7-9]. Analyses demonstrated that they were all made of a natron-based soda-lime-silica glass, although some compositional differences were detected: for tesserae with gold leaf (Au13 and Au15), the same type of glass for both the support and the *cartellina* had been used, while the tessera with silver leaf (Ag12, taken from 9th century CE mosaics) had been made by using two different glasses: a green one for the support, and a yellow one for the *cartellina*, with an almost double manganese oxide content (1.6 wt%) compared to the support (0.84 wt%). In samples Au13 and Au15 antimony and manganese were both detected, acting as decolourants [7].

2.3 The Basilica of San Vitale (6th century CE)

The construction of the Basilica of San Vitale begun under the Bishop Ecclesius, depicted in the apsidal mosaic while offering the basilica to Christ; the church was, however, completed only twenty years later under the Bishop Maximian, thanks to the conspicuous support of the rich banker Iulianus Argentarius, founder of the Basilica of Sant'Apollinare in Classe as well. At the end of 1980s, the first assemblage to be studied was collected from the Basilica of San Vitale on the occasion of conservative interventions carried out on the entrance arch to the presbytery between 1988 and 1989. Cesare Fiori carried out the first preliminary study on their composition and colours [10], followed by

further discussion about their state of conservation [11]. A total of 32 glass tesserae from the presbytery arch, mainly attributable to collapsed materials, was analysed by atomic absorption spectroscopy (AAS); the majority of samples was opaque, coloured in different shades of yellow, green, turquoise, blue, purple, brown, orange and red apart from 2 colourless tesserae supporting, respectively, gold and silver leaf. Analysed tesserae had relatively high SiO₂ contents (60–70 wt%), Na₂O ranging from 16 to 20 wt% and CaO between 5 and 9 wt%. The presence of lead and tin oxides, presumed to act as opacifiers, was detected in the yellow and green tesserae, where copper and iron oxides were interpreted as colouring agents; in one yellow tessera, antimony oxide was also detected and interpreted as opacifier, found in the white and pinkish tesserae as well. In turquoise and blue samples, lead oxide was not detected: copper and iron oxides were identified as colourants in the turquoise tesserae, while either cobalt or iron and manganese oxides were found in the blue ones. Purple hues were obtained by adding manganese oxide. In the brown tesserae, the presence of higher iron oxide contents was detected (between 0.40 and 0.75 wt%), interpreted as responsible for the colour; iron and copper oxides were also interpreted as colourants for orange and red samples. Last, transparent colourless tesserae were decoloured by the addition of manganese oxide (values around 1.00 wt%).

In 1992, mosaics adorning the right side of the presbytery were also restored. On this occasion, a further set of 9 glass tesserae, mainly opaque coloured green, yellow, turquoise, blue, black-purple, brown, red and orange plus one colourless with gold leaf, was analysed by X-ray fluorescence spectroscopy (XRF) [12]. Tesserae showed SiO₂ ranging from 69.5 to 75.5 wt%, Na₂O between 16.0 and 22.5 wt% and CaO from 5.5 to 11.0 wt%. Lead oxide was detected in all yellow and green tesserae and interpreted as opacifying agent; in the yellow tesserae, iron and manganese oxides were identified as colourants, while copper oxide was detected in the green tesserae. Turquoise shades were ascribed to copper oxide, blue to cobalt oxide. Black-purple tessera was coloured by manganese oxide (MnO = 2.30 wt%), acting as a decolourant for the colourless support destined to receive the gold leaf. Iron oxide was detected in the brown samples, interpreted as colouring agent (Fe₂O₃ = 0.65 wt%). Red and orange tesserae were coloured by relatively high iron and copper oxides contents (orange tessera: Fe₂O₃ = 4.97 wt% and CuO = 8.43 wt%; data were not provided for the red tessera). Antimony was found in the white tessera, responsible for the opacity (Sb₂O₃ = 4.54 wt%).

Between 1997 and 1998, mosaic decorations on the left side of the presbytery, the apse arch and the left side of the apse, were restored as well. Results for a total of 33 glass tesserae, both coloured (opaque and transparent – or more precisely translucent) and colourless, investigated by XRF and inductively coupled plasma-atomic emission spectroscopy (ICP-AES), were published by Ruffini and colleagues [3,4]. All analysed samples were classified as silica-soda-lime glass, presumably natron-based according to MgO and K₂O contents (MgO between 0.63 wt% and 1.66 wt%; K₂O between 0.57 wt% and 1.20 wt%). Orange, red and reddish-brown tesserae were coloured by iron and copper oxides, with darker shades showing relative percentages of Fe₂O₃ in the glassy matrix around 2.5 wt%. In some red or orange tesserae not containing lead oxide, the percentage of CuO in the matrix was approximately found double compared to Fe₂O₃ (about 2.07 wt% of CuO and 1.15 wt% Fe₂O₃), leading to the hypothesis of metallic Cu dispersed into the matrix. Analyses demonstrated that the green shades were determined by the combination of copper, iron and manganese oxides. Copper oxide was always detected in a relative percentage of less than 20%, resulting in a duller shade of colour. Manganese was also identified as responsible for purple colour shades. In the yellow or greenish yellow tesserae the joint presence of lead and tin oxides was diagnosed, acting as colourant and opacifier. In the blue tessera, cobalt oxide was detected as colouring agent.

To date, the total of mosaic glass tesserae sampled and analysed from the Basilica of San Vitale in Ravenna amounts to 136: all previously published data have been revised, reported and discussed by Fiori and co-workers in 2004 [13], with the addition of a new assemblage of 46 tesserae from the Justinian and Theodora panels sampled on the occasion of a restoration carried out between 2000 and 2001. Samples were taken from both original portions of the mosaic decoration and areas of restoration, in order to achieve data on compositional features of the original tesserae from the Basilica and, consequently, to distinguish the non-original glasses, dating back to well-documented restoration interventions. Analyses demonstrated that the original tesserae were mainly made of a silica-soda-lime glass, with natron as fluxing agent. The concentrations of alumina and lime allowed identifying two main compositional categories: Roman and Levantine I. Among the tesserae ascribable to the original mosaics, 112 samples were further selected to investigate the materials used to gain the desired shades of colour and degrees of opacity. The attainment of different colours was hypothesised to be strongly dependent on whether the tesserae contained or not lead oxide in the glassy matrix. Tesserae containing lead oxide were mainly in colour shades of green and yellow, with some red and orange, too. In the green tesserae, copper oxide was identified as the main colourant, combined with iron oxide; almost all of them also contained tin oxide. Yellow tesserae showed the presence of antimony oxide, presumed to act as both colourant and opacifier. Copper and iron oxides were detected in the orange and red tesserae, containing lead oxide as well. Some non-lead dullish red and brown tesserae were also detected, with higher iron oxide contents (>2.5 wt%) compared to red and orange with lead oxide. Tesserae where lead oxide had not been detected were mainly in the shades of light blue, blue, brown and purple: copper and cobalt oxides were identified as colourants, acting in combination with iron; purple was obtained by manganese oxide, while brown by iron oxide. White and pink tesserae showed the presence of antimony, interpreted to act as both colourant and opacifier; the pink shade was due to manganese oxide. Last, transparent colourless tesserae were decoloured by the addition of manganese oxide.

In 2013, Neri and Verità published a paper focusing on an archaeometric study of 40 gold leaf tesserae from mosaics in Italy dated 1st to 9th century CE and, among them, a set of 7 colourless and slightly coloured tesserae from the Basilica of San Vitale was also included [9]. The composition of the tesserae was found in agreement with natron-based soda-lime-silica glass prevailing in the Roman age until the 8th–9th centuries CE and only one tessera from the Basilica (SV.V5) was made with a soda plant ash glass. The pale colours were due to iron content in the melt (between 0.45 and 0.80 wt%), controlled by addition of manganese (between 0.30 and 1.05 wt%); colourless tesserae were decoloured by manganese as well, MnO ranging between 0.80 and 1.05 wt%.

2.4 From the suburb of Ravenna: the Monastic Complex of San Severo in Classe

Nothing more than a rural area before the 5th century CE, the suburb of Classe grew into a proper city when Ravenna became *sedes imperii* in 402, with all the typical settings and structures of Late Antique urban centres. Of all these elements, only a few traces survive, recovered thanks to archaeological research conducted through decades of collaboration between the University of Bologna, the Superintendence for the Archaeological Heritage of Emilia-Romagna and the *RavennAntica* Foundation.

Archaeological research has underpinned evidence for the existence of the impressive defensive track in salvaged bricks, with a thickness of 3 m and towers of 10–11 m in diameter. Unearthed between 2001 and 2005, the imposing port structure has provided information about the predominant role of Classe in the economic equilibrium of the whole Adriatic area in late antiquity [14]. The variety and quantity of products recovered in the numerous warehouses of the port have made it possible to estimate a capacity of commercial attraction capable of satisfying a total population of around 120,000 inhabitants, far above the population density estimated for the nearby Ravenna [15]. Thanks to the careful study of the finds recovered from the excavations, we know today that raw materials and finished products from southern Italy, the eastern Mediterranean and northern Africa arrived here [16–18]. If the defensive apparatus and the port demonstrate the strategic and economic importance of Classe, it is nevertheless in its monumental buildings that the highest expression of its magnificence is made explicit even today. Between the 5th and the 6th century CE several basilicas were built here: the Basilica Petriana, the Basilica of San Severo, the Basilica of the blessed Probo, the Basilica of San Demetrio (better known as Basilica of Ca' Bianca) and the Basilica of Sant'Apollinare, the only one that survived the passing of the centuries [14].

The Basilica of San Severo was erected at the end of the 6th century CE at the behest of the Archbishop of Ravenna, Peter III, next to a small *sacellum* which, from the 4th century CE, housed the mortal remains of the Holy Bishop Severus (4th century CE). The Church was consecrated in 582 with the transfer of the relics of the Saint inside the Basilica, where they remained, according to tradition, until 836 when a monk stole them and brought them to Germany [19]. From the 9th century CE to the mid-16th century CE, an important male monastery was built next to the Basilica. In the 1960s, archaeological excavations were carried out in the Late Antique Basilica, while the Monastery was studied in the frame of a research project conducted by the University of Bologna between 2006 and 2017 [20,21].

Tesserae found inside the Basilica of San Severo, started in the 6th century CE [22–25], the *sacellum* [25], first nucleus of the monumental area, dated to the second half of the 4th century CE, and the monastery, whose construction begun at the end of the 9th century CE [22,23,25], were analysed, for a total amount of 107 samples. A small set of 6 tesserae sampled from the detached pavement of the northern aisle of the Basilica and now stored in the Cripta Rasponi, Ravenna, was also analysed [25]. According to compositional data, all but red-coloured tesserae were manufactured by using a silica-soda-lime natron-based glass; red samples all showed slightly higher potassium and magnesium oxides contents, presumably ascribable to the addition of vegetal fuel ash during the melting process (natron-based tesserae, MgO ranges between 0.36 and 0.80 wt%, K₂O is found between 0.30 and 0.86 wt%; red tesserae have MgO contents between 0.96 and 1.14 wt%, while K₂O is found between 1.04 and 1.17 wt%). All the tesserae were produced with siliceous calcareous sand, with compositional features resembling the two well-known groups of Roman and Levantine I type; as reported by Fiori [23], some of the analysed samples showed intermediate chemical features between Roman and Levantine I categories. Antimony oxide was found in amounts higher than 1 wt% in the turquoise and blue opaque tesserae. All the turquoise and light blue samples were coloured with intentionally added copper (CuO between 0.16 and 3.44 wt%), while the dark blue samples owe their colour to cobalt (CoO = 0.01 wt%). Calcium antimonate was detected in some opaque turquoise and blue tesserae, acting as opacifier. The same compound was also found in the white tesserae, interpreted acting as both colouring agent and opacifier. Green tesserae were made of lead-rich glasses, where different colour shades were achieved by the addition of copper in the presence of either lead and tin oxides [23,25] or lead and antimony oxides [22]. The co-presence of either lead and antimony oxides [22,23] or lead, antimony and tin oxides [25] was detected in the yellow-coloured tesserae. Red colour was obtained through copper being used as the main chromophore: in the lead-rich red tesserae from San Severo, copper seems to have been introduced independently of lead and tin, since no correlation was detected; nanoparticles of metallic copper were found in the glassy matrices under SEM inspection. Last, colourless tesserae from the monastery of San Severo were decolourised with antimony (Sb₂O₃ between 0.40 and 1.50 wt%); manganese was only detected in the tesserae from the *sacellum* (MnO between 1.29 and 2.17 wt%) apart from sample SAC3, with low contents of both oxides (MnO = 0.38 wt% and Sb₂O₃ = 0.16 wt%). Manganese alone was also used to obtain black and purple hues in combination with iron (black tesserae: MnO between 1.21 and 2.17 wt% and Fe₂O₃ between 0.53 and 1.43 wt%; purple tessera: MnO = 0.49 wt% and Fe₂O₃ = 0.94 wt%).

2.5 Sporadic and missing data from other monuments

At the beginning of the 90s, analyses were carried out on 7 glass tesserae from the Basilica of Santa Croce (5th century CE), located in the historical centre of Ravenna close to the monumental area where, in the 6th century CE, the Mausoleum of Galla Placidia and the Basilica of San Vitale would have been erected. Dedicated to the Holy Cross, the Basilica was erected at the behest of the Empress Galla Placidia (4th–5th–5th century CE) and the famous Mausoleum traditionally dedicated to the Empress herself was nothing more than a side chapel of this Church. According to tradition, the Empress used to pray inside the Church during the night, prostrated on its porphyry floor. The basilica was later reduced and remodelled, and only a few portions can be seen nowadays, recovered thanks to archaeological excavations conducted in the 20th century CE. Fiori and Roncuzzi-Fiorentini [12] report a total of 7 analysed tesserae (although only 3 are described in the paper), coloured in shades of red, green, blue, black and white, plus a colourless one with a gold leaf. They are all made of a silica-soda-lime natron-based glass, but not all the chromatic shades were discussed in the study. According to available data, the red tessera was found containing either metallic copper or cuprite hypothesised acting as colouring agent, the white tessera was opacified by the addition of antimony, the blue was coloured by cobalt (without showing the presence of opacifiers) and the black was ascribed to iron, manganese and copper.

Only 2 green and 1 yellowish green tesserae from the Basilica of Sant'Apollinare in Classe were analysed [12,24]. This building is, to date, the only Late Antique Basilica still visible in Classe, built at the beginning of the 6th century CE by the will of the Bishop Ursicinus to house the relics of Saint Apollinaris. The Church, funded by the banker Iulianus Augentarius, was consecrated by the Bishop Maximian in 549. Data showed that they were made of silica-soda-lime glass, with natron used as a flux. Lead, antimony and tin oxides were detected, presumably acting as colouring and opacifying agents.

If archaeometric data on glass tesserae from the Basilica of Santa Croce and the Basilica of Sant'Apollinare in Classe are extremely limited, those on mosaics adorning the Arian Baptistery, the Mausoleum of Galla Placidia and the Chapel of Sant'Andrea are totally lacking from the literature. Built at the end of the 5th century CE in the cosy square of the church of the Holy Spirit, former Arian cathedral, the dome of Arian Baptistery is adorned with sumptuous mosaics depicting the procession of the twelve Apostles and the baptism of Christ. Also known as Archiepiscopal Chapel, the Chapel of Sant'Andrea is the only entirely preserved archiepiscopal chapel of the early Christian era. Erected by Bishop Peter II (494-519) during the domain of Theodoric as a private oratory and originally dedicated to Christ, the chapel was then dedicated to Saint Andrew, whose relics were transported from Constantinople to Ravenna around the mid-6th century CE.

3 How far can we go with the available data?

To date, the total number of mosaic glass tesserae sampled from Ravenna monuments amounts to 291. Data achieved by archaeometric analyses carried out on the aforementioned individual assemblages are undoubtedly not few, but what exactly do they tell if we look at them as a whole, taking into account the actual information that we can obtain with the different analytical techniques used?

In order to correctly assess the possible answers to this question, a brief digression is needed on the current state of knowledge regarding the manufacture of mosaic glass tesserae. These objects, composed of small cubes or parallelepipeds of coloured glass, have always received a marginal attention compared have always, from an archaeometric perspective, received a marginal attention compared to glassware, unfeasible to be studied on the basis of typological criteria able to define a distribution of peculiar shapes and decorative features through time and space. As a consequence, the picture of the manufacturing process and supply of mosaic glass tesserae is, to date, still incomplete and puzzling, and many questions still remain without proper answers, like how and where the raw glass was opacified and coloured [1,26-29]. Tesserae could have been made by directly adding colourants either to the primary batch, or in a secondary process, as mentioned, for instance, by Pliny the Elder (Pliny, *Naturalis Historia*, 36, 66, 193). It is, however, still unclear whether the secondary manufacture of tesserae was a centralised business, where a single workshop produced tesserae of different colours, or whether multiple workshops specialised in one colour at the time.

As we cannot benefit from the support of chrono-typological studies, the contribution of archaeometry to the study and understanding of mosaic glass tesserae plays an unquestionably fundamental role, since an in-depth and multi-analytical characterisation of the base glass and the colouring/opacification technology is an invaluable source of information for shedding new light on their manufacturing processes.

3.1 The base glass

Figs. 2-5 show scatter plots drawn by putting together all published data on mosaic glass tesserae assemblages from Ravenna (Table S1 - supplementary materials), after having calculated the reduced compositions and normalised to 100 following the method proposed by Brill [30]. This procedure was selected to more accurately compare the composition of the base glass with the categories reported in the literature for naturally coloured glass since, when dealing with opaque coloured tesserae, compositional data can be affected by the addition of materials acting as colourants/decolourants and opacifiers.

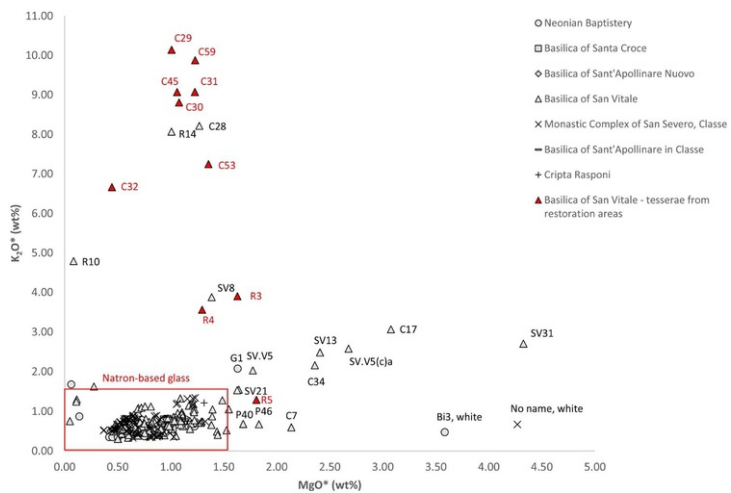


Fig. 2 K_2O versus MgO scatter plot, recalculated wt% contents used. References: Neonian Baptistery [3-6]; Basilica of Santa Croce [12]; Basilica of Sant'Apollinare Nuovo [7-9]; Basilica of San Vitale [3,4,9-11,13]; Monastic Complex of San Severo [22-25]; Basilica of Sant'Apollinare in Classe [12,24]; Cripta Rasponi [25].

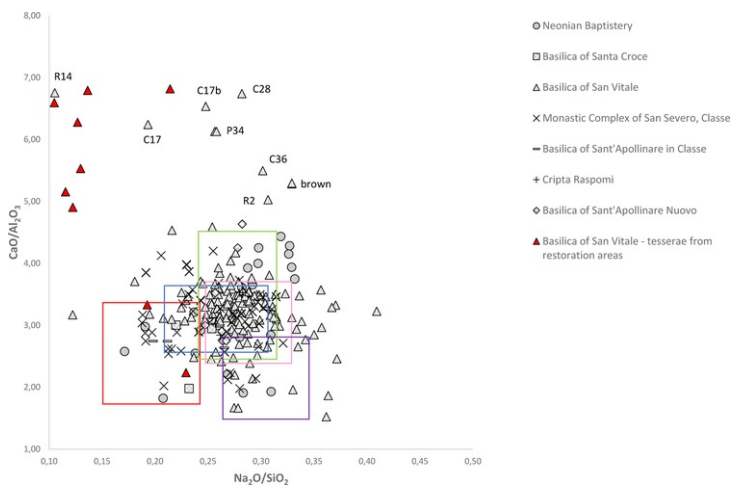


Fig. 3 CaO/Al_2O_3 versus Na_2O/SiO_2 bi-plot, recalculated wt% contents used. References: Neonian Baptistery [3-6]; Basilica of Santa Croce [12]; Basilica of Sant'Apollinare Nuovo [7-9]; Basilica of San Vitale [3,4,9-11,13]; Monastic Complex of San Severo [22-25]; Basilica of Sant'Apollinare in Classe [12,24]; Cripta Rasponi [25]; blue area: Roman glass [41,44,45]; red area: Apollonia-type glass [38,39]; green area: Série 3.2 [40,53]; pink area: Série 2.1 [40,53]; purple area: Group 1 from the ancient harbour of Classe [53].

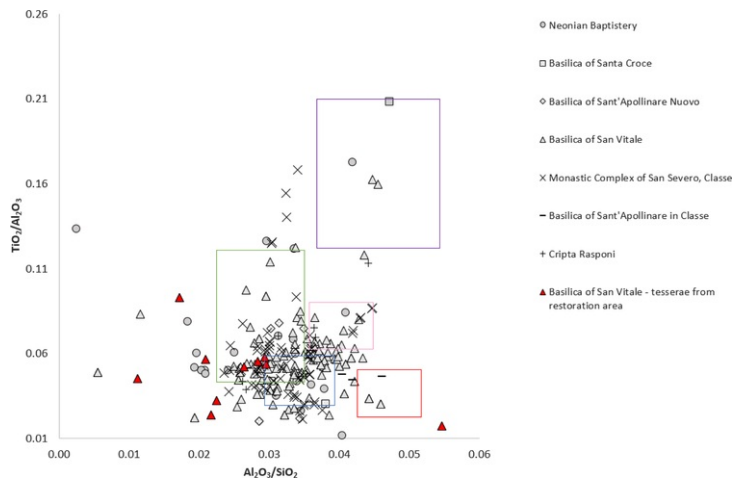


Fig. 4 $\text{TiO}_2/\text{Al}_2\text{O}_3$ versus $\text{Al}_2\text{O}_3/\text{SiO}_2$ bi-plot, recalculated wt% contents used. References: Neonian Baptistery [3-6]; Basilica of Santa Croce [12]; Basilica of Sant'Apollinare Nuovo [7-9]; Basilica of San Vitale [3,4,9-11,13]; Monastic Complex of San Severo [22-25]; Basilica of Sant'Apollinare in Classe [12,24]; Cripta Rasponi [25]; blue area: Roman glass [41,44,45]; red area: Apollonia-type glass [38,39]; green area: Série 3.2 [40,53]; pink area: Série 2.1 [40,53]; purple area: Group 1 from the ancient harbour of Classe [53].

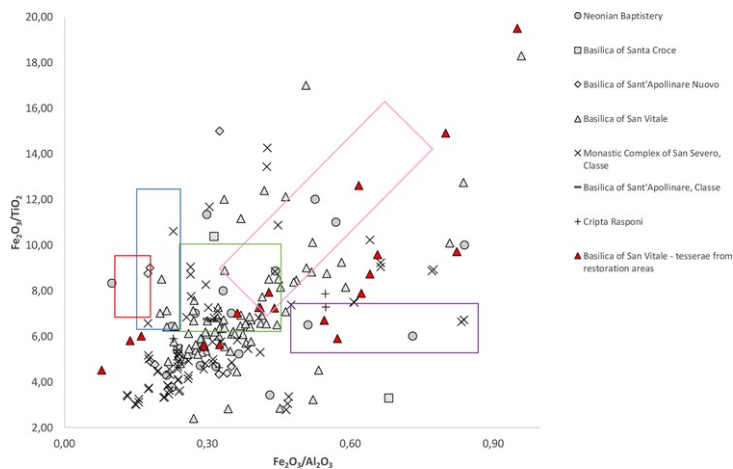


Fig. 5 $\text{Fe}_2\text{O}_3/\text{TiO}_2$ versus $\text{Fe}_2\text{O}_3/\text{Al}_2\text{O}_3$ bi-plot, recalculated wt% contents used. References: Neonian Baptistery [3-6]; Basilica of Santa Croce [12]; Basilica of Sant'Apollinare Nuovo [7-9]; Basilica of San Vitale [3,4,9-11,13]; Monastic Complex of San Severo [22-25]; Basilica of Sant'Apollinare in Classe [12,24]; Cripta Rasponi [25]; blue area: Roman glass [41,44,45]; red area: Apollonia-type glass [38,39]; green area: Série 3.2 [40,53]; pink area: Série 2.1 [40,53]; purple area: Group 1 from the ancient harbour of Classe [53].

K_2O versus MgO diagram (Fig. 2) highlights that most of the tesserae fall into the range of silica-soda-lime glass made with natron as fluxing agent, being wt% contents of both oxides below the value of 1.5 [31]. If, however, the assemblage of tesserae from the Basilica of San Vitale is taken into account, it can be noticed that there are several samples with higher contents of magnesium and potassium oxides. According to Fiori and colleagues [32], the majority of these outliers can be classified as non-original tesserae made of a plant ash-based glass (C29, C59, C45, C31, C30, C53, C32, R3, R4 and R5). Comparison with archive documents also made it possible to assign these non-original samples to specific restoration works on the mosaics of the Basilica: C29, C59, C45, C31, C30, C32 and C53 have been associated with the intervention carried out by Felice Kibel between 1863–1864 in the lower part of the Theodora's panel [33]; R3, R4 and R5 were taken from the section depicting San Matteo, located on the presbytery, left side, from re-made areas datable back to the intervention undertaken in 1885 [34].

Regarding the other outliers found in the set of tesserae from San Vitale, samples SV13, SV21, C34, C17 and P40 belong to the chromatic categories of red and orange; higher amount of K_2O (1.55–2.48 wt%) and MgO (1.64–2.41 wt%) are, thus, consistent with technological issues for obtaining colours [35]. The same hypothesis can be made for an orange tessera from the Neonian Baptistery (G1), with K_2O = 2.08 wt% and MgO = 1.63 wt%. Interestingly, one opaque white tessera from the Neonian Baptistery (Bi3) [6] and one from the Monastic Complex of San Severo (sample with no name) [12], show distinctively high MgO contents (Bi3 = 3.58 wt % and no name,

white = 4.27 wt%). This feature can be compared to opaque white Roman enamels, where high magnesium oxide (about 3.3. wt%) had hypothesised being related to a possible use of ankerite $[Ca (Mg, Fe) (CO_3)_2]$ as a source of magnesium [36]. Interestingly, in a more recent study on mosaic glass tesserae from Antioch, Wypyski and Beker [37] noticed high MgO contents in opaque white samples containing antimony and, thus, this feature has been possibly related to the antimony source. As tesserae from the Neonian Baptistery and the Monastery of San Severo both contain antimony oxide (ranging from 4.54 to 5.00 wt%), this possibility stands a reliable assumption. Samples R14 (Au-leaf with brown support) and C28 (red) from the Basilica of San Vitale show higher K_2O contents (being, respectively, equal to 7.77 and 7.70 wt%) and it can be observed that they cluster with tesserae taken from documented restoration areas. As it is highly comparable to tesserae R4 and R5, taken from a restoration area, sample SV8 (yellow green) from the Basilica of San Vitale could be interpreted as non-original as well; sample R10 (red) shows similar K_2O (4.79 wt%) but distinctively lower MgO contents. Last, tesserae P46 (green) and C7 (white) from the same monument show slightly higher MgO contents (respectively being 1.64 and 2.14 wt%; this anomaly had already been noticed by Fiori and colleagues [32], but it was not considered enough, as the only anomalous value, to formulate specific related hypotheses. Last, samples SV-V5 and SV.V5c(a) are also labelled in the diagram as they do refer to the only slightly coloured support for metal leaf and colourless *cartellina* from San Vitale made of a soda plant ash glass [9].

Remarkable considerations can be made by plotting re-calculated data on major and minor oxides from all the analysed assemblages in the combined $CaO/Al_2O_3:Na_2O/SiO_2$, $TiO_2/Al_2O_3:Al_2O_3/SiO_2$ and $Fe_{oxy}/TiO_2:Fe_2O_3/Al_2O_3$ scatter plots (Fig. 3-5s. 3-5). Comparison with compositional categories from the literature highlights that the tesserae sampled from the monuments of Ravenna mainly match three compositional categories: Roman [40-45], Série 2.1 [20,29,46-48] and Série 3.2 [40].

According to what is reported in the above discussed literature, this statement would seem to disagree with what has been asserted so far, since, where indicated, Roman and Levantine I had been identified as the main compositional categories detected within the assemblages of tesserae from Ravenna [6,13,22,23,25]. This discrepancy can be interpreted, rather than as a misunderstanding in the interpretation of data, as a natural consequence of their discussion and classification based on what was actually known, up until a few years ago, about the composition of glass from the Levantine area. The term "Levantine I" has, in fact, been widely used for describing glass made at sites located along the Syro-Palestinian coast; however, as recently demonstrated by Phelps and colleagues, the recurrent use of this label has possibly masked differences among different types of glass made at different production sites, as the case of erroneously mixed Jalame- and Apollonia-type compositional groups [38]. The term "Levantine I" should, therefore, be dismissed, and compositional groups should be linked to and named after known production sites when compositional similarities are detected (i.e. Jalame, Apollonia, Bet Eli'ezer).

Mosaic tesserae from Ravenna do not seem to show close similarities with Apollonia-type glass, a compositional category identifying glass made at the primary and secondary production centre of Apollonia-Asurf, where furnaces operated between the 6th and the 7th century CE [38,39]; this is especially marked in $TiO_2/Al_2O_3:Al_2O_3/SiO_2$ and $Fe_{oxy}/TiO_2:Fe_2O_3/Al_2O_3$ plots (Fig. 4,5s. 4 and 5). Contrariwise, the same plots suggest interesting matches between assemblages from different monuments and other compositional categories: most of the tesserae from the Neonian Baptistery (5th century CE) are consistent with Série 3.2, with some samples matching Roman-type glass; tesserae from the Basilica of San Vitale (6th century CE) mainly match Série 2.1, followed by Série 3.2 and Roman; tesserae from the Basilica of San Severo (end 6th century CE) are mostly comparable with Série 3.2, followed by Série 2.1 and Roman.

The term Roman identifies silica-soda-lime glass found at different sites in the Western regions of the Roman Empire from 1st century CE up to the end of 6th century CE at least [40-45]. This type of glass is thought to have been made by using coastal sands from the Syro-Palestinian area, probably near the mouth of the river Belus, Israel [40]. Tesserae consistent with Roman-type glass show the following compositional features in terms of major and minor oxides: CaO ranging between 6.00 and 6.50 wt%; Al_2O_3 ranging between 1.92 and 2.39 wt%; SiO_2 ranging between 68.20 and 70.35 wt%; Na_2O ranging between 14.50 and 17.70 wt%; Fe_{oxy} ranging between 0.31 and 0.75 wt%; TiO_2 ranging between 0.09 and 0.11 wt%.

First identified by Danièle Foy and colleagues and believed to be of an Egyptian origin [40], Série 2.1 is a primary production group that, together with Série 2.2, showing signs of recycling, defines the so-called Foy-2 category. The production of Série 2.1 may have begun in the 5th century, with a main spread between the 6th and 7th century CE [29,46-48], while the recycled Série 2.2 dates from 7th to late 8th to late 8th century CE [40]. Glass tesserae matching Série 2.1 category have been identified among late antique assemblages from Kilise Tepe [29], Hierapolis [29], Constantinople [49], Cyprus [46], Durrës [48] and Padova [50]. Compositional features of tesserae from the Ravenna monuments matching Série 2.1 compositional category are the following: CaO ranging between 6.29 and 8.84 wt%; Al_2O_3 ranging between 2.53 and 2.75 wt%; SiO_2 ranging between 63.86 and 67.69 wt%; Na_2O ranging between 16.01 and 18.64 wt%; Fe_{oxy} ranging between 0.80 and 1.67 wt%; TiO_2 ranging between 0.12 and 0.22 wt%.

Série 3.2 group was identified by Danièle Foy and co-authors [40] among glass found in France, Tunisia, Lybia, Lebanon and Egypt. Very little is still known of this compositional category, dated between the end of the 5th and the beginning of the 6th century CE and thought to have been made at primary working sites located on the Levantine coast, though sound evidence has not been provided yet. This type of glass does not seem to be very common among glass tesserae, as it appears to have been documented only in the votive chapel of St. Maria Mater Domini in Vicenza (6th century CE) [51] and in the paleo-Christian church of St. Prodocimus, Padua (6th century CE) [52], both located in the Northern Adriatic area like Ravenna. Compositional features of tesserae from the Ravenna monuments matching Série 3.2 category are the following: CaO ranging between 6.94 and 7.20 wt%; Al_2O_3 ranging between 1.98 and 2.50 wt%; SiO_2 ranging between 67.29 and 73.74 wt%; Na_2O ranging between 14.48 and 20.13 wt%; Fe_{oxy} ranging between 0.51 and 0.66 wt%; TiO_2 ranging between 0.09 and 0.12 wt%.

It is, at this point, relevant to indicate that Série 2.1 and Série 3.2 compositional categories have both been found within an assemblage of glasses found in the port area of Classe (Ravenna), near the Monastic Complex of San Severo [53,54]. This assemblage consisted of vessel fragments, some of which have been referred to specific typologies, chunks and working wastes, providing evidence for glass-working. The productive vocation of the port area was also confirmed by the excavations carried out in Classe between 2001 and 2005, when the main context for glass-working was identified inside one of the warehouses, named Building 6 and dated back to the beginning of the 5th century CE: a small circular kiln was identified, with massive concentration of glass fragments and glass-working wastes [55]. Archaeological data allow, thus, to state that the main glass-working activity took place in Classe in the 5th century, dating that is consistent with the production and circulation of Série 2.1 and 3.2. In addition, isotopic analyses performed on vessel fragments and working indicators from Classe seem to shed further light on the possible geographical localisation of primary production areas for Série 2.1 and Série 3.2 compositional categories, as sand deposits more influenced by the Nile sediments and, therefore, probably located in Egypt, have been identified [53]. Last, a few tesserae from the Basilica of San Vitale, San Severo and the Neonian Baptistery show similarities with so-called CL1a and CL1b groups identified among analysed vessels and working indicators from the harbour of Classe [53]. These groups are quite similar to the “strong” HIMT composition named Group1 by Foy and co-workers [40], started to be extensively traded along the Mediterranean shores from the beginning of the 5th until the beginning of the 6th century CE and though to have been produced in Egypt.

Although this correspondence of compositional features between mosaic tesserae, vessels and working wastes would seem to be in favour of a possible local production of tesserae using raw glass imported in Classe, it should be emphasised that the archaeological evidence supporting this hypothesis is currently too much labile. Furthermore, traces of glass-working have recently been identified near the Basilica Petriana, another context of the suburb of Classe, not far from the port or from the Basilica of San Severo, dated to the 5–8 century [56]. Working wastes that could refer to a craft district distributed up to the Basilica of Sant’Apollinare in Classe [57] have been found; one of them, currently under study, is made of a deep blue colour.

Moving back to CaO/Al₂O₃:Na₂O/SiO₂ plot (Fig. 3), the presence of some outliers can also be observed, seeming to split into two main clusters. The first cluster, encompassing glass tesserae from the Basilica of San Vitale (C17, C17b, C28, P34), shows higher CaO contents (between 10.71 and 13.26 wt%); interestingly, these samples also have relatively higher P₂O₅ contents (0.56–4.23 wt%), this could possibly implying the use of phosphorus-based compounds as opacifiers - to be verified through further analyses. The second cluster is composed of tesserae from restoration areas, plus sample R14 which had already shown similar features in K₂O:MgO plot. Last, samples R2, C36 and brown from the Basilica of San Vitale are characterised by intermediate CaO contents between identified compositional groups from the literature and the first cluster of outliers.

In light of what emerged from the reassessment of the data relating to the composition of the base glass used in the manufacture of mosaic glass tesserae from Ravenna, it is possible, at first, to highlight a correspondence between the historical period of construction of the monuments and the documentation and diffusion of the identified compositional categories (Fig. 6). In addition, it has been observed that the compositional categories Série 3.2 and Série 2.1 are prevalently found in the analysed assemblages from the Neonian Baptistery, the Basilica of San Vitale and the Basilica of San Severo; the only three available samples from the Basilica of Sant’Apollinare in Classe seem to match Série 3.2 category as well. All these monuments are linked to an ecclesiastical commission belonging to the Roman aristocracy, unlike other monuments in Ravenna as the Basilica of Sant’Apollinare Nuovo, the Basilica of Santa Croce and the Mausoleum of Galla Placidia, and the Arian Baptistery, referable to a laic, imperial or Ostrogoth commission. The scarcity of archaeometric data for the mosaic decorations of Sant’Apollinare Nuovo and the Basilica of Santa Croce, as well as the total lack of analysed tesserae from the Mausoleum of Galla Placidia, the Arian Baptistery and the Chapel of S. Andrea, do not currently make it possible to further verify this correlation between the commission and the selection of the material used.

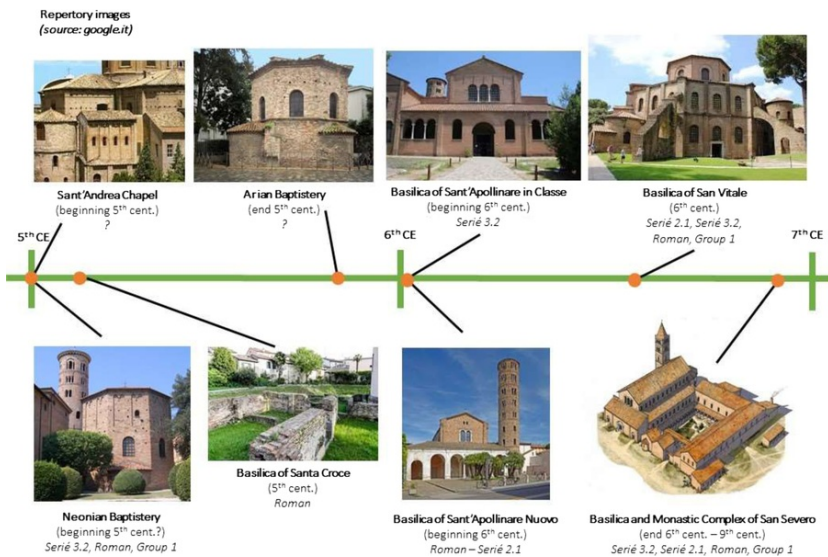


Fig. 6 Time line of re-examined monuments in Ravenna and the suburb of Classe, with identified compositional categories of glass.

3.2 Colourants and opacifiers

Table 2 summarises all available information on colourants/decolourants and opacifiers identified in mosaic glass tesserae from Ravenna monuments as they are given in the literature. The emerged picture appears to be quite intricate and puzzling, both in terms of analyses carried out and with regard to the materials used to achieve the desired chromatic shades and degrees of opacity.

To better explain this statement, it is necessary to start with some methodological considerations. When the first archaeometric investigations on the mosaics of Ravenna were carried out between 1990 and the early 2000, dedicated analyses for the study of the microstructure of the tesserae, aimed at acquiring specific data on colourants and opacifiers, were not carried out. It is the case of the Neonian Baptistery [3,4], the Basilica of Santa Croce [12], the Basilica of San Vitale [4,10,13,58], the Monastic Complex of San Severo [24] and the Basilica of Sant'Apollinare in Classe [12,24]. Thus, inferences upon likely materials used for colouring the glass were here made from bulk compositional data obtained by XRF-WDS, AAS, ICP-AES and ICP-OES, at a time when little was known regarding the colouring and opacification technologies of mosaic tesserae. Starting from 2010, SEM-EDS measurements were, though only in a few cases, carried out to characterise the inclusions in the glassy matrices responsible for the colour and opacity of the tesserae [6,22] and, where found, the gold and silver leaves [8].

SEM-EDS is undoubtedly appropriate to carry out high-resolution morphological inspection of the inclusions dispersed in glassy matrix, as well as a qualitative and semi-quantitative analysis of their elemental composition. However, in order to provide a more in-depth characterisation of these inclusions, necessary to identify raw materials responsible for the colour and opacity of the tesserae, SEM-EDS inspection is not sufficient, as it needs to be integrated with spectroscopic (i.e. μ -Raman) and/or diffractometric (i.e. m-XRD, XRPD, SEM-EBSD) analyses. Apart from one study related to opaque coloured tesserae from the Monastic Complex of San Severo where XRPD was also performed [25], spectroscopic and diffractometric analyses able to more accurately characterise the composition of the inclusions detected in the mosaic glass tesserae from Ravenna have, to date, never been performed. Furthermore, the comparison between data relating to tesserae presumably belonging to the same chromatic category (like red, blue, green, yellow) is made particularly problematic by the absence of data relating to an objective measurement and definition of the different chromatic shades, as $L^*a^*b^*$ coordinates and VIS-RS curves.

As a consequence, the scenario that can presently be depicted with available data on materials used as colourants/decolourants and opacifiers is extremely fragmented and only some preliminary inferences can be drawn. A noticeable variety of materials emerges: tin- and antimony-based phases (both individually and jointly) for achieving yellow and green shades, here acting in combination with copper dissolved into the glass; nano-particles of metallic copper were detected in the red tesserae from the Monastic Complex of San Severo, and copper-based phases were detected in opaque red tesserae from all the Ravenna monuments; in the blue tesserae, calcium and antimony-based compounds and cobalt were identified only in San Severo, while in some tesserae from San Vitale iron and manganese oxides were also identified in place of cobalt; in turquoise/light blue tesserae from Neonian Baptistery calcium phosphate is also identified, while in white tesserae phosphorus-based phases were identified only in Neonian Baptistery. In black tesserae, iron and copper (the last only in Santa Croce) were found, in addition to manganese. manganese was also detected in the colourless tesserae, either alone or combined with antimony for decolourising glass. All the aforementioned materials are documented in the literature as colourants/decolourants and opacifiers in

the manufacture of coloured glass [59].

Tin-based opacifiers and colourants were used to produce yellow, green (in combination with copper oxides) and white glass and glazes. Their use followed that of antimony-based opacifiers, widely attested in Egypt and the Near East in the production of opaque glasses since the mid second millennium BC and up to about the 4th century CE [60]. Tin-based opacifiers started, thus, being systematically used from the 4th century CE to replace antimony-based ones, probably either to face a breakdown in the supply of antimony or consequently to the establishment of closer relations between the Roman Empire and India [61]. Studies undertaken by Lahlil and colleagues have thoroughly explored the crystallisation process of antimony-based opacifiers in glass [62,63]. Recent research has extensively explored the diffusion and use of tin-based phases in Western and Eastern regions, also demonstrating a strong correlation between the methods for producing the calx, the colouring/opacification technology (i.e. the source of raw materials, the temperature and duration of the heat treatment) and the different types of micro-crystalline structures that can precipitate into the glassy matrix [64]. Therefore, more in-depth analyses would be necessary to gain further compositional data on tin- and antimony-based crystalline inclusions detected in the Ravenna tesserae, in order to frame them in a broader picture accounting new research and comparing them with Late Antique assemblages. Specific attention should also be paid to the possible jointed occurrence of tin- and antimony-based colourants and opacifiers in the same tesserae, as recent studies have highlighted a co-occurrence of both the technologies since the 1st century CE [35,65] possibly linkable to specific raw materials provenance [66].

Analogous considerations can be made for opaque red tesserae, whose colouring technology is of a specific interest due to the fact that it has been documented in two technological variants. The former, named “sealing-wax red glass”, is a high-lead glass coloured and opacified by dendritic crystals of Cu₂O. Dating back to the 8th century BC [67], this glass disappeared from the Mediterranean and northern Europe around the 1st century CE [68] and it was replaced by so-called “dullish red glass”, characterised by sub-micrometric rounded particles of metallic copper. This glass usually has low contents of iron and lead oxide and plant ashes seem to have been used as fluxing agent [26,35,69-72]. According to the literature, in-depth multi-analytical study of copper-based phases in the opaque red tesserae from Ravenna has only been performed on the assemblage from the Monastic Complex of San Severo in Classe, where nano-particles of metallic copper were detected [25]. On red (and, where present, orange) tesserae from all other assemblages further analyses should be carried out to achieve a more exact characterisation, in order to avoid indiscriminately talking of metallic copper or cuprite.

Interestingly, phosphorus-based inclusions were also found in some white and turquoise tesserae from the Neonian Baptistery [6]. The addition of powdered bone ash acting as an opacifying agent has been, to date, detected in several assemblages of mosaic glass tesserae: late antique church at Kilise Tepe, Turkey [29]; the Baptistery of Tyana, Turkey [73]; Polis Chrysochous, Ayioi Pente, the Acropolis Basilica, Kalavassos-Kopetra and the Kourion, all sites located in Cyprus, Greece [74]; the Petra Church, Jordan [75,76]; the Chapel of St. Prodocimus, Padova, Italy [50]; the Baths of Qusayr ‘Amra, Jordan [77]; the *qasr* of Khirbat al-Mafjar, Palestine [78], the Lower City Church at Amorium, Turkey [79]. According to the literature, the use of bone ash as opacifier seems to be not attested before the 5th century CE; moreover, the majority of the aforementioned study cases concern mosaic glass tesserae coming from archaeological sites mainly located in the eastern Mediterranean basin. To the current state of knowledge, we do not yet know exactly where and when this specific glass opacification technology was born and how widely it spread. Recent studies of experimental archaeology have shed new light on this particular opacification technology, providing insights into the type of bones it was made by [80]. Therefore, preliminary SEM-BSE inspection should be integrated with further analyses in order to acquire more specific data to be placed in present-day research panorama.

In Fig. 7, the previously proposed time line of the examined monuments (Fig. 6) has been reworked to focus the attention on colouring and opacifying agents, comparing the most recurrent colours among the assemblages of tesserae. It can be noticed that within the same chromatic categories (yellow, green, red, blue, etc.) an almost frequent use of the same colouring and opacifying agents occurs. However, a more in-depth characterisation of the employed materials from a compositional and structural point of view is necessary to confirm a similar hypothesis.

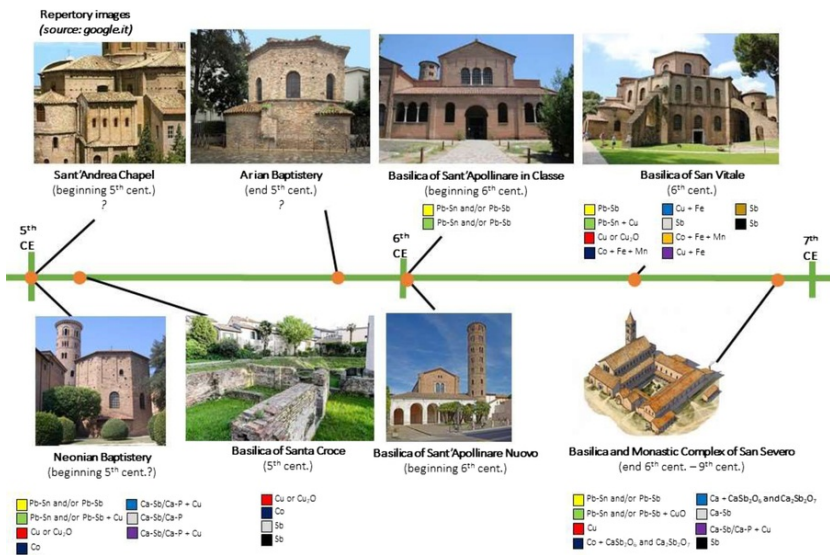


Fig. 7 Time line of re-examined monuments in Ravenna and the suburb of Classe, with identified colouring and opacifying agents according to the literature.

4 Conclusions

Almost thirty years after the publication of the very first archaeometric studies performed on mosaics glass tesserae from Ravenna monuments, authors have felt the need to reassess and review the data achieved so far. The huge debt of gratitude owed to all scholars who, in the last decades, have dedicated their research to Ravenna and its mosaics is undeniable, but it is clearly perceivable that available data require further analytical integrations, to allow a more accurate comparison with and a more precise framing in the scenario emerged from recent studies and research on mosaic glass tesserae and their manufacturing technologies.

Available studies in the literature date back, with the exception of the most recently published data on the assemblages from the Monastic Complex of San Severo, to the eighties and nineties, when the archaeometric approaches for the study of coloured mosaic tesserae were at an early stage. In addition, it has to be emphasised that, as in the case, for example, of the Neonian Baptistery and the Basilica of Sant'Apollinare Nuovo, analyses were carried out in conjunction with conservative interventions of the mosaic decorations and were not specifically aimed at thoroughly investigating their production technology.

According to available archaeometric data, it is currently impossible to ascertain if mosaic tesserae were imported to Ravenna from Byzantium. It has recently been stated that there is no evidence for primary glass-making there, and it cannot be excluded that the colouring and cutting of tesserae could have been happened anywhere in the Mediterranean basin, in specialised factories as well as in at individual sites [1]. Until otherwise proven, this account can be considered valid for tesserae adorning the Ravenna monuments as well.

Furthermore, re-examination of published data has shown that three main compositional categories of base glass are likely to have been used: Roman, Série 2.1 and Série 3.2. The first, whose primary production sites were located along the Syro-Palestinian coast, is attested in the Mediterranean basin from the 1st century BC up to at least the 6th century CE [40-45]; the second, whose primary production sites could have been located in Egypt, has mainly been detected among assemblages of glass tesserae found across the Mediterranean basin and datable between the 6th and the 8th century CE [29,40,46-48]; the third, little is still known about, is dated between the end of the 5th and the beginning of the 6th century CE, shows an isotopic signature of the sands consistent with an Egyptian origin and it has, to date, seldom been attested within mosaic tesserae assemblages [40,51,52]. Regarding Ravenna tesserae, it has also been observed that Série 3.2 and Série 2.1 glass categories are mainly found in buildings connected to an ecclesiastic commission, while Roman-type glass seems to be more commonly found among tesserae from monuments linked to an imperial commission. Could one then speak of a different supply of materials linked to the different commissioning of buildings? At the present state of knowledge this stands as a hypothesis to be verified through the analysis of further assemblages of tesserae from still not investigated monuments, like the Arian Baptistery, the Chapel of Sant'Andrea and the Mausoleum of Galla Placidia. Last, a special note deserves the correspondence found with vessels and manufacturing wastes from the port of Classe, where remains of a small kiln dedicated to glass-working have been detected. Although this comparability may directly lead to think of a possible manufacture of tesserae at Classe, there is still no archaeological evidence to exclude any other hypothesis.

Regarding colouring materials and technologies, additional data are undoubtedly needed before any sound hypothesis can be formulated. This reassessment certainly highlights uncertainties and open questions related both to

the raw materials used in the manufacture of glass tesserae of the Ravenna monuments and to their provenance, to which it will not be possible to answer unless more in-depth analyses will be carried out. Given the high degree of heterogeneity that coloured glass tesserae (especially if opaque) can have in terms of micro-structural and compositional features, their characterisation cannot be adequately and completely developed by resorting to a single analytical technique and, thus, a multi-analytical approach should be set up (an example is provided in Fig. 8). As, for tesserae, we cannot benefit from any typological study, colours and opacity are the only macro-features that can be used in order to methodically select among copious assemblages of samples, like the case of Ravenna. A combined Standard Colour System Chart (like NCS Index, PANTONE, Munsell) and Visible Reflectance Spectroscopy (VIS-RS) approach can be proposed as starting point, as it would allow objectively defining the chromatic hues and shades of opaque deeply coloured glasses, avoiding any subjective nomenclature. The next step would be, after proper selection within the assemblages, the material characterisation of colourants and opacifiers from a morphological, micro-textural and compositional aspect; to achieve this, it would be desirable to integrate, as suggested, SEM-EDS data with at least one spectroscopic and one diffractometric analysis. In-depth characterisation of the colouring and opacifying agents carried out prior to the analysis of the base glass could also be useful in order to avoid (or at least minimising) any subjective subtraction and recalculation of compositional data in accordance with the method developed by Brill [30]. Given the high heterogeneity and considering the presence of inclusion dispersed into the glassy matrix, in order to investigate the composition of the base glass and draw sound inferences upon the provenance of raw materials EPMA and LA-ICP-MS analyses are recommended, as they do allow to obtain punctual chemical analyses: the former will allow quantification of major and minor oxides, the latter will allow identifying the geographic area of provenance of the vitrifying agent. The selection of a tailored and multi-analytical protocol would allow considerably implementing the currently available data, shedding new light on still unsolved issues related to the provenance and raw materials used in the manufacture of the Ravenna glass tesserae. In addition, acquired data could be compared with the current scenario of knowledge about production technology, manufacture and supply of mosaic tesserae in the Eastern Mediterranean basin, thus representing an opportunity for more specific and detailed comparisons.

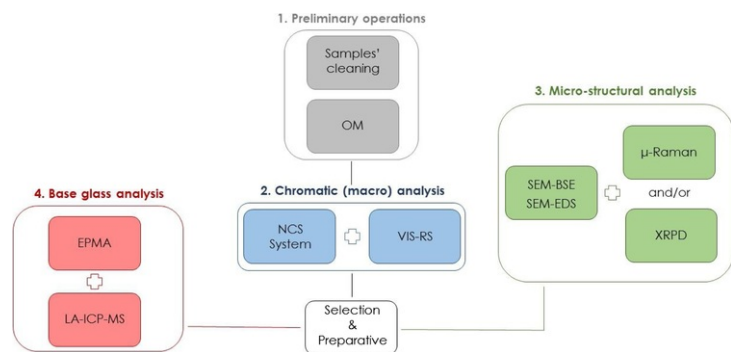


Fig. 8 Scheme of suggested multi-analytical approach for a thorough characterisation of mosaic glass tesserae.

This paper will hopefully encourage further research on tesserae from Ravenna and its fascinating monuments, being aware that a reasoned and well-structured integration between not only different analytical techniques, but also among different expertise, is the most powerful weapon we have to unravel the mysteries of this huge, challenging black hole in the history of mosaics.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at <https://doi.org/10.1016/j.culher.2020.06.003>.

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Appendix A. Supplementary data

The following are Supplementary data to this article:

[Multimedia Component 1](#)

Highlights

- Comprehensive literature review of archaeometric analyses on Ravenna glass tesserae.
 - At-a-glance compositional data on base glass, colourants and opacifiers.
 - Placing data in context with findings from research on glass tesserae manufacture.
 - Re-starting fixed point for future in-depth research on the topic.
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Queries and Answers

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