

# Laboratory Study of Byzantine Enamels from the Louvre Museum: Techniques of Manufacturing and Materials

Sixteen Byzantine *cloisonné* enamels on gold in the Louvre Museum, supposedly from Constantinople, were studied in the laboratory of the Centre de Recherche et de Restauration des Musées de France (C2RMF) (tab. 1; figs 1-3, 6-8)<sup>1</sup>. This paper presents the results gained in a study on the manufacturing techniques and the nature of the glass used in these enamels (for the history of these enamels see essay by Jannic Durand<sup>2</sup>).

The techniques of the enamels were studied under high magnification and with X-ray radiography. Non-destructive ion beam analyses were made directly on the glass surface of the objects by using an external proton beam of 2.95MeV on the target, produced by the AGLAE accelerator of the C2RMF in PIXE and PIGE modes (respectively proton-induced X- and Gamma-rays emission). Details about the experimental set-up have been published elsewhere<sup>3</sup>.

Byzantine craftsmen have produced enamels of high quality since the sixth century<sup>4</sup>. These high-quality objects were made from melted glass on gold and enjoyed an exceptional reputation. It has long been thought that Western enamels were made under the influence of Byzantine models, but a thorough technical and stylistic study of these enamels sheds a different light on this question<sup>5</sup>. The few enamels considered to be Early Byzantine (fifth-sixth centuries) are actually made using the filigree technique described below, inherited from ancient Greece, and not that of *cloisonné* enamels<sup>6</sup>. The *cloisonné* technique, which made the Byzantine enamellers very famous, was actually imported from the West in the early ninth century.

Nr.	Date	Technol. period	Objects	Size	Inv. Nr.	Bibliography
1	End 9 <sup>th</sup> - beg. 10 <sup>th</sup> c.	2	The Stoclet paten	Total diam. 12.3 cm medallion 3.2 cm	OA11878	Durand, Les émaux; L'art byzantin; Nouvelles acquisitions; Patène Stoclet; Patène. – Cat. New York 1997, cat. 28
2	End 9 <sup>th</sup> - beg. 10 <sup>th</sup> c.	2	Medallion with the bust of a winged Archangel	Diam. 2 cm	OA6270	Cat. Paris 1992, cat. 227
3	10 <sup>th</sup> c.	3A	Medallion the Crucifixion	Diam. 3.8-3.9 cm	OA12136	Durand, Les émaux
4	10 <sup>th</sup> c.	3A	Medallion the Blessing Christ	Diam. 2.3-2.4 cm	OA12137	
5	10 <sup>th</sup> - 11 <sup>th</sup> c.	3A	Rectangular decorative plate with two rosettes	L. 2. l. 3.5 cm	OA12139	
6	11 <sup>th</sup> - beg. 12 <sup>th</sup> c.	3B	Medallion the Bust of Archangel Saint Michel	Diam. 2.6-2.7 cm	OA12138	
7	End 11 <sup>th</sup> - beg. 12 <sup>th</sup> c.	3B	Medallion Saint Demetrios	Diam. 8.4 cm	OA6457	Cat. Paris 1992, cat. 239
8-11	11 <sup>th</sup> - 12 <sup>th</sup> c.	4	Four large trapezoidal decorative plates	L. 5.6-5.8, l. 2-2.1, P. 2.6-2.7 cm L. 6.1-6.2, l. 2-2.1, P. 2.6-2.7 cm	OA12140-12143	
12-15	11 <sup>th</sup> - 12 <sup>th</sup> c.	4	Four smaller rectangular plates	L. 2.1, l. 1.8-1.9 cm	OA12144-12147	
16	11 <sup>th</sup> - 12 <sup>th</sup> c.	4	Icon cover plate	L. 11.3, l. 5.4, thickness 0.2 cm	OA6458	Cat. Paris 1992, cat. 242

**Tab. 1** List of the Byzantine enamels from the Louvre Museum, with their date, period concerning their manufacturing technique, size, inventory number and bibliography.

1 Pieces not presented in this text, see Biron et al., Les émaux 139-157; Durand, Les émaux 65-69.

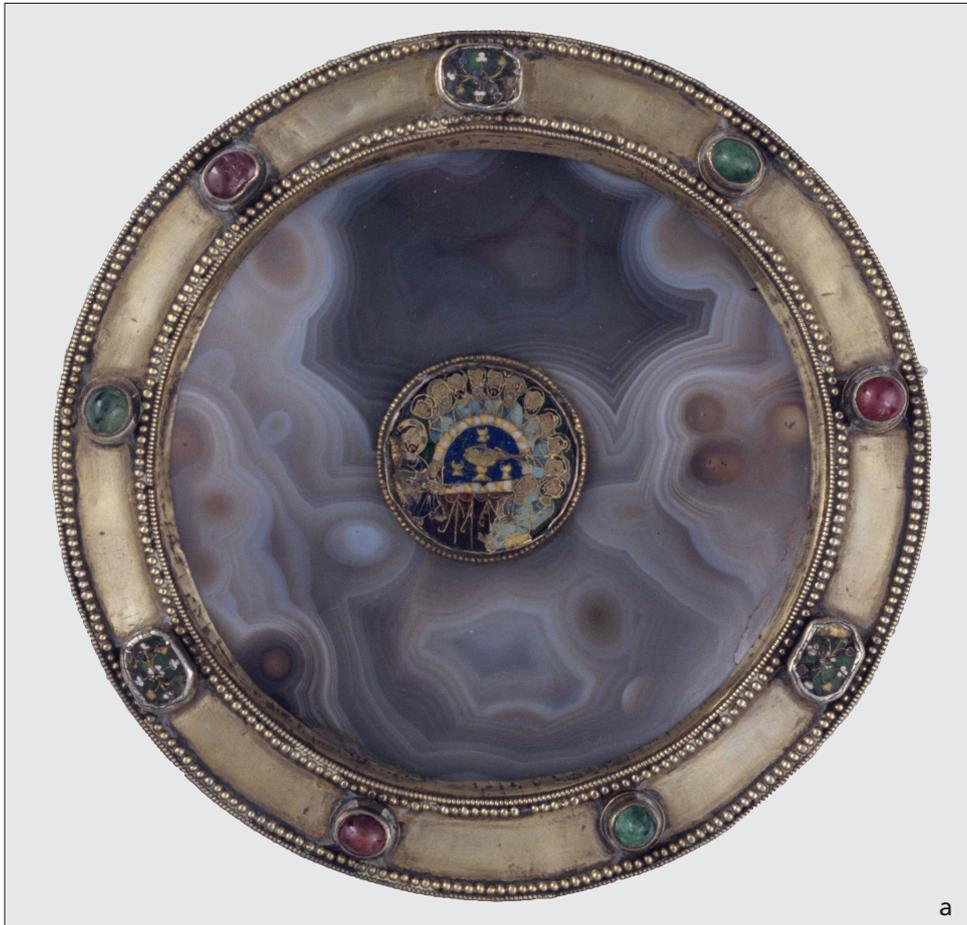
2 Durand, Les émaux 65-69. – Durand, Smalto. – Durand, L'art byzantin.

3 Pichon et al., Development. – Biron et al., Les émaux 427-429.

4 Overviews in Durand, Les émaux 65-69. – Bosselmann-Ruickbie, Byzantine Jewelry and Enamels.

5 Buckton, Byzantine Enamel.

6 Buckton, Byzantine Enamel.



**Fig. 1** The »Stoclet Paten« is made of a hard stone (sardonyx) with a gilt silver mount, enhanced with six gemstone cabochons and three *plique cloisonné* enamels on gold (made in Paris around 1300). Musée du Louvre, Paris, inv. no. OA11878. **a** Paten. – **b** Detail of the Byzantine *cloisonné* enamel (c. tenth century) on gold in the centre presenting the Last Supper. – (Photo C2RMF D. Bagault).



## Techniques of Manufacturing

Byzantine *cloisonné* enamels consist of a gold support plate surrounded by a border (strapping ribbon or support) to create a cavity in which the *cloisons* are deposited. The cells are then filled with coloured glass powders. Stamping the

metal to shape details was used in several periods. Gold sheets, ribbons and *cloisons* were obtained from ingots by hammering the metal along with regular heating to reduce internal stresses.



Fig. 2 Medallion representing Christ. Musée du Louvre, Paris, inv. no. OA12137. **a** Face. – **b** Reverse. – (Photo C2RMF A. Maigret).



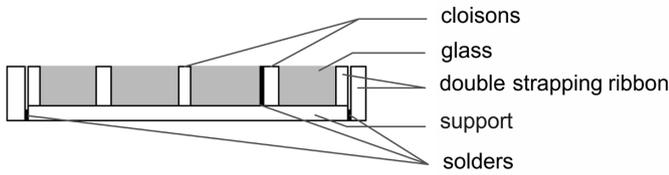
Fig. 3 Medallion representing the bust of Saint Demetrios. Musée du Louvre, Paris, inv. no. OA6457. **a** Face. – **b** Reverse. – (Photo C2RMF D. Bagault).

### Chronological Evolution of the Manufacturing Technique

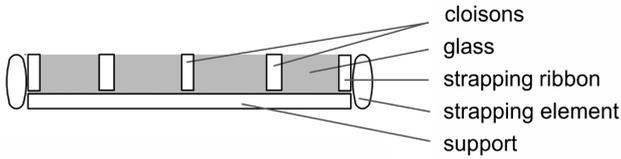
Four periods can be distinguished in the production of *cloisonné* enamel according to David Buckton. The main parameters are the manufacture of the support; the way in which the surfaces are enamelled; and the colours and type of

glass used (opaque or translucent)<sup>7</sup>. Our work confirms the stylistic-technical classification as proposed by Buckton, but enriches it with new data, thanks to more in-depth examinations than those carried out so far. The diagrams below describe in detail the technical structure of each enamel.

<sup>7</sup> Buckton, *Chinese Whisper*. – Buckton, *Enamel on Copper*.



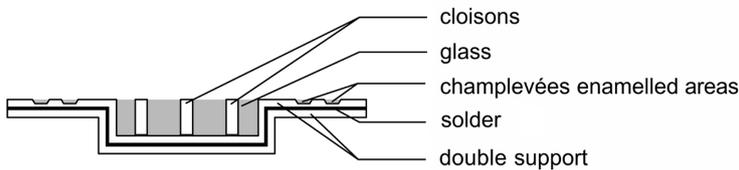
Byzantine *cloisonné* enamels Louvre  
period 2 - OA 6270



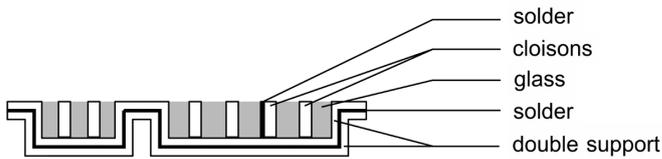
Byzantine *cloisonné* enamels Louvre  
period 2 - OA 11878

**Diagram 1** Drawings of the cross-section of Byzantine *cloisonné* enamels from the Louvre Museum. – (Drawing S. Martinetti).

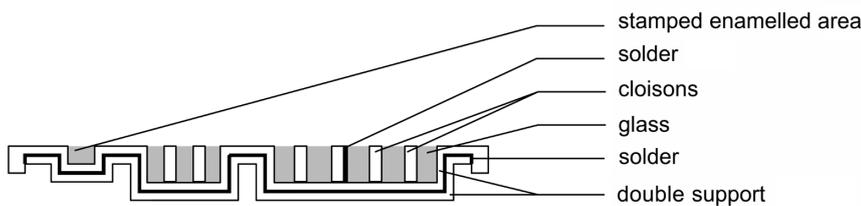
8 The first securely dated object is the so-called Fieschi Morgan Staurotheke in the Metropolitan Museum, New York. Its early ninth-century date was established through the iconography of the Anastasis scene. See, Kartsonis, Anastasis 99. 123.



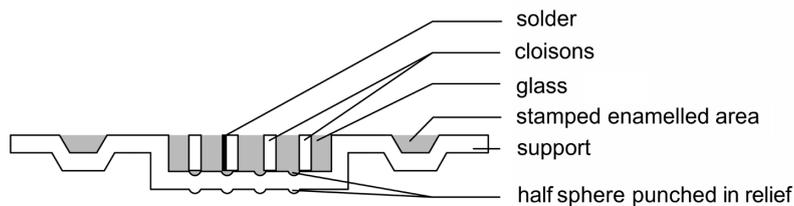
Byzantine *cloisonné* enamels Louvre  
period 3A - OA 12137



Byzantine *cloisonné* enamels Louvre  
period 3A - OA 12139

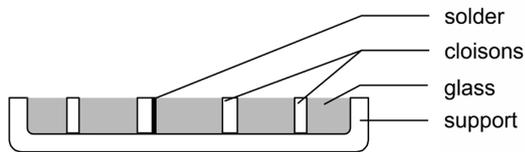


Byzantine *cloisonné* enamels Louvre  
period 3A - OA 12136

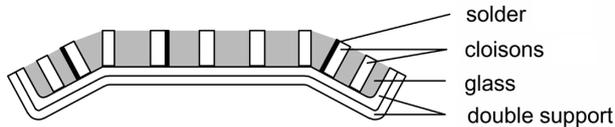


Byzantine *cloisonné* enamels Louvre  
period 3B - OA 12138 and OA 6457

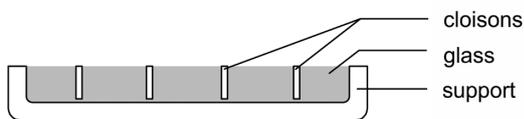
**Diagram 2** Drawings of the cross-section of Byzantine *cloisonné* enamels from the Louvre Museum. – (Drawing S. Martinetti).



Byzantine *cloisonné* enamels Louvre  
period 4 - OA 12140 to 12143



Byzantine *cloisonné* enamels Louvre  
period 4 - OA 12144 to 12147



Byzantine *cloisonné* enamels Louvre  
period 4 - OA 6458

**Diagram 3** Drawings of the cross-section of Byzantine *cloisonné* enamels from the Louvre Museum. – (Drawing S. Martinetti).

Two objects belong to this group (**tab. 1**; OA11878, **figs 1a-b** and OA6270); their dating corresponds well to this period. Their manufacturing technique is very similar, the enamels are placed on a gold sheet of varying thickness and a gold banding ribbon delineates the contours of the medallions. They are circled with a second metal ribbon.

**Period 3 (diagram 2):** From about the middle of the tenth century<sup>9</sup>, the motif that was to be enamelled in *cloisonné* was then placed inside a large cavity, arranged in the support plate, which is obtained by stamping the gold leaf in a recessed shape presumably with small hammers or pre-formed tips. The enamels stand out from a gold background (technique called *Senkschmelz*, «*émail enfoncé*»). The inscriptions are worked into this gold background, formed by the support plate, then enamelled. Enamels are both opaque and translucent.

Five objects belong to this group (**tab. 1**, OA12136, OA12137; **fig. 2a-b**, OA12139, OA12138, OA6457; **fig. 3a-b**) that are dated between the tenth and the beginning of the twelfth century.



**Fig. 4** View of the rim of the enamel of Christ (see **fig. 2a-b**) showing the two overlapping metal sheets welded together with the enamelled sheet being substantially thicker than the other. Paris, Louvre Museum, inv. no. OA12137. – (Photo C2RMF I. Biron).

For the first time, two new technical subgroups for the gold support with a chronological evolution are highlighted by our radiographs (to confirm on more objects):

**Period 3A/double-welded support:** the support of three objects (**tab. 1**, OA12136, OA12137, OA12139) is formed of two sheets of gold superimposed and welded together (**fig. 4**, OA12139). The solder marks are visible in transparency on the X-rays (**fig. 5a**). These enamels date to the tenth and eleventh centuries.

**Period 3B/simple punched support:** the supports of the two medallions are made of a single thick gold sheet (**tab. 1**; **fig. 5b**). On the reverse, a dotted relief pattern draws a figure, which can be totally different (Archangel), or close enough (Saint Demetrios) (**fig. 3a-b**), from that enamelled on the face<sup>10</sup>. These patterns were obtained with a small spherical punch struck on the inside of the cavity before placing the *cloisons*. These enamels are dated a little later than the previous ones, from the eleventh (or the end of this century) to the beginning of the twelfth century.

**Period 4 (diagram 3):** in the twelfth and thirteenth century, the technique of «full enamel» was again employed and co-existed with the previous one, but this time the bottom was enamelled with opaque glasses, as well as inscriptions (often enamelled with white on a blue background). Translucent enamels are a minority.

Eight decorative plates belong to this group (**tab. 1**; **figs 6a-b. 7a**). Their estimated date is in the eleventh-twelfth centuries, but they should rather be dated to the twelfth century, according to the criteria of this period (after Buckton).

These plates have common elements: the gold support – whose thickness varies according to the objects – is curved on the outer edges to create a large cavity. The technique of a double-support sheet, characteristic for period 3A, is found

<sup>9</sup> Not before 920-940, according to Durand, Patène Stoclet.

<sup>10</sup> Such dotted drawings are found on other medallions of this period (figures of Saints and the Virgin, Metropolitan Museum of Art, inv. no. 17. 190. 670-678, see Cat. New York 1997 no. 234.

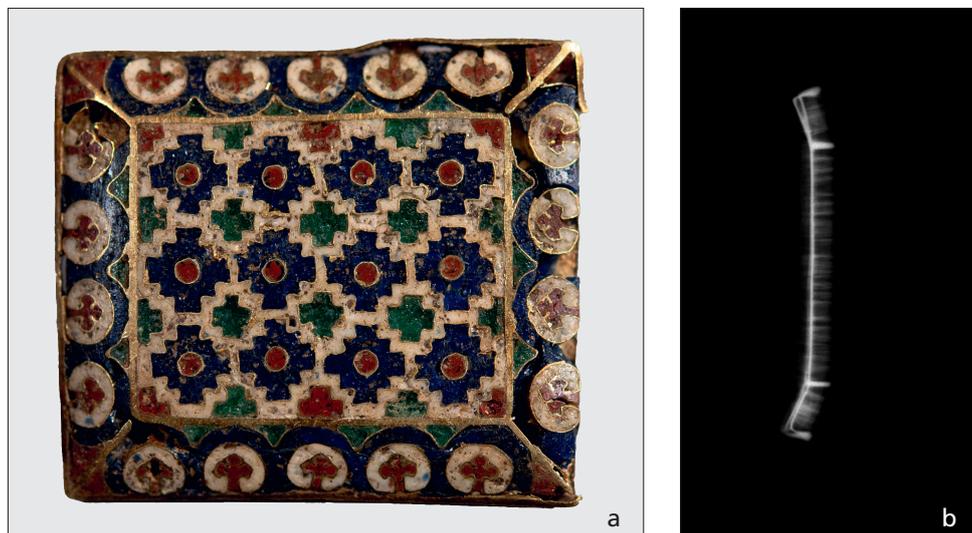


**Fig. 5** X-ray radiographies of Byzantine enamels from the Musée du Louvre, Paris: **a** Christ (inv. no. OA12137) showing the presence of solders between the two support sheets (clear areas of rounded shape distributed heterogeneously over the entire surface). – **b** Saint Demetrios (inv. no. OA6457), showing the absence of solder between the two support sheets; invisible *cloisons* on the surface are visible on the X-ray image immersed mid-height in the glass (halo, cheeks, chin, hair and hands). – (Photos C2RMF T. Borel).



**Fig. 6** **a-b** Two trapezoidal plaques decorated with geometric and floral motifs, Musée du Louvre, Paris, set of four plaques, inv. no. OA12140-12143. – (Photos C2RMF A. Maigret).

**Fig. 7 a-b** Ornamental plate of rectangular shape decorated with geometric and floral motifs. Musée du Louvre, Paris, set of four plaques, inv. no. OA12144-12147. **a** Face. – **b** Profile X-ray radiography showing the presence of two metal sheets for the support. – (Photos C2RMF, a A. Maigret; b T. Borel).



**Fig. 8** Icon cover plate. Musée du Louvre, Paris, inv. no. OA6458. – (Photo C2RMF D. Bagault).



**Fig. 9** Detail of the icon cover plate in **fig. 8**. Musée du Louvre, Paris, inv. no. OA6458. – (Photo C2RMF I. Biron).

in this group in rectangular plates, but without solder welding between them (and probably also for the rectangular ones).

Special case: The enamelled plate that was made for an icon (**fig. 8**, OA 6458) is a special case. It belongs to period 4 by dating, and by the use of a double sheet of gold for the support. The outer sheet was folded along the edges to create a cavity to receive the enamel. However, this plate is distinguished from other objects by some technical criteria and a remarkable quality of execution. This could testify to the ex-

istence of a workshop distinguished by its perfectly executed fine *cloisons*, the use of translucent and opaque glasses in an equivalent proportion, a very rare purple-violet glass, the absence of solder to fix the *cloisons* (**fig. 9**). Moreover, the chemical composition of the glasses used differs from that of the other enamels – only the cobalt sources of the blue glasses are identical to those of most objects of the periods 3 and 4.

### **Cloisons and Solders**

For a single object, *cloisons* of uniform or of varying thickness can be chosen for aesthetic reasons. Two widths of *cloisons* have been observed in the double rosette OA12139 and the eight decorative plates (**figs 6a-b. 7a. 12**, OA12140-OA12143 and OA12144-OA12147). Two main groups of objects appear in the manufacturing of these *cloisons* according to our observations and X-rays radiographies, distributed seemingly randomly within each period (**fig. 10 a-b**). One group is characterised by thin *cloisons* (or parts of which). They are rarely placed rather perpendicularly on their support and can be more or less deformed and even



**Fig. 10 a-b** Details of Saint Demetrios. Musée du Louvre, Paris, inv. no. OA6457. **a** Face. – **b** Clothing showing the different type of *cloisons*, solders, coloured enamels and mixtures of opaque and translucent glass. – (Photos C2RMF I. Biron).



**Fig. 11 a-b** Details of the X-ray radiographies of the two trapezoidal decorative plaques (set of four plaques) showing two manufactures. Musée du Louvre, Paris, inv. no. OA12140-12143). **a** One with thin and distorted *cloisons* (see fig. 6a) and **b** the other with thicker and rigid *cloisons*, well positioned on the edge (see fig. 6b). – (Photos C2RMF a-b T. Borel).

damaged (paten, Christ, Crucifixion, double rosette, some decorative plates of period 4; fig. 11a).

The *cloisons* of the other group are thicker. More resistant, they are held well perpendicular to the support. Their surfaces are smooth, apparently with a more regular thickness (Saint Demetrios (fig. 10b), the Archangel Michael, the winged Archangel, some decorative plates of period 4; fig. 11b).

Byzantine goldsmith enamellers employed metal solders to keep some *cloisons* in place during enamelling (fig. 10b), except for the icon covering plate (figs 8-9).

## Art of Enamelling: The Glass Powders

Pieces of glass are ground in a mortar until the desired particle size is achieved. The powder granulometry varies according to the objects. Powders are then washed (rinsed in water several times) and preserved in water to be protected from dust.

The goldsmith enamellers filled the cavities with humid glass powders of coloured translucent glass, or of a mixture of more or less opaque or even opaque and translucent glasses (figs 9. 10a-b). Each colour is separated by *cloisons*, except for some very rare details (fig. 12). Byzantine enamellers offer an extraordinary palette of colours, with different kinds of blues (lapis lazuli, sky, pale, dark and light, grey-blue opaque, dark), turquoise, yellow, white, red, light and dark green, wine-coloured, colourless, brown-amber, black in appearance, flesh, brown-pink and for the icon cover plate parma-violet (figs 1b. 2a. 3a. 6a-b. 7a. 8-9. 10a-b).

## Firing and Surface Polishing

When powders are dried, the objects are introduced in the furnace to fuse the glass. The filling of the cavities is made as many times as necessary, until to obtain fully filled cavities without depression of glass after successive firings. The thickness of the glass is generally between 1 and 1.5 mm. The enamelling seems complete in most cases. Only Saint Demetrios presents small depressions or gaps of glass on the surface, which testify to an incomplete enamelling (fig. 3a).

Based on our laboratory experiences and on our viscosity calculations from industrial models, the melting temperatures of the translucent lead-free soda-lime silicates used are around 800°C<sup>11</sup>.

The flat surface of the glass attests to a final polishing with abrasive powders, as recommended by Theophilus Presbyter in the twelfth century<sup>12</sup>. Such polishing produce on the surface some gold aggregates, which are more abundant for very thin *cloisons*, but could be also related to the gold composition (pure gold is softer than an alloy – to be checked by analyses) (figs 9. 10a-b. 12).

11 For more details, see Biron et al., *Les émaux 396-400*.

12 Blanc, Théophile 734. – Although traditionally credited to Theophilus Presbyter, the authorship of the *Schedula diversarum artium* is now the subject of scholarly debate; see the volume Speer, *Schedula*.

**Fig. 12** Detail of a trapezoidal plate (see fig. 6) showing two clearly defined thicknesses of the *cloisons*, aggregates of gold on both sides of the *cloisons*, overflow of white glass in the blue and juxtaposition of opaque red and blue glasses without *cloisons* to separate them. Musée du Louvre, Paris, inv. no. OA12140-44. – (Photo C2RMF I. Biron).



### Nature of the Glass

Quantitative chemical analyses of the glass are reported in **table 2**. The first unpublished analysis made by I. Freestone (pers. comm.) on a dozen of Byzantine enamels from the British Museum, dated from the ninth to the twelfth century (mainly eleventh-twelfth) will be compared to our results (**tab. 3**).

### Type of Composition

Byzantine goldsmith enamellers used different types of glass coming probably from different sources of supply. According to our analyses, these enamels are mainly soda-lime silica glasses, whose nature of alkaline sources, depending on the levels of magnesium, potassium and phosphorus, allows us to distinguish five types of composition<sup>13</sup> (1 to 5), within which several sub-groups can be identified (**tab. 3**). Each object is enamelled with various compositions, except Saint Demetrios using only glass of composition 3.

**Composition 1 / natron (or Roman type):** The different range of aluminium, calcium and titanium suggest various silica sources and probably various primary glass productions.

**Composition 3 / plant ash type:** The levels of sodium, potassium, magnesium and calcium are highly variable depending on the glass. This can be explained by the chemistry of plant ash glass, which is more complex than natron glass. Indeed, the chemical composition of the plants vary according to the type of plant, their geographic origin, the time of col-

lection and the method of preparation<sup>14</sup>. Moreover, calcium can be introduced as part of the plant ash, but also as part of the silica source (if sand). The various amounts of aluminium and titanium suggest different silica sources.

**Special soda-lime silica glass not belonging to any family of well-known compositions:**

**Composition 2A**, may be of plant ash type, whose nature is different compared to the glass of composition 3 because of their lower levels of magnesium. They could also be of natron type, with an addition of potash (plant ash, glass or cullet), but the magnesium contents observed remain low. Very similar compositions are observed on glasses of the Carolingian enamel of Saint-Denis and on some *cloisonné* enamels around the year 1000<sup>15</sup>.

**Composition 2B** may be of natron type, because of their low levels of magnesium and potassium, but could be different with higher levels of phosphorus. The addition of phosphorus as bone ash to opacify the glass cannot be certified through the chemical composition, but is possible as a partial re-use of glass. Such opacification practice has already been demonstrated in glass tesserae of Byzantine mosaics, dated from the fifth to the beginning of the eighth century<sup>16</sup>. Similar compositions are observed in some glass of *cloisonné* enamels around the year 1000 and *plique* enamels around 1400<sup>17</sup>. Silica sources appear more homogeneous than for the other compositions.

**Two compositions rich in lead for the icon cover plate (OA6458):**

**Composition 4** is a mixed alkali silicate (plant ash) containing lead. The base glass contains about 12 % of sodium,

13 Identified through the composition of the base glass containing only silica and alkali sources and then normalized to 100%.

14 Jackson et al., Glass; Barkoudah/Henderson, Plant Ashes 22-54; Henderson, Ancient Glass 22-54.

15 Biron et al., Les émaux 117-123. 125-138.

16 Marii/Rehren, Coloured Glass Cakes. – Verità, Glass Mosaic. – Silvestri et al., Palaeo-Christian. – C2RMF analyses unpublished.

17 Biron et al., Les émaux 125-138. 159-175.

Byzantine enamels Louvre Museum Objects and Inv. Nrs.	Analyses CZRMF Colours	TP	TC	Na <sub>2</sub> O	MgO	Al <sub>2</sub> O <sub>3</sub>	SiO <sub>2</sub>	P <sub>2</sub> O <sub>5</sub>	SO <sub>3</sub>	Cl	K <sub>2</sub> O	CaO	TiO <sub>2</sub>	Cr <sub>2</sub> O <sub>3</sub>	MnO	FeO	CoO	NiO	CuO	ZnO	As <sub>2</sub> O <sub>3</sub>	SrO	ZrO <sub>2</sub>	Nb <sub>2</sub> O <sub>5</sub>	Ag <sub>2</sub> O	SnO <sub>2</sub>	Sb <sub>2</sub> O <sub>3</sub>	BaO	Au	PbO	Bi <sub>2</sub> O <sub>3</sub>	
Archangel Saint Michael (OA12138)	dark blue opaque	P3	1	13.55	1.08	3.73	59.08	0.26	0.63	0.79	1.10	7.74	0.2625	0.0261	0.46	3.04	0.6842	0.0059	0.5363	0.0563	0.3860	0.0603	0.0060	0.0104	0.1284	0.1060	4.0879	0.0166		1.90		
Archangel Saint Michael (OA12138)	yellow opaque	P3	1	8.11	0.60	5.83	58.95	0.27	0.62	1.06	1.30	6.00	0.3580	0.0190	0.26	1.52	0.0366	0.0016	0.4566	0.0553		0.0532	0.0261	0.0032	0.1254	0.2635	1.3646	0.0233		12.26	0.0407	
Crucifixion (OA12136)	opaque white	P3	1	14.72	0.97	4.08	49.33	0.36	0.72	0.84	1.30	7.82	0.1369	0.20	0.96	0.0484	0.0043	0.0043	0.3058	0.0392	0.0008	0.0564	0.0146	0.0047	0.0319	4.0833	3.7646	0.0412		9.94	0.0351	
Double rosette plaque (OA12139)	translucent green	P3	1	14.96	1.09	3.22	66.80	0.26	0.17	1.11	0.83	6.18	0.0842	0.0025	0.10	0.78	0.0082		3.9628	0.0122	0.0349	0.0348	0.0054	0.0088	0.0122	0.0204	0.0232	0.0132		0.15		
Double rosette plaque (OA12139)	opaque white	P3	1	13.22	0.67	3.28	64.09	0.03	0.51	0.53	0.72	8.01	0.1174	0.0130	0.22	0.48	0.0033	0.0010	0.1156	0.0088		0.0527	0.0049	0.0012	0.1083	0.0146	7.3179	0.1046		0.30	0.0050	
Trapezoidal plate (OA12140-12143)	dark blue opaque	P4	1	13.55	1.19	3.14	63.20	0.10	0.37	0.66	0.89	7.38	0.1181	0.0258	0.44	1.69	0.6047	0.0050	0.3021	0.0132	0.3482	0.0552	0.0049	0.0075	0.0444	0.1461	4.0385	0.0340		1.48		
Trapezoidal plate (OA12140-12143)	opaque light green	P4	1	13.63	0.64	3.21	57.19	0.04	0.08	1.00	0.88	8.08	0.0981	0.0077	0.22	0.51	0.0053		1.1617	0.0100	0.0120	0.0596	0.0206		0.0259	1.2261	0.0116	0.0191		11.65	0.0355	
Rectangular plate (OA12144-12147)	dark blue opaque	P4	1	13.41	0.79	3.43	61.82	0.13	0.34	0.67	0.82	7.25	0.1153	0.0177	0.39	2.52	0.9828	0.0239	0.8732	0.0603	0.0044	0.0525	0.0075		0.0350	0.0325	4.5992	0.0546		1.41	0.0100	
Rectangular plate (OA12144-12147)	translucent green	P4	1	14.62	1.05	2.71	67.82	0.15	0.12	1.12	0.83	5.89	0.0753	0.0056	0.11	0.69	0.0081	0.0007	4.3091	0.0142	0.0377	0.0344	0.0057	0.0098	0.0339	0.0220	0.0255	0.0683		0.12		
Rectangular plate (OA12144-12147)	opaque white	P4	1	10.83	1.21	2.23	48.42	0.18		0.66	1.03	5.43	0.0773		0.08	0.54	0.0068	0.0020	0.1296	0.0136	0.0099	0.0360	0.0191		0.0455	12.1446	1.9334	0.0153		14.64	0.0267	
Paten *(OA11878)	translucent dark green	P2	1	2.92*	1.24	3.91	66.24			1.03	1.57	7.81	0.1620		0.76	1.47	0.0660	0.0151	7.5900	0.4870							0.4139	0.8090	0.0570	3.00	0.98	
Archangel* (OA6270)	translucent dark green	P2	1	15.28*	0.88	4.60	60.09		0.07	0.71	1.44	5.93	0.2647		0.11	1.57	0.0200	0.0100	5.1350	0.0587						0.1500	0.0450	0.0450	0.0591	1.39	0.90	
Blessing Christ (OA12137)	translucent look- ing black	P3	2A	12.25	1.11	3.17	55.87	2.00	0.37	0.98	1.39	6.88	0.1394	0.0062	0.45	7.55	1.4734	0.0265	2.2767	2.1859	0.0393	0.0489	0.0109	0.0010	0.0772	0.0534	0.0637	0.0331		1.37	0.0037	
Blessing Christ (OA12137)	opaque red	P3	2A	11.46	0.89	2.38	53.98	1.73	0.46	0.92	2.19	9.99	0.1977	0.0104	1.43	10.22	0.0622		2.3607	0.0555	0.0118	0.0921	0.0143	0.0038	0.1190	0.0680	0.0413		1.14	0.0137		
Crucifixion (OA12136)	translucent green	P3	2A	16.33	0.98	4.85	59.01	0.68	0.38	0.93	1.49	7.67	0.1509	0.0155	0.38	1.05	0.0126	0.0030	4.7948	0.0770	0.0098	0.0425	0.0111	0.0068	0.0655	0.0232	0.0592	0.0436		0.79	0.0186	
Crucifixion (OA12136)	translucent red violet	P3	2A	7.18	0.37	5.75	73.12	0.46	0.33	1.12	2.78	4.87	0.1741	0.0171	2.03	0.91	0.0059	0.0020	0.2631	0.0273		0.0327	0.0158		0.0890	0.0190	0.0106	0.1613		0.13		
Paten* (OA11878)	dark blue	P2	2A	15.37*	0.69	2.26	58.11		0.39	1.10	1.63	5.42	0.1020		0.03	3.49	0.9000	0.0604	0.8550	0.0441					0.1300	0.0650	4.0300	0.0122	0.66	3.85		
Paten* (OA11878)	wine colour	P2	2A	9.9*	0.67	1.99	73.87		0.10	0.96	2.61	5.51	0.0948		1.44	0.63	0.0100		0.2550	0.0117					0.2450	0.0300	0.0100	0.0171	1.52	0.06		
Blessing Christ (OA12137)	opaque white	P3	2B	11.90	1.16	3.09	52.32	0.75	0.50	0.92	1.15	7.98	0.1565	0.0155	0.10	1.10	0.0073	0.0037	0.4067	0.0308	0.0083	0.0563	0.0146	0.0020	0.0570	4.7992	5.1507			8.05	0.0307	
Blessing Christ (OA12137)	opaque dark blue	P3	2B	13.06	0.74	3.01	61.13	0.44	0.55	0.94	1.03	8.56	0.1212	0.0300	0.64	2.31	0.4517	0.0130	0.7355	0.2864	0.0198	0.0668	0.0081	0.0008	0.0507	0.0998	4.1699	0.0176		1.46	0.0017	
Blessing Christ(OA12137)	opaque flesh	P3	2B	13.99	0.77	3.60	65.54	1.29	0.29	1.05	0.96	7.05	0.2154	0.0159	0.06	1.41	0.0014		0.4347	0.0061	0.0114	0.0467	0.0283	0.0013	0.0583	0.0391	1.9658			1.10		
Double rosette plaque (OA12139)	opaque dark blue	P3	2B	13.63	0.82	3.62	59.67	0.54	0.39	0.66	0.77	7.55	0.1272	0.0225	0.40	2.60	0.9650	0.0208	1.1369	0.0669	0.0088	0.0590	0.0082	0.0023	0.0490	0.0373	5.0663	0.0410		1.63	0.0157	
Double rosette plaque (OA12139)	opaque red	P3	2B	13.00	1.17	2.95	51.98	2.85	0.18	0.95	1.20	8.17	0.1825	0.0100	0.59	7.02	0.0539		6.6967	0.0483	0.0363	0.0558	0.0130	0.0069	0.1933	0.0669	0.0814	0.0947		1.96	0.0101	

Byzantine enamels Louvre Museum Objects and Inv. Nrs.	Analyses C2RMF	TP	TC	Na <sub>2</sub> O	MgO	Al <sub>2</sub> O <sub>3</sub>	SiO <sub>2</sub>	P <sub>2</sub> O <sub>5</sub>	SO <sub>3</sub>	Cl	K <sub>2</sub> O	CaO	TiO <sub>2</sub>	C <sub>2</sub> O <sub>3</sub>	MnO	FeO	CoO	NiO	CuO	ZnO	As <sub>2</sub> O <sub>3</sub>	SrO	ZrO <sub>2</sub>	Nb <sub>2</sub> O <sub>5</sub>	Ag <sub>2</sub> O	SnO <sub>2</sub>	Sb <sub>2</sub> O <sub>3</sub>	BaO	Au	PbO	Bi <sub>2</sub> O <sub>3</sub>
Archangel Saint Michael (OA12138)	opaque light green	P3	2B alter.	4.99	0.65	4.30	64.95	0.51	0.42	1.53	0.66	8.65	0.4413	0.0158	0.04	1.84	0.0243		4.3913	0.1641	0.0856	0.0480	0.0132	0.0051	0.1485	0.3987	3.2493	0.0483		2.21	0.0024
Crucifixion (OA12136)	opaque dark blue	P3	2B	15.89	0.87	4.07	53.95	0.65	0.58	0.66	1.05	7.59	0.1311	0.0130	0.57	2.68	0.8358	0.0219	1.0963	0.1500		0.0584	0.0086	0.0014	0.0364	1.0961	4.7233	0.0318		3.06	0.0209
Crucifixion (OA12136)	opaque red	P3	2B	15.73	1.12	3.60	57.69	1.27	0.31	0.89	1.37	7.71	0.1299	0.0046	0.53	4.82	0.0336		3.2762	0.0446	0.0510	0.0389	0.0110	0.0046	0.0702	0.0287	0.0296	0.0354		0.99	0.0044
Crucifixion (OA12136)	opaque flesh	P3	2B	18.27	1.11	3.30	63.97	0.48	0.53	1.04	0.95	7.06	0.1131	0.0013	0.07	0.82	0.0042	0.0011	0.1863	0.0398	0.0093	0.0769	0.0092	0.0011	0.0247	0.0088	1.7650	0.0103		0.10	
Archangel Saint Michael (OA12138)	opaque flesh	P3	3	10.86	2.16	3.53	62.23	0.72	0.69	0.69	1.79	10.50	0.9712	0.0132	0.93	1.06	0.0526	0.0010	0.3661	0.03417	0.0023	0.0861	0.0285	0.0025	0.2972	0.3749	1.4080	0.0989		0.45	0.0025
Archangel Saint Michael (OA12138)	dark brown	P3	3	10.47	1.88	3.32	58.21	1.50	0.84	1.02	3.71	11.45	0.3060	0.0255	3.14	1.35	0.1257	0.0059	0.8426	0.0706	0.0010	0.1988	0.0128	0.0037	0.1148	0.5331	0.0316	0.0830		0.48	
Saint Demetrius* (OA6457)	translucent/ opaque dark blue	P3	3	4.45*	4.43	3.39	61.73		0.00	0.75	2.59	9.56	0.1584		0.72	6.16	0.0298	0.0172	3.6794	0.0246					0.7806	0.3146			5.13	0.82	
Saint Demetrius* (OA6457)	opaque clear blue	P3	3	3.13*	2.94	3.31	65.78	0.48	0.71	0.65	1.68	7.05	0.1361		0.58	5.35	0.6487		0.2433						0.3133	1.0136	3.4147		0.71	1.05	
Saint Demetrius* (OA6457)	opaque black	P3	3	12.54*	5.38	4.10	64.39	0.78	1.09	0.67	1.95	7.35	0.1623		0.00	0.00		0.0295		0.0238								0.0971			
Saint Demetrius* (OA6457)	looking black	P3	3	11.32*	6.11	3.24	61.29	0.69	0.92	0.79	2.49	7.81	0.0882		2.91	1.00	0.0100		0.0900	0.0189					0.0200		0.0100	0.3607	0.02	0.16	
Archangel Saint Michael (OA12138)	opaque red	P3	3	15.13	2.63	7.83	56.27	0.48	0.37	1.31	2.44	5.32	0.4145	0.0129	0.40	4.64	0.0347	0.0024	1.9391	0.0494		0.0429	0.0191	0.0034	0.1401	0.0234	0.0211	0.0839		0.19	0.0219
Trapezoidal plate (OA12140-12143)	opaque red	P4	3	16.00	1.94	5.73	49.00	2.96	0.15	1.29	2.56	6.99	0.5992	0.0200	0.51	6.70	0.0450		2.8825	0.0483	0.0096	0.0617	0.0275	0.0048	0.1687	0.1500	0.0573	0.0735		1.74	0.0217
Decorative plates* (OA6458)	dark blue opaque	P4	3?	13.79	1.44	2.45	59.11		0.32	0.78	1.57	7.19	0.1454		0.68	1.59	0.5950	0.0191	0.2300	0.0462					0.0700	1.4150	2.2800	0.0343	0.49	5.42	
Trapezoidal plate (OA12140-12143)	opaque white	P4	3	10.21	1.78	1.92	46.91	0.49	0.00	0.73	1.37	5.59	0.0872	0.0052	0.46	0.73	0.0111	0.0019	0.3928	0.0179		0.0373	0.0207	0.0014	0.0475	8.7136	0.4683	0.0637		19.60	0.0541
Rectangular plate (OA12144-12147)	opaque red	P4	3	13.40	1.63	3.84	61.59	0.41	0.09	0.91	1.26	5.75	0.1237	0.0116	0.54	5.14	0.0393		4.4578	0.0217	0.0088	0.0468	0.0096	0.0053	0.0615	0.0501	0.0539	0.0377		0.44	0.0019
Archangel Saint Mi- chael (OA12138)	opaque white	P3	3	8.16	1.10	5.26	44.27	0.55	0.06	0.66	2.04	4.92	0.2412	0.0102	0.54	1.16	0.0169	0.0050	1.1195	0.0684		0.0408	0.0264		0.0955	8.0240	0.2129	0.0284		21.01	0.0767
Decorative plates* (OA6458)	translucent green	P4	4	0.82	1.16	0.83	44.36			1.55	3.34	1.39	0.0521		0.06	0.22	0.0100	0.0108	0.5850						0.1400	0.3800	0.0800	0.1046	1.69	43.42	
Decorative plates* (OA6458)	opaque violet- parma	P4	5	8.82	1.70	1.69	47.92		0.29	0.68	5.86	4.02	0.1741		2.91	1.42	0.0200	0.0274	0.3900						0.0600	3.4100	0.1200	0.7535	0.47	20.21	

**Tab. 2** Ion beam chemical analyses of the Byzantine enamels from the Musée du Louvre made in the C2RMF laboratory; each composition is the average of at least three analyses in different areas of the surface (in wt% oxides). Results are classified by technological group or period of manufacturing (TP, technological periods P2 to P4), and by type of composition (TC, 1 to 5). The sodium values are obtained by PIXE (for analysis with\* treatment of the data only with low energy spectra instead of both low and high energy ones).

Byzantine Enamels Louvre	Composition 1	Composition 2A	Composition 2B	Composition 3	Composition 4	Composition 5
Type of glass	soda-lime silica	soda-lime silica	soda-lime silica	soda-lime silica	mixed alkali silica with lead	potassic glass with lead
Sodium source	mineral – natron	plant ash?	mineral – natron?	plant ash	plant ash?	potassic glass with lead
Amounts of some chemical elements	MgO, K <sub>2</sub> O < 1.5, P < 0.30 %	MgO < 1.5, K <sub>2</sub> O > 1.5, P > 0.3 %	MgO, K <sub>2</sub> O < 1.5 %, P > 0.3 %	MgO, K <sub>2</sub> O > 1.5, P > 0.30 %  various type, origin, preparation of plants Ca (4.92-11,45 %)	MgO < 1.5, K <sub>2</sub> O > 1.5 PbO 20-40 %, SiO <sub>2</sub> 40-50 %	MgO, K <sub>2</sub> O > 1.5  PbO 20-40 %, SiO <sub>2</sub> 40-50 %  very low in Na
Silica source	different sources various levels of Al (1.35-5.83 %), Ca (4.89-7.82 %), Ti (0.03-0.36 %)	different sources various levels of Al (1.99-5.75 %), Ca (4.87-9.99 %), Ti (0.09-0.20 %)	more close sources Al (2.95-4.30 %), Ca (7.05-8.65 %), Ti (0.11-0.44 %)	different sources various levels of Al (1.92-7.83 %), Ca (4.92-11.45 %), Ti (0.09-0.97 %)		
Objects	all except OA6458	all except OA6458	all except OA6458	all except OA6458  St Demetrios higher levels of Mg (2.94-6.11 %)	only plaque OA6458	only plaque OA6458
Colours	all	all	all	all	parma violet	green
Technol. Periods	P2, P3, P4	P2, P3	P3	P3, P4	P4	P4
Number of glass C2RMF (total 42)	13	6	9	12	1	1
Number of glass C2RMF and BM (total 65)	33			15		

**Tab. 3** Types of chemical composition obtained by ion beam analysis made in the C2RMF laboratory on the Byzantine enamels from the Louvre Museum depending on their alkali sources. The number of glass samples analyzed at the British Museum (BM) by I. Freestone is added for comparison (C2RMF Centre de Recherche et de Restauration des Musées de France).

8 % of potassium, 2 % of magnesium, 5.6 % of calcium and 2 % of aluminium, to which was added 20 % of lead.

**Composition 5** is a potash-lime glass with lead. The base glass contains about 1.5 % of sodium, 6.3 % of potassium, 2 % of magnesium, 2.6 % of calcium, 1.5 % of aluminium, to which was added more than 40 % of lead.

- for opaque reds: copper, associated with iron
- for pink (flesh): a mixture of red glass, probably translucent, and opaque white, as shown by the iron and copper contents; the Archangel Michael also contains manganese (wine-coloured originally)
- for blue: cobalt, associated with copper and contain various levels of iron.

## Colourants

Whatever the period concerned, the colourants or metal oxides added to the glass to colour it are according to our analyses:

- for glass appearing black: either a high concentration of cobalt, iron, copper and zinc (producing a very dark blue), or a high level of manganese (wine colour)
- for brown: manganese associated with iron
- for wine colour: manganese and some iron
- for greens: copper

## Copper Sources for Green Glasses

Various sources of copper have been used in each period. According to the nomenclature of Bourgarit and Thomas<sup>18</sup> (2012), it can be observed that almost pure copper (97-99 %) was used to colour the green glasses of nearly half of the objects and copper, brass or bronze for the others.

<sup>18</sup> Bourgarit/Thomas, Late Medieval Copper.

## Cobalt Sources for Blue Glasses

Various sources of cobalt or ore extracted from different areas within those deposits were used, as were different purification processes. The cobalt used for the majority of the objects studied is correlated with copper at different levels. Except for the cobalt ore of Saint Demetrios, which appears very pure, the others contain impurities, such as nickel (Ni), zinc (Zn) and arsenic (As) which could be associated with cobalt: Co-Cu-Ni high Zn (OA11878, 6457), Co-Cu-Ni low Zn (OA12136, 12139, 12144-12147, 6458 and OA12137 different for the Zn values), Co-Cu-Ni low Zn-As (OA12138, 12140-12143). The ore used for the majority of these Byzantine enamels could be of Oriental origin with the presence of zinc and nickel, which – associated with cobalt – have already been identified in Egyptian glasses<sup>19</sup>.

## Opacifiers – Colourants

Small crystals render the glass opaque by a refractive index different from that of the vitreous matrix in which they are distributed. They can be added in the raw materials or in the batch, as crystals synthesized independently or as a very opaque glass, or even their precipitation can also be induced *in situ*. It is the case of the red Byzantine enamels, which are usually coloured and opacified with small particles of copper (in metallic or oxide form), whose precipitation is induced during the glass making from the raw materials.

Our results show that goldsmith enamellers used mixtures of opaque glasses in the same colour, which Freestone's work has already shown, but on a smaller scale. According to our analyses, two, and perhaps three kinds of opacifiers are used for opaque blue, white, pink or flesh, green and yellow enamels:

- either antimonates or tin compounds like stannates independently in the same glass
- either a mixture of antimonates and stannates in the same glass<sup>20</sup>
- the presence of small amounts of calcium phosphate could be also possible in some cases in addition to the previous opacifiers(?).

Antimony-compounds are still predominant within each composition, while tin compounds are a minority. Half of the opaque glass are opacified by antimony or tin compounds alone and the other half with a mixture.

Opacifying crystals are also involved in the colouring of opaque enamels by their own colour. For example, the white

crystals of calcium antimonate and/or tin oxide act as the main colourant for white glasses, or they lighten the colour of blue glasses produced by cobalt, forming a rich palette of hues, from the darkest to the lightest. The yellow crystals of lead antimonate and lead stannate colour yellow glasses and help to expand the colour palette of green glasses, which are coloured with copper.

## Discussion and Conclusion

### Type of Production

Despite the limited number of objects studied, all our results suggest a practice of Byzantine enamelling in small independent workshops, rather than in large organised and controlled structures, evidenced by the diversity of technical and analytical criteria presented on each object (whatever the periods of manufacturing – different compositions, sources of cobalt, of copper and technical criteria were used). For instance, Saint Demetrios is different from the others with the choice of only one type of glass composition and a very pure cobalt source. The icon cover plate, also different from the others (by *cloisons* and colour), could have a different origin than a Byzantine one because of the lead glasses used.

However, these workshops had to be close to each other, probably united by teaching and exchanges, given the relative technical homogeneity prevailing within each period described above.

### Carolingian Influences

*Cloisonné* enamels on gold originated in Carolingian Europe and not – as was long believed – in early or Iconoclastic Byzantium<sup>21</sup>. This technique was indeed mastered by Carolingian goldsmith enamellers at the end of the eighth century<sup>22</sup>. According to our study of the enamel fragment of Saint-Denis (ninth to beginning of the tenth century)<sup>23</sup> and the photographic documents available<sup>24</sup>, the technique of Carolingian *cloisonné* enamel on gold and the glass compositions used correspond well to those of the Byzantine enamels of period 2 (middle of the ninth to the middle tenth century) – the period during which Western *cloisonné* enamels were introduced to Byzantium. Nevertheless, the particle size of glass powders and the way how to deposit the powders in the cells are specific to each production<sup>25</sup>. Moreover, Byzantine enamels offer an extraordinary palette of colours, undoubtedly the richest, among all the medieval enamel productions studied<sup>26</sup>.

19 Kaczmarczyk, Source of Cobalt. – Lilyquist et al., Glass.

20 Attested by Ian Freestone's scanning electron microscope observations on enamel samples.

21 Buckton, Byzantine Enamel. – Bacchi, Byzantium. – Brubaker, Elephant.

22 Durand, L'art byzantin. – Durand, Smalto.

23 Biron et al., Les émaux 117-123.

24 Capponi, L'Altare d'Oro.

25 Biron et al., Les émaux 117-123. 139-158.

26 Biron et al., Les émaux Part. II.

## Byzantine Enamels and Glasses

Byzantine goldsmith enamellers working in Constantinople at the end of the ninth to the twelfth century used glasses of compositions 1 and 3, which are not specific to the art of enamelling. While Byzantine glass analyses are still limited in number and mainly concern mosaics and objects dated from the fourth to the beginning of the eighth century, soda-lime silica glass of natron type is strongly represented with differences within this family<sup>27</sup>. Similarly, some analyses of Greek, Byzantine and Italian mosaics, dating from the tenth, eleventh and thirteenth centuries, show the use of soda-lime silicates of plant ash type. The opacifiers employed are, as in our enamels, tin oxides and mixtures of tin and antimony oxides, but also quartz grains (sites of Hosios Loukas, Daphni, Torcello, Monreale etc.)<sup>28</sup>.

## Glass Compositions and Dates

From the ninth to the twelfth centuries, composition 1 appears to be predominant, whereas composition 3 remains relatively stable as a function of time, representing 22 % to 25 % of the analyses (including Freestone's results). Compositions 2A and B are observed only during the periods 2 and 3, and composition 4 and 5 only for the period 4 (tab. 3).

Natron glass is widely employed in the Mediterranean since the middle of the first millennium BC until the ninth century AD. Byzantine enamels illustrate the remarkable change which occurred in glass technology at the beginning of the ninth century (or a little earlier) in the Near East. Plant

ash was reintroduced as a sodium source and gradually replaced natron, which continued to be used in the Levantine workshops until the end of the eleventh century, in Italy until the twelfth century<sup>29</sup> and in Europe for medieval enamels until the beginning of the thirteenth century<sup>30</sup>.

## Origin of the Natron Glass

The differences observed for the cobalt levels, cobalt sources, fashions of making opacifiers, the natron glass opacified with (or mainly with) tin and plant ash ones opacified with antimony (or mainly with) clearly demonstrate that natron glass of our Byzantine enamels are not a re-use of Roman glass tesserae<sup>31</sup>. However, the origin of this glass remains unknown.

The natron glass compositions do not match very well with the other kind of natron glass already identified – the mixture of glass powders makes probably the comparison difficult. The majority of these glasses are close to the Levantine II glass<sup>32</sup> type by their levels of calcium and aluminium, but not for the other elements.

Three glasses contain high levels of aluminium (5-7 %) compared to the others (3-4 % and one very low with 1.16 %) – OA12138, OA12136 and OA6270. They could be close to the Late Byzantine high alumina glass type containing elevated concentrations of boron and lithium identified on the eighth to fourteenth century glasses from Pergamon (Turkey)<sup>33</sup>. These glasses could have used probably a mineral soda-rich efflorescence. However, ion beam analyses are not precise enough for the trace elements to compare with LA-ICP-MS analyses already published.

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## Summary / Zusammenfassung / Résumé

### Laboratory Study of Byzantine Enamels from the Louvre Museum: Techniques of Manufacturing and Materials

A group of Byzantine *cloisonné* enamels from the Louvre Museum was studied at the Centre de recherche et de restauration des musées de France (C2RMF) using various methods of chemical material analysis and technical observations. The aim was to understand the techniques used to manufacture these enamels (vitreous materials and gold supports) and the nature of the glass used. The results showed a chronological evolution in the manufacture of these enamels, with four technological periods that had already been described before. These were characterised by the structure of the support, the way in which the enamel was applied, their colours and their degree of transparency. However, in-depth study of these objects has revealed two new chronological sub-groups, distinguished by the gold support, which were previously unknown.

These enamels display a very wide range of colours, shades and degrees of transparency. Chemical analyses revealed the use of different types of glass, mainly soda-lime silica with varying soda sources, and two glasses containing lead (potassium-lime and mixed alkali glass). Several compositions are generally used simultaneously on the same object. Opaque enamels are opacified by antimony or tin compounds, or by a mixture of both, sometimes with low levels of calcium phosphate. As well-dated Byzantine enamels are rare, the present research enriches our knowledge of the technological skills and glassmaking practices that characterised the art of enamelling in early medieval Byzantium.

### Laboruntersuchung byzantinischen Emails im Musée du Louvre: Herstellungstechniken und Materialien

Eine Gruppe von byzantinischen Cloisonné-Emails aus der Sammlung des Musée du Louvre wurde am Centre de recherche et de restauration des musées de France (C2RMF) mit verschiedenen chemischen Analysemethoden untersucht und die Techniken erforscht. Ziel war es, die Herstellungstechniken dieser Emails (Glasmassen und Goldträger) sowie die Art des verwendeten Glases zu verstehen. Die Ergebnisse zeigten die bereits bekannte chronologische Entwicklung bei der Herstellung dieser Emails mit vier technologischen Perioden. Sie unterscheiden sich durch den Aufbau des Trägers, die Art des Emailauftrags, ihre Farben und den Grad der Opazität und Transparenz. Die eingehende Untersuchung dieser Objekte ließ jedoch zwei neue chronologische Untergruppen erkennen, die sich durch die Struktur des Goldträgers unterscheiden und bis dahin unbekannt waren.

Die Emails weisen eine sehr große Bandbreite an Farbtönen, Schattierungen und Transparenzgraden auf. Die chemischen Analysen ergaben die Verwendung verschiedener Glastypen, vorwiegend Kalknatron-Silikatglas, wobei die Art der Natriumquellen variiert. Darüber hinaus konnten zwei bleihaltige Glastypen nachgewiesen werden: ein kaliumkalziumhaltiges sowie ein gemischtalkalisches Glas. Dabei werden meist mehrere dieser Typen gleichzeitig auf einem Objekt verwendet. Opake Emails werden durch Verbindungen auf Antimon- oder Zinnbasis oder durch eine Mischung dieser Verbindungen getrübt, wobei in Einzelfällen auch geringe Gehalte an Kalziumphosphat möglich sind. Da gut datierte byzantinische Emails selten sind, erweitert die vorliegende Studie unser Wissen über die technologischen Fertigkeiten und die Glasherstellung, die die frühmittelalterliche Emailkunst in Byzanz kennzeichneten.

### Étude en laboratoire des émaux byzantins du musée du Louvre: Techniques de fabrication et matériaux

Un ensemble d'émaux cloisonnés byzantins du musée du Louvre a été étudié au Centre de recherche et de restauration des musées de France (C2RMF) à l'aide de diverses méthodes d'analyses chimiques des matériaux et d'études techniques. L'objectif était de comprendre les techniques de fabrication de ces émaux (verres et supports en or) et la nature des verres employés. Les résultats ont montré une évolution chronologique dans la fabrication de ces émaux avec quatre périodes technologiques, déjà observées. Elles se distinguent par la structure du support, la façon d'appliquer les émaux, leurs couleurs et leur degré d'opacité et de transparence. Cependant, l'étude approfondie de ces objets a révélé deux nouveaux sous-groupes chronologiques distincts par le support en or, inconnus jusqu'alors.

Ces émaux présentent une très large gamme de couleurs, de nuances et de degrés d'opacité et de transparence. Les analyses chimiques ont révélé l'utilisation de différents types de verres majoritairement des silicates sodo-calciques, dont la nature des sources sodiques varie et deux verres contenant du plomb (potasso-calcique et alcalin mixte). Plusieurs compositions étaient généralement utilisées simultanément sur un même objet. Les émaux opaques sont opacifiés par des composés à base d'antimoine ou d'étain, ou bien par un mélange de ces composés, avec parfois de faibles teneurs en phosphate de calcium. Comme les émaux byzantins bien datés sont rares, les présentes recherches enrichissent notre connaissance des compétences technologiques et des pratiques verrières qui caractérisaient l'art de l'émaillerie du début du Moyen Âge à Byzance.