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Characterization and Source of Sedimentary Rocks of the Alexandria Lighthouse Archaeological Objects, Egypt

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Abstract: The present study was aimed to present a detailed study concerning the nature and characterization of stones constituting some of the Alexandria Lighthouse monumental objects that are made of sedimentary rocks, as well as indicating their corresponding ancient quarries. A field inspection of the objects that were salvaged from the seabed and are presently displayed or stored at different locations in Alexandria city is conducted and a series of samples from objects that are still underwater are collected and studied. Petrographic studies, XRD, XRF/ ICP-AES and $\delta^{13}C$ and $\delta^{18}O$ isotopes analyses were carried to characterize the different rock types in terms of their petrographic types of stone and chemical properties. The studies revealed that these archaeological objects (stone blocks, columns, part of columns, statues and obelisks) are constructed from different igneous, metamorphic and sedimentary rocks. The archeological objects made of sedimentary rocks are formed of quartzitic sandstones (orthoquartzite), greywacke (siltstone and sandstone) and limestone (lime-mudstone and sandy dolomite/dolomite sandstone). The source area of each type of stone constituting the archaeological samples is performed, including delimitation of the corresponding ancient quarries when possible. Wadi Hammamat and Gebel Ahmar quarries were the provenance areas of the greywacke and quartzitic sandstones used in the Alexandria Lighthouse objects, respectively. Moreover, results and the data derived expand the knowledge concerning Egyptian monumental stones and provide inspiration for future investigations and studies.

Key words: Alexandria lighthouse, ancient quarries, monumental objects, provenance, lime-mudstone, sandy dolomite

INTRODUCTION

The Alexandria Lighthouse (also known as Pharos) was built between 290 and 270 BC and is located on the eastern tip of the Island of Pharos in Alexandria, Egypt. It was initiated by Ptolemy I and finished during the region of his son, Ptolemy II. For seven centuries, it served as a navigation guide into the city harbor for seafarers approaching the coast of Egypt until its final destruction in the mid-14th century AD. The Lighthouse (~122 m tall) is considered one of the wonders of the world. It was constructed from large blocks of light-colored stone and was made up of three stages: a lower square section with a central core, a middle octagonal section and a circular section at the top (Thiersch, 1909). A violent earthquake brought down the top part of the tower in 955 AD. A series of earthquakes from the 10th to the 14th century completed its destruction (Dominique, 1995). The Lighthouse archaeological site is essentially underwater today, just off the coast of Alexandria. Its ruins consist of about 3.000 architectonic blocks and statues that lie on the seabed, at depths between six and eight meters (Empereur, 1998; Hairy, 2004, 2006). A Fortress (QaitBay) was built at the end of the 15th century on the same site as the former Lighthouse and utilized its ruins in the construction (Thiersch, 1909).

During 1961 and 1994-1998, Egyptian and French teams, respectively, conducted a salvage inspection of the submerged sea ruins of the Alexandria Lighthouse. About 2,500 pieces were found over an area of 2.5 hectares and are comprised of column bases and capitals, sphinxes, statues, pieces of obelisks and some immense blocks of granite which certainly came from the Lighthouse, given where they lie (Empereur, 1996, 1998, 2000; Hairy, 2004, 2006). During the salvage operation, about fifty blocks of stone and statues were recovered from the seabed. They were desalinated and exhibited in different locations in Alexandria: QaitBay fortress, Eastern harbour platform, Roman Theatre, Kom El Dikka, Shallalat Garden, front of Alexandria Library and Marine Museum

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garden (Dessandier *et al*., 2008a, b). The stone blocks were made of different igneous, metamorphic and sedimentary rocks (especially, rose granite, granodiorite, marble, limestone, greywacke and quartzitic sandstone.

Sedimentary rocks played an important role in the registration of the Egyptian civilization in very ancient times from the early dynastic onward to Greco-Roman periods. From early dynastic times onward, limestone was the material of choice for pyramids, mastaba tombs and temples. From the late Middle Kingdom onward, sandstone was used for all temples within the sandstone region. Both limestone and sandstone were also used for statuary and other non-architectural applications. Quartzitic sandstones were used sparingly as a construction material from the old kingdom onward; it was also used extensively for door steps, pots, statuary, obelisks and sarcophagi. Greywackes (also known Bekhen stone) were used for large objects such as statuary, stelae and sarcophagi (Aston *et al*., 2003).

The present study highlights the results concerning the nature and characterization of stones constituting some of the monumental objects that are made of sedimentary rocks, as well as determining their source areas and, if possible, the former quarry sites. Provenance investigation will help to locate the best materials for restoration (when needed) and will help to provide more information about the ancient trade routes during the Ptolemy Empire.

MATERIALS AND METHODS

Field inspection of the objects that were salvaged from underwater and are presently displayed at different locations in Alexandria City revealed that these objects (stone blocks, columns, part of columns, statues and obelisks) were made of different igneous, metamorphic and sedimentary rocks (especially, rose granite, granodiorite, marble, limestone, greywacke and quartzitic sandstone). Table 1 lists the samples collected from the displayed monumental objects for the present study. In addition, several samples were collected from the underwater objects in autumn of 2006 by archaeologists of the Centre d' Etude Alexandrine and were given to the authors for study (Table 1). The archeological objects considered in the present study belong to the monumental objects and are comprised of sedimentary rocks quartzitic sandstones (quartzite), greywackes and limestones). The studied quartzites are represented by nine archaeological samples. The greywackes are represented by two archaeological samples (Table 1). The limestones are represented by three light-colored samples A3 to A5 and one dark-grey sample A68. Samples A3 and A4 represent the blocks that constitute the base of QaitBay Fortress, based on the hypothesis that the fortress was built in the same place as the Alexandria Lighthouse using its ruins. A5 is not an archaeological sample and is taken from the bedrock of QaitBay Fortress. The most probable ancient quarries for the various types of stones used in the monumental objects have been surveyed and sampled (Table 1). Thin sections were made from samples of sufficient size and were studied petrographically to determine their nature and characteristics. The carbonate samples were stained with Alizarin Red-S and Potassium Ferricyanide (Dickson, 1966) to reveal the presence of calcite and ferroan and non-ferroan dolomite. XRD analysis was carried out to supplement the microscopic examination in determining the mineralogical composition of the samples. Chemical analyses of selected samples were performed at the laboratories of BRGM Institute Marseille, France.

Table 1: List of samples collected from salvaged and still underwater objects and the potential quarries

Sample No.	Object	Displayed/Present at/Potential quarries
A8	Ochre-beige quartzitic sandstone, Sphinx of Sesostris III	Open-air Museum close to the Roman Theatre excavation, Kom El dikka
A10	Beige-yellowish quartzitic sandstone,Base of Obelisk Seti I	
A11	Beige-yellowish quartzitic sandstone, Obelisk of Seti I	
A12	Beige quartzitic sandstone, Sphinx of Psammeticus	
A9	Dark-grey greywacke, Sphinx of Ramses II	
A3, A4	Yellowish to brownish sandy limestone, Wall in the cave, base of the fortress	Base of Qaitbay Fortress
A5*	Soft beige limestone Base under the masonry, bedrock, base of the fortress	
A54	Ochre-yellowish quartzitic sandstone, Base of statue	Underwater site of Qaitbay , at depth between six and eight meters
A59	Beige-yellowish quartzitic sandstone, Prism	
A62	Beige-yellowish quartzitic sandstone, Base of obelisk	
A64	Beige-orange quartzitic sandstone, Obelisk	
A66	Ochre-yellowish s quartzitic sandstone, Architrave block	
A68	Dark-grey limestone, Prism	
A69	Dark-grey greywacke, Prism	
A 117, A119-121	Quartzitic sandstones	Gebel Al Ahmar area quarries
A122-129	Quartzitic sandstones	Gebel Gulab area quarries
A131-136	Greywackes	Wadi Hammamat area quarries
A33-38	Limestones	El Mex- Abu Sir area quarries

*Not an archaeological object

Major and trace elements were determined by XRF or by ICP-AES. The isotopic composition ($\delta^{13}C$ and $\delta^{18}O$) of some carbonate samples was determined by mass spectrometry (Mccrea, 1950). The microfacies analysis of the carbonate samples were carried out using the polarizing microscope and utilized the usual scheme proposed by Folk (1959) and Dunham (1962). The carbonate contents were determined by acid attack using diluted 10% HCl.

RESULTS AND DISCUSSION

Petrographic and chemical characteristics

Quartzitic sandstone (quartzite): Thin section investigations indicate that the archaeological quartzite samples are petrographically similar and can be characterized as orthoquartzite (Pettijohn *et al*., 1987). The samples (Fig.1 a, b) consist mainly of quartz detrital grains that are monocrystalline, moderately to well-sorted, medium to very coarse in size and exhibit undulatary extinction in several grains. They are rounded to well-rounded and are outlined by a thin layer of darker material (probably iron oxides and/or clays). This outer rim occasionally separates the quartz grains from the surrounding quartz overgrowths. The grains are cemented by chalcedony crystals (first generation) and later by quartz overgrowth. Few micritic calcite grains are observed, usually filling the pores. Feldspar grains and chert fragments are found in small proportions. Authigenetic overgrowth often shows euhedral crystal shape where quartz is fully developed. Some grains exhibit pressure-solution compaction, where sutured contacts are present and the grains are highly packed and interlocking, forming a mosaic texture.

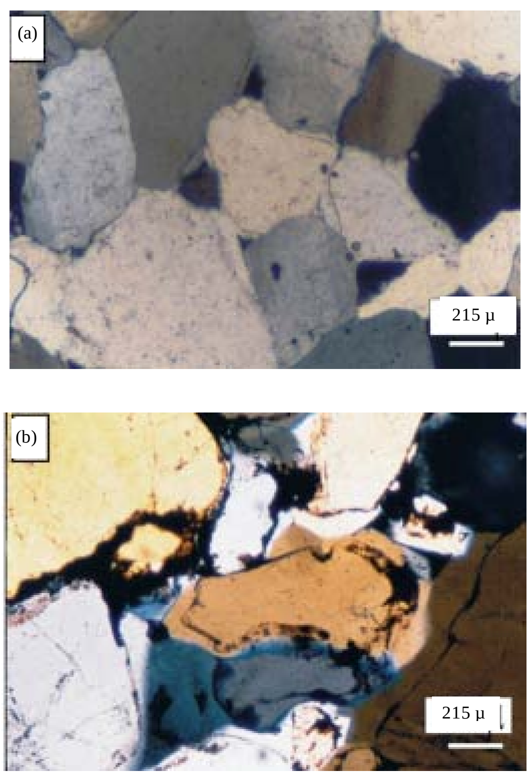

Fig. 1: Quartzitic sandstone archaeological samples: (a) Medium to coarse, subrounded to well rounded quatrz grains (b) Well developed authogenic quartz overgrowths, A10, C.N

The investigated major and trace elements of seven orthoquartzite samples are listed in Table 2. Generally, both the displayed and still underwater quartzite objects are chemically similar. SiO_2 content ranges from 84-93% (average~90%) and TiO_2 ranges from 0.08-0.42% (average 0.21%). CaO is present in low proportions in most of the samples but reaches 2.4 and 5% in samples A54 and A64, respectively; this may be due to calcitic secondary cement in the stone (and potentially from remains of marine fossils contaminating the sample). Other elements are either present in insignificant amounts or under the detection limits. Among the detected trace elements, the significant ones are Zr, Sr and Zn with average values of 139, 128 and 14 ppm, respectively and are present in all analyzed samples. Pb is detected in five samples (range from 15-24 ppm).

Greywackes: Petrographic examination of the archaeological samples reveals that the displayed sample A9 exhibits poor sorting and a slightly oriented texture. It is comprised of sub-angular to rounded fine sand grains of quartz, plagioclase and lithic fragments embedded in a fine-grained matrix comprised of quartz and mica minerals (muscovite). Epidote and chlorite are also recorded within the sample. According to the USDA scale (Pettijohn *et al*., 1987), the grain size of sample A9 ranges from very fine to fine sand (80 to 150 μm) and can be categorized as sandstone. Matrix materials constitute more than 20% of the rock by volume; thus, sample A9 is a greywacke sensu stricto (Fig. 2a). XRD analysis confirmed the petrographic results and also identifies traces of carbonates (calcite and ankerite), hematite and illite. On the other hand, the underwater sample, A69, is composed mainly of fairly well-sorted, fine to very fine (silt size) grains exhibiting a slight lamination. The clasts are comprised of sub-angular crystals composed mainly of quartz and minor plagioclase and float in a very fine-grained groundmass of quartz, sericite and muscovite. According to the USDA scale

Table 2: Major and trace elements content of Alexandria Lighthouse objects and their corresponding qurries

	Alexandria Lighthouse objects*							Gebel Ahmer quarry samples*				Gebel Gulab quarry samples*								Alexandria Lighthouse objects**		Wadi Hammam at quarries**	
	A8	A10	A54	A59	A62	A64	A66	A117	A119	A120	A121	A122	A123	A124	A125	A126	A127	A128	A129	A9	A69	A133	A136
SiO_2	88.6	90,6	92.2	91.7	93.3	84.8	89.6	91.1	92.5	92.5	92.6	88.4	90,6	88.4	88.9	95.8	90.3	90	93.7	66.2	43.6	72.3	65.5
Al_2O_3	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	13.8	13.8	12.1	14.1
TiO_2	0.42	0.36	0.11	0.08	0.15	0.22	0.15	0.19	0.09	0.09	0.11	0.5	0,38	0.43	0.29	0.2	0.18	0.18	0.18	0.79	0.74	0.58	0.9
F_2O_3	<1	<1	<1	<1	<1	<1	<1	3	2.6	2.6	<1	1	<1	<1	<1	<1	<1	<1	<1	6	3.4	4.2	5.5
MnO	<0.01	<0.01	0.01	<0.01	<0.01	<0.01	<0.01	<.01	<0.01	<0.01	<0.01	0.01	<0.01	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.15	0.04	0.13	0.12
CaO	1.6	<1	2.4	1.5	1.5	5	<1	<1	<1	<1	<1	1.3	<1	<1	<1	<1	<1	<1	<1	3.3	19	1.9	2.6
MgO	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	2.8	3	2.2	2.9
K_2O	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	2.1	3.2	2	2.2
P_2O_5	0.03	0.02	0.04	0.04	0.04	0.09	0.03	0.05	0,04	0,04	<0.01	0.05	0.01	0.04	<0.01	<0.01	<0.01	<0.01	<0.01	0.14	0.15	0.11	0.17
ppm																							
B	<10	<10	11	<10	11	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	30	194	30	33
Ba	<10	14	11	<10	<10	<10	<10	10	<10	<10	10	35	12	27	14	<10	<10	<10	<10	538	264	607	538
Bi	10	<10	<10	<10	<10	<10	<10	10	<10	<10	10	<10	<10	<10	<10	<10	<10	<10	<10	17	<10	<10	<10
Ce	10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	12	<10	<10	<10	<10	<10	47	32	39	55
Cr	22	<10	<10	10	<10	<10	<10	16	12	12	10	30	17	21	<10	17	<10	<10	<10	132	128	104	144
Ni	10	35	<10	<10	<10	<10	<10	11	16	16	<10	17	12	14	12	11	10	<10	<10	72	42	63	60
Pb	24	<10	15	15	15	22	15	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	18	<10	19	16
Sb	10	<10	<10	12	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	<10	20	<10	<10	<10
Sr	68	45	140	117	125	316	85	24	13	13	15	32	21	40	13	12	12	11	12	301	360	305	278
V	18	<10	<10	<10	<10	<10	<10	16	21	21	12	16	<10	11	<10	<10	<10	<10	<10	132	118	100	116
Zn	24	24	9	10	9	14	9	8	21	21	11	7	5	11	<5	<5	<5	<5	<5	77	66	59	84
Zr	250	69	173	63	198	116	104	125	53	53	172	137	100	103	102	77	66	55	74	218	236	118	225

*Quartzitic sandstone samples, **Greywacke samples

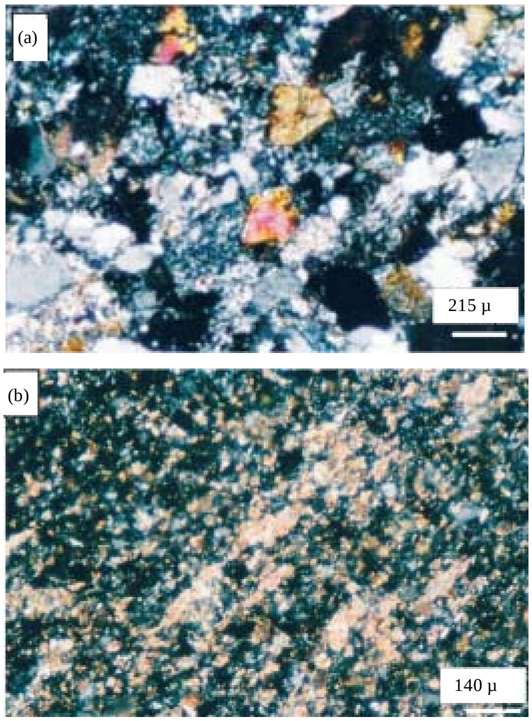

Fig. 2: Greywackes archaeological samples: (a) Sandstone showing poor sorting of fine sand grains and slightly oriented texture,A9,C.N. (b) Siltstone showing fairly well sorting of fine to very fine (silt size) grains, exihibiting slight lamination, A69, C.N

(Pettijohn *et al*., 1987), the grain size of sample A69 ranges from fine to coarse silt (0.020 to 0.05 mm) and can be categorized as siltstone (Fig. 2b).

Major and trace elements detected in the studied greywackes are listed in Table 2. From Table 2, it is apparent that sample A9 is richer in SiO_2 and Fe_2O_3. SiO_2 is 66.2 and 43.6% while F_2O_3 is 6.0% and 3.4% for samples A9 and A69, respectively. In contrast, sample A69 is richer in CaO. CaO is only 3.3% for sample A9, compared to 19% for A69. This difference could be linked to a different content of calcitic lithoclasts among samples. Nevertheless, a more probable explanation is the underwater impact on the archaeological objects and the presence of the remains of calcitic marine concretions on sample A69 (kept underwater without cleaning as opposed to the sample A9 object). Other major elements are present in very similar proportions in both samples. The most significant trace elements for samples A9 and A69 (Table 2) are Sr (301 and 360 ppm), Ba (538 and 264 ppm), Zr (218 and 236 ppm) and V (132 and 113 ppm), Zn (77 and 66 ppm), Cr (132 and 126 ppm) and Ni (72 and 42 ppm), respectively.

Table 3: Isotopic data of the limestone samples from Alexandria Lighthouse and corresponding quarries

Sample	Sample descriptions	δ^{18} O‰ vs PDB	δ^{13} C‰ vs PDB
A3	Lighthouse limestone object	-0.7	0.7
A4		-1	0.6
A5		0.3	2.4
A68		-12.8	-0.2
A33	El Mex area; outcrop at km 8	-1.6	3.4
A34	El Mex area; recent quarry at km 21	-1.1	3.7
A35	El Mex area; ancient quarry at km 21	-1.4	3.8

Limestones: The light-colored limestone samples are classified as dolomitic sandstone (sample A3, Fig. 3a) and sandy dolostone (sample A4, Fig. 3b) based on the percent of the carbonate cement (30% for sample A3 and 68% for sample A4). Quartz, dolomite and rare feldspar, along with few shell fragments, are the main constituents. Quartz grains are enriched in sample A3 (Fig. 3a) and are very fine to fine (50-120 µm), sub-angular to sub-rounded and moderately sorted. The carbonate cement is comprised of ferroan dolomite which is identified by X-Ray analysis and stained blue with potassium ferricyanide. The dolomite rhombs are fine-to medium-sized, polymodal, planar to non-planar, can contain a cloudy core and clear rim and are usually unzoned, though some can show zoning. The bedrock (sample A5) is a light beige-grey calcarenite, sandy in texture and having a semi-friable surface (the carbonate content is about 95%). It is classified as a biosparite (bioclastic grainstone) and consists mainly of sub-angular to sub-rounded (300 µm) allochemical grains; mainly skeletal fragments as red algae, echinoderms, corals and foraminifera (Fig. 3c). Some are coated with micrite envelopes and are embedded in a sparite matrix. XRD analysis confirms that it is a pure calcium carbonate composed mainly of calcite plus aragonite. The dark grey-bluish limestone sample (A68) is petrographically classified as lime-mudstone (Fig. 3d). It is a mud-supported stone composed of micrite which is usually recrystallized into microsparite. It contains about 10% fossil allochems (mainly recrystallized shell fragments). This lime-mudstone has sparitic-filled fenestrae ("bird-eye" structure) in the micritic matrix (dismicrite). Very fine (silt-size) quartz grains are also observed. The carbonate content of sample A68 is about 80% and the XRD analysis confirmed the presence of calcite plus little quartz, kaolinite and illite.

The isotopic signature of the studied carbonate samples are given in Table 3. Samples A3 and A4 have similar carbon and oxygen isotopic values; thus, they belong to the same geologic formation which differs from the values of sample A5 (calcarenite) and sample A68 (lime-mudstone). This result indicates that the bedrock of QaitBay is not the provenance of both the underwater lime-mudstone monumental object and of the stones constituting the current basement of QaitBay Fortress.

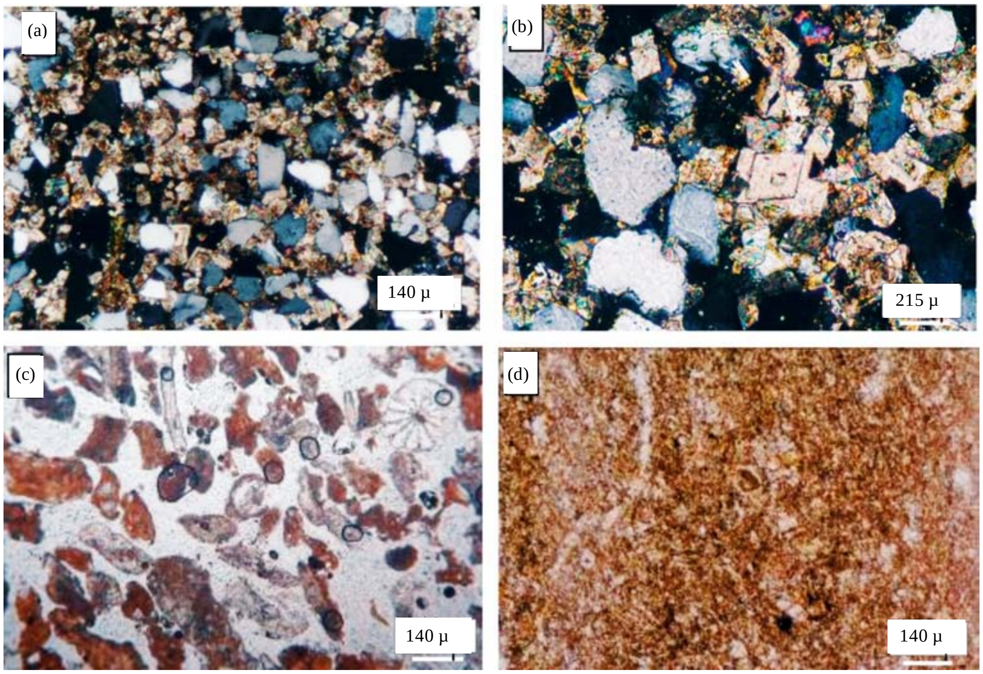

Fig. 3: Limestone archaeological samples. (a) Dolomitiic sandstone, A3, C.N (b) Sandy dolostone, A4, C.N (c) Biosparite, bedrock of QaitBay Fortress, A5, P.P.L (d) Lime- mudstone, A68, P.P.L

SEARCH OF REFERENCE QUARRIES

Quartzite quarries: Two ancient quarries are believed to be the main source of quartzite used in ancient Egyptian monuments and objects. These are the Gebel Ahmar quarry, near Cairo and the Gebel Gulab on the western bank of the River Nile, opposite Aswan City (Aston *et al*., 2003; Klemm and Klemm, 2008). A survey of both areas was carried out and representative samples were collected (Table 1). The Gebel Ahmar quartzite sandstone deposit belongs to the Oligocene Gebel Ahmar Formation (Barron, 1907) and was exploited from the Old Kingdom to the Roman period. It supplied (Harrell *et al*., 1996) a quartz-cemented stone (orthoquartzite).

The survey of the Gebel Ahmar area revealed that the Gebel Ahmar ancient quarries mentioned in the bibliography have, unfortunately, been destroyed during the last years, due to the extension of the city of Cairo; even the name has changed to Gebel Akhdar. The outcropping area is now occupied by buildings and only two silicified sandstone outcrops were encountered, investigated and sampled. The first outcrop lies close to "Autostrad Road", near the gate of the "Arab Contractors Club". It corresponds to the remains of a small hill and is comprised of many sandstone blocks distributed across an area of approximately one hundred meters long. The sandstones exhibit different colors ranging from yellowish to red-brownish. They appear hard, silicified and contain pebble fragments (pebbly sandstone). The second outcrop lies in the back side of the "Arab Contractor Club" forming a sequence, about 30 m thick, of various colored (yellow, red, dark red and yellowish white), bedded sandstones with some conglomerate intercalations, containing flint pebbles and silicified wood fragments.

The Gebel Gulab quarries lie in the vicinity of Gebel Gulab-Gebel Tingar area, opposite to Aswan City on the west bank of the River Nile. It was exploited from the New Kingdom period to the Roman period (Bloxam *et al*., 2007, Klemm and Klemm, 2008) and supplied quartz-cemented stones (orthoquartzites) (Harrell *et al*., 1996). The quartzitic sandstones of the Gebel Gulab area are Upper Cretaceous in age and are contained in the Um Barmil Formation (Taref sandstones) (Klitzsch *et al*., 1986; Issawi *et al*., 1999).

Field inspection of Gebel Gulab revealed that the quartzitic sandstones quarries correspond to a specific restricted area showing highly silicified facies ranging in color from beige to brownish and pinkish to reddish. Remains of an unfinished obelisk and traces of ancient exploitation are numerous over a large area of approximately five hundred meters long. The various colors for both quarries are linked to variable contents of iron oxides (hematite and goethite) in the quartz cement and manganese oxides likely cause the purplish color.

Greywacke quarries: The most important ancient greywacke quarries are located in Wadi Hammamat, in the Eastern Desert and were exploited from the Early Dynastic period to the Roman period (Harrell *et al*., 1996; Aston *et al*., 2003; Klemm and Klemm, 2008).The Wadi Hammamat greywacke deposit belongs to the Hammamat Group (Neoproterozoic), lies about 70 km west-southwest of Quseir and comprises a sequence about 4 km thick (Akaad and Noweir, 1980).

Field inspections indicate that the ancient greywacke quarries, in the Wadi Hammamat area, occur along a stretch of the Wadi just over one kilometer in length and contain grey siltstones and greywacke sandstones. They are covered by many inscriptions. The Wadi Hammamat greywackes range from dark greenish-grey to mainly grayish-green in color and from medium-to very fine-grained and they may be occasionally pebbly.

Limestone quarries: It is worth mentioning that the provenance area of the building stones, because of the large volumes necessary, is generally limited in terms of distance between the deposit of material and the place of construction. Inversely, decorative stones used in ancient times could travel long distance because of their high value and the lower volumes ordered. The only referenced ancient quarries near Alexandria (exploited from the Ptolemaic period to the Roman period) are located to the west of the City on both sides of Mariut marsh (Harrell *et al*., 1996) between the villages of Abu Sir and Burg el-Arab to the southwest and El-Mex to the northeast. The corresponding limestones are light-colored and their deposits belong to the Pleistocene Alexandria Formation (Said, 1990). No ancient quarry is believed to be located near Alexandria that could supply the dark-grey limestone (sample A68). However, Harrell *et al*. (1996) indicated that Wadi Abu Mu = aymil, near St. Antony Monastery in the Wadi Arab area of the Eastern Desert, is the quarry for the dark grey and black limestones. The stone belongs to the Middle Eocene Mokattam Formation which supplied "silty/sandy, occasionally clayey mudstones" (Harrell, 1992; Harrell *et al*., 1996). Petrographic study suggests that sample A68 is also a mudstone, containing silt-sized quartz grains and clays. Nevertheless, based on the limited data available, it is not possible to deduce the provenance of the dark grey-bluish limestone, although Wadi Abu Mu = aymil quarry remains a possible provenance area.

In situ investigations focused on two light-colored limestone quarry areas (El-Mex and Abu Sir), including a survey and a sampling of each one. The El-Mex area is located close to Alexandria city and is now occupied by many buildings which resulted in the destruction of most of the quarries. Remains of small outcrops of fine-grained, white chalky limestone are present in some construction-free areas (kilometer 8, Alexandria-Marsa Matrouh road). Moreover, some ancient and recent quarries are observable at kilometer 21 of the Alexandria- Marsa Matrouh road. Megascopically, the stones are whitish to light beige pure limestones (average carbonate content is about 95%), very friable, sandy in texture and are weathered on the surface. The Abu Sir ancient quarries lie about 45 km to the southwest of Alexandria city. The main quarry is large, with many quarrying fronts and hosts a thick and expansive sedimentary formation. This formation is a porous calcarenite limestone, light beige (unweathered surface) to beige (weathered surface) in color.

POSSIBLE SOURCE AREAS

Source of quartzite: To determine the provenance of quartzite used in the monumental objects, the samples collected from both the Gebel Ahmar and Gebel Gulab quarries are characterized petrographically and geochemically and are compared to the archaeological samples. According to microscopic observations, the quartzite samples from Gebel Ahmar and those from Gebel Gulab can be characterized as orthoquartzite (Pettijohn *et al*., 1987). They are composed mainly of quartz grains (>95% of the frame study). The grains are mostly monocrystalline (rarely polycrystalline), some show wavy extinction and some are sutured. The quartz grains display syntaxial quartz overgrowths. Grains are cemented with quartz in optical continuity with the detrital ones. Thin sedimentary overgrowths of silica on the detrital grains are very common in Gebel Ahmar samples. These overgrowths are separated from the detrital core by a thin line of impurities represented by clayey material but mainly by iron oxide. Quartz grains are highly packed and interlocked forming a mosaic texture. The differences recognized are: (1) the roundness of quartz grains- more rounded (sub-rounded to rounded) for the Gebel Ahmar samples (Fig. 4a) than in the Gebel Gulab ones which are mainly sub-angular (Fig. 4b), (2) presence of chert grains in Gebel Ahmar samples which are not recorded in the Gebel Gulab samples, (3) the cement overgrowth which has the same optical continuity as the grains, is dominant at Gebel Ahmar (Fig. 4a); in Gebel Gulab, quartz grains display a slight sedimentary syntaxial overgrowth (Fig. 4b).

In sum, the quartzites from the two areas are usually indistinguishable megascopically. However, in thin sections, they differ mainly in the roundness of their grains, presence of chert and predominance of quartz

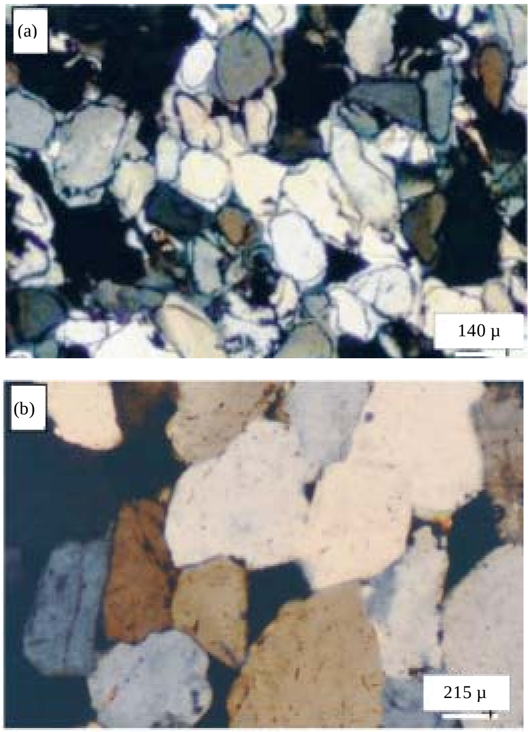

Fig. 4: (a) Gebel Ahmar orthoquartzite: Sub-rounded to rounded, sorted quartz grains with common quartz overgrowth, A119, C.N (b) Gebel Gulab orthoquartzite: Sub-angular to sub-rounded quartz grains with slight syntaxial overgrowth, A129, C.N

authigenic overgrowths. The presence of chert pebbles, the roundness (sub-rounded to rounded) of quartz grains and the presence of obvious syntaxial overgrowths in the samples collected from the Alexandria Lighthouse quartzite objects seem to correspond to Gebel Ahmar.

The chemical data of the selected samples from both Gebel Ahmar and Gebel Gulab areas are given in Table 2; both are chemically similar and no chemical elements present seem to discriminate them. The samples contain high contents of SiO_2 averaging about 91% (ranging from 88-96%). No other major element is detected in significant concentration. K, Mg and Mn are below the detection limits. In terms of chemical signature, Ti is the sole element present in the whole samples that may show a higher content in Gebel Gulab samples. Nevertheless, according to the limited number of samples, this result cannot be considered definitive. The SiO_2 and TiO_2 contents detected in samples of both quarry areas and from Alexandria Lighthouse objects made of quartzite exhibit similar values with no specific trend. The most significant trace elements are Zr and Sr with average contents of 97 and 20 ppm, respectively, for Gebel Ahmar samples and 89 and 19 ppm, respectively for Gebel Gulab samples. Traces of Ba, Cr, Ni, Zn and V are also detected in many samples. Zr and Sr values recorded in Gebel Ahmar and Gulab quarry samples are comparable to those recorded by Klemm *et al.* (1984) and Klemm and Klemm (2008) on other series of samples collected from the same quarry areas (Zr ranging from 10 to 130 ppm for Gebel Ahmar and 15 to 110 ppm for Gebel Gulab; Sr ranging from 3 to 19 ppm for Gebel Ahmar and 3 to 18 ppm for Gebel Gulab). Zr content in the archaeological samples is rather similar to the content measured in both quarry areas. On the other hand, Sr content is slightly (for samples A8 and A10) to clearly higher (for samples A54, A59, A62, A64 and A66) relative to those from both quarry areas (Table 2). The measured values range from 45 to 316 ppm with an average content of 128 ppm. The most probable explanation is the seawater impact on the archaeological objects which is suspected by the presence of the remains of Sr-rich marine concretions on the samples (sea water contains about 8 mg of Sr per liter). This seems to be confirmed by the lower values of Sr in samples A8 and A10 which were collected from desalinated objects, than those collected from the "still raw" underwater objects. The trace elements, Cr, Ni, Zn and V, detected in many samples in very minor concentrations from Gebel Ahmar and Gebel Gulab quarries, are similar to those from the Alexandria Lighthouse samples (Table 2). In sum, the chemical data for both areas are similar and comparable to those from the archaeological objects without highlighting any discriminatory parameter of provenance. However, based on petrographic data, the presence of chert pebbles, the roundness (sub-rounded to rounded) of quartz grains and the common syntaxial overgrowths in both the archaeological samples (both the outer exhibited objects and the underwater objects) and in the Gebel Ahmar quarry samples indicate that Gebel Ahmar Quartzite sandstone quarries (near Cairo) are the provenance area.

Source of greywacke: Petrographic studies show that the greywackes of the Wadi Hammamat area (samples A131 to A136) can be classified as greywacke sandstones (Fig. 5a) and siltstones (Fig. 5b) (Pettijohn *et al.*, 1987). The siltstone samples are comprised mainly of rather well sorted silt-size grains (0.02 to 0.05 mm) which results in a fine homogeneous appearance. The grains are formed from quartz with some plagioclase and opaques in a fine-grained matrix comprised of quartz and muscovite, plus rare epidote, chlorite and sericite. Greywacke sandstone samples are composed of fine to medium

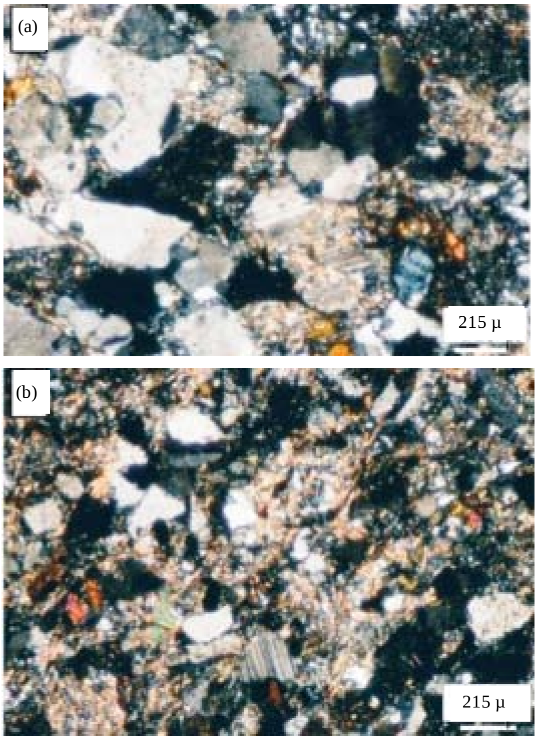

Fig. 5: Greywacke samples of Wadi Hammamat quarries: (a) Greywacke sandstone, A133, C.N (b) Greywacke siltstone, Shows some sort of foliation, A136, C.N

poorly sorted subrounded grains (0.05 to 0.15 mm) that consist mainly of quartz and plagioclase, lithic fragments and rare muscovite. The grains are lightly cemented by a matrix (~40% of the rock by volume) and are formed mainly of silt and clay-sized grains of quartz and feldspar, chlorite and sericite, with calcite and epidote as minor minerals. According to microscopic observations, the greywacke (sandstone and siltstone) samples from Wadi Hammamat are very similar to those of the Alexandria Lighthouse objects (samples A9 and A69).

The major and trace element analyses of two representative samples, greywacke sandstone (A133) and siltstone (A136) are listed in Table 2. The main major oxides are SiO_2 (72.3 and 65.5%), Al_2O_3 (12.1 and 14.1%), F_2O_3 (4.2 and 5.5%), TiO_2 (0.58 and 0.90), CaO (1.9 and 2.6) and MgO (2.2 and 2.9) for the sandstone and siltstone, respectively. The most significant trace elements are: Ba (607 and 538 ppm), Sr (305 and 278 ppm), Zr (118 and 226 ppm), Cr (104 and 144 ppm), V (100 and 116 ppm), Zn (59 and 84 ppm), Ni (63 and 60 ppm) and Ce (39 and 55 ppm) for samples A133 and A136, respectively. The results agree well with those obtained by Holail and Moghazi (1998), for a series of greywacke samples selected to cover variations in color and grain size among siltstone and greywacke beds of the Wadi Hammamat area. Sodium was not measured but the same authors determined an average value of around 3%. By comparing the chemical data recorded on the studied samples from the Wadi Hammamat area to those from

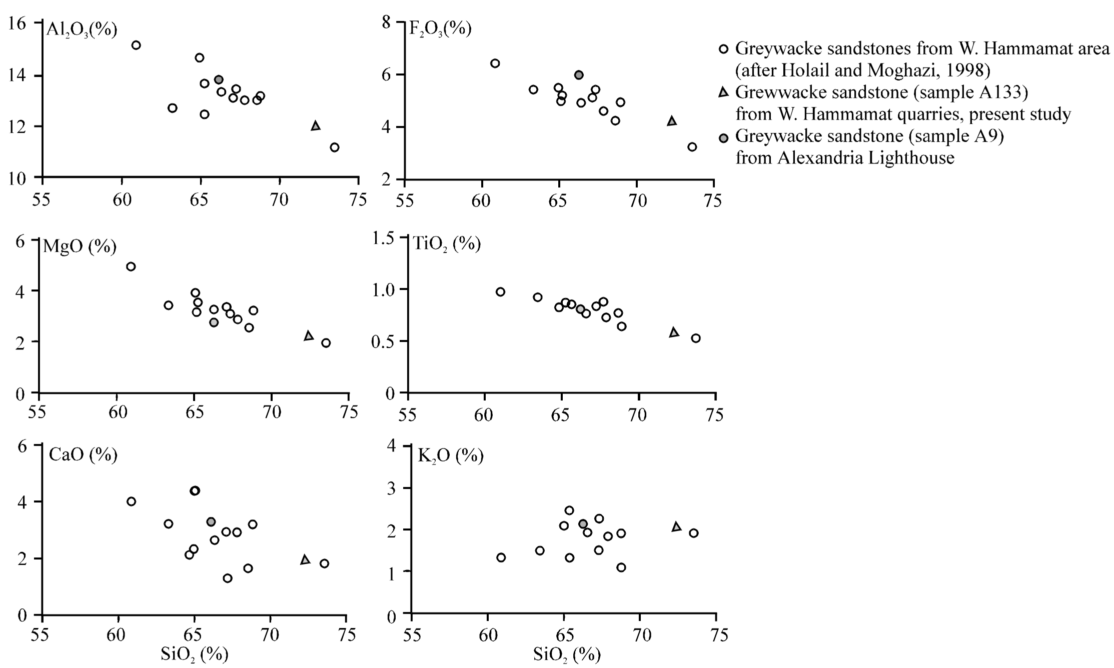

Fig. 6: Covariation of SiO_2 versus some major elements for the greywacke sandstones of Wadi Hammamat (Holail and Moghazi, 1998) compared to the studied quarry and lighthouse samples

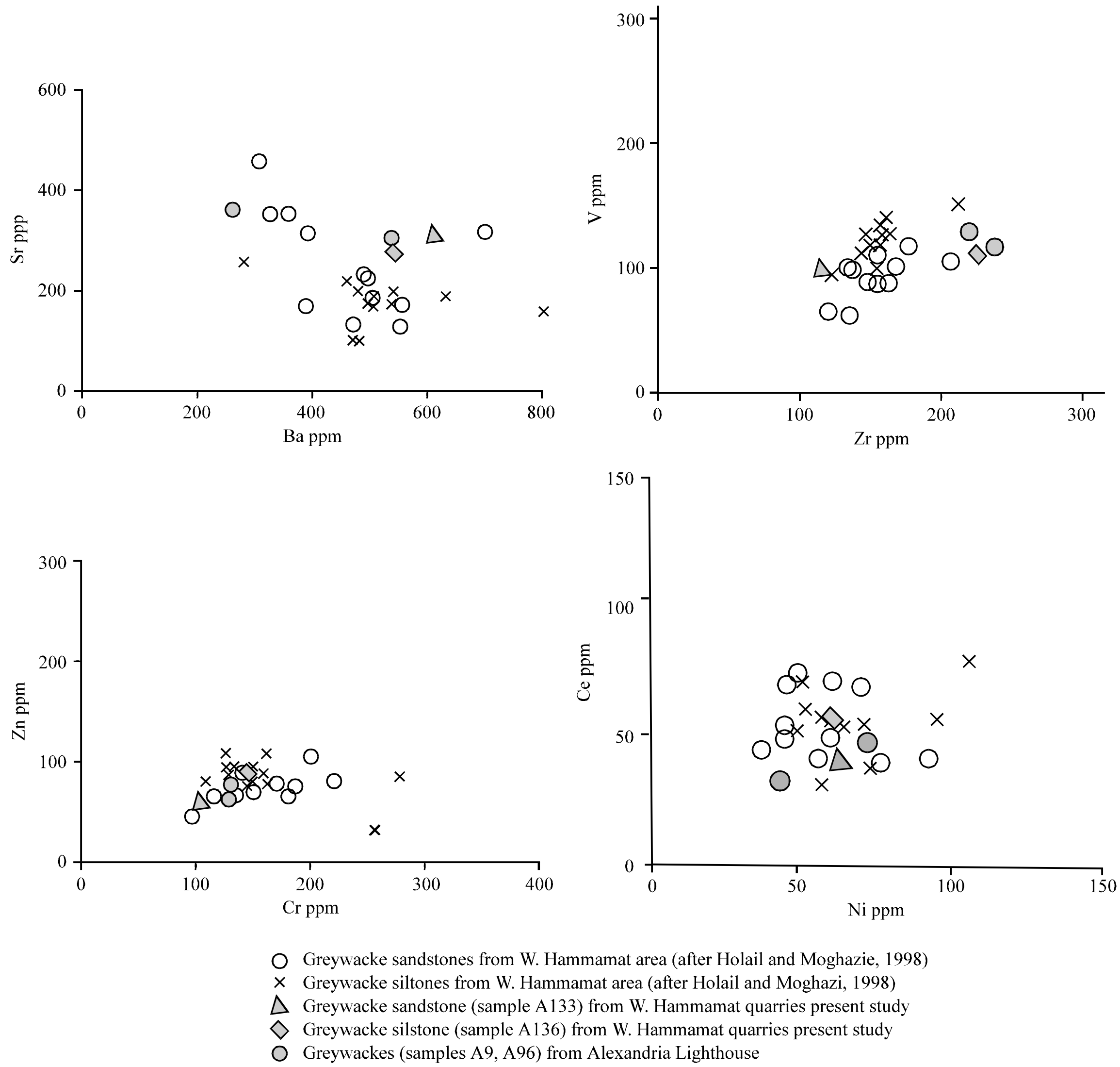

Fig. 7: Plots of Ba/Sr, Cr/Zn, Zr/V and Ni/Ce of Wadi Hammamat greywackes (Holail and Moghazi, 1998) compared to studied quarries and Lighthouse samples

the Alexandria Lighthouse greywacke objects (A9 and A69); similar values are observed (Fig. 6-7). The petrographic investigation and chemical composition analysis confirms that Wadi Hammamat quarries are the provenance area of the greywackes that constitute the two sampled Alexandria Lighthouse objects.

Source of Limestones: Microscopic examination of samples collected from El-Mex and Abu Sir quarries (A36 to A38) suggest that they are predominately composed of: calcarenite; ooid grainstone or oosparite, consisting of well-sorted ooids that range from 200 to 300 µm in size; and rare foraminifera, gastropods and skeletal fragments imbedded in sparite matrix (Fig. 8). Ooids are tangential and aragonitic. The nuclei are mostly composed of microcrystalline carbonate grains and in a lesser proportion, skeletal fragments and siliciclastic grains. The cortex consists of tangential, predominately aragonitic lamellae. Some ooids are superficial and a few of them are complex and oomolds. Many of the ooids are micritized. Molds are frequently present which are ooids, dissolved due to their aragonitic composition during sub-aerial exposure. The isotopic signatures of the El-Mex-Abu Sir quarries samples A33 to A35 are listed in Table 3 and compared to those collected from the basement of the QaitBay Fortress (samples A3 and A4, Table 3). The comparison of analytical data (petrographic description and isotopic signature) of both

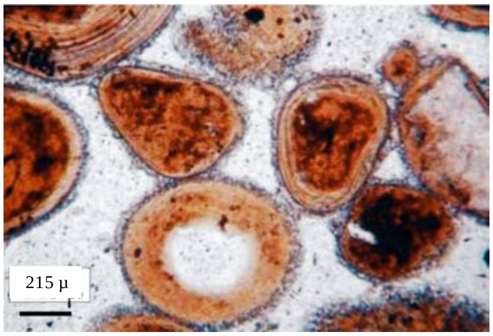

Fig. 8: Calcarenite (oosparite), showing well sorted aragonotic ooids embedded in sparite matrix. Abu Sir quarry, A37, P.P.L

archaeological samples A3-A4 and quarry samples A33 to A38, clearly suggest that El-Mex - Abu Sir quarries (and more generally the Alexandria Formation) are not the provenance area of the light-colored stones that constitute the basement of the QaitBay Fortress. The archaeological samples A3 and A4 are sandy dolostones to dolomitic sandstones characterized by high quartz content (30 -70%) while El- Mex - Abu Sir quarries supply pure calcarenite comprised of more than 90% carbonate. Also, no correlation is found when the isotopic values of sample A3-A4 are compared with isotopic data from the Pleistocene calcareous ridge along the Mediterranean coast of Egypt, given by various authors (Holail, 1993; El-Hinnawi and Loukina, 1993; Abd-Alla, 2000). Moreover, comparing the present data with those obtained by Harrell (1992) and Harrell *et al.* (1996) from various Egyptian limestone formations (Mokattam, Samalut, Minia, Drunka, Serai and Tarawan) used for quarrying, yielded no lithological and mineralogical correlation.

CONCLUSIONS

The present study presents a detailed study on the sedimentary rocks and provenance areas constituting some archaeological objects, related to the Alexandria Lighthouse. The identified rock types were described and characterized in terms of their petrographic types of stone and chemical properties. They are formed of quartzitic sandstones (orthoquartzite), greywackes (siltstone and sandstone) and limestones (lime-mudstone and sandy dolomite/dolomitic sandstone). Wadi Hammamat quarries belong to the Hammamat Group in the Eastern Desert are confirmed to be the provenance area for the greywacke that constitutes the two sampled Alexandria Lighthouse objects. Gebel Ahmar quarries which are related to the Oligocene Gebel Ahmar Formation (east of Cairo City), were the provenance area of the quartzite used in the archaeological objects. It was not possible to deduce the provenance of the lime-mudstone archaeological sample, even though (in accordance with the bibliography) the Wadi Abu Mu'aymil quarry (Eastern Desert) which belongs to the late Middle Eocene Mokattam Formation, remains a possible provenance area. The source of the dolomitic sandstone/sandy dolostones blocks (now constituting the basement of the QaitBay Fortress and potentially the ruins of the Alexandria Lighthouse) which are megascopically described as light-colored “limestones” remains unknown.

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