Historical restorations of the Maqṣūrah glass mosaics from the Great Mosque of Córdoba

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ABSTRACT

The Great Mosque of Córdoba is the only mediaeval Islamic monument in al-Andalus that still contains some of its original 10th-century glass mosaic decoration, even though they were significantly altered and restored several times in the 18th, 19th and 20th centuries. By examining analytical, textual, and graphic evidence, this study attempts to reconstruct the different transformations of the Maqṣūrah, focusing on the glass mosaics in order to assess possible implications for their state of preservation. The results show that high-alumina glass, which can be associated with modern tesserae, was used to restore the Mihrab and Sābīt mosaics. Modern pigments were also detected in the paints that were applied in situ to the surface of the colourless glasses. Textual and analytical evidences prove that Bāb Bayt al-Mal mosaic was completely removed in the 20th century and a replica with high-lead tesserae was installed in the same place.

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Las restauraciones históricas de los mosaicos de vidrio de la Maqṣūrah de la Gran Mezquita de Córdoba

RESUMEN

La Gran Mezquita de Córdoba es el único monumento islámico en al-Andalus que aún contiene restos de su decoración original del s. X en mosaico de vidrio, a pesar de haber sido significativamente alterado y restaurado en varias ocasiones en los ss. XVIII, XIX y XX. Mediante el estudio analítico y las evidencias gráficas y textuales, este estudio pretende reconstruir las diferentes transformaciones de la Maqṣūrah, especialmente en los mosaicos

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Introduction

Córdoba became the capital of the Roman province of Hispania Ulterior and was also an important administrative centre during the Visigoth period. The city prospered particularly after the Muslim conquest of the Iberian Peninsula, first as the capital of the Umayyad Emirate (756–929 AD), and later the Caliphate of Córdoba (929–1031 AD). ʿAbd al-Rahmān I (Reign: 756–788 AD), the founder of the Umayyad dynasty of al-Andalus and the Emirate of Córdoba, commissioned substantial urban developments, including the construction of the Alcázar on the ruins of the Visigothic palace, and above all the foundation of the Great Umayyad Mosque (786–787 AD) [1–3]. The original Umayyad Mosque, finished by his son Hisham I, had eleven naves and twelve corridors from East to West (Fig. 1). This building was repeatedly modified and extended in the following centuries by ʿAbd al-Rahmān II (∼840 AD), Al-Hakam II (∼960 AD), and Almanzor (988 AD) [4] (Fig. 1). In the process, the original qiblah was destroyed and a new Maqṣūrah, with three chambers, was built in the mid of 10th century (Fig. 1) [4–6]. The Mihrāb in the centre is flanked by two lateral chambers, the Bāb Bayt al-Māl (treasury) on the left and the Sābāt chamber on the right connected with a corridor to the caliphal palace [7–9]. The façades of the three chambers (Bāb Bayt al-Māl, Mihrāb, and Sābāt) and the dome of the entrance hall of the Mihrāb were decorated with multi-coloured glass mosaics mainly composed of gold leaf tesserae and different shades of red, green and blue (Fig. 2).

The entrance hall of the Mihrāb is crowned by a qubba almost 15 m above floor level. It is divided by eight ribs into segments thus forming an octagon decorated with verses from the Quran [22:76; 22:77 & 22:78] along its eight sides [11]. The central cupola is divided into eight petals separated again by eight ribs (Fig. 2a). The façade of the Mihrāb is decorated with a broad horseshoe arch formed of nineteen vousoirs with symmetric floral decorations on alternating red, gold, and blue backgrounds (Fig. 2b). Around the arch, a verse from the Quran [99:23] appears in a horizontal line with blue letters on a golden background. Around this verse and the arch appear two more verses [32:5 & 40:6] as well as an inscription that commemorates al-Hakam al-Mustansir as the patron of the mosaics. The inscription furthermore specifies that the work was carried out by the freeman and ḥāyib (chamberlain) Yaʿfar ibn ʿAbd al-Rahmān under the supervision of the sāḥāb al-shūrta (labour inspectors and police) Muhammad ibn Tamūl, Ahmad ibn Naṣr, Jal ibn Hāṣhim and Muṭarrif ibn ʿAbd al-Rahmān from the kāṭib (secretary/scribe) [11,12]. These texts are written in vertical and horizontal lines, surrounding the arch. Seven niches on top of the arch are decorated with mosaics of flowers, symmetrically arranged.

The Sābāt and Bāb Bayt al-Māl façades, which are formed by an arch with 15 symmetric vousoirs façades, show the same mosaic consisting of vegetal motifs on red and gold backgrounds [4]. Around them, the ʿalīf was decorated with three texts alternating with geometric motives (Fig. 2c, d). The two inner inscriptions are commemorative texts about the work and the people involved in its execution, similar to the one from the Mihrāb. However, the external inscription contains verses [2:236 & 3:6] from the Quran. The frames of the small windows above the mosaic are likewise decorated with Quranic verses [6:101 & 6:102] surrounded by the same geometric pattern. Under the horseshoe arch, verses [41:30, 41:31 & 41:32] are written in gold lettering on a blue background (Fig. 2c, d). Some inscriptions are partially lost. For example, the mosaic inscription on the façade of the Sābāt chamber was restored without following the original inscription.

The mosaics have undergone considerable changes over the centuries, especially in the aftermath of the building’s conversion into a Christian cathedral in 1236 AD [4,8,13–16]. The original mosaics were thoroughly characterized in previous works [17,18] and, therefore, the main objective of the present study is to identify the historical changes and restorations of the Maqṣūrah mosaics based on a combination of textual and graphic sources as well as the material and compositional evidence of the mosaics. The close examination of the architectural and decorative modifications of the Maqṣūrah over time reveals the impact these had on the preservation of the mosaics. The characteristics of the different restoration campaigns in turn shed light on different traditions of conservation, which at different times were contingent on intrinsic cultural and aesthetic values and principles.

Methodology

For the historical review, different digital archives and libraries were consulted to obtain the historical documentation. This includes the Biblioteca Nacional de España, the Biblioteca Virtual de Prensa Histórica, the institutional repository of the Universitat Politècnica de Catalunya, and the Repositorio Real Academia de Córdoba, among others.

For the analytical characterization, 91 tesserae from the maqṣūrah mosaics of the Mosque-Cathedral of Córdoba were removed for analysis by optical microscopy (OM), scanning electron microscopy – energy dispersive X-ray spectroscopy (SEM-EDX), laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS), micro-particle-induced
Fig. 1 – Plan of the Great Mosque of Córdoba indicating the different expansions and alterations. Adapted from Biblioteca Digital Hispánica, Biblioteca Nacional de España [10].

Fig. 2 – Mosaics in situ: (a) the dome of the entrance hall of the Mihrab; (b) the Mihrab chamber; (c) Bab Bayt al-Mal chamber; (d) Sabat chamber. Source: Authors.
Results and discussion

Mosaics’ creation and their modifications over the centuries

Muhammad al-Idrisi, in the 12th century, and Ibn ‘Idari, in the 14th century, wrote that the qibla of the Great Mosque was decorated with al-fusayfisa al-mud hab wa-l-muluwan (golden and coloured mosaics) and musayyaya (with glaze) tiles, which were sent by the emperor of Constantipole to ‘Abd al-Rahmân III, father of Al-Ḥakam II [8,13,19]. The mosaics of the Mihrāb and the dome, were the first to be finished, followed by the decoration of both lateral chambers [4]. An inscription on the Bāb Bāyt al-Māl façade specifies that the decoration here was finished in 354 H (965 AD). This date also appears in a marble inscription inside the Mihrāb and in the cymatium of the Mihrāb’s arch [11,20]. Ocaña Jiménez argues that since the date appears in a restored part of the Mihrāb it may have been incorrectly attributed, and that a date in late 360 H (971 AD) is more likely for the completion of the mosaics [11]. The mosaics of the Sābāt door appear to have been finished between 970 AD and 973 AD [21]. The left border of the mosaic of the Sābāt door was mutilated around the year 366 H (976 AD) in connection with the opening of a narrow door to the left, where the Minbar (wooden pulpit) was typically stored [4].

On 29 June 1236, King Ferdinand III of Castile conquered Córdoba and the Bishop of Osma (Soria) consecrated the Great Mosque of Córdoba as a Christian church, dedicated to the Assumption of the Virgin. It eventually became the Cathedral of Córdoba and in 1368–1371, King Henry II of Castile ordered substantial architectural modifications to turn the mosque into a proper Christian ecclesiastical structure (Fig. 1) [1,22–25]. In this process, the Mihrāb was converted to the sacristy of the chapel of Saint Peter known as the Chapel of Zancarrón (Fig. 3).

From documentary and pictorial evidence we know that in 1390, the mosaics of the Mihrāb were partially covered up with an altarpiece depicting Saint Catherine of Alexandria, Saint Francis of Assisi, Saint Peter, Saint Paul, and the Nursing Madonna [26–28]. The chapel progressively fell into total disrepair and was all but forgotten. In 1892, a newspaper notice in the Diario de Córdoba pointed out the existence of a partition wall in front of the Mihrāb [27]. This agrees with the existence of a wall in front of the door and a corridor on the right side of the Sābāt chamber that appears in the historical plans of

X-ray emission (µ-PIXE), Fibre Optic Reflectance Spectroscopy (FORS), and µ-Raman spectroscopy (for detailed description of the analytical methods see [17]).

Additionally to these techniques, Gas Chromatography (GC) was applied to identify the organic compounds of the paints. For the determination of lipophilic substances, such as drying oils, resins and waxes; and of hydrophobic substances, such as proteins and gums – polysaccharide (gum Arabic and related products), samples are treated with the Meth-prep II methylation reagent. For carbohydrates and proteins, a hydrolysis is carried out with microwave-assisted 6 M HCl and a derivatization with MTBSTFA in pyridine of the resulting fatty acids, amino acids and monosaccharides.

Finally, Fourier transform infrared spectrometry (FTIR) was used to characterize the surface layers. The instrumental setup was a PerkinElmer Spectrum 3 FT-IR/NIR Spectrometer coupled to an Attenuated Total Reflection (FTIR-ATR) accessory, microscopy spotlight 200 and detector MIR TG5. The analyses in cross-section were done with a spectral range from 4000 to 400 cm⁻¹ with a spectral resolution of 4 cm⁻¹.
the Mosque made in the 18th century by the architects Juan de Villanueva and Juan Pedro Arnal (Fig. 3b) [10,29–31] and in an engraving from 1812 [32,33]. This wall was also hinted at in the description of the chapel of Saint Peter by Ambrosio de Morales in 1572 [34]. The historian described the chapel as consisting of two rooms (one inside the other) decorated with mosaics and another small room (inside the inner one), the Mihrab [34]. He described the decoration as a delicate mosaic work with small patterns of floral motifs and pointed out that the designs were less perceptible in the mosaic of the lateral chamber than in the Mihrab façade, probably due to low contrast, reduced lighting or poor conditions of the mosaic.

Until 1586, the Báb BAYt al-Mál chamber to the left of the Mihrab housed the sanctuary of the cathedral [35]. In 1595, the canons Antonio and Hernando Mohedano de Saavedra founded the Chapel of the Last Supper in the Báb BAYt al-Mál and covered the mosaics with the canvas of the “La Última Cena” (“Last Supper”) by Pablo de Céspedes [35–37]. The canvas, which is still in the building, completely covered the façade of the chamber, as a result of which the mosaics fell into oblivion. Ancient plans of the mosque show a wall behind the canvas both in the theoretical mosque as well as in drawings of the cathedral (Fig. 2) [10]. Some engravings and photographs from the 19th century show the canvas in its original location in front of the mosaic [28,38–40] (Fig. 4). Even newspaper reports and books denied the possibility of the existence of two lateral chapels to either side of the Mihrāb [23,41,42]. It was believed that they had disappeared entirely during the 15th-century modifications initiated by the bishop Íñigo Manrique [43].

For more than two centuries, the mosaics were covered with altarpieces. As a consequence of the Lisbon earthquake in 1755, several parts of the Mosque-Cathedral were severely damaged, such as the tower, causing serious structural damages [14,44]. The Mihrāb dome was probably also affected because in 1767, the cathedral chapter ordered its repair as water filtered through several leaks into the chapel that...
increasingly sank into total ruin [45,46]. The repairs were carried out in 1771 under the direction of the French architect Baltasar Dreveton and cost 24,000 reals [45,47]. According to the orders of the dean, the restorations were made “without altering or changing anything of the architecture” [14,15,45,46] following the principles of the San Fernando Royal Academy of Fine Arts [48,49]. There is no information about the restoration materials, but Romero de Torres pointed out that the horse-shoe arches from the tappizwerk, as perfect as skylights, were painted [13,14].

In 1815, Pedro Antonio de Trevilla, bishop of Córdoba, ordered the dismounting of the altarpiece of the Nursing Madonna and other furniture that was put in the Chapel of Saint Peter. This led to the re-discovery of the mosaics of the Mihrab and the Sabil, which were heavily damaged, especially in the lower part of the mosaics as a consequence of the installation and removal of the altarpieces [50]. Patricio Furriel was hired by Tiburcio María de la Torre, acting Governor of Córdoba, to restore the mosaics in 1817–1818 [47]. According to the documentary evidence, work was carried out on the lower part of the voussoirs and the intrados of the Mihrab as well as the lower part, frame, and part of the inscriptions of the Sabat mosaic. In areas where the tesserae were lost, the mortar was painted and colourless glasses were fixed with screws or glue, so the colour was visible [8,42,47]. These parts are easily identifiable to this day (Fig. 5). Some of the material we analyzed appears to confirm this remark (see Section 3.2). Stern suggested that Patricio Furriel also used paté de verre tesserae in some areas such as the pendentives, the ribs of the dome, some parts of the window frames and in the central voussoirs of the Sabil façade [13]; however, he might have confused them with lead glass tesserae, which appear very homogenous [17]. In places where the motifs were completely destroyed, Furriel re-designed the decoration in a baroque style, introducing some modifications in the epigraphic texts [8,43,47]. As a result of this intervention, eleven of the nineteen voussoirs of the Mihrab arch were restored, leaving only the central eight voussoirs in their original state. Similar interventions were carried out

Fig. 6 – Schematic representation of the different interventions on the basis of textual and graphic material, highlighting the areas from where the photos were taken for Fig. 5. Images adapted from G. Ruiz Cabrero, G. Rebollo, and S. Herrera's planimetry.

Fig. 7 – Principal Component Analysis (PCA) of the 91 analyzed tesserae divided according to the different groups of compositions [17]. Please note that the coefficient vectors are given on an enlarged scale (2×).
Table 1 – Description of non-medieval tesserae from the Great Mosque in Córdoba. Partially extracted from [17].

<table>
<thead>
<tr>
<th>Location</th>
<th>Name</th>
<th>Colour</th>
<th>Core description</th>
<th>Chromophore</th>
<th>Crystalline inclusions</th>
<th>Surface painted</th>
</tr>
</thead>
<tbody>
<tr>
<td>Báb Bayt al-Mál</td>
<td>MAQ E 001base</td>
<td>Yellowish</td>
<td>Transparent</td>
<td>Fe²⁺</td>
<td></td>
<td></td>
</tr>
<tr>
<td>door</td>
<td>MAQ E 001cart</td>
<td>Red</td>
<td>Transparent</td>
<td>Cu⁰, Cu²⁺</td>
<td>KAlSi₃O₈, Pb₅Sb₃O₁₀, Ca₃Sb₂O₇</td>
<td></td>
</tr>
<tr>
<td></td>
<td>MAQ E 002</td>
<td>Blue</td>
<td>Opaque</td>
<td>Co²⁺, Fe³⁺</td>
<td>Pb₂Sb₂O₇, Ca₃Sb₂O₇</td>
<td></td>
</tr>
<tr>
<td></td>
<td>MAQ E 003</td>
<td>Blue</td>
<td>Small crystals (white and red)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>MAQ E 004</td>
<td>Blue</td>
<td>Small crystals (white and red)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>MAQ E 005</td>
<td>White</td>
<td>Small white crystals</td>
<td>Fe³⁺?</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>MAQ E 006</td>
<td>Red</td>
<td>Opaque</td>
<td>Cu⁰</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>MAQ E 007</td>
<td>Black</td>
<td>Small crystals (white and red)</td>
<td>Co²⁺, Fe³⁺</td>
<td>Pb₂Sb₂O₇, Ca₃Sb₂O₇</td>
<td></td>
</tr>
<tr>
<td></td>
<td>MAQ E 008</td>
<td>Dark grey</td>
<td>Small crystals (white and red)</td>
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<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>MAQ E 009</td>
<td>Red</td>
<td>Opaque</td>
<td>Co⁰, Fe³⁺, Cu²⁺₀,₂⁺, Mn³⁺?</td>
<td>Pb₂Sb₂O₇, Ca₃Sb₂O₇, SiO₂, Fe₂O₃</td>
<td></td>
</tr>
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<td></td>
<td>MAQ E 012</td>
<td>Black</td>
<td>Small crystals (white and red)</td>
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<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>MAQ E 013</td>
<td>Light grey</td>
<td>Small white crystals</td>
<td>Cu²⁺</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>MAQ E 014</td>
<td>Light blue</td>
<td>Small crystals (white and red)</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>MAQ E 015</td>
<td>Light grey</td>
<td>Small white crystals</td>
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<td></td>
<td></td>
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<tr>
<td>Sâbât door</td>
<td>MAQ O 004</td>
<td>Burgundy</td>
<td>Transparent</td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>MAQ O 005</td>
<td>White</td>
<td>Homogeneous opaque matrix</td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>MAQ O 007</td>
<td>Burgundy</td>
<td>Transparent</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>MAQ O 030</td>
<td>Light blue</td>
<td>Transparent, homogeneous</td>
<td>Cu²⁺</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Mîhrâb door</td>
<td>MAQ C 001</td>
<td>Colourless</td>
<td>Transparent</td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>MAQ C 014</td>
<td>Colourless</td>
<td>Transparent</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mîhrâb ceiling</td>
<td>MAQ C 037base</td>
<td>Burgundy</td>
<td>Transparent</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>MAQ C 037cart</td>
<td>Burgundy</td>
<td>Transparent</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>MAQ C 042</td>
<td>Dark blue</td>
<td>Transparent</td>
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</table>

Fig. 8 – OM image (a–c) different paint layers on glass tesserae; (d) gold-plating on an original gold-leaf tessera, (e) tessera with adhesive.
Table 2 – Type of glass and LA-ICP-MS glass bulk composition (wt%), calculated as the average of three point analyses, in non-mediaeval tesserae from the Great Mosque in Córdoba. Partially extracted from [17].

<table>
<thead>
<tr>
<th>Location</th>
<th>Name</th>
<th>Composition</th>
<th>Na₂O</th>
<th>MgO</th>
<th>Al₂O₃</th>
<th>SiO₂</th>
<th>P₂O₅</th>
<th>Cl</th>
<th>K₂O</th>
<th>CaO</th>
<th>TiO₂</th>
<th>MnO</th>
<th>Fe₂O₃</th>
<th>CuO</th>
<th>SnO₂</th>
<th>PbO</th>
<th>ppm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Babýt al-Malí door</td>
<td>MAQ E 001 base</td>
<td>Lead-silica glass</td>
<td>17.1</td>
<td>0.13</td>
<td>0.20</td>
<td>53.1</td>
<td>0.04</td>
<td>0.13</td>
<td>1.92</td>
<td>2.07</td>
<td>0.02</td>
<td>2.78</td>
<td>3.73</td>
<td>0.02</td>
<td>0.011</td>
<td>18.4</td>
<td>502</td>
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<tr>
<td></td>
<td>MAQ E 001 cart</td>
<td>Lead-silica glass</td>
<td>15.8</td>
<td>0.11</td>
<td>0.24</td>
<td>59.6</td>
<td>0.04</td>
<td>0.13</td>
<td>4.36</td>
<td>2.19</td>
<td>0.03</td>
<td>2.53</td>
<td>0.75</td>
<td>0.04</td>
<td>0.037</td>
<td>13.7</td>
<td>510</td>
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<tr>
<td></td>
<td>MAQ E 002</td>
<td>Lead-silica glass</td>
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<td>0.82</td>
<td>58.6</td>
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<td>0.16</td>
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<td>4.71</td>
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<td>2.24</td>
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<td>744</td>
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<td>MAQ E 003</td>
<td>Lead-silica glass</td>
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<td>0.19</td>
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<td>59.9</td>
<td>0.02</td>
<td>0.18</td>
<td>0.64</td>
<td>5.59</td>
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<td>0.40</td>
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<td>475</td>
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<td></td>
<td>MAQ E 004</td>
<td>Lead-silica glass</td>
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<td>0.57</td>
<td>56.2</td>
<td>0.02</td>
<td>0.26</td>
<td>0.80</td>
<td>4.88</td>
<td>0.03</td>
<td>0.21</td>
<td>0.38</td>
<td>1.12</td>
<td>0.022</td>
<td>17.6</td>
<td>511</td>
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<tr>
<td></td>
<td>MAQ E 005</td>
<td>Lead-silica glass</td>
<td>15.6</td>
<td>0.14</td>
<td>0.56</td>
<td>57.7</td>
<td>0.01</td>
<td>0.18</td>
<td>0.73</td>
<td>6.04</td>
<td>0.02</td>
<td>0.21</td>
<td>0.16</td>
<td>0.005</td>
<td>0.015</td>
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<td>57.4</td>
<td>0.08</td>
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<td>2.07</td>
<td>5.33</td>
<td>0.03</td>
<td>2.51</td>
<td>0.80</td>
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<td>0.02</td>
<td>0.16</td>
<td>0.59</td>
<td>5.22</td>
<td>0.02</td>
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<td>59.9</td>
<td>0.02</td>
<td>0.17</td>
<td>0.63</td>
<td>5.62</td>
<td>0.02</td>
<td>0.40</td>
<td>0.63</td>
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<td>MAQ O 005</td>
<td>Mixed-alkali glass</td>
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<td>72.3</td>
<td>0.39</td>
<td>1.03</td>
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<td>Soda-rich glass</td>
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<td>0.88</td>
<td>71.7</td>
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<td>Calco-potassic glass</td>
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<td>2.92</td>
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<td>2E-04</td>
<td>0.001</td>
<td>3</td>
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<td>Mihráb ceiling</td>
<td>MAQ C 037 base</td>
<td>Soda-rich glass</td>
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<td>0.000</td>
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<tr>
<td></td>
<td>MAQ C 042</td>
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<td>1.00</td>
<td>1.99</td>
<td>68.0</td>
<td>0.08</td>
<td>0.87</td>
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<td>0.93</td>
<td>0.25</td>
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out on the façade of the Sáibát chamber, where only the 5th to the 11th voussoirs still have their original decoration (Fig. 6).

In 1912, the canvas of “La Última Cena” was removed, revealing the mosaics of the Báb Bayt al-Mál façade. The construction of the adjacent chapel of Cardinal Salazar (Fig. 3) together with the mounting and dismounting of the altarpiece resulted in the destruction of the mosaic [16]. For this reason, the Cathedral Chapter of Córdoba ordered their complete restoration. In keeping with the principles of Eugène Viollet-le-Duc, the architect responsible for the restoration campaign, R. Velázquez Bosco, commissioned a replica of the mosaic from the atelier J. & H. Maumejean Frères in Madrid. A. Gilbert, the artistic director of the atelier, hired the Venetian mosaic artist F. Morolin to make the facsimile that was installed in 1916 [4,13,16,51,52] (Fig. 6).

Finally, in 1997 and 1999, the dome was consolidated by the Andalusian Historical Heritage Institute (IAPH) due to the poor condition of the mortars that contributed to the dislodging of the tesserae. This pathology was directly related to water infiltration. The fallen tesserae were reintegrated in the mosaics [53].

Characterization of the restoration’s tesserae

The analyses of 91 tesserae revealed highly variable compositions (Fig. 7). Of the ten compositional groups, eight groups can be attributed to the original tenth-century decoration, including three types of Byzantine high boron glasses (number of tesserae, n = 46), two different types of soda-rich plant ash glasses (n = 9), and two types of high lead glasses (n = 14) as well as a single sample that represents the re-use of a Roman tessera (MAQ C 042) [17,54]. The remaining 21 tesserae can be attributed to non-mediaeval material from later restorations due to the morphological characteristics and chemical composition of the glasses (Table 1). A principal component analysis (PCA) was performed on a selected subset of LA-ICP-MS data (Cs, Sr/CaO, Al₂O₃, Cl, PbO, As, Sb) using the openly accessible RESET database (https://c14.arch.ox.ac.uk). These elements were chosen as they represent the mineral impurities in the silica source (e.g. Al₂O₃), the alkali and alkaline earths (Cs, Sr/CaO), chlorine that can separate ancient from modern raw materials [55,56], the type of glassy matrix (PbO) as well as additives (As, Sb) that have a clear chronological range. The first two principal components (PC) cover 68% of the variance of the dataset and single out the 20th-century tesserae as having elevated As, Sb, and very low alumina, chlorine and strontium to lime ratios (Fig. 7; Table 2). These features indicate the use of modern raw materials, and the elevated arsenic and antimony levels clearly point to a date after the 17th-century date [57]. Seven painted tesserae (MAQ O 004, MAQ O 005, MAQ O 007, MAQ O 030, MAQ C 001, MAQ C 014, MAQ C 037) (Table 1) were also identified as material originating from restoration campaigns but with very different compositional characteristics [17].

Painted samples

Most of the seven painted restoration tesserae were transparent, colourless or weakly coloured glasses (Table 1). It was not possible to characterize the chromophore by FORS because its pale hue reduced the light reflected from the surface. Their analysis showed a great variety of compositions (Table 2) such as soda-rich glasses (MAQ C 037, MAQ O 007, and MAQ O 030),

Fig. 9 – PIXE maps (a) original tessera painted with white lead and green aluminosilicates (MAQ O 03), (b) original gold-leaf tessera with a preparation layer and a second gold leaf (MAO C 34), (c) modern painted tessera (MAQ O 05).
a calco-potassic glass (MAQ C 001), a mixed-alkali glass (MAQ O 005), and high-lime-low-alkali glasses (MAQ C 014 and MAQ O 004).

The soda-rich glasses have a chemical composition similar to some 17th-century glasses, specifically European Façon de Venise, Venetian common, or Vitrum Blanchum [58]. This composition has been maintained in commercial glasses from the second half of the 19th century and the first decades of the 20th century [59,60]. The potash glass was similar to that developed in Central Europe in the 17–19th century [59,61]. The white glass MAQ O 005, found in one voussoir of the Sâbâṭ door, has similar amounts of Na₂O and K₂O (7% and 9.5%, respectively) and it was classified as mixed-alkali glass. Even though its content did not agree with 17th-century mixed-alkali glasses [58], the combination of a very homogeneous matrix opacified by Ca₂Sb₂O₇ crystals and high arsenic levels indicates a post-17th-century date [62,63].

Despite their different composition, the painted tesserae located in the Sâbâṭ door (MAQ O 30, MAQ O 05, MAQ O 07, and MAQ O 04) have high levels of TiO₂ relative to Al₂O₃ as a common feature (Table 2). This provides solid evidence that these glasses are derived from different raw material sources and represent a distinct production from the other samples in the Mihrâb mosaics, especially with respect to the silica source.

Fig. 10 – FTIR-ATR spectra of (a) the blue paint on the tessera MAQ O 30, (b) the adhesive on the tessera MAQ O 13. Peaks attributions made using [64,65].

Fig. 11 – FORS spectra of the tesserae (a) MAQ E 002, (b) MAQ E 004 and (c) MAQ E 012. Bands attributions made using [73].
The surface of these tesserae together with 11 original tesserae [17] was coated with different colours (blue, red, green, and golden) (Fig. 8). The analyses made by SEM-EDX and PIXE detected high contents of lead in the surface paints (Fig. 9), and FTIR-ATR confirmed the use of white lead (2PbCO₃·Pb(OH)₂) (Fig. 10a), as a base where pigments were dispersed. High contents of iron and alumina was detected in green crystals of the green paints (Figs. 8a and 9a) that could be related to the use of iron aluminosilicates. In the blue paints, FTIR-ATR spectra identified the Prussian blue – Fe₄[Fe(CN)₆]₃ – as pigment (Figs. 8b and 10a), while the high levels of mercury detected by SEM-EDS in the red paint agrees with the use of vermillion – HgS – (Fig. 8c) to produce the red paint. Grains of hematite – Fe₂O₃ – (45.6 – 216 µm) were also detected on the red paint, as well as calcite grains on the blue. To restore the golden areas, the surface was covered with a preparative layer to which the gold leaf was applied, occasionally even over an original gold-leaf tessera (Figs. 8d and 9b). A yellowish adhesive, identified by FTIR-ATR as gum tragacanth, was identified on some repopulation tesserae (Fig. 8e).

Vermilion as red and lead white as white pigments were known since ancient times [66,67]; Prussian blue, however, was introduced only in the early 1700s, being widely used until 1970 when it was replaced by the phthalocyanine blue [68]. The glasses are similar to those of the 17th and 18th centuries. They may have either been imported to the Iberian Peninsula or produced by Italian or Bohemian glass makers in Spanish factories [69].

The analyses of the green painting layer on the Byzantine sample MAQ C 025 by GC showed the presence of linseed oil and traces of conifer resin as binders of the paint without residue of varnish, and FTIR-ATR identified gum tragacanth in sample MAQ O 13. The use of linseed oil together with white lead was already used in antiquity and described by Heraclius for the preparation layers on a wooden support [70]. It was particularly popular during the Renaissance until the middle of the 20th century when it was replaced by cobalt or zirconium-based driers due to toxicological and environmental concerns [71].

It is thus reasonable to conclude that all the painted tesserae are related to the intervention of 1817–1818. The fact that both original and new samples were painted suggests the paint was applied directly to the mosaic surface in some areas. The implicit goal of the 19th-century restoration was to restore the Islamic mosaics without altering their overall appearance. The original parts were not touched but the gaps were filled with painted glass and plaques of modern tesserae. This approach is similar to the modern tradition of conservation, which consists of preserving the original areas as much as possible and filling in the missing parts with materials that are easily recognizable, while preserving the overall appearance of the work from a distance [72].
### Table 3 - Summary of the main interventions and type of tesserae used in the Maqsūrah of the Mosque-Cathedral of Córdoba.

<table>
<thead>
<tr>
<th>Data</th>
<th>Principal</th>
<th>Fact</th>
<th>Type of tesserae</th>
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<tr>
<td>The Great Mosque of Córdoba</td>
<td>Abd al-Rahman I</td>
<td>Construction of the mosque</td>
<td>Homogeneous coloured and gold-leaf soda-lime silicate and high-lead glasses</td>
</tr>
<tr>
<td>~840</td>
<td>Abd al-Rahman II</td>
<td>Expansion of the mosque</td>
<td></td>
</tr>
<tr>
<td>~960</td>
<td>Al-Hakam II</td>
<td>Expansion of the mosque and construction of the Mihrāb and mosaics</td>
<td></td>
</tr>
<tr>
<td>988</td>
<td>Almanzor</td>
<td>Expansion of the mosque</td>
<td></td>
</tr>
<tr>
<td>The Mosque-Cathedral of Córdoba</td>
<td>King Ferdinand III of Castile</td>
<td>Consecration of the Great Mosque of Córdoba to the Assumption of Mary</td>
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</tr>
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<td>Installation of the altarpiece of the Nursing Madonna in front of the Mihrāb</td>
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<tr>
<td>1390</td>
<td>–</td>
<td>“Última Cena” in front of the Bab Bayt al-Māl chamber</td>
<td></td>
</tr>
<tr>
<td>1595</td>
<td>Antonio and Hernando Mohedano de Saavedra</td>
<td>Restoration of the Mihrāb dome</td>
<td></td>
</tr>
<tr>
<td>Modern interventions</td>
<td>Baltasar Dreveton</td>
<td>Restoration of the Mihrāb dome</td>
<td>Very pale high-alkaline glasses painted with blue, red, green or golden colours</td>
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<td>1771–1772</td>
<td>Bishop Pedro Antonio de Trevilla</td>
<td>Dismounting the altarpiece of the Nursing Madonna from the Mihrāb chamber</td>
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<tr>
<td>1812</td>
<td>Mr. Patricio Furriel</td>
<td>Restoration of the mosaics of the Mihrāb and Sábat façades</td>
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<td>1912</td>
<td>Ricardo Velázquez Bosco</td>
<td>Dismounting the altarpiece “Última Cena” from of the Bab Bayt al-Māl chamber</td>
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<td>1914–1916</td>
<td>J. &amp; H. Maumejane Fréres</td>
<td>Reproduction and installation of the mosaic in the Bab Bayt al-Māl chamber</td>
<td>Homogeneous coloured and gold-leaf high-lead glasses</td>
</tr>
<tr>
<td>1997–1999</td>
<td>Instituto Andaluz del Patrimonio Histórico (IAPH)</td>
<td>Consolidation of the mortars and reintegration of the tesserae</td>
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</table>

The 20th-century tesserae

The other group of non-mediaeval tesserae (n = 15) was formed by the samples from the Bab Bayt al-Māl door, and includes one transparent gold-leaf tessera, red opaque samples, and coloured bulk glasses with a high density of crystals (Table 1).

Of all them were lead-silica glasses with high contents of Na2O (17–20 wt%) (Table 2). In comparison with the historical tesserae, they have higher contents of arsenic, antimony, and low levels of aluminium oxide and chlorine (Fig. 7) [17].

The gold-leaf tessera was formed by a transparent glass support with a leaf of gold (~16 μm of thickness) on its surface that was protected by a thin layer of glass, the so-called cartellina (~500 μm). The composition of the cartellina was slightly different from the support [17].

The red tesserae were completely opaque due to the presence of small nanoparticles of copper (Fig. 11a), which agrees with the high content of copper and iron in these samples (Table 2). The red glasses do not contain additional inclusions; however, isolated crystals of Pb2Sb2O7 were detected in one of the analyzed samples (MAQ E 009).

The transparent glasses with inclusions (Fig. 11) have a similar composition despite a great variety of colours due to the addition of chromophores. Co²⁺ and Cu²⁺ ions are the most common chromophores in the bluish and greyish tesserae (Fig. 11b) (Table 1). The black samples also contain manganese to darken the glass colour (Table 2), but the absorption bands were difficult to be distinguished due to the overlapping of the bands from the different chromophores (Fig. 11c).

Lead antimonate (Pb2Sb2O7) and calcium antimonate (Ca2Sb2O7) particles dispersed the light in most of the tesserae, independent of their colouration (Table 1). Pb2Sb2O7 inclusions are small whitish crystals (~20 μm), and Ca2Sb2O7 accumulate into very small deposits forming large and irregular structures (150–250 μm). Some regular feldspars (KAlSi3O8) were additionally detected in the blue tesserae (Fig. 12a), but typically in smaller amounts than the antimonate crystals. An agglomeration of SiO2 and Fe2O3 in varying proportions was found in the black samples (Fig. 12b) that may be residues of the sand raw material. Similarly, the dark grey sample displayed some big rounded quartz grains (~300 μm). In all cases, the addition of these big inclusions modified the material and optical properties and contribute in case of the mosaic tesserae to an increase in glass opacity.

Tesserae with similar features (high-lead silicate glasses with lead and calcium antimonate) were found in the 18th-century tesserae from the Capela de São João Baptista (Lisbon, Portugal) [77]; although each colour showed different compositions with concentrations of PbO from 2 wt% to ~50 wt%.

These evidently modern tesserae appeared only in the mosaic from the Bab Bayt al-Māl door and not in the other two façades. This means that the other mosaics in the Great Mosque were probably not touched during the early 20th-century
restorations. This agrees with the news published at the beginning of the 20th century that talked about the installation of a mosaic facsimile due to the poor state of conservation of the original one following the principles of “stylistic restoration” by Eugène Viollet-le-Duc [78,79].

Conclusions

The mosaics of the Mosque-Cathedral of Córdoba offer a unique opportunity to study the evolution of the architectural and decorative traditions and the significance attributed to them over the centuries because the various restoration campaigns reflect changing attitudes towards the cultural and aesthetic value of Islamic art and architecture, as well as a paradigm shift in art conservation.

In the first centuries, the mosaics were part of the private Maqsura of the caliph. Access was only allowed to people dedicated to worship and religious service. This testifies to the value and prestige associated with the art of glass mosaics. After the Christian conquest, the Islamic mosaics were covered with altarpieces, either because the mosaics were deemed inappropriate in the context of the ecclesiastical space of the cathedral or mosaics were no longer considered a desirable art form. The main degradation factor of the mosaics was the water leaks and dampness in the walls, which caused the mortar to disintegrate and the glass tesserae to detach. The lack of ventilation, especially during the period when the mosaics were hidden, together with the mounting and dismounting of the altarpieces accelerated this process, so that the lower parts of the Mihrab and Saba mosaics and the whole of the Bab Bayt al-Mal mosaics were lost entirely.

The façades of the Mihrab and the Saba still preserved original mosaic tesserae, despite different interventions particularly in the 19th and 20th centuries. In the first quarter of the 19th century, colourless tesserae were inserted and painted to reproduce the colour of the original mosaics. The high-alkaline silicate composition of these glasses identifies these tesserae as modern glass. Similarly, some of the pigments that were applied, such as Prussian blue, and the binder correspond to technical developments in the 18th century, confirming once more their modern origin.

On the other hand, the Bab Bayt al-Mal façade no longer contains any original mosaics as it has been completely restored in compliance with the Viollet-le-Duc’s principle of “stylistic restoration”. The tesserae used in this mosaic have a completely different composition (high-lead glasses) with lead antimonate and calcium antimonate as inclusions to opacify the glass. These types of tesserae have not been identified in any other part of the mosaics, suggesting that the restorations remained confined to the Bab Bayt al-Mal mosaic in line with contemporary newspaper reports.

The main changes in the Maqsura mosaics and the characteristics of the tesserae used in each intervention are summarized in Table 3.

Glossary

Hijri year (H): The era used in the Islamic lunar calendar.

Maqsura: The ‘closed-off space’ near the centre of the Qiblah wall in the direction of prayer, usually reserved for the caliph
Mihrab: Prayer niche in the Qiblah wall
Minbar: Wooden pulpit for the imam’s sermon.
Muzayyana: tesserae with glaze.
Qiblah: Wall of the mosque where the Mihrab opens, which is normally the direction towards the Sacred Mosque in Mecca.
Qubba: Islamic domed shrine.

Conflict of interest

No potential conflict of interest was reported by the authors.

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References


