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MUGHAL SANDSTONE HERITAGE OF LAHORE: FORMULATING THE FUTURE RESTORATION STRATEGY

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Abstract

The magnificent city of Lahore in Pakistan is characterized by its rich cultural history that rose to the height of splendor during the Mughal period when richly decorated monuments were built. Presently, the accelerated deterioration of built heritage is largely attributed to the lack of information about the historic materials, which results into deficient restoration work. Seven sampled groups of stones including those used for restoration purposes have been analytically (petrography, XRD, XRF and ICPMS) and categorized into three stone types (quartz arenite, argillaceous siltstone and lithic arenite). The historic quarries from where the stone was transported in Mughal period are now in India. The restoration Khewra/ Sargodha sandstones have apparently similar characteristics but do not fit with the Vindhyan and Malani historic sandstones. The new data provide a framework to improve decision making in the selection of appropriate stone for repairs and ensure the long-term survival of historic Mughal buildings in Lahore. It becomes necessary to import stone from historic or new quarries that can supply identical stone.

Keywords: *Sandstone; Mughal; Heritage; Lahore; XRF; SEM-EDS; LA-ICPMS*

Introduction

The historical city of Lahore rose to its prominence during the Mughal era (1526-1857AD) when it was the seat of power [1]. The rulers of the time constructed splendid edifices and gardens in perfect geometry and symmetry with intricate and delicate ornamentation. The Shahdara Complex is the only surviving example of Mughal Tomb Architecture and Funeral Landscape in Pakistan. At present this heritage site is exposed to numerous environmental threats and is suffers from inadequate conservation [2, 3]. Many of its elements and features are decaying and ultimately vanishing with time as witnessed at various locations.

This paper presents the first analytical investigation of Mughal sandstone from the Shahdara Complex (Fig. 1). The incentive of this work was to assess the future stone masonry skills and the stone material needed to repair and preserve the stone-built heritage of Lahore. Educated action can further help formulating the future repair strategy for the heritage site. It is also recognized that shortage in the availability of funds, stonemasonry skills and training,

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along with a lack of supply of appropriate stone for repairs, are having detrimental impact on stone-built heritage of Lahore, and Pakistan in general.

Fig. 1. Mughal Sandstones Heritage showing; a) Jahangir tomb rear façade under restoration, b) newly carved sandstone slab ready for inlay works, c) sandstone slab replaced in 1989-90 with elongated flattened whitish spots, d) deteriorated siltstone dado slab, e) yellow coloured sandstone used geometrically with red coloured sandstone, f) sandstone slab used during Mughal period, g) sandstone slabs imported from India after partition for restoration and h) Khewra/ Sargodha sandstone

Experimental

Sampling

Sampling was carried out with the help of in charge staff. Samples were collected from different parts of the buildings (Table 1). The samples were thin sectioned, powdered and fused in glass beads [4] according to the type of analysis described below.

Analytical Techniques

Optical Microscopy

Thin sections were observed by means of an Olympus BH@ BHSP petrographic polarizing microscope to identify and characterize the mineral phases, to locate sources and geological origins, and to study the manufacturing technology. Thin sections were also used to define the porosity and texture of the materials. The microscope was equipped with Nikon digital camera for micrographs.

X-Ray Diffraction

X-ray diffraction was performed on sample powders using Bruker, AXS D8 Advance powder diffractometer with CuKα radiation. The patterns were obtained with a Lynxeye super speed detector, step scanning from 5^o to 80^o with a count for 0.5 s per step and 40 kV and 40 mA in the X-ray tube to determine the mineralogical components or crystalline phases in the samples.

X-ray Fluorescence

The X-ray fluorescence analysis was employed for the chemical characterization of the materials by determining the major and trace elemental composition. The XRF was performed on fused glass beads by using wave-length dispersive X-ray fluorescence spectrometer (WD-XRF, Axios, PAN analytical) equipped with 5 diffraction crystals for ten major and 21 trace elements.

LA-ICPMS

The laser ablation microprobe with inductivity coupled plasma-mass spectrometry was used for the high accuracy determination of trace element composition keeping major elements as standard for chemical characterization. The laser ablation microprobe was also used to determine the geological origin of the materials from elemental concentrations compared with geological samples. The instrumentation used was a Coherent CompexPro Excimer ArF laser with beam homogenization and the Elan 6100 DRC ICP-MS (Perkins Elmer) equipped with the software SILLS (developed in 2008).

Table 1. Description of the studied samples, mineral composition and rock identification

Sample	Location	Setting	Mineralogical Composition			Rock Type	Remarks
			Major	Minor<6%	Others<2%		Groups
1	Jahangir Tomb Main Building	Dado Slab at Front Façade	Q, Mi	Hem, Cy, Che, Alb	Bt, Mus, Tou, Mag, Ch, Zir	Quartz Arenite (Red)	Group-I Vindhayan Sandstone
3	Jahangir Tomb Main Building	Dado Slab at Rear Façade	Q, Mi	Hem, Cy, Che, Alb	Bt, Mus, Tou, Mag, Ch, Zir	Quartz Arenite (Red)	Group-I Vindhayan Sandstone
75	Main Chamber Internal Wall	Panel at 4 feet High	Q, Mi	Hem, Cy, Che, Alb	Bt, Mus, Tou, Mag, Ch, Zir	Quartz Arenite (Red)	Group-I Vindhayan Sandstone
38	Front Entrance-AkbariSerai	Dado Slab Front Façade	Q, Mi	Hem, Cy, Che, Alb	Bt, Mus, Tou, Mag, Ch, Zir	Quartz Arenite (Red)	Group-I Vindhayan Sandstone
55	Front Entrance-AkbariSerai	Internal Wall	Q, Mi	Hem, Cy, Che, Alb	Bt, Mus, Tou, Mag, Ch, Zir	Quartz Arenite (Red)	Group-I Vindhayan Sandstone
63	Archaeology Office-AkbariSerai	Room Side wall	Q, Mi	Hem, Cy, Che, Alb	Bt, Mus, Tou, Mag, Ch, Zir	Quartz Arenite (Red)	Group-I Vindhayan Sandstone
73	Jahangir Tomb Gateway	Deteriorated Dado Slab	Q, Mi	Hem, Cy, Che, Alb	Bt, Mus, Tou, Mag, Ch, Zir	Quartz Arenite (Red)	Group-II Vindhayan Sandstone
74	Jahangir Tomb-Main Chamber	Rear Façade Central Arch	Q, Mi	Hem, Cy, Che, Alb	Bt, Mus, Tou, Mag, Ch, Zir	Quartz Arenite (Red)	Group-II Vindhayan Sandstone
13	Jahangir Tomb-Main Chamber	Main Entrance Arch	Q, Mi	Hem/Lim, Cy, Che, Alb	Bt, Mus, Tou, Mag, Ch, Zir	Quartz Arenite (Yellow)	Group-III Vindhayan Sandstone
13-A	Jahangir Tomb-Main Building	Front Façade Corner Arch	Q, Mi	Hem/Lim, Cy, Che, Alb	Bt, Mus, Tou, Mag, Ch, Zir	Quartz Arenite (Yellow)	Group-III Vindhayan Sandstone
13-B	Jahangir Tomb-Main Building	Rear Façade Central Arch	Q, Mi	Hem/Lim, Cy, Che, Alb	Bt, Mus, Tou, Mag, Ch, Zir	Quartz Arenite (Yellow)	Group-III Vindhayan Sandstone
75-A	Jahangir Tomb-Main Chamber	Front Entrance	Q, Mi	Hem/Lim, Cy, Che, Alb	Bt, Mus, Tou, Mag, Ch, Zir	Quartz Arenite (Yellow)	Group-III Vindhayan Sandstone
63-B	Jahangir Tomb-Main Chamber	Rear Entrance	Q, Mi	Hem/Lim, Cy, Che, Alb	Bt, Mus, Tou, Mag, Ch, Zir	Quartz Arenite (Yellow)	Group-III Vindhayan Sandstone
51	Jahangir Tomb-Main Building	Rear Façade Restored Panels	Q, Mi	Hem, Cy, Che, Alb	Bt, Mus, Tou, Mag, Ch, Zir	Quartz Arenite (Red)	Group-IV Vindhayan Sandstone
89	Jahangir Tomb-Main Building	Rear Façade Restored Panels	Q, Mi	Hem, Cy, Che, Alb	Bt, Mus, Tou, Mag, Ch, Zir	Quartz Arenite (Red)	Group-IV Vindhayan Sandstone
114	Jahangir Tomb-Main Building	Front Façade Restored Panels	Q, Mi	Hem, Cy, Che, Alb	Bt, Mus, Tou, Mag, Ch, Zir	Quartz Arenite (Red)	Group-IV Vindhayan Sandstone
49	Asif Khan Tomb-Main Building	Dado Slab Front Entrance	Q, Cy, Hem	Cal, Dol, Mus	Mi, Alb, Bt, Tou, Ch, Sp, Ep	Argillaceous Siltstone	Group-V Malani Siltstone
149	Asif Khan Tomb-Main Building	Dado Slab Rear Entrance	Q, Cy, Hem	Cal, Dol, Mus	Mi, Alb, Bt, Tou, Ch, Sp, Ep	Argillaceous Siltstone	Group-V Malani Siltstone
49-A	Asif Khan Tomb-Main Building	Front Arcade	Q, Cy, Hem	Cal, Dol, Mus	Mi, Alb, Bt, Tou, Ch, Sp, Ep	Argillaceous Siltstone	Group-V Malani Siltstone
150	Asif Khan Tomb-Main Building	Front Entrance Arch Base	Q, Cy, Hem	Cal, Dol, Mus	Mi, Alb, Bt, Tou, Ch, Sp, Ep	Argillaceous Siltstone	Group-VI Malani Siltstone
147	Asif Khan Tomb-Main Building	Rear Entrance Arch Base	Q, Cy, Hem	Cal, Dol, Mus	Mi, Alb, Bt, Tou, Ch, Sp, Ep	Argillaceous Siltstone	Group-VI Malani Siltstone
133	Jahangir Tomb-Main Building	Front Façade Restored Panels	Q, Cal, Mi	Hem	Alb, Cy, Che, Bt, Mus, Tou, Ch, Ep	Lithic Arenite	Group-VII Khewra/ Sargodha Sandstone
133-A	Jahangir Tomb-Main Building	Rear Façade Restored Panels	Q, Cal, Mi	Hem	Alb, Cy, Che, Bt, Mus, Tou, Ch, Ep	Lithic Arenite	Group-VII Khewra/ Sargodha Sandstone
133-B	Jahangir Tomb-Main Building	Market Samples in Storage	Q, Cal, Mi	Hem	Alb, Cy, Che, Bt, Mus, Tou, Ch, Ep	Lithic Arenite	Group-VII Khewra/ Sargodha Sandstone

Q-Quartz, Mi-Microcline, Hem-Hematite, Lim-Limonite, Cy-Clay, Che-Chert, Alb-Albite, Bt-Biotite, Mus-Muscovite, Tou-Tourmaline, Mag-Magnetite, Ch-Chlorite, Zi-Zircon, Cal-Calcite, Dol-Dolomite, Sp-Sphene, Ep-Epidote

Results and Discussions

The red colored stones locally known as Sang-e-Surkh were sampled in 7 groups based on their physical appearance and architectural use in different historic buildings of Shahdara Complex. The samples were analytically classified into 3 stone types (Fig. 2a, b) showing different petrographic-microscopic features, mineralogical and textural characteristics and chemical major and trace elemental compositions.

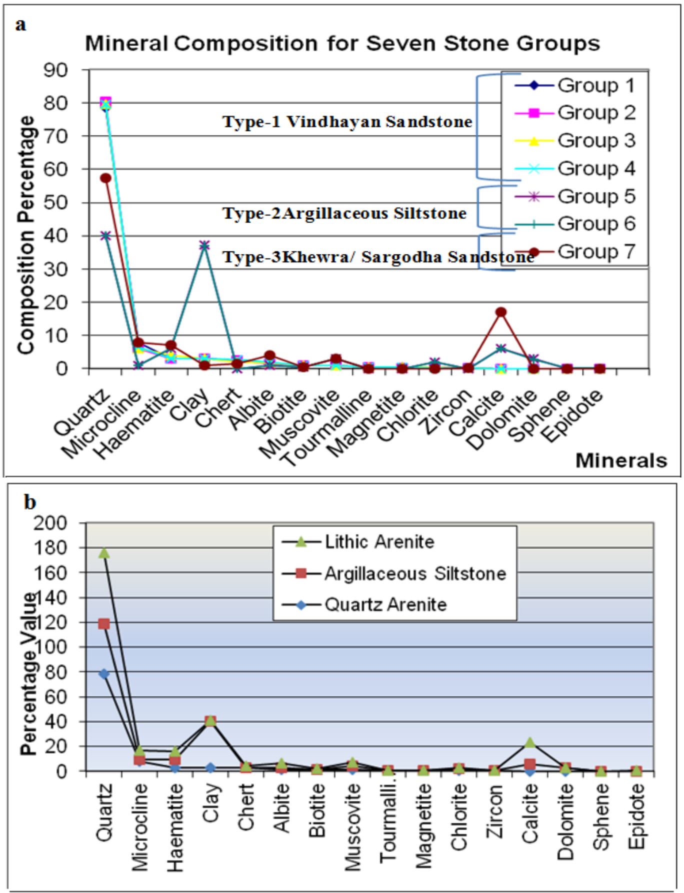

Fig. 2. Mineral compositon of sampled stones from Shahdara Complex, Lahore (a) and Mineralogical composition of three types of red stones from Shahdara Complex, Lahore (b)

Petrographic and mineralogical analysis

Type-1 Vindhyan Sandstones

Group 1 typifies medium to fine grained Vindhyan Red sandstone (Fig. 1a) used in Mughal times. This group includes samples from Jahangir tomb (Table-1) where sandstone has been employed in geometric panels. The rock is mica-poor quartz-arenite [5-7]. It is moderately to well-sorted with hematite coating imparting the strong red color. Porosity is 5-10% with small pore size [2, 6]. Cementing material is predominantly quartz and subordinate hematite. Quartz (75-78%) grains are mainly sub angular to sub rounded with normal optics; about 6-10% quartz grains showing strong strain extinction. Microcline occurs as sub rounded to sub angular crystals and shows well-developed cross hatched twinning with only slight alteration to clay. Chert is sub rounded and shows salt and pepper structure. Microcrystalline hematite occurs mainly as subordinate cement. It also occurs as stains and specks. Albite occurs as sub angular, generally fresh grains with slight alteration to clay. Biotite is an accessory mineral occurring as randomly distributed tiny flakes. It is medium brown and strongly pleochroic from straw yellow to medium brown, Muscovite occurs as tiny, randomly distributed flakes. Light green and slightly pleochroic from almost colorless to neutral green chlorite is an accessory mineral. Magnetite occurs as anhedral to subhedral black metallic grains that may show slight marginal alteration to limonite. Eumorphic to subhedral zircon is accessory. It is generally colorless but slightly brown grains were also found. Tourmaline forms elongated to equant grains. It is slightly pleochroic from light yellow to deep brown. Clay occurs as films associated with hematite cement. Whitish spots are poor in hematite. The XRD mineralogical analysis further defines group 1 sandstones (Table 2) as mainly composed of quartz with iron oxide, microcline and clay minerals, the latter partially filling the porosity as observed microscopically.

Table 2. Results of XRD analysis of investigated stone samples

Sample #		Q	Mi	Hem	Lim	Cy	Gy	Anh	Cal	Dol
Group-I	Type-1	+++	++	++	-	+	-	-	-	-
Group-II	Type-1	+++	++	++	-	+	+	+	-	-
Group-III	Type-1	+++	++	+	++	-	-	-	-	-
Group-IV	Type-1	+++	++	++	-	-	-	-	-	-
Group-V	Type-2	+++	+	++	-	+++	-	-	++	+
Group-VI	Type-2	+++	+	++	-	+++	+	?	++	?
Group-VII	Type-3	+++	++	++	-	+	-	-	++	-

Q-Quartz, Mi-Microcline, Hem-Hematite, Lim-Limonite, Cy-Clay, Gy-Gypsum, Anh-Anhydrite, Cal-Calcite, Dol-Dolomite;
+++ dominant; ++ present; + traces; ? possibly present; -not detected

Group 2 also includes Vindhyan sandstones sampled from the weathered stone surfaces of the Jahangir tomb historic buildings in Shahdara. These samples were taken from the deteriorated stone slabs which were marked for replacement during restoration work in Jahangir tomb main building. Group 2 sandstones are petrographically identical to group 1 with the same mineral phases in XRD analysis with traces of weathering phases like gypsum and anhydrite (Table 2). The rock is a mica-poor quartz-arenite whose cement is quartz and haematite. The weathered rock has undergone repeated cycles of heating and cooling due to the semi-arid climate of Lahore [2]. The exposed surfaces have undergone physical disintegration as assessed from macroscopic visual analysis. Optical microscopy supportively demonstrates that quartz grains have become loose and at places fractured/rusted (Fig. 3 and 4).

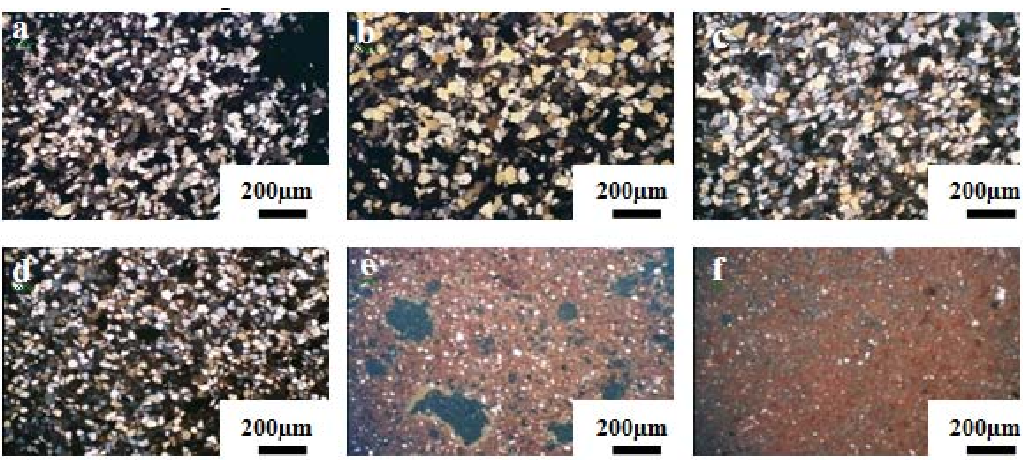

Fig. 3. Microphotographs under crossed polars (200µm) showing; a) quartz-rich, medium to fine grained red sandstone, b) yellow sandstone, c) red sandstone used for restoration, d) red sandstone from restored panels, e) poorly sorted quartz with uniform red color (hematite) with clay and carbonate and f) fine to medium grained with calcite and hematite.

Group 3 represents yellow Vindhyan sandstone whose color is due to limonite instead of hematite with quartz as subordinate material cementing quartz grains. Samples of this particular group were taken from Jahangir tomb where they were used in combination with red Vindhyan sandstone in Mughal geometric panels to decorate the façades. The rock is medium to fine grained mica-poor quartz-arenite. The cementing material is predominantly quartz and subordinate limonite/hematite. Quartz grains are sub angular to sub rounded, with normal optics, 6-10% quartz grains showing strain extinction. Accessory minerals are limonite/ with traces of hematite, magnetite, chert, zircon, tourmaline, chlorite, biotite, microcline, albite, muscovite and clay. Group 3, yellow quartz-arenite was used with the red sandstones for the blended architecturally appealing Mughal style of architecture. The source of yellow sandstone is the same as that of red sandstone [9, 10].

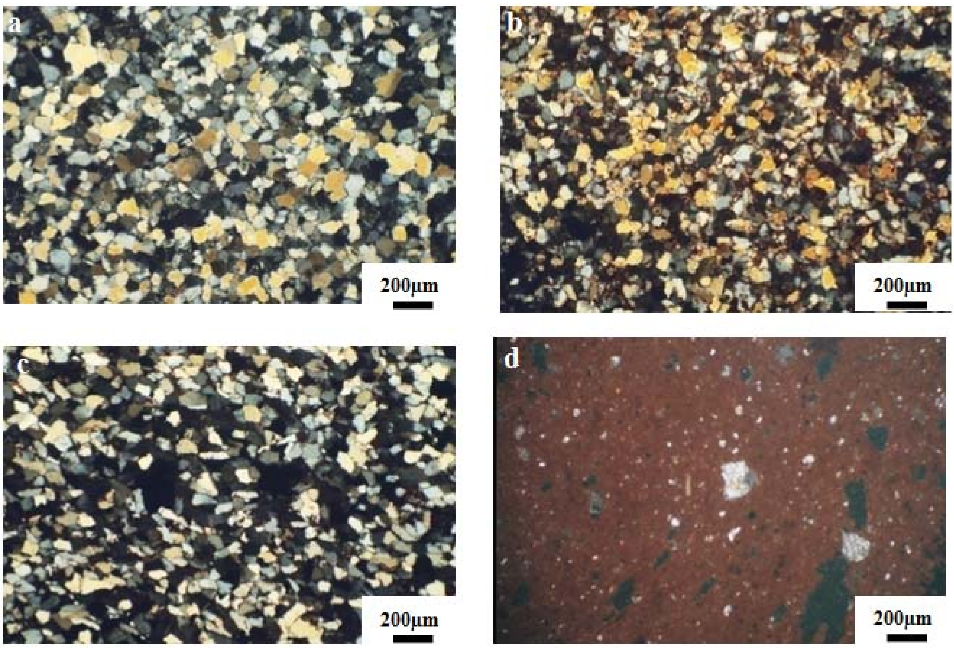

Fig. 4. Microphotographs under crossed polars showing; a) quartz-rich, medium to fine grained red sandstone, well sorted grain distribution, b) weathered sandstone with rusted boundaries and cracked fragmented grains of quartz along with in filled clay particles and organic patches, c) absence of hematite (reddish hue) in red sandstone used in restoration and hollow patches lined with altered clay minerals and d) carbonate cemented siltstone with open pore structure partially filled with calcite and hematite.

Group 4 is also from the Vindhyan system and was imported from the historic quarries in India for restoration work after the independence (1947) [3, 11]. This sample group has the same origin/mineralogy as the other Vindhyan sandstones; the rock is a mica-poor quartz-arenite. The only difference is in the physical appearance, which is aesthetically observed in the visual-microscopic analysis. Group 4 stones have a pale red color with whitish elongated flattened spots whereas stones used in the Mughal period were deep red with small rounded whitish spots [8, 10].

Type-2 Malani Argillaceous Siltstone

Groups 5 and 6 are comprised of argillaceous siltstone [11] with a poorly sorted texture and a uniform brick-red color due to 5-6% hematite content (Table-1). XRD analysis confirmed the presence of carbonate and clay minerals (Table-2). The rock contains pores occasionally lined by calcite and has an estimated porosity of 15-20%. It is mainly composed of silt-sized grains of quartz and small particles of the parent rock. Quartz principally occurs as angular grains. Clay is microcrystalline, intimately associated with hematite, which impartsthe brick-red hue to the stone. Calcite in the pore spaces includes particles of quartz, clay and hematite. Dolomite is found to be associated with calcite. Muscovite is randomly distributed in the clay fraction. Chlorite, microcline, albite, biotite, zircon and tourmaline have the same optical characteristics as in group 1-4. Sphene and epidote are rare. These rocks are weaker than the quartz-arenites. They are vulnerable to deterioration due to clay matrix and high porosity. Malani Argillaceous-siltstone was used for Asif Khan's Tomb and other ancillary buildings of less priority. Group 6 samples were sampled from the deteriorated façades and were further microscopically identified as weathered disintegrated stones. Hand specimens displayed surface abrasion and loosening of the material constituents, which was confirmed by thin sections microscopy (Fig. 4).

Type-3 Khewra/ Sargodha Sandstone

Group 7 represents the Cambrian Khewra red sandstone from Salt Range [7, 12] which has been used in restoration after shortage of sandstone imported from India; Group 7 is commercially available as Khewra and Sargodha sandstones. This fine to medium grained rock superficially resembles the Vindhyan Red Sandstone but is analytically very different. It is a carbonate cemented lithic arenite with 18-21% porosity [13-15]. Quartz and hematite cement are subordinate to carbonate cement. Quartz occurs as angular to sub rounded grains. Calciteis the second most important mineral as spar cement. However a few microspars to spar clasts are present. Calcite cement fills pores and interstices. Hematite occurs both as discrete grains and subordinate cementing material. K-Feldspar is both microcline and orthoclase both slightly altered to clay and sericite. Muscovite is randomly distributed. Biotite, chert, zircon and tourmaline present the same aspects as in the other groups. Epidote occurs as tiny sub rounded grains of both zoisites and clinozoisite. Clay is the disseminated phase. The deteriorated conditions of the Shahdara Complex restored façades clearly reflect differences in mineralogical composition [13]. Group 7 sandstones is prone to chemical weathering and disintegration due to the quicker dissolution of carbonate cement than quartz and hematite cemented Vindhyan Red Sandstone.

Chemical Analysis

Petrographic and mineralogical observations were further particularized and quantified by major and trace elemental (Fig. 5 and 6 for representative samples) chemical compositions determined by XRF and LA-ICPMS. The major element chemistry gives clue to the provenance type as well as weathering conditions of the parent rock [17].

The XRF analysis (Fig. 5) showed significant differences among the studied samples, further establishing their different origins. The Vindhyan sandstone is mainly composed of silica with appreciable amounts of Al_2O_3, Fe_2O_3 (88.81, 4.36 and 2.07% respectively) and negligible amount of CaO while the Malani argillaceous siltstone contains a comparatively low amount of SiO2 (65.98%) and high amounts of Al_2O_3 (14.30%) and Fe_2O_3 (5.88%) for a CaO content of about 4.77%. The replacement Khewra/ Sargodha sandstone has about 51% silica with considerably high amounts of Al_2O_3 (16.55), Fe_2O_3 (5.43) and CaO (10.6%). The silica cemented Vindhyan sandstone is more resistant thanks to strong inter-granular bonds while Malani siltstone naturally absorbs moisture and swells which weakens inter-granular bonds. The carbonate cemented Khewra sandstones easily undergoes chemical decay.

Table 3. Chemical major element composition of representative samples determined by XRF analysis (%)

Sample	Type-1				Type-2		Type-3
	Group I	Group II	Group III	Group IV	Group V	Group VI	Group VII
wt%							
SiO_2	88.815	88.715	87.918	86.342	65.984	66.858	51.782
TiO_2	0.148	0.205	0.169	0.162	0.764	0.679	0.142
Al_2O_3	4.636	3.916	4.807	4.836	14.3	14.837	16.55
Fe_2O_3	2.07	2.301	2.057	3.071	5.885	5.675	5.43
FeO	0	0	0	0	0	0	0
MnO	0.022	0.066	0.06	0.028	0.011	0.096	0.007
MgO	0.163	0.161	0.154	0.376	2.436	2.177	1.9
CaO	0.247	0.804	0.505	0.94	4.778	4.304	10.667
Na_2O	0.189	0.183	0.155	0.166	1.549	1.549	1.6
K_2O	3.27	3.147	3.728	3.251	2.994	2.734	1.22
P_2O_5	0.02	0.013	0.367	0.077	0.17	0.133	0.106
Cr_2O_3	0.037	0.011	0.021	0.015	0.016	0.013	0.007
NiO	0.009	0.006	0.007	0.003	0.003	0.005	0
H_2O	0	0	0	0	0	0	0
CO_2	0	0	0	0	0	0	0
LOI	0.673	0.55	0.654	0.94	1.85	1.232	9.66
Total	100.299	100.078	100.602	100.207	100.74	100.292	99.071

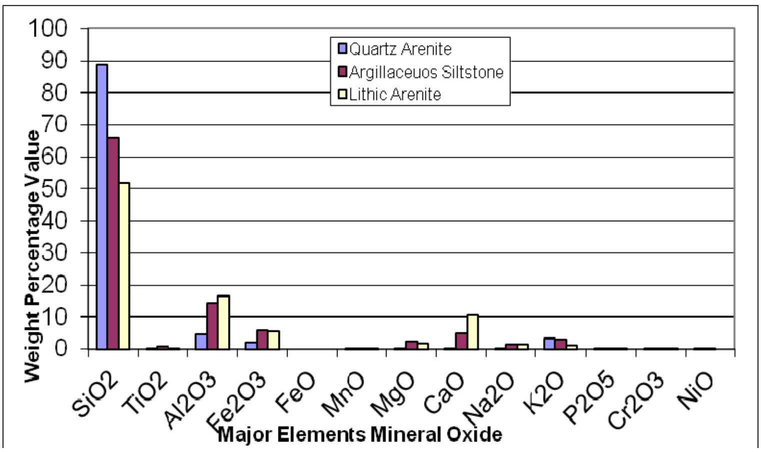

Fig. 5 Comparitive chemical-major average elemental analysis of three types of red stones from Shahdara Complex, Lahore

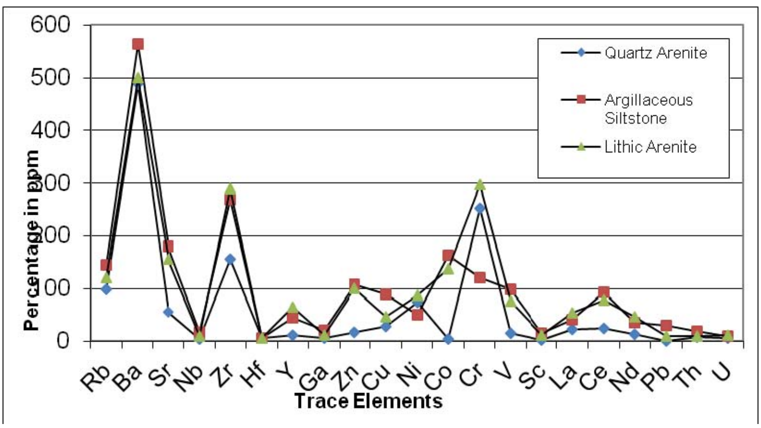

Fig. 6 Comparitive chemical-trace elemental analysis of three types of red stones from Shahdara Complex, Lahore

Table 4. Chemical trace elemental composition of representative samples determined by XRF analysis (%)

Traces/ Samples	Type-1				Type-2		Type-3
	Group I	Group II	Group III	Group IV	Group V	Group VI	Group VII
Rb	98.9	98.9	97.6	99.7	145	143.8	120
Ba	489.4	476.5	480.9	494.5	565.2	563.7	500.25
Sr	55	53.25	54.34	65.3	181.2	187	156.1
Nb	3.1	3.7	3.5	3.4	17.2	19.4	10.2
Zr	156.5	146.76	153.5	177.1	269.9	250.45	289.7
Hf	4.9	4.7	4.9	3.8	5.5	5.9	4.756
Y	11.2	13	11.8	12.5	45.2	43.26	65
Ga	5.5	4.7	5.4	4.6	20	23.56	10.79
Zn	16.8	20	18.76	15.3	108.2	107.65	99.76
Cu	27.5	23.5	25.54	40.5	89.8	90.67	45.89
Ni	73.5	80	77.89	100.4	50.3	51.76	88
Co	4.3	4.75	4.79	3.3	164.2	167.98	137
Cr	252.7	275.2	252.7	377.1	121.8	120.98	297
V	15.7	15	18	23.1	98	97.5	76
Sc	2.5	3.75	4.37	2.7	15.2	15.2	10.76
La	22.6	20.3	22.98	13.7	40.2	40.8	54.7
Ce	24.2	24.7	24	22.1	93.7	95.68	78.9
Nd	12.8	14.9	12.98	12	35.5	35.5	45.7
Pb	0	0	0	0	30	35	10
Th	7	9	7	10.3	18.6	17.9	9
U	5.4	5	5	4.9	9	7.8	12

The relative concentrations of trace elements (Fig. 6) emphasize the compositional differences between the three studied stone types [16, 17].

Origin of studied sandstones

The first four groups of quartz-arenite (Vindhyan Red Sandstone) were historically transported in the Mughal period (1526-1857).The petrographic-mineralogical characteristics and the studied historic trade route support the transportation of stones along with their production in the 16th century from quarries in Bharatpur and Fatehpur Sikri. This original rock belongs to the Torridonian (Mesoproterozoic, ca 1000-1200 Ma) Bhander and Kaimur series (Purana Group) [11].

The argillaceous siltstones (groups 5 and 6) from Malani series near Jodhpur in Rajhistan were used in the same period for the construction of tombs other than the Emperors Tombs [18].

Group 7 samples were characterized as Khewra/ Sargodha Sandstone of Cambrian age (ca 540-500 Ma) from Salt Range, Punjab, Pakistan [7, 15]. This particular stone is locally available in abundance and is presently being employed as a substitute for red sandstone in restoration of various Mughal historic structures [3].

New data presented here and the analysis of historical account show that different types of red sandstone/ siltstone were used to build the Shahdara Complex. The accomplished hierarchical system in the Mughal Dynasty influenced decisions regarding the use of superior quality stones for the emperor's buildings and inferior quality stones for other royals [1]. This is observed, if not proven with the Vindhyan quartz arenite used for the Jahangir's Tomb, which is more durable and of higher quality than the Malani argillaceous siltstone used for Asif Khan's Tomb (brother-in-law of Emperor Jahangir) in the Shahdara Complex. The other noticeable stone was the locally available Khewra lithic arenite which is now used for restoration works within the complex. This Khewra/ Sargodha sandstone was also historically used for the monuments built during the Hindu (before 1000AD) and Pathan (1000-1526 AD) periods but not in the Mughal period (1526-1857AD) [18].

Present Deterioration Scenario

The comparative analysis of three red stone types (quartz arenite, argillaceous siltstone and lithic arenite) is shown in figures 4, 5 and 6. The Vindhyan Sandstones-Quartz arenite contains about 80% of quartz and nearly 20% matrix whereas the Malani Siltstone contains about 40% of quartz and nearly 40% clay along with the 20% accessory minerals. Clay minerals are the main component responsible for accelerated weathering of red stones in Asif Khan Tomb (Fig. 7a). Swelled joints and weathered edges in carbonate rich restoration Khewra sandstone-lithic arenite being quite rich in carbonates [19] make it easily vulnerable to environment (Fig. 7b and c) soon after its fixing. This particular stone easily absorbs water and is highly reactive when exposed to acidic rainwater in the polluted environmental conditions of mega cities like Lahore. Results are erosion, discoloration, loss of materials etc. Further use of this rock can accelerate the deterioration in the buildings of Shahdara Complex as shown in Fig. 7d.

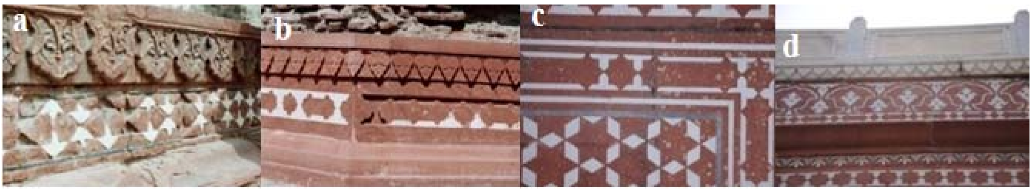

Fig. 7. Stone dado slabs in Asif Khan Tomb (a), opening of restorated joints due to difference in material characteristics of historic and restoration stone pieces (**b**), restoration stone panel have undergone weathering immediately after its placement in Jahangir Tomb rear façade (**c**) and detachment of stone constituents in parapet due to water retention in restored stone panel (**d**)

Conclusions

Petrography, Mineralogical and chemical analyses were performed on red rocks sampled from the 17th century Mughal heritage site of Shahdara Complex, Lahore. The samples were categorized into three types based on origin and composition: Vindhyan sandstones, Malani siltstones and Khewra/ Sargodha sandstone. The employment of Khewra/ Sargodha sandstone (carbonate-rich) as a replacement for originally used Vindhyan sandstones and Malani siltstones in restoration works is causing accelerated decay of historic structures. The new stones should be compatible in all respects (composition, colour, texture etc.) to enable successful and effective restoration of historic structures. Selection of new stones should be founded on scientific examination employing latest analytical techniques to restore the original fabric and the historic value.

This study has depicted that the particular character of monumental Mughal Architecture is based on the Vindhyan red and yellow sandstone employed in characteristic decorative style with geometric panel façade to establish the Mughal glorious era over the sub-continent. This visual authenticity should not be wrecked by using incompatible stones (with different color shades). With reference to the new analyses presented in this work, it becomes possible to identify alternative sandstones with similar characteristics as original rocks and select adequate active quarries in Pakistan for restoration works. This approach will ensure the survival of the stone-built heritage of Lahore to the benefit of present and future generations.

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