



# Glass and metal analyses of gold leaf tesserae from 1st to 9th century mosaics. A contribution to technological and chronological knowledge



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## ARTICLE INFO

### Article history:

Received 11 February 2013

Received in revised form

7 July 2013

Accepted 13 July 2013

### Keywords:

Mosaic

Glass tesserae

Gold leaf

Gold coins

X-ray microanalysis

Production technology

Dating

## ABSTRACT

An archaeometric study was carried out on 40 gold leaf tesserae from mosaics in Italy dated 1st to the 9th century AD. Glass layers and gold leaf were both analysed by X-ray microanalysis. The main aim was the identification of the composition of the glass and of the gold leaf, in order to assess the variations in composition and nature of the tesserae in the examined period.

The analytical results show that the tesserae were obtained with natron type glass; three compositional groups were identified, each characterized by a specific colour. The coexistence of colourless (antimony-manganese as decolourizer) and naturally coloured (manganese as decolourizer) glass in each mosaic suggests the simultaneous use of the two materials, probably related to aesthetic choices.

The analyses of the gold leaves indicate the use of pure gold or of gold-silver alloys. The good matches between the compositions of the gold leaves and the analyses of contemporary gold coins in the late antique and byzantine samples (3rd–9th c.) suggest that the leaves were made by beating circulating gold coins. This, in some cases, can help the dating of the tesserae and a more precise information on the type of glass used in this period.

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## 1. Introduction

Gold leaf tesserae are composite materials made of a thin gold leaf hot sandwiched between two glass layers. This is first specified in the *Manoscritto di Lucca* (217r, 30 ch. *De inoratione musiborum*), a late 8th century manuscript of Greek tradition (Hedfors, 1932).

The tesserae were obtained by cutting cakes consisting of three hot fixed layers: a layer of poured glass (the support, less than 10 mm thick), a thin beaten gold leaf (less than 1 µm thick) and a thin layer of blown glass (less than 1 mm thick), the *cartellina*, protecting the gold leaf and increasing its brilliance (Verità, 2000, 2006). The making of these cakes requires a complex procedure whose variations in time are not yet fully understood (Neri and Verità, 2013a,b).

The earliest examples of their use date back to the 1st c. A.D. in Rome, in the *Nymphaeum* of Lucullus (Bartoli et al., 2013) and the *Domus Aurea* (Lavagne, 1970; Sear, 1977). From the end of the 2nd c.,

sporadic occurrences of gold tesserae are found (Boschetti, 2011; Scheibelreiter, 2009); their use for large backgrounds in mosaics is supposed, according to the sources, to begin in the Constantinian age (early 4th c.) and they spread widely in the 5th–6th c. (Brenk, 1972; Guidobaldi and Pedone, in press).

### 1.1. The glass

Between the 1st and 9th centuries AD, both the *cartellina* and the support were made with transparent colourless or naturally weakly coloured glass. The chemical composition of the support and *cartellina* was similar (Silvestri et al., 2011; Conventi et al., 2012), corresponding to a soda–lime–silica glass characterized by low potassium, magnesium and phosphorous contents (natron type glass). Their composition, similar to that of other glass artefacts of the same period (Wypyski, 2005), did not change substantially until the 8th–9th centuries, when a new type of soda–lime–silica glass with higher potassium, magnesium and phosphorous content, produced using soda–lime plant ashes as a flux, was introduced beside conventional natron glass (Verità and Rapisarda, 2008; Silvestri et al., 2011).

Dating the tesserae is complicated by the fact that natron type glass technology included two phases. Melting of the raw materials

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took place in a few specialized centres (now identified on the Syro-Palestinian coast and in Egypt)<sup>1</sup>; subsequently, the raw glass (primary glass) was transported to a large number of secondary workshops, where it was remelted and shaped (Nenna, 2007; Freestone, 2005).

This fact implies that:

1. Only a few compositions can be distinguished, which remain substantially unchanged over long periods of time;
2. The chemical composition is not specific to the production workshop of the glass artefact, but rather to the primary workshop producing the raw glass.

The differentiation of some compositional groups was proposed, but the time range is rather wide and the characteristics cannot always be distinguished (Freestone, 2005; Freestone et al., 2005).

On the other hand, the knowledge of late antique and early medieval glass technology for mosaics is limited, so that some scholars suggest that the glass tesserae from mosaics later than the 4th–5th c. could have been recovered from the dismantling of older mosaics (re-use) (Freestone, 1993; DeLaine, 1997; Wypyski, 2005).

## 1.2. The gold

Some scholars suggested that native gold to which silver was added to lower the melting point, or electrum (a natural gold–silver alloy) was used (Colomban et al., 2005). Ancient recipes to produce the leaves provide interesting information. Pliny (*Naturalis Historia*, XXXIII, XI) writes that from one ounce of pure gold, 750 leaves with a four-inch side length could be obtained for marble, wood and copper gilding. The *Manoscritto di Lucca* (124r, 7) reports that gold leaves were obtained by beating gold between two copper sheets. The source refers to interaction between mints and leaves production: the provenance of gold from Byzantium, the indication of weight and the manufacturing process similar to minting. Medieval and Renaissance recipes specify that the leaves are made from gold coins or mint gold. The *Libro dell'arte* (ch. 39) by Cennino Cennini (late 14th century) reports that gold coins (Venetian *ducats*) were beaten for this purpose. Likewise, 13th century (second half) documents report the use of gold florins and ducats to make gold foils (Travaini, 2005). The use of circulating gold coins to obtain gold leaves also during Late Antique and Byzantine period (from late 3rd to 9th c.) cannot be excluded. This hypothesis is supported by the fact that the circulation of gold was strictly controlled, in particular between 325 and 610, when the institution of *sacrae largitiones* controlled the operations from extraction to mint and circulation. There was no free commerce of raw gold and *sacrae largitiones* also controlled the major transactions of gold coins (including taxes) and gold not minted (e.g. the activity of the palace goldsmith) (Carlà, 2009; Guest, 2005; Johns, 2011).<sup>2</sup> Further

support to this hypothesis arises from late antique and Byzantine sources explaining that jewellery may also have been made from coins (Ross, 1962<sup>2</sup>; Oddy and La Niece, 1986; Gosonovà and Kondoleon, 1994; Yeroulanou, 1999; Carlà, 2009; Giostra, 2011).

It is known that the composition of circulating gold coins varied in time and sometimes also according to the mint of coinage (Morrisson et al., 1985). The control over the purity of minted gold was exerted in Byzantine age too, also when debasement phenomena occurred in the provincial mints, especially from the end of the 7th c. onwards (Oddy, 1988; Morrisson, 2002). Coins are amenable to close dating, even if the time of coin circulation varies according to the period: an estimation of about 30 years during the 3rd–5th c. (Depeyrot, 1988; Arslan, 1994; Callu, 2010), but up to a hundred years in the 6th c. was made (Morrisson, 2002).

The aim of this paper is to improve present knowledge on the materials used to produce gold leaf tesserae by means of X-ray microanalysis on the glass and metal leaves of tesserae from mosaics from the 1st to the 9th centuries AD. Any correspondence between the composition of gold leaves and that of circulating gold coins published in the literature has been also verified in order to improve the dating of the tesserae and of glass decolouration techniques and to tell between new and reused materials, or restoration inlays.

## 2. Experimental

### 2.1. Samples

About forty gold leaf tesserae from mosaics in Italy, dated to between the 1st and 9th centuries A.D., were analysed (gold leaf, on 31 samples). The date range begins with the first evidence of gold tesserae, to see the variation or the continuity in this period with respect to the Late Roman period, and it ends when there is a change in the technology of glass and coins gold content is no longer stable. The tesserae were sampled during restoration of in situ mosaics, well dated by archaeological and historical records (paleochristian church from Rome and Ravenna) or found during archaeological excavations in the layer of building demolition (Rome, Villa dei Quintili; Ostia; Milan) or belonging to a collection (Aquileia). A description of the analysed samples is summarized in Table 1.<sup>3</sup> The samples were either whole tesserae, for which the support, gold leaf and *cartellina* were analysed separately (samples indicated as (sc)), or tesserae for which only the support (s) or *cartellina* (c) with remains of the gold leaf adhering to them were available. About 2 mm thick sections (including support, gold leaf and *cartellina*) were cut perpendicularly to the surface from the tesserae with a thin diamond wheel. Samples were embedded in cross-section in an acrylic resin, ground and polished with diamond pastes down to 3 µm grain size. Samples were carbon coated before analysis.

### 2.2. Analytical methods

#### 2.2.1. Glass

The quantitative composition of the glass was determined by wavelength-dispersive X-ray microanalysis with a microprobe

<sup>1</sup> Despite the archaeological evidences of primary glass production in the Levant and in Egypt, the production of primary glass by melting natron and silica-lime sand in other places and specifically in Europe, as proposed by some scholars (Brehms et al., 2012; Wedepohl and Baumann, 2000) cannot be excluded. This hypothesis is also supported by the description of Pliny in the *Naturalis Historia* (Pliny the Elder, *Naturalis Historia*, 36, 66) about the use of sands from the mouth of the Volturno river (north of Naples, Italy) and by the archaeometric investigation on this subjects (Vallotto and Verità, 2002; Silvestri et al., 2006).

<sup>2</sup> The vignette of *Notitia dignitatum* (5th c.) includes gold and silver foils among the products controlled by *sacrae largitiones*. The purity of gold was tightly controlled through mandatory melting before minting from the reform of Valentinian in 368. Since then, the acronym OB (abbreviation of *obryza* = purified) is marked on coins. In this historical background, unless we suppose a state-run industry, the use of native gold to produce gold leaves is less probable than the use of mint gold (coins or ingots) or re-molten treasures and jewellery, which represent an easily accessible source of gold.

<sup>3</sup> See the references in Table 1 for more precise indications about the provenance of mosaics. See also Andaloro 2006, with references for the dating of Rome's paleochristian mosaics, frequently dated by the patron's name in epigraphic evidence on the mosaic; and Arena 2005 for numismatic dating of the mosaic at Ostia, Porta Marina. Historical and iconographic elements date the mosaic at St. Apollinare Nuovo (Urbano, 2005) and St. Vitale (Angiolini Martinelli, 1997) in Ravenna. The archaeological layers associated to the building phase date the villa of the Quintilii (unpublished data) and the tesserae from the wall mosaics of the baptistery of Milan. The archaeometric data of St. Lorenzo suggest the dating for mosaics (Neri and Verità, 2013a,b).

**Table 1**

Provenance (mosaic and site), code, age (century AD), number (in parenthesis the number of tesserae analysed only for glass) and literature reference of the analysed gold leaf mosaic tesserae.

Provenance of the tesserae	Site	Code	Century AD	N. Analyzed samples	Reference
Nymphaeum of Lucullus	Rome	GR	1st	1	Bartoli et al., 2013
Villa of the Quintilii	Rome	QUI	2nd–3rd	1	
Musei Civici, Udine	Aquileia	AQ	1st–4th	2	Verità, 2006
Porta Marina	Ostia	PM	4th	2 (2)	Verità et al., 2009
S. Pudenziana	Rome	PU	4th	1	Verità and Vallotto, 2003
S. Sabina	Rome	SA	5th	4	
S. Apollinare Nuovo	Ravenna	AN	5th–6th	3	Verità, 2012
S. Lorenzo	Milan	MiSL	4th–5th	2	Neri and Verità 2013a,b
S. Giovanni baptistery	Milan	MIB	5th–6th	3 (5)	Neri et al., 2013
S. Vitale	Ravenna	SV	6th	5	
S. Lorenzo	Rome	LO	6th	1 (1)	
SS. Cosma e Damiano (arch)	Rome	CeD	7th	1	Verità et al., 2002
S. Stefano Rotondo	Rome	SR	7th	3 (1)	Verità and Santopadre, 1993
S. Cecilia	Rome	CEC	9th	3 (1)	Verità and Santopadre, 2009

(Cameca SX-50) equipped with three wavelength-dispersive X-ray spectrometers (PET, LiF and TAP crystals). Twenty elements were quantified: X-ray K $\alpha$ -lines were analysed except for Pb (M $\alpha$ -line), Sb, As and Sn (L $\alpha$ -lines). Operating conditions were: accelerating potential 15 kV, beam current 20 nA (major and minor components) or 100 nA (trace elements) respectively. A 40  $\times$  50  $\mu$ m scanning electron beam and limited counting time (10 s for major and minor elements, 20–30 s for traces) were employed to minimize alkali drift during the irradiation. The net X-ray intensities were quantified by means of a PAP correction program supplied by Cameca. X-ray microanalysis applied to the glass analysis is discussed in Verità et al. (1994). Reference glasses of certified composition (B-Corning, D-Corning, NBS-620) were analysed under the same experimental conditions as the glass tesserae to verify the accuracy of the method. The accuracy for SiO<sub>2</sub>, Na<sub>2</sub>O and CaO is below 1% and for the remaining oxides, K<sub>2</sub>O, MgO, Al<sub>2</sub>O<sub>3</sub>, SO<sub>3</sub>, P<sub>2</sub>O<sub>5</sub>, Cl, TiO<sub>2</sub>, Fe<sub>2</sub>O<sub>3</sub>, MnO and Sb<sub>2</sub>O<sub>3</sub> is below 5%. Lower limits of detection in the range of 0.02%–0.05% for most of the oxides were calculated.

### 2.2.2. Gold leaf

Quantitative analysis of the metal leaf was performed by energy-dispersive X-ray microanalysis (Edax in a scanning electron microscope Philips XL30). Analyses of gold artefacts by X-ray microanalysis are discussed in (Northover, 1998; Guerra, 2008), and the application to the gold leaves is discussed in (Conventi et al., 2012). The electron beam was scanned across an area 5  $\mu$ m long and as wide as the gold leaf. The analysis was repeated in three areas for each sample and the average value was considered.

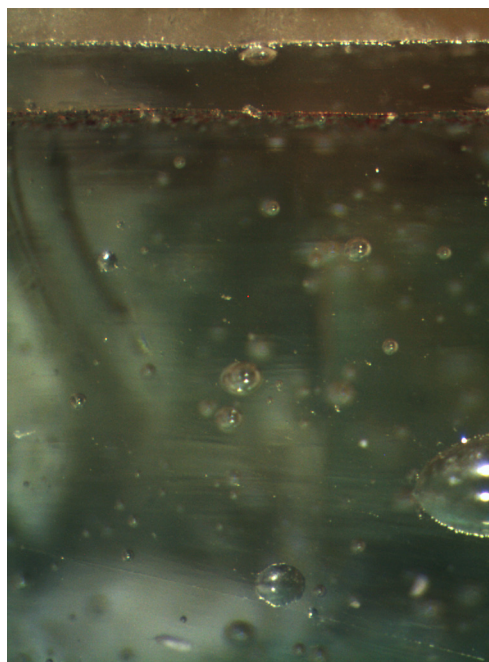
During analysis SEM operated at 20 kV, with beam intensity adjusted to give an input rate of approximately 1500 count per

second (cps) and counting live-time of 200 s. Of the resulting spectrum, only gold, silver and copper were quantified and calculated to 100 wt% of the elements, excluding other elements related to the surrounding glass composition. A standardless ZAF correction of the raw data was performed.

An accuracy of the method within 2% was calculated on Au 80%–Ag 20% (NBS-481A) and Au 80%–Cu 20% (NBS-482A) reference alloys analysed under the same experimental conditions as for metal leaves. The analytical conditions allowed us to calculate a lower limit of detection of 0.10% for silver and 0.20% for copper. Nevertheless the analyses of the metal leaves are affected by further uncertainties verified by measuring the Ag content in two tesserae respectively with a high and a low silver content. Twelve different areas of the metal leaves were analysed: a standard deviation of 20% was verified in sample SV.G4 (Ag 9  $\pm$  1.8%) and of 35% in sample SV.G7 (Ag 0.8  $\pm$  0.28%).

Copper was detected in a number of tesserae only in one of the three measurements. In this case, the presence of copper in the leaf was excluded and the measure was discarded. Probably occasional copper-bearing particles were fixed between the two glass layers during forming of the gold leaf cake. This hypothesis is supported by the fact that in these tesserae the glass–gold interface is frequently quite heterogeneous due to the presence of small particles and bubbles. Their origin can be attributed to the deposition of particles suspended in the atmosphere of the furnace during the hot forming of the glass cake or to particles flaked off from the metal tools used during these operations. According to written sources (*Manoscritto di Lucca*, 124r, 7; and Discorides according to Merzenich, 1996) a contamination of the gold leaf could also occur during the last steps of the beating process between two copper plates.

No lead and platinum were detected in the analyses. The lead and platinum contents (Pb less than 0.03% and Pt less than 0.05%, respectively) found in gold coins (Hawkes et al., 1966; Metcalf and Schweizer, 1970; Oddy and La Niece, 1986; Blet-Lemarquand et al.,



**Fig. 1.** Optical micrograph of the polished cross section of the tessera SV.V5 from the mosaic of S. Vitale, Ravenna. Top, the homogeneous, colourless cartellina. Short side of the micrograph: 2.5 mm.



**Table 2**

Chemical composition of the glass (in wt% of the oxides; the glass colour is also given) and of the gold leaves (given in wt% of the elements) of the tesserae.

Tessera	Glass colour	Period AD	Glass													Gold leaf		
			SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Na <sub>2</sub> O	K <sub>2</sub> O	CaO	MgO	SO <sub>3</sub>	P <sub>2</sub> O <sub>5</sub>	Cl	TiO <sub>2</sub>	Fe <sub>2</sub> O <sub>3</sub>	MnO	Sb <sub>2</sub> O <sub>3</sub>	Au	Ag	Cu
GR.Au1(sc)	Slightly coloured	1st	66.6	2.70	20.2	1.15	3.10	1.45	0.25	0.42	1.05	0.25	0.95	1.75		100.0		
QUI.Au1(sc)	Colourless	2nd–3rd	74.7	2.00	14.0	0.65	5.40	0.47	0.25	0.07	0.90	0.08	0.45	0.20	0.70	95.0	4.5	0.5
AQ.659p(sc)	Slightly coloured	1st–4th	71.7	2.72	15.0	0.64	7.60	0.52	0.13	0.13	0.85	0.06	0.35	0.25		98.5	0.5	1.0
AQ.659g(s)	Slightly coloured	1st–4th	69.8	2.90	15.3	0.58	7.90	0.57	0.15	0.16	0.93	0.06	0.50	1.10		92.5	7.0	0.5
AQ.659g(c)	Colourless	1st–4th	69.6	2.45	17.8	0.60	6.50	0.52	0.23	0.12	1.00	0.05	0.52	0.28	0.32			
PM.8B(s)	Colourless	4th	68.8	2.00	19.2	0.73	5.80	0.55	0.28	0.09	1.15	0.07	0.38	0.23	0.65			
PM.11(s)	Colourless	4th	67.2	1.95	21.2	0.45	6.10	0.79	0.30	0.04	1.05	0.06	0.40	0.06	0.40			
PM.2(sc)	Slightly coloured	4th	68.5	2.55	16.8	0.50	8.30	0.64	0.22	0.07	0.90	0.05	0.33	1.05		99.5	0.5	
PM.1A(s)	Slightly coloured	4th	67.0	2.30	20.4	0.43	5.90	0.88	0.32	0.05	1.15	0.12	0.58	0.75	0.12	99.0	1.0	
PU.Oro(sc)	Colourless	4th	68.7	2.10	19.5	0.54	5.00	0.65	0.32	0.08	1.05	0.09	0.55	0.23	1.00	95.0	5.0	
SA.E(sc)	Colourless	5th	68.8	2.05	19.0	0.44	5.80	1.00	0.22	0.12	1.15	0.08	0.57	0.53	0.20	99.5	0.5	
SA.G(sc)	Colourless	5th	67.4	1.84	19.9	0.43	6.71	0.74	0.29	0.14	1.15	0.08	0.53	0.61	0.20	99.5	0.5	
SA.D(sc)	Colourless	5th	68.7	2.11	19.6	0.64	5.88	0.54	0.28	0.16	1.08	0.05	0.39	0.13	0.42	92.5	7.5	
SA.F(sc)	Slightly coloured	5th	69.1	2.89	15.8	0.61	7.90	0.89	0.16	0.21	0.89	0.06	0.52	0.93		99.5	0.5	
AN.Au13(sc)	Colourless	5th–6th	70.0	2.00	18.4	0.50	5.80	0.48	0.35	0.07	1.20	0.04	0.36	0.32	0.50	100.0		
AN.Au14(sc)	Slightly coloured	5th–6th	66.2	2.00	18.4	0.50	8.50	0.95	0.40	0.08	0.85	0.15	0.70	1.30		96.2	3.8	
AN.Au15(sc)	Colourless	5th–6th	70.0	2.00	18.8	0.50	5.50	0.45	0.32	0.08	1.10	0.04	0.35	0.24	0.63	96.2	3.8	
MISL.2P(sc)	Colourless	4th–5th	68.0	2.33	19.0	0.58	5.90	0.57	0.28	0.08	1.20	0.14	0.70	0.73	0.40	99.0	1.0	
MISL.2O(sc)	Coloured	4th–5th	64.8	3.01	17.8	0.43	6.00	1.20	0.22	0.12	1.02	0.48	3.27	1.63		100.0		
MIB.Au1(s)	Colourless	5th–6th	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	100.0		
MIB.3(c)	Coloured	5th–6th	63.7	2.53	21.0	0.41	6.40	1.20	0.35	0.06	1.15	0.25	1.40	1.50				
MIB.1(c)	Coloured	5th–6th	64.0	2.55	20.4	0.39	6.00	1.47	0.25	0.05	1.25	0.30	1.60	1.70				
MIB.2(s)	Coloured	5th–6th	64.3	2.50	20.0	0.42	6.25	1.40	0.32	0.06	1.10	0.26	1.50	1.85				
MIB.C1(s)	Coloured	5th–6th	62.8	2.60	21.5	0.40	5.60	1.40	0.32	0.08	1.15	0.40	1.75	2.00				
MIB.D2(s)	Coloured	5th–6th	61.7	2.60	21.8	0.38	5.10	1.35	0.30	0.06	1.15	0.40	3.15	2.00		100.0		
MIB.E2(s)	Coloured	5th–6th	62.3	2.75	21.5	0.37	5.10	1.40	0.38	0.05	1.20	0.41	1.50	3.00		100.0		
MiB.Aua(s)	Coloured	5th–6th	65.8	2.55	19.3	0.38	5.90	1.15	0.25	0.08	0.80	0.50	1.25	1.90		100.0		
SV.INC6(s)	Colourless	6th	67.5	1.95	20.5	0.40	6.00	0.60	0.25	0.10	1.30	0.07	0.53	0.80	0.30	100.0		
SV.INC6(c)	Colourless	6th	68.6	1.75	20.5	0.30	5.40	0.50	0.20	0.10	1.40	0.05	0.35	0.95	0.30			
SV.V5(s) <sup>a</sup>	Slightly coloured	6th	68.2	2.30	14.7	2.00	7.30	1.75	0.20	0.30	0.90	0.15	0.80	1.05	0.20	93.5	6.5	
SV.V5(c) <sup>a</sup>	Colourless	6th	68.8	1.85	13.4	2.55	7.70	2.65	0.15	0.30	0.90	0.10	0.60	1.05	0.20			
SV.G4(sc)	Slightly coloured	6th	68.5	2.30	18.9	0.45	6.25	0.75	0.30	0.10	1.10	0.11	0.68	0.50		91.2	8.8	
SV.G7(sc)	Slightly coloured	6th	66.2	2.15	19.0	0.55	8.10	0.90	0.45	0.18	0.80	0.11	0.68	0.85		99.0	1.0	
SV.G8(sc)	Slightly coloured	6th	68.7	1.95	20.0	0.30	6.05	0.50	0.38	0.10	1.10	0.07	0.45	0.30	0.30	92.2	7.8	
LO.15(s)	Colourless	6th	68.5	1.97	19.4	0.50	6.45	0.60	0.32	0.05	1.10	0.08	0.41	0.15	0.50	98.5	1.5	
LO.15(c)	Colourless	6th	68.4	1.92	20.0	0.50	6.20	0.58	0.32	0.04	1.17	0.07	0.42	0.07	0.35			
CeD.A10(sc)	Colourless	7th	67.8	2.35	19.0	0.45	6.40	0.75	0.28	0.10	1.30	0.10	0.57	0.82	0.10	100.0		
SR.1(sc)	Colourless	7th	69.9	2.18	18.6	0.65	5.70	0.55	0.30	0.17	0.60	0.07	0.60	0.15	0.55	96.0	4.0	
SR.3(sc)	Colourless	7th	69.6	1.90	19.7	0.40	5.40	0.50	0.30	0.09	0.80	0.05	0.44	0.15	0.62	95.0	5.0	
SR.2(s)	Coloured	7th	64.5	2.35	20.3	0.20	5.30	0.90	0.30	0.08	0.75	0.45	2.50	2.40		98.5	1.5	
SR.2(c)	Coloured	7th	65.0	2.35	20.7	0.25	5.30	0.90	0.30	0.05	0.70	0.45	1.55	2.40				
CEC.O1(s)	Colourless	9th	66.5	2.15	20.5	0.42	6.30	0.63	0.20	0.07	1.55	0.11	0.55	0.98		99.5	0.5	
CEC.O1(c)	Colourless	9th	68.3	1.90	20.6	0.28	5.30	0.55	0.16	0.04	1.55	0.08	0.32	0.82				
CEC.H(s)	Slightly coloured	9th	70.3	2.10	16.5	0.28	5.60	0.70	0.20	0.05	0.80	0.20	1.20	2.00	0.07	99.0	1.0	
CEC.O2(sc)	Slightly coloured	9th	69.6	2.35	16.6	0.35	5.95	0.73	0.10	0.02	1.25	0.26	1.00	1.80		97.5	2.5	

<sup>a</sup> Traces of lead (PbO 0.3%) and tin (SnO<sub>2</sub> 0.2%) not reported in the table were also found in the cartellina and support of the tesserae SV.V5.

2010; Morrisson et al., 1985) are under the lower limit of detection of our analytical method (about 0.3% for both elements).

### 3. Results

The preliminary observation by optical microscopy revealed that the *cartellina* (a thickness in the range 0.3–0.8 mm and an average value of 0.5 mm was measured) was made with homogeneous, bubble free glass, which confirms that it was obtained from pieces of blown glass. Instead, the glass heterogeneity resulting from cords and bubbles indicates that the supports were made by pouring molten glass (Fig.1). The glass of the support is homogeneous only in two tesserae from S. Vitale (SV.G7 and G8).

It was also observed that the colour of the *cartellina* and of the support is the same, except in two samples (AQ.659g and SV.V5). It must be recalled, anyway, that the observation was hindered by weathered layers covering the tesserae and by the reduced thickness of the polished sections.

The quantitative chemical composition of the glass support (s) and *cartellina* (c) are reported in wt% of the oxides in Table 2 together with the gold leaf composition (wt% of the elements).

#### 3.1. Glass analysis

In the intact tesserae the composition of the *cartellina* resulted to be similar to the composition of the support (tesserae indicated with (sc) in Table 2). Only in one colourless tessera from S. Cecilia (CEC-O1) and one slightly coloured cake from Aquileia (AQ.659g) differences in concentration concern almost all of the components of the two glass layers. Furthermore, in sample AQ.659g the support is green (decolourized with manganese) and the *cartellina* is colourless (decolourized with manganese and antimony). Minor differences were detected in one tessera from S. Stefano Rotondo (SR-2) and one from S. Vitale (SV.INC6), where the iron content is higher in the support than in the *cartellina*.

The composition of the tesserae is in agreement with the glass type prevailing in the Roman time until the 8–9th centuries AD (soda–lime–silica glass), with the oxides of potassium and

**Table 3**  
Comparative table between the chemical composition of gold leaves from mosaic tesserae and the composition of coins (given in wt% of the elements), associated to glass type: N: natron glass (N1: colourless; N1\*: colourless without antimony; N2: slightly coloured; N3: coloured); C: soda ash glass.

Site	Archaeological date	Samples	Glass type	Gold leaf alloy			Gold coins alloy			Coins date	Hypothetical interpretation
				Au	Ag	Cu	Au	Ag	Cu		
Rome, Nymphaeum of Lucullus	37–54	GR-Au1	N2	100.0							
Rome, Villa dei Quintili	182–300	QUI-Au1	N1	95.0	4.5	0.5	95.5	3.7	0.5	214–275/257/285	New production
Aquileia	1st–4th	AQ.659p	N2	98.5	0.5	1.0	98.2	1.5	0.3	214–275	New production
	1st–4th	AQ.659g	N2	92.5	7.0	0.5	92.5	6.3	1.2	214–275	New production
Ostia, Porta Marina	383–388	PM.2	N2	99.5	0.5		99.5	0.5	0.0	378–383	New production
	383–388	PM.1A	N2	99.0	1.0		99.0	0.9	0.4	378–383	New production
Rome, S. Pudenziana	390–417	PU.Oro	N1	95.0	5.0		95.1	4.8	0.3	350–368	Coins with a long circulation
Milan, S. Lorenzo	390–410	MISL.2P	N1	99.0	1.0		99.1	0.9	0.1	347–395	New production
	390–410	MISL.2O	N3	100.0							Restoration 5th–7th sec.?
Rome, S. Sabina	422–440	SA-E	N1	99.5	0.5		99.4	0.7	0.1	347–491	New production
	422–440	SA-G	N1	99.5	0.5		99.4	0.7	0.1	347–491	New production
	422–440	SA-F	N2	99.5	0.5		99.4	0.7	0.1	347–491	New production
	422–440	SA-D	N1	92.5	7.5		92.5	6.3	1.2	214–275	Reuse
Ravenna, S. Apollinare Nuovo	454–456	AN.Au13	N1	100.0							New production
	557–569	AN.Au14	N2	96.2	3.8		96.2			527–565	Justinian restoration
	557–569	AN.Au15	N1	96.2	3.8		96.2			527–565	Justinian restoration
Milan, S. Giovanni Baptistery	489–512	MIB.Au1	N1	100.0							New production?
	489–512	MIB.D2	N3	100.0							New production?
	489–512	MIB.E2	N3	100.0							New production?
	489–512	MiB.Au4	N3	100.0							New production?
Ravenna, S. San Vitale	527–548	SV.V5	N1	93.5	6.5		93.0	6.1	0.9	913–1055	Restoration/reuse
	527–548	SV.G4	C2	91.2	8.8		91.0	8.0	1.0	913–1055	Restoration/reuse
	527–548	SV.G8	N2	92.2	7.8		92.9	6.3	0.9	913–1055	Restoration/reuse
	527–548	SV.G7	N2	99.0	1.0		99.1	0.8	0.1	518–527	New production
Rome, S. Lorenzo	579–590	LO.15	N1	98.5	1.5		98.6	1.8	0.3	491–582	New production
Rome, SS. Cosma e Damiano (arch)	7th	CeD.A10	N1	100.0							New production?
Rome, S. Stefano Rotondo	640–649	SR.1	N1	96.0	4.0		96.1	3.0	0.3	610–685	New production
	640–649	SR.3	N3	95.0	5.0		94.6			610–685	New production
	640–649	SR.2	N3	98.5	1.5		98.5	1.3	0.2	610–685	New production
Rome, S. Cecilia	817–824	CEC.O1	N1*	99.5	0.5		99.5	0.5	0.0	378–383	Reuse
	817–824	CEC.H	N2	99.0	1.0		99.1	0.9	0.1	347–395	Reuse
	817–824	CEC.O2	N2	97.5	2.5		97.7	2.2	0.1	717–912	New production

magnesium 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,<sup>4</sup> 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. One tessera from S. Vitale (SV.V5) is made with a soda–lime–silica glass where the higher magnesium, potassium and phosphorous contents indicate the use of a soda plant ash glass.

### 3.2. Glass colour

The glass tesserae were classified perfectly decolourized glass, i.e. without any hue (indicated as *colourless* in Table 2 and with open circles in the diagrams), and glass coloured in natural hues from green to yellow. Coloured tesserae were subdivided as follows: slightly coloured tesserae in yellow and green hues (indicated with *slightly coloured* in Table 2 and diamonds in the diagrams) and intensely coloured tesserae in a yellow–green hue (indicated with *coloured* in Table 2 and triangles in the diagrams). The colour of these glasses is the result of the iron content and to its oxidation state (ferrous or ferric) in the melt, which was controlled by addition of manganese and/or antimony.

Small differences in the main components are observed in these groups. A few peculiar cases are found, such as the unusually low

sodium (Na<sub>2</sub>O 14%) and high silica (SiO<sub>2</sub> 74.7%) contents of tessera QUI-Au1, or the low calcium content (CaO 3.1%) and surprisingly high magnesium (MgO 1.45%) and phosphorous contents (P<sub>2</sub>O<sub>5</sub> 0.42%) of tessera GR.Au1.

By reporting in a plot the iron and titanium contents (Fig. 2), a positive correlation between the two elements is apparent (average Fe/Ti ratio 5/1), indicating that iron was introduced as Fe–Ti mineral contaminant of the raw materials (probably of the silica–lime sand). For samples MIB.D2, MISL.2D and SR-2 the exceptionally high iron content (Fe<sub>2</sub>O<sub>3</sub> about 3%) and low titanium content indicate an addition of iron through another source. The voluntary addition of iron to colour the glass is confirmed by the Fe/Mn diagram (Fig. 3), showing that the iron content of these three samples is not compensated by a corresponding addition of manganese (low manganese content).

In both diagrams the colourless group is located in the lower left part (Fe<sub>2</sub>O<sub>3</sub> 0.3–0.7%, TiO<sub>2</sub> less than 0.14% and MnO less than 1%) showing a low iron, titanium and manganese content. Also the alumina content (see Fig. 4) is lower in the colourless group. These results indicate the use of a pure silica–lime sand with low contents of contaminants for the production of the colourless glass. These tesserae were decolourized with a mixture of manganese (MnO 0.06–0.73%) and antimony (Sb<sub>2</sub>O<sub>3</sub> 0.3–1.2%), with the exception of one tessera from S. Cecilia (CEC.O1) and one from S. Vitale (SV.INC6) where only manganese was used (MnO 0.8–1.0%).

As concerns the coloured tesserae, the intensity of the hue is strictly related to the iron content: lower iron values (Fe<sub>2</sub>O<sub>3</sub> 0.3%–1.2%) for the slightly coloured tesserae and higher values (Fe<sub>2</sub>O<sub>3</sub> 1.2%–3.3%) for the coloured ones.

<sup>4</sup> According to Plinius, *Nat. Hist.*, XXXI 107 also Macedonia, Media and Thrace were rich in natron. Dotsika et al., 2003 have identified possible natron sources in Macedonia.

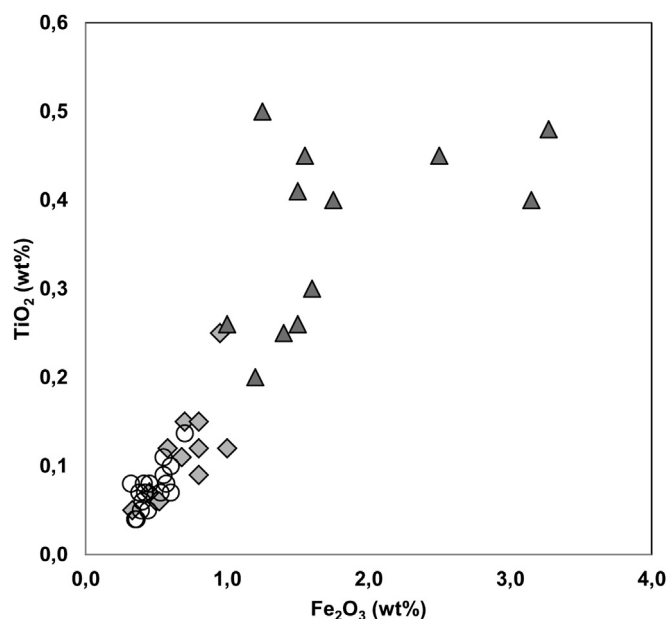


Fig. 2.  $\text{Fe}_2\text{O}_3$  versus  $\text{TiO}_2$  contents of the colourless (circles), slightly coloured (diamonds) and coloured (triangles) glass of the tesserae.

### 3.3. Gold leaf analysis

Due to the irregular beating of the leaf present in a single tessera, important differences were found in the thickness of the metal leaf measured by SEM in SE mode in the polished cross-sections. Maximum thickness is around 1  $\mu\text{m}$ ; most of the measurements are in the range  $0.4 \pm 0.2 \mu\text{m}$ .

The compositions of the metal leaves analysed reported in Table 2, can be classified into some groups.

In 8 tesserae the metal leaf is made of pure gold (Au 100%): one dates to the 1st c. (nymphaeum of Lucullus), six date between the 5th and 6th c. (Milan, S. Lorenzo and S. Giovanni alle Fonti; Ravenna, S. Apollinare Nuovo and S. Vitale) and one dates to the 7th c. (Rome, SS. Cosma and Damiano).

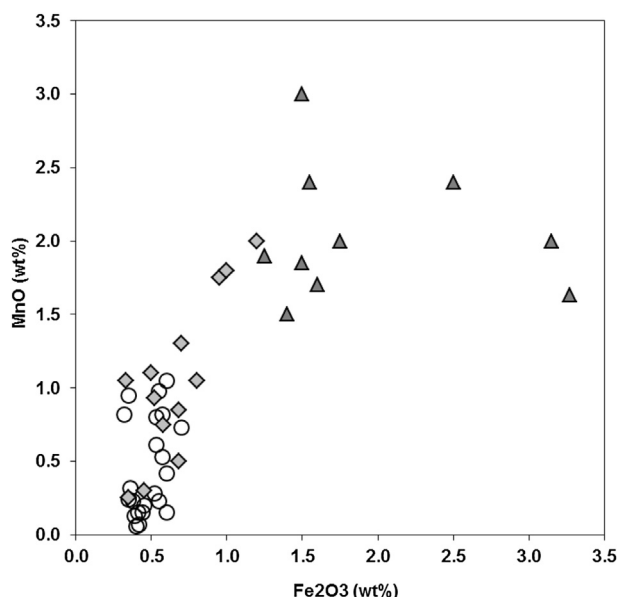


Fig. 3.  $\text{Fe}_2\text{O}_3$  versus  $\text{MnO}$  contents of the glass of the tesserae. Symbols as in Fig. 2.

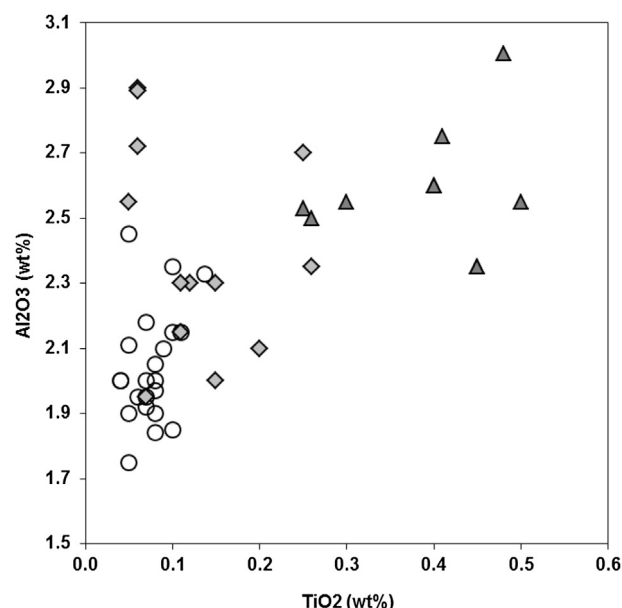


Fig. 4.  $\text{TiO}_2$  versus  $\text{Al}_2\text{O}_3$  contents of the glass of the tesserae. Symbols as in Fig. 2.

In 8 samples, the gold content varies within a restricted range (Au 99%–99.5%): two samples date to the 4th c. (Ostia, Porta Marina), four date to the 5th c. (Rome, S. Sabina and Milan, San Lorenzo), one dates to the 6th c. (Ravenna, S. Vitale) and two date to the 9th c. (Rome, S. Cecilia).

In 10 samples from sites dated to between the 3rd and the 9th c. (seven from Rome: Villa of the Quintilii, S. Pudenziana, S. Lorenzo, S. Stefano Rotondo, S. Cecilia; one from Aquileia; and two from Ravenna, S. Apollinare Nuovo), the gold content varies between 95% and 99%.

In 5 samples from Aquileia, S. Vitale, and S. Sabina, lower gold percentages were found (Au between 91.2% and 94%).

In all leaves, silver is completing the alloy. Small amounts of copper (Cu 0.5–1%) were detected in one tessera from the Villa of the Quintilii, and two from Aquileia. In the tessera AQ.659g a high silver content (Ag 7%) was detected, in QUL.Au1 an intermediate content (Ag 4.5%) and only traces (Ag 0.5%) in AQ.659p.

## 4. Discussion

### 4.1. Glass analysis

Some sub-groups can be distinguished, according to a classification of glass compositions in use from the Roman time to the Middle Ages (Freestone, 2005).

The compositional characteristics of the coloured tesserae are compatible with a natron glass termed HIMT (high iron, manganese and titanium), which becomes widespread between the 5th and 7th centuries.

A second group includes the slightly coloured tesserae where the iron, titanium and manganese levels are lower than in the HIMT group. These tesserae are a distinct compositional group characterized by a high calcium content (Fig. 5) and the absence of a correspondence between alumina and glass contaminants (iron and titanium, see Fig. 4).

A third group is formed by the colourless glass tesserae obtained from purer sand and decolourized with antimony in association with manganese. In this type of glass, hold to be in use between the 2nd and 4th centuries, the amount of manganese increased during the 4th century AD (Jackson, 2005; Foster and Jackson, 2010). However, the justification of this transition with the disappearance

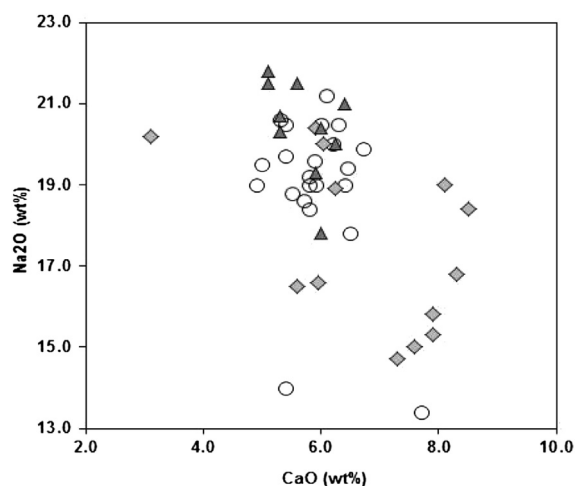


Fig. 5. CaO versus Na<sub>2</sub>O contents of the glass of the tesserae. Symbols as in Fig. 2.

of antimony sources has been questioned in recent studies demonstrating that antimony had been still in use at least until the 9th century (Verità, 2010). By reporting in a diagram the antimony and manganese concentrations (Fig. 6), a significant positive correlation is found for samples on the left side of the diagram ( $\text{MnO} < 0.5\%$ ). For samples MISL.2P, SA-E and G and CeD.A1, characterized by high manganese ( $\text{MnO} 0.5\text{--}0.9\%$ ) and low antimony contents ( $\text{Sb}_2\text{O}_3 0.1\text{--}0.4\%$ ), the involuntary addition of antimony by recycling Sb-bearing glass cullet cannot be excluded.

Finally, tessera GR.Au1 (1st c.) does not fall into any compositional group, owing to its characteristics mentioned above and tessera SV.V5 was made after the 8th c. (with plant ash type glass) and may indicate a medieval restoration. In fact in this tessera, traces of antimony, lead and tin ( $\text{PbO} 0.3\%$  and  $\text{SnO}_2 0.2\%$ , not reported in Table 2) were detected, which are considered as an indication of the addition to the batch of natron type glass cullet contaminated by opaque glass (antimony) and metals. The use of this kind of glass (defined: intermediate between natron-type and plant ash-type) was common between the 8th–12th centuries, when the contemporary use of natron and plant ash glass was attested in Italy (Verità et al., 2002; Ubaldi and Verità, 2003). In the period considered in this work the practice of making glass was

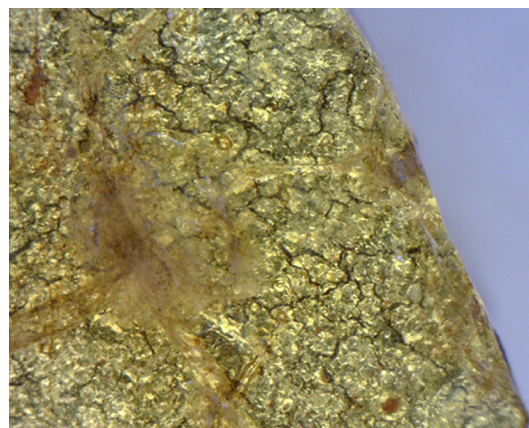


Fig. 7. Optical micrograph of tessera from S. Lorenzo (Milan). Long side of the micrograph: 2 mm.

carried out in a limited number of places located near the sources of the raw materials (primary centres), in tank furnaces where several tons of glass could be melted. Once the melting was completed, the furnace was left to cool and then demolished. The transparent glass in form of chunks (raw glass) was traded throughout the Mediterranean and Europe and distributed to workshops where it was remelted in pot furnaces and made into artefacts (Freestone, 2005). No secondary centres for the production of glass cakes for mosaic tesserae have been identified until now.

Archaeological finds attest to the circulation of raw glass decolourized with manganese (for instance: Vallotto and Verità, 2002; Foy et al., 2000), as well as raw glass decolourized only with antimony (for instance: Foy et al., 2004; Fontaine and Foy, 2007). This means that the secondary centres could get supplies of different types of raw glass, and just remelt it to make the gold leaf glass cakes. Nevertheless, it cannot be excluded that the decolouration with antimony and manganese could be made in the secondary centres. This is plausible because in glass mosaic production workshops, antimony was used for preparing white and coloured opaque tesserae (calcium antimonate).

As concerns the difference in composition between the *cartellina* and the support detected in few tesserae, different explanations can be found. The larger iron content detected in the support of two tesserae (SR-2 from S. Stefano Rotondo and SV.INC6 from S. Vitale) as compared to the *cartellina*, could be explained in terms of an occasional contamination of the glass (for instance from the dissolution of particles of the metal tools used to mix and work the melt). For tessera CEC.01a apparently after blowing of the *cartellina*, glass cullet was added to the melt before forming the support. In conclusion, the only exception to the rule that the *cartellina* and the support were made from the same glass melt is the cake from Aquileia (AQ.659g), in which completely different glass compositions (and different discolouration techniques) were detected.

In seven sites<sup>5</sup> (5th–9th c.) different types of glass are used in the same mosaic, while the composition of the gold leaf is the same. This is probably due to an aesthetical choice because the glass colour could give the gold leaf a different final appearance.

#### 4.2. Gold leaf

The final appearance of the gold leaf tesserae is the result of several parameters. The main ones are: composition and thickness

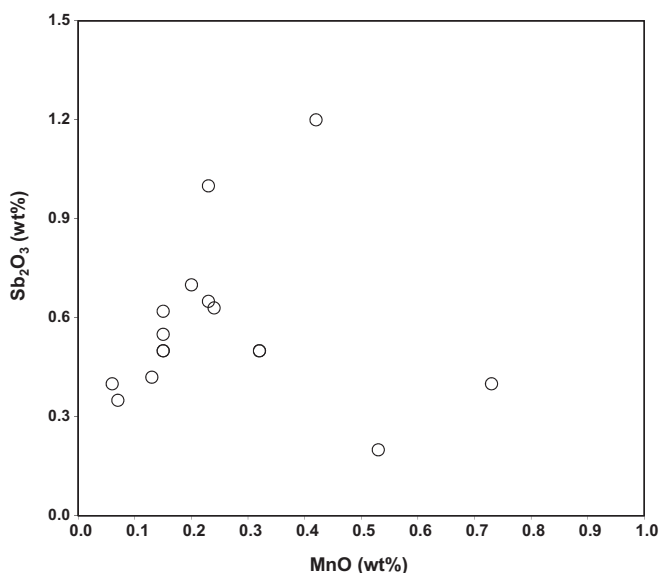
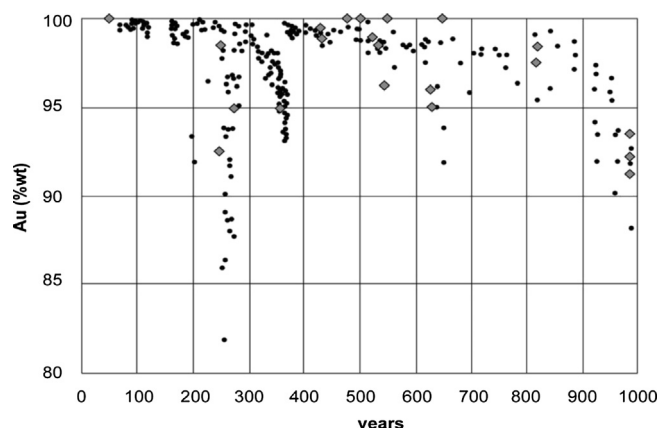


Fig. 6. MnO versus Sb<sub>2</sub>O<sub>3</sub> contents of the colourless glass of the tesserae.

<sup>5</sup> S. Lorenzo and S. Giovanni (Milan), S. Apollinare Nuovo and S. Vitale (Ravenna), S. Sabina, S. Stefano Rotondo and S. Cecilia (Rome).





**Fig. 8.** Diagram of years versus Au (%) content: circles represent coins (according to Oddy and Hughes, 1975; Morrisson et al., 1985 with references; Barrandon and Estiot, 1999; Besombes, 2008; Johns, 2011), diamonds represent mosaic gold leaves.

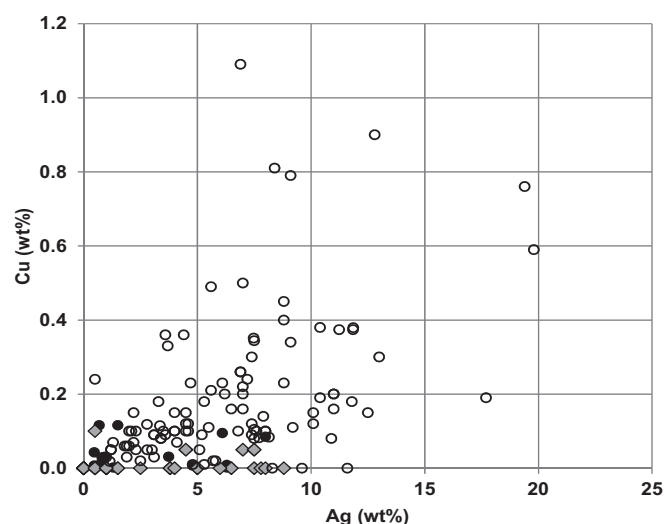
of the gold leaf and colour or decolouration of the cartellina. The colour of the support also plays an important role: the gold leaf is so thin that during the shaping of the gold leaf cake, the pressure applied to help the adhesion of the layers leads inevitably to breaching of the leaf (Fig. 7) and the support becomes visible through these fractures.

A voluntary addition of silver and copper to gold to modify the aesthetics of the tesserae is in use today<sup>6</sup>, and cannot be excluded in Antiquity (Ogden, 1993). Nevertheless, only the addition of silver in amounts exceeding a few percentage units allows a significant aesthetic change of the tesserae. On the other hand, gold leaves with a copper content more than a few percentage units change their appearance (by the formation of zones and spots) when in contact with the hot glass and cannot be used for the production of mosaic tesserae. Instead, the strict correlation between the two materials, as seen in Fig. 8 and discussed hereafter makes us think that the composition of gold leaf was not controlled by the glass-makers but simply derives from the beating of circulating coins.

The analyses of silver and copper in gold jewellery and coins show that their content varies in a larger range in jewels (Ag 0.9–17% and Cu 0.3–4.1%) (Ross, 1962;<sup>2</sup> Oddy and La Niece, 1986; Yeroulanou, 1999; Gosonová and Kondoleon, 1994; Johns, 2011) compared to coins (Ag 1–8.8%, Cu 0–1%). Furthermore, the Ag–Cu content of the jewels varies from one object to another, according to the adopted technique (Cowell and Hook, 2010). These results strongly support the hypothesis that the source of the gold mosaic leaves could not be jewels (Fig. 9). The gold and silver percentages are very similar in the coins and the leaves. A comparison of the copper content with coins and jewels is not possible in this work, since the concentrations of this element in gold leaves should be measured with more sensitive analytical techniques.

Coin analyses were performed on a large number of pieces with different methods: specific gravity (SG), XRF, proton activation analysis, PIXE/PIGE, SEM–EDS, LA–IC–MS (Hall and Metcalf, 1972; Metcalf and Schweizer, 1970; Cope, 1972; Hawkes et al., 1966; Oddy, 1972; Oddy and Hughes, 1975; Grierson and Blackburn, 1986; Morrisson et al., 1985; Oddy, 1988; Arslan et al., 1983; Guest, 2005; Blet-Lemarquand et al., 2010; Bartlett et al., 2011). The gold coins were either made from the native gold or refounded gold purified by cementation and cupellation or, during specific periods of devaluation, by the intended addition of silver (Ag < 30%) (Morrisson et al., 1985).

According to the measurements performed (Oddy and Hughes, 1975; Morrisson et al., 1985 with references; Barrandon and



**Fig. 9.** Ag (%) versus Cu (%) contents: filled circles represent coins mentioned in Table 3 (see references in Fig. 8), open circles represent jewellery (analyses by Ross, 1962;<sup>2</sup> Oddy and La Niece, 1986; Yeroulanou, 1999; Gosonová and Kondoleon, 1994; Johns, 2011), diamonds represent mosaic gold leaves (analyses in Tables 1 and 3).

Estiot, 1999; Blet-Lemarquand, 2006; Besombes, 2008; Johns, 2010; Suspène et al., 2011), the following periods can be distinguished: in period 63–253 AD the gold content is never below 99%; between 254 and 261 (Valerian) it decreases to 92% and further decreases to 85% from 263 to 283 (Claudius) to 214–275 (Aurelianus). A new increase is observed (Au between 91% and 99.2%) from 276 to 268 (Tacitus to Probus) to stabilize during the 317–345 (Au 97–98%). After a decrease below 95% between 346 and 368, after the Valentinian reform, it remains stably above 99%.

Analytical data about coins minted in Constantinople are less homogeneous for the Byzantine time (Morrisson et al., 1985; Hahn and Metcalf, 1988; Oddy, 1998). From Anastasius (491–518) up to Justinian I (527–565) the Ag% varies between 0.2 and 1.6%. Gold percentages become less stable in later times: 95.7–100% from Justin II (565–578) to Maurice (582–602), 90–98% from Phokas (602–610) to Theodosius III (717–741). From Leo III (717–741) to Leo IV (775–780) the gold percentage is stable again (Au 98%). A decrease is observed from Constantine VI (780–797) and Leo VI (886–912) (Au from 98.7% to 95%); from the 950s onward the gold content decreases (in any case Au < 90%) until Michael IV (1034–1041) (summary of these complex data in Morrisson, 2002).

However the debasement phenomena of the province mints began in the 7th c. (Hahn and Metcalf, 1988; Morrisson, 1994). In Italy, data are lacking: the only Byzantine workshop examined with analytical approach is Syracuse (Oddy, 1988); moreover the analysis of the Ostrogothic coinage are insufficient (Arslan, 1993; Grierson and Blackburn, 1986) and Lombard coins have a lower gold content than the contemporary Byzantine coinage (Arslan et al., 1983).

The composition of the gold leaves of the examined mosaic tesserae shows several correspondences with those of the Roman and Byzantine coins. The gold content varies in the same range (Au 90–100%) for both leaves and coins, and during the same time (Fig. 8). The possible correlation between circulating coins and gold leaves is shown in Table 3, in connection with the three types of natron glass identified by the analyses.

The compositions of coins and gold leaves matches in 17 samples (out of 31), dated between 3rd and 9th c. The composition is exactly the same in 13 samples.<sup>7</sup>

<sup>6</sup> Today gold–silver alloys in the range Au 30%–90% are used to make leaves for mosaic tesserae to obtain several colour hues.

<sup>7</sup> PM.2, PM.1A, MISL.2P, SA-E, F, AN.Au14e15, SV.G7, LO15, SR.1, SR.3, SR.2, CEC.O2.



One sample from S. Pudenziana (Rome) may have been produced from coins with a long time of circulation: the leaf has a gold content (Au 95%) comparable to that of the coins between Mag-nentius and Valentinian I (350–368). For 3 samples (Qui.Au1, AQ.659p and g) the match between gold leaves and gold coins re-fines the range of archeological dating. For the tessera from the villa of the Quintilii in Rome (QUI.Au1), dated to the 2nd–3rd c., the gold content (Au 95%) is quite similar to the gold content of coins dated to the second half of the 3rd c. (Au 95% in coins of Gallienus and Carinus). The two samples from Aquileia fell into the same range (Au 93.8–98.2%) that was found in coins of the 3rd c.<sup>8</sup>

The match between gold coins and mosaic leaves allows supposing that 3 samples, dated from the 5th to 9th (SA.D, CEC.O1, CE.O2), have been re-used. On the other hand tesserae SV.V5, SV.G8 from S. Vitale could be pertinent to an ancient restoration. In fact the tessera SV.G4 has a plant ash glass composition (i.e. after the 8th–9th c.) and a gold content (Au 91.2–93.5%) similar to two natron-type tesserae from the same site. Similar gold contents are found in the 3th c. coins, in the 7th c. coins minted in Italy (Oddy, 1988; Morrisson, 2002)<sup>9</sup> and in the coins minted in Constantinople during the times of Constantine VII (913) and Romanos II (959) (Au 92–97.5%), as well as in the coins with a more stable composition (Au 92%) minted in the periods of Nikephoros Phokas (963–969) and Constantine IX (1042–1055). The use of plant ash glass suggests that at least the tessera SV.V5 pertains to a restoration probably of the 10th–11th c. This is also a likely dating for the tesserae SV.V5, SV.G8.

The leaves of 8 tesserae are of pure gold (Au 100%): 1 from the 1st c., 7 from the migration period. It is likely to occur in circulating coins contemporary to the decoration, though this percentage is never identified in coins.

Concerning the 1st c. sample, the gold percentage of the analysed Neronian coins is slightly different (average Au 99.4%); closer percentages were found for Julio-Claudian coins (Suspène et al., 2011) and coins of Trajan (Besombes, 2008, e.g. sample 45, Au: 99.9%). However a different source of gold cannot be excluded, because the gold coins minted are more limited and the economic background of gold circulation is different from Late Antiquity.

For 7 samples, dated from the 5th to the 7th c., (MISL.20; MIB.Au1, MIB.D2, E2, Aua; AN.Au13, CeD.A10), it can be reasonably assumed that coins with a similar gold content were circulating in the time (368–451) when the mosaics were built: for instance, a Valentinian I coin with Au 99.9% is known (BN1902). However 5 samples come from building of the Goths' age (S. Apollinare Nuovo in Ravenna and S. Giovanni in Milan). Another source of gold (native gold or purified recycled objects) cannot be excluded. The complexity of the circulation of gold during the migration period, better studied for other geographical contexts (e.g. Guerra and Roux, 2002), requires further studies to define the source of gold of leaves of the mosaic tesserae.<sup>10</sup>

Many factors impose to be cautious in the relationship between coins and mosaic leaves: the limited number of analytical data, the diversity of the analytical techniques, the relatively high LLD of

copper in the analyses of the gold leaves of the tesserae, the lack of knowledge of workshop location for glass cakes from which the tesserae were cut and the lack of chemical analysis of coins minted by Goths and in the early Byzantine period (except Oddy, 1988). Despite these limits, the match between gold leaves tesserae and gold leaves coins appears significant.

## 5. Conclusions

The analytical data discussed in this paper demonstrate that the combined analysis of glass and metal leaf of mosaic gold tesserae is a useful tool to improve technological knowledge and the available information as to their provenance and dating.

A clear correspondence between the Au content of gold leaves and the coins circulating in the time when the mosaic was set up was found for about 23 tesserae out of 31. Additional analyses of coins and gold leaves, as well as the use of more sensitive analytical techniques, are necessary to better define this issue. The investigated samples come from late antique and Byzantine mosaics. This confirms the strict control, especially between 325 and 610 AD, on the circulation of gold within the empire and the absence of the use of raw gold, unless under the state monopoly, as suggested by historical and archaeological sources. The gold leaves of the tesserae belonging to the Nymphaeum of Lucullus (1st c.) and to 5th–7th c. mosaics are of pure gold and do not have any precise comparison in coin analysis, even if the circulation of coins with Au 100% cannot be excluded. To better investigate the supply of gold for mosaics between the 1st and 3rd centuries and in the migration period, in which the historical and economic context was undoubtedly less rigid and fewer coins were minted than in the Late Antique and Byzantine periods, will be therefore necessary.

The analysis of the gold leaves allowed distinguishing reused tesserae recovered by dismantling ancient mosaics, as well as to ascertain the presence of newly made tesserae (beside reused ones) even in 7th–9th c. mosaics in Rome. It must be considered that no generalization can be drawn, since the correlation between gold leaf and coin compositions was found for a restricted number of tesserae over a time period of nine centuries. Additional analyses of coins and mainly of mosaic gold leaf tesserae are necessary to better define this issue.

The match of gold coins and gold leaves compositions allows dating the tesserae, according to the limits of coin dating power. In some of the mosaics investigated, the date of a restoration can be confirmed by iconographic evidence (S. Apollinare Nuovo, Ravenna) or by the composition of the glass of the tesserae (one tessera from S. Vitale, Ravenna). However, in other cases (S. Lorenzo in Milan, 2 tesserae from S. Vitale) only the composition of the gold leaves allows a restoration to be assumed, with the use of new made or re-used mosaic gold tesserae.

The gold leaf dating can also ascertain the period in which the different types of glass were used. Glass decolourized with antimony and manganese, which is generally dated to within the 4th c., has been identified in tesserae dated on the basis of the gold leaf composition to the 6th c. in Ravenna and to the 7th c. in Rome. This would confirm the use of antimony well beyond the time supposed up to now.

Coloured glass appears to have been used in a restricted time period, i.e., between the 5th and 7th centuries, while the slightly coloured glass occurs over the period 3rd–9th c., with an almost unvaried composition.

Finally, the results suggest that the use in the same mosaic of gold leaf tesserae made with a colourless glass together with tesserae made with a coloured or slightly coloured glass seems to have been a deliberate choice intended to give the gold leaf a

<sup>8</sup> Specifically, the silver content and the presence of copper are comparable with the coins of Claudius II (213–270) and Aurelian (214–275) from the mints of Milan and Siscia. This relationship is supported by the fact that in this period the mint of Milan exerted a complementary activity with the mint of Aquileia in the manufacture of gold and silver coins (Gorini, 1983; Grierson and Blackburn, 1986). The colourless glass of these three tesserae shows a sodium content (Na<sub>2</sub>O 14%) that is unusually low for natron glass, found also in the two slightly coloured samples from Aquileia dating to the same period.

<sup>9</sup> There is no analysis for the coins of the mint of Ravenna, which operated up to 751, and of Rome, which operated up to 776.

<sup>10</sup> Here we should recall the decision taken by Theodoric concerning the recovery of gold from graves and the new sources for gold mining (Cassiodorus, *Variae*, 4.34 and 9.3). The free circulation of gold in the *barbaricum* is also attested by the ingot without imperial mark found at Sutton Hoo (Kent, 1975, 646–647).

different final appearance. Also for this aspect a specific, wider sampling is necessary before drawing any definite conclusion.

## Acknowledgements

The authors would like to thank ISCR (Rome), Cetty Muscolino (Ravenna) and Silvia Lusuardi Siena (Milan) for supplying most of the samples for the analyses; Cécile Morrisson, Ermanno Arslan, Claudia Perassi (numismatics), François Baratte (circulation of gold in late Antiquity) and, above all, Maria Filomena Guerra (analytical techniques applied to gold alloys) for the discussions and suggestions; Maryse Blet-Lemarquand for the literature. A special thanks to the companies Mario Berta Battiloro di Sabrina Berta & C. S.n.c., Venice-Italy (metal leaves hand beating), and Angelo Orsoni s.r.l. (Trend Group), Venice-Italy (gold mosaic tesserae production) for their most useful help in understanding the ancient gold leaf mosaic tesserae production techniques. Finally, thanks to the anonymous referees for the improvements to our text.

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