Journal of Archaeological Science 49 (2014) 546–555

Contents lists available at ScienceDirect

Journal of Archaeological Science

journal homepage: http://www.elsevier.com/locate/jas

Tradition and indigeneity in Mughal architectural glazed tiles

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ARTICLE INFO

Article history:
Received 12 March 2014
Received in revised form
10 June 2014
Accepted 12 June 2014
Available online 19 June 2014

Keywords:
Glazed tiles
Mughal
Islamic
Indian glass
Technology

ABSTRACT

Glazed tiles were employed by the Mughals for the decoration of their monuments in northern India over the sixteenth and seventeenth century. The character and composition of thirty tile samples from Mughal buildings at Delhi, in northern India, were investigated by EPMA-WDS and SEM-EDS. Analysis shows that the tiles have stonepaste bodies, indicating that they form part of the family of Islamic ceramics. The glaze layers are determined to have local characteristics, through comparisons with traditional Indian glass compositions. A local source for the cobalt oxide used to colour dark blue coloured glazes has been suggested. Overall, the study considers the impact of an imported luxury/high status technology on local traditions, and how the two converge to develop a new *chaîne opératoire* which has aspects of Islamic and indigenous technologies.

1. Introduction

Although the use of glazed tiles as a form of building embellishment in northern India pre-dates the period of Mughal rule (1526–1857 CE), it is in the sixteenth and seventeenth century era of the Great Mughals (1526–1707 CE) that they were most frequently employed on monuments (Nath, 1989; Degeorge and Porter, 2002). During this period, tiles in a greater multitude of colours and forms began to be used across the region, covering also larger expanses on building surfaces than hitherto seen. While the sixteenth century saw developments centred on Delhi, a shift in activity towards the Punjab (centred on Lahore, Pakistan) occurred in the seventeenth century (Fig. 1); the latter region and period also witnessing a proliferation of this art/craft form and developing its own style.

Recent studies on seventeenth century tiled Mughal monuments in northern India and Pakistan have demonstrated that tiles associated with the Lahore style of tile-work, characterised by a distinctive palette and high degree of standardisation, bear technological similarities with contemporaneous Western and Central Asian tiles, both in their glaze and body characteristics (Gill and Rehren, 2011; Gulzar et al., 2013). In contrast, investigations now undertaken on a wide range of Mughal monuments bearing the Delhi form of tile-work, as defined below, reveal that although the bodies of these tiles are similar to their counterparts from central Islamic lands, their glaze compositions are notably different, having a character that is typical of Indian or South Asian archaeological glass. This belies to some extent the widely-held notion of Mughal tile-work being an imported technique (Nath, 1989), introducing a dimension of indigeneity in their manufacture.

The analyses of glazed tiles from a series of sixteenth and early seventeenth century Mughal period monuments in and around Delhi are presented in this study, which for the first time allows a comprehensive picture to be gained on the material character and technology of the Delhi style of tile-work. The glaze compositions of these tiles, notably, highlight their technological distinctiveness vis-à-vis other forms or styles of tile-work, while drawing a parallel with materials and technologies employed in local traditional glass manufacture.

2. The Delhi style of tile-work

A tradition of tiling commenced in Delhi and its environs during the reign of the Lodhi Sultans (1451–1526 CE), the employment of glazed tiles in shades of blue on their buildings marking the first consistent use of tiles here. Later, an increase in tile-work commissions in an expanded palette comprising yellow, green, white, turquoise, and dark blue glaze colours occurred during Mughal rule, especially in the reigns of the Mughal emperors Akbar (1556–1605 CE) and Jahangir (1605–1627 CE). Art and architecture now became to be increasingly influenced by Iran and Central Asia, spurred by the emigration of architects, artisans and craftsmen from these

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http://dx.doi.org/10.1016/j.jas.2014.06.007

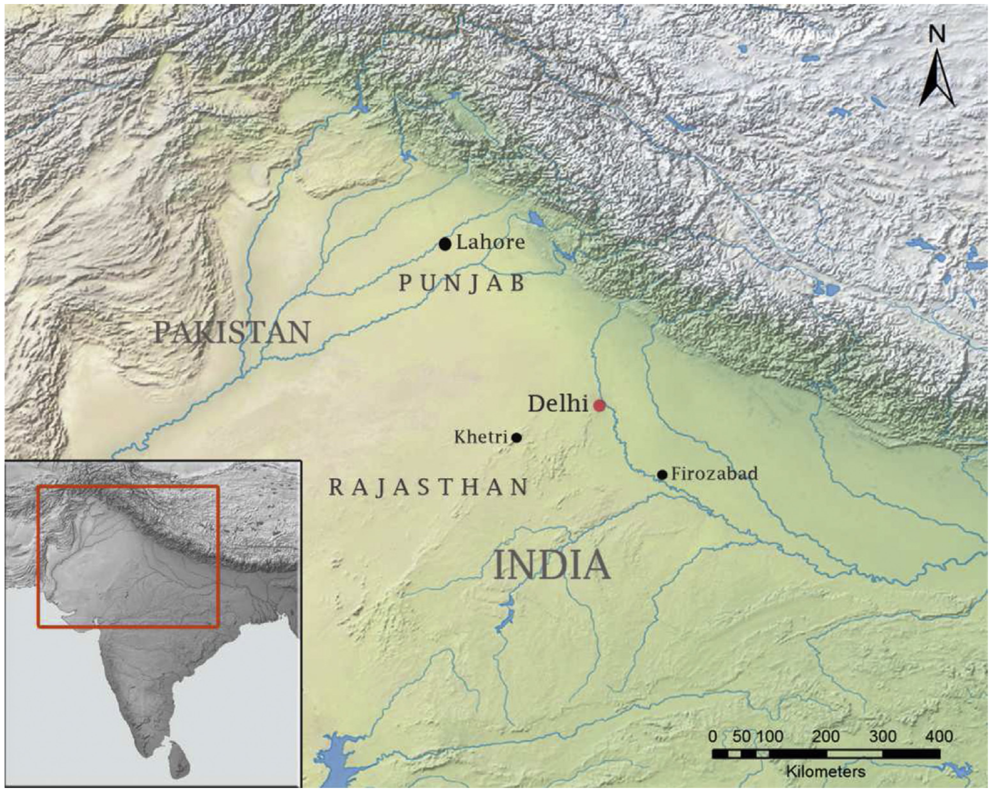

Fig. 1. Map showing the location of Delhi in northern India. The region of Punjab lies further above to its north-west.

lands (Blair and Bloom, 1995; Nath, 1989). Numerous buildings erected at Delhi during this period were decorated with tiles on their walls, arches, *jharokhas* (projecting windows), parapets, *chhatris* (kiosks), and in an uncommon instance, in the case of Nila Gumbad, on an entire dome. Although the tiles were individually monochrome, they were more often than not arranged in polychromatic compositions on application, at times being just simple narrow composite bands outlining architectural features, and in more detailed instances, complex geometrical mosaic patterns. The notable characteristics of the Delhi style are the colour scheme and patterns employed, and the restraint followed in the application of the tiles on buildings, with a view to highlight architectural features rather than dominating the building form (Figs. 2 and 3). An additional notable feature of this style of tile-work is the distinct joint noticeable between adjoining tiles, allowing an appreciation of the shapes of individual pieces especially in cases of mosaic compositions. This is in marked contrast to the Punjab style of tile-work where the delineation between individual tiles forming mosaic patterns is hard to discern, which suggests that different techniques in the assembling and fitment of tiles on buildings were employed in the two regional styles. Seventeenth century tiles at Lahore/Punjab are also more liberally employed, emphasis seemingly being placed more on the visual impact produced by the coloured tile-work than the design of the building itself.

Seven buildings bearing the Delhi style of tile-work as defined above, all ascribed to the period of Akbar and Jahangir's rule, were taken up for study. These include Bu Halima Gate, Arab-ki-Sarai Gate, Khairul Manzil Masjid, Atgah Khan's Tomb, Sabz Burj, Nila Gumbad, and Quli Khan's Tomb, all of which are located within the urban precincts of the modern city of Delhi (Fig. 4). At Sabz Burj, no extant remnants of white coloured tiles are visible on the monument, the colour scheme here possibly being limited to yellow, green, turquoise, and dark blue only, whereas the five characteristic colours can be seen on all the other buildings.

It is pertinent to note that while the art of tiling may be considered to have begun towards the end of the 15th century CE, the history of glass making in the region is much older, excavations having yielded numerous glass objects and production remains at sites here dating from the 1st millennium BCE through to the medieval period and later (Chaudhuri, 1983; Kanungo et al., 2010). In fact traditional, or close to traditional, glass making is still a thriving industry around Firozabad in the vicinity of Delhi. Just as

Fig. 2. Glazed tiles employed on a *jharokha*, an ornamental architectural feature, on Arab-ki-Sarai Gate.

Fig. 3. A mosaic composition of glazed tiles on the wall mosque at Atgah Khan's Tomb.

foreign influences are thought to impact or inspire the employment of glazed tiles as a means of architectural embellishment it is not inconceivable to imagine that the existence of a local glass making industry would have influenced the technology employed in the manufacture of the tile glazes.

3. Sampling and experimental procedures

No direct sampling from the monuments was undertaken in accordance with local regulations, samples being limited to fragments of tiles that had fallen off the buildings and were in the custody of the local conservation official-in-charge. Not all samples were complete tiles, *i.e.* comprising both the tile body and its overlying glaze layer, approximately half being just fragments of glazes that had separated from the bodies. A total of 30 samples sourced from the studied buildings were subject to laboratory experimental procedures, emphasis being laid on the analyses of the glazes.

Fragments taken for analysis were first examined macroscopically to study distinguishing features. Polished cross-sections of the samples, mounted in resin blocks, were then examined in a JEOL JSM6610LV scanning electron microscope (SEM) by backscattered electron imaging, allowing phases to be distinguished on the basis of differences in their atomic number. Bright particles that could be seen evenly distributed in the yellow and green glazes were subject to spot analyses using an attached Oxford Instruments X-Max energy dispersive spectrometer (EDS) at an accelerating potential of 20 kV. Quantitative analyses of the glaze layers was carried out using a JEOL electron probe micro-analyzer (EPMA:JXA 8600) equipped with a wavelength dispersive spectrometer (WDS) through area scans using a rastered beam at 15 kV, 50 nA, and a count time of 20 s per element. Sodium migration was minimised by being the first element checked and limiting area scan magnification to an optimal 800× (Shugar and Rehren, 2002), the analytical area being approximately 100 × 140 μm.

Bulk area scans of the glaze layers that were carried out typically excluded bubbles, pores, and minor randomly present inclusions such as quartz grains, but included pigment or opacifier particles when present, as in the case of the yellow and green coloured glazes. Quantitative analytical results were calculated for each sample taking the average of 4–5 analyses spread over its glaze layer. Corning A and C, and Sheffield No. 3 glass standards were analysed at the same settings to check the accuracy of the system employed. Results obtained on analyses of the standards were found to be in reasonably good agreement with published values,

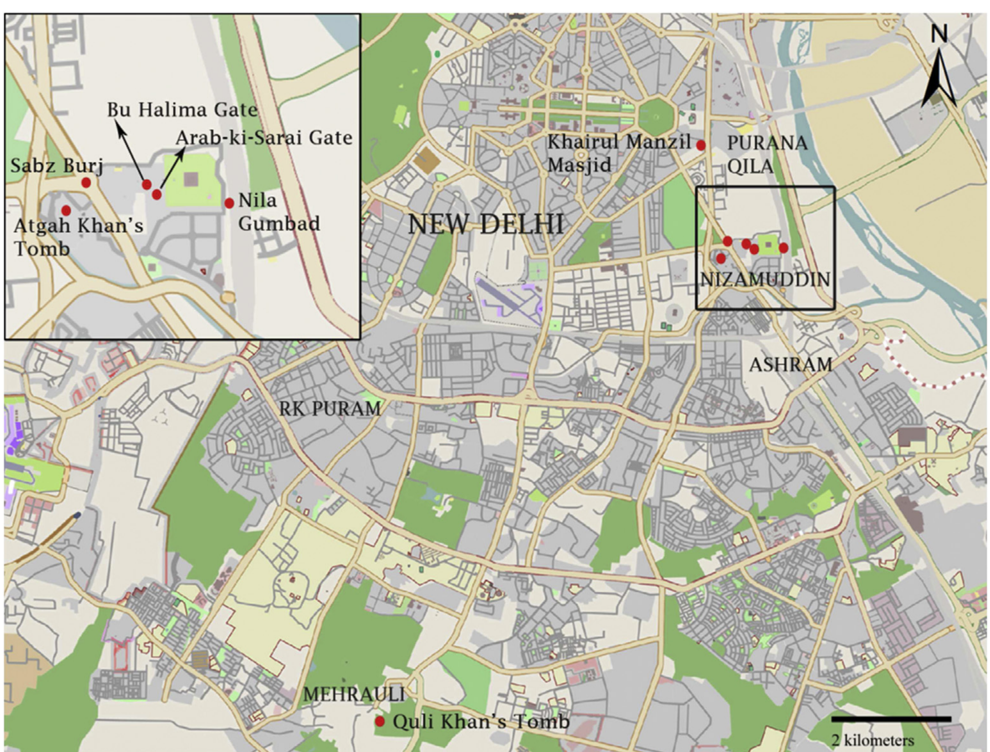

Fig. 4. Map showing the location of the seven buildings taken up for study, all of which lie within the boundaries of urban Delhi. Five of these buildings are in close proximity of each other in the locality of Nizamuddin (given in inset).

the departure from accepted values being in the range 2–5% relative for major elements and mostly lower than 10% relative for elements present at 1 wt% or less (Table 1). All quantitative results of chemical analyses are reported as oxides by stoichiometry. Analytical results that lie below 0.05 wt%, the detection limit of the instrument, have not been presented.

4. Results

4.1. Macro and microstructure

Macroscopically, all fragments of tiles when taken were similar, comprising dirt covered muddy-brown coloured bodies with an overlying glaze layer, colours of the glazes being notably vibrant. In freshly cut sections, however, the tile bodies are found to be creamy coloured with a reddish tinge, depicting their actual original look. A general consistency in thickness of the bodies across the buildings is noticeable, being typically 2 cm or so across, which seemed to be a standard size for tiles that were employed on vertical wall surfaces. Roofing tiles are much thicker, as in the case of a sample representative of the tiling on the dome of Nila Gumbad, whereas specimens representing the less-commonly found tiles inlaid in brickwork, as in the wall mosque of Atgah Khan's tomb, are thinner as compared to the standard size. Glaze layers on the tile bodies are evenly spread but have a slightly rough surface texture, perceptible to the naked eye and on feeling the glaze surface. In some samples, the glaze-body interface is visually distinguishable as a narrow whitish coloured band just below the coloured glaze layer. Pinholing is not uncommon and can be found on almost all the glaze samples, the number of holes however being few and not marring the glaze surface presentation to be of concern. No evidence of any other form of glaze deterioration could be seen.

On detailed microscopic examination through sections, it is evident that all the tile bodies are highly porous, composed mainly of angular quartz grains with slightly rounded edges, varying in size from about 50 μm to 700 μm along their longer edges (Fig. 5). Pores of different shapes and sizes, and a moderately-developed glassy phase that is seen bonding the quartz grains together make up the rest of the body matrices. A few individual grains of feldspars and alumina-soda-potash-rich phases on some of the large quartz grains could however also be distinguished by their relatively bright appearance. No clear slip layer could be discerned in any of the samples, the area of the tile bodies immediately below the glaze layer and the glaze-body interaction zone comprising both large and small quartz grains, similar in size to those found elsewhere in the bodies. The glaze layers were of a fairly consistent thickness in all the samples, ranging from about 400 to 600 μm across. Bright angular particles could be seen spread across the yellow and green glazes (Fig. 6), the glaze layers being otherwise clear, barring randomly dispersed bubbles of varying sizes.

4.2. Analyses of glaze layers

All glazes are soda-silica types, with varying amounts of alumina and lime. Green and yellow glazes also contain substantial amounts of lead and tin oxides, related to the colouration process. Soda values in the clear glazes range from 15 to 22 wt%, and are lower at between 12 and 17 wt% for the yellow and green glazes (Table 2). Alumina is significantly high, varying over 5 to 8 wt%, except for NG/01 where it is lower at c 2 wt%. Potash content is found to mostly vary over 1.8 to 2.5 wt% while magnesia is notably low, mostly lying between 0.5 and 1 wt%. Slightly elevated values of magnesia, from 1.2 to 1.9 wt%, are noticeable in

Table 1
Chemical compositions of glass standards as published and analysed. Results report the average of three analyses by EPMA-WDS. Analytical results below the detection limit of the instrument are given for comparison with published results only. '–' indicates 'not published' or 'not detected' on analysis.

Details	Na_2O	CaO	K_2O	MgO	Al_2O_3	Fe_2O_3	SiO_2	TiO_2	MnO	CuO	CoO	As_2O_5	NiO	SnO_2	PbO	ZnO	P_2O_5	SO_3	Sb_2O_5	BaO	Total
Corning A																					
Published	14.30	5.03	2.87	2.66	1.00	1.09	66.56	0.79	1.00	1.17	0.17	–	–	0.19	0.12	0.04	0.13	–	1.75	0.56	99.43
Analysed	14.23	4.86	2.93	2.74	0.96	0.97	66.41	0.76	0.91	1.14	0.10	0.01	0.02	0.20	0.11	0.08	0.06	0.09	1.61	0.42	98.59
Std. Dev.	0.08	0.36	0.14	0.09	0.04	0.13	1.04	0.01	0.06	0.05	0.02	0.02	0.03	0.04	0.04	0.04	0.05	0.01	0.08	0.02	
Corning C																					
Published	1.07	5.07	2.84	2.76	0.87	0.34	34.87	0.79	–	1.13	0.18	–	–	0.19	36.70	0.05	0.14	–	0.03	11.40	98.43
Analysed	1.25	5.10	2.94	2.94	0.89	0.28	35.85	0.95	0.01	1.13	0.12	–	0.05	0.17	37.23	0.06	0.11	–	–	11.54	100.61
Std. Dev.	0.02	0.02	0.08	0.05	0.15	0.03	0.60	0.17	0.01	0.11	0.01	–	0.01	0.03	0.54	0.06	0.02	–	–	0.07	
Sheffield Glass No. 3																					
Published	0.22	0.10	11.12	0.04	0.13	0.02	55.33	0.02	–	–	–	0.67	–	–	31.70	–	–	–	–	–	99.35
Analysed	0.20	–	11.35	–	0.03	0.03	56.52	0.02	–	0.02	0.01	0.79	–	–	31.50	0.03	0.06	–	–	0.01	100.56
Std. Dev.	0.01	–	0.12	–	0.04	0.04	1.11	0.03	–	0.00	0.01	0.01	–	–	0.39	0.04	0.00	–	–	0.02	

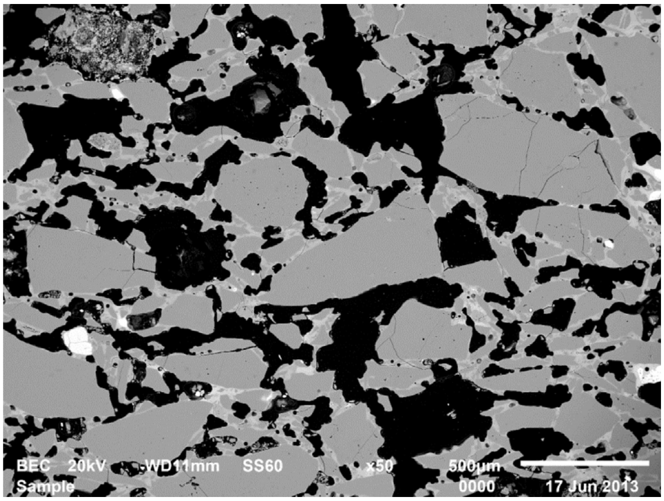

Fig. 5. Backscattered SEM image of a typical Delhi tile body section. The bodies are dominated by angular quartz grains (grey) connected with a glassy phase. Black areas are pores.

some of the dark blue glazes, and in the outlier NG/01, where it is much higher, standing at 3.2 wt%. Lime is typically between 1.5 and 2.5 wt%. Iron oxide, varying over 1.3 to 2.3 wt%, follows a parallel relationship to titanium oxide, that ranges between 0.3 and 0.45 wt %.

Lead and tin oxide could be detected only in the yellow and green coloured glazes, ranging from 9 to 16 wt% and 1–3 wt% respectively. Spot analyses of the bright particles visible in these glazes identify them to be the pigment lead–tin yellow ($PbSn_{1-x}Si_xO_3$), the presence of lead and tin oxide thus being attributable to the colourant used. Notably, the lead–tin yellow particles are not widely dispersed individually but are found to exist in small clusters of several particles each, such clusters being in turn relatively evenly distributed through the glazes. Of the other colourants, copper oxide, in the range 1.3–3.5 wt%, is found in the turquoise and green coloured glazes while cobalt oxide in low concentrations, typically 0.2–0.5 wt%, is detected in the dark blue coloured glazes. Interestingly all the dark blue glazes are found to have unusually high arsenic content, between 0.4 and 1.2 wt%, the cobalt:arsenic ratio in these glazes ranging from 1:1.5 to 1:2. No

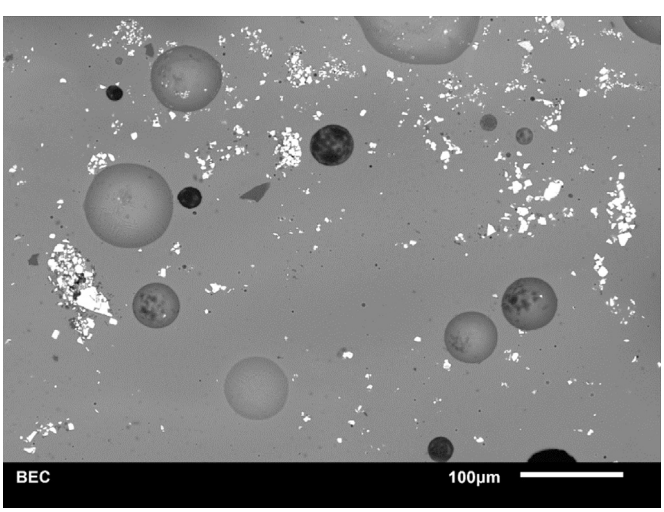

Fig. 6. Backscattered SEM image of a yellow glaze layer from Sabz Burj (SB/06). Note the visible clustering of bright particles of the colourant dispersed within the glaze.

colourant or opacifier could be determined in the white coloured glaze of NG/01.

On reducing the analytical results to the base glass forming oxides (Brill, 1999) and plotting the normalised values so obtained, a positive correlation is seen to exist between alumina and iron oxide, indicative of a common source for the two (Fig. 7, Table 3). A weak positive correlation can also be seen between magnesia and lime (Fig. 8), deviations occurring more so in the dark blue glazes. Surprisingly, no clear association is found on plotting magnesia versus potash (Fig. 9), both alkalis generally assumed to be coming from the same source when employed as a flux, usually plant ash in the case of glazed Islamic ceramics. Re-calculated soda values for the majority of the tiles lies between 17 and 20 wt%, while alumina is more consistent, in the narrow range of 7–8 wt%. A general consistency in the soda, magnesia and lime contents for tile samples taken from the same building is also noticeable (Table 3). Variations in their values that can be seen between buildings, notably those of magnesia, seem to exemplify the varying composition of the flux that was employed in the manufacture of the tile glazes over time and place.

5. Discussions

An association between the Delhi tiles and glazed Islamic ceramics in general can be quickly established through the tile bodies, the predominance of quartz grains in all the body matrices highlighting them as 'stonepaste', a characteristic variety of high quality ceramics widely produced in the Islamic world (Mason and Tite, 1994; Mason, 2004; Wulff, 1966). The angularity of the quartz grains indicates they are more likely to have been derived from crushing quartz pebbles, or quarried quartz, as opposed to the crushing of sand, in which case a more rounded shape would have been expected. The whitish colour of the tile bodies, their porous nature, and the glassy phase that is seen to bond the quartz particles together, are all features that are typical of stonepaste bodies (Freestone et al., 2009; Mason, 1995). Studies on tile specimens from Lahore/Punjab, investigated in other studies, also reported the presence of a stonepaste body type (Gill and Rehren, 2011; Gulzar et al., 2013). Given the period over which the tiles were employed, it is apparent that the geographical spread of stonepaste technology, that was well-established in the central Islamic lands by the 12th–13th century CE, extended to cover and prevail over northern India as well, at least over the 16th–17th century CE.

The glazes on the other hand do not conform to the conventional Islamic typology in terms of their compositions. Their low magnesia and significantly high alumina content distinguishes them from their Lahore/Punjab counterparts (Fig. 10), and from contemporary or earlier glazed Islamic ceramics in general attributed to lands further west (Fabbri et al., 2002; Gill and Rehren, 2011; Gulzar et al., 2013; Mason et al., 2001). Glazes on most Islamic tiles, as in the Lahore/Punjab Mughal variety for instance (Gill and Rehren, 2013; Gulzar et al., 2013), are generally accepted as having been made with a plant ash flux, but the low magnesia found in the vast majority of the Delhi tile glazes, less than 1.5 wt%, indicates that a mineral soda flux would have been used in their manufacture (Sayre and Smith, 1961). Similar low magnesia values are also known to occur in early Indian glass (Brill, 1987). The high alumina that is noticeable in all but of one of the Delhi glazes is also a feature typical of Indian glass compositions (Brill, 1987), with these levels of alumina being attributed to its presence in high concentrations as a component in the local sand/silica used (Brill, 1987; Dussubieux et al., 2010). Together, the high-alumina and mineral soda (m-Na-Al) signature that the glazes carry is in fact considered a characteristic marker of Indian glass. Indeed, the analyses of glass specimens from numerous sites all over the country,

Table 2
Chemical composition of the tile glazes in wt% determined through EPMA-WDS analyses. '–' indicates 'below detection limit'.

No.	Sample	Colour	Building	Date	Na_2O	CaO	K_2O	MgO	Al_2O_3	Fe_2O_3	SiO_2	TiO_2	MnO	CuO	CoO	As_2O_5	NiO	SnO_2	PbO	ZnO	P_2O_5	SO_3	Total
1	BH/01	Turquoise	Bu Halima Gate	16th cent.	21.5	2.01	1.49	0.75	7.40	1.48	60.6	0.33	–	2.66	–	–	–	–	–	–	0.17	0.16	98.56
2	BH/02	Dark Blue	Bu Halima Gate	16th cent.	17.1	1.89	2.40	0.78	7.96	1.91	64.3	0.37	0.05	–	0.46	1.02	0.07	–	–	–	0.20	0.23	98.68
3	BH/03	Dark Blue	Bu Halima Gate	16th cent.	17.1	1.94	2.17	0.75	8.11	1.76	64.6	0.40	–	–	0.44	0.98	0.06	–	–	–	0.18	0.22	98.68
4	AS/01	Dark Blue	Arab-ki-Sarai Gate	1560–61	16.5	2.53	1.95	1.23	8.45	1.55	66.1	0.41	–	–	0.21	0.47	0.05	–	–	–	0.14	0.16	99.79
5	AS/02	Dark Blue	Arab-ki-Sarai Gate	1560–61	16.2	2.38	2.13	1.26	8.29	1.64	66.2	0.40	–	–	0.18	0.37	–	–	–	–	0.17	0.13	99.38
6	AS/03	Yellow	Arab-ki-Sarai Gate	1560–61	13.7	1.76	1.21	0.94	6.36	1.39	53.4	0.27	–	–	–	–	–	1.21	15.77	0.09	0.14	–	96.30
7	KM/01	Dark Blue	Khairul Manzil Masjid	1561–62	18.0	2.56	2.61	0.83	8.17	2.11	61.8	0.45	0.05	–	0.31	0.50	–	–	–	–	0.11	0.22	97.69
8	KM/02	Dark Blue	Khairul Manzil Masjid	1561–62	18.7	2.31	1.64	0.81	8.15	2.28	62.4	0.44	0.06	–	0.31	0.74	–	–	–	–	0.06	0.25	98.09
9	KM/03	Green	Khairul Manzil Masjid	1561–62	17.2	1.46	1.69	0.60	6.34	1.47	54.2	0.31	–	1.89	–	–	–	1.21	9.04	–	0.08	0.16	95.62
10	AK/01	Yellow	Atgah Khan's Tomb	1566–67	14.1	1.20	1.56	0.79	6.12	1.54	53.9	0.36	0.07	–	–	–	–	2.75	14.68	0.65	0.18	–	97.89
11	AK/02	Turquoise	Atgah Khan's Tomb	1566–67	18.4	1.49	2.07	0.87	8.38	1.96	63.2	0.38	0.09	2.18	–	–	–	–	–	–	0.33	0.16	99.42
12	AK/03	Turquoise	Atgah Khan's Tomb	1566–67	19.0	1.61	1.77	0.82	8.15	1.69	63.4	0.36	0.09	1.53	–	–	–	–	–	–	0.25	0.18	98.92
13	AK/04	Turquoise	Atgah Khan's Tomb	1566–67	19.1	1.64	1.80	0.80	8.01	1.73	62.8	0.37	0.06	1.36	–	–	–	–	–	–	0.25	0.12	98.10
14	AK/05	Turquoise	Atgah Khan's Tomb	1566–67	17.3	1.76	3.57	0.80	7.96	1.72	62.5	0.37	0.08	2.02	–	–	–	–	–	0.06	0.29	0.14	98.60
15	SB/01	Dark Blue	Sabz Burj	16th cent.	18.4	2.72	1.78	1.19	6.15	1.59	64.2	0.35	0.06	0.06	0.18	0.60	–	–	–	–	0.25	0.26	97.82
16	SB/02	Dark Blue	Sabz Burj	16th cent.	14.9	1.94	2.50	1.09	6.62	1.61	68.8	0.39	–	0.05	0.16	0.46	0.05	–	–	–	0.19	0.24	98.93
17	SB/03	Yellow	Sabz Burj	16th cent.	14.8	2.12	1.81	1.53	3.92	0.85	54.3	0.21	–	0.08	–	–	–	2.75	16.81	0.26	0.24	–	99.71
18	SB/04	Yellow	Sabz Burj	16th cent.	15.1	1.40	1.94	0.78	6.77	1.44	55.5	0.34	–	0.05	–	–	–	2.00	12.70	0.24	0.15	–	98.38
19	SB/05	Turquoise	Sabz Burj	16th cent.	17.5	2.02	1.88	1.06	6.05	1.30	65.3	0.32	0.05	3.56	–	–	–	–	–	–	0.17	0.22	99.46
20	SB/06	Turquoise	Sabz Burj	16th cent.	17.1	1.85	1.90	0.92	6.22	1.28	66.9	0.35	0.05	2.60	–	–	–	–	–	–	0.18	0.28	99.59
21	NG/01	White	Nila Gumbad	c. 1625	18.1	4.55	2.37	3.21	1.87	0.53	64.6	0.09	–	–	–	–	–	–	–	–	0.40	0.26	96.01
22	NG/02	Yellow	Nila Gumbad	c. 1625	12.8	1.46	1.51	0.82	5.64	1.30	52.7	0.30	–	–	–	–	–	1.89	15.29	0.37	0.10	–	94.17
23	NG/03	Dark Blue	Nila Gumbad	c. 1625	17.0	2.81	2.47	1.84	4.84	1.29	61.7	0.26	0.05	–	0.24	0.60	0.05	–	–	–	0.23	0.27	93.66
24	NG/04	Green	Nila Gumbad	c. 1625	14.6	1.52	1.57	0.78	6.59	1.61	56.7	0.34	–	1.27	–	–	–	1.87	11.18	0.34	0.12	–	98.41
25	NG/05	Turquoise	Nila Gumbad	c. 1625	18.0	1.98	2.51	1.03	5.59	1.40	63.8	0.31	–	3.09	–	–	–	–	–	–	0.15	0.28	98.20
26	NG/06	Dark Blue	Nila Gumbad	c. 1625	17.9	2.61	2.46	1.49	5.92	1.64	64.5	0.31	–	–	0.30	0.63	–	–	–	–	0.23	0.34	98.33
27	QK/01	Dark Blue	Quli Khan's Tomb	17th cent.	18.4	2.62	1.80	0.96	7.69	1.76	62.4	0.35	–	–	0.62	1.25	0.06	–	–	–	0.19	0.18	98.22
28	QK/02	Dark Blue	Quli Khan's Tomb	17th cent.	18.9	2.02	2.68	1.24	8.35	2.10	60.9	0.37	0.05	0.05	0.23	0.46	–	–	–	–	0.16	0.30	97.84
29	QK/03	Dark Blue	Quli Khan's Tomb	17th cent.	18.0	1.97	2.88	0.95	7.99	1.90	62.7	0.37	0.07	–	0.31	0.53	–	–	–	–	0.16	0.19	98.05
30	QK/04	Dark Blue	Quli Khan's Tomb	17th cent.	18.8	2.13	2.81	0.98	7.40	1.77	62.6	0.34	0.06	–	0.31	0.82	–	–	–	–	0.16	0.21	98.38

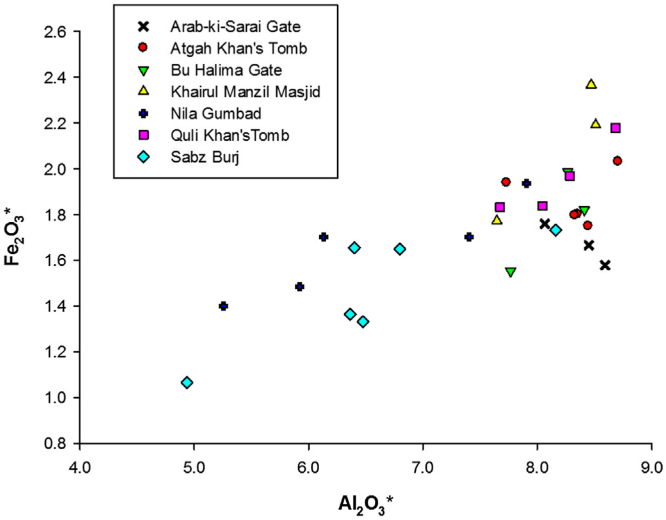

Fig. 7. Scatter plot of alumina versus iron oxide contents of the tile glazes (excluding NG/01). The positive correlation noticeable suggests that they both are derived from a common source. * indicates reduced composition.

dating from the early centuries of the first millennium BCE to the modern times, reveal similar compositional profiles, signifying a long unchanged tradition and technology, not least on account of the nature of locally available raw materials (Brill, 1987; Dussubieux et al., 2010; Kanungo and Brill, 2009; Sode and Kock, 2001). NG/01, the one exception, could either be representative of a later undocumented restoration or the employment of glaze frit taken from a different source.

Potash, that otherwise together with magnesia is taken as an indicator of the flux used, has proven to be less reliable for Indian mineral soda glass. In Indian glass it is only seldom present in concentrations below 1.5 wt%, levels typical for most mineral soda glasses from elsewhere, as in mineral natron glass (Brill, 1999). The high potash vis-à-vis low magnesia values recorded for the glazes analysed here, typically 1.7 wt% or more potash and less than 1.5 wt % magnesia, follow this trend. The most likely reason for the elevated potash levels seems to be the chemical composition of the silica/sand employed. If significant concentrations of alumina in sand are seen to be indicative of the presence of alkali feldspars [$(Na,K)AlSi_3O_8$], then the high alumina content is quite likely to have brought with it a higher potash level as well. Increased potash content being on account of absorption of fuel ash vapour, as proposed by Paynter (2009) and archaeologically shown by Yin et al. (2011: Table 5), or attributable to higher concentrations of potash in local naturally occurring mineral soda as compared to deposits in most other regions, however also remain a possibility.

Magnesia on the other hand is comparatively more consistent, near-similar concentrations being recorded for samples taken from the same building. With the noted lime–magnesia relationship suggesting that they are both from the same mineral source, it would seem that the two-ingredient batch concept proposed by Brill (1987) for early Indian glass would hold equally well in the case of the Delhi tiles as well. Glass used for the glazes would thus have been produced by melting a batch of feldspathic sand, the basic ingredient and source of silica, with a local easily available fluxing agent, mineral soda in this case. The sand would have been locally sourced, being easily available in the region, while the soda flux would have been *reh*, or *sajji mitti*, a crude bicarbonate of soda traditionally refined from evaporate deposits found in abundance across the alluvial plains of northern India (Brill, 1987; Coggin Brown and Dey, 1955, Silver, 1917). The rather low levels of lime in the glazes indicate that the sand was not calcareous, which would potentially have led to less-stable glaze compositions. However, this is compensated for by the presence of adequate alumina in the melt, acting as a stabiliser in lieu.

Colourants detected are those usually associated with contemporary Islamic glazed ceramics or tiles, and found in Indian glass specimens as well. Lead–tin yellow is the sole colourant in the yellow coloured glazes (Gill and Rehren, 2013). It is worth mentioning here that lead–tin yellow has a long history of use in the region, yellow and green glass coloured by the pigment being produced in India from at least the first century CE onwards (Brill, 1999; Tite et al., 2008). Turquoise glazes are coloured by copper oxide in concentrations of 1.3–3.5 wt%, while copper oxide with lead–tin yellow is responsible for the green coloured glazes. No colourant was detected in the single white coloured glaze, NG/01, the effect achieved by the opacification of a transparent glaze by grains of silica present at the glaze-body interface. Orange glazes coloured by lead–tin orange (Gill and Rehren, 2013), as well as purple glazes that are found in abundance in the Punjab are notably lacking here, again indicating the independent nature of the glaze industry of Delhi. Dark blue glazes are coloured by cobalt oxide in low concentrations, between 0.2 and 0.6 wt%. The clustering of pigment particles that is noticeable in the yellow and green glazes suggests that the colourants were produced separately (Heck et al., 2003) and added to fritted glaze powders in dry form, the mix then being liquefied with water into slurries and applied on the tile bodies, much as in current traditional practice (Khan, 1985; Yadav, 1999). Should pre-coloured powdered frits have been applied, a greater separation between individual pigment particles should have been realised, and their more even distribution through the glaze layers seen.

The unusually high levels of arsenic recorded in the dark blue glazes, in concentrations that are significantly on an average close to twice that of cobalt, and the noted preference for use of locally available raw material in the glaze production, suggests the possibility of a local source for the colourant as well. The fact that the dark blue glazes from the Lahore/Punjab style of tile-work have little or no arsenic content, not exceeding 0.2 wt% when present, and rarely being more than half the cobalt concentration in such instances (based on results from ongoing research), clearly implies that cobalt from different sources were being used for tile-work at the two centres of Delhi and Lahore/Punjab in Mughal northern India. Further, as the compositional profiles of the Lahore/Punjab tile glazes are akin to tiles from Iran and Central Asia, and given the geographical proximity between these regions, there seems a greater likelihood of cobalt employed in the Lahore/Punjab tiles coming from a source lying in these lands, as compared to chances for the Delhi tiles. Traditionally, following the historical description of Abu'l Qasim (Allan, 1973), dark blue Islamic glass or glazes containing cobalt and arsenic are assumed to be coloured by cobalt originating from Qamsar or Kashan in Iran, geological surveys confirming the presence of arsenic bearing cobalt ores at these locations. Cobaltite is however also known to occur in India in the ancient Babai copper mines at Khetri in the province of Rajasthan, adjoining Delhi (Mallet, 1887; Coggin-Brown and Dey, 1955). Coggin Brown and Dey (1955) mention that the cobalt ore, locally referred to as *sehta*, was extracted by the crushing and panning of black slate taken from the copper mines, the concentrate so produced used as a colourant for blue enamel work by jewellers. On analyses by Mallet (1887), the mineral was found to contain 28 wt% cobalt and 44 wt% arsenic together with traces of nickel, other impurities present being iron and sulphur. Although the extraction of *sehta* reportedly ceased in 1908 CE, being replaced by an imported variety of cobalt of better quality (Coggin-Brown and Dey, 1955), it is highly probable that it would have been mined in

Table 3
Chemical composition of the tile glazes reduced to the base glass forming oxides, and normalised to 100 wt%.

No.	Sample	Colour	Building	Date	Na_2O	CaO	K_2O	MgO	Al_2O_3	Fe_2O_3	SiO_2
1	BH/01	Turquoise	Bu Halima Gate	16th cent.	22.6	2.1	1.6	0.8	7.8	1.6	63.7
2	BH/02	Dark Blue	Bu Halima Gate	16th cent.	17.7	2.0	2.5	0.8	8.3	2.0	66.7
3	BH/03	Dark Blue	Bu Halima Gate	16th cent.	17.8	2.0	2.2	0.8	8.4	1.8	67.0
4	AS/01	Dark Blue	Arab-ki-Sarai Gate	1560–61	16.8	2.6	2.0	1.3	8.6	1.6	67.2
5	AS/02	Dark Blue	Arab-ki-Sarai Gate	1560–61	16.5	2.4	2.2	1.3	8.5	1.7	67.5
6	AS/03	Yellow	Arab-ki-Sarai Gate	1560–61	17.4	2.2	1.5	1.2	8.1	1.8	67.8
7	KM/01	Dark Blue	Khairul Manzil Masjid	1561–62	18.8	2.7	2.7	0.9	8.5	2.2	64.3
8	KM/02	Dark Blue	Khairul Manzil Masjid	1561–62	19.4	2.4	1.7	0.8	8.5	2.4	64.8
9	KM/03	Green	Khairul Manzil Masjid	1561–62	20.7	1.8	2.0	0.7	7.6	1.8	65.3
10	AK/01	Yellow	Atgah Khan's Tomb	1566–67	17.8	1.5	2.0	1.0	7.7	1.9	68.1
11	AK/02	Turquoise	Atgah Khan's Tomb	1566–67	19.1	1.5	2.1	0.9	8.7	2.0	65.6
12	AK/03	Turquoise	Atgah Khan's Tomb	1566–67	19.7	1.7	1.8	0.9	8.4	1.8	65.7
13	AK/04	Turquoise	Atgah Khan's Tomb	1566–67	19.9	1.7	1.9	0.8	8.4	1.8	65.5
14	AK/05	Turquoise	Atgah Khan's Tomb	1566–67	18.1	1.8	3.7	0.8	8.3	1.8	65.3
15	SB/01	Dark Blue	Sabz Burj	16th cent.	19.1	2.8	1.9	1.2	6.4	1.7	66.9
16	SB/02	Dark Blue	Sabz Burj	16th cent.	15.3	2.0	2.6	1.1	6.8	1.6	70.6
17	SB/03	Yellow	Sabz Burj	16th cent.	18.7	2.7	2.3	1.9	4.9	1.1	68.4
18	SB/04	Yellow	Sabz Burj	16th cent.	18.2	1.7	2.3	0.9	8.2	1.7	66.9
19	SB/05	Turquoise	Sabz Burj	16th cent.	18.4	2.1	2.0	1.1	6.4	1.4	68.7
20	SB/06	Turquoise	Sabz Burj	16th cent.	17.8	1.9	2.0	1.0	6.5	1.3	69.6
21	NG/01	White	Nila Gumbad	c. 1625	19.0	4.8	2.5	3.4	2.0	0.6	67.8
22	NG/02	Yellow	Nila Gumbad	c. 1625	16.7	1.9	2.0	1.1	7.4	1.7	69.2
23	NG/03	Dark Blue	Nila Gumbad	c. 1625	18.5	3.1	2.7	2.0	5.3	1.4	67.1
24	NG/04	Green	Nila Gumbad	c. 1625	17.5	1.8	1.9	0.9	7.9	1.9	68.0
25	NG/05	Turquoise	Nila Gumbad	c. 1625	19.1	2.1	2.7	1.1	5.9	1.5	67.6
26	NG/06	Dark Blue	Nila Gumbad	c. 1625	18.6	2.7	2.6	1.5	6.1	1.7	66.8
27	QK/01	Dark Blue	Quli Khan's Tomb	17th cent.	19.2	2.7	1.9	1.0	8.0	1.8	65.3
28	QK/02	Dark Blue	Quli Khan's Tomb	17th cent.	19.7	2.1	2.8	1.3	8.7	2.2	63.3
29	QK/03	Dark Blue	Quli Khan's Tomb	17th cent.	18.7	2.0	3.0	1.0	8.3	2.0	65.0
30	QK/04	Dark Blue	Quli Khan's Tomb	17th cent.	19.5	2.2	2.9	1.0	7.7	1.8	64.9

Mughal times. Given the close similarity in the cobalt:arsenic ratio of the analysed dark blue glazes and the cobaltite ore from Khetri, and for reasons as detailed above, there is thus strong reason to suggest that the cobalt colourant employed in the Delhi glazes was sourced locally from the Khetri mines in Rajasthan, of which it bears its signature.

In the broader context of tile-work in northern India, a clear distinction can now be drawn between tiles employed at Delhi and Lahore/Punjab based on the chemical compositions, and as an extrapolation, the technology used in their making. Delhi and Lahore were seemingly independent centres of production, with established workshops manufacturing tiles meant primarily for local or at most regional consumption. From this, it can be inferred that the skills of locally available artisans, and their technological awareness, dictated to some extent the style of decoration chosen to be employed on buildings in this period. It is interesting to note that the choice exercised by the tile-work artisans in the selection of raw material was influenced not

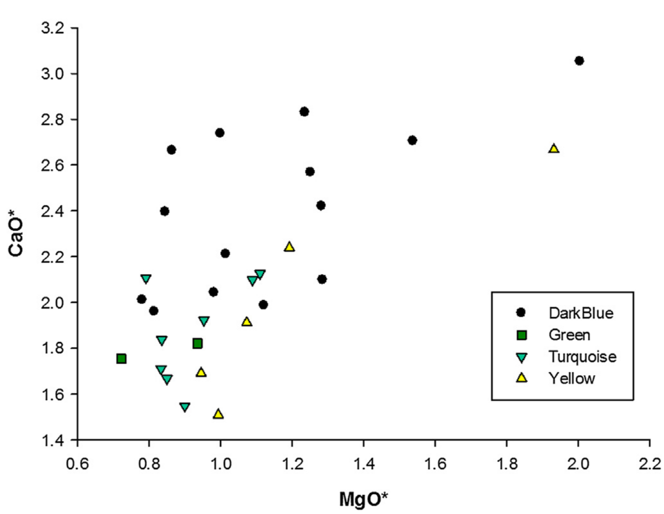

Fig. 8. Scatter plot of magnesia versus lime contents of the tile glazes (excluding NG/01). While a positive correlation between the two oxides is seen to exist, it is not entirely consistent, particularly so for the dark blue coloured glazes. * indicates reduced composition. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

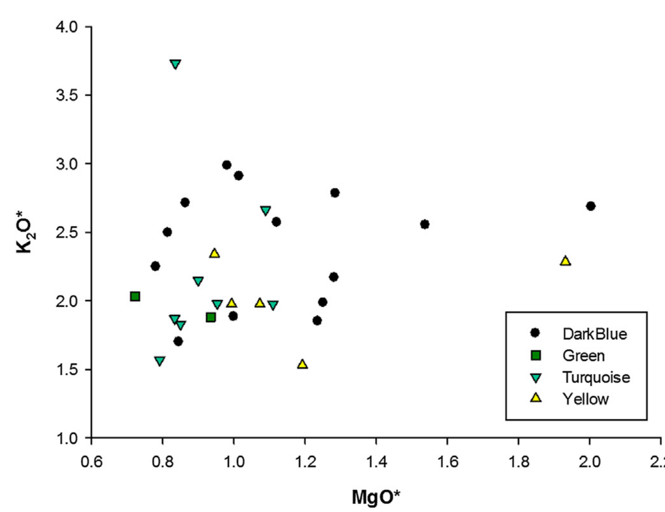

Fig. 9. Scatter plot of magnesia versus potash contents of the tile glazes (excluding NG/01). No relationship is discernible between the two oxides for any of the colours. Magnesia concentrations are seen to be notably low, mostly less than 1.5 wt%. * indicates reduced composition. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

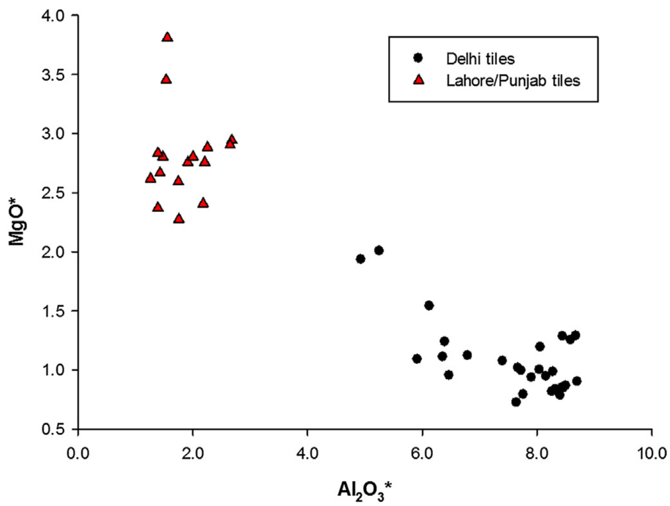

Fig. 10. Alumina and magnesia contents of Delhi tile glazes compared with those from Lahore/Punjab, reported in other analyses (Gill and Rehren, 2013; Gulzar et al., 2013). The Delhi tiles, with relatively higher alumina and lower magnesia, are seen to form a group distinct from the Lahore/Punjab variety. * indicates reduced composition.

only on the basis of their working properties, but by their ease of availability as well. In the case of the Delhi tiles, there are clear indications that features of a locally existent indigenous tradition of glass making were adapted into the technology of glazed tile manufacture, the demand of architectural tiling itself being influenced by external contemporary tastes. Finally, from the Delhi tile-work it becomes apparent that a glass industry was also functional at Delhi or its vicinity in Mughal times, the products of which should bear similar characteristic chemical compositions as that of the analysed Delhi tile glazes, and may thus be potentially identified and provenanced.

6. Conclusions

Glazes of tiles employed at Delhi in the Mughal period are notably different in their chemical composition from those of glazed ceramics typically associated with the central Islamic lands, exhibiting indigenous characteristics instead. The high alumina mineral soda signature that these glazes carry match that found in typical Indian glass, and indicates the technology employed in their manufacture. High alumina is attributable to local sand used, while locally occurring *reh* or *sajji mitti* was the mineral soda flux utilised in their production. Alkali feldspars present in the sand are most probably responsible for the high alumina as well as the higher than expected potash values recorded, as compared to most mineral soda fluxed glasses. Cobalt oxide, used in the colouring of the dark blue glazes, was probably obtained locally from a lesser known source of the colourant, the Khetri mines in nearby Rajasthan province. Other pigments found employed are lead–tin yellow, in the yellow and green glazes, and copper oxide, in the turquoise and green glazes. In contrast to the strongly local Indian aspects of the glaze, the tile bodies are of the Islamic stonepaste variety, in line with those found in the Punjab and in the Islamic world in general. The Mughal glazed tiles from Delhi, which are otherwise Islamic in character and tradition, thus show an interesting hybrid technology with aspects of local glass and colourant technologies blending with imported body recipes and application styles. The tiles as such befittingly complement the very buildings on which they were installed; Mughal architecture itself showcasing an amalgamation of Indian and Persian construction techniques and styles.

Acknowledgements

The authors are thankful to the Archaeological Survey of India for permissions accorded for this study. Kevin Reeves and Harriet White at the UCL Institute of Archaeology are gratefully acknowledged for their assistance towards the analyses. We thank Qatar Foundation for Education, Science and Community Development and the Qatar Museums Authority for providing financial support to make this study possible.

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