

# 1 AN ANALYTICAL EVALUATION OF HISTORIC GLAZED TILES FROM MAKLI AND LAHORE, 2 PAKISTAN

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## 6 Abstract

7 The composition and production of early modern glazed tiles in Pakistan are poorly understood. Here,  
8 38 glazed tile samples sourced from various monuments at Makli Hill and Lahore Fort in Pakistan,  
9 dating mainly from the sixteenth and seventeenth centuries CE, were investigated with scanning  
10 electron microscopy and energy dispersive X-ray spectrometry for a comprehensive technological  
11 study to understand the methods used in their production. The analyses were supplemented by laser  
12 ablation-inductively coupled plasma-mass spectrometry to more fully characterise the raw materials  
13 used for the glazes. The Makli tile bodies are composed of clay-based ceramic whereas those from  
14 Lahore are stonepaste. Both are coated with soda-lime-silica glazes made using plant ash. Cobalt,  
15 copper, lead-tin yellow and lead-tin orange are identified as the glaze colorants. White glazes do not  
16 have an added opacifier or colorant, but are white due to the presence of an underlying layer of silica  
17 particles. Technological variations between the Makli and Lahore tiles are highlighted in the  
18 discussions, the former found to resemble traditional *kashi* ware of Sindh-Multan in their make-up,  
19 while the latter matches Mughal tile-work that prevailed for a while locally in the seventeenth century.

## 20 Keywords

21 GLAZED TILES, KASHI, PAKISTAN, MAKLI, LAHORE, TECHNOLOGY, SEM-EDS, LA-ICP-MS

## 22 1. INTRODUCTION

23 The use of glazed revetments to decorate buildings goes back to the Late Bronze Age, where tiles of  
24 Egyptian faience were embellishing the temples and palaces of the pharaohs (Friedman 1998, Delange  
25 2015), continuing with clay-based ceramic tiles or bricks such as those found on the famous Iron Age  
26 Ishtar Gate and Processional Way, originally from Babylon in Iraq (Matson 1986, Paynter 2008). Later,  
27 in the medieval period, the use of glazed tiles reached a new height in Islamic architecture (Porter  
28 1995), both in Turkey (Carswell 1998) and in Central Asia from Iran to Uzbekistan (Grazhdankina et al.  
29 2006). From here, the tradition spread south into India and Pakistan, in the wake of the establishment  
30 of Islamic dynasties in the Indian Subcontinent.

31 In Pakistan, the art or craft of tiling is virtually synonymous with the term *kashi*, which refers to the  
32 manufacture of a particular variety of fine glazed ware, mainly tiles for the ornamentation of buildings.  
33 Although the *kashi* traditions are specific only to a geographic region covering the arid lands of the  
34 lower Punjab (Multan in central Pakistan being the main centre here) and Sindh (Hala, Thatta and  
35 Nasarpur in SE Pakistan being known centres of production here) provinces, the term is often loosely,  
36 and perhaps erroneously, applied to other historic tiles or tile-work in Pakistan as well, notably to a  
37 different and distinct stylistic form found in Lahore city and its environs in the northern part of Punjab  
38 (Figure 1). Between the two, the *kashi* or Sindh-Multan type of tile-work, characterized by a dominant  
39 blue-and-white colour scheme, is the older and longer-established of the two forms, carrying on

40 apparently as an unbroken tradition from the 14th century through to the present date (Degeorge and  
41 Porter 2002, 244-253, Akhund and Askari 2011, 65-70, UNESCO 2015). The Lahore variety of tile-work,  
42 marked by the extensive use of a multi-coloured tile-mosaic, appears much later, in the early 17th  
43 century, and flourishes for a considerably shorter duration, practically ceasing by the third quarter of  
44 the same century (Vogel 1920, 6-15, Rehmani 1997-98).



Figure 1. Map of the region showing the location of the sites.

45 While numerous buildings adorned with these two broad varieties of tile-work are known to exist,  
46 little is known of the original technologies that went into their making. We are aware of only one  
47 published technical study on the Lahore tiles (Gulzar et al. 2013), and none on the *kashi* Sindh-Multan  
48 type despite its cultural longevity and importance. Most available information on these tiles is from  
49 various surveys, compilations, and ethnographic studies (Birdwood 1884, Furnival 1904, Cousens  
50 1906, Cousens 1929, Rye and Evans 1976, Khan 1990), which although detailed for their own purposes,  
51 are insufficient for reconstructing the production processes originally involved. This paucity of data  
52 has led to an incomplete understanding of the Sindh-Multan and Lahore tiling traditions, necessitating  
53 a detailed study to identify the materials and characteristics associated with each.

54 For this, 38 tile fragments made available through the UNESCO World Heritage Centre (Paris) in  
55 collaboration with the governments of Sindh and Punjab (Pakistan) were analysed at the  
56 Archaeological Materials Science Laboratories of UCL Qatar (see Supporting Online Material A).  
57 Twenty nine of these samples are from various historic buildings at the World Heritage Site (WHS) of  
58 Makli Hill. The site, located near Thatta in Sindh, comprises a vast cemetery of numerous  
59 medieval/early-modern tombs and graves, the larger and more impressive of which represent the  
60 architectural (and embellishing) traditions of the various dynasties that ruled Sindh from the 14th to  
61 18th centuries, from the Samma (mid-14th to early-16th centuries), Arghun (early- to mid-16th  
62 century) and Tarkhan (mid- to late-16th century), to the Mughal (early-17th to early-18th century).  
63 Most of the buildings from where the samples have been sourced are ascribed to the 16th and 17th  
64 centuries. One sample (MA-20) is from a building dating to the 14th century. Sampling details provided  
65 together with the samples indicate that the majority of the tiles were originally installed on the  
66 exteriors of the buildings, as detailed in SOM A.

67 The other nine samples are from the 'Picture Wall' of Lahore Fort, a monumental Mughal citadel that  
68 forms part of the WHS listed Fort and Shalamar Gardens ensemble at Lahore city. The fort is  
69 considered to have been given its current basic form by the third Mughal emperor Akbar (1556-1605),  
70 but the tile-work that it has is attributed to his descendants and successors, Jahangir (1605-1627) and  
71 Shah Jahan (1628-1657) (Vogel 1920, 50-55). The tiles from the Makli buildings are representative of  
72 the *kashi* tile-work of Sindh, while those from Lahore Fort are on the lines typically associated with  
73 Lahore city.

## 74 2. METHODOLOGY

75 The samples were first documented and examined macroscopically using a hand lens. Representative  
76 sections of each were then cut through the body and glaze, and mounted in resin blocks. One sample  
77 from Lahore Fort, LF-07, which first appeared to be a single green-and-yellow polychrome glazed tile,  
78 was found to actually comprise two distinct tiles, one of which (yellow-glazed) had been inlaid in the  
79 other (green-glazed). These were accordingly treated as two separate tiles for the purpose of analysis,  
80 and numbered as LF-07a and LF-07b respectively. Sample MA-28 from Makli was also found to consist  
81 of several individual tiles of two distinct colours (turquoise and dark-blue) that had been arranged in  
82 the form of a polychromatic composition. One representative sample of each of these colours was  
83 taken for analysis, and numbered as MA-28a (turquoise) and MA-28b (dark-blue).

84 All mounted samples were ground and polished using standard procedures to expose clean cross-  
85 sections for detailed microscopic examination. Optical microscopy was undertaken using a Leica  
86 DM2500P microscope with reflected light. The polished blocks were then carbon coated to make them  
87 conductive and examined using a JEOL JSM6610LV scanning electron microscope (SEM). Observations  
88 were made in backscattered electron (BSE) mode, and chemical analysis was conducted using an  
89 attached Oxford Instruments X-Max energy dispersive spectrometer (EDS), operating at an  
90 accelerating potential of 20 kV, count time 60 seconds, and average dead-time of 35-40%.  
91 Quantitative analyses report the average of 5 area analyses spread across the body or glaze layer of  
92 each tile as applicable. Individual particles or phases in the bodies and glazes were subject to spot or  
93 small-area analysis at the same settings. Each area analysis covered an expanse of c. 1.25 x 1 mm on  
94 the sample surface in the case of the bodies, and c. 150 x 110  $\mu\text{m}$  in the case of the glaze layers. Areas  
95 scanned through small-area analysis were typically of the order 50 x 50  $\mu\text{m}$  or less.

96 High analytical totals, mostly  $100 \pm 1$  wt%, were achieved in the bulk analyses of the glaze layers, the  
97 glazes individually being homogeneous and remarkably free of corrosion. The tile bodies, while also  
98 being consistent across in their composition individually, returned lower totals, in the range of 60-75  
99 wt%, on account of their inherent porosity. Results of the chemical analyses for the bodies and glaze  
100 layers are reported as oxides by stoichiometry, normalized to 100%, while the trace element data  
101 obtained through LA-ICP-MS is given in element ppm. Reduced compositions of the glaze layers, where  
102 given, have been calculated by subtracting the colorants from the analytical results and normalizing  
103 the totals of the base glass forming oxides to 100%. The lower detection limits of the EDS and LA-ICP-  
104 MS systems have been considered to be 0.3 wt% and 10 ppm respectively.

105 A limited number of the Makli and Lahore glazes were further analysed through Laser Ablation-  
106 Inductively Coupled Plasma-Mass Spectrometry (LA-ICP-MS). The aim of this was to get a full trace  
107 element characterization to facilitate discussion of raw materials and differences between and within  
108 glazes from the two sites. The analyses were carried out at the Institut de Recherche sur les

109 Archéomatériaux (IRAMAT UMR-5060 CEB), CNRS Orléans. The LA-ICP-MS system employed consisted  
110 of a Thermo Fisher Scientific ELEMENT XR ICP-MS coupled to a Resonetic M50E 193 nm ArF excimer  
111 laser source. The spot size of the laser beam varied over 30-100 µm, while the frequency was set to 7  
112 Hz (Gratuze 2013). Precision and accuracy of the SEM-EDS and LA-ICP-MS systems were checked  
113 against Corning reference material (Corning A and C glass standards).

### 114 3. MACROSCOPIC EXAMINATION

115 The samples from the two sites differ from each other even macroscopically. The Makli tile samples  
116 (MA series) have characteristic terracotta-red coloured bodies, which together with their general  
117 bulky size (several being as large as 20 cm across) and opaque glazes resemble glazed bricks (Figure  
118 2). They are, however, distinct from bricks having superior, highly refined body matrices with very few  
119 visible voids or inclusions. The distinctiveness of these tiles from bricks is further illustrated by the  
120 tapering or bevelling of their sides, indicating that they were purposefully constructed to be decorative  
121 wall-revetments rather than for masonry work.



**Figure 2.** A polychrome blue-and-white glazed tile (MA-11) from a monument at Makli Hill. Note the reddish coloured underlying body where the glaze is missing.



**Figure 3.** A monochrome turquoise coloured glazed tile (LF-05) from Lahore Fort. All the Lahore Fort tiles have glazes of one colour only.

122 Both monochrome and polychrome glazes are found among the MA samples, with individual glaze  
123 layers being generally around half a millimetre or so in thickness. The colour scheme is restricted to  
124 shades of turquoise, dark-blue, and white. No outlining of patterns or delineating line is found  
125 between adjacent colours on the polychrome glazes. In spite of this no major flowing or bleeding of  
126 colours is noticed.

127 In contrast, the bodies of the Lahore Fort samples (LF series) are off-white with the hint of a reddish  
128 tinge (Figure 3). These bodies are visibly porous, being made up of small particles or grains that have  
129 been cemented or fused together. Some variation in the body fabrics, in terms of the size/texture of  
130 the grains, is apparent. In thickness, the bodies are however generally uniform, averaging about one  
131 centimetre and a half or so. The one exception is LF-08, the body of which is clearly less than a  
132 centimetre thick. These tiles are on the whole considerably smaller than those from Makli in their  
133 overall size, the largest being around 7 cm across.

134 All the LF samples are monochrome, having opaque glazes of one colour only. The range of glaze  
135 colours found includes turquoise, dark-blue, white, yellow, orange, and green, with some tonal  
136 variations among samples of the same glaze colour. The glaze thicknesses are generally up to half a

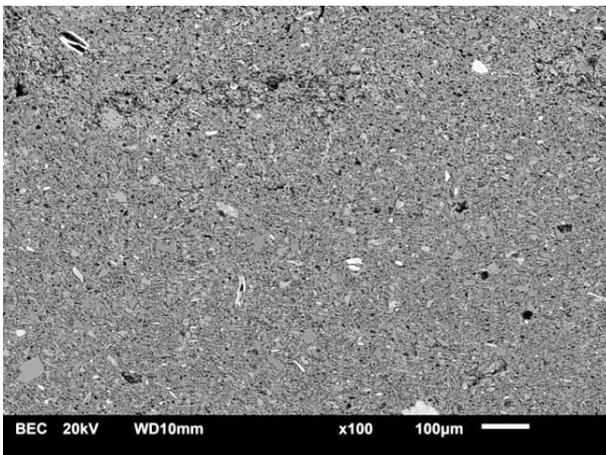
137 millimetre or so, with the exception of LF-04 and LF-06; their glaze layers are substantially thinner than  
138 the others, appearing more like a thin coloured slip.

#### 139 4. ANALYTICAL RESULTS

##### 140 4.1 Electron microscopy

###### 141 *Microstructure and tile bodies*

142 Most terracotta Makli bodies are essentially composed of fine clay-silt minerals that are closely packed  
143 together (Figure 4). The infrequent presence of coarser inclusions suggests that little temper, if at all,  
144 was added. Only the bodies of samples from the Tomb of Sultan Ibrahim (MA-01 to MA-04) and  
145 Unknown Enclosure-1 (MA-10 and MA-11) are somewhat different, having significant numbers of  
146 mineral (mainly silica) particles of a medium-coarse size (250-300 microns) distributed uniformly  
147 across their matrices. A typical body composition for the Makli samples is: SiO<sub>2</sub>-58.8%; Na<sub>2</sub>O-1.8%;  
148 CaO-8.3%; K<sub>2</sub>O-3.2%; MgO-3.5%; Al<sub>2</sub>O<sub>3</sub>-16.9%; FeO-6.8%; and TiO<sub>2</sub>-0.8%, indicating that the clay or  
149 clays employed for their making are calcareous, feldspathic and ferruginous.



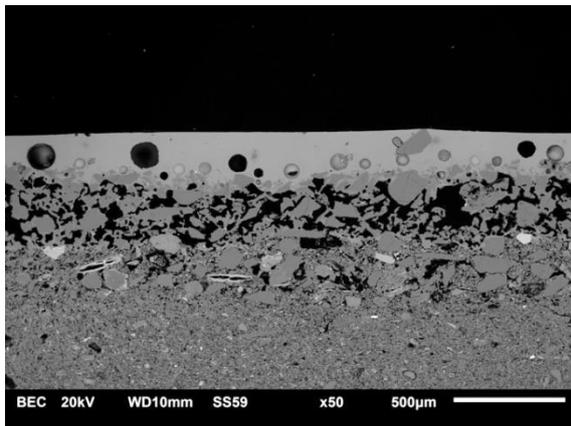
**Figure 4.** SEM photomicrograph of a typical Makli tile body (MA-09) showing it to be made up mainly of only fine clay-silt minerals.

150 A slip is found employed in almost all the Makli samples, as a separate layer of fine silica particles at  
151 the body-glaze interface (Figure 5). The slip is usually around 200-250 microns in thickness, although  
152 in some cases (as in MA-21, MA-24, and MA-25) it may be indistinct or no more than a sprinkling of  
153 particles on the body. The glaze layers largely match the slips in thickness, being mostly 250-300  
154 microns thick, although in some instances (as in MA-13 and MA-18) they are noticeably thinner, while  
155 in few others (as in MA-21, MA-24, and MA-25) they are up to 500 microns or so thick. A visible sloping  
156 of the glaze layers towards the edges that is seen in many of the samples suggests that the tiles were  
157 prepared with the intention of being glazed and finished as individual pieces, and were not attained  
158 by first producing larger sized tiles that were then cut into smaller pieces (Figure 6). This is  
159 corroborated through the macroscopic detection of 'overflow' or 'run-down' patches of the glaze on  
160 to the sides of some of the tiles, indicating that the finished fired product was of the same shape/size  
161 as that originally covered with the raw glaze.

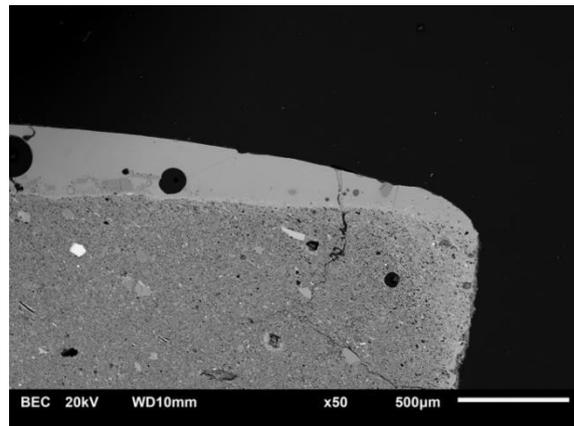
162 The Lahore bodies on the other hand are all stonepaste, with highly porous matrices made up almost  
163 entirely of silica particles or grains (Figure 7). The silica particles generally fall into two size categories,

164 a finer group of 25-100 microns, while the rest are coarser, ranging over 300-500 microns. Although  
165 the two size groups are more or less equitably distributed in all the samples, LF-01, LF-04, LF-07a, and  
166 LF-08 clearly have enhanced numbers of large coarse grains (c. 500 microns) dispersed in their  
167 matrices. Variations are also determined in the textural character of the silica particles in individual  
168 samples, and in the employment of slips. In most samples the silica grains appear rounded or semi-  
169 rounded in shape, but this is less apparent in LF-02, LF-03, and LF-08, where appreciable numbers of  
170 angular particles can be found as well. A slip layer of fine silica particles is clearly discernible only in  
171 samples LF-04, LF-05, and LF-06, where it is around 500-600 microns thick (Figure 8). In others, the  
172 presence of a slip may be correlated with the existence of an interaction zone of silica particles that  
173 lie submerged in the glaze layers, but this cannot be stated so confidently for LF-03, LF-07a, LF-07b,  
174 and LF-08, where the interaction zone contains coarse silica particles as well, or is conspicuously  
175 absent.

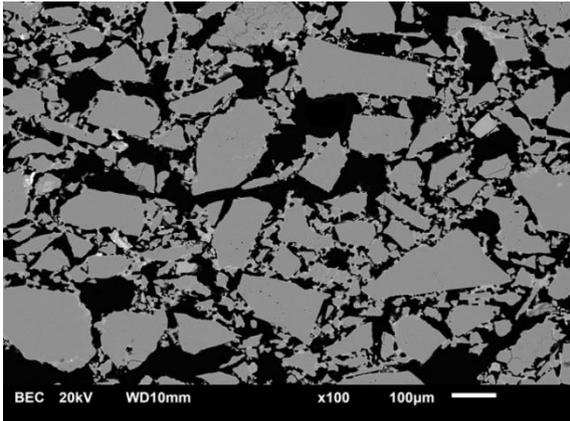
176 The average body composition of: SiO<sub>2</sub>-94.5%; Na<sub>2</sub>O-1.2%; K<sub>2</sub>O-0.7%; CaO-0.7%; MgO-0.5%; Al<sub>2</sub>O<sub>3</sub>-  
177 1.8%; and FeO-0.6% is consistent with their stonepaste character. The glaze layers of these samples  
178 are generally 350-500 microns thick, but are thinner in LF-02, LF-04 and LF-06 where they are of the  
179 order of 250 microns or so. The glaze overflow features detected on the Makli tiles are notably absent  
180 here, the uniformity in thickness of the glaze layer up to the edges of these tiles implying that they  
181 were probably cut from larger-sized specimens. This would certainly have been the most economical  
182 approach, given that the individual finished tile pieces were of a fairly small size, and were often  
183 modelled in complex shapes.



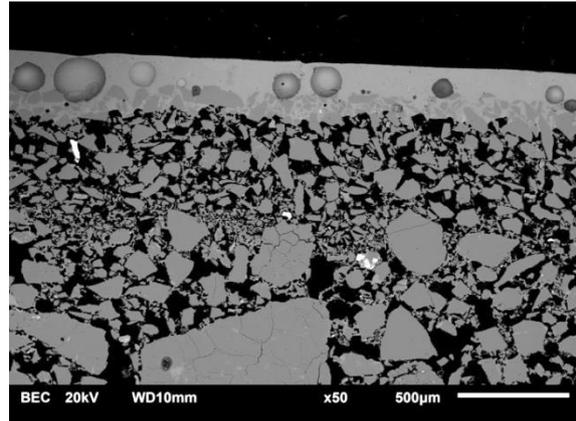
**Figure 5.** SEM photomicrograph of a turquoise coloured Makli tile (MA-22) in section. The slip layer of fine particles seen between the body below, and the bright glaze layer on top, is typical of samples from this site. Note the pristine state of the glaze, a feature common to almost all the samples.



**Figure 6.** SEM photomicrograph of a white coloured Makli tile (MA-07) illustrating the downward sloping of the glaze towards the edges. Some of the glaze in this case can be seen to have overflowed over the edge, on to the side.



**Figure 7.** SEM photomicrograph of a Lahore Fort tile body (LF-03) showing it to be almost entirely composed of silica particles, and not clay minerals. The black areas are pores.



**Figure 8.** SEM photomicrograph of a dark-blue coloured Lahore Fort tile (LF-04) in section, illustrating its stratigraphy. A slip layer is clearly noticeable here, distinguished from the body by the smaller size of its particles.

184 *Glazes and colorants*

185 As opposed to the distinctions noted for their bodies, the Makli and Lahore glazes are found to be  
 186 compositionally similar, both being of the silica-lime-soda type (Tables 1 and 2). The reduced  
 187 (colorant-free) magnesia and potash contents (SOM Tables S1 and S2), typically 3-3.5 wt% for each,  
 188 imply that a plant ash flux was used. Within these broad similarities, there are some variations in the  
 189 glaze compositions between the two sites. Soda is consistently lower in the MA samples, averaging  
 190 around 13%, compared to 17-18% for the LF specimens. Lime is conversely higher in the MA samples,  
 191 averaging around 6%, compared to around 4.5% for the LF samples. Potash and magnesia values are  
 192 mostly comparable in individual samples, although they are together marginally higher by about 0.5%  
 193 in the MA samples as opposed to those from LF. Alumina varies more across the LF samples, ranging  
 194 over 1.5-3.5%, but otherwise mostly lies between 2-2.5% for samples from both the regions. Iron oxide  
 195 contents are slightly enhanced in the MA samples over those from LF, averaging 1.3% and 1.1%  
 196 respectively. Titania, measured at an average of 0.3% in the MA samples, is constantly below the  
 197 detection limit (c. 0.3 wt%) of the instrument for the LF samples. Silica typically lies in the range of 65-  
 198 70%, varying inversely with soda and being accordingly higher in the Makli samples.

199 Among the Makli samples, MA-12, MA-13, and MA-18 are notably different from the standard. Their  
 200 unusually low magnesia contents and the presence of significant quantities of lead oxide (in the case  
 201 of MA-13 Dark-Blue/White/Turquoise, and MA-18 Turquoise) indicate that they were differently  
 202 prepared, and are probably representative of some later restoration effort. Lead oxide is otherwise  
 203 only determined in the yellow, green, and orange LF glazes, where it is due to the colorant employed.

204 The compositional similarities between the samples extend to the colorants. The three glaze colours  
 205 common to the MA and LF samples (turquoise, dark-blue, and white) are all coloured in the same  
 206 manner, although the techniques of applying or adding the pigments is likely to have been different  
 207 for the monochrome and polychrome glazes. The three additional colours that are specific only to the  
 208 LF glazes (yellow, orange, and green) are all based on lead stannate (lead-tin yellow) in one way or the  
 209 other.

210 *Turquoise*

211 All turquoise tiles and areas are coloured by c. 2-6 wt% copper oxide, with varying concentrations  
212 resulting in the tonal variations noticeable between different individual tiles of this colour. Pigment  
213 concentrations across individual glaze layers at the same time are clearly more consistent in the  
214 monochrome glazes as compared to the polychrome glazes, the same feature observed for the dark-  
215 blue glazes too.

#### 216 *Dark-blue*

217 The dark-blue glazes are all coloured by 0.5-1 wt% cobalt oxide. Cobalt oxide is also detected in the  
218 dark-blue coloured areas on the MA polychrome glazes, but in relatively higher concentrations, more  
219 often in excess of 1% and up to as high 2%. This indicates underglaze-painting on these tiles, since  
220 such high quantities would otherwise not be needed to attain a dark-blue shade. A few small bright  
221 particles suspended in some of these glazes are cobalt-rich with some associated nickel, iron, and  
222 arsenic contents. Arsenic oxide is accordingly detected in the bulk compositions of the dark-blue glazes  
223 only. A newly-formed arsenic-rich phase with significant calcium and little or no cobalt content  
224 frequently appears in many of these glazes as bright small grains scattered among the silica particles  
225 in the glaze-slip interaction zone. This phase probably formed inadvertently by the volatilization of  
226 some arsenic associated with the cobalt pigment during the melting of the glaze, and its combining  
227 with some lime in the batch to form a stable calcium arsenate compound.

#### 228 *White*

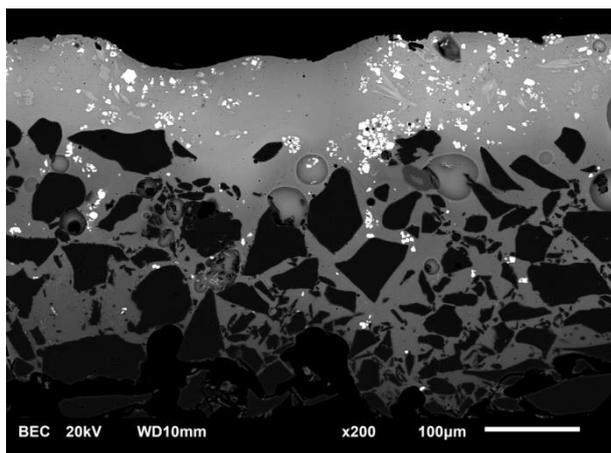
229 No colorant is found in the white MA and LF glazes, the white colour apparently resulting from the use  
230 of a white slip below a colourless glaze. The use of the glaze frit by itself, without a colorant, was  
231 apparently sufficient to obtain this effect - given that the employment of a silica-rich slip (or body) was  
232 an inherent aspect in the production technology of the tiles at both the sites.

#### 233 *Yellow and orange*

234 The yellow and orange LF glazes are both found to contain undissolved particles of the colorant lead  
235 stannate dispersed across their glaze layers (Figure 9). Particles in the yellow glazes are the silica-  
236 containing version of lead stannate known as lead-tin yellow Type II (Rooksby 1964, Kuhn 1968, Clark  
237 et al. 1995), while those in the orange glazes conform to the lesser-known zinc-containing variant,  
238 lead-tin orange (Gill and Rehren 2014).

#### 239 *Green*

240 The green LF glazes contain particles of lead-tin yellow Type II spread across the glaze layers with 2-3  
241 wt% copper oxide. The colour was therefore achieved by the combination of yellow and blue resulting  
242 in green.



**Figure 9.** SEM photomicrograph of an orange glaze (LF-06) showing the distribution of lead stannate pigment particles within. Note the clustering associated with the particles.

## 243 4.2 Mass spectrometry

244 The LA-ICP-MS results for the bulk compositions correlate well with those attained through SEM-EDS  
 245 (SOM Table S3).<sup>1</sup> Differences in colorant content can be attributed to the selection of different spots  
 246 or areas for analysis by the two techniques that were carried out independently of each other, and  
 247 the varying concentrations of the colorants at these places.

248 Trace element data shows a general consistency in the distribution of elements for samples from the  
 249 same building, although some variations are noticeable for glazes of different colours (Table 3). The  
 250 MA samples together (excluding MA-12, MA-13, MA-18, and MA-21) form a group distinct from the  
 251 LF specimens through their respective Li, Ti, V, Cr, Zn, and Ba contents, which are notably higher in the  
 252 Makli specimens (Li:170-330 ppm, Ti:1020-1950 ppm, V:20-30 ppm, Cr:20-40 ppm, Zn:60-320 ppm,  
 253 Ba:180-490 ppm) as compared to those from Lahore Fort (Li:30-50 ppm, Ti:440-690 ppm, V:1-10 ppm,  
 254 Cr:1-10 ppm, Zn:20-40 ppm, Ba:120-170 ppm). The other metallic elements, leaving aside the  
 255 colorants (Cu, Co) and their correlated elements (Ni, As), are more homogeneously distributed across  
 256 the two sample groups. Among these B (160-230 ppm), Mn (310-490 ppm), Rb (30-130 ppm), Sr (260-  
 257 520 ppm), and Zr (40-80 ppm) are present in appreciable concentrations. Higher than usual Fe values  
 258 reported for some samples within a group can be related with the enhanced Co contents recorded in  
 259 the same. MA-12, MA-13, and MA-18, with significant Pb contents, are clear outliers among the MA  
 260 samples, as determined earlier on the basis of SEM-EDS analysis.

## 261 5. DISCUSSIONS

### 262 5.1. The body fabrics

263 The tiles at the two sites were differently made, although some commonalities are also apparent in  
 264 their production. The Makli tiles have earthenware or terracotta bodies, comprising little other than

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<sup>1</sup> The few noticeable variations in the major/minor oxides (MA-13; CaO, MA-18; FeO, and LF-02; CaO) seem to be on account of some limitations associated with the techniques employed. For instance, the lime contents of LF-02 as measured by LA-ICP-MS is 5.7%, while the corresponding figure recorded through SEM-EDS is about a third less. The higher reading for LA-ICP-MS in this case is most likely due to the unusual high presence of lime-rich crystal phases in the glaze layer of this sample, and the difficulties associated in deliberately avoiding such inclusions while measuring by this technique as compared to the SEM-EDS system.

265 clay that has been worked to a fine degree prior to firing. Such bodies are also used in modern *kashi*  
266 ware being manufactured in Sindh (notably at Hala) and Multan (Rye and Evans 1976, 107-108,  
267 Akhund and Askari 2011, UNESCO 2015). The clay used for the Makli tiles would doubtless have been  
268 procured locally, most likely in the vicinity of where they were being manufactured. The sophistication  
269 of the body finish further indicates that the clay or clays were of a particularly fine quality, with care  
270 being taken to ensure that minor grit or impurities were removed prior to the modelling stage. The  
271 use of just well-prepared clay by itself for the preparation of the bodies, with little or no temper, is  
272 reported for current traditional practice as well (Rye and Evans 1976, 107-108).

273 The stonepaste Lahore Fort tile bodies on the other hand follow the technology that was dominant  
274 elsewhere in the northern part of the Indian subcontinent in Mughal times (Gill and Rehren 2011,  
275 Gulzar et al. 2013, Gill et al. 2014). Their microstructural characteristics are consistent with Abu'l  
276 Qasim's historical recipe (Allan 1973), with the bodies being typically prepared using about eight to  
277 nine parts of silica-rich quartz, and half to one part each of glass frit and/or clay. The presence of two  
278 body groups among these samples, distinguished by the shape and distribution of the quartz particles  
279 in each, suggests that more than one workshop was involved in the production of these tiles, or that  
280 they were produced at two different times in the history of the building.

## 281 **5.2. Glaze recipes**

282 The plant ash glaze of the Makli and Lahore Fort tiles is a feature they share with 17th century  
283 specimens from Jahangir's tomb in Lahore (Gulzar et al. 2013), and with coeval Mughal tiles in the  
284 Indian Punjab (Gill and Rehren 2011, Gill and Rehren 2014). A similar plant ash-based technology for  
285 glaze and glass production is also known to have prevailed in the central Islamic lands, to the west and  
286 north of Pakistan, through medieval to pre-modern times (Brill 1999, 482-484, Fabbri et al. 2002,  
287 Vandiver et al. 2010, Gradmann et al. 2014). In contrast, tile glazes made in the same period to the  
288 east, notably at Delhi and beyond, are predominantly of the mineral soda 'Indian' variety (Gill et al.  
289 2014). This indicates that the geographic expanse of plant ash glass- or glaze-making technologies,  
290 otherwise typically associated with the core Islamic lands only, includes the larger region around these  
291 two sites as well, and by extension probably the whole of Pakistan. Ethnographic studies conducted  
292 in Sindh and Punjab over the last century and a half further suggest that the glaze frit is likely to have  
293 been prepared in the manner ascribed to a particular traditional practice in the region (Hallifax 1892,  
294 Rye and Evans 1976, pp. 95-96), through the manufacture of glass balls in a furnace, which were then  
295 broken down and milled to obtain a glaze powder. This seems to be the case at least for the Sindh-  
296 Multan *kashi* variety of tiles. Certainly no evidence for local glaze manufacture by the typical method  
297 of melting glass in a furnace and its subsequent pouring in water, as reported for other places in the  
298 Islamic world, has yet come to light.

299 Silica (quartz) and plant ash soda would have been used as the raw material for the production of the  
300 frit. The plant ash is likely to have been obtained by the burning of *Haloxylon recurvum* (*Haloxylon*  
301 *stocksii*), a local desert plant, and a known common source for crude soda in the region (Tite et al.  
302 2006). Silica would probably have been similarly derived as for the bodies, and/or slips, for the Lahore  
303 and Makli tiles respectively. Chemical compositions and trace element patterns indicate that the silica  
304 is likely to have been drawn from different geological sources for the two sites. Relatively lower values  
305 of the heavy accessory minerals (as indicated by levels of Fe, Ti, Ba), together with the general  
306 roundedness of the quartz grains in the Lahore Fort body matrices, suggest the employment of a

307 mature high silica sand in their case. A different source was used for the Makli tiles. The higher  
308 contents of these elements, notably the elevated titania and iron oxide levels, may be suggestive of  
309 silica derived from quarried quartz (deposits), as recorded for current traditional practice in the region.

310 Differences in the soda contents of the glazes suggest that either different proportions or different  
311 varieties of the two ingredients were utilized at the two places (Fig. 10 Na<sub>2</sub>O vs CaO). The Lahore tiles,  
312 with average soda contents of around 18 wt%, are likely to have been produced using roughly equal  
313 parts of silica (quartz) and soda (plant ash), as described in Abu'l Qasim's historical recipe, whereas  
314 the Makli tiles that are typically 5 wt% or so lower in soda, probably used a higher proportions of silica.  
315 The differences in the soda values could, however, also indicate the use of different plant species, as  
316 further indicated by the differences in trace alkalis lithium and rubidium (Fig. 11 Li vs Rb), or the use  
317 of different techniques to obtain and refine plant ash at the two places.

318 Five of the Makli tiles fall away from the main group: MA-12 and MA-13 with very low CaO and MgO  
319 values; MA-14 and MA-18 with relatively low lime and soda levels, and MA-21 with very high soda  
320 (see Fig. 10 Na<sub>2</sub>O vs CaO and Table #). We have trace element analyses of four of these samples (MA-  
321 12, MA-13, MA-18, and MA-21) which show that they also differ in other characteristics, such as low  
322 arsenic for the two cobalt-blue samples MA-12 and -13 compared to other cobalt-blue samples (MA-  
323 4, -5, -16 and -27). Three of these (MA-12, MA-13, and MA-18) are characterised by significantly high  
324 boron values (2000-8150 ppm – ten to forty times more than the average of the remaining Makli tiles;  
325 Table 3), very high lead (particularly in MA-13 and MA-18 where it is a few hundred times more in  
326 ppm than the others), low strontium (80 to 160 ppm, compared to typically 250 to 400 ppm for the  
327 other Makli samples), and very low manganese (75-120 ppm, only a third to a fifth of the levels seen  
328 in the other tiles). It is possible that these tiles represent a different production group, and are likely  
329 to be later repairs, although they do appear overall similar to the main samples in that they, too, seem  
330 to be plant-ash based and using a silica source with similar concentrations of accessory minor oxides,  
331 and their bodies and manufacture do not show any major differences from the remaining tiles. The  
332 high boron values associated with some of these can be related to the reported use of borax for a  
333 secondary refinement of glazes in traditional local manufacture from the late 19th century onwards  
334 (Birdwood 1884, 401, Rye and Evans 1976, 96), reiterating the suggestion that these are more likely  
335 to be resultant of some later date restoration effort.

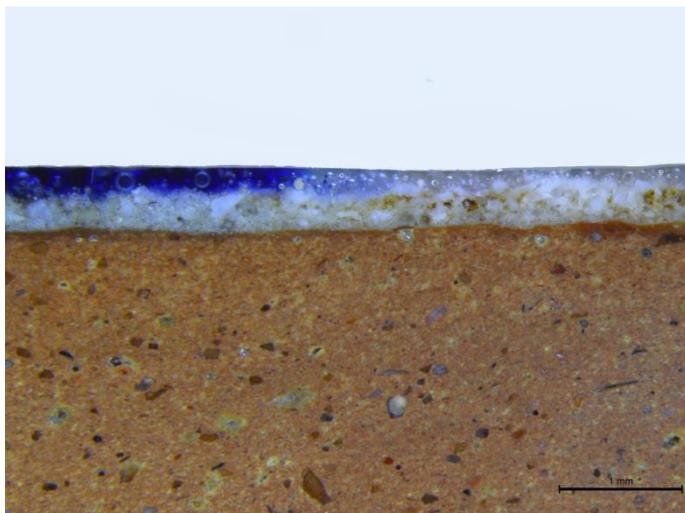
336 The SEM-EDS bulk glaze analyses indicated that the glazes from Makli and Lahore Fort have two  
337 slightly distinct compositions, most markedly in their soda and lime content; the trace element data  
338 make this separation even more clear, with distinct differences in a number of elements which can be  
339 linked to the flux of the glaze (Li, B, Cl, Rb) as well as to the silica source (Ti, Sr, Ba, REEs). These  
340 consistent and significant differences further underline the co-existence of two distinct glazed tile  
341 manufacturing traditions which were already indicated by the sharp difference in body composition.

342 The turquoise glaze on sample MA-21, badly preserved on a clay-based body which is indistinguishable  
343 from the other Makli tile bodies, shares many chemical characteristics with the Lahore Fort glazes.  
344 This includes the very high soda and chlorine levels as well as rather low lithium and rubidium content  
345 (see Fig. 11) Since little is known about the tomb from which this tile originates it is not possible to  
346 speculate about potential reasons for this combination of local clay-based tile body with a Lahore-  
347 type glaze otherwise only found on stonepaste bodies.

348

349 **5.3 Coloration**

350 The glazes were clearly similarly coloured at the two sites, using the same colorants. While the bulk  
351 composition of differently coloured areas in the polychrome glazes differ depending on the nature  
352 and amount of colorants added, it is important to stress that the reduced compositions, that is the  
353 composition of these glazes without the added colorants and re-cast to 100 wt%, are identical within  
354 analytical uncertainty and normal variability across all colours. Thus, we are confident to say that for  
355 the production of polychrome tiles the different colorants were added to one and the same base glass,  
356 and that no pre-coloured glaze frit mixtures were procured from different sources using different base  
357 glass recipes. The 14th century sample (MA-20), and one dating to the 17th century (MA-19), were  
358 also found to be coloured in the same manner. The colorants employed are consistent with those  
359 known from pre-modern glazes in the subcontinent (Gill and Rehren 2011, Gulzar et al. 2013, Gill et  
360 al. 2014). The turquoise, dark-blue, and white glazes that are common to the two sites are thus  
361 coloured using copper oxide, cobalt oxide, and through a white slip/body respectively, while the  
362 yellow and green glazes of Lahore Fort are coloured with lead stannate and lead stannate + copper  
363 oxide respectively. The orange Lahore Fort glazes are coloured by the same zinc-containing variant of  
364 lead stannate as found in their counterparts in Indian Punjab, corroborating the other evident  
365 connections in the technologies of the two.



**Figure 102.** Optical microscopy image of the blue and white coloured areas of a polychrome Makli glaze (MA-10). Note the extent of coloration of the glaze in the dark-blue zone.

366 Analytical findings confirm that the polychrome tiles, which are specific to Makli only, were  
367 underglaze-painted, the pigments seemingly being first painted on the slips and then a transparent  
368 glaze applied-on. The silica-rich slip that was typically applied on these bodies apparently performed  
369 three functions; it provided an even surface for painting where needed, effectively masked the  
370 redness of the underlying terracotta body, and produced a white background where left unpainted  
371 and covered with a transparent glaze. The monochrome specimens from the two sites, in contrast,  
372 are more likely to have had only a single stage involved for the coloration of their glazes, with the  
373 pigments being dry-mixed into the glaze powder beforehand, as usually done in traditional practice.  
374 This is supported to an extent by the general clustering noticeable for the undissolved pigment  
375 particles that lie suspended in the lead stannate coloured glazes, while a more even distribution would  
376 be expected in the case of pre-coloured frits. It is interesting to see that no clearly defined separate

377 layer of a transparent glaze is visible over the body in the case of the polychrome tiles (Figure 12), the  
378 pigments apparently having worked their way into the glazes and colouring them through their entire  
379 thicknesses at the time of melting. The noted variations in pigment concentrations in the coloured  
380 zones of these tiles individually, however again makes a case for these being underglaze-painted, as  
381 opposed to suggesting the use of a coloured frit or glaze.

#### 382 **5.4 Comparison to contemporary practice**

383 While the *kashi* tile-work now being produced at Sindh and Multan by and large utilize the same glaze  
384 preparation and colouring techniques as determined for the Makli tiles, some changes to the glaze  
385 and glazing recipes seem to have been introduced over time. The consistent use of lead glazes since  
386 the last century or so for instance (Birdwood 1884, 401, Hallifax 1892, 16-17, Furnival 1904, 225, Rye  
387 and Evans 1976, 109-110), in addition to alkaline glazes, does not seem to have any historical parallel,  
388 and no such glazes have been found so far in the examined corpus of historical samples (other than  
389 the obvious outliers which are probably a restoration effort, as stated earlier). The use of borax for a  
390 secondary refinement of the raw glaze frit at Multan, or the use of different coloured slips at Hala in  
391 Sindh likewise (Rye and Evans 1976, 109-110), appear to be technological alterations that have arrived  
392 at a relatively more modern date. It is therefore seen that only a part of the technologies that are  
393 being currently followed in traditional practice in Sindh-Multan can be related to the historic tile-work  
394 originally employed on monuments in the region. These identified technologies are likely to be more  
395 appropriate for conservation programmes that may be initiated for the tile-work from time to time. It  
396 is worth mentioning in this context that a remarkably accurate rendition of the same technologies  
397 were apparently employed in the restoration of the tile-work on Shaikh Rukn-e-Alam's tomb at Multan  
398 (Khan 1985), undertaken on the orders of the Government of Pakistan-Punjab. The Sindh Makli tiles,  
399 should the need arise, may be conserved or restored in broadly the same manner, with suitable  
400 modifications being applied based on the findings of this study. For now, it would be appropriate to  
401 just state that the Makli tiles can be considered antecedents of the modern traditional *kashi* ware in  
402 so far as materials and technologies are concerned. Further work is needed to correlate historic tiles  
403 from elsewhere in Sindh-Multan to the same technological style.

#### 404 **6. CONCLUSION**

405 The Makli tiles are different from those from Lahore in their glaze and body compositions, range of  
406 glaze colours exhibited, and glaze decoration techniques. They both, however, share the same basic  
407 glaze characteristics using plant ash as the main flux, and are more 'Central Asian' or 'Persian' as  
408 opposed to being 'Indian' in this respect. The colorants used in all these glazes are consistent with  
409 those known to have been employed in the wider region in pre-modern times. In the larger context of  
410 Islamic tile-work, the Lahore tiles can be said to be closer in character to those from the central Islamic  
411 lands in terms of their overall make-up. Their relatively short duration of employment, and the yet  
412 unreported presence of any similar tradition in Pakistan before their appearance, suggests that they  
413 were a 'foreign' import, likely executed at the hands of migrant artisans. The Makli *kashi* tiles in  
414 comparison are clearly a more local development, with roots in the Sindh-Multan region. While  
415 conforming in spirit and character to the typical Islamic traditions of architectural tiling, they stand  
416 apart as being one of few examples of craft practices that has survived and remained steadfast over  
417 time. Indeed they are perhaps the only true living representations of the blue-and-white tiling  
418 traditions which made their appearance in the Islamic world as early as the 14th century.

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**Table 1.** Chemical compositions of the Makli tile glazes determined through SEM-EDS analyses. All results are in wt% and normalised to 100%. Results below the detection limit of the instrument are provided for comparative purposes only. '-' indicates 'not detected'.

Sample	Type	Glaze colours	SiO <sub>2</sub>	Na <sub>2</sub> O	CaO	K <sub>2</sub> O	MgO	Al <sub>2</sub> O <sub>3</sub>	FeO	TiO <sub>2</sub>	P <sub>2</sub> O <sub>5</sub>	SO <sub>3</sub>	Cl	CuO	CoO	As <sub>2</sub> O <sub>3</sub>	PbO
MA-01	Polychrome	Dark-Blue, White, Turquoise	64.3	14.4	5.6	3.0	3.1	2.5	1.6	0.2	0.4	0.4	0.5	1.7	1.4	1.0	-
MA-02	Polychrome	Dark-Blue, White, Turquoise	66.9	12.6	6.8	3.5	3.6	1.9	1.0	0.2	0.4	0.3	1.2	0.9	0.6	-	-
MA-03	Monochrome	Turquoise	69.5	10.5	5.8	3.9	3.2	2.7	1.1	0.2	0.4	0.4	0.1	2.1	-	-	-
MA-04	Polychrome	Dark-Blue, White, Turquoise	64.8	13.8	5.3	2.6	3.0	2.4	1.5	0.2	0.4	0.3	0.5	3.3	1.0	0.8	-
MA-05	Monochrome	Dark-Blue	65.3	14.3	6.6	2.9	3.8	2.8	1.7	0.3	0.5	0.4	0.4	-	0.7	0.6	-
MA-06	Monochrome	Turquoise	63.6	12.9	6.0	3.1	3.6	2.6	1.0	0.2	0.4	0.3	0.5	5.6	-	-	-
MA-07	Monochrome	White	65.7	14.5	6.8	2.9	4.1	2.9	1.3	0.2	0.5	0.4	0.5	-	-	-	-
MA-08	Monochrome	Turquoise	70.0	11.5	4.9	3.0	3.1	2.6	1.1	0.2	0.2	0.2	0.8	2.4	-	-	-
MA-09	Monochrome	White	66.4	13.4	7.3	3.0	4.3	2.8	1.2	0.2	0.6	0.4	0.3	-	-	-	-
MA-10	Polychrome	Dark-Blue, White	65.9	11.6	6.1	3.9	3.6	3.2	1.8	0.3	0.6	0.2	0.4	0.2	1.3	0.8	-
MA-11	Polychrome	Dark-Blue, White, Turquoise	68.6	10.5	5.8	3.7	3.5	2.4	1.5	0.3	0.3	0.3	0.3	1.6	0.8	0.6	-
MA-12	Polychrome	Dark-Blue, White, Turquoise	73.5	15.1	1.4	3.3	0.3	2.0	0.7	0.2	-	0.6	0.1	1.8	1.0	-	-
MA-13	Polychrome	Dark-Blue, White, Turquoise	63.6	11.0	1.8	3.5	0.4	2.1	0.7	0.2	-	0.1	0.5	2.0	1.0	-	13.1
MA-14	Polychrome	Dark-Blue, White	71.1	6.1	3.8	5.1	2.4	5.9	1.9	0.4	0.3	0.3	0.1	0.3	2.0	0.3	-
MA-15	Monochrome	Turquoise	68.5	9.7	5.9	3.7	3.8	2.7	1.1	0.3	0.4	0.3	0.5	3.0	-	-	-
MA-16	Polychrome	Dark-Blue, White, Turquoise	68.8	9.2	6.2	4.0	3.8	2.2	1.1	0.3	0.2	0.3	0.2	2.9	0.7	0.2	-
MA-17	Polychrome	Dark-Blue, White	69.1	11.7	6.6	3.5	3.9	2.5	1.2	0.3	0.3	0.3	0.2	-	0.3	0.2	-
MA-18	Monochrome	Turquoise	66.5	10.6	3.9	3.4	0.7	2.0	1.0	0.2	0.1	0.2	0.1	4.1	-	-	7.2
MA-19	Polychrome	Dark-Blue, White, Turquoise	69.5	9.6	5.4	4.0	3.4	2.2	1.0	0.3	0.2	0.3	0.3	2.9	0.4	0.4	-
MA-20	Monochrome	Turquoise	65.9	10.7	5.8	4.3	3.5	3.1	1.2	0.3	0.4	0.3	0.7	4.0	-	-	-
MA-21	Monochrome	Turquoise	60.4	20.1	4.0	2.2	2.9	2.5	1.2	0.3	0.3	0.3	1.7	4.2	-	-	-
MA-22	Monochrome	Turquoise	67.5	10.0	5.3	3.8	2.7	2.9	1.3	0.3	0.4	0.3	0.6	5.0	-	-	-
MA-23	Monochrome	Turquoise	69.3	8.8	5.3	5.8	3.5	2.6	1.1	0.3	0.3	0.3	0.1	2.6	-	-	-
MA-24	Monochrome	Turquoise	67.2	12.3	6.0	3.0	3.8	2.7	1.1	0.3	0.3	0.2	0.6	2.6	-	-	-
MA-25	Monochrome	Turquoise	64.8	13.8	7.1	2.5	3.8	3.3	1.6	0.3	0.4	0.3	0.4	1.8	-	-	-
MA-26	Polychrome	Dark-Blue, White, Turquoise	68.5	10.5	5.3	3.4	3.6	2.2	0.9	0.2	0.3	0.3	0.1	4.9	-	-	-
MA-27	Polychrome	Dark-Blue, White	69.2	9.6	6.3	3.4	4.2	2.8	1.2	0.3	0.3	0.3	0.5	0.3	0.9	0.7	-
MA-28a	Monochrome	Turquoise	68.7	10.2	5.8	3.4	3.6	1.9	0.9	0.2	0.3	0.3	0.4	4.2	-	-	-
MA-28b	Monochrome	Dark-Blue	67.8	10.0	6.4	3.8	3.8	2.9	1.7	0.3	0.3	0.4	0.2	0.3	1.1	0.8	-

**Table 2.** Chemical compositions of the Lahore Fort tile glazes determined through SEM-EDS analyses. All results are in wt% and normalised to 100%. '-' indicates 'not detected'.

Sample	Type	Glaze colour	SiO <sub>2</sub>	Na <sub>2</sub> O	CaO	K <sub>2</sub> O	MgO	Al <sub>2</sub> O <sub>3</sub>	FeO	P <sub>2</sub> O <sub>5</sub>	SO <sub>3</sub>	Cl	CuO	CoO	ZnO	SnO <sub>2</sub>	PbO
LF-01	Monochrome	Yellow	55.2	12.2	2.8	6.0	2.1	1.5	0.6	0.3	-	0.7	-	-	0.4	3.7	14.4
LF-02	Monochrome	White	64.6	19.2	3.6	3.3	3.3	2.7	1.1	0.5	0.6	1.3	-	-	-	-	-
LF-03	Monochrome	Dark Blue	65.5	17.4	5.0	2.8	2.9	2.3	1.9	0.3	0.5	0.7	-	0.8	-	-	-
LF-04	Monochrome	Dark Blue	65.4	16.5	4.7	3.3	3.1	3.4	1.2	0.4	0.4	1.2	-	0.4	-	-	-
LF-05	Monochrome	Turquoise	65.1	16.0	5.4	2.4	3.1	2.0	0.7	0.4	0.5	0.9	3.8	-	-	-	-
LF-06	Monochrome	Orange	50.1	12.0	3.1	2.5	2.2	1.5	0.6	0.3	-	0.9	-	-	1.9	5.6	19.5
LF-07a	Monochrome	Green	55.9	14.2	3.3	3.3	2.5	2.0	0.9	0.3	-	0.9	2.2	-	-	3.3	11.3
LF-07b	Monochrome	Yellow	52.9	18.1	3.9	2.4	2.6	1.8	0.7	0.3	-	1.3	-	-	-	2.0	13.9
LF-08	Monochrome	Green	52.2	15.1	4.2	2.4	2.8	2.1	0.8	0.3	-	1.1	2.8	-	-	3.2	13.1

**Table 3.** Trace element compositions of select Makli and Lahore glazes determined through LA-ICP-MS analyses and reported in ppm. Elements that are diagnostic of the two groups are highlighted in bold. The outliers in the Makli group are highlighted in light-gray. 0 ppm indicates values below 0.5 ppm.

Sample	Colours analysed	Li	B	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	As	Rb	Sr	Y	Zr	Sn	Sb	Ba	La	Ce	Nd	Pb
<b>Makli samples</b>																								
MA-01	Turquoise	<b>211</b>	183	<b>1203</b>	20	<b>15</b>	325	8108	125	39	19026	<b>114</b>	163	54	410	7	49	202	25	245	12	22	10	55
MA-02	Dark-Blue, White	<b>215</b>	193	<b>1111</b>	19	<b>19</b>	414	7839	2571	164	4611	<b>104</b>	229	97	518	7	36	2	3	367	13	24	10	70
MA-04	Dark-Blue, White	<b>328</b>	165	<b>1271</b>	23	<b>36</b>	308	10590	3285	306	1460	<b>243</b>	2384	57	383	8	43	3	0	415	14	27	13	59
MA-05	Dark-Blue	<b>276</b>	211	<b>1280</b>	26	<b>18</b>	410	11187	3115	288	938	<b>148</b>	4013	72	386	12	40	4	0	490	13	23	10	75
MA-08	Turquoise	<b>172</b>	161	<b>1176</b>	18	<b>18</b>	361	8471	16	56	17336	<b>63</b>	63	82	275	6	44	6	8	139	12	22	9	130
MA-09	White	<b>222</b>	228	<b>1223</b>	21	<b>19</b>	338	8237	28	12	219	<b>85</b>	17	69	348	7	79	1	0	319	14	26	11	32
MA-12	Dark-Blue, White, Turquoise	<b>266</b>	3154	<b>1024</b>	22	<b>25</b>	74	4366	1234	35	18625	<b>294</b>	31	80	84	6	67	2743	24	242	12	22	9	2345
MA-13	Dark-Blue, Turquoise	<b>209</b>	2004	<b>1017</b>	22	<b>20</b>	118	5932	6440	120	28817	<b>2300</b>	70	132	157	6	115	2052	5306	358	12	22	9	8911 1
MA-16	Dark-Blue, White, Turquoise	<b>204</b>	168	<b>1387</b>	19	<b>14</b>	444	7926	3149	338	23451	<b>320</b>	964	105	311	8	37	34	7	228	12	23	10	108
MA-18	Turquoise	<b>167</b>	8136	<b>937</b>	17	<b>27</b>	77	4275	172	43	29778	<b>3794</b>	80	59	117	6	105	2814	2160	338	10	20	7	4962 7
MA-20	Turquoise	<b>196</b>	191	<b>1945</b>	23	<b>27</b>	494	9775	15	90	29995	<b>207</b>	122	125	324	8	66	77	49	182	13	24	10	249
MA-21	Turquoise	<b>53</b>	238	<b>1486</b>	23	<b>14</b>	391	9163	57	63	30050	<b>1045</b>	93	32	238	5	31	384	12	98	8	14	6	240
MA-24	Turquoise	<b>167</b>	213	<b>1489</b>	23	<b>20</b>	390	7859	5	71	18081	<b>191</b>	36	97	260	6	37	228	10	124	8	16	7	162
MA-27	Dark-Blue, White	<b>268</b>	178	<b>1426</b>	26	<b>23</b>	411	10294	3466	268	1723	<b>132</b>	2773	92	383	9	77	4	1	307	14	27	11	39
MA-28a	Turquoise	<b>213</b>	161	<b>1049</b>	19	<b>22</b>	309	6895	123	54	31778	<b>135</b>	152	74	359	7	64	41	32	243	13	25	11	562
<b>Lahore samples</b>																								
LF-02	White	<b>32</b>	225	<b>559</b>	11	<b>3</b>	333	5600	2	5	53	<b>42</b>	4	40	226	6	50	2	0	124	9	17	7	420
LF-03	Dark-Blue	<b>40</b>	233	<b>595</b>	12	<b>8</b>	451	17471	6909	127	374	<b>22</b>	1294	28	311	7	72	4	0	168	9	17	7	178
LF-04	Dark-Blue	<b>48</b>	177	<b>685</b>	13	<b>11</b>	466	8226	3186	51	362	<b>34</b>	553	68	271	7	55	9	6	164	10	19	8	757
LF-05	Turquoise	<b>30</b>	166	<b>439</b>	9	<b>7</b>	313	4552	11	40	24724	<b>23</b>	91	50	248	5	47	28	25	173	7	13	6	587



**Appendix A.** List of samples with details of the buildings from where sourced. The MA series are from various buildings at Makli Hill, while the LF series are from Lahore Fort.

No.	Sample	Type	Glaze colours	Building	Period/date*
1	MA-01	Polychrome	Dark-Blue, White, Turquoise	Tomb of Sultan Ibrahim	1558-1559 CE
2	MA-02	Polychrome	Dark-Blue, White, Turquoise	Tomb of Sultan Ibrahim	1558-1559 CE
3	MA-03	Monochrome	Turquoise	Tomb of Sultan Ibrahim	1558-1559 CE
4	MA-04	Polychrome	Dark-Blue, White, Turquoise	Tomb of Sultan Ibrahim	1558-1559 CE
5	MA-05	Monochrome	Dark-Blue	Tomb of Dewan Shurfa Khan	c. 1638 CE
6	MA-06	Monochrome	Turquoise	Tomb of Dewan Shurfa Khan	c. 1638 CE
7	MA-07	Monochrome	White	Tomb of Dewan Shurfa Khan	c. 1638 CE
8	MA-08	Monochrome	Turquoise	Tomb of Dewan Shurfa Khan	c. 1638 CE
9	MA-09	Monochrome	White	Tomb of Dewan Shurfa Khan	c. 1638 CE
10	MA-10	Polychrome	Dark-Blue, White	Unknown Enclosure-1	Unknown
11	MA-11	Polychrome	Dark-Blue, White, Turquoise	Unknown Enclosure-1	Unknown
12	MA-12	Polychrome	Dark-Blue, White, Turquoise	Tomb of Mirza Jani Beg	c. 1600-1601 CE
13	MA-13	Polychrome	Dark-Blue, White, Turquoise	Tomb of Mirza Jani Beg	c. 1600-1601 CE
14	MA-14	Polychrome	Dark-Blue, White	Enclosure	Unknown
15	MA-15	Monochrome	Turquoise	Enclosure	Unknown
16	MA-16	Polychrome	Dark-Blue, White, Turquoise	Tomb of Khusrau Khan Charkhas	1601-1602 CE
17	MA-17	Polychrome	Dark-Blue, White	Unknown Platform	Unknown
18	MA-18	Monochrome	Turquoise	Enclosure of Mirza Baqi Baig Uzbek	1641 CE
19	MA-19	Polychrome	Dark-Blue, White, Turquoise	Sayyid Amir Khan grave enclosure	1715 CE
20	MA-20	Monochrome	Turquoise	Tomb of Shaikh Hammad Jamali	c. 1389-1392 CE
21	MA-21	Monochrome	Turquoise	Unknown Tomb-1	Unknown
22	MA-22	Monochrome	Turquoise	Unknown Tomb-2	17th cent.
23	MA-23	Monochrome	Turquoise	Unknown Enclosure-2	16th cent.
24	MA-24	Monochrome	Turquoise	Unknown Enclosure-3	17th cent.
25	MA-25	Monochrome	Turquoise	Unknown Enclosure-3	17th cent.
26	MA-26	Polychrome	Dark-Blue, White, Turquoise	Unknown Tomb Enclosure	17th cent.
27	MA-27	Polychrome	Dark-Blue, White	Unknown Tomb Enclosure	17th cent.
28	MA-28a	Monochrome	Turquoise	Unknown Tomb Enclosure	17th cent.
29	MA-28b	Monochrome	Dark-Blue	Unknown Tomb Enclosure	17th cent.
30	LF-01	Monochrome	Yellow	Lahore Fort	c. 1625-1630 CE
31	LF-02	Monochrome	White	Lahore Fort	c. 1625-1630 CE
32	LF-03	Monochrome	Dark-Blue	Lahore Fort	c. 1625-1630 CE
33	LF-04	Monochrome	Dark-Blue	Lahore Fort	c. 1625-1630 CE
34	LF-05	Monochrome	Turquoise	Lahore Fort	c. 1625-1630 CE
35	LF-06	Monochrome	Orange	Lahore Fort	c. 1625-1630 CE
36	LF-07a	Monochrome	Green	Lahore Fort	c. 1625-1630 CE
37	LF-07b	Monochrome	Yellow	Lahore Fort	c. 1625-1630 CE
38	LF-08	Monochrome	Green	Lahore Fort	c. 1625-1630 CE

\*Dates where assigned require ratification.

**Appendix B.** Reduced chemical compositions of the Makli tile glazes. All results are in wt% from SEM-EDS analyses and normalised to 100%. Results below the detection limit of the instrument are provided for comparative purposes only.

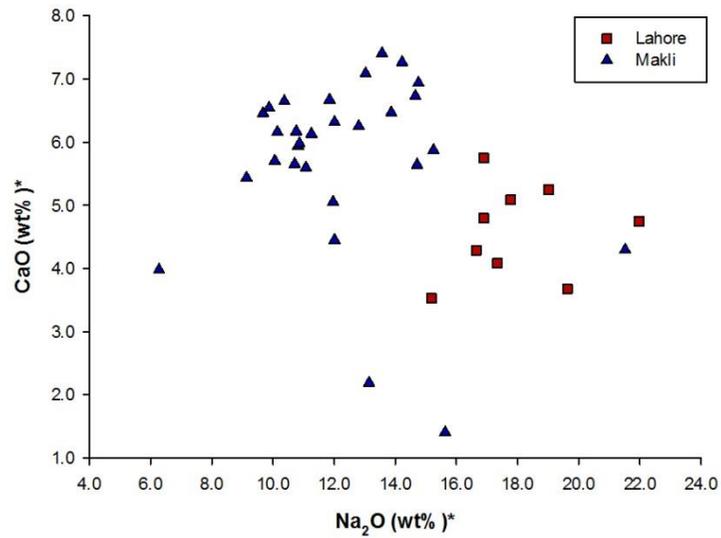
Sample	Type	Glaze colours	SiO <sub>2</sub>	Na <sub>2</sub> O	CaO	K <sub>2</sub> O	MgO	Al <sub>2</sub> O <sub>3</sub>	FeO	TiO <sub>2</sub>
MA-01	Polychrome	Dark-Blue, White, Turquoise	67.9	15.3	5.9	3.2	3.3	2.6	1.7	0.3
MA-02	Polychrome	Dark-Blue, White, Turquoise	69.3	13.0	7.1	3.6	3.7	2.0	1.0	0.2
MA-03	Monochrome	Turquoise	71.8	10.8	5.9	4.0	3.3	2.8	1.2	0.2
MA-04	Polychrome	Dark-Blue, White, Turquoise	69.2	14.7	5.6	2.8	3.2	2.5	1.6	0.3
MA-05	Monochrome	Dark-Blue	67.0	14.7	6.7	2.9	3.9	2.8	1.7	0.3
MA-06	Monochrome	Turquoise	68.2	13.9	6.5	3.3	3.9	2.8	1.1	0.3
MA-07	Monochrome	White	66.7	14.8	6.9	3.0	4.1	3.0	1.3	0.2
MA-08	Monochrome	Turquoise	72.6	12.0	5.1	3.1	3.2	2.6	1.1	0.2
MA-09	Monochrome	White	67.3	13.6	7.4	3.0	4.4	2.8	1.2	0.3
MA-10	Polychrome	Dark-Blue, White	68.3	12.0	6.3	4.0	3.8	3.4	1.9	0.3
MA-11	Polychrome	Dark-Blue, White, Turquoise	71.3	10.9	6.0	3.8	3.6	2.5	1.6	0.3
MA-12	Polychrome	Dark-Blue, White, Turquoise	76.2	15.6	1.4	3.4	0.3	2.1	0.7	0.2
MA-13	Polychrome	Dark-Blue, White, Turquoise	76.3	13.1	2.2	4.2	0.5	2.6	0.9	0.2
MA-14	Polychrome	Dark-Blue, White	73.4	6.3	4.0	5.3	2.4	6.1	2.0	0.5
MA-15	Monochrome	Turquoise	71.5	10.1	6.2	3.9	4.0	2.8	1.2	0.3
MA-16	Polychrome	Dark-Blue, White, Turquoise	72.1	9.7	6.5	4.2	3.9	2.3	1.2	0.3
MA-17	Polychrome	Dark-Blue, White	70.0	11.9	6.7	3.5	3.9	2.5	1.2	0.3
MA-18	Monochrome	Turquoise	75.3	12.0	4.4	3.8	0.7	2.3	1.2	0.2
MA-19	Polychrome	Dark-Blue, White, Turquoise	72.8	10.1	5.7	4.2	3.6	2.4	1.0	0.3
MA-20	Monochrome	Turquoise	69.6	11.3	6.1	4.5	3.7	3.2	1.2	0.3
MA-21	Monochrome	Turquoise	64.6	21.5	4.3	2.4	3.1	2.6	1.2	0.3
MA-22	Monochrome	Turquoise	72.0	10.7	5.7	4.0	2.8	3.1	1.4	0.3
MA-23	Monochrome	Turquoise	71.6	9.1	5.4	6.0	3.6	2.7	1.1	0.3
MA-24	Monochrome	Turquoise	69.7	12.8	6.2	3.1	3.9	2.8	1.1	0.3
MA-25	Monochrome	Turquoise	66.8	14.2	7.3	2.5	3.9	3.4	1.7	0.3
MA-26	Polychrome	Dark-Blue, White, Turquoise	72.5	11.1	5.6	3.6	3.8	2.3	0.9	0.2
MA-27	Polychrome	Dark-Blue, White	71.4	9.9	6.5	3.5	4.4	2.9	1.2	0.3
MA-28a	Monochrome	Turquoise	72.5	10.8	6.2	3.6	3.8	2.0	0.9	0.2
MA-28b	Monochrome	Dark-Blue	70.1	10.4	6.6	3.9	3.9	3.0	1.7	0.3

**Appendix C.** Reduced chemical compositions of the Lahore tile glazes. All results are in wt% from SEM-EDS analyses and normalised to 100%.

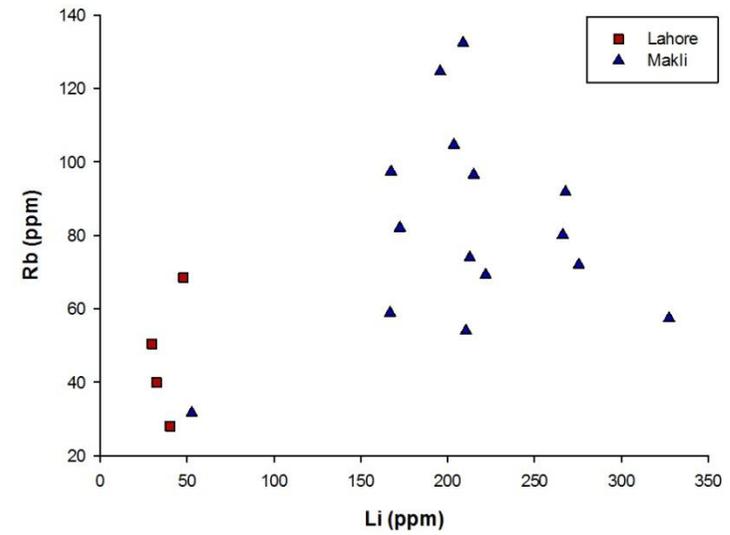
Sample	Type	Glaze colour	SiO <sub>2</sub>	Na <sub>2</sub> O	CaO	K <sub>2</sub> O	MgO	Al <sub>2</sub> O <sub>3</sub>	FeO
LF-01	Monochrome	Yellow	68.6	15.2	3.5	7.4	2.7	1.9	0.8
LF-02	Monochrome	White	66.1	19.6	3.7	3.4	3.3	2.7	1.1
LF-03	Monochrome	Dark-Blue	67.1	17.8	5.1	2.8	3.0	2.3	1.9
LF-04	Monochrome	Dark-Blue	67.0	16.9	4.8	3.4	3.1	3.5	1.2
LF-05	Monochrome	Turquoise	68.9	16.9	5.7	2.5	3.2	2.1	0.7
LF-06	Monochrome	Orange	69.6	16.6	4.3	3.4	3.1	2.1	0.8
LF-07a	Monochrome	Green	68.1	17.3	4.1	4.0	3.1	2.4	1.1
LF-07b	Monochrome	Yellow	64.2	22.0	4.7	2.9	3.2	2.1	0.8
LF-08	Monochrome	Green	65.6	19.0	5.3	3.0	3.5	2.6	1.0

**Appendix D.** Reduced chemical compositions of select Makli and Lahore tile glazes. All results are in wt% from LA-ICP-MS analyses, and normalised to 100%. Results have been rounded off to one decimal place for comparison with SEM-EDS analyses.

Sample	Type	Glaze colours	SiO <sub>2</sub>	Na <sub>2</sub> O	CaO	K <sub>2</sub> O	MgO	Al <sub>2</sub> O <sub>3</sub>	FeO	TiO <sub>2</sub>
<b>Makli samples</b>										
MA-01	Polychrome	Dark-Blue, White, Turquoise	68.5	15.8	5.9	2.9	3.2	2.5	1.1	0.2
MA-02	Polychrome	Dark-Blue, White, Turquoise	69.0	13.1	7.1	3.5	3.6	2.5	1.0	0.2
MA-04	Polychrome	Dark-Blue, White, Turquoise	70.9	14.0	5.8	2.4	2.6	2.7	1.4	0.2
MA-05	Monochrome	Dark-Blue	67.5	14.0	6.9	3.1	3.6	3.3	1.5	0.2
MA-08	Monochrome	Turquoise	72.3	12.3	4.9	2.9	3.1	3.1	1.1	0.2
MA-09	Monochrome	White	68.7	13.7	6.3	2.9	3.8	3.2	1.1	0.2
MA-12	Polychrome	Dark-Blue, White, Turquoise	77.4	14.8	1.5	3.2	0.3	2.0	0.6	0.2
MA-13	Polychrome	Dark-Blue, White, Turquoise	75.7	12.7	3.2	4.0	0.6	2.8	0.9	0.2
MA-16	Polychrome	Dark-Blue, White, Turquoise	72.3	9.8	6.2	3.9	3.9	2.6	1.1	0.2
MA-18	Monochrome	Turquoise	76.0	11.7	4.6	3.6	0.8	2.4	0.6	0.2
MA-20	Monochrome	Turquoise	68.3	11.7	6.7	4.1	4.0	3.5	1.3	0.3
MA-21	Monochrome	Turquoise	64.6	21.9	4.5	2.2	2.9	2.5	1.3	0.3
MA-24	Monochrome	Turquoise	71.0	12.6	5.7	2.9	3.6	2.8	1.0	0.3
MA-27	Polychrome	Dark-Blue, White	71.4	9.9	6.6	3.3	4.3	2.9	1.3	0.2
MA-28a	Monochrome	Turquoise	72.7	10.7	6.1	3.5	3.7	2.3	0.9	0.2
<b>Lahore samples</b>										
LF-02	Monochrome	White	64.7	20.1	5.7	3.0	3.1	2.6	0.7	0.1
LF-03	Monochrome	Dark-Blue	64.1	19.0	5.8	2.5	3.2	3.0	2.3	0.1
LF-04	Monochrome	Dark-Blue	68.3	15.3	5.4	3.1	2.8	3.9	1.1	0.1
LF-05	Monochrome	Turquoise	70.3	15.9	4.9	2.5	2.7	3.0	0.6	0.1



**Appendix E.** Scatter plot of soda versus lime contents of the Makli and Lahore glazes. \* indicates reduced composition.



**Appendix F.** Scatter plot of lithium versus rubidium contents of select Makli and Lahore glazes. MA-21 is an exception to the Makli grouping, lying closer instead to the Lahore group.