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Christian-Muslim contacts across the Mediterranean: Byzantine glass mosaics in the Great Umayyad Mosque of Córdoba (Spain)

María Auxiliadora Gómez-Morón [a,b,1], Teresa Palomar [c,d,*,1], Luis Cerqueira Alves [e], Pilar Ortiz [b], Márcia Vilarigues [d], Nadine Schibille [f,*]

[a] Instituto Andaluz de Patrimonio Histórico (IAPH), Camino de los Descubrimientos s/n, Sevilla, 41092, Spain
[b] Departamento de Sistemas Físicos, Químicos y Naturales, Universidad Pablo de Olavide, Ctra. de Utrera Km. 1, 41013, Sevilla, Spain
[c] Instituto de Cerámica y Vidrio, Consejo Superior de Investigaciones Científicas (ICV-CSIC), C/ Kelsen 5, Campus de Cantoblanco, 28049, Madrid, Spain
[d] Unidade de Investigação VICARTE "Vidro e Cerâmica para as Artes" e Departamento de Conservação e Restauro, FCT-NOVA, Campus de Caparica, Quinta da Torre, 2829-516, Caparica, Portugal
[e] C2TN, IST/CTN, Universidade de Lisboa, E.N. 10, 2686-953, Sacavém, Portugal
[f] IRAMAT-CEB, UMR5060, CNRS/Université d'Orléans, 3D, Rue de la Férollerie, 45071, Orléans, CEDEX 2, France

A R T I C L E I N F O

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A B S T R A C T

Glass mosaic decorations were used throughout the medieval Mediterranean as a powerful medium to convey religious and political agendas, yet we know next to nothing about the source of the materials and the transmission of the necessary technical know-how. Mosaics are generally considered a Byzantine art form, not least due to their prominence in Byzantine church architecture and because medieval Islamic textual sources assert that the glass tesserae of some of the most important early mosques were of Byzantine origin. This article provides solid analytical evidence that glass used in the tenth-century mosaics of the Great Umayyad Mosque of Córdoba (Spain) came from Byzantium. Most of the tesserae have high boron contents, for which the only compositional match are Byzantine glasses made with raw materials from Asia Minor. In addition, some of the glass has a chemical fingerprint that suggests that it was prepared by mixing local raw materials with imported high boron glass, indicative of local mosaic glassmaking. Our study thus illustrates the value of analytical studies in re-assessing long-held assumptions about the making of mosaics as well as the movement of materials and people across cultural barriers. The presence of Byzantine materials and craftsmen in Córdoba demonstrates that Muslims and Christians were interacting the length of the Mediterranean, corroborating the close diplomatic ties between the Caliphate of Córdoba and the Byzantine Empire during the tenth century. Our findings further underscore the importance of glass in trade and diplomatic exchange, reflecting its cultural and economic value in the medieval world.

1. Introduction

Built in 786–787 CE, the Great Umayyad Mosque of Córdoba is arguably the most emblematic monument of Islamic religious architecture in Spain, and has been a UNESCO world heritage site since 1984. Over the centuries, the building underwent several changes including various architectural expansions and decorative additions, before being converted into a Christian church following the fall of Córdoba in 1236 (Nieto Cumplido, 1998). Among the decorative features that survive from the Islamic period, the mosaics of the *maqṣūrah* stand out. Commissioned by Al-Hakam II (~965–972 CE), the mosaics are exceptional within medieval Islamic Spain and one of only ten tenth-century mosaic decorations that survive in the entire Mediterranean region (James, 2017; Signes Codoñer, 2004; Stern, 1976). The Iberian Peninsula never really developed its own tradition of wall mosaics, and even the Roman and late antique periods left only relatively few traces usually in the form of floor mosaics (James, 2017; San Nicolás Pedraz, 2018). During the Islamic period, *azulejos* (glazed tiles) were much more common in architectural decorations, such as in the Alhambra of Granada or the Alcazar of Seville, a tradition that has been preserved in the *Mudejar* style until today. This raises important questions as to how the unique mosaic decoration in the maqṣūrah came into

* Corresponding authors.
E-mail addresses: t.palomar@csic.es (T. Palomar), nadine.schibille@cnrs-orleans.fr (N. Schibille).
[1] joint first authors.

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being. Historical written sources report that the glass mosaic tesserae were a gift from the Byzantine Emperor to the Caliph of Córdoba in the tenth century. The earliest mention of the mosaics dates to the twelfth century, when Muhammad al-Idrīsī specified that the mosaic tesserae had been sent by the Byzantine Emperor, Constantine VII Porphyrogenitus (Stern, 1976). By the fourteenth century, Ibn ʻIḏari (writing in c. 1312 CE) attributed the mosaics to a Byzantine mosaicist sent by the Byzantine emperor along with 320 qin ârs of tesserae (an estimated 16 tons) (Signes Codoñer, 2004). The veracity of these accounts remains a matter of debate given the lack of clear material evidence (Bloom, 1988; James, 2017; Khoury, 1996). What these textual sources suggest is that the mosaics of the mosque in Córdoba echoed the decoration of the Dome of the Rock in Jerusalem and the Great Umayyad Mosques in Damascus and Medina built two and a half centuries earlier, not only in terms of style but also as regards the legends surrounding their creation. Al-Idrīsī and Ibn ʻIḏari followed the example of al-Baladhuri, who in the ninth century was the first in a long line of Islamic sources to report on the Byzantine origin of the tesserae and mosaicists used for some of the most iconic early Islamic mosques in Medina, Damascus and Jerusalem (James, 2017, pp. 264–265). The choice of using mosaics for the mosque in Córdoba was certainly a deliberate decision, intended to affirm imperial legitimacy by evoking the earlier Umayyad Caliphate of Damascus and its building works (Calvo Capilla, 2018; James, 2017).

Within the context of first millennium CE glass production, mosaic tesserae represent specialized products and their provenance is a largely unsolved scientific problem. Before the eighth century, the Iberian Peninsula received its glass supplies exclusively from the eastern Mediterranean, from the Levantine coast and Egypt (de Juan Ares et al., 2019). The demise of these imports triggered an increase in glass recycling and eventually the innovation of new glassmaking recipes based on locally available raw materials sometime in the second half of the eighth century CE (Schibille et al., 2020b). Compared to earlier periods, glass is relatively rare in early Islamic al-Andalus in terms of its absolute quantities as well as its application. By the tenth century, primary glassmaking appears to have been firmly established, including the manufacture of soda-rich plant ash glass as well as a unique type of soda-ash lead glass (de Juan Ares and Schibille, 2017a). There is not much evidence of a local Andalusian production of strongly coloured glass and none of opacified glass, with the exception of glass beads. It may thus be assumed that the glass tesserae for the mosaic decoration of the Great Mosque must have come from somewhere other than the Iberian Peninsula. The chemical analysis of glass is a means to directly test this hypothesis.

In this study, we have analysed 91 mosaic tesserae from the Great Mosque in Córdoba, using laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS), micro-particle-induced X-ray emission (μ-PIXE), Scanning Electron Microscope (SEM), Fiber Optic Reflectance Spectroscopy (FORS) and μ-Raman spectroscopy to gain insights into tenth-century mosaic making, not only in Islamic al-Andalus, but also within the wider Mediterranean region. Our data provide the first analytical proof that the majority of the tenth-century glass tesserae used for the decoration of the Umayyad mosque indeed originated in the Byzantine Empire, while a handful of samples exhibit features pointing to the exploitation of local raw materials and by extension the transfer of technological know-how to al-Andalus from outside the Iberian Peninsula. The presence of quintessentially Byzantine glass tesserae in al-Andalus is a striking testimony to Byzantine-Umayyad diplomatic connections and the movement of goods and possibly craftsmen during the tenth century, reflecting complex geopolitical and economic dynamics in the medieval Mediterranean.

2. Materials and methods

2.1. The mosaics

The mosaics of the Great Mosque in Córdoba are concentrated in the *maqṣūrah* (literally the ‘closed-off space’ near the centre of the *qiblah* wall in the direction of prayer, usually reserved for the caliph) that is formed by three chambers: the *Miḥrāb* (prayer niche in the *qiblah* wall) in the middle, flanked by the *Bab Bayt al-Mal* chamber (treasury) to the left, and the *Sābāṭ* chamber to the right that used to be connected to a secret corridor to the caliphal palace, no longer in existence. The three façades and the dome of the entrance hall of the *Miḥrāb* are decorated with glass mosaics, which are mainly gold leaf tesserae along with different shades of green and blue, as well as some red, purple and yellow tesserae (Fig. 1). A set of 91 tesserae from the *maqṣūrah* mosaics of the Mosque-Cathedral of Córdoba were removed from the mosaic for analysis. 15 tesserae come from the *Bab Bayt al-Mal* chamber, 30 tesserae from the *Sābāṭ* chamber, 16 tesserae from the *Miḥrāb* façade, and 30 tesserae from the *Miḥrāb* dome. In general, the samples are all in a good state of conservation.

2.2. Characterization techniques

The glass samples were analysed by optical microscopy (OM), Scanning Electron Microscope (SEM), laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS), micro-particle-induced X-ray emission (μ-PIXE), Fiber Optic Reflectance Spectroscopy (FORS) and μ-Raman spectroscopy.

To characterize the morphology of the tesserae’s surface and glass core, OM and SEM observations were carried out. OM was done in a LEICA DM400M microscope equipped with the objectives × 5, × 10, × 20, and × 50 in reflective light mode with the bright field. The images were taken with a Scion mod. CFW 1308C digital camera connected to the microscope and run by the software Scion Visicapture V2.0 from Scion Corporation. SEM observations were undertaken by a JSM 5600 LV electron microscope, using acceleration voltages of 25 kV in the backscattered electrons mode (BSE). Samples were micro-analysed on resin inlayed polished cross-sections, using a gold conductive coating deposited through a sputter coater Baltec SCD 005, or a carbon coating deposited with a Baltec CEA035. EDS micro-analyses were accomplished by an Inca X-Sight spectrometer attached to the SEM equipment.

To determine the base glass composition at high resolution, the mounted glass samples were analysed by LA–ICP–MS at IRAMAT-CEB in Orléans as described previously (Schibille et al., 2020b). The Resonetic UV 193 nm Excimer laser microprobe was operated at 5 mJ, a frequency of 10 Hz and a spot size diameter of 100 μm. The analytical time was set at 30 s, following a 20 s pre-ablation time. The 58 isotopes measured were converted into quantitative results using an internal standard and a set of international glass standards (NIST SRM610, Corning B, C and D) as well as an archaeological glass of known composition (ALP1) for the determination of chlorine (Gratuze, 2016). To determine the accuracy and precision of the analyses, NIST SRM612, and Corning A were repeatedly run alongside the archaeological specimens.

Additionally, elemental distribution maps and quantitative chemical composition was determined to examine the homogeneity of the glass matrix, the distribution of the crystals and to analyse the gold leaves. These analyses were conducted by μ-PIXE using the 2.5 MV Van de Graaff accelerator installed at CTN (Portugal). Samples were analysed in polished cross-sections. Bulk glass analysis was carried out using an Oxford Microbeams OM150 type scanning nuclear microprobe setup with in-vacuum configuration (Alves et al., 2000). Samples were irradiated with a 700 keV proton beam and an 8 μm thick Be windowed SDD detector with 145 eV resolution used to collect the induced X-rays. The used experimental configuration allows determining major and minor glass elemental composition for elements down to Na while preventing backscattered protons from entering the detector. The proton beam was focused down to 3 × 4 μm^2 and a scan area up to 4490 × 4490 μm^2 allowed the selection of representative sample regions of interest for quantitative analysis. Quantitative analyses were obtained with the GUPIXWIN program (Campbell et al., 2010). The results are expressed in weight percent oxides and were normalised to 100%. In order to validate

Fig. 1. Mosaics in the *maqṣūrah* of the Mosque-Cathedral of Córdoba. (not to scale).

the obtained concentration results, the Corning glass reference standards were also analysed.

To identify the glass chromophores, the colour of the glass samples was characterized by FORS with an Ocean Optics MAYA 200 PRO spectrophotometer. The illumination is an Ocean Optics HL-200-HP with 20 W halogen light source in a single optical path covering the 360–2400 nm range. Spectra were obtained with an integration time of 8 ms and 15 scans to average. The measuring head, in a 45°/45° (illumination/acquisition angles) configuration, gives a diameter of analysis of about 2 mm. Spectralon® standard was used as reference.

The analysis by μ-Raman spectroscopy was applied on the crystals embedded in the glass tesserae to identify the opacifying compounds. The analyses were performed with a Labram 300 Jobin Yvon spectrometer, equipped with a semiconductor diode laser operating at 785 nm. The laser beam was focused with a × 50 magnification Olympus objective lense. The analyses were the result of 10 accumulations of 20 s carried out without filter on the surface of the glasses. The attribution of the Raman spectra was made using the RRUFF database on minerals.

3. Results

3.1. *Original tesserae identification*

To isolate the original tenth-century tesserae, the materials from later restorations were identified and excluded. The entire mosaic (glass tesserae, n = 13) from the *Bab Bayt al-Mal* chamber (Fig. 1) is a facsimile commissioned by R. Velazquez Bosco to the atelier J. & H. Mauméjean Frères in Madrid in 1912 and installed in 1916 (Nieto Cumplido, 1998; Stern, 1976). Our analytical results confirmed that these thirteen tesserae are all modern material. They are characterized by high soda, very low chlorine and silica-related impurities that suggest the use of synthetic raw materials, as well as high arsenic and antimony not usually encountered in tenth-century glass (Table S1). Other tesserae that can be attributed to restorative interventions include one colourless sample from the *Miḥrāb* door (MAQ C 001) that contains almost 19% potash but hardly any impurities, one homogeneous white tessera from the *Sābāṭ* door (MAQ O 005) with high antimony ($Sb_2O_3 \sim 5\%$) and almost 1% As_2O_3, as well as a burgundy-coloured gold leaf tessera from the *Miḥrāb* dome (MAQ C 037) that has surprisingly high soda (20%), very low potash and magnesia (<0.2%), and low silica-related impurities (Table S1). Four colourless samples with painted layers are the result of a nineteenth-century restoration campaign (Gomez-Moron et al., 2019), and nine tesserae are white stone. The remaining 61 glass tesserae can be considered original and form part of the tenth-century mosaics. LA-ICP-MS analysis identified seven distinct compositional groups, including four sub-groups of high boron containing samples, two types of plant ash glass, as well as yellow and green tesserae with exceptionally high lead contents (PbO > 68%), and a single re-used Roman natron-type glass (Tables 1 and S1).

3.2. High boron tesserae

A large number of the analysed tesserae (n = 46) have relatively high boron concentrations (B > 400 ppm). They can be further separated into four compositional groups (Table 1; Fig. 2). A group of cobalt and copper blue tesserae (high boron blue, n = 15) have been grouped together because they share base glass characteristics as well as opacifying agents that give rise to a similar morphology. Although the three copper blue tesserae do not exactly coincide with the cobalt blue samples in terms of the absolute contents of some trace elements such as strontium or caesium, they fit well within the overall internal variability of the high boron blue group. They have high soda and surprisingly low potash, magnesia, and lime levels as well as low alumina, zirconium, and titanium contents (Table S1). Their high Na_2O/K_2O ratios may be related to the use of a mineral fluxing agent (Fig. 2a). A second group of samples (high boron 1, HB1, n = 15) exhibits a very strong positive correlation between boron (400 ppm < B < 1600 ppm) and lithium (60 ppm < Li < 300 ppm) (Fig. 2b). Both elements are also correlated with sodium and uranium, while all four elements (Li, B, Na, U) exhibit a strong negative correlation with both magnesium and potassium oxide (Table S1), indicative of the use of a mineral source of soda. Some of the gold leaf tesserae of the HB1 group show a positive linear correlation between K_2O and P_2O_5 and they incidentally all originate from the *Sābāṭ* door mosaic (Fig. 2c). They do not differ macroscopically from the other gold leaf tesserae. The elevated phosphorus and potash levels may be the result of either the deliberate addition of plant ash to augment the quantity of the available vitreous material or the accidental contamination of the melt by fuel ash (Barfod et al., 2018; Freestone, 2015; Paynter, 2008; Schibille et al., 2017). This group has moderate silica-related impurities such as alumina (~1.5%), titanium oxide (~0.08%), and zirconium (~26 ppm) (Table 1). Finally, the group high boron 2 (HB2, n = 7) has the highest boron (>1700 ppm) and lithium (>320 ppm) levels (Fig. 2a and b), as well as the highest concentrations of accessory elements like aluminium, titanium and most notably thorium (Table 1).

Most of the gold leaf tesserae belong to either HB1 or HB2. In addition to the difference in the chemical composition of the base glass of these tesserae, the purity of the gold leaf also differs. The tesserae of the HB1 group have typically very pure gold leaves, whereas the gold leaf of the tesserae belonging to group HB2 contains notable amounts of silver (Fig. 2d). The HB1 tesserae are mainly from the mosaics on the *Miḥrāb* and the *Sābāṭ* door, while the HB2 tesserae appear principally in the *Miḥrāb* dome. The latter tend to be larger (1–1.5 cm^2) than those used in the façades at the lower levels (0.2–0.8 cm^2) (Stern, 1976). The systematic difference in terms of the base glass composition, purity of the gold leaf as well as the size of the tesserae strongly suggests independent glassmaking events, the use of different raw materials and the selective use of the material within the mosaic decoration.

In addition to the gold leaf tesserae (n = 17), the majority of the high boron glasses are of different shades of blue (n = 15) and less often black, turquoise, purple and red (Table S1). The blue, turquoise and greyish-blue tesserae are typically translucent with plenty of rounded or elongated bubbles and some dispersed quartz crystals (~100 μm) that occasionally appear together with crystals of cristobalite (Fig. 3a, d, 4). Some of the bluish glasses contain crystals of alkaline sulphate previously observed in ancient glass (Ricciardi et al., 2009; Stapleton and Swanson, 2002), resulting from the limited solubility of alkali earth sulphates during glassmaking (Rehren, 2008). In contrast, the black tesserae are relatively homogenous and owe their colour to a combination of manganese and iron, and to a lesser degree cobalt and copper. μ-Raman spectroscopy identified some inclusions of hausmannite ($Mn^{2+}Mn^{3+}{}_2O_4$) and braunite ($Mn^{2+}Mn^{3+}{}_6O_8(SiO_4)$) (Fig. 4). These rounded crystals may be remnants of the raw materials (Öztürk et al., 2019). Wollastonite inclusions ($CaSiO_3$) were identified in some red, purple and black tesserae. Quartz particles were detected also in a homogeneous dark turquoise tessera with isolated rounded bubbles.

Table 1

Average chemical compositions of the different glass groups identified among the mosaic tesserae of the Great Mosque in Córdoba (LA-ICP-MS). Data were reduced to the given oxides and elements and normalised, except for lead and tin oxides.

Groups	wt%											ppm (μg/g)				wt%	
	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	Cl	K_2O	CaO	TiO_2	MnO	Fe_2O_3	Li	B	Sr	Zr	PbO	SnO_2
high boron blue (n = 15)	19.1	0.45	0.82	71.8	0.11	0.95	0.33	5.48	0.05	0.35	0.62	32.5	798	168	19.7	0.05	–
stdev	*0.7*	*0.08*	*0.16*	*1.1*	*0.01*	*0.20*	*0.08*	*1.02*	*0.01*	*0.69*	*0.37*	*28.6*	*58*	*104*	*2.5*	*0.03*	-
HB1 (n = 26)[a]	16.6	1.79	1.53	69.3	0.20	0.93	1.18	6.59	0.08	1.08	0.74	126	863	685	27.3	0.10	0.008
stdev	*1.0*	*0.48*	*0.21*	*0.7*	*0.06*	*0.12*	*0.33*	*0.80*	*0.01*	*0.17*	*0.10*	*45*	*289*	*158*	*2.6*	*0.05*	*0.004*
HB2 (n = 12)[a]	14.8	2.07	2.13	65.1	0.11	0.33	1.29	10.8	0.10	1.59	1.61	462	2070	2005	27.9	0.02	0.002
stdev	*0.8*	*0.30*	*0.27*	*1.6*	*0.02*	*0.07*	*0.14*	*0.7*	*0.01*	*1.15*	*0.89*	*91*	*248*	*281*	*2.9*	*0.03*	*0.003*
Opaque high boron (n = 7)	11.8	0.89	0.83	77.9	0.12	1.60	0.64	4.3	0.06	1.14	0.70	53.4	409	296	13.4	38.0	6.6
stdev	*2.8*	*0.32*	*0.41*	*6.0*	*0.06*	*0.65*	*0.30*	*1.0*	*0.02*	*1.09*	*0.18*	*31.2*	*211*	*171*	*7.9*	*17.2*	*2.3*
Iberian plant ash (n = 5)	17.3	3.34	2.79	63.0	0.50	1.36	1.86	4.47	0.14	0.41	4.81	23.0	183	217	34.7	5.92	0.24
stdev	*1.6*	*0.24*	*0.29*	*1.6*	*0.07*	*0.28*	*0.22*	*0.42*	*0.01*	*0.59*	*2.15*	*7.7*	*27*	*32*	*1.8*	*6.04*	*0.42*
Levantine plant ash (n = 4)[a]	12.6	3.20	1.51	69.0	0.266	0.81	2.55	8.72	0.062	0.89	0.34	6.30	89.99	539	30.8	–	–
stdev	*0.1*	*0.03*	*0.06*	*0.3*	*0.004*	*0.02*	*0.02*	*0.14*	*0.002*	*0.08*	*0.01*	*0.52*	*0.92*	*5*	*0.8*	-	-
High lead (n = 7)[b]	0.30	0.04	0.05	22.1	0.007	0.63	0.016	0.25	0.005	0.005	0.09	2.38	1.55	5.13	1.56	72.0	4.20
stdev	*0.08*	*0.01*	*0.02*	*2.5*	*0.004*	*0.16*	*0.007*	*0.05*	*0.002*	*0.003*	*0.02*	*2.43*	*0.70*	*2.03*	*0.46*	*2.4*	*1.25*

[a] Includes separate measurements for the support and the cartellina of the gold leaf tesserae.

[b] The reduced composition included the lead and tin oxides.

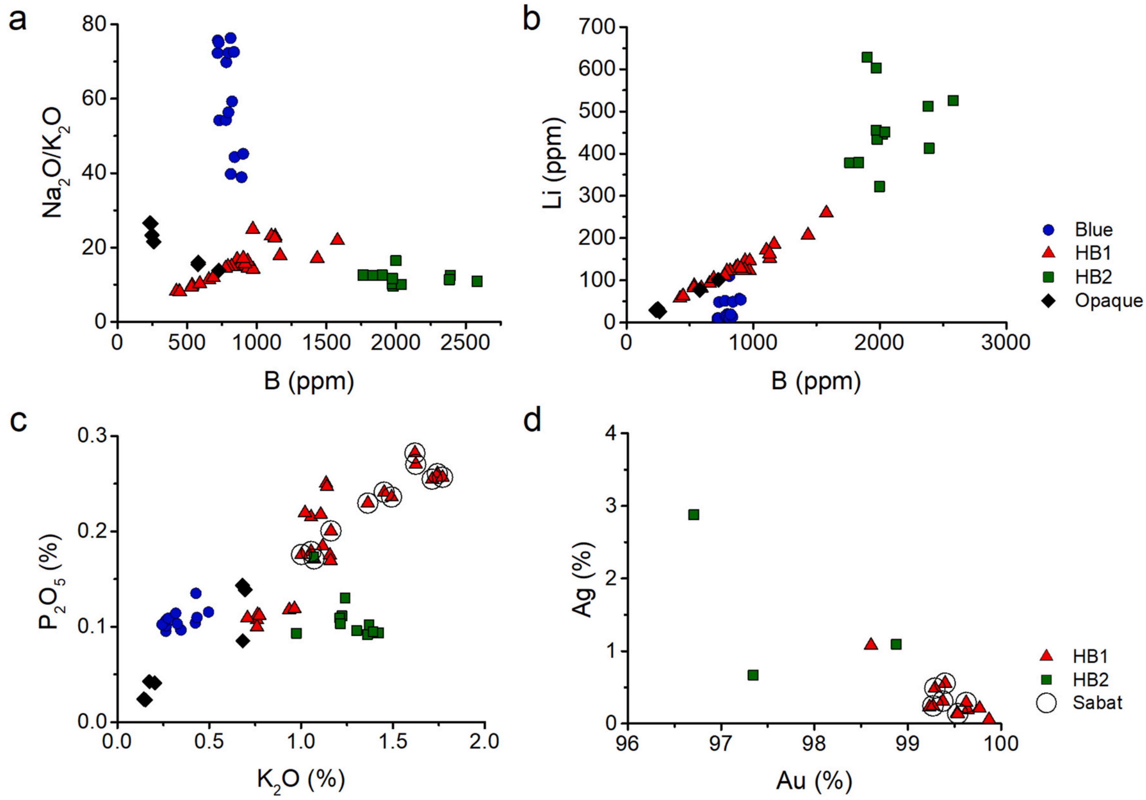

Fig. 2. Compositional characteristics of the different high boron groups (LA-ICP-MS). (A) Na_2O/K_2O ratios versus boron show a clear difference between the fluxes; (B) lithium and boron are positively correlated in the high B1, high B2 and opaque glasses; (C) K_2O and P_2O_5 are elevated in the high B1 group possibly due to a batch contamination or an addition of plant ash. The circled data points represent gold leaf tesserae of the HB1 group from the Sabat door mosaic. (D) Gold leaf composition of the high boron glasses (μ-PIXE). Gold versus silver contents show different compositions that match with the two sub-groups of high boron glasses. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

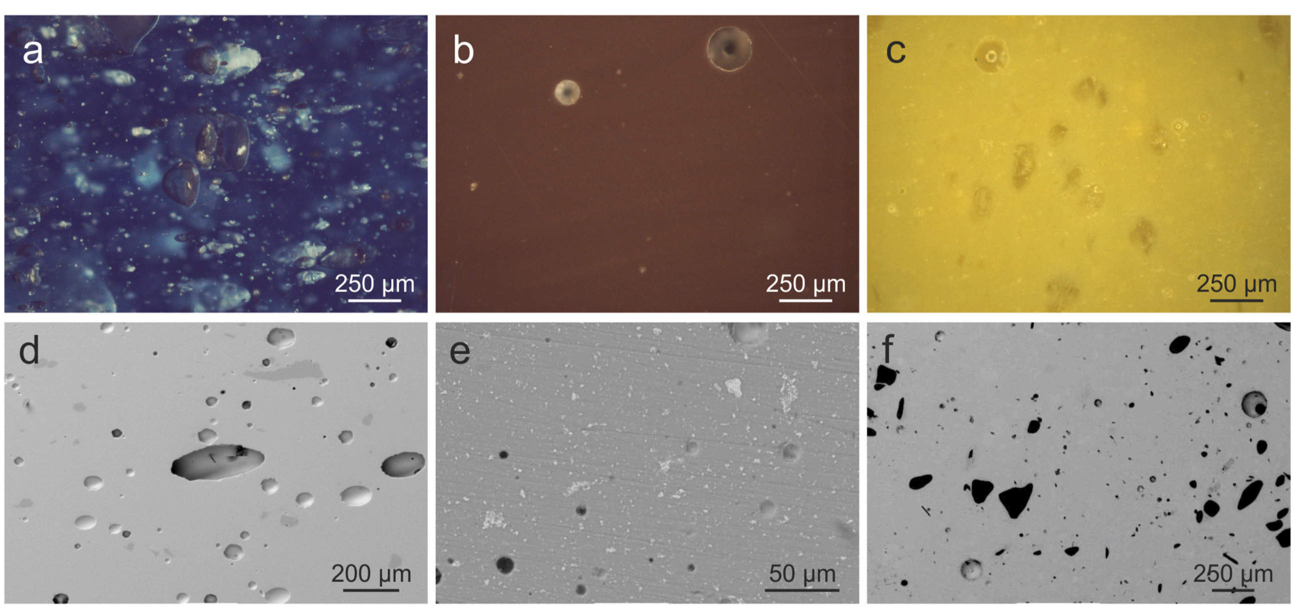

Fig. 3. Optical microscope and SEM images of different glass tesserae. (A)(D) The high boron blue glasses show big bubbles and isolated quartz inclusions in a transparent matrix (samples MAQ O 17 and MAQ C 23); (B)(E) the brown opaque high boron samples MAQ O 23 and MAQ C 26 were opacified by the presence of small crystals of cassiterite; (C)(F) the yellow high lead glass (sample MAQ C 039) owes its colour and opacity to lead stannate, quartz and isolated bubbles.

Finally, seven opaque tesserae belong to the opaque high boron group. They have varying and relatively high levels of lead (19%–56%) and tin oxide (3%–9%) (Table S1). These tesserae are very homogeneous; they do not contain any bubbles but numerous small crystals of cassiterite ($SnO_2 < 15$ μm) uniformly spread throughout the glass matrix (Fig. 4b, e, 5a). The lithium, boron and strontium levels in the reduced and normalised base glass composition of these opaque tesserae resembles the HB1 type, but with lower overall alkali and alkaline earth

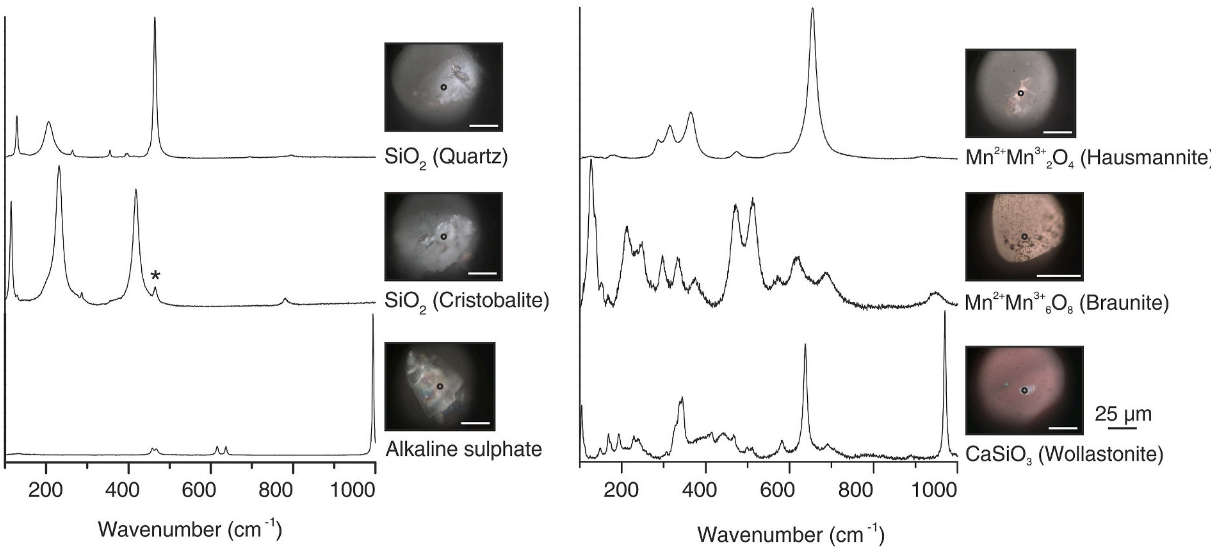

Fig. 4. Raman spectra of different opacifying elements. Quartz and cristobalite phases have been detected in sample MAQ C 05 (* the Raman band of the adjacent quartz), the alkaline sulphate in MAQ C 13, the hausmannite in MAQ C 31, the braunite in MAQ C 10 and wollastonite in MAQ C 22. Scale bar is 25 µm.

metals, lower alumina and higher chlorine contents (Table 1). High levels of chlorine, in the order of 2% of the reduced composition, are unusual for natron or soda-rich plant ash glass, and more commonly found in soda-ash lead glasses of early Islamic al-Andalus (de Juan Ares et al., 2021; Duckworth et al., 2015). Three of the opaque tesserae (MAQ C 025, MAQ C 027, MAQ O 015) with around 20% lead oxide may be explained by the mixing of equal proportions of an Iberian soda-ash lead glass that typically contains between 40% and 50% PbO (de Juan Ares et al., 2021), and a Byzantine high boron glass that introduced high amounts of lithium, boron and strontium to the melt. A simple graphical comparison of a hypothetical 1:1 mixture of HB1 (n = 26) and a contemporary Iberian soda-ash lead glass (n = 185) highlights the possibility of such a mixing model (Fig. 6). All elements (except the trace elements W and Ta) distribute along the 45° line representing equity between the hypothetical composition and the average value of the three opaque tesserae. This strengthens the idea that some materials were produced or processed in al-Andalus. The remaining four samples have significantly higher lead oxide contents (46%–55%) and are not easily explained. The eighth- to ninth-century lead slag glass from the suburb of Saqunda in Cordoba has on average about 52% lead oxide, but has otherwise very different trace element patterns (Schibille et al., 2020a, 2020b). Instead, elevated traces of silver, tin and bismuth and low levels of lime and barium suggest the use of litharge from silver cupellation rather than the addition of slag from lead metallurgy

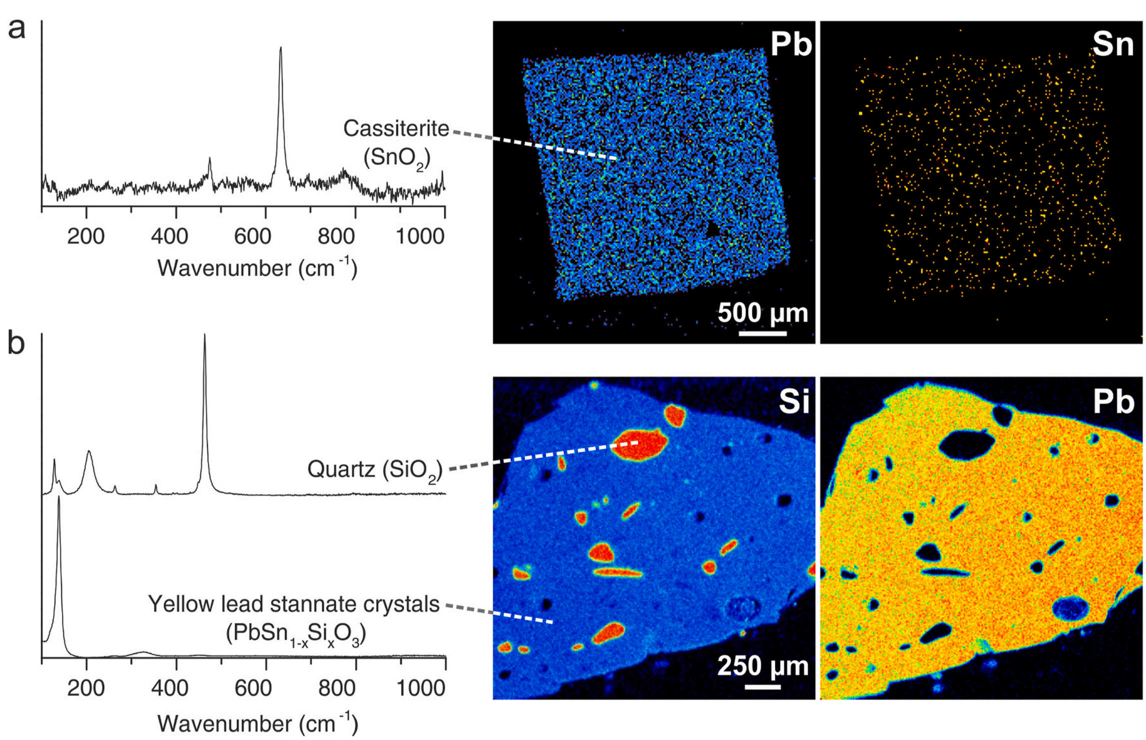

Fig. 5. Raman spectra of the inclusions and µ-PIXE mappings. (A) Turquoise tessera (MAQ O 003) of the opaque high B group; (B) yellow tessera (MAQ O 012). Intensities are indicated in false colours (blue = low intensity, yellow = medium intensity, red = high intensity).

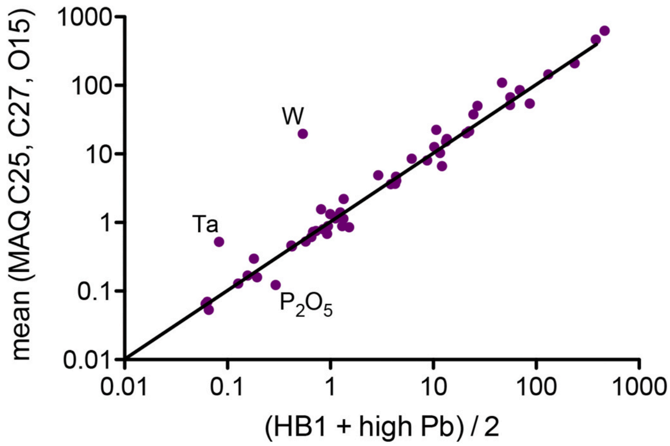

Fig. 6. Hypothetical mixing of high boron HB1 with Iberian lead glasses. The average composition of the opaque tesserae (MAQ C 025, MAQ C 027, MAQ O 015) was approximated by a hypothetical 1:1 mixture of HB1 (n = 26) and an alkali lead glass from contemporary Madīnat al-Zahrā (n = 185; Schibille unpublished). The overwhelming majority of elements lie close to the 45° line that indicates compositional identity.

(Gratuze et al, 2003, 2014, 2017; Wedepohl et al., 1995).

3.3. The other tenth-century tesserae

The base glass composition of two gold leaf tesserae (base and cartellina, hence four separate analyses) from the dome decoration is consistent with Islamic soda-rich plant ash glass produced on the Levantine coast (Fig. 7a and b) (Brill, 2002; Freestone, 2002; Phelps, 2018). Similar gold leaf tesserae are known from the eleventh-century mosaic of the Church of Santa Maria Assunta in Torcello (Italy) (Andreescu-Treadgold et al., 2006), the Nativity Church in Bethlehem dating to the twelfth century (Neri et al., 2016), and Hagia Sopia in Istanbul probably dating to the thirteenth century (Schibille, unpublished). However, no Iberian mosaic tesserae belonging to this group have previously been identified.

Four red and one dark green tesserae also have a plant-ash signature but different trace element patterns (Fig. 7a and b). They have considerably higher thorium to zirconium ratios than those normally found in early Islamic plant ash glass from the eastern Mediterranean, which are associated with Iberian glass production (de Juan Ares et al., 2021; de Juan Ares and Schibille, 2017b). The red tesserae owe their colour to the presence of nanometric particles of metallic copper or Cu_2O that are unevenly distributed throughout the glass matrix in alternating red opaque and translucent layers (Bandiera et al., 2019). At high magnification, metallic micro-particles of copper are distinguishable in the red areas, while they are absent from the translucent layers. In terms of the colouring technique, the red tesserae resemble Roman and late antique copper red glasses, but for the exceptionally high iron contents ($Fe_2O_3 >$ 4%) (Table 1). Although iron oxide concentrations in copper red glass can be highly variable, they seldom exceed 3% (Barber et al., 2009; Freestone et al., 2003; Wypyski, 2005) and tend to be lower in Roman red plant ash glass (Schibille et al., 2020a).

Finally, seven yellow and green tesserae have very high contents of lead (average ~ 75%), moderate silica (average ~ 23%), and negligible levels of silica-related elements such as alumina ($Al_2O_3 < 0.1\%$), titanium (Ti < 60 ppm) and zirconium (Zr < 2 ppm), and considerable amounts of tin (2%–5.5%) (Tables 1 and S1). These yellow and green tesserae are compositionally similar to medieval glass beads and rings found throughout Europe (e.g. Neri et al., 2019a; Siemianowska et al., 2019), as well as to the intermediate yellow vitreous pigment known as *anima,* a glassy mixture of lead-tin calx and silica that is typically present in ancient glass in the crystalline form of $Pb(Sn,Si)O_3$ (Matin, 2019; Moretti and Hreglich, 1984). Big rounded quartz crystals (100–250 μm) accompanied by small aggregations of $PbSn_{1\text{-}x}Si_xO_3$ (5–20 μm) homogenously dispersed in a translucent matrix were confirmed by OM, μ-PIXE mapping as well as μ-Raman spectra (Fig. 3c, f, 5b). The composition of these glasses is very similar to some glazed ceramics from Madīnat al-Zahrā (Salinas et al., 2019), the city built by Abd-al-Rahman III on the western outskirts of Córdoba.

4. Discussion

The most remarkable finding is the presence of a large number of samples with high boron levels among the glass mosaic tesserae of the Great Mosque of Córdoba (47 out of 61 tesserae). Boron contents in ancient glass commonly range from about 40 ppm to 200 ppm (e.g. Phelps, 2018; Phelps et al., 2016; Schibille et al., 2019, 2018) and are considered an impurity of the raw materials, mostly the fluxing agent (Devulder et al., 2014). In recent years, examples of high boron glasses have been identified among Byzantine assemblages and/or finds from Asia Minor, dating from the sixth or seventh century (e.g. Aphrodisias, Brill, 1999, 1969), to the twelfth or thirteenth century (e.g. Zeyrek Camii, Brill, 2005; Pergamon, Schibille, 2011; Ḥiṣn al-Tīnāt, Swan et al., 2018; Hagia Sophia, Schibille, unpublished), and as late as the fifteenth century and later in the form of Iznik glazes (e.g. Tite et al., 2016). Although these high boron glasses display an immense variability in terms of the elements related to the fluxing agent as well as elements

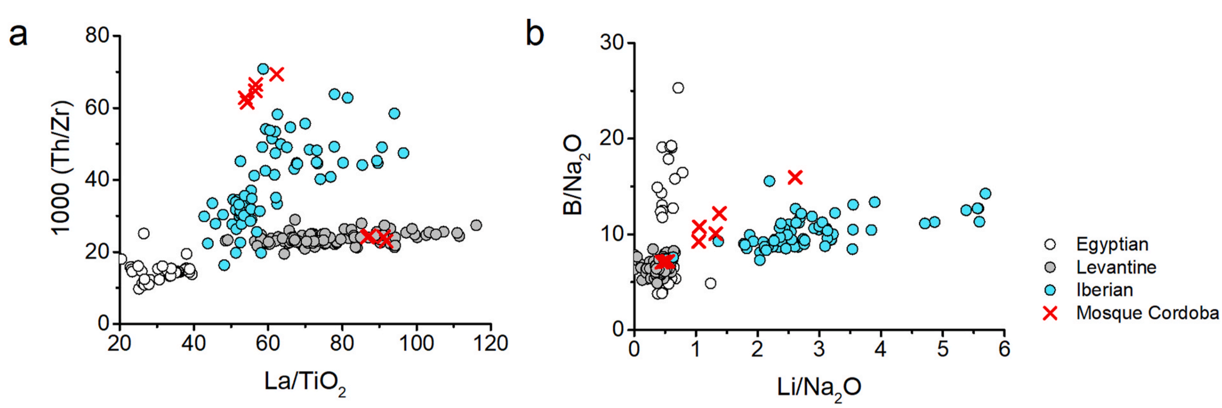

Fig. 7. Plant-ash glasses from Córdoba in comparison with contemporary glass reference groups (LA-ICP-MS). Plant-ash glasses are compared to samples from the Levant P1 (Phelps, 2017), Egypt E2, E3 & E4 (Schibille et al., 2019) and Ciudad de Vascos groups 3, 4, 5 (de Juan Ares and Schibille, 2017b) representing Iberian plant ash glass. (A) Th/Zr and La/TiO_2 ratios clearly distinguish the silica sources of the three major production regions. Iberian plant ash glasses have typically higher thorium relative to zirconium; (B) boron and lithium to soda ratios confirm the differences in the raw materials and/or the production procedures in relation to the alkali component.

associated with the silica source, the presence of boron has been interpreted as a specific marker for an origin in Asia Minor. Robert Brill was the first to suggest the origin of these high boron glasses to be Turkey, where the world's largest boron deposits are found (Brill, 1969, 2002, 2005). This idea has been confirmed by the compositional data of a range of thermal waters from western Turkey, which produced a good match for some of the Byzantine high boron glasses and Iznik glazes (Tite et al., 2016).

The composition of the mosaic tesserae from Córdoba presented here fall within the broad range of earlier findings of high boron glasses as regards the alkali and alkaline earth metals (Fig. 8). Our analytical data show that at least three different sources of alkali fluxes were exploited, which is reflected in the contrasting Na_2O/K_2O ratios relative to the boron levels as well as the absolute lithium and boron concentrations (Fig. 8). Samples from Aphrodisias (Brill, 1969, 1999), Ḥiṣn al-Tīnāt dated to the tenth to twelfth century (Swan et al., 2018), and a few mosaic tesserae from the church of Hagia Sophia in Constantinople (Schibille, unpublished) provide a close match for the HB2 group in terms of their Na_2O/K_2O ratios and lithium and boron concentrations. Some Iznik glazes (Tite et al., 2016), and some of the late Byzantine glasses from Pergamon (Schibille, 2011) and Sardis (Brill, 1999) show similarities with the group HB1 from Córdoba. One tessera from Hagia Sophia (Schibille, unpublished) and some of the late Byzantine glasses from Pergamon (Schibille, 2011) have lithium and boron levels that resemble the high boron blue group from Córdoba.

Our data reinforce the model of Byzantine glass production in the latter part of the first millennium CE using mineral fluxing agents from soda-rich evaporites characterized by elevated boron levels. It is highly probable that hot springs in western Turkey were the source of the alkali fluxes and that several primary productions of high boron glass existed in Byzantine Asia Minor that operated in parallel on a relatively small scale, thus yielding a greater variety of glass compositions. The production of the cobalt blue glass, for instance, was evidently a specialized technology based on the use of very clean starting materials and a mineral soda as fluxing agent (Table 1). Hot springs in western Anatolia could have supplied this mineral soda, poor in potassium and magnesium and enriched with boron. The high boron blue glass from Córdoba has significantly higher Na_2O/K_2O ratios than any of the other known high boron glasses (Fig. 2). This could partly be the result of using a relatively clean silica source low in accessory minerals such as feldspar, and/or additional purification processes of the extracted mineral soda (Tite et al., 2016). A possible alternative is natron from Lake Van in eastern Anatolia that is known from historical sources to have been used since Roman times (Shortland et al., 2006), but this would not explain the elevated lithium and boron concentrations in these glasses. The cobalt colorant does not exhibit any distinctive features and is reminiscent of relatively pure Roman cobalt with low nickel and zinc, and only somewhat elevated arsenic, tin and lead contents (Table S1; Gratuze et al., 2018). This clearly distinguishes the cobalt of the mosaic tesserae from Córdoba from contemporaneous cobalt sources used in Islamic glassmaking in the eastern Mediterranean and Mesopotamia (Schibille et al., 2018).

The mosaic tesserae from Córdoba represent the largest assemblage of high boron glass found outside of Asia Minor to date and the one furthest west, testifying to the close diplomatic relationship between Byzantium and the Caliphate of Córdoba. The exchanges of gifts was a common practice, and diplomatic relations seem to have particularly thrived between Constantine VII Porphyrogenitus (905–959 CE), the fourth Emperor of the Macedonian dynasty of the Byzantine Empire, and Abd al-Rahman III (891–961 CE), the first Caliph of Córdoba (Signes Codoñer, 2004; Valdés Fernández, 2013). Described by Islamic writers including Muhammad al-Idrīsī in the twelfth century and Ibn ʻIḏari in the fourteenth century, the material for the mosaics of the Great Mosque in Córdoba were a gift from the Roman (Byzantine) emperor of Constantinople to the Caliph of Córdoba (Nieto Cumplido, 1998; Ocaña Jiménez, 1976). Al-Idrīsī even specified that the mosaics had been sent by Constantine VII (Stern, 1976). However, the mosaic decoration of the *maqṣūrah* was commissioned by Abd al-Rahman's son, al-Hakam II (915–976, reigned 961–976 CE), and the work on the *Miḥrāb* probably began around the year 965 CE and was completed in 971–972 CE (Ocaña Jiménez, 1976). Hence, the Byzantine emperor at the time should have been Nikephoros Phokas (912–969, reigned 963–969 CE). There is the distinct possibility that the plan to decorate the mosque with mosaics was conceived by al-Hakam's father, Abd al-Rahman III before his death, as described in the text of Muhammad al-Idrīsī (Signes Codoñer, 2004). The mosaics could then have arrived together with an embassy sent by the emperor Romanos II (939–963, reigned 959–963 CE), son of Constantine VII, around the year 961 CE (Signes Codoñer, 2004). Irrespective of which emperor actually sent the tesserae, our data prove that the material for a large proportion of the mosaics of the Mosque of Córdoba came from Byzantium, most likely as a gift of high material and ideological value. The diplomatic exchange and reception of Byzantine embassies in the courts of Cordoba and Madinat al-Zahra' in the tenth century strengthened the political ties in the Mediterranean, and the mosaics of the Great Mosque are a visual expression of these allegiances and of imperial power. No other Islamic monumental mosaic is known from the tenth century or mentioned in Islamic textual sources (Leal, 2020). The Byzantines played a key role as ally against both the Abbasids in the Near East and the Fatimids in North Africa (Anderson and Pruitt, 2017; Signes Codoñer, 2004). The choice of decoration in the

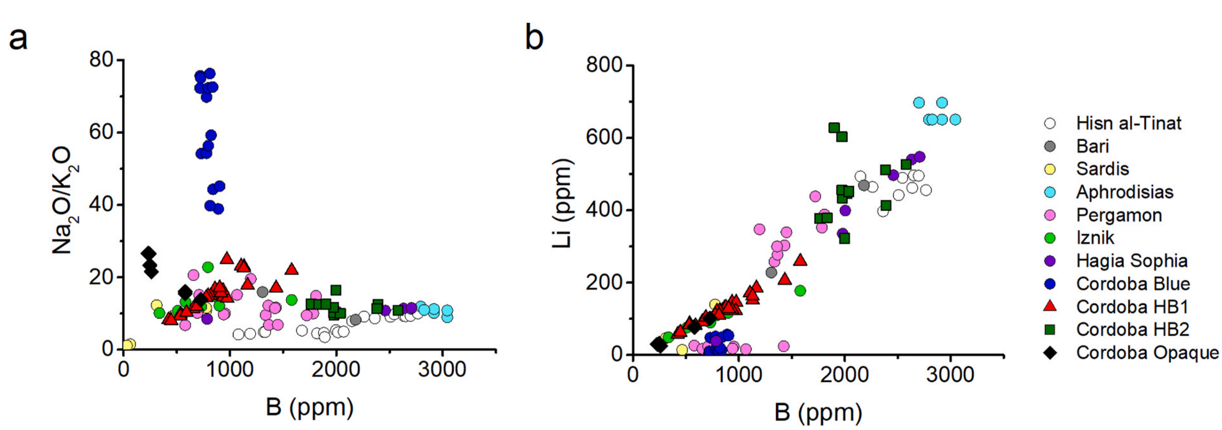

Fig. 8. High boron glasses from Córdoba in comparison with high boron samples (LA-ICP-MS). High boron glasses are compared to samples from Ḥiṣn al-Tīnāt (Swan et al., 2018), Bari (Neri et al., 2019b), Sardis, Aphrodisias (Brill, 1999), Pergamon (Schibille, 2011), Iznik (Tite et al., 2016) and Hagia Sophia (Schibille, unpublished). A) Na_2O/K_2O ratios show the great variability of the boron glasses. Córdoba HB1 glasses match with samples from Iznik, Sardis and Pergamon, and Córdoba HB2 with Aphrodisias, Ḥiṣn al-Tīnāt and Hagia Sophia also in terms of their lithium and boron contents (B).

Great Mosque of Córdoba therefore serves a clear political purpose. The mosaics provide a visual link with the long-lost Umayyad Caliphate in Syria and bestow legitimacy on the Caliphate of Córdoba. In both cases, it was (allegedly) Byzantium that supplied the necessary material and technical expertise.

In the fourteenth century, Ibn ʻIḏari informs us that the Byzantine emperor not only sent mosaic tesserae but also the mosaicist who taught Mamluk apprentices and slaves in the art of mosaic making . According to Ibn ʻIḏari, the apprentices acquired skills of invention and eventually came to surpass the master mosaicist (Signes Codoñer, 2004). It is doubtful whether this story is true, because the alleged mosaic school has left no other trace in the historical or archaeological record of al-Andalus (de Juan Ares et al., 2021)(James, 2017). However, the presence of Byzantine craftsmen may account for some of the compositional peculiarities of the other tenth-century tesserae that exhibit signs of mixing, recycling and possibly local secondary production. The characteristics of some of the opaque tesserae with elevated boron are best explained by a mixture of an imported Byzantine high boron glass with an Iberian alkali lead glass (Fig. 6). These tesserae are likely to have been produced locally, given that a suitable soda-ash lead glass with relatively high chlorine values predominates the archaeological record of Córdoba in the tenth century (de Juan Ares et al., 2021; Schibille et al., 2020b) . Similarly, the red tesserae with high thorium to zirconium ratios are without precedent among the available corpus of analytical data of medieval glass mosaics. It is tempting to speculate that these objects resulted from a local production of some mosaic tesserae. A plausible scenario is that due to a shortage of imported mosaic tesserae, the mosaicists responsible for the decoration of the *maqṣūrah* in the Mosque of Córdoba used local resources to supplement the available material. Judging by the absence of a mosaic-making tradition in the Iberian Peninsula, it can be assumed that this local production of mosaic tesserae was indeed instigated by skilled Byzantine craftsmen, suggesting a transfer of technologies from Byzantium to al-Andalus. This is not to say that there was a lack of glassmaking skills in Iberia, because there is ample evidence for the local production of soda-ash lead glass as well as lead and tin glazes that could have provided the necessary expertise for the manufacture of tin opacified glasses (Duckworth et al., 2015; Molera et al., 2018; Schibille et al., 2020b). However, the production of mosaic tesserae represents a specialized craft that was, as far as we know, more widely practiced in Byzantium. In 1321 at Orvieto (Italy), documentary evidence makes it clear that part of the tesserae used for the decoration of the façade of the Orvieto cathedral were coloured and made on site, and that a furnace was explicitly built for this purpose (Harding, 1989). Even though we cannot extrapolate from fourteenth-century Orvieto to mosaic making practices in tenth-century Islamic al-Andalus with any certainty, the Orvieto evidence demonstrates the feasibility of a production model that differs from that of the Roman and late antique periods with specialized workshops for mosaic making. Our data from Córdoba thus add new information not only about the movement of materials, but potentially also the movement of skilled craftsmen and the possible long-distance transfer of technological know-how. This sheds new light on the connectivity of the medieval Mediterranean region and adds a human dimension.

5. Conclusions

Medieval wall mosaics are regarded as an essentially Byzantine and relatively expensive art form that has survived from religious foundations and palaces across the Mediterranean world. Despite the ubiquity of glass mosaics, we know surprisingly little about their material characteristics and where they came from. Islamic sources promoted and celebrated the Byzantine nature and origins of the mosaics of some of the most important Islamic monuments, including the Great Mosque in Damascus and the Umayyad Mosque of Córdoba. Historical writings are notoriously unreliable when it comes to extracting facts, but they often reveal how a work of art was regarded at the time. Our compositional analysis shows that the tesserae of the Mosque of Córdoba were mostly made from boron-rich raw materials from western Anatolia and therefore confirm the written sources. The mosaic decoration of the Umayyad mosque presents in fact the largest collection of Byzantine high boron glasses outside the Byzantine Empire to date, highlighting the scale of Byzantine glass production and illustrating the fact that tesserae and craftspeople travelled the entire Mediterranean, crossing political and religious divisions. The Byzantine glass industry is fully independent of contemporary Islamic glassmaking traditions, which also extends to colouring agents such as cobalt. Our data also provide striking evidence for a possible local production of some mosaic tesserae in the Iberian Peninsula, which points to the transfer of unique technical expertise in mosaic glassmaking in addition to the import of the material itself. The scale of this local production may have been very limited, but could foreshadow later developments of localised and temporary workshops in connection with monumental building campaigns.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jas.2021.105370.

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