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Investigating the construction methods of an *opus vermiculatum* mosaic panel

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Summary From the third century BC to the second century AD small detailed central panels (*emblemata*) made using the *opus vermiculatum* technique were used as focal points in larger mosaic pavements. They were custom made in stone or terracotta trays to facilitate their transport and placement. Although mosaic panels in *opus vermiculatum* have been discovered throughout the Hellenistic and Roman Mediterranean, the location of the workshops specializing in the production of these finely worked panels is still unclear. Their association with named artists, for example Dioskourides of Samos, and the location of finds (such as the fragment of the floor by Hephaistion at Pergamon) point to workshops in the eastern Mediterranean.

A large unidentified fragment of an *emblema*, still in its terracotta tray, from the collections of the Department of Greece and Rome in the British Museum was the subject of analytical examination. These investigations of the tesserae (glass cubes), traces of pigments and mortar aimed to determine the raw materials and manufacturing processes for the mosaic and to characterize the nature of the application of paint to the mortar. Egyptian blue pigment and traces of hematite and carbon suggest that a fully coloured drawing was executed on the fresh mortar to guide the positioning of the tesserae. In addition, samples from the terracotta tray were taken in an attempt to identify its provenance. This contribution describes how the results of these investigations have been used to provide a deeper understanding of *opus vermiculatum* construction methods.

INTRODUCTION

Emblemata are detailed centrepieces of mosaic floors that were prefabricated in specialized workshops in terracotta or stone trays and subsequently exported so that they could be set into locally made mosaic floors. Several examples were discovered in the House of the Faun at Pompeii. The vast majority of *emblemata* were pictorial in character, making effective use of light, shade and perspective. They were often very successful imitations of well-known paintings and were described by Dunbabin as "painting in stone" [1]. The fragment of an *emblema* panel (1985,0802.1: Figure 1a) from the collections of the Department of Greece and Rome at the British Museum is an example of such a tradition and was made using the *opus vermiculatum* technique, a refined mosaic procedure in which very small, fine elements (tesserae) are used to produce intricate, highly detailed images. Tesserae are small independent pieces of hard material cut in regular – usually cubic – shapes that are arranged on a base mortar to create a mosaic design. The most common material used for the tesserae was stone, but occasionally ceramics and vitreous materials such as glass or faience were also used. The glass – which was usually recycled from broken vessels – and faience tesserae were frequently used to provide contrast that highlighted certain features in the pattern.

The technique of *opus vermiculatum* is believed to have begun in the third century BC in Greece and Egypt [2]. From then until about the third century AD, specialized workshops in eastern Mediterranean cities, including Pergamon, Ephesos and Alexandria, produced these striking and artistically important *emblemata* [3]. *Emblemata* are thought to have been produced by the 'direct method', in which mortar was first spread over the terracotta or stone tray and the tesserae were then inserted into this bedding mortar. The use of trays produced *emblemata* that were both portable and transferable, and could be incorporated as the central pieces of larger floor pavements. Thin lead strips were commonly used to outline and emphasize details of the figurative design in *emblemata* [4], but these have only been reported for *emblemata* found in Greece or Egypt and not in those from Italy [5]. The final stage in the production, after all the

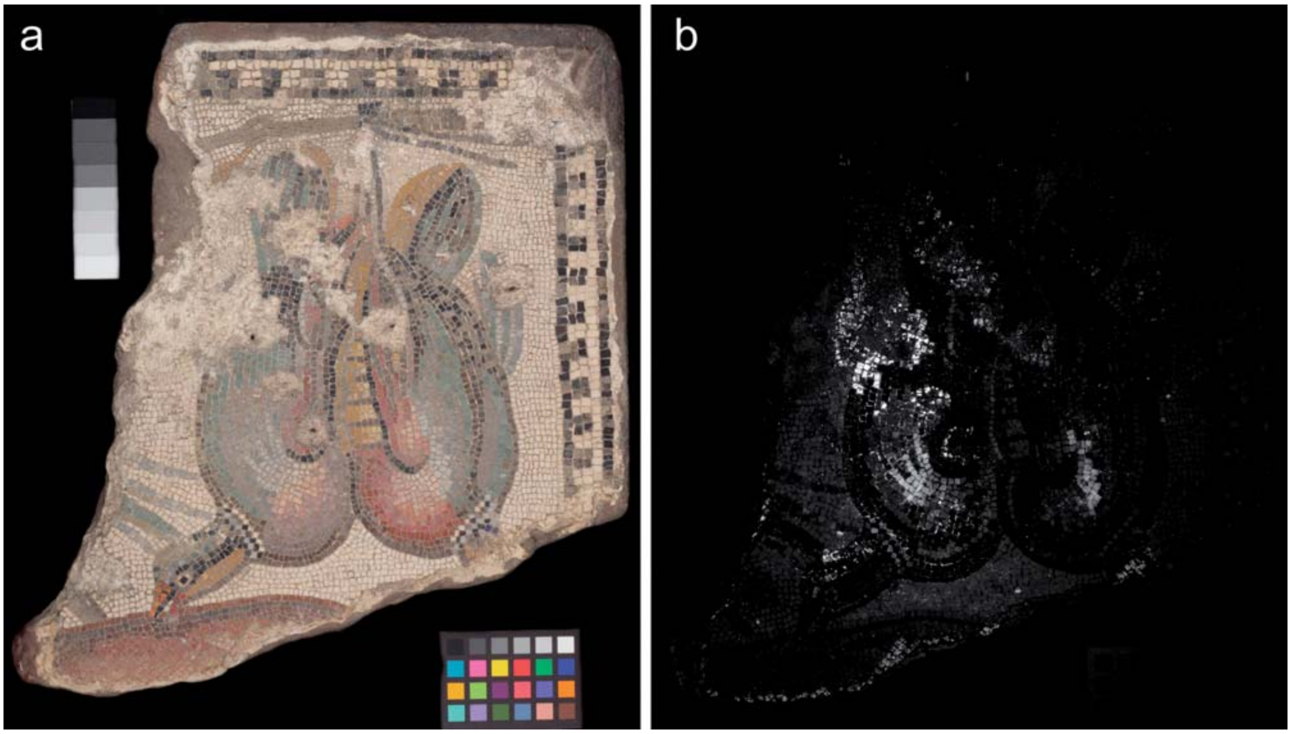


FIGURE 1. Mosaic *emblema* (1985,0802.1) from the Department of Greece and Rome at the British Museum: (a) visible image; and (b) visible-induced luminescence (VIL) image

pieces were laid, seems to have included a painted finish layer along the mortar joins to hide them in an attempt to create an effect similar to painting [4]. An archaeometric study of 84 *emblemata* from Republican Roman Italy revealed that the pigments used on the interstitial mortar were part of an extensive palette that included Egyptian blue, cinnabar, carbon black, green earth and yellow ochre [6].

The designs for *emblemata* often derived from paintings that portrayed scenes from daily life or nature. When echoing contemporaneous paintings, artists used a particular palette of colours and precision techniques that allowed close attention to be paid to details of the design in order to achieve effects of light, shade and perspective [2]. It seems that there were artists who specialized in the production of *emblemata* and two well-known mosaicists of the second century BC were Sosus of Pergamum, mentioned by Pliny in book XXXVI of his *Historia naturalis* [7; p. 145], and Dioskourides of Samos; works by both these artists survive – whether as originals or copies – at Pompeii.

EMBLEMA 1985,0802.1

The fragment of an *emblema* under investigation is made in *opus vermiculatum* and measures approximately 352 × 378 mm (1985,0802.1: Figure 1a). It depicts two birds, possibly doves, facing in opposite directions. The two doves are placed on a white background, framed within a geometric border composed of white and black stone tesserae arranged in a regular checked or crenellated pattern. The birds, which share the same colour scheme, appear to be hanging from a branch or other vegetation, most of which is now missing. The history of this *emblema* before it entered the collections of the British Museum is not known, so it is not associated with any particular findspot or location. However, based on the artistic tradition of *opus vermiculatum*, the mosaic can be dated between the third century BC and the second century AD.

The construction of the *emblema* follows the typical pattern described above, with the tesserae embedded in a mortar foundation that varies in depth from 0.3 to 1.5 cm; the mortar is thinner at the edges and thicker in the centre. Although the *emblema* is a 'true' example (as it is set in a terracotta tray), the quality of its workmanship seems coarse when compared to the finest examples, such as the mosaic of doves drinking from a golden bowl, found in Hadrian's Villa at Tivoli and now in the Musei Capitolini, Rome (inv. MC402). No lead strips of the type noted in other *emblemata* from the eastern Mediterranean region were detected anywhere on this panel. Although the use of lead strips was common in Hellenistic mosaics it was abandoned in later periods [3], suggesting that this *emblema* is more likely to have been constructed during the Roman rather than Hellenistic period.

Most of the tesserae used in the panel are made of marble or other calcium-rich stones in a variety of colours including white, grey, black, yellow, red and different shades of blue. The length of the sides of the tesserae ranges from 2 to 5 mm; the tesserae used for the border are much coarser than those in the figurative central motif. The finest tesserae (average 2–3 mm) are concentrated in the centre of the panel where they comprise and enhance the most important parts of the design, while the larger tesserae (around 5 mm) are located in the background of the motif and in the borders. A minority of the tesserae are made from glass, in a variety of colours, including red, orange, turquoise and three shades of blue – dark, mid and light. In the beaks of both birds only glass tesserae were employed, most probably to highlight these features.

The aim of this study was to investigate, through detailed examination and scientific investigation, the materials and methods of manufacture of this unprovenanced *emblema* in an attempt to shed light on its origin and history. While the provenance of the object could not be determined, the detailed scientific analysis revealed new and unexpected insights into the manufacturing processes of *emblemata*.

METHODOLOGY

Non-invasive analysis

The mosaic was first examined with the naked eye and under magnification using a Leica MZ 9.5 low power microscope with ×6.3 to ×60 objectives and a ×10 eyepiece. Two methods were then used to investigate the surface materials of the *emblema* in more detail and to inform the choice of sample sites for further analysis.

The technique of visible-induced luminescence imaging (VIL) has been developed at the British Museum as a means of revealing and mapping the presence of the pigment Egyptian blue ($CaCuSi_4O_{10}$), which was in common use in the Mediterranean region from about 2500 BC until the end of the Roman Empire and beyond [8]. As described in more detail elsewhere, Egyptian blue emits infrared radiation when irradiated with visible light [9–11]. In the study of the *emblema*, the panel was illuminated using red light-emitting diodes (peak wavelength 629 nm) and the infrared emission recorded using a modified Canon 40D camera fitted with a Schott RG830 filter to maximize response in the 800–1000 nm range; for full details see [10]. A set of white and grey Spectralon® reference samples was imaged alongside the mosaic panel. As these samples do not show any luminescence properties, any area in the image appearing lighter than the white reference sample must contain a luminescent material, Egyptian blue being the only candidate in this period and region.

In addition, X-ray fluorescence (XRF) spectrometry was used to determine the elemental composition at the surface of a number of the vitreous tesserae. A Brucker Artax spectrometer was employed to examine areas with a diameter of approximately 0.65 mm *in situ*. The spectrometer was operated at 50 kV, 0.8 mA and data were collected for 200 seconds. The region between the spectrometer head and the sample was flushed with helium gas to improve the detection of elements with low atomic numbers.

Analysis of samples

Small samples of a few grains were taken from the mortar on areas where tesserae were missing and analysed using Raman microscopy to identify pigments that might have been used during the construction of the mosaic. In particular, Raman microscopy was used to confirm the identification of Egyptian blue in areas that had shown luminescence in the VIL images. A Jobin Yvon LabRam Infinity spectrometer with green (532 nm) and near-infrared (785 nm) lasers with maximum powers of 2.4 and 4 mW respectively was used, equipped with a liquid nitrogen cooled CCD detector and attached to an Olympus microscope system. The resultant spectra were identified by comparison with a British Museum in-house database.

To complement the XRF surface analysis, small (1 mm side) samples were taken from six glass tesserae for further analysis using laser ablation high resolution inductively coupled plasma mass spectrometry (LA-HR-ICP-MS) to determine quantitatively the content of major, minor and trace elements. The system comprised a neodymium–YAG laser coupled with a Thermo Finnigan ELEMENT XR mass spectrometer.[1] The system was operated at its full energy of *c*.4 mJ with a laser beam diameter of 80 μm and a pulse frequency of 7 Hz. The sample was pre-ablated for between 15 and 25 seconds to ensure that the results of the analysis were not affected by signals caused by surface contamination or surface corrosion. Two ablation passes were made and the average was calculated. National Institute of Standards and Technology (NIST) standard reference materials 610 and 612, along with Corning glass A, were used as external standards and the concentrations, which are reported as percentages of the oxide, were calculated according to the method given by Gratuze [12].

Samples were also taken from the terracotta tray and the mortar in an attempt to determine the provenance of the clay and, thereby, perhaps identify the place of manufacture of the mosaic. The mineral inclusions were analysed by petrographic analysis in thin-section using a Leica DMRX microscope. Elemental analyses of the fabrics were carried out using an Inca Oxford Instruments energy dispersive X-ray (EDX) spectrometer attached to a Hitachi S-3700N variable pressure scanning electron microscope (VP-SEM) running at a pressure of 30 Pa. To obtain reliable mean composition, four areas of each sample were studied at a magnification of ×50 (*c*.2.5 × 2.5 mm) using a voltage of 20 kV and the results were averaged.

RESULTS AND DISCUSSION

Pigments

There are previous reports of traces of pigments detected on the interstitial mortar of *emblemata* from Greece [4] and from Italy [6]. In the latter study, a mosaic from Rome and two mosaics in *opus vermiculatum* from Privernum, some 85 km south of Rome, were analysed by Boschetti *et al*., who identified the palette of colours used in their construction, including materials such as cinnabar and Egyptian blue – two pigments generally considered of 'high quality' [6]. The pigments were employed on the mortar, where they served to conceal the joins. The brushstrokes gave the designs a high degree of finish in imitation of paintings.

Initially, VIL imaging was used to determine whether Egyptian blue had been used in the construction of the *emblema* and, if so, to examine its distribution (the high sensitivity of VIL imaging allows the presence of single crystals of Egyptian blue, which may be almost invisible – even under magnification – to be detected and mapped). The VIL image shows the presence of Egyptian blue as 'glowing' white areas in the marks left on the fresh lime mortar by the tesserae that have now been lost, see the areas outlined in Figures 2 and 3. In some cases, traces of this pigment were revealed by VIL in the areas of mortar between the tesserae, indicated by the blue arrows in Figure 3b. These results strongly suggest that Egyptian blue was applied on the fresh lime-based mortar to lay out the composition prior to the application of the coloured tesserae. The blue pigment is found only in those instances where coloured tesserae are (or were) present and not, for example, in other areas such as the white background or the monochromatic border pattern. It is worth mentioning that Egyptian blue is found predominantly, but not exclusively, in areas that were intended to be covered by blue tesserae; some blue pigment is also found, for example, on areas of the bedding for the brown branch from which the birds are hanging and on the red feature at the bottom of the surviving composition.

The concept that the pigment was in some way used to define the composition is supported by the finding that the traces of pigment detected in areas in the wing of the left bird, from which the tesserae have now been lost, correspond exactly to the position of the wing of the second bird. Similar instances were found on the bird's neck and in the vegetation. The presence of a preparatory drawing (underdrawing) is not surprising considering the complexity of the composition.

Some tesserae, for instance those close to the centre of the birds, show some luminescence in the near-infrared range. The origin of this luminescence, which is not due to the presence of Egyptian blue pigment and is less intense, is still under investigation, but preliminary analysis by XRF found no significant compositional differences between the tesserae that exhibited luminescence and surrounding tesserae that did not; both types show very similar (calcium-rich) compositions.

Raman analysis was undertaken to confirm the presence of Egyptian blue in those areas in which it seemed likely that blue tesserae had originally been embedded and which had shown luminescence in the VIL images. Analysis was also undertaken on the areas of the motif where tesserae of other colours might once have been located to determine if traces of pigment of a corresponding colour remained. While no coloured underdrawing is visible to the naked eye, under the microscope, pigment particles can be seen in the mortar beneath lost tesserae. Very small samples were taken from the mortar in areas once occupied by yellow, red, black and blue tesserae. In addition to Egyptian blue, red and black particles were found in the samples taken from the mortar where tesserae of the corresponding colour were missing; Raman examination identified these particles as hematite and carbon black respectively. No pigment was identified in any sample taken from an area from which a yellow tessera was missing.

The association of these coloured particles with areas of similarly coloured tesserae strongly suggests the use of a coloured underdrawing to assist in the construction of the mosaic. To delineate the areas to be filled with a particular hue, it is possible that a fully coloured underdrawing was executed prior to the insertion of the corresponding coloured tesserae. The use of preparatory compositions, or *sinopiae*, is known for the production of large-scale mosaics [13]. A monochromatic *sinopia* was painted using red ochre, yellow ochre or a carbon-based black onto the *arriccio*, or preliminary lime-based bed. These *sinopiae* may also have included incised, ruled and snapped lines to define geometrical features. On top of the *arriccio* a final lime-based bed was applied, onto which the tesserae were applied following the guidelines provided by the detailed *sinopia*. The *emblema* analysed in this study seems to have been executed rather differently and a possible sequence for the execution of this mosaic might be:

1. A lime-based bed is laid directly onto the terracotta tray;
2. A coloured drawing is rapidly executed on the lime-based bed;
3. The tesserae are placed in the fresh lime-based bed following the guidelines provided by the coloured drawing.

The very different techniques used for large-scale mosaics and for *emblemata* of *opus vermiculatum* can easily be explained by their extremely different scale and function.

Although Egyptian blue is generally considered a high quality pigment that was traded extensively in the ancient world [6], its use as a material for the preliminary composition seems to suggest the opposite; composed of easily available raw materials and made by a process that had been in use for centuries, Egyptian blue was certainly less expensive than, for example, azurite, which had to be mined. It is noticeable that in this *emblema* the blue pigment was used alongside the naturally occurring mineral hematite and easily produced carbon black, two inexpensive pigments that would have been readily available in workshops. *Emblemata* were extremely laborious, and therefore expensive, works of art to produce and so the use of high quality materials, such as cinnabar for the underdrawing [6], would not be entirely surprising.

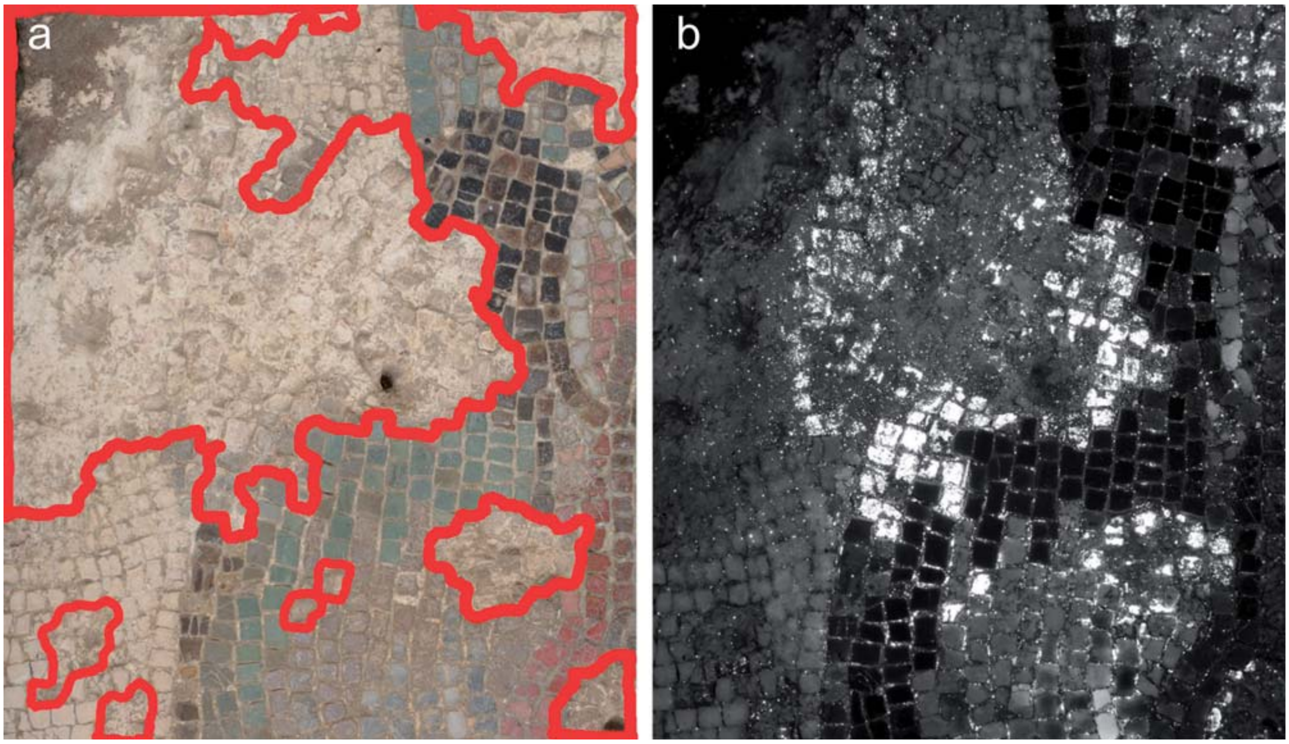


FIGURE 2. Detail of the *emblema* showing the wing of the bird on the left: (a) visible; and (b) visible-induced luminescence images. The red lines in (a) mark the areas of the bedding from which the tesserae are missing. The presence of Egyptian blue crystals, which 'glow' white in (b), is clear in the areas from which tesserae have been lost

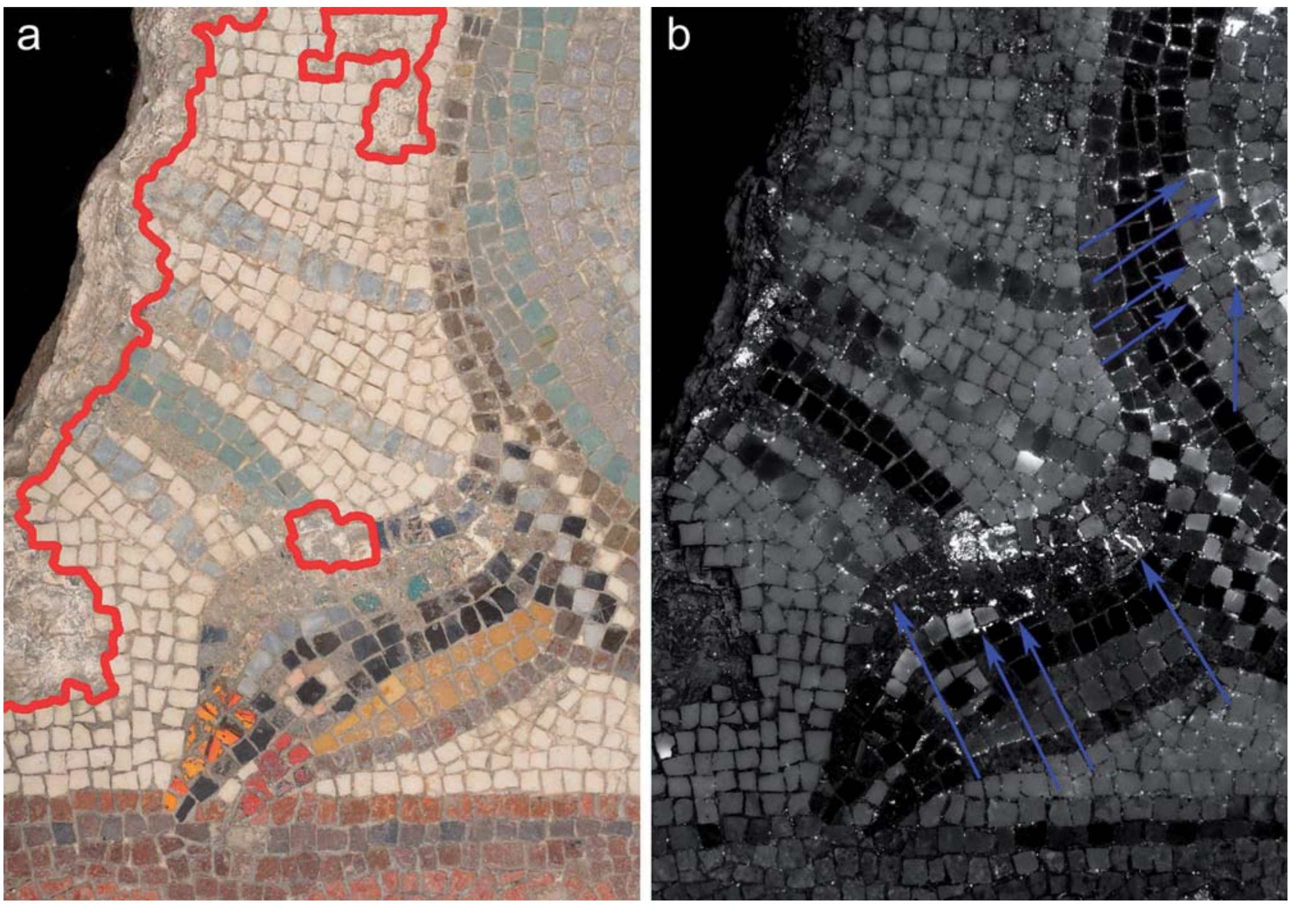


FIGURE 3. Detail of the neck of the bird on the left showing the presence of Egyptian blue crystals in areas from which blue tesserae are missing: (a) visible; and (b) visible-induced luminescence images. The red lines in (a) mark the areas of the bedding from which the tesserae are missing; the blue arrows in (b) show examples of the presence of interstitial Egyptian blue as 'glowing white' on the mortar between the tesserae

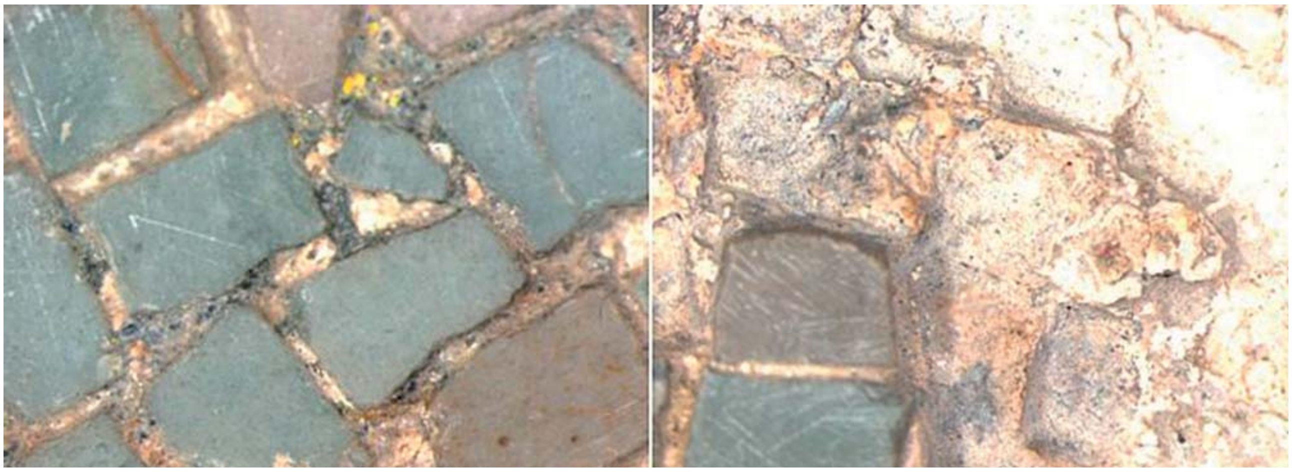


FIGURE 4. Details showing traces of Egyptian blue on the mortar: (left) in the joins in the mortar; and (right) on areas from which blue tesserae have been lost

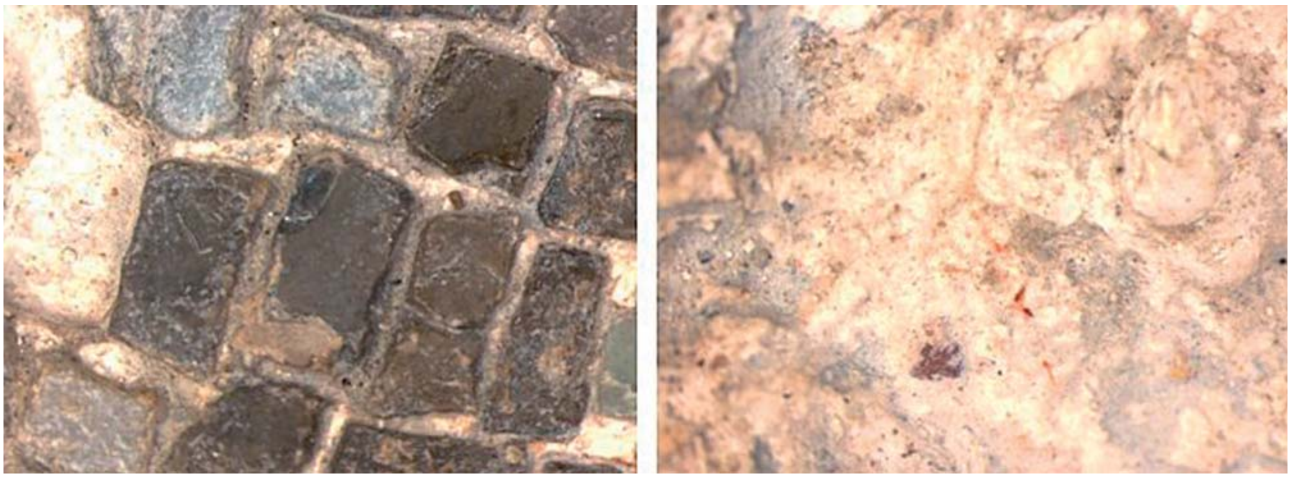


FIGURE 5. Details showing traces of pigment on the mortar: (left) carbon black on the mortar joins between black tesserae; and (right) traces of red pigment on areas from which red tesserae have been lost

In common with other *emblemata* examined previously by Boschetti *et al.* [6], panel 1985,0802.1 shows traces of pigment on the interstitial mortar. Under the microscope, black, red and blue pigment particles, similar to those seen on the backing mortar, can be observed, Figures 4 and 5. The presence of pigment in the mortar between tesserae could be the result of an intentional act, as described previously [6], but might equally be the result of the backing mortar – with its pigmented lines – being extruded between tesserae as they were pressed into place.

Glass

The term 'ancient glass' can be loosely applied to refer to any glass made before the seventeenth century AD [14, 15]. It is primarily a mixture of silica, soda and lime, albeit made according to recipes that employed different proportions of these materials at various times.

Silica acts as the network forming oxide in the glass matrix. At its melting point of around 1650°C it is highly viscous and on slow cooling can form an irregular vitreous network structure. Sodium-containing materials, added to the glass act as a flux, react with the silica and lower its melting point, while lime acts as a stabilizer, enhancing the durability and chemical resistance of glass.

There were two sources of silica used in ancient glass production: quartz sand and crushed quartz pebbles. The use of quartz sand introduced a number of impurities, such as alumina, lime and iron oxide, the levels of which depended on the particular sand source used. In contrast, crushed white quartz pebbles contain almost no impurities.

Three main sources of alkali-rich flux have been used in glass production throughout history: plant ash, wood ash and mineral soda (natron: sodium carbonate decahydrate). Plant and wood ash also introduce elevated levels of potassium and/or magnesium oxides, while natron contributes only sodium to the glass contents. Sayre and Smith were the first to group glass types according to their compositions into high magnesia glasses (HMG) and low magnesia glasses (LMG) [16].

The colour of glass largely depends on the presence or absence of transition metals oxides, as well as on the nature of the production process. Variation of these parameters

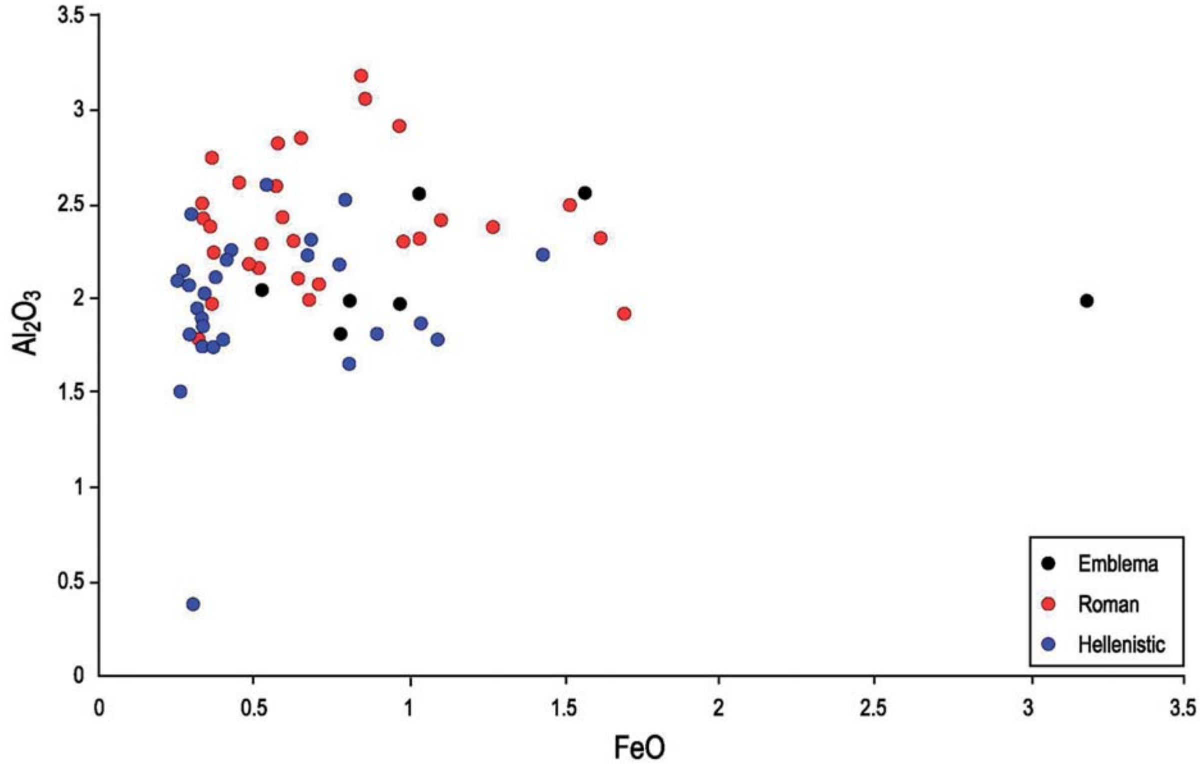


FIGURE 6. Aluminium oxide and iron oxide contents of the six glass tesserae from the *emblema* that were analysed by LA-HR-ICP-MS in comparison with Hellenistic glass from Rhodes or Morgantina [19], and Roman glass from the canton of Ticino [20]

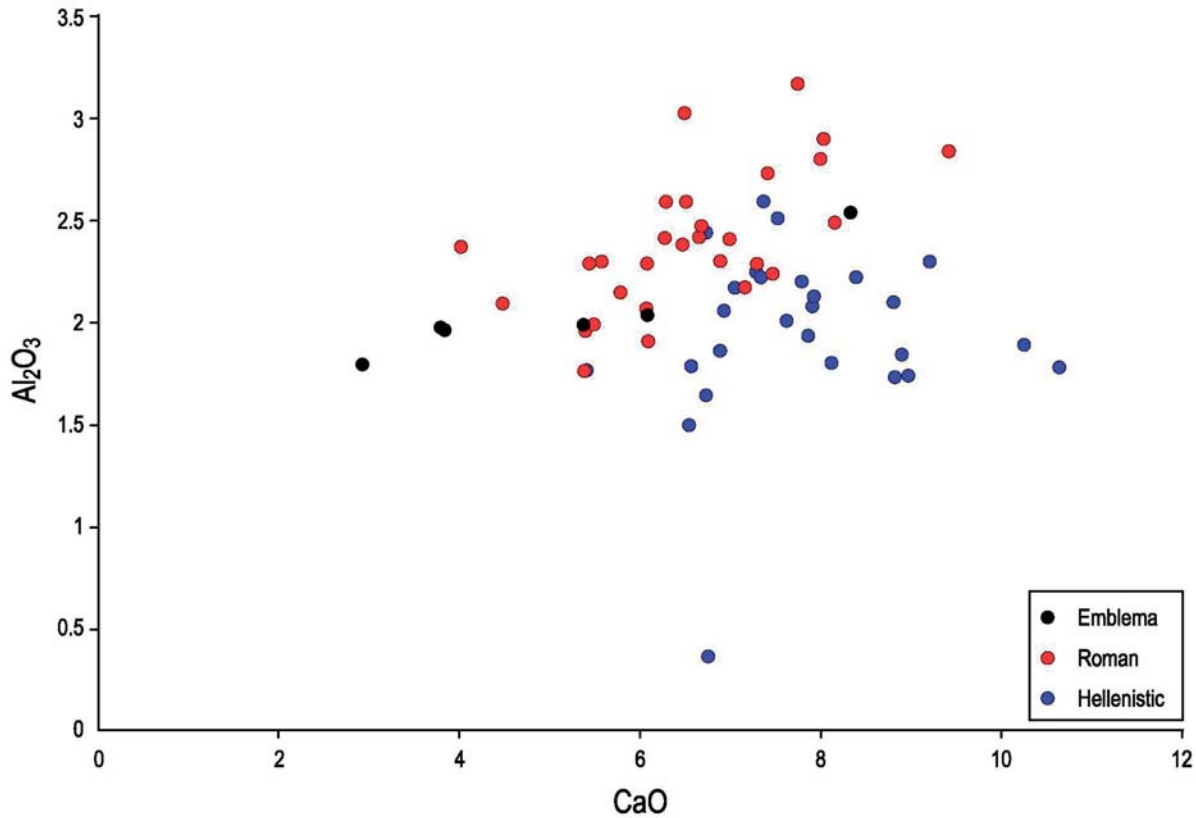
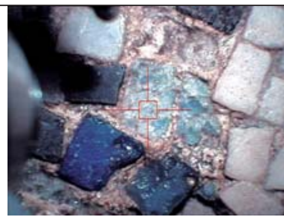
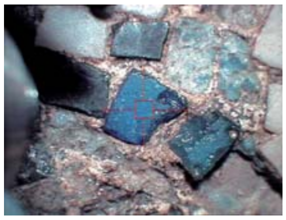
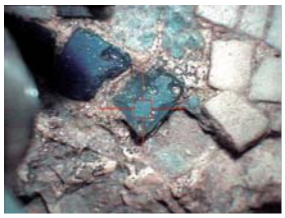
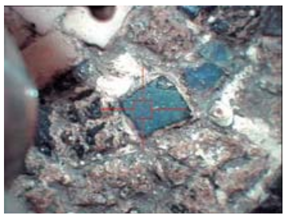
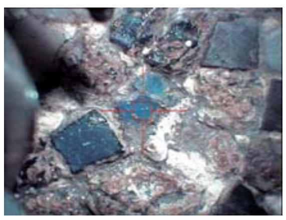
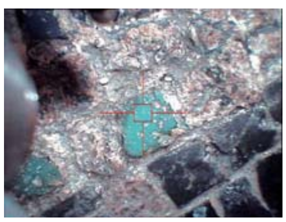
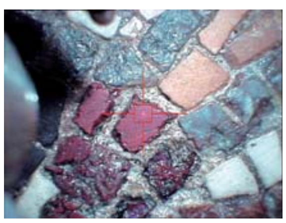
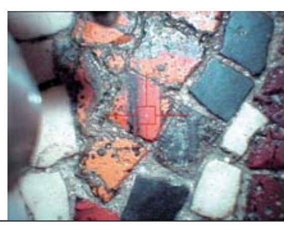


FIGURE 7. Aluminium oxide and calcium oxide contents of the six glass tesserae from the *emblema* that were analysed by LA-HR-ICP-MS in comparison with Hellenistic glass from Rhodes or Morgantina [19], and Roman glass from the canton of Ticino [20]

TABLE 1. Details of the glass tesserae analysed in this study

Tessera		Colour	Analytical technique(s)
Tess 1		Pale turquoise	XRF LA-HR-ICP-MS
Tess 2		Dark blue	XRF LA-HR-ICP-MS
Tess 3		Mid blue	XRF
Tess 5		Dark blue	XRF LA-HR-ICP-MS
Tess 6		Mid–dark blue	XRF LA-HR-ICP-MS
Tess 7		Turquoise	XRF LA-HR-ICP-MS
Tess 9		Red	XRF LA-HR-ICP-MS
Tess 10		Orange	XRF

can produce glasses that are coloured, colourless, transparent, translucent, opalescent or opaque [17].

Eight glass tesserae were analysed using X-ray fluorescence (XRF) spectrometry to identify the elements present, Table 1. Micro-samples were taken from six of these to allow further analyses to be made using LA-HR-ICP-MS to determine the chemical compositions quantitatively. The six tesserae analysed by LA-HR-ICP-MS were all found to be soda–lime–silica (SLS) glasses with low levels of potassium, magnesium and phosphorus, so that they fall under the category of LMGs, Table 2 [16, 18]. This suggests that in each case mineral soda (natron) was used as the alkali source and the base glass composition of all the samples is, therefore, completely typical of Roman glass. All the samples have elevated levels of alumina, at around 2% (Figure 6), and the proportion of lime to alumina is fairly consistent, with a calcium to aluminium ratio of between two and four, Figure 7. This suggests that a calcium-containing sand was used as the silica source and Figures 6 and 7 show compositions that are comparable with those of Hellenistic and Roman glasses reported in the literature [19, 20].

Trace element analyses can be used to show variations in the sources of sand used to produce the tesserae. Tesserae 1, 5 and 6 have compositions that are low in strontium and high in zirconium, suggesting the use of an inland sand source, Table 3 [21]. Conversely, tesserae 2 and 7 have high strontium, low zirconium compositions, suggesting the use of a coastal, shell-containing sand [21]. As the tesserae are made of glass produced using two distinct silica sources, they are likely to have been produced at two different locations. A comparison with previous work by Freestone (summarized in [22]) suggests inland Egypt and the Levantine coast, respectively, as possible sources for the 'inland' and 'coastal' groups. Tessera 9 has an intermediate composition and may have been produced from a mixture of two sand sources or glass types, or its trace element signature may have been influenced by the addition of the extra ingredients added to give it its red colour and opacity.

The pale turquoise (Tess 1), mid–dark blue (Tess 6) and two dark blue (Tess 2 and Tess 5) samples were all coloured by the use of cobalt (Co), with Co contents ranging between around 350 and 900 parts per million (ppm), Table 2. The pale turquoise sample also contains a significant amount of copper (around 1% or 10000 ppm), which points to a deliberate addition rather than contamination from the cobalt colourant. The other three cobalt-containing blue samples show much lower levels of copper oxide, less than 0.15%. Previous studies have identified a cobalt-containing alum that is thought to have been used in glass production at the Kharga oasis in the western deserts of Egypt [23, 24]. Glasses produced using this source typically contain elevated levels of aluminium, nickel and zinc. However, the cobalt contents of the samples of blue tesserae from this *emblema* are not correlated with elevated levels of zinc, perhaps pointing to a different source of the cobalt colourant. All samples coloured using cobalt also have elevated levels of arsenic, suggesting that an arsenic-rich cobalt ore may have been used. Tessera 3, which was only analysed using XRF, was also found to have been coloured using cobalt.

The turquoise and red samples (Tess 7 and Tess 9) both appear to owe their colour to the presence of copper, with copper oxide contents of *c.*1.7 and 1.2% respectively. Both also contain significant levels of tin oxide, signifying that scrap bronze was used as the source of the copper colourant.

TABLE 2. Major and minor oxide composition of selected glass tesserae from *emblema* 1985,0802.1 analysed by LA-HR-ICP-MS

	Composition (weight %)																
Tessera	SiO_2	Na_2O	CaO	K_2O	MgO	Al_2O_3	FeO	TiO_2	Sb_2O_5	MnO	CuO	CoO	SnO_2	PbO	As_2O_5	Cl	P_2O_5
Tess 1	74.8	12.7	3.76	0.93	0.46	1.98	0.80	0.14	2.72	0.02	1.00	0.047	0.003	0.110	0.010	1.18	0.10
Tess 2	68.5	15.0	8.29	0.56	0.58	2.55	1.02	0.06	1.98	0.22	0.14	0.088	0.002	0.007	0.016	0.67	0.18
Tess 5	70.4	19.3	2.91	0.41	0.42	1.80	0.77	0.14	2.27	0.04	0.09	0.036	0.004	0.160	0.008	1.05	0.06
Tess 6	75.7	11.9	3.81	0.74	0.41	1.97	0.96	0.14	2.63	0.02	0.09	0.046	0.004	0.150	0.011	1.19	0.11
Tess 7	67.7	17.6	6.05	0.55	0.47	2.04	0.52	0.07	1.56	0.50	1.67	0.001	0.082	0.059	0.004	0.85	0.14
Tess 9	62.8	18.9	5.34	0.61	0.48	2.00	3.17	0.10	0.42	0.13	1.23	0.003	0.069	3.550	0.004	0.97	0.12

TABLE 3. Trace element compositions of selected glass tesserae from *emblema* 1985,0802.1 analysed by LA-HR-ICP-MS

	Composition (ppm)												
Tessera	V	Cr	Ni	Zn	Rb	Sr	Y	Zr	Ba	La	Ce	Pr	Nd	Sm
Tess 1	11.20	9.70	18.17	53.10	6.25	224.79	6.00	85.57	149.03	7.55	11.49	1.40	5.73	1.16
Tess 2	12.28	14.05	27.52	36.72	7.01	441.20	7.30	41.38	218.61	8.19	11.66	1.49	6.39	1.32
Tess 5	11.01	10.02	15.26	31.17	4.35	180.76	5.45	93.07	125.39	7.20	11.62	1.25	5.33	1.12
Tess 6	10.77	25.03	17.03	31.30	5.01	231.03	6.38	82.31	143.82	7.77	11.92	1.43	5.77	1.16
Tess 7	16.15	13.29	11.74	30.62	8.41	407.88	6.17	46.73	205.55	7.65	11.76	1.47	6.25	1.22
Tess 9	13.40	14.53	26.68	43.10	10.32	351.02	6.01	67.24	155.65	7.81	12.64	1.52	6.32	1.19

In the case of the pale turquoise sample (Tess 1) no tin was detected, indicating that for this glass either a copper ore, such as malachite, or pieces of copper ingot may have been used to provide the colour. The turquoise sample (Tess 7) shows surprisingly elevated levels of manganese oxide of around 0.5%. Since the second century BC, manganese has been used to produce a colourless glass by oxidizing the iron impurities that might otherwise impart a green colour [16]. However, the use of manganese in this sample of opaque blue copper-containing glass is surprising as its deliberate addition would presumably not have been with the aim of producing a colourless glass. It is suggested that this tessera may have been produced using manganese-decoloured cullet (crushed recycled glass) or manganese-rich primary raw materials.

The red tessera (Tess 9) contains elevated copper, iron and lead oxide levels (1.23, 3.2 and 3.5% respectively) that are typical of some Roman opaque red glasses [25, 26]. Based on visual examination, the orange tessera (Tess 10) was initially thought to be ceramic. Although it was not further analysed with LA-HR-ICP-MS, XRF analysis suggests that it is a lead-rich opaque glass coloured with copper. The orange tesserae in the *emblema* vary in hue and the colour of some of the individual orange tesserae was rather inhomogeneous.

Finally, all the samples, apart from the red sample Tess 9, contain around 2–3% antimony oxide. The high levels suggest the deliberate addition of antimony as an opacifier for these glasses. Antimony functions as an opacifier by reacting with calcium present in the glass to precipitate opaque calcium antimonite crystals. It was the most common opacifier used in glass production from *c*.1450 BC until the fourth century AD [27].

Terracotta tray and mortar

The samples from the terracotta tray (M1) and mortar (M2) were first examined as thin-sections. The terracotta sample shows a red non-calcareous fabric, rich in quartz with bimodal size distribution, occasional plagioclase and rare opaque particles, Figure 8. Some of the quartz grains are very rounded, suggesting either a long fluvial transport or aeolic erosion. The mortar sample is rich in lime and contains very occasional fine quartz grains.

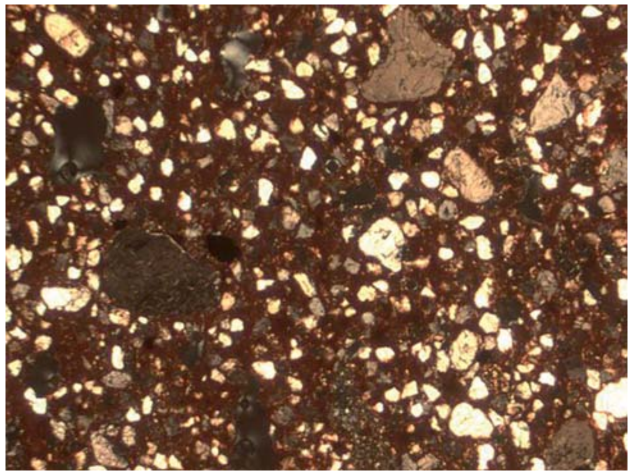


FIGURE 8. Micrograph of a thin-section of sample M1 from the terracotta tray in crossed polar light, showing abundant quartz sand with bimodal size distribution. Field of view 3.5 mm

The samples were both also analysed by SEM-EDX and the elemental composition reported as normalized percentages of the oxides, Table 4. The terracotta tray has a very high silica content, with some calcium and iron oxides (*c*.4% in each case), Table 4. The high silica content reflects the abundant quartz inclusions, while the calcium is probably either post-depositional or derives from the mortar. On the other hand, calcium oxide accounts for more than 88% of the oxides measured in the calcium carbonate mortar.

Silica and lime are not diagnostic of provenance and quartz is a very common and widespread mineral. In the absence of any systematic studies of terracotta trays for *emblemata* or allied wares of known provenance, the source of this mosaic is difficult to determine and at this stage none of the potential manufacturing centres can be excluded.

TABLE 4. Individual and averaged SEM-EDX results for four bulk analyses of samples from the terracotta tray (M1) and mortar (M2)

Oxide	Sample from terracotta tray (M1)					Sample from mortar (M2)				
	Bulk 1	Bulk 2	Bulk 3	Bulk 4	Average	Bulk 1	Bulk 2	Bulk 3	Bulk 4	Average
Na_2O	0.4	0.5	0.4	0.5	0.5	0.5	0.5	0.4	0.4	0.4
MgO	1.9	2.0	1.9	2.1	2.0	0.8	0.9	0.9	0.9	0.9
Al_2O_3	11.6	13.1	12.2	12.4	12.3	1.1	1.2	1.3	1.7	1.4
SiO_2	76.1	73.5	75.2	73.3	74.5	7.1	7.2	10.3	7.0	7.9
K_2O	1.9	2.1	2.0	1.9	2.0	0.3	0.2	0.3	0.3	0.3
CaO	3.6	3.8	3.9	4.8	4.0	89.4	89.4	86.5	89.2	88.6
TiO_2	0.6	0.7	0.6	0.8	0.7	0.2	0.2	0.0	0.0	0.1
MnO	0.2	0.1	0.0	0.0	0.1	0.0	0.1	0.0	0.0	0.0
FeO	3.7	4.2	3.9	4.2	4.0	0.5	0.4	0.3	0.5	0.4

Note. The results are reported as normalized percentages of the oxides measured by bulk analysis at a magnification of ×50.

CONCLUSIONS

The mosaic fragment 1985,0802.1 is an original and true *emblema* constructed using the *opus vermiculatum* technique. Such *emblemata* are known from the third century BC to the second century AD, but the absence of lead strips in its construction, along with the abundance of glass and the absence of faience tesserae, makes it more likely that this panel was made during the later part of that period.

Analysis of the glass tesserae that were used to highlight the design found that they had a common Roman low-magnesia, soda–lime–silica composition. There is nothing significant about the basic raw materials, colourants and opacifiers used in the production of these glass tesserae that would allow their period of manufacture to be defined more specifically than 'Roman'. The trace element data showed that some of the glasses used to make the tesserae were produced from raw materials from different sources and may, therefore, have originated in more than one location. However, in the Roman Empire trade in glass was so extensive that even if the place of primary production of the glass used to produce the tesserae was determined, this would not necessarily assist with assigning a place of production to the *emblema*.

The analysis of the terracotta tray was inconclusive and has not helped to resolve the question of provenance. Further analysis of clays of known provenance used in workshops in the Mediterranean may narrow down the range of possible production centres.

Although the examination did not provide evidence to locate the production centres for such *emblemata*, associations with named artists, for example Dioskourides of Samos, and the location of finds (such as the fragment of the floor by Hephaistion at Pergamon), point to workshops in the eastern Mediterranean. Against this, the use of travertine stone for some of the trays suggests at least some were Italian products.

However, examination has provided interesting insights into the technology of *emblemata* production. The examination and analysis of pigments showed that at least Egyptian blue, hematite and carbon were used throughout the bedding of the panel. This observation suggests that a preliminary drawing – possibly fully coloured – was executed on the damp lime bedding to guide the placement of the coloured tesserae. VIL imaging demonstrated that the distribution of Egyptian blue on the fresh lime mortar corresponded principally to the areas from which blue tesserae have since been lost. In the same way traces of hematite and carbon black were found where red and black tesserae had once been placed. All three pigments were also present on the interstitial mortar joins. Although the presence of interstitial pigment could be intentional, as suggested by other authors, it could also be the result of the bedding being extruded between tesserae during their placement.

The future examination of further *emblemata*, such as 'A lion taunted and bound by cupids' (BM 1856,1213.5; mosaic 1), using VIL imaging will help to establish the extent to which preliminary drawings were used for the production of these complex works of art.

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NOTE

1. LA-HR-ICP-MS analysis was carried out at the Centre Nationale de la Recherche Scientifique (CNRS) in Orléans (France) by Dr Bernard Gratuze.