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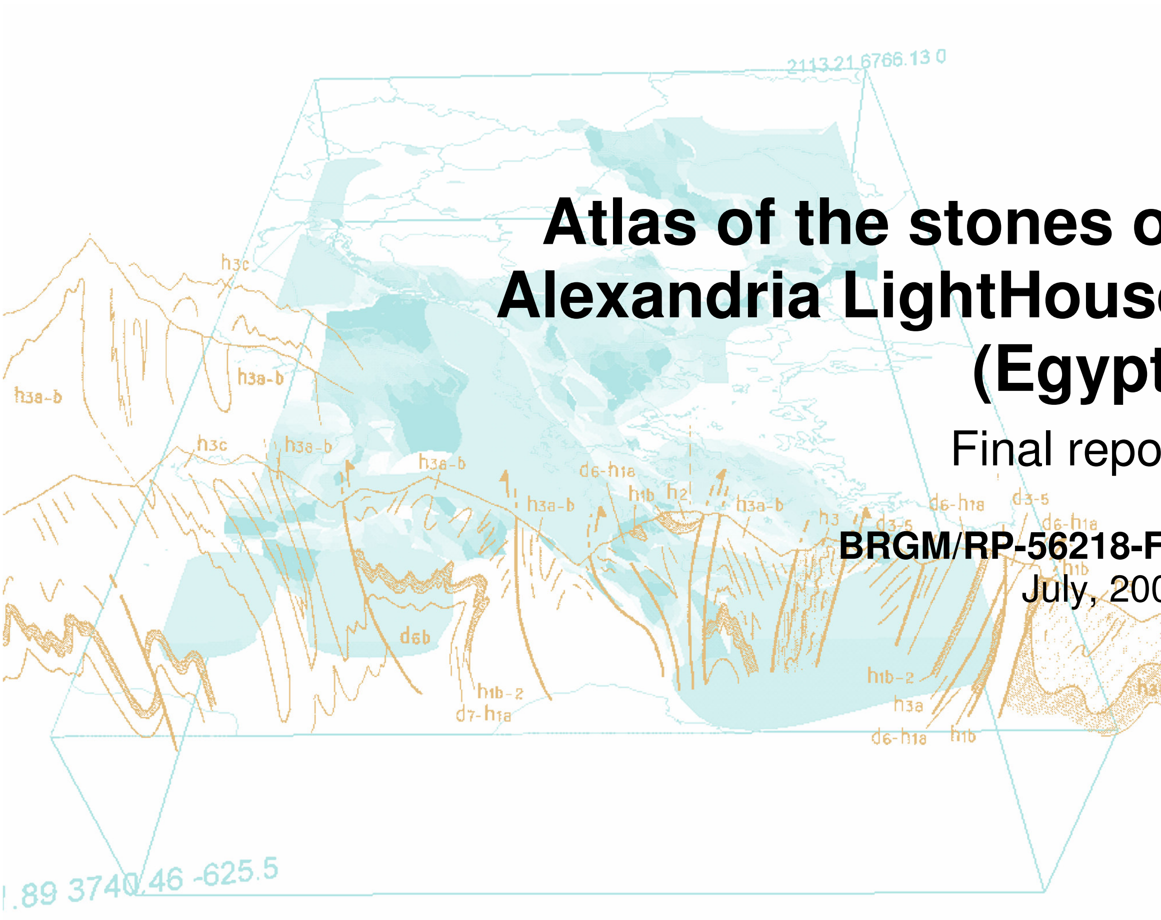

Atlas of the stones of Alexandria LightHouse (Egypt)

Final report

BRGM/RP-56218-FR

July, 2008

Sixth Framework Programme

Geoscience for a sustainable Earth

brgm

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Study carried out in the framework of MEDISTONE project
(European Commission supported research program FP6-2003-INCO-MPC-2 / Contract n°15245)

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Keywords: Egypt, Alexandria Lighthouse, ancient site, stones, identification, provenance, quarries.

In bibliography, this report should be cited as follows:
D. Dessandier with the collaboration (in alphabetical order) of A. Akarish, F. Antonelli, L. Lazzarini, L. Leroux, A. Nageh, A. Shoeib and M. Varti-Matarangas (2008) – Atlas of the stones of Alexandria Lighthouse (Egypt). BRGM/RP-56218-FR, 161 p., 109 fig., 9 tab., 6 app.

Synopsis

The present study titled “Atlas of the stones of Alexandria Lighthouse” was performed in the framework of the project MEDISTONE (“Preservation of ancient MEDIterranean sites in terms of their ornamental and building STONE: from determining stone provenance to proposing conservation/restoration techniques”) supported by the European Commission (research program FP6-2003-INCO-MPC-2 / Contract n° 015245).

Its scientific objective was to identify the stones (ornamental and building ones) of the Lighthouse and to determine their provenance in terms of geographic areas (and of former quarry sites when possible). The obtained data and results in an accessible form including photos and maps (so-called “Atlas”).

First of all, one should remember that the Alexandria Lighthouse was toppled into the sea. The archaeological site is nowadays essentially underwater just off the coast of Alexandria. Its ruins consist of about three-thousand architectonic blocks and statues lying on the seabed at depths between six to eight meters.

Until the beginning of modern underwater excavations only few and contradictory informations about the building materials of the Pharos were available. Some authors mentioned the Lighthouse was build of white stone whereas others indicated the presence of marble, limestone and bronze for the decorated statues. Various theories followed one another talking about local limestone, nummulitic limestone, granite, alabaster, white marble…

According to new results following many underwater excavations from 1994, Jean-Yves Empereur (Centre d’Etude Alexandrine) first made scientific and systematic investigation and review of the materials constitutive of the blocks, encountering granites essentially and sandstones as well as few graywacke, marble and limestones. The archaeologist explained the relative lack of limestone and marble blocks by three reasons: these softer stones are difficult to identify underwater after having been eroded over the centuries by marine flora and fauna, the need for chalk to manufacture cement for Alexandria city, these stones are much easier worked and therefore were taken to be re-employed in later constructions such as the fortress itself and the adjacent Ottoman tower.

Up till nowadays, the various undersea excavations in QaitBay extracted from under the sea about fifty blocks of different sizes (architectonic blocks and statues). Therefore, guided by Centre d’Etude Alexandrine (special acknowledgement to Mrs. Isabelle Hairy), an overall examination of the sites of exhibition and / or storage of these blocks reputed coming from the collapsed Alexandria Lighthouse was undertaken. A detailed study of the blocks was performed to inventory megascopically the main types of stones related to the Pharos and a first series of thirty-two samples were collected. As most of the stones related to the lighthouse are still occurring underwater, a second series of thirty-five samples was collected by diving from still underwater architectonic blocks.

The whole sixty-six archaeological samples were described megascopically and characterized in laboratory in terms of their petrographic types of stone and physical-chemical properties, classified as follows:

Fifty samples are granitoïds (forty-two coarse pink granites and eight dark-grey granodiorites) mostly grouped together in monzogranite (± syenogranite) and tonalite (± granodiorite) fields (according to chemical classification of De la Roche et al., 1980).

Nine are megascopically beige-yellowish to ochre-brownish siliceous sandstones made of fine-grained to coarse-grained (almost conglomeratic) more or less bedded materials with color and classified as orthoquartzites (according to Folk, 1954).

Two samples are medium to coarse grained pure whitish crystalline marbles.

Two look like greywackes of dark-grey color and slightly oriented texture (foliation) megascopically, classified under microscope as metasandstone and coarse-grained metasiltstone (according to Pettijohn et al., 1987).

One sample is a fine dark grey-bluish limestone, corresponding to a lime-mudstone (micrite) containing a few silt-size grains of quartz and micaceous clays.

Two samples looking like light-colored limestones megascopically are classified as fine sandstones with dolomitic cement to sandy dolostones. Contrary to the others, both were not collected on underwater archaeological objects but on blocks constituting the basement of Qaitbay Fortress according to the hypothesis that the fortress was located in the same place than the Alexandria Lighthouse using its ruins.

The search of reference quarries of the various petrographic types of stones constituting the archaeological samples was relied on bibliographic data and field investigations and sampling. Collected quarries representative samples were described megascopically and studied in laboratory before being compared to the archaeological samples.

Concerning granitoïds in accordance with bibliography, quarries were located in Aswan City area. A geological survey of modern and ancient ones was performed and thirty-two samples were collected. On the basis of their petrographic observations and chemical measurements (notably major elements contents), the granitoïds from Aswan quarries (Neoproterozoic age) are monzogranite (± syenogranite) and tonalite (± granodiorite) as the archaeological objects. Then Aswan granitoïd quarries are the provenance area of the stone of the whole studied archaeological objects made of coarse pink granite or dark-grey granodiorite from Alexandria Lighthouse.

About siliceous sandstones, the bibliography focused the quarries investigations on quarries areas of Gebel Ahmar (from “Gebel Ahmar Formation”; Oligocene age) near Cairo and Gebel Gulab (from “Umm Barmil Formation” of the Nubia Group; Upper Cretaceous age) near Aswan. Based on petrographic observations on fourteen samples collected, the siliceous sandstones from Gebel Ahmar and Gebel Gulab areas are both orthoquartzites made of about 90% of coarse to medium-size quartz grains and resemble to those from Alexandria Lighthouse. Concerning chemical measurements (major and trace elements contents) the obtained values from both quarries samples are similar and compatible to those from the archaeological objects without nevertheless highlighting any discriminatory parameter of provenance. Only the presence of chert pebbles and the roundness (sub-rounded to rounded) of quartz grains in the nine archaeological samples as in Gebel Ahmar quarries ones seem to indicate in accordance with bibliography that Gebel Ahmar silicified sandstone quarries are the provenance area of the stone of these archaeological objects from Alexandria Lighthouse.

Concerning white marbles, no search and study of local marbles was necessary. Indeed according to analytical results (specific mineralogical-petrographic methods and isotopic analysis), both samples (and their source archaeological objects) are made of two imported classical white marbles very appreciated and largely distributed during the Roman age: the Thasian marble from Vathy (Greece) and the Proconnesian marble from Turkey.

For greywackes in accordance with bibliography, quarries were located in Wadi Hammamat area (Precambrian basement age) in Eastern Desert. Fields controls were performed and six samples were collected. As the two archaeological ones, the quarries samples correspond petrographically to metasiltstone and greywacke metasandstone. According to this petrographic similarities and also concordant chemical measurements (major and trace elements contents) Wadi Hammamat quarries are confirmed as the provenance area of graywacke (s.l.) constituting the two sampled Alexandria lighthouse objects.

About the fine dark-grey limestone provenance (one single sample of lime-mudstone – micrite - containing a few silt-size grains of quartz and micaceous clays), the only ancient quarry referred in bibliography as supplying dark grey and black limestones is located at Wadi Abu Mu'aymil (Eastern Desert). Belonging to the Mokattam Formation (late Middle Eocene age), theses stones are described as “silty/sandy, occasionally clayey mudstones” (Harrel et al., 1996). On the basis of few available data and no field control undertaken for a single sample, it was not possible to conclude about the provenance of the archaeological sample even though Wadi Abu Mu'aymil quarry remains a possible provenance area.

Finally, the search of provenance of fine sandstones with dolomitic cement to sandy dolostones (two blocks nowadays constituting the basement of Qaitbay Fortress and supposed to correspond to the ruins of the Alexandria Lighthouse; resembling megascopically resembling to light-colored limestones”) focused on two quarries areas El Mex and Abu Sir (from the “Alexandria Formation”; pleistocene age) near Alexandria City. Based on petrographic observations on six samples collected, both areas supply calcarenite made of more than 90% of calcite clearly indicating that El Mex and Abu Sir quarries are not the provenance area of the current basement blocks of Qaitbay Fortress. By comparing with available data for other Egyptian limestone formations (Mokattam, Samalut, Minia, Drunka, Serai and Tarawan) used for quarrying, no lithological and mineralogical correlation was either found and the fine sandstones with dolomitic cement to sandy dolostones provenances remains still unknown.

In final conclusion, the present study tried successfully to identify the stones of the Alexandria Lighthouse and determine their provenance areas. Moreover the accomplishment of this objective, the whole gained data constitutes a knowledge improvement available for further investigations and studies dealing with Egyptian stones.

A special acknowledgement to Mr. Jean-Yves Empereur and Mrs Isabelle Hairy (Centre d'Etudes Alexandrines) for their precious guidance.

Contents

1. Introduction

The present "Atlas" was performed in the framework of the project MEDISTONE ("Preservation of ancient MEDIterranean sites in terms of their ornamental and building STONE: from determining stone provenance to proposing conservation/restoration techniques") supported by the European Commission (research program FP6-2003-INCO-MPC-2 / Contract n° 015245).

The MEDISTONE project proposes to contribute to the knowledge and the conservation of three of the most important ancient sites in North Africa (Volubilis in Morocco, Djemila in Algeria, Alexandria Lighthouse in Egypt) by the mean of three research axes and corresponding objectives:

- Identification of stones and determination of their provenance (objective 1 / work package WP1) in terms of geographic areas and, if possible, the former quarry sites; at the present time, the region of origin of numerous stones used in constructions and ornamentations dating from antiquity, both in the west and the orient (and often reused in the Middle Ages) remains poorly defined or even unknown.

- Diagnosis of the conservation state of the stones (objective 2 / WP2) at the sites; whilst the causes and the mechanisms of the deterioration of stone are relatively well known for temperate European climates, the semi-arid continental climate of the selected sites, characterised by strong thermal amplitudes, high evaporation and strong wind action, together bring about specific weathering and alteration requiring more thorough investigations.

- Development of appropriate conservation / restoration techniques (objective 3 / WP3) ; the objective is to provide answers to the main problems regarding stone conservation / restoration that are liable to be met at the selected sites ; it involves developing techniques for reassembling fractured and fissured stones ; this phase is based on European know-how and will take into account the climatic.

Moreover, data management of the obtained results includes circulation of the information between the non-European Mediterranean countries, and dissemination of the obtained results to partners but also to the whole scientific and technical community (objective 4 / WP4).

MEDISTONE coordination is carried out by BRGM (French geological survey) represented by Dr. David DESSANDIER (d.dessandier@brgm.fr). Twelve organizations having experience in the field of ornamental and building stone studies and / or deterioration and conservation of cultural heritage stones are involved in MEDISTONE project, representing both users and suppliers:

- Mediterranean Governmental institutions in charge of Cultural Heritage: Moroccan Culture Ministry (DPC, Morocco), Algerian Culture Ministry (MCA, Algeria), Supreme Council for Antiquities (SCA, Egypt).
- Universities and Research Organisations: Università IUAV di Venezia (IUAV, Italy), Moulay Ismail University of Meknès (MIUM, Morocco), University M'Bougara of Boumerdès (UNIB, Algeria).
- Scientific and Technical Institutes: BRGM (Co-ordinator of the project, French Geological Survey, France), Centre Interregional de Conservation et de Restauration du Patrimoine (CICRP, France), Institute of Geology and Mineral Exploration (IGME, Greece), Laboratoire de Recherche des Monuments Historiques (LRMH, France).
- Small and Medium Enterprises (SME): LITHOS SNC (Italy), PONS-ASINI GmbH (Germany).

The "Atlas of the stones of Alexandria Lighthouse" is a delivrable of work package 1 (WP1) answering to the objective of identifying of the used stones and determining their provenance. Co-ordinated by Dr. David Dessandier (Geologist, specialist of building stones, BRGM), it was carried out by the following main contributors (in alphabetical order):

- Dr. Adel Akarish, Geologist, National Research Centre, Collaborated to Supreme Council of Antiquities).
- Dr. Fabrizio Antonelli, Geologist, specialist of ancient decorative stones, LAMA-IUAV University of Venice.
- Prof. Lorenzo Lazzarini, Geologist, specialist of ancient decorative stones, LAMA-IUAV University of Venice.
- Dr. Lise Leroux, Geologist, specialist of cultural heritage stones, LRMH.
- Mr. Ashraf Nageh, Conservator and Doctorate Student, Supreme Council of Antiquities
- Prof. Ahmed Shoeib, Conservator, Cairo University, Collaborated to the Supreme Council of Antiquities
- Dr. Myrsini Varti-Matarangas, Geologist, specialist of sedimentary rocks, IGME.

The first part of the atlas introduces the Alexandria Lighthouse in terms of historical and topographical context, state of knowledge of building materials and history of underwater archaeological excavations. In a second part, the various archaeological monuments and artefacts considered (nowadays stored or exhibited in Alexandria or still underwater) are described and characterized in terms of their petrographic types of stone and physical-chemical properties. The third and last part deals with the search of potential provenance areas (reference quarries when possible) of the stones relying on bibliographic data and in situ investigations (geological survey and sampling) and then on characterisation of collected samples and their comparison to those from Alexandria Lighthouse objects.

A special acknowledgement to Mr. Jean-Yves Empereur and Mrs Isabelle Hairy (Centre d'Etudes Alexandrines) for their precious guidance.

2. Overall presentation of Alexandria Lighhouse

2.1. HISTORICAL AND TOPOGRAPHICAL CONTEXT

Until 332 BC when Alexander the Macedonian was crowned king of Egypt, Memphis was the old Pharaonic capital of Egypt (Empereur, 2002). Then, after consulting group of Greek experts and architects for choosing a site, he ordered the building of a city between the Mediterranean Sea and Lake Mareotis nearby a small fishing village called Rhakotis. The city was built and expanded becoming the Capital Alexandria. Alexander died in June 323 BC and one of his army leaders Ptolemy ruled Egypt. Ptolemy declared his independence in 305 BC and named himself a king and a pharaoh of Egypt. The Ptolemaic Period began and went on until 30 BC when Egypt came under the Roman Empire (Figure 1).

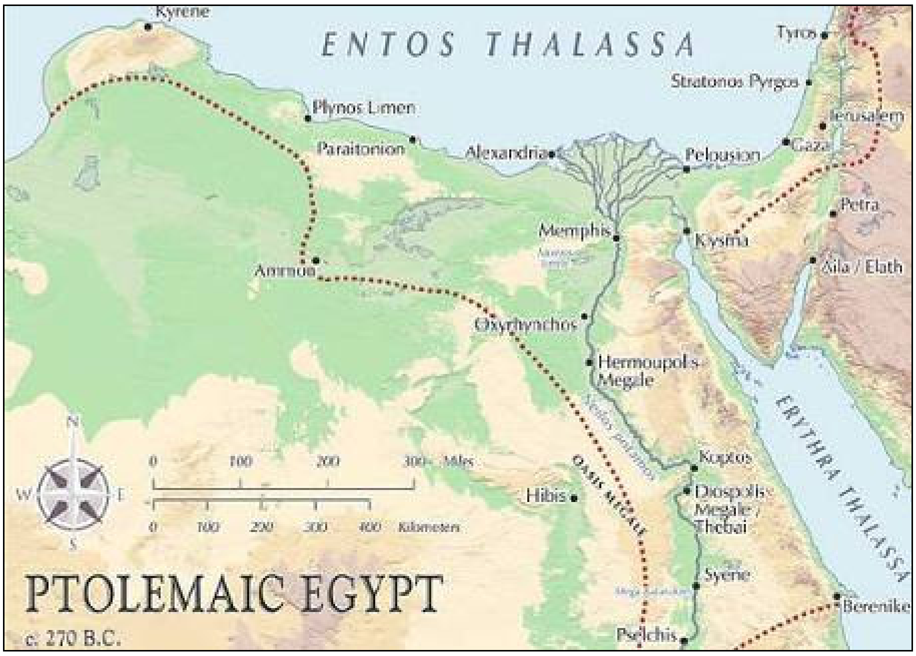

Figure 1 – Map of Ptolemaic Egypt (© Ancient World Mapping Center, 2003, non-profit educational reproduction permitted).

Due to dangerous conditions and flat coastline in the region, the construction of a lighthouse for Alexandria city was necessary and the famous lighthouse rose on Eastern Cape of Pharos Island. It was a small island located just off the coast of Egypt and connected to the main land by means of a dike (Heptastadion, built up of deposits) which gave the Alexandria city a double harbour (Figure 2).

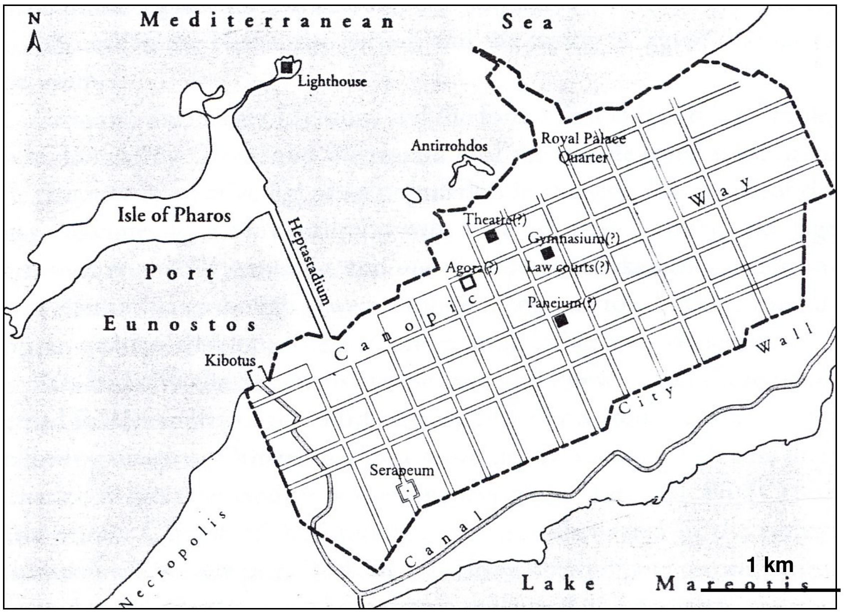

Figure 2 - Map of Pharos Island and the Eastern Harbor. (Forster, 1961).

The project for building a lighthouse was initiated by Ptolemy I and was designed and constructed by Sastrotus of Cnidus (son of Dexiphanes, Greek architect) during the time of Ptolemy II. Soon the building itself acquired the name of the island. The relationship of the name with the function became so strong that the word "Pharos" is nowadays the root of the word “lighthouse” in many languages (French, Italian, Spanish…)

For seventeen centuries from its construction in 290 BC to its final destruction in the mid-14th century AD (when Sultan Qaitbay built a fort at the same site using the lighthouse ruins), it served as a guide to seafarers into the city harbour approaching the coast of Egypt. Prototype of all such buildings and considered one of the wonders of the world, it was also a propaganda tool demonstrating the power and strength of the “new” Greek authority that ruled over Egypt (Empereur, 2002).

According to notes written by an Arabic traveller, a modern archaeologist (Thiersch, 1909) recalculated the dimensions of the lighthouse considered to be formed of three floors: a square first floor of 55.90m high, an octagonal intermediate floor of 18.30m side length and 27.45m high and a circular third one of 7.30m high formed of eight columns. The tower was surmounted by a cupola and a bronze statue (probably of Poseidon). Total height including the foundation basement was about 117m (384ft) that is to say one of the tallest man-made structures in that time. Various other authors proposed different values between 100 and 137m. The building contained about three hundred rooms which were used as living rooms for the lighthouse-keepers and staff or as storeroom. At the top floor, the mirror reflected sunlight during the day while fire was used during the night. The graphic reconstruction elaborated by Thiersch (Figure 3) remained up to nowadays the popular view of the Alexandria lighthouse (modern view in Figure 4).

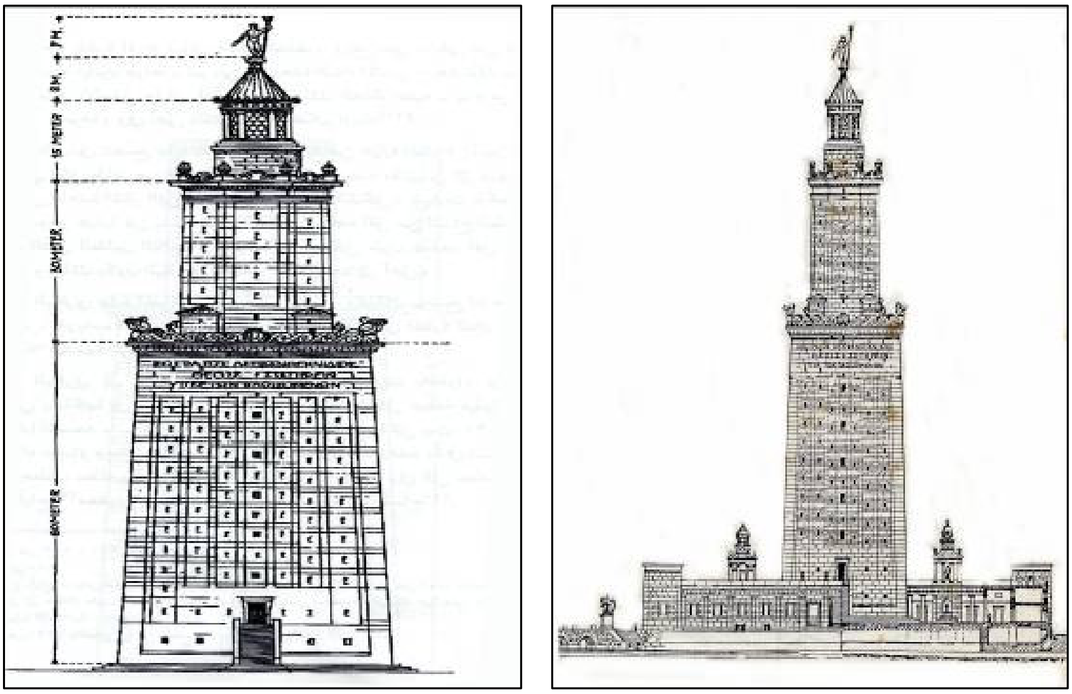

Figure 3 – Graphic reconstruction of Alexandria Lighthouse (Thiersch, 1909).

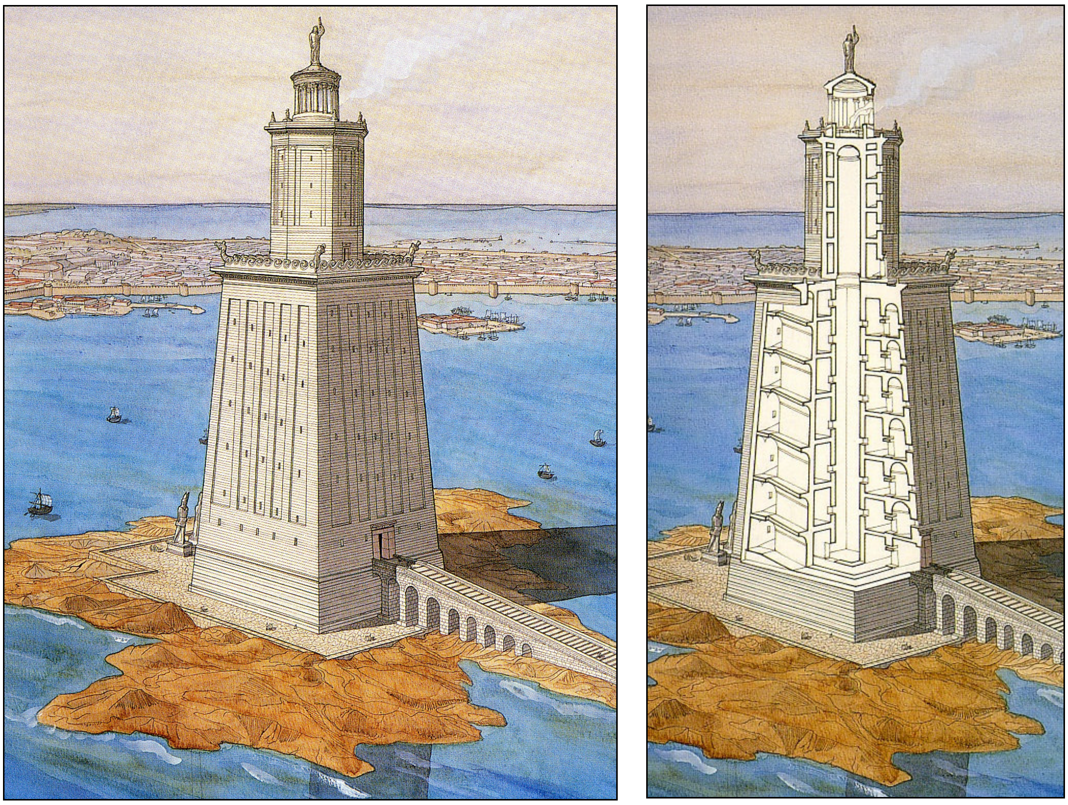

Figure 4 – Graphic reconstruction of Alexandria Lighthouse (Empereur, 2004).

The previous reconstruction was established studying lighthouses images on various objects as Roman coins (Figure 6), terra-cottas or Mosaics (Figure 5).

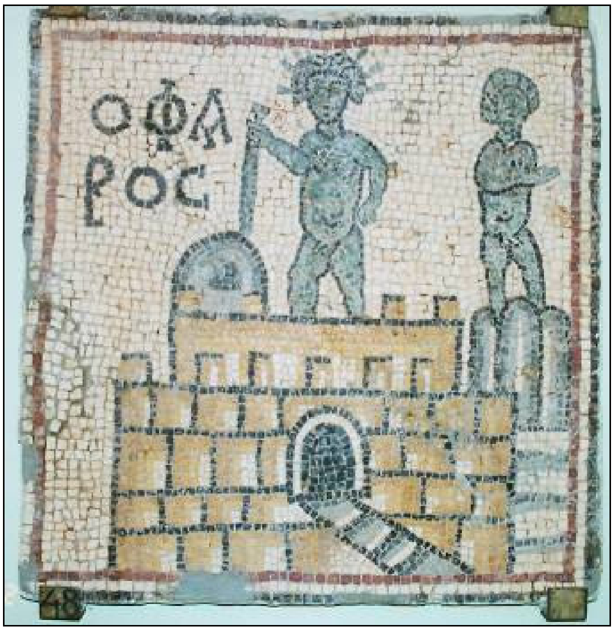

Figure 5 – Example of Roman mosaic representing the lighthouse (Empereur, 2004).

Figure 6 – Example of Roman coins representing the lighthouse (Handler, 1971).

With the exception of the Great Pyramid of Giza, the lighthouse survived the longest of the seven wonders. It stood for about 1500 years, before being damaged by a series of earth tremors between the 4^{th} and the 14^{th} century. The tower remained intact until the 8^{th} century when the whole upper part was thrown down by an earthquake (796 AD; date given by Ibn Al Athir and Ibn Adhari Al Bayano al Magrib in Creswell, 1926). In the Islamic period, the structure was reconstructed (domed mosque on the summit) by Tulunids during the period 868-905 AD. In 950 and 956, part of the surface cracked and the tower was reduced in height by 22m. In 1261, the lighthouse was again hit by an earthquake and another section collapsed. Later on in 1272 AD, Salah el Din ordered restoration works (Ferrand, 1935-1944). Therefore, the lighthouse survived until severe damages by two earthquakes in the 14th century (1303, 1326) and collapsed to the point that the Arab traveller Ibn Battuta (Dominique, 1995) reported the lighthouse was in ruins. It remained thus for just over a century until Sultan Qaitbay decided to build on its ruins the fortress which still stands nowadays (Figure 7).

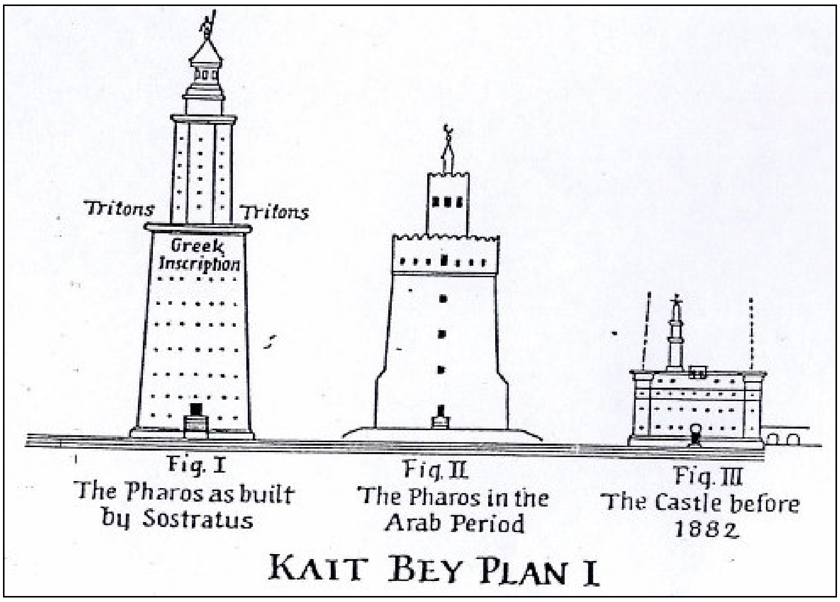

Figure 7 – Different stages of destruction of Alexandria Lighthouse (Thiersch, 1909).

2.2. BUILDING MATERIALS OF THE LIGHTHOUSE

The ancient authors supplied only a few informations about the Pharos and in particular its building materials. The Greek geographer Strabo (visiting Alexandria about 25 BC) mentioned the pharos was build of white stone (in Empereur, 2002). None of the many past Arabic travellers who saw the tower gave any idea about the kind of stones used for building and decoration. Thiersch (1909) indicated the presence of marble, limestone and bronze for the decorated statues.

Between this publication in 1909 and the beginning of the modern underwater excavations in 1994, many authors proposed various theories. According to Breccia (1922), the building material of the lighthouse was mainly a nummulitic limestone, its sculptural decoration and other ornamentation were partly made of marble and bronze, and its columns mainly of granite (deduced from the sunken objects forming a breakwater surrounded the fortress). Langer (1941) gave his deduction about the lighthouse constructed with alabaster and white marble. Forster (1961) also gave a deduction about the building materials of the lighthouse: local limestone, marble and reddish-purple granite from Aswan.

According to new research results following modern underwater excavations begun in 1994, Empereur (1998) painted another view telling: “Even if our researchers do not permit us to paint a picture very different from that proposed by Thiersch, the archaeological data have given the lighthouse a new appearance…We can no longer regard it as a purely in a Greek style, its builders will have borrowed from the Pharaonic tradition…”. About the building materials, he specified that Aswan granite was used by skilful workers for parts of the lighthouse that needed reinforcing, without imagining such parts in marble let alone limestone. At the same time, the relative lack of limestone and marble blocks in comparison with the large number of granite blocks (identified during submarine excavations) could be explained according to Empereur by three reasons: 1. these softer stones are difficult to identify underwater after having been eroded over the centuries by marine flora and fauna; 2. The need for chalk to manufacture cement for Alexandria city; 3. these stones are much easier worked and therefore were taken to be re-employed in later constructions such as the fortress itself and the adjacent Ottoman tower.

2.3. UNDERWATER ARCHAEOLOGICAL EXCAVATIONS

The existence of a submarine archaeological site was ever suspected and its importance was noted by travellers of previous centuries. Richard Pococke visiting Alexandria in 1737 rented a boat and observed ancient blocks: “And the pillars seen in a calm sea within the entrance [to the port], may be the remains of that superb building [the Pharos]: these pillars I saw when I went out in a boat on a calm day, and could see to the bottom.” Scholars with Bonaparte’s expedition also mentioned this site. Breccia (1922) mentioned that in 1910 during the enlargement of the western harbour, Gaston Jondet an engineer who has studied in detail the shores of the Pharos Island reported the presence of numerous underwater foundations and constructions. In 1933, 30km far from Qaitbay Fortress east of Alexandria, a British aircraft pilot noticed ancient vestiges shaped as a horseshoe deep in the water, encouraging Prince Omar Tousson to engage a deep sea diver. On 5th of May 1933, a marble Alexander’s head was lifted from underwater about 450m far from the coast of Ramleh Fortress. Prince Omar Tousson went on with his discovers which revealed a temple with dozen columns 240m far from the coast. He also discovered within Aboukir Bay near Alexander’s head, masonry jetties, marble and granite columns and pedestals. The Alexandrian archaeologist Kamel Abu El Saadat (1934-1984) called attention to the importance of this site (Pharos) and persuaded in 1961 the Egyptian Navy to retrieve from the water the colossal statue of Isis of Aswan granite which can be admired today on the lawn of the Marine Museum (Halim, 2003)

If the ruins were known since a long time, the circumstances of Egypt’s modern history were such that they had never been scientifically explored with the means required by the extent of the site, until 1993 when a submerged breakwater was constructed just outside the eastern harbour in order to protect the Qaitbay Fortress from winter storms. Unfortunately (and fortunately) the blocks of concrete were dropped on part of an ancient site that lied in some six to eight meters of water at the foot of the Fortress. In order to estimate the damage done by the rather hasty construction of the modern breakwater, the Egyptian authorities asked to the French archaeologist Jean-Yves Empereur (Centre d'Etude Alexandrine) to lead a salvage excavation in the underwater site close to Qaitbay Fortress (Empereur, 1996). This mission began in October 1994 by diving investigations and has continued until now mapping about three thousands blocks including hundred huge ones (Figure 8).

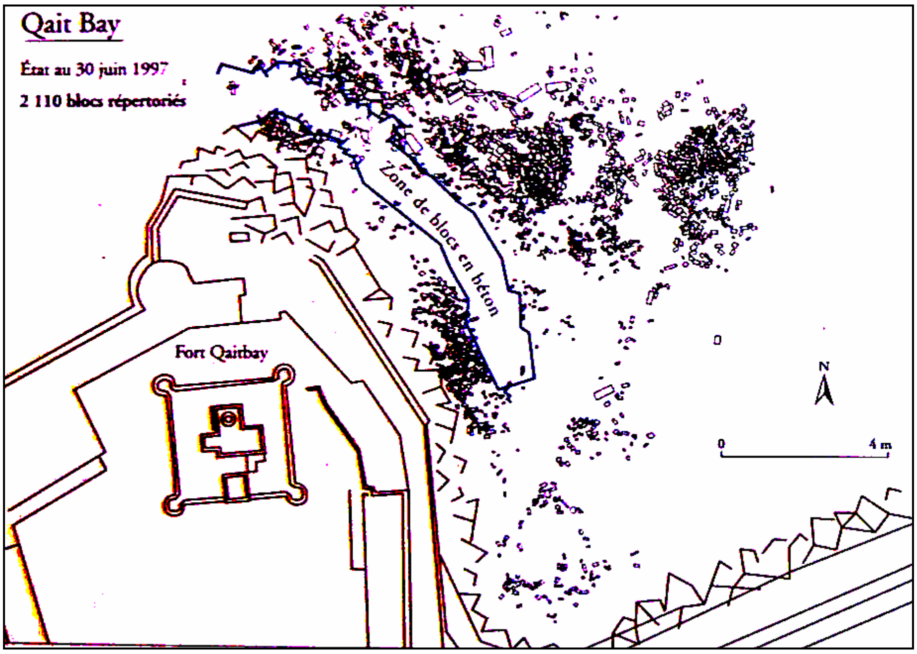

Figure 8 – Map of the underwater site of Qaitbay figuring the concrete blocks area (in blue color) and more than 2000 (inventory state of june 1997) archaeological pieces; (Empereur, 1998).

The number of columns and columns fragments runs into hundreds. The bigger columns are carved from Aswan granite. There are also several columns bases with moulded profile. Fragment of three obelisks were found in the same area. The sphinxes proved to be even more numerous than the obelisks; they are all different and made of various stones (Empereur, 1998). According to the archaeologists of Centre d'Etude Alexandrine, many of the material found seems to be from earlier periods than the Lighthouse. They may have been re-used in the construction of the Pharos from even older buildings. If few stone blocks were picked up from underwater (Centre d'Etude Alexandrine, Catalogue des objets renfloués, 2005; examples in Figure 9) and desalinated before being exhibited or stored nowadays in various locations in Alexandria, the majority remains nowadays underwater.

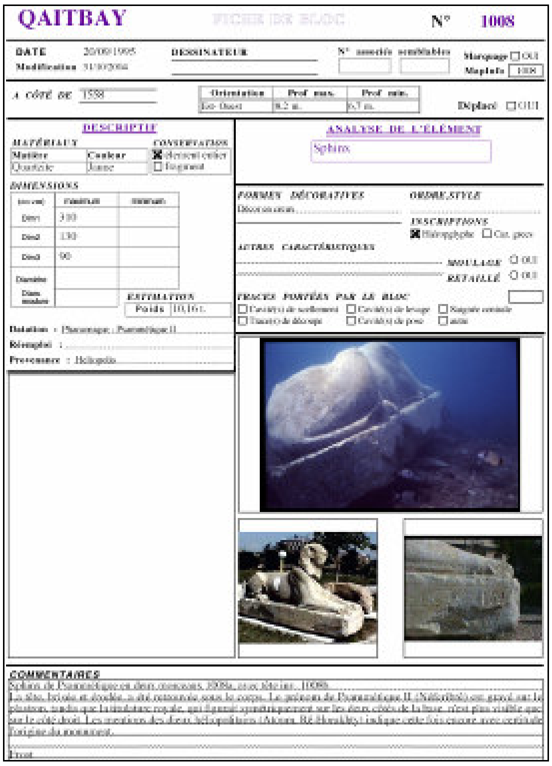

Figure 9 – Examples of files of two raised objets (Centre d'étude Alexandrine, Catalogue des objets renfloué, 2005).

3. Monuments and artefacts considered

First of all, one should remember that Alexandria Lighthouse was toppled into the sea. The archaeological site is nowadays essentially underwater just off the coast of Alexandria, its ruins consisting of about three-thousand architectonic blocks and sculpture lying on the seabed at depths between six to eight meters.

3.1. PRESENT OUTER EXHIBITION OR STORAGE SITES

The undersea excavations (leaded by Centre d'Etude Alexandrine) undertaken in QaitBay since 1994 (and still in progress) permitted to extract from under the sea about fifty blocks of different sizes (Empereur, 1996; Centre d'Etude Alexandrine, 2005). The majority of them were cleaned and desalinated before to be exposed in different open-air areas in Alexandria.

In the framework of MEDISTONE, a first campaign permitted to inventory and to make an overall examination of the following different sites of exhibition and / or storage of the lifted out blocks or contain stones related to the lighthouse (Figure 10; numbered spots): QaitBay Fortress (spot 3), open-air Museum close to the Roman Theatre excavation (Kom El Dikka) (spot 6), Shallalat Garden close to the restoration workshop of Centre d'Etude Alexandrine (spot 5), eastern harbour platform at QaitBay (spot 2), Marine Museum garden (spot 7), front of Alexandria Library (spot 4). The stones examined are present in a form of various architectonic elements (columns, part of columns, large blocks, small blocks, statues, obelisks…).

Figure 10 – Location of the considered outer exhibition and storage sites in Alexandria.

During a second campaign, an *in situ* detailed study of the whole of the blocks exposed in the previous mentioned sites was completed with the aim to inventory the main types of the building and the ornamental stones related to the lighthouse. In addition, representative samples of each kind of stones were collected and submitted to in-laboratory characterisation and identification tests.

3.1.1. Qaitbay Fortress

A view of Qaitbay Fortress is given in Figure 11. Many blocks of different types of stones used as building materials in Qaitbay Fortress are re-used materials. According to the hypothesis that Qaitbay Fortress is located instead of the Alexandria Lighthouse using its ruins, some of these re-used blocks could logically belong to the original lighthouse.

Figure 11 – View of Qaitbay Fortress

They mainly correspond to frame elements of the gate (Figure 12) and lintels for windows and door made of coarse-grained pinkish granite, and basement blocks (Figure 13) made of yellowish to brownish sandy limestones (according to megascopic observations ; in fact, fine sandstone with dolomitic cement to sandy dolostone; cf. 3.3.5) observable in the basement of the fortress. Moreover, outcrops of the bedrock corresponding to a soft beige limestone showing oblique layers (Figure 14) are observable in the basement of the monument.

Figure 12 – Gate of Qaitbay Fortress made made of coarse-grained pinkish granite.

Figure 13 - foundation blocks made of (megascopically) yellowish to brownish sandy limestones.

Figure 14 – Soft beige limestone bed-rock at the base of Qaitbay Fortress.

Five samples (referenced A1 to A5; see Table 1; detailed informations of each sampled archaeological object in Appendix 1) were collected from the re-used stones at Qaitbay Fortress.

Sample Reference	Present location of the corresponding monument or artefact	Monument or artefact description and name	Centre d'Etudes Alexandrines reference	Megascopic lithological description
A1	Qaitbay Fortress	Re-used base of statue, element of the frame of the entrance gate	-	Coarse pinkish granite
A2		Re-used block at the base of the wall on the right hand to the main entrance.	-	Coarse pinkish granite
A3		Wall in the cave 5th right course in the corner, base of the fortress	-	Yellowish sandy limestone
A4		Wall in the cave 3rd course in the left corner, base of the fortress	-	Brownish sandy limestone
A5 *		Base under the masonry, bedrock, base of the fortress	-	Soft beige limestone

Table 1 – Main informations of the five samples collected on Qaitbay Fortress (*Sample not exactly archaeological taken to be compared with some referred quarries samples).

3.1.2. Open-air Museum close to the Roman Theatre excavation

Twenty-six monumental objects related to the stones of the lighthouse are nowadays exposed at the open-air Museum close to the Roman Theatre excavation (Kom el Dikka quarter, Alexandria). An overview of the open-air Museum is given in Figure 15.

Figure 15 - Overview of the open-air Museum (Kom El Dikka quarter).

They mainly correspond to elements of monumental statues, columns and obelisks lifted from undersea and desalinated by Centre d'Etude Alexandrine before exhibiting. By visual checking, they can be divided into the following different kinds of stones:

Coarse pinkish granites (example in Figure 16): they are coarse-grained constituted of large potash feldspar crystals, quartz, plagioclase and dark minerals (biotite…), forming a porphyritic texture. Some objects show significant contour scaling (typical weathering form of granites).

Figure 16 – "Red Sphinx" (Ref. CEA = 1192) made of coarse pinkish granite.

Dark-grey granodiorites (example in Figure 17): the corresponding objects show medium to coarse-size grained texture formed of large light plagioclase phenocrystals, dark minerals and quartz.

Figure 17 - "Black Sphinx" (Ref. CEA = 1011) made of dark-grey granodiorite.

Yellowish siliceous sandstones (example in Figure 18): sandstone objects range in color from beige to brownish with various shades. They present fine to coarse-size grains and sometimes contain pebble-rich layers.

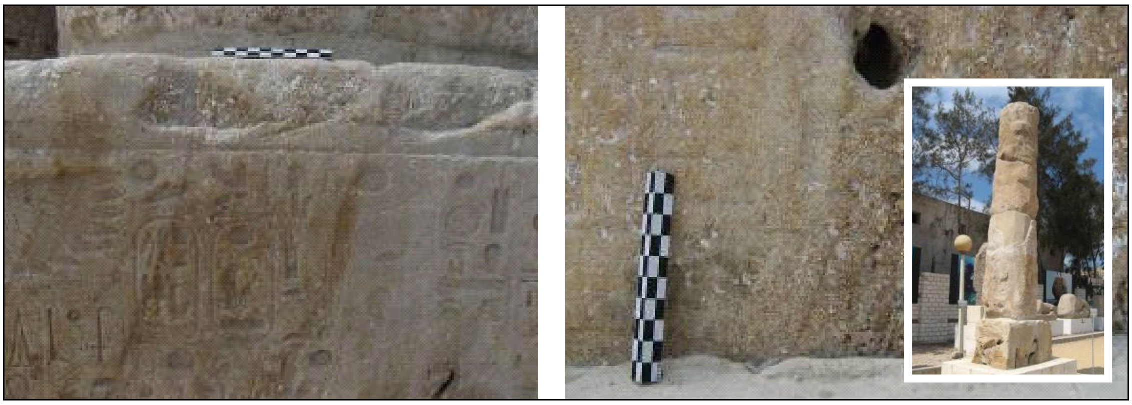

Figure 18 - “Base of Seti I Obelisk” (Ref. CEA = 2260) made of siliceous sandstone.

Dark-grey greywacke (one object exposed; Figure 19): greywacke is dense, hard, and fine to medium grained with dark grey color. It exhibits pronounced foliation where a dark lamina (dark minerals) alternate with light grey lamina (lighter minerals).

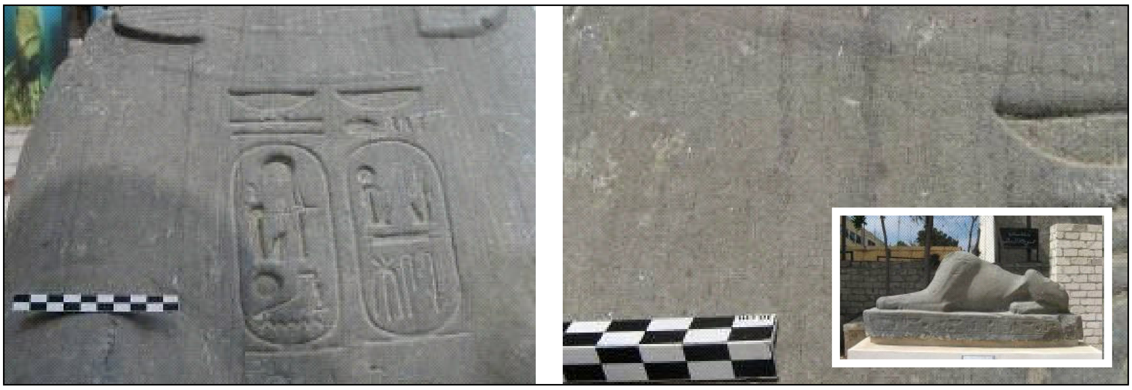

Figure 19 – “Sphinx of Ramsès II” (Ref. CEA = 2002) made of greywacke.

White marble (one object exposed; Figure 20): the marble stone object has white to pale greyish color. It is hard, massive and exhibited fine to medium-size grains. It bears low relief of Greek inscriptions.

Figure 20 – “Fragment of a Greek inscription” (Ref. CEA = 3001) made of white marble.

Nineteen samples (referenced A6 to A24; see Table 2; detailed informations of each sampled archaeological object in Appendix 1) were collected from the exhibited objects of the open-air Museum close to the Roman Theatre excavation.

Sample Reference	Present location of the corresponding monument or artefact	Monument or artefact description and name	Centre d'Etudes Alexandrines reference	Megascopic lithological description
A6	Open-air Museum close to the Roman Theatre excavation	Corinthian Capital	2246	Dark-grey granodiorite
A7		Black Sphinx	1011	Dark-grey granodiorite
A8		Sphinx of Sesostris III	2003	Ochre-beige siliceous sandstone
A9		Sphinx of Ramses II	2002	Dark-grey greywacke
A10		Base of Obelisk Seti I	2260	Beige-yellowish siliceous sandstone
A11		Obelisk of Seti I	2001	Beige-yellowish siliceous sandstone
A12		Sphinx of Psammeticus	1008	Beige siliceous sandstone
A13		Red Sphinx	1192	Coarse light-pink granite
A14		Plastron of a sphinx	1325	Dark-grey granodiorite
A15		Sphinx with scarab	2606	Dark-grey granodiorite
A16		Fragment of a Greek inscription	3001	White marble
A17		Crown of Hathor	1017	Coarse pinkish granite
A18		Papyriform Column 1	2006	Coarse pinkish granite
A19		Papyriform Column 2	2005	Coarse pinkish granite
A20		Bust of a colossal female statue	1004	Coarse pinkish granite
A21		Lower trunk of a colossal male statue	1583	Coarse pinkish granite
A22		Head of a colossal male statue 1	1321	Coarse pinkish granite
A23		Head of a colossal male statue 2	1314	Coarse pinkish granite
A24		Sphinx of Ramses II	3002	Dark-grey granodiorite

Table 2 – Main informations of the nineteen samples collected on objects exhibited in the open-air Museum close to the Roman Theatre excavation.

3.1.3. Shallalat Garden

About twenty blocks are nowadays exposed in the so-called open-air storage site of Shallalat Garden close to the restoration workshop of Centre d'Etude Alexandrine (Tabiat El Nahassin quarter; Alexandria). An overview of the open-air storage is given in Figure 21.

Figure 21 - Overview of Shallalat Garden storage site (Tabiat El Nahassin quarter).

They correspond to parts of monumental statues and architectonic elements (mainly formed of coarse pinkish granite; example in Figure 22) lifted from undersea since 1994 and desalinated by Centre d'Etude Alexandrine before storing.

Figure 22 - "Mortar" (ref. CEAlex = 1792) made of pinkisk coarse granite.

Five samples (referenced A25 to A29; see Table 3; detailed informations of each sampled archaeological object in Appendix 1) were collected from Shallalat Garden storage site.

Sample Reference	Present location of the corresponding monument or artefact	Monument or artefact description and name	Centre d'Etudes Alexandrines reference	Megascopic lithological description
A25	Shallalat Garden storage site	Hand of the Ptolemy statue	1230	Pinkish granite
A26		Part of a monumental statue	6071	Dark-grey granodiorite
A27		Mortar	1792	Pinkish granite
A28		Calf of a monumental statue	6084	Pinkish granite
A29		Head of a sphinx	-	Pinkish granite

Table 3 – Main informations of the five samples collected on objects stored at Shallalat Garden.

3.1.4. Eastern Harbour platform

The two broken halves of a thirteen-meters long monumental block (supposed by Centre d'Etude Alexandrine archaeologists to be the right jamb of a gigantic door) formed of pinkish coarse granite are laying down on the western platform of the Eastern Harbour at Qaitbay, close to the sea-side since they were uplifted from underwater (Figure 23).

These two elements suffered from active degradation mostly sea water effect, human decaying, missing part and present of micro fissures. One sample (referenced A30; see Table 4; detailed informations of each sampled archaeological object in Appendix 1) was taken from that monumental object.

Sample Reference	Present location of the corresponding monument or artefact	Monument or artefact description and name	Centre d'Etudes Alexandrines reference	Megascopic lithological description
A30	Eastern Harbour Platform	Right Jamb of a gigantic door	1009	Coarse pinkish granite
A31	Marine Museum Garden	Colossal female statue	1077	Coarse pinkish granite
A32		Base of colossal statue	1062	Coarse pinkish granite

Table 4 – Main informations of the samples collected on objects exhibited on the Eastern Harbour Platform and in the Marine Museum garden.

Figure 23 - Right Jamb of a gigantic door (ref. CEAlex = 1009+1010) made of coarse pinkish granite.

3.1.5. Marine Museum Garden

Three monumental elements (two parts of an Isis supposed colossal statue: Figure 25 and a base of another colossal statue: Figure 24) are exposed in the garden of the Marine Museum (Youssef Kamel Palace). They were lifted from undersea in 1962 by the Egyptian Navy. Those three pieces are formed of coarse-grained pink granite. The base of the statue is highly decayed (granular disintegration). Two samples (referenced A31 and A32; see Table 4 above; detailed informations of each sampled archaeological object in Appendix 1) were taken from the monumental objects exhibited in the Marine Museum Garden.

Figure 24- Basement of a colossal statue (ref. CEAlex = 1062) made of coarse pinkish granite.

Figure 25 – Isis supposed statue (ref. CEAlex = 1077 + 1861) made of Coarse pinkish granite.

3.1.6. Front of Alexandria Library

A statue of king Ptolemy formed of coarse-grained pinkish granite is located at the front of Alexandria Library (Figure 26). Several parts of the statue were lifted from undersea by the Egyptian Navy (1962) and then by the Centre d'Etude Alexandrine. This colossal statue may be one of those that have stood at the base of the Pharos as indicated from different studies.

One sample was collected (referenced A25 = Hand of Ptolemy statue nowadays stored at Shallalat garden, see Table 3; detailed informations of this sampled archaeological object in Appendix 1).

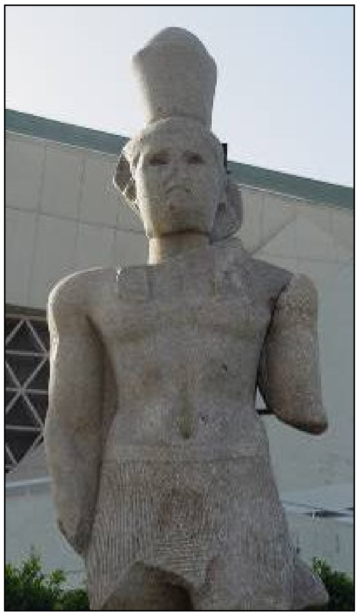

Figure 26 – Statue of King Ptolemy in front of Alexandria Library.

3.2. UNDERWATER SITE OF QAITBAY

As most of the stone related to the lighthouse are still occurring underwater and thus not easily available for study, cooperation between MEDISTONE team and archaeologists of Centre d'Etude Alexandrine took place. It resulted by providing for the present study additional samples collected by diving (during autumn 2006) from the many stone blocks existing in the underwater site (examples in Figure 27 and 28).

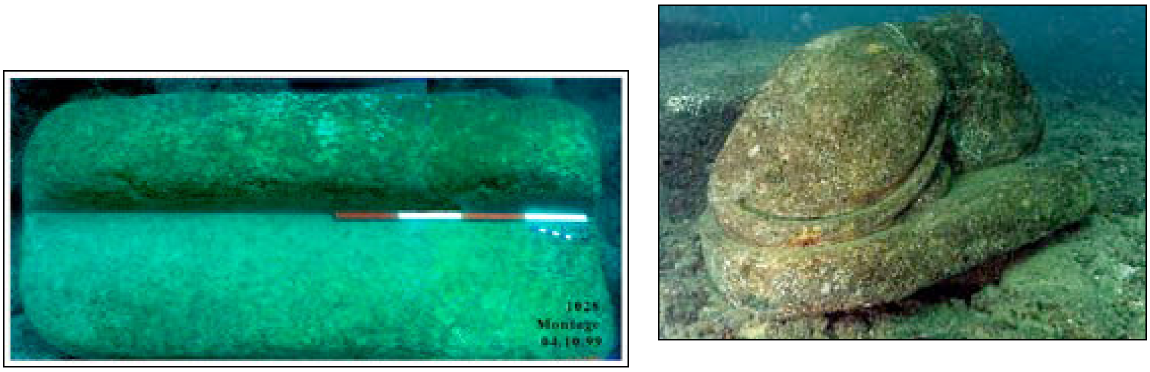

Figure 27 – Views of some underwater archaeological objects sampled by diving during autumn 2006: (left) Jamb (ref. CEAlex = 1028) made of coarse grained granite (collected sample A48); (right) Sphinx (ref. CEAlex = 2499) made of coarse grained granite (collected sample A63).

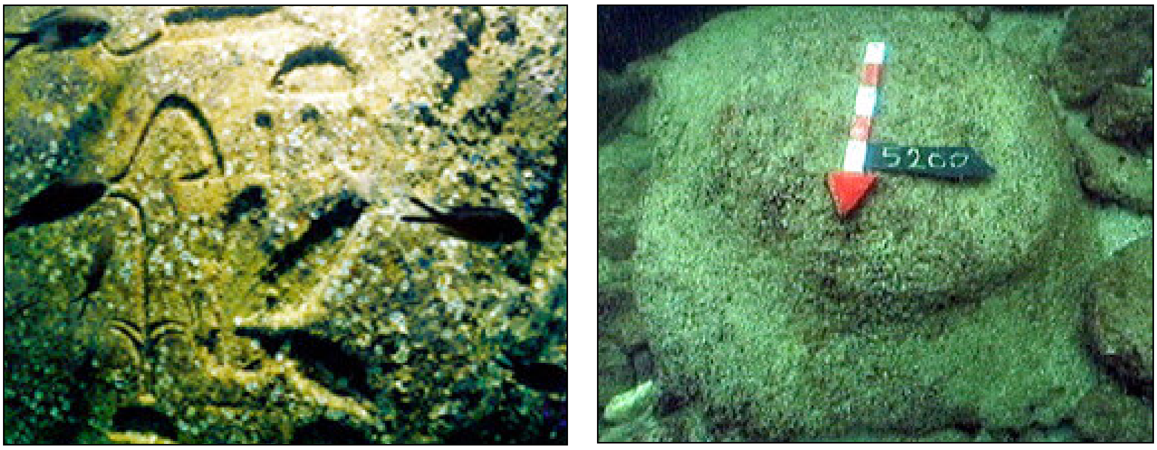

Figure 28 – Views of some underwater archaeological objects sampled by diving during autumn 2006: (left) Obelisk (ref. CEAlex = 2500) made of siliceous sandstone (collected sample A64); (right) Capital (ref. CEAlex = 5200) made of marble (sample A71).

Precisely, a second series of thirty-five underwater stone monumental objects (parts of statues and various architectonic elements like lintels, jamb, door slab, cornish, base of obelisk…) were sampled (referenced A39 to A73; see Table 5; detailed informations of each sampled archaeological object in Appendix 1) and delivered by the Centre d'Etude Alexandrine.

Sample Reference	Present location of the corresponding monument or artefact	Monument or artefact description and name	Centre d'Etudes Alexandrines reference	Megascopic lithological description
A39		Lintel	1003	Coarse pinki granite
A40		Naos	1004	Dark-grey granodiorite
A41		Base of statue	1019	Coarse pink granite
A42		Base of statue	1020	Coarse pink granite
A43		Base of statue	1021	Coarse pink granite
A44		Base of statue	1024	Coarse pink granite
A45		Threshold	1025	Coarse pink granite
A46		Door slab	1026	Coarse pink granite
A47		Door slab	1027	Coarse pink granite
A48		Jamb	1028	Coarse pink granite
A49		Door slab	1029	Coarse pink granite
A50		Naos	1038	Dark-grey granodiorite
A51		Jamb	1048	Coarse pink granite
A52		Jamb	1060	Coarse pink granite
A53		Oblique prism	1065	Coarse pink granite
A54		Base of statue	1164	Ochre-yellowish siliceous sandstone
A55		Lintels	1172	Coarse pink granite
A56		Prism	1218	Coarse pink granite
A57		Cornish block	1221	Coarse pink granite
A58	Underwater site of Qaitbay	Cornish block	1276	Coarse pink granite
A59		Prism	1292	Beige-yellowish siliceous sandstone
A60		Lintels	1295	Coarse pink granite
A61		Base of statue	1404	Coarse pink granite
A62		Base of obelisk	2431	Beige-yellowish siliceous sandstone
A63		Sphinx	2499	Coarse pink granite
A64		Obelisk	2500	Beige-orange siliceous sandstone
A65		Pyramidion	2807	Coarse pink-reddish granite
A66		Architrave block	3043	Ochre-yellowish siliceous sandstone
A67		Lintel	5007	Coarse pink granite
A68		Prism	5086	Dark-grey limestone
A69		Prism	5103	Dark-grey greywacke
A70		Naos	5120	Dark-grey granodiorite
A71		Capital	5200	White marble
A72		Regular polyhedron	6014	Coarse pink-reddish granite
A73		Pillar	6500	Coarse pink-reddish granite

Table 5 – Main informations of the thirty-five samples collected from the underwater site of Qaitbay.

3.3. CHARACTERIZATION AND IDENTIFICATION OF THE STONES

The physical-chemical characterization and petrographic identification of the sixty-six samples collected from monuments and artefacts from Alexandria Lighthouse were performed on the basis of various in-laboratory measurements and tests.

First, thin sections (restricted to the samples of the sufficient size) were prepared and examined by optical microscopy for determining their petrographic characteristics and classify the stones according to the standard classifications and nomenclatures. The qualitative mineralogical composition of many of them was determined by X-ray diffraction (XRD).

Moreover, geochemical measurements were carried out on numerous samples after adequate preparations (drying, grinding). Major elements contents were determined by X-Ray Fluorescence (XRF) for samples of the sufficient size or by Inductively Coupled Plasma / Atomic Emission Spectrometry and Mass Spectrometry (ICP-AES) for some others. Trace elements contents were measured by ICP-AES.

For carbonated samples, carbonate content was measured using acid attack (according to Norm NF X 31-105) and isotopic analyses were realized following the procedure of McCrea (1950) by Mass spectrometry (isotopic composition values expressed in terms of $\delta^{13}C$ and $\delta^{18}O$, in ‰, relative to the international reference standard PDB, Craig, 1957).

Finally, total porosity and bulk density measurements were carried out (according to norm NF EN 1936) for few samples to improve their physical properties knowledge.

3.3.1. Granitoïds

Among the sixty-six stone samples collected from the monuments and artefacts of Alexandria Lighthouse, fifty are granitoïds. According to megascopic observations, forty-two are more precisely pinkish granites and eight are dark-grey granodiorites.

First of all, granitoïd samples were studied **petrographically**. Thirty-two thin sections were examined by polarizing optic microscope equipped with a mechanical point counting stage. It was not possible to produce and examine thin sections of the whole samples because of the limited size of some of them.

Pinkish granites:

Megascopically (Figure 29), the studied granite samples are coarse (grain size comprised between 5 mm to 3 cm) to very coarse (grain size > 3 centimeters) exhibiting a more or less bright pinkish color. The observable grains are coarse alkali feldspars (pinkish to reddish ones), plagioclases (milk-white ones), quartz (translucent) and few black spangles of biotite.

Figure 29 – Representative megascopic views of coarse pinkish granite samples: light pink one (left) and more reddish one (right).

According to microscopic examinations (Figure 30), they exhibit a porphyritic texture. Phenocrystals are mainly large alkali feldspars (microcline and orthoclase) up to four centimeters long. The groundmass minerals are composed of smaller feldspars crystals, quartz and ferromagnesian minerals (biotite and hornblende) filling the interspaces between phenocrystals. Minor amounts of sphene, apatite, allanite, zircon and opaque minerals are present as accessory minerals.

Feldspars (alkali feldspars and plagioclase) are the most important group of minerals represented by microcline, microcline perthite, orthoclase and orthoclase perthite. Microcline occurs as fresh subhedral to euhedral crystals up to four centimeters long exhibiting cross-hatching. Orthoclase occurs as subhedral crystals up to three centimeters long exhibiting simple twining and partly altered to sericite and clay minerals.

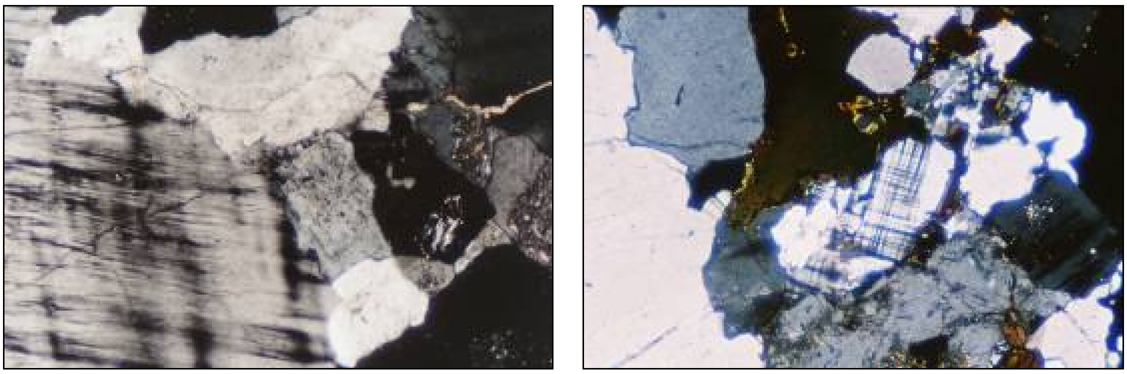

Figure 30 – Microscopic observations (N+; magnification x70) of pinkish granite samples: porphyritic texture; large microcline phenocrystal on the left (left); microcline groundmass (right).

Microcline and orthoclase perthites are observed in most of thin-sections examinated, in the form of irregular veins of exsolved albite intergrown with microcline or orthoclase (Figure 31).

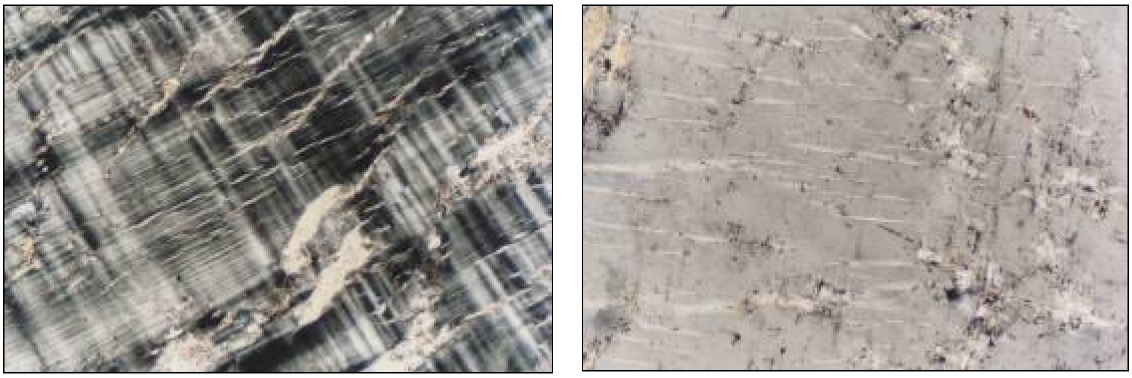

Figure 31 - Microscopic observations (N+; magnification x70) of pinkish granite samples: veins of exsolved albite in microcline (left) and orthoclase (right) perthites.

Quartz occurs as subhedral to anhedral crystals up to three millimeters. Three generations of quartz growths are observed: the first one has a wavy extinction; the second is interstitially filling spaces between the other essential minerals; the third generation is present in the form of vermicular quartz in myrmekitic texture (Figure 32 left).

Plagioclase (mainly oligoclase) occurs as subhedral to euhedral crystals up to four millimeters long. It is slightly zoned and shows lamellar twinning. Oligoclase is slightly altered especially along cleaving layouts to sericite and occasionally to calcite and epidote (Figure 32 right).

Concerning the ferromagnesian minerals, biotite occurs as subhedral crystals or as clusters of flakes and shows brown color. It is partly altered to chlorite and iron oxides. Hornblende occurs as subhedral crystals up to two millimeters long and exhibits distinct pleochroism from pale yellow to yellowish green to olive green.

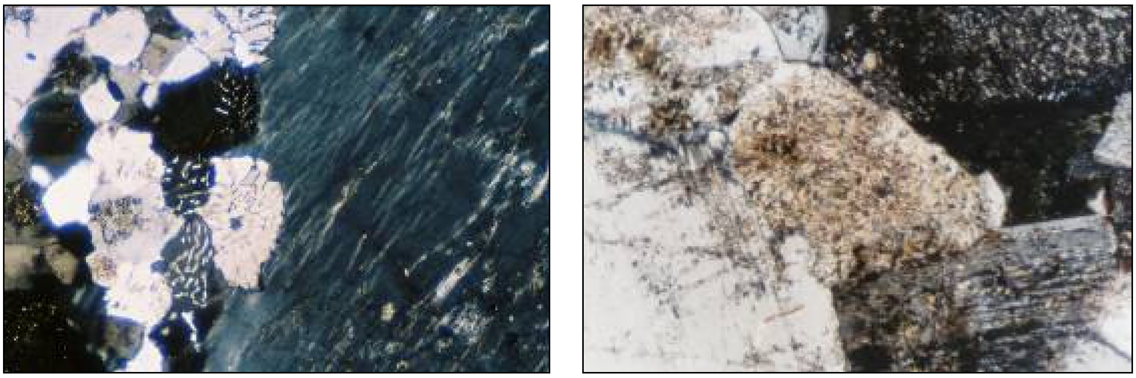

Figure 32 - Microscopic observations (N+; magnification x70) of pinkish granite samples: myrmekitic texture (left) and plagioclase altered to sericite and occasionally to calcite and epidote (right).

Dark-grey granodiorites:

Megascopically, the studied granodiorite samples (Figure 33) are hard, massive, medium (1 to 5mm) to coarse-size grained (5mm to 3cm) exhibiting a dark-grey color.

They include a variable proportion of milk-white sometime slightly pinkish plagioclase phenocrystals (size up to two centimetres). In some varieties, the plagioclase phenocrystals are completely absent.

Figure 33 – Representative megascopic view of a dark-grey granodiorite sample: porphyritic texture with pluricentimetric white-milk plagioclase phenocrystals.

According to microscopic examinations (Figure 34), they frequently exhibit a porphyritic texture with the up to two centimetres plagioclase phenocrystals in a variable proportion and sometime hypidiomorphic texture without phenocrystals.

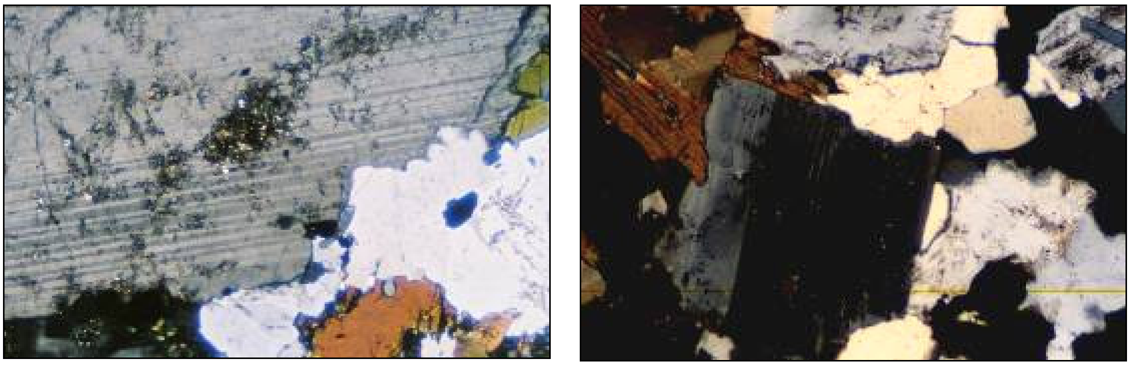

Figure 34 - Microscopic observation (N+; x70) of granodiorite samples: porphyritic texture with a plagioclase phenocrystal partly altered to clay minerals (left) and hypidiomorphic texture (right).

In terms of essential minerals, they are composed of plagioclase (as phenocrystals as well as groundmass minerals; locally altered to clay minerals; Figure 35), quartz, ferromagnesian minerals (hornblende and biotite) with subordinate amount of microcline and / or orthoclase (in the most acid variety samples). Epidote, sphene, apatite, chlorite and opaque minerals are present also as accessory minerals.

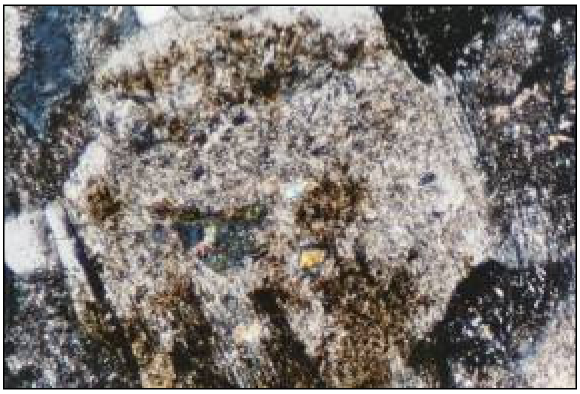

Figure 35 - Microscopic observation (N+; x70) of a granodiorite sample: plagioclase altered to sericite in the center and along the cleaving layout.

Quartz occurs as subhedral to anhedral crystals up to two millimeters long exhibiting wavy extinction. Hornblende occurs as subhedral crystals up to two millimeters long exhibiting distinct pleochroism from pale-yellow to yellowish-green to dark-green color. Biotite occurs as brown color subhedral crystals up to one millimeter long. Some biotite crystals are partly altered to chlorite and iron oxides.

From a **geochemical point of view** (whole data in Appendix 2) using the QAPF mineralo-petrographic classification (Le Maitre et al., 1989) in order to give a preliminary classification of the granitoïd samples, one referred to the total alkalis versus silica (TAS) diagram for plutonic rocks as proposed by Wilson (1989). Following this scheme (Figure 36), the whole granitoïd samples from Alexandria Lighthouse objects are oversaturated rocks grouped together in the granite / alkali-granite and diorite (± granodiorite) fields.

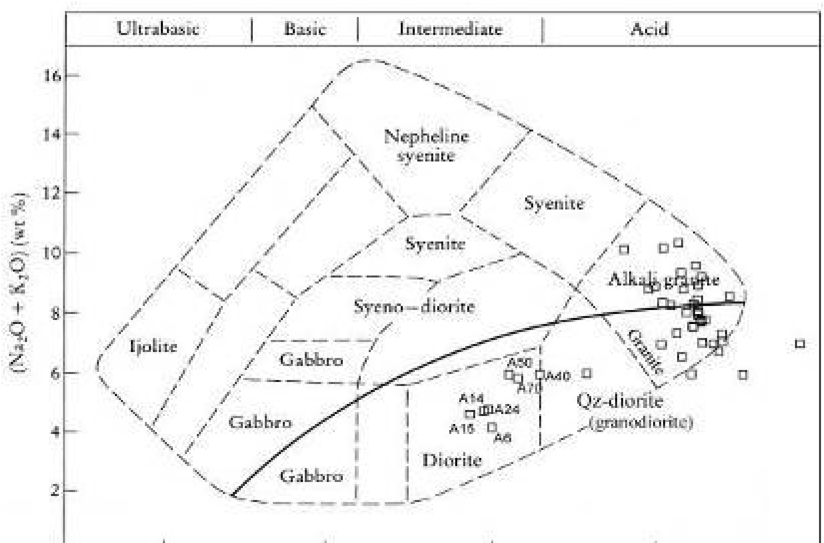

Figure 36 - Classification of Alexandria Lighthouse granitoïd samples according to TAS diagram for plutonic rocks (Wilson, 1989).

These results are conformable with megascopic observations: the eight samples visually classified as “dark-grey granodiorite” are well located in the realm of “diorite” (A6, A14, A15, A40, A50 and A70) or Quartz-diorite (A26) and those described as “coarse pinkish granites” are granite or alkali granite.

The previous diagram of very practical use is the one chemical classification of intrusive rocks. Unfortunately, the nomenclature of the different rocks is not perfectly consistent with these showed by the QAPF diagram. For this reason, one referred also to the classification scheme based upon the cation proportions (expressed as millications) proposed by De la Roche et al. (1980). The main advantages of this classification scheme are that the whole major elements chemistry of the rock is used and that this rocks nomenclature is well consistent with that used in the QAPF diagram. This scheme is also sufficiently general to be applicable to the whole types of igneous rocks. According to this classification (Figure 37) the considered Alexandria Lighthouse “coarse pinkish granite” samples resulted mostly grouped together in **monzogranite** and **syenogranite** fields and the “dark-grey granodiorite” in **tonalite** and **granodiorite** fields.

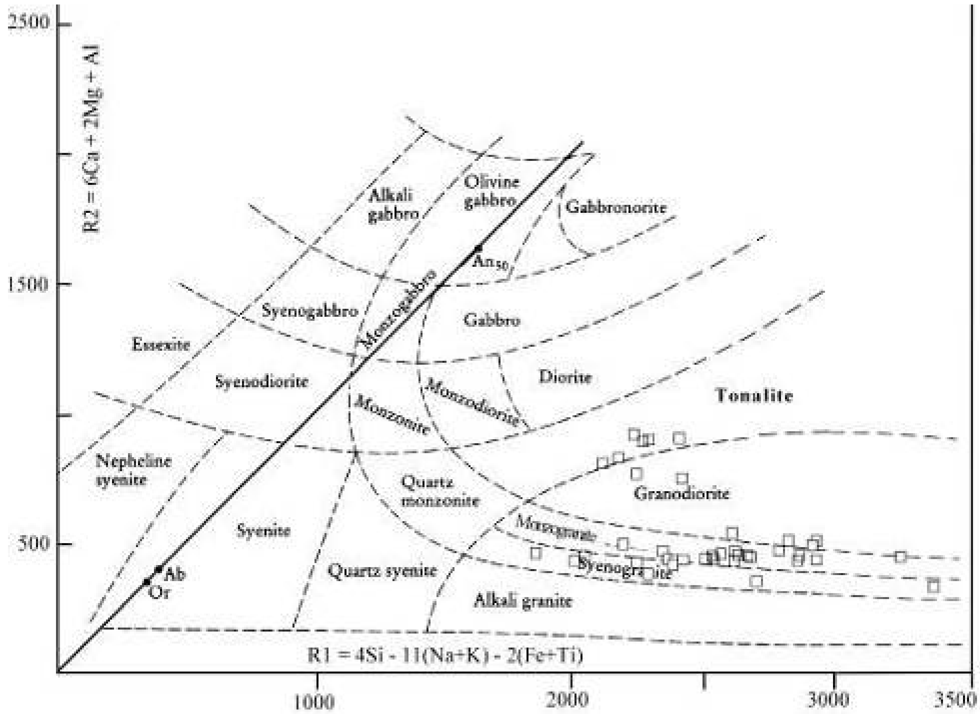

Figure 37 **-** Petrographic classification of the Alexandria Lighthouse granitoïd samples according to De La Roche et al., 1980 (R1 = 4Si – 11(Na + K) – 2(Fe + Ti); R2 = 6Ca + 2Mg + Al; R1 and R2 are calculated from millication proportions).

This later aspect is well highlighted also by a general comparison of the chemical data listed in Appendix 2 as well as by other possible bivariate oxide-oxide major element plots showing a clear distinction between granites and tonalites / granodiorites samples (Figure 38).

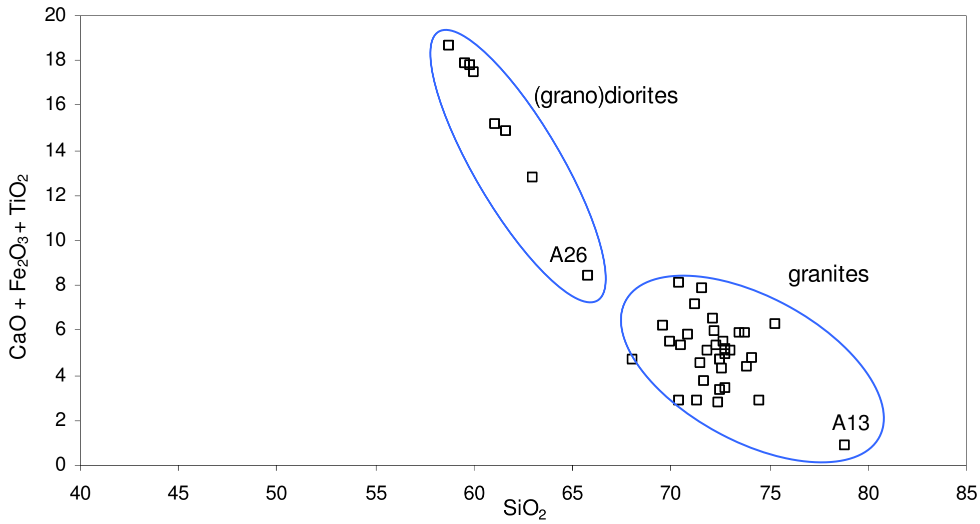

Figure 38 - SiO_2 vs (CaO+Fe_2O_3+TiO_2) variation diagram showing the separation between granite and tonalite (± granodiorite) groups.

Two samples (A26 and A13 that correspond megascopically to a dark-grey granodiorite and to a very clear pinkish granite; Figure 39) are slightly different than the others.

Figure 39 – Megascopic views of the archeological objects corresponding to A26 (left) and A13 (right) samples.

3.3.2. Siliceous sandstones

Among the sixty-six stone samples collected on monuments and artefacts from Alexandria Lighthouse, nine (referenced A8, A10, A11, A12, A54, A59, A62, A64 and A66) visually look like siliceous sandstones.

In a megascopic point of view, the considered siliceous sandstone samples correspond to fine-grained to coarse-grained (almost conglomeratic) more or less bedded materials with beige-yellowish to ochre-brownish color (Figure 40).

Figure 40 - Megascopic views of siliceous sandstone objects: (up) beige-yellowish to ochre coarse-grained (almost conglomeratic) siliceous sandstone (sample A10); (down) beige fine-grained siliceous sandstone (sample A12).

According to microscopic observations and sedimentary rocks usual classifications, the whole samples can be characterized as **quartzarenites** (Scolari et Lille, 1973) or **orthoquartzite** (Folk, 1954).

The **outer exhibited objects** made of siliceous sandstone are represented by four samples A8, A10, A12 and A13. Megascopically, they have fine to medium sand-size grains to pebbles (about 1cm). They range in color from beige to brownish due to variable content of iron oxides or hydroxides and show graded bedding. Thin sections studies show that they consist mainly of quartz detrital grains, less amount of opaque grains. Grains are well sorted (size ranging from 1 to 3 mm) and some of them have wavy extinction. They are sub-rounded to well rounded and are outlined by a thin layer of inclusions (probably iron oxides and / or clays) and locally by thicker layer that separate them from the authigenetic quartz overgrowths (Figure 41, left). Sometimes the opaque minerals are dominant giving brownish color to the stone. The grains are cemented by chalcedony crystals (first generation) and the next of parallel stage is quartz overgrowth cementation. The last generation of cement is micritic calcite usually filling the pores (Figure 41 right and Figure 43). Feldspar grains and chert fragments are found in a small proportion. Authigenetic overgrowth often shows euhedral crystal shape where fully developed. Because of the significant overgrowth cementation of sub-rounded detrital grains of quartz, the pores are restricted (Figure 42).

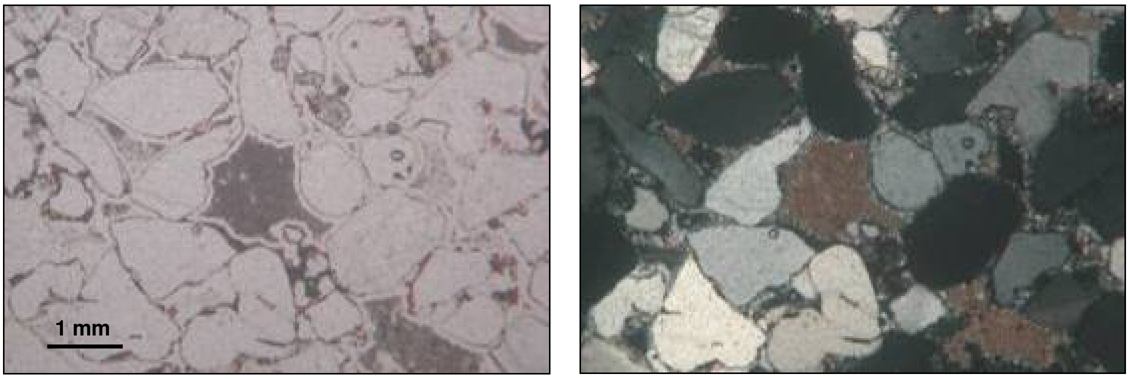

Figure 41 - Microscopic observations of A8 siliceous sandstone sample (left: N//; right: N+).

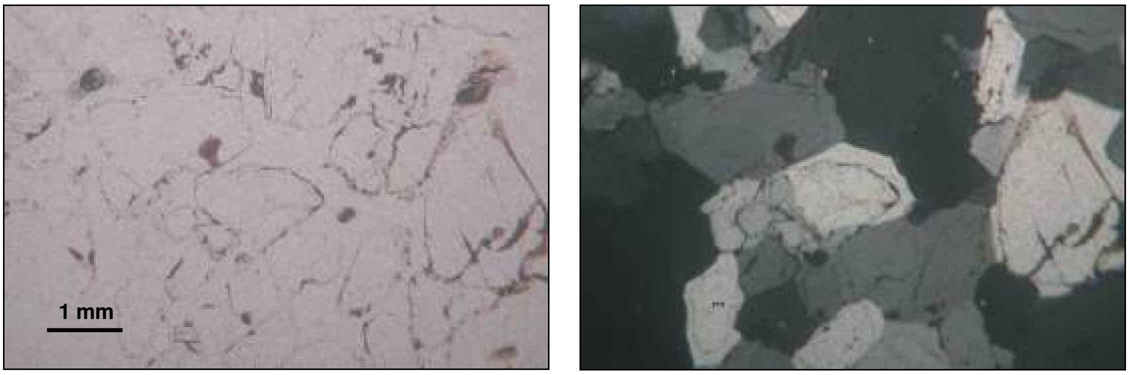

Figure 42 - Microscopic observations of A10 siliceous sandstone sample (left: N//; right: N+).

Figure 43 - Microscopic observations of A12 sandstone sample (left: N//; right: N+).

Regarding the **still underwater objects** made of siliceous sandstone, the five samples (A54, A59, A62, A64 and A66) were petrographically studied.

They consist of more than 95% of quartz grains that form the frame work. Grains are sub-angular to sub-rounded sometime rounded to well round, varying from medium to coarse size and mostly showing quartz overgrowths. Most of the quartz grains are monocrystalline with mild waving extinction. They exhibit pressure – solution compaction where concavo – convex and sutured contacts are developed. In some of the samples, the grains have a highly packed and interlocked formed mosaic texture. They are texturally mature and are cemented by authigenetic quartz overgrowths. Few feldspar grains and chert fragments are also present. Grains are cemented mainly by chalcedony crystals (first generation) and the next of parallel stage is quartz overgrowth cementation. The last generation of cement is micritic calcite usually filling the pores.

Figure 44 - Microscopic observations of A64 sandstone sample (N+): overview (left) and mosaïc texture (right).

The whole analytical data measured on the nine siliceous sandstones samples collected on Alexandria Lighthouse objects (ref. A8, A10, A11, A12, A54, A59, A62, A64 and A66) are detailed in Appendix 3.

According to these data, the samples correspond to quite hard stones correlated with a low porosity (about 4% in average).

In a mineralogical point of view, they contain as any quartzarenite a high proportion of SiO_2 (average about 90% ranging from 84% to 93%). A few percents of Calcium are also present (ranging from <1 to 5%) corresponding to the calcitic (micritic) secondary cement of the stone (and probably also for a part to remains of marine concretions).

About the trace chemical elements, the significant ones are Zirconium with an average value of 139 ppm and Strontium (128 ppm) present in the whole analysed samples. The Barium high value (567 ppm) measured in sample A62 (while this element is absent for other samples) is probably anthropogenic (possible pigment).

3.3.3. White Marbles

Among the sixty-six stone samples collected on monuments and artefacts from Alexandria Lighthouse, only two (samples A16 and A71) are precisely pure whitish crystalline marbles.

As regards the determination of their geological origin, both were investigated by mineralogical-petrographic methods and isotopic analysis. Thin sections were studied under polarizing microscope to determine and describe the petrographic parameters with particular diagnostic significance. For marbles those widely used in this type of study (Lazzarini et al., 1980; Moens et al., 1988; 1992; Gorgoni et al., 2002) are fabric, maximum grain-size (MGS), calcite boundary shapes, and frequency and distribution of accessory minerals. The petrographic data obtained were compared with those reported in the specific literature and with available reference samples from ancient quarries. XRD analyses were performed to evaluate the presence of a possible dolomitic fraction in marbles. Isotopic analyses were realized following the procedure of McCrea (1950) by Mass spectrometry and isotopic composition values (expressed in terms of $\delta^{13}C$ and $\delta^{18}O$ in ‰ relative to the international reference standard PDB; Craig, 1957) were plotted in the updated diagrams proposed by Gorgoni *et al*. (2002).

The complete petrographic-mineralogical features and the isotopic signatures of the two white marbles samples of Alexandria Lighthouse are shown in Figure 45 and 46, and detailed in Appendix 4.

According to analytical results, both studied objects are sculpted in **two medium to coarse grained classical white marbles** very appreciated and largely distributed during the Roman age: the **Thasian marble** from Vathy (Greece) and the **proconnesian marble** from Turkey.

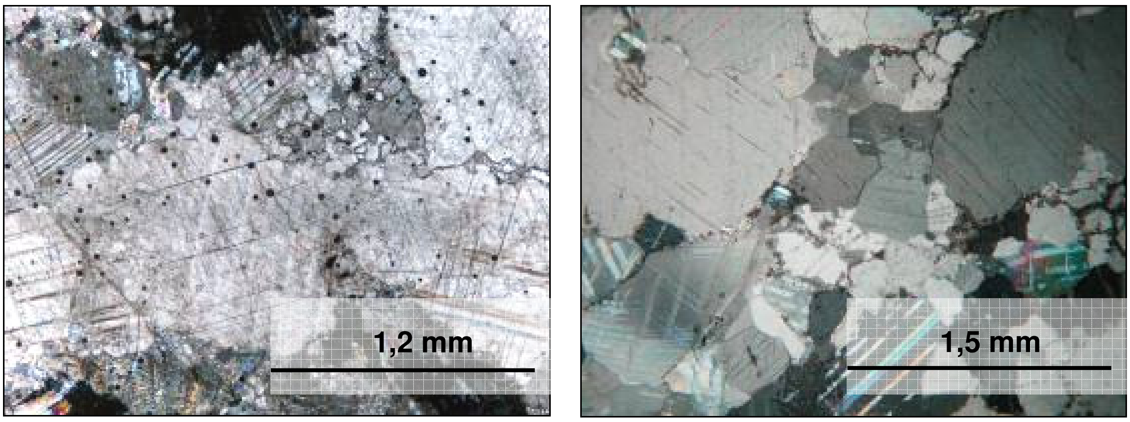

Figure 45 – Microfacies of the two samples of white marbles from Alexandria Lighthouse: (left) sample A16 of Thasian marble (Vathy, Greece); (right) sample A71 of proconnesian marble (Turkey); both present medium to coarse grain-size (photomicrographs N+).

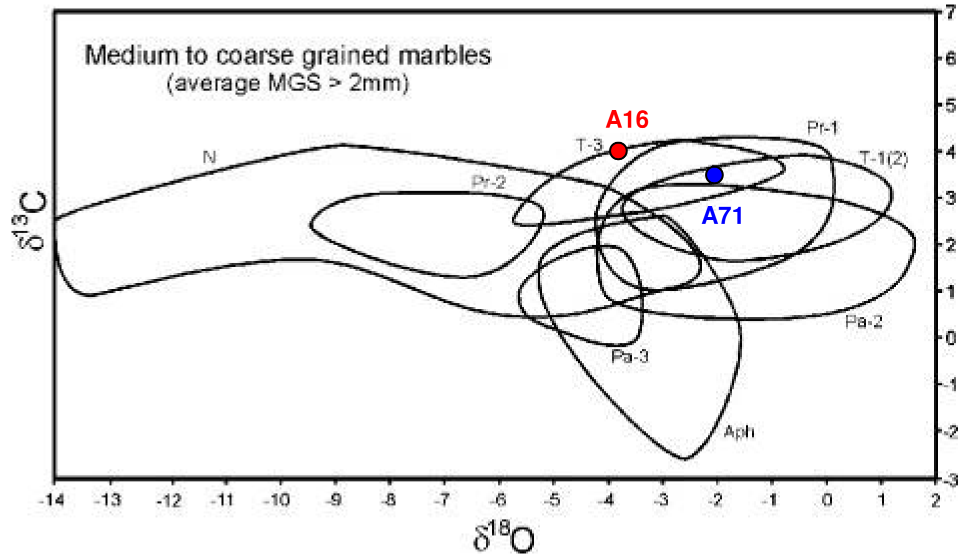

Figure 46 – Position of white marbles from Alexandria Lighthouse in the $\delta^{13}C$ vs $\delta^{18}O$ plot (isotopic fields from Gorgoni et al., 2002) – Pa-2 = Parian (Lakkoi); Pa-3 = Parian (Karavos); Pr = Proconnesian; T-1(2) = Thasian (Aliki) ; T-3 = Thasian (Vathy) ; N = Naxian; Aph = Aphrodisian.

3.3.4. Greywackes

Among the sixty-seven stone samples from monuments and artefacts of Alexandria Lighthouse, two samples (A9 and A69) megascopically look like greywackes (

Figure 47).

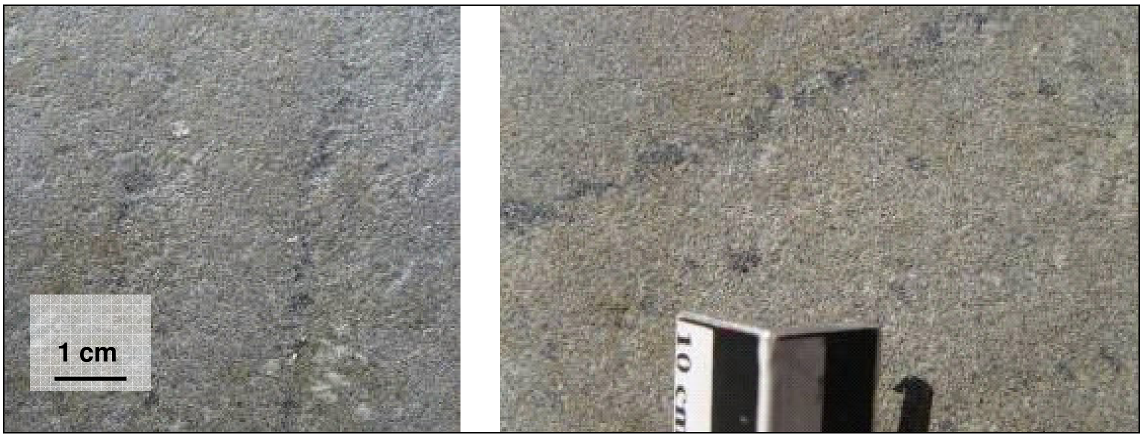

Figure 47 – Megascopic view of a sampled greywacke object (sample A9).

Greywacke or graywacke (German grauwacke, signifying a grey, earthy rock) is a variety of sandstone generally characterized by its hardness, dark color, and poorly-sorted, angular grains of quartz, feldspar, and small rock fragments set in a compact, clay-fine matrix.

According to thin sections observations by optic microscope (Figure 48), sample A9 shows a poor sorting and a slightly oriented texture (foliation). It is built up of sub-angular to rounded fine sand grains of quartz, plagioclase and lithic fragments, embedded in a fine grained recrystallized matrix formed of quartz and mica minerals (muscovite). Epidote and chlorite are also recorded.

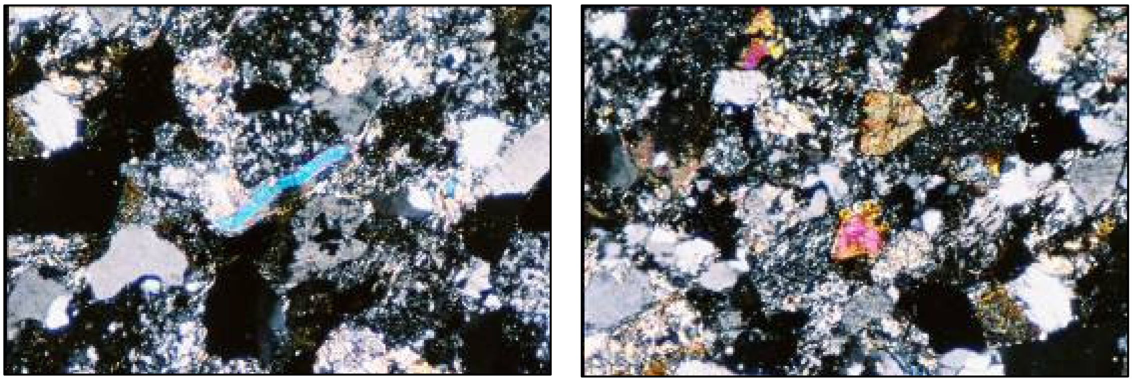

Figure 48 – Microscopic view (N+; magnification x110) of the greywacke sample A9: bad sorting of fine sand grains and slightly oriented texture; crystals of quartz (grey color), muscovite (blue) and epidote (pink).

According to the USDA scale (Pettijohn et al., 1987) the grain size of sample A9 ranges from very fine to fine sand (0.06 to 0.1mm) and it is termed (metamorphosed) sandstone (metasandstone). On the base of its matrix content (> 15% even about 50%), sample A9 is a greywacke *sensu stricto*.

Its mineralogical analysis by X-Ray diffraction (Figure 49) also identifies traces of carbonates (calcite and ankerite), hematite and clay minerals (illite).

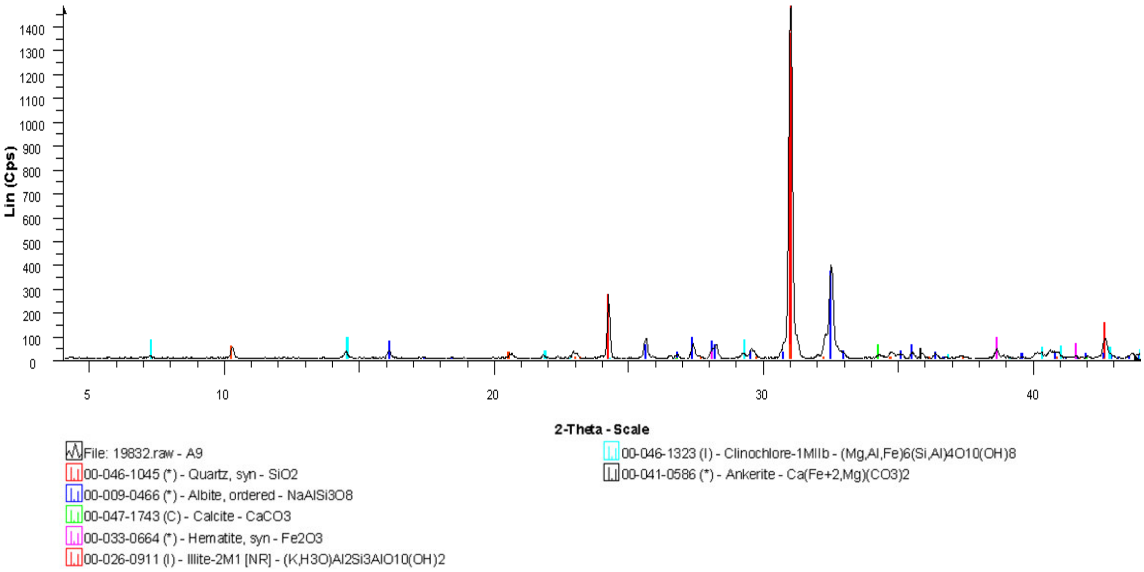

Figure 49 – X-Ray diffractogram of the greywacke sample A9.

On the other hand, the underwater sample (A69) is composed mainly of fairly well-sorted fine to very fine grains showing a slight foliation (Figure 50). The clasts are sub-angular silt-size crystals represented mainly by quartz (and plagioclase) floating in a very fine-grained groundmass of quartz, sericite and muscovite. According to the USDA scale (Pettijohn et al., 1987), the grain size of sample A69 ranges from fine to medium silt (0.01 to 0.05mm) and it is termed (metamorphosed) siltstone (meta-siltstone).

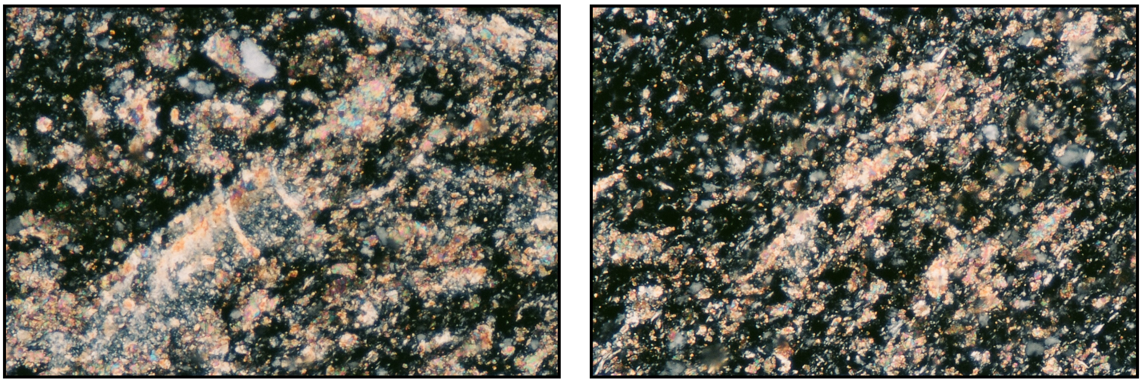

Figure 50 – Microscopic view (N+; x70) of the greywacke* sample A69: fairly well sorting of fine to very fine (silt size) grains showing a slight foliation (* this stone identified megascopically as a greywacke correspond to a siltstone according to microscopic observations).

The chemical data measured on both greywacke samples (ref. A9 and A69) collected on Alexandria Lighthouse objects are detailed in Appendix 5.

According to these measures, A9 is richer in Siliciium (about 66%) than A69 (about 44%) and inversely the proportion of Calcium is only of 3% for A9 for almost 20% for A69. This difference could be link to a different content of calcitic lithoclasts between samples. Nevertheless, a more probable explanation is the underwater impact on the archaeological objects and the presence of remains of calcitic marine concretions in the sample A69 (kept underwater without special cleaning contrary to sample A9 object). The other major chemical elements are present in very similar proportions in both samples. About the trace elements, the most significant ones are Strontium (301 and 360 ppm), Barium (538 and 265 ppm), Zirconium (218 and 236 ppm) and Vanadium (132 and 113 ppm); A9 also contain Bora (194).

3.3.5. Limestones

Among the sixty-six stone samples collected on monuments and artefacts from Alexandria Lighthouse, three (samples A3 to A5) correspond megascopically to light-colored limestones and one (sample A68) looks like a Dark-grey limestone. One has to remember that samples A3 and A4 were collected from the blocks constituting the base of Qaitbay Fortress according to the hypothesis that the fortress is located in the same place than the Alexandria Lighthouse using its ruins. A5 is not exactly an archaeological sample as coming from the bedrock of QaitBay Fortress. Sample A68 was kept from still underwater object.

The microfacies analysis of the considered limestone samples were carried out using the polarizing microscope and adapting the usual scheme proposed by Folk (1959) and Dunham (1962). The whole analytical data measured on the four samples are detailed in Appendix 6.

Light-colored limestones:

Sample A3 and A4 are relatively similar in a petrographic point of view, with nevertheless slight differences.

Of yellowish color, sample **A3** is a **fine sandstone with dolomitic cement** according to petrographic observations by optic microscope (Figure 51): it contains a large proportion of fine to very fine (60 to 120 µm) sub-angular to angular detrital grains of quartz (mainly) and feldspar (minor) in carbonated cement (content about 30% measured by acid attack; ferrean dolomite i.e. ankerite identified by X-Ray diffraction). Few opaque minerals are also observed.

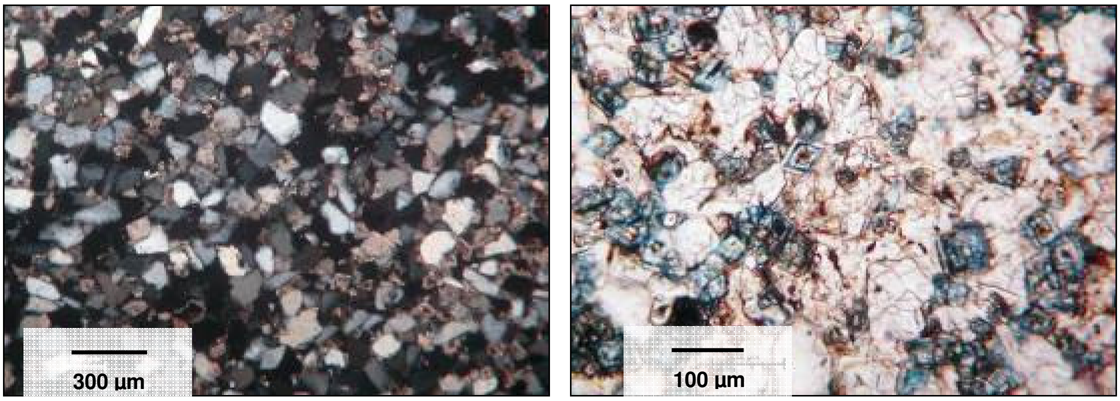

Figure 51 – Microscopic views (left: N+; right: N//) of sample A3 (fine sandstone with dolomitic cement).

On the other hand, sample **A4** is a brownish **sandy dolostone** showing shell fragments and a silty to sandy texture (Figure 52).

Figure 52 – Megascopic observation of sample A4 (brownish sandy dolostone).

Microscopically (Figure 53 left), it consists of detrital quartz mainly and rare feldspars grains that are angular to sub-angular, very fine to fine (50 to 100 µm). In addition minor proportion of opaque minerals (hematite, pyrite?) is present. The detrital grains are well sorted and cemented by carbonates (content about 68% measured by acid attack; ferrean dolomite i.e. ankerite identified by X-Ray diffraction). Very characteristic in cement (Figure 53 right) is idiomorphic rhombic outline and sharply defined zoning of ankerite crystal (0.05mm in size). The zoning consists of alternating intervals of more of less iron-rich (ankerite) and iron-poor dolomite. The porosity is high and mainly secondary (moldy). Sometimes clay mineral and hydroxides are developed at the periphery of the big pores.

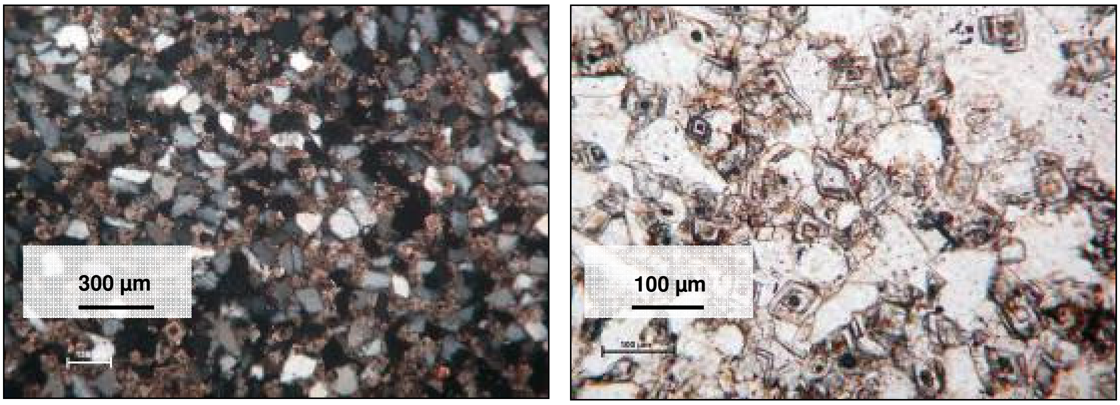

Figure 53 – Microscopic views (left:: N+; right: N//) of sample A4 (brownish sandy dolostone).

Besides quartz and ankerite, the mineralogical X-Ray diffraction analyses of both previous samples (Figure 54) show traces of albite and microcline feldspars (higher content in sample A3). Halite is not intrinsic to the stones, only due to the marine influence.

The main difference between samples A3 and A4 is the ratio grains (quartz and feldspars) / cement (ankerite): sample A3 is less carbonated (lower quantity of ankerite cement) and inversely richer in detrital grains of quartz and feldspar than sample A4.

Concerning sample **A5**, it is a **light beige-grey calcarenite** sandy in texture (Figure 55 left) and very friable to almost loose stone (very low degree of coherence). It is a biosparite and a foraminifera grainstone. It consists of calcareous grains (sub-angular to sub-rounded; size about 0.3mm), mainly skeletal fragments as red algae, echinoderms, corals, brachiopods, foraminifera, etc (Figure 55 right). The cementation is almost absent, except in some places with a meniscus cement.

Its mineralogical X-Ray diffraction analysis confirms that it is a pure calcium carbonate composed mainly of calcite and also aragonite. The carbonate content measured by acid attack is about 95%.

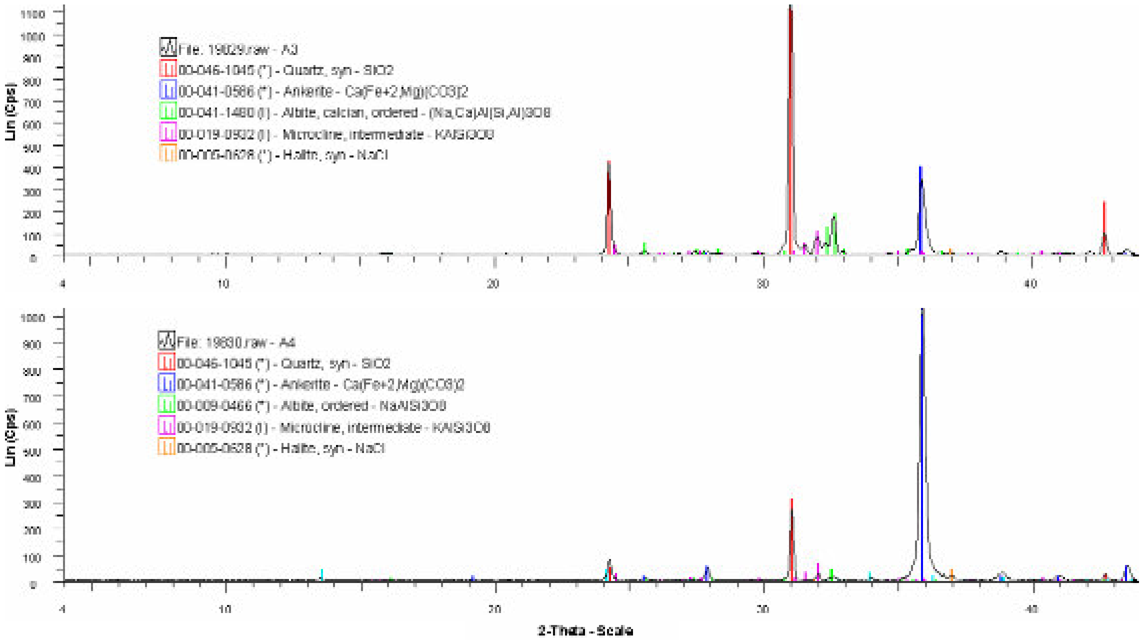

Figure 54 – X-Ray diffractograms of samples A3 and A4: the main mineralogical difference is the ratio grains (quartz and feldspars) / cement (ankerite).

Figure 55 – Megascopic (left) and microscopic view (N//) of the bedrock of Qaitbay Fortress (sample A5): light beige-grey calcarenite sandy in texture and very friable.

The isotopic signature of the light-colored stones three samples A3, A4 and A5 (expressed in terms of $\delta^{13}C$ and $\delta^{18}O$ in ‰ relative to the international reference standard PDB; Craig, 1957) are plotted in the Figure 59.

On the basis of the whole previous analytical data (detailed in Appendix 6), samples A3 (sandstone with dolomitic cement) and A4 (sandy dolostone) belong to a same geological formation different than sample A5 (calcarenite) one. This result indicates that the bedrock of Qaitbay is not the stone deposit of provenance of the stones constituting the current basement of Qaitbay Fortress and supposed corresponding to the ruins of the Alexandria Lighthouse.

Dark-grey limestone:

Megascopically (Figure 56), sample A68 collected underwater looks like a fine dark grey-bluish limestone.

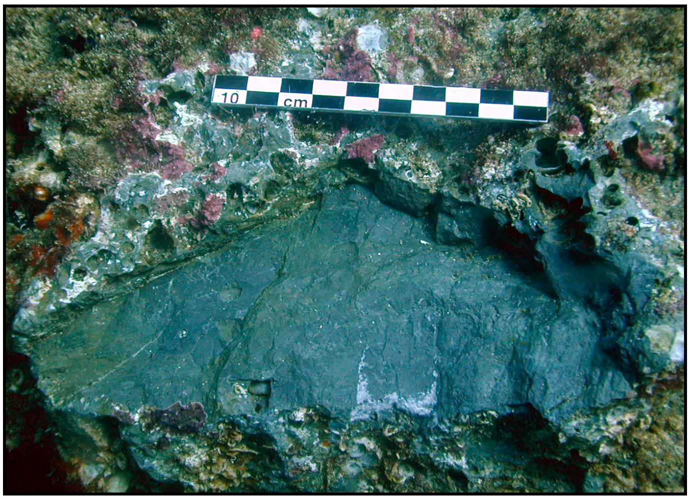

Figure 56 – Megascopic view of the Dark-grey limestone (sample A68).

According to optical microscope observations (Figure 57), it is a lime-mudstone (micrite and dismicrite). It is a mud supported stone composed of carbonate (micrite) mainly recrystallized into microsparitic calcite, and probably clay minerals, and containing about 10% fossils allochems (mainly foraminifera and shell fragments mostly recrystallized). This mudstone has sparitic-filled fenestrae ("bird-eye" structure) in the micritic matrix (dismicrite). Some fissures are observed sometimes filled with sparite. Very fine (silt-size) grains of quartz disseminated are also observed.

Figure 57 - Microscopic view(N//) of sample A68 (micrite).

By carbonate content measurement (by acid attack), sample A68 is constituted of about 80% of calcite. Besides calcite, mineralogical X-Ray diffraction analysis (Figure 58) confirms the presence of few percents of quartz and of clay minerals (chlorite and muscovite/illite).

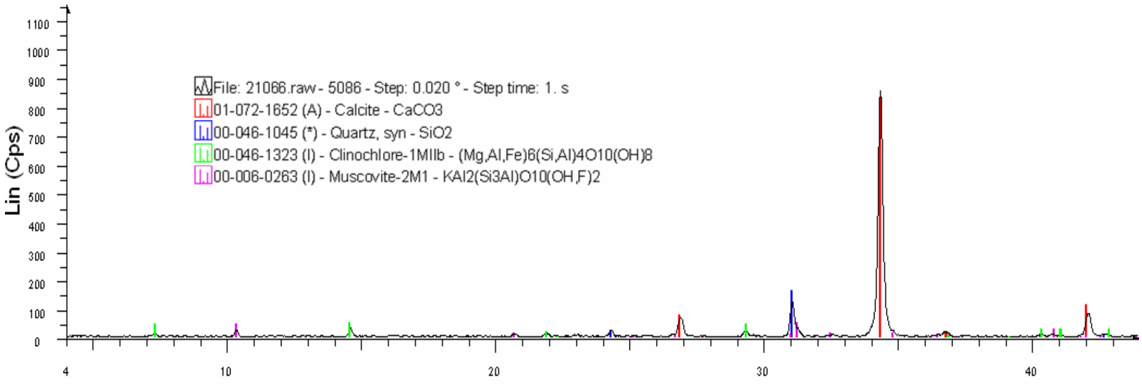

Figure 58 – X-Ray diffractograms of sample A68 (fine dark grey-bluish limestone).

According to chemical analyses (major and trace elements determined by ICP/AES), it is logically made of Calcium mainly. The main other major elements are Siliciium (about 13%), Aluminium (4.7%) and Iron (2.3%) corresponding to the occurrence of quartz and clay minerals. Among the trace chemical element detected, the most important ones are Strontium (323 ppm), then Barium (83 ppm) and Zirconium (74 ppm).

The isotopic signature (expressed in terms of $\delta^{13}C$ and $\delta^{18}O$ in ‰ relative to the international reference standard PDB; Craig, 1957) of the sample is plotted in Figure 59.

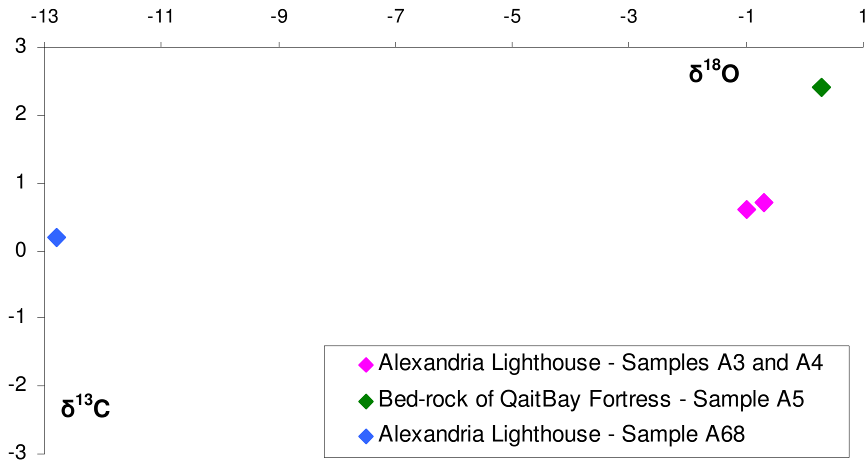

Figure 59 - Isotopic signature of the limestone samples (A3, A4, A5 and A68) from Alexandria Lighthouse.

4. Search of reference quarries

After studying stones from Alexandria Lighthouse (precisely sixty-seven samples of several types of stones from blocks lifted out of sea and exposed in Alexandria or still underwater), the search of provenance of each kind of stone was carried out including delimitation when possible of corresponding ancient quarries.

4.1. GRANITOIDS

Keeping in mind that fifty granitoid samples are among the sixty-seven collected from monuments and artefacts from Alexandria Lighthouse (visually pink granites and dark-grey granodiorites), the study first of all focused on the search and study of ancient granitoïd quarries.

4.1.1. Investigated quarries

According to bibliography the granitoïds used in ancient times are commonly reputed coming from Aswan area, more precisely in various localities between Aswan and Shellal District (coordinates: N24°3.7’ - E32°53.7’; Harrel et al., 1996). In terms of varieties, the Aswan area supplied four types of granitoïds (from Precambrian basement) referred (a) to (d) (Harrel et al. 1996).

Type (a) corresponds to the famous “**Monumental red granite**”, **coarse pink granite** used from the Early Dynastic period to the Roman period. It is a pinkish to occasionally reddish stone, very coarse to mainly coarse-grained (Figure 60), occasionally gneissified and porphyritic (phenocrystals up to 4 cm) varying gradually up to the type (b).

Type (b) corresponds to the famous "**Monumental black granite**", **coarse black granite to mainly granodiorite** used from the Early Dynastic period to the Roman period. It is a dark gray to nearly black stone, coarse to mainly medium-grained (Figure 62), commonly porphyritic (phenocrysts up to 3 cm) and gneissified, varying gradually up to the type (b). The phenocrysts vary from white to pink in color and may be largely or entirely absent in some specimens.

Type (c) corresponds to the **transitional stone** (Figure 61) between the coarse pink granite (a) and the coarse black granodiorite (b).

Type (d) corresponds to fine gray to pink granite used from the New Kingdom period to the Roman period. It is a light-grey to pinkish stone, medium- to mainly fine-grained (Figure 63), occasionally gneissified.

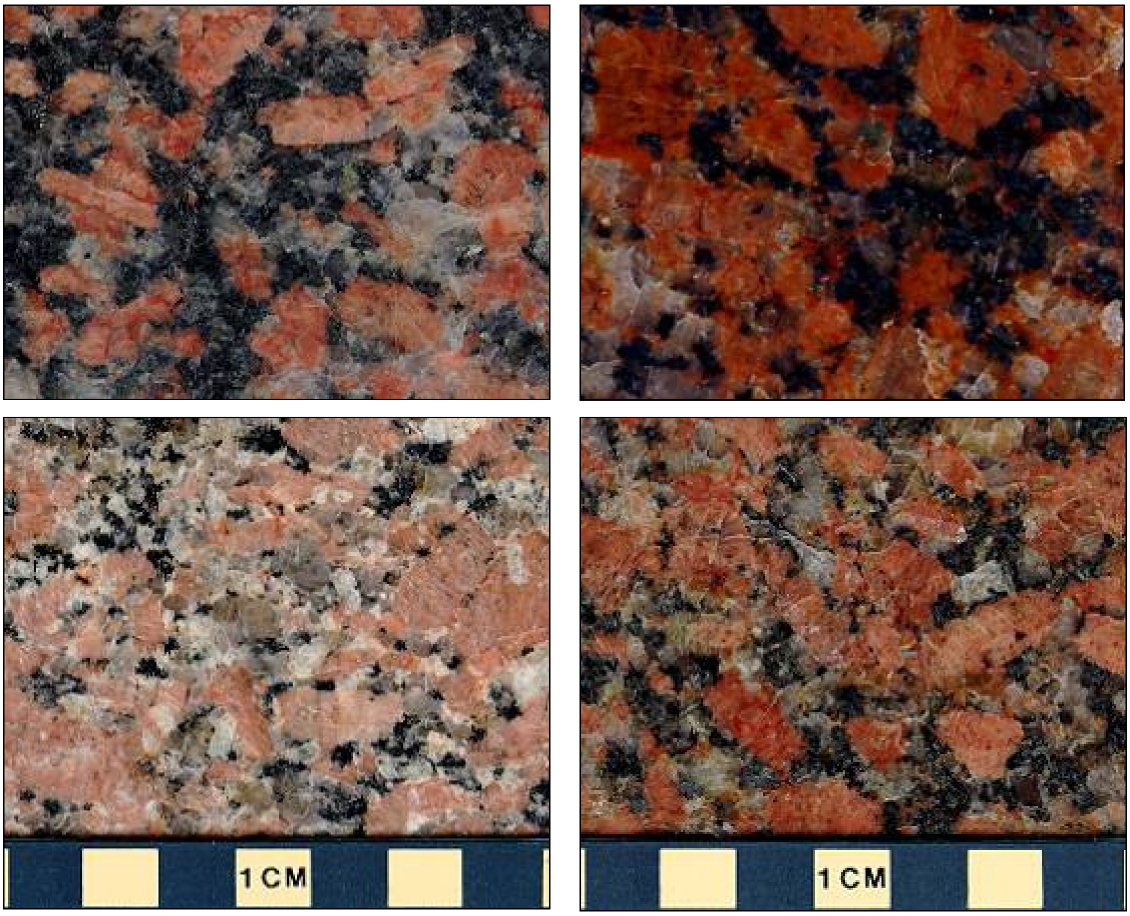

Figure 60 - Megascopic view of type (a) Aswan granitoïd (from J.A. Harrel, modified, http://www.eeescience.utoledo.edu/Faculty/Harrell/Egypt/Quarries/Quarries_Menu.html).

Figure 61 - Megascopic view of type (c) Aswan granitoïd (from J.A. Harrel, modified, http://www.eeescience.utoledo.edu/Faculty/Harrell/Egypt/Quarries/Quarries_Menu.html).

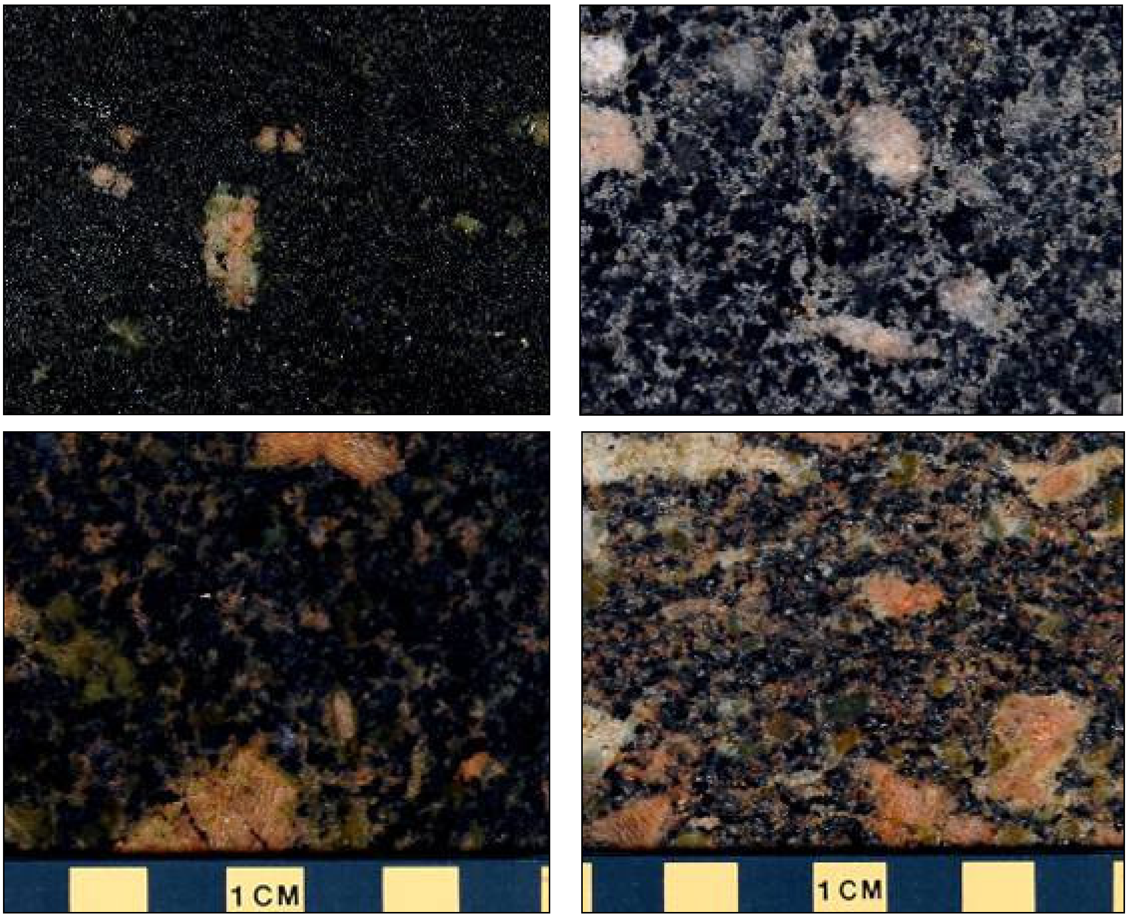

Figure 62 - Megascopic view of type (b) Aswan granitoïd (from J.A. Harrel, modified, http://www.eeescience.utoledo.edu/Faculty/Harrell/Egypt/Quarries/Quarries_Menu.html).

Figure 63 - Megascopic view of type (d) Aswan granitoïd (from J.A. Harrel, modified, http://www.eeescience.utoledo.edu/Faculty/Harrell/Egypt/Quarries/Quarries_Menu.html).

As abstracted by Harrel, the types (a) and (b) are the *marmor syeniten* or *lapis syenites* ("stone of Syene", the Greek name for Aswan) and *lapis Thebaicus* ("stone of Thebes") of the Romans, and *lithos pyrrhopoecilus* ("red-spotted stone") of the Greeks.

Italian stonecutters refer to rock type (a) as *granito rosso* ("red granite"), rock type (b) as *granito nero* ("black granite"), *granito nero di Siene* ("black granite of Syene") and *granito antico bigio* ("ancient grey granite"), and rock type (d) as *granito rosso minuto* ("fine red granite")".

Aswan granitoïd quarries were worked in very ancient times from Early Dynastic to Roman period, selected because of beauty of the stone and easiness of carriage from quarries located on the banks of the Nile. The Ancient Egyptian mastered the arts of quarrying, removing the over burden and weathered upper part to extract the solid and fresh stone with its best material characteristics and properties.

Original ancient Aswan quarries were increasingly used for industrial activities starting with the construction of Aswan Reservoir in 1898, followed by the construction of Aswan High Dam in 1960 and up till now for industrial and decorative purposes. Aswan quarries cover an area of about fifteen square-kilometers extending from the "unfinished obelisk" quarry at the north to El Shellal railway station at the south. Besides a few ancient quarries, seven modern quarries are nowadays in activity comprising five quarrying of – type (a) coarse pink granite (intrusions of type (d) also possible) and two of coarse black granite to mainly granodiorite - type (b). Location of the whole investigated quarries is given in Figure 64 and in Table 6.

	Quarry reference	Modern (M) or ancient (A)	Stone type	Latitude	Longitude
I	**Unfinished obelisk**	A	(a)	24° 04' 38"	32° 53' 40"
II	**South unfinished obelisk (Gebel Masala)**	M	(a) (d)	24° 04' 17"	32° 53' 41"
IIb		A	(a)	24° 04' 21''	32° 53' 42''
III	**El Shellal Road**	M	(a)	24° 03' 35"	32° 54' 30"
VI		M	(a)	24° 04' 13"	32° 53' 33"
V		M	(a)	24° 02' 57"	32° 54' 36"
VI		M	(a)	24° 02' 07"	32° 54' 29"
VII	**Unfinished Basins**	A	(a)	24° 03' 01"	32° 54' 35"
VIII	**Unfinished Ramsès Statue**	A	(a)	24° 02' 49"	32° 54' 34"
IX	**Gebel Ibrahim Pasha**	M	(b)	24° 04' 15"	32° 53' 26"
X		M	(b)	24° 04' 07"	32° 53' 30"
XIII	**Saluja Island**	A	(d)	24° 04' 24''	32° 52' 35''
XIV	**Sehel Island**	A	(d)	24° 03' 26''	32° 52' 22''

Table 6 - Location of Aswan granitoïd quarries: (a) coarse pink granite; (b) black granite to mainly granodiorite; (d) fine granite.

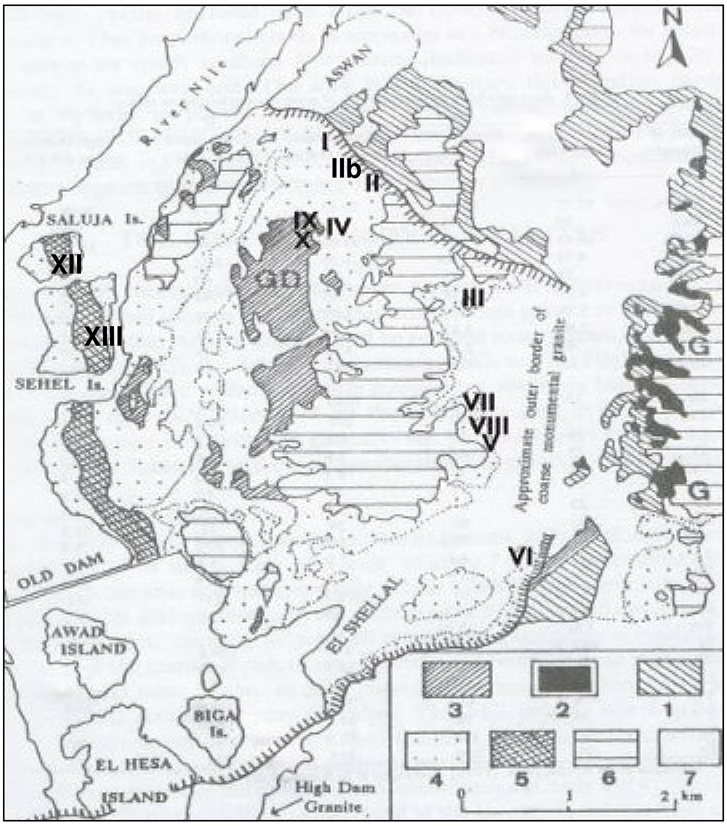

Figure 64 – Location of Aswan granitoids quarries (Gindy, 1956, modified) : 1. Gneisses and migmatites 2. Schists 3. Coarse-grained porphyritic granodiorite, 4.Coarse-grained porphyritic monumental granite, 5. Fine-grained granite, 6. Nubian Sandstones, and 7. Nile alluvium.

Igneous and metamorphic rocks of Aswan area are located between latitudes N 24º01′ to 24º05′ and longitudes E 32º51′ to 32º55′. They comprise (starting from the oldest rock unit) gneisses, schists, granodiorite, coarse-grained pink granite, fine-grained granite and leuco-granite (Neoproterozoic age; Abdel Monem and Hurley, 1980; Abdel Karim and Arva-Sos, 2002) covered by Nubian Sandstones (Cretaceous age).

Quarries of **coarse pink granite** ("Monumental red granite") – type (a) - are mainly located at the eastern bank of the Nile Valley in an area between Aswan City and El Shellal district to the south. The most famous localities are at the vicinity of unfinished Obelisk (Figure 65) and near El Shellal railway station (Figure 66). Coarse pink granites outcrops are abundant and widely distributed. They form most of the hills and are topped by weathered kaolinized rock that separated them from the overlain Nubian Sandstones. At the surface, the outcrops are usually highly weathered (Figure 67) showing spheroid boulders with exfoliation (contour-scaling).

Figure 65 - Aswan City Unfinished Obelisk ancient quarry of type (a) coarse pink granite.

Figure 66 - El Shellal road modern and ancient quarries area of type (a) coarse pink granite.

Figure 67 - Unfinished Ramsès statue ancient quarry area of type (a) coarse pink granite with typical spheroid boulders with exfoliation (contour-scaling).

Quarries of **coarse black granite to mainly granodiorite** ("Monumental Black granite) – type (b) - are restricted to Gebel Ibrahim Pasha (Figure 68) and Gebel Togok areas in the south of Aswan city. Nowadays, Gebel Ibrahim Pasha and Gebel Togok constitute the basement of modern part of Aswan. Coarse black granites to mainly granodiorites outcrop as a big sheet (like mass trending roughly north-south) in coarse pink granites. At the surface, outcrops are usually highly weathered showing the same king of spheroid boulders with exfoliation (contour-scaling) than coarse pink granites ones.

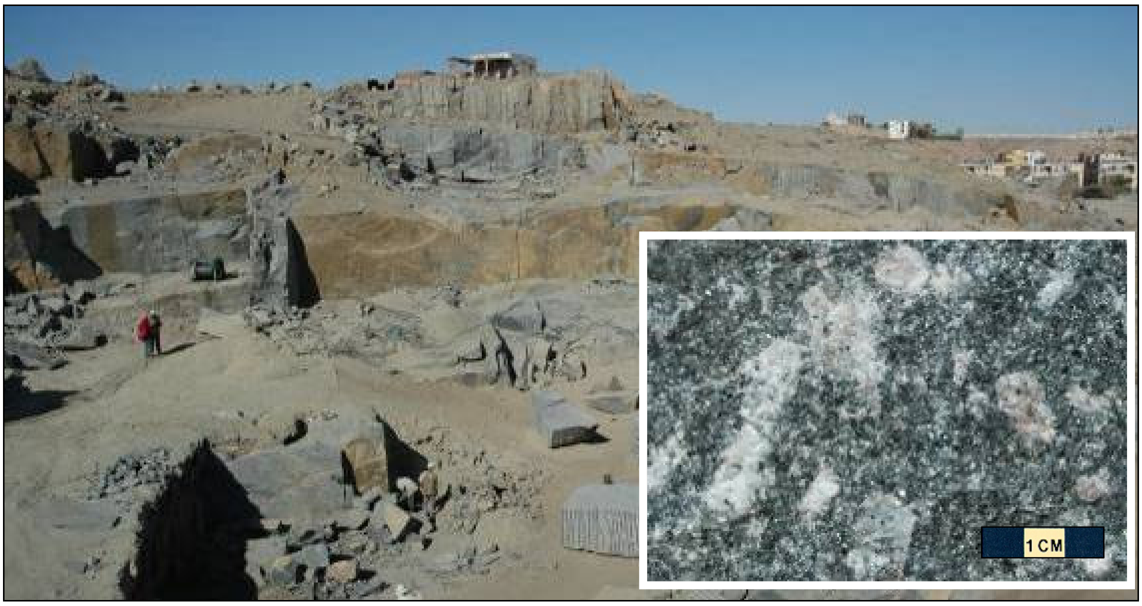

Figure 68 – Gebel Ibrahim Pacha quarries area of type (b) coarse black granite to granodiorite.

Quarries of **fine grey to pink granite** - type (d) - occurs in Sehel, Saluga (Figure 69) and Elephantine islands in the Nile forming an appreciable portion of many hills. They occur as sheets or dyke like intrusion cutting coarse pink granites with a general north-south trend. They are fine to medium grained, hard, non-porphyritic and have pinkish to greyish color. Some other intrusions are probable as the example of Gebel Masala modern quarry that presents few fine pink granite outcrops.

Figure 69 – Saluga island of ancient quarry of type (d) fine grey to pink granite.

4.1.2. Characterisation of the stones and comparison to those from monuments and artefacts

Thirty-two samples of granitoïds (referenced A74 to A105; cf. Table 7) were collected from Aswan quarries area and submitted to the same analytical procedure than those of Alexandria Lighthouse objects (cf. 3.3.1).

First of all, these granitoïd samples from Aswan quarries were studied petrographically and thin sections were examined by polarizing optic microscope. Here after their detailed petrographic description gathered together per type.

	Quarry reference	Modern (M) Ancient (A)	Stone type	Samples reference
I	**Unfinished obelisk**	A	(a)	A74-A88
II	**South unfinished obelisk (Gebel Masala)**	M	(a)	A86-A89-A90
			(d)	A87
IIb		A	(a)	A85
III	**El Shellal Road**	M	(a)	A81-A82-A91- A92
IV		M	(a)	A93
V		M	(a)	A75-A76 -A96-A97
VI		M	(a)	A98
VII	**Unfinished Basins**	A	(a)	A77-A78-A94-A95
VIII	**Unfinished Ramsès Statue**	A	(a)	-
IX	**Gebel Ibrahim Pasha**	M	(b)	A79-A80-A99
X		M	(b)	A100-A101-A102-A105
XI	**Saluja island**	A	(d)	A83-A103
XII	**Sehel island**	A	(d)	A84-A104

Table 7 – Informations about the thirty-two granitoïd samples collected in Aswan quarries area: (a) coarse pink granite; (b) coarse black granite to mainly granodiorite; (d) fine granite.

Coarse pink granites - type (a):

Microscopically, the samples present typically porphyritic texture mainly constituted by alkali feldspars phenocrystals (Figure 70). The groundmass minerals are represented by smaller feldspars crystals, quartz, hornblende and biotite filling the interspaces between the phenocrystals. Minor amounts of sphene, apatite, allanite and opaque minerals (mainly magnetite and illmenite) occur as accessory minerals.

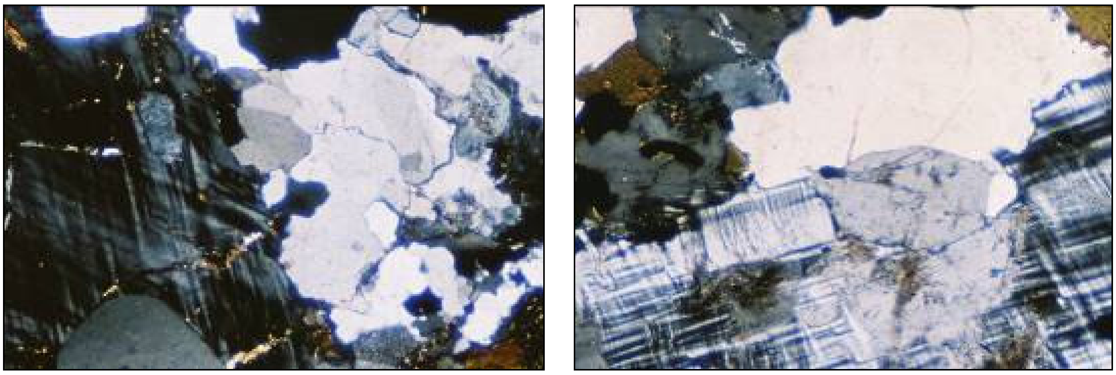

Figure 70 – Microscopic observations (N+; magnification x70) of coarse pink granite - type (a) - samples from Aswan quarries: (left) porphyritic texture; (right) microcline phenocristal.

Coarse pink granites are not homogeneous in mineral composition with abundant potash feldspar phenocrystals. Basic, acidic and gneissified varieties can also be distinguished. These varieties are not sharply separated but they merge into each other. The basic variety contains abundant ferromagnesian minerals (biotite and hornblende), less feldspars and it approaches composition of granodiorite and is mainly encountered near granodiorite contact. The acidic variety is lighter in color and contains less ferromagnesian minerals. The gneissified variety shows a sub-parallel arrangement of feldspars and ferromagnesian minerals and is especially observed near contacts with gneisses and schists.

Feldspars are represented by alkali feldspars and plagioclase. Alkali feldspars are represented by microcline, microcline perthite, orthoclase and orthoclase perthite. Microcline occurs as subhedral to euhedral crystals up to four centimetres long, fresh, exhibiting cross-hatching (Figure 71 right). Microcline perthite contains small irregular patches or veinlets of albite intergrown with microcline. Orthoclase occurs as subhedral crystals up to three centimetres long, exhibits simple twinning and slightly altered to sericite and clay minerals. Orthoclase also exhibits perthitic texture (Figure 71 left). Plagioclase although common is less abundant than microcline and orthoclase. It exhibits subhedral to euhedral crystals showing lamellar twinning and occasionally zoned. Some plagioclase crystals are slightly altered especially along cleavage planes to sericite and occasionally to calcite and epidote. Quartz is present in considerable amounts especially in more acidic variety samples. It is present in three generations: the first one has wavy extinction, the second is interstitial filling spaces between other minerals and the third generation is present in form of vermicular quartz in myrmekitic texture. Ferromagnesian minerals are represented by dark pleochroic biotite and hornblende. Both increase in the more basic variety samples and decrease in the more acidic variety showing parallel or sub-parallel arrangement in gneissified variety. Biotite usually of brown color occurs as subhedral crystals up to one millimetre long or as cluster of flakes. Some biotite crystals are slightly altered to chlorite and iron oxides. Hornblende occurs as subhedral to anhedral crystals with pleochroism from pale yellow to yellowish green to dark green color. Granular or rarely idiomorphic sphene and little calcite are closely associated with hornblende. Minor crystals of epidote, apatite, zircon and opaque minerals are present as accessory minerals.

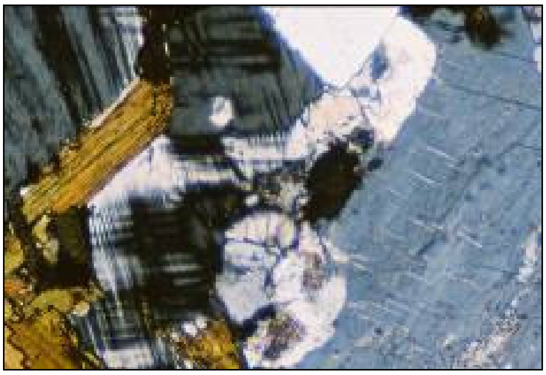

Figure 71 – Microscopic observations (N+; magnification: left x70 – right x110) of coarse pink granite - type (a) - samples from Aswan quarries: (left) Orthoclase perthite ; (right) microcline perthite.

Black granites to mainly granodiorites - type (b):

Microscopically, the samples present commonly porphyritic texture with large plagioclase and / or alkali feldspars phenocrystals often up to three centimetres long.

Groundmass minerals are represented by smaller plagioclase, hornblende, biotite, quartz and microcline with minor accessories. Sphene, zircon, apatite and opaque minerals are the accessory minerals.

Coarse black granites to granodiorite are heterogeneous in mineral composition. The most common variety is grey in color and spotted with whitish sometimes pinkish feldspars phenocrystals. As for coarse pink granites, basic, acidic and gneissified varieties can be distinguished. The basic variety is dark grey to nearly black in color containing abundant ferromagnesian minerals with less (sometimes without) feldspars phenocrystals. The acidic variety is lighter in color containing more feldspars and less ferromagnesian minerals, occurring near contact with coarse-grained pink granite. The gneissified variety exhibits sub-parallel arrangement of ferromagnesian minerals.

Feldspars are represented by plagioclase and subordinate microcline. Plagioclase occurs as phenocrysts as well as groundmass minerals. It occurs as subhedral to euhedral crystals up to three centimetres long, twinned according to albite law and occasionally zoned (Figure 72 left). Some plagioclase crystals are slightly altered to sericite especially towards the centre of the crystals and along the cleavage planes (Figure 72 right). Microcline is present in appreciable amounts in the acidic variety. It occurs mainly as groundmass minerals and occasionally as phenocrystals. It is fresh usually showing cross-hatching. Perthites intergrowths between albite and microcline are observed however not as common as in coarse-grained granites. Quartz is present as clusters or individual anhedral to subhedral crystals and exhibits wavy extinction. Myrmekitic intergrowths of plagioclase and quartz are observed in majority of thin-slices examined. In such cases vermicular quartz is noticed near the periphery of large plagioclase crystals. Ferromagnesian minerals in granodiorites include hornblende and biotite. Generally hornblende is more abundant than biotite. Hornblende occurs as subhedral to anhedral crystals up to one millimetre. It exhibits distinct pleochroism from pale yellow to yellowish green to deep green color. Biotite is present as subhedral to anhedral crystals up to one millimetre. It exhibits brown color with greenish shade or occasionally green. Some biotite crystals are slightly altered to chlorite and iron oxides.

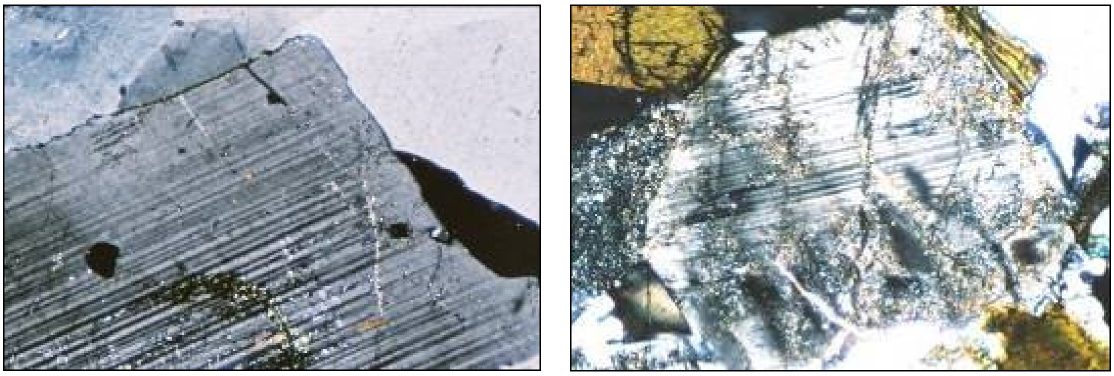

Figure 72 – Microscopic observations (N+; magnification x110) of black granite to mainly granodiorite - type (b) - samples from Aswan quarries: (left) Plagioclase phenocristal ; (right) Plagioclase crystals are slightly altered to sericite.

Fine granites - type (d):

Microscopically, the samples are medium to fine-grained and exhibit hypidiomorphic texture. They are composed of feldspars and quartz with subordinate biotite. Accessory minerals include apatite, sphene and opaque minerals. Feldspars are represented by microcline and plagioclase (mainly oligoclase). Orthoclase is probably present in small amounts. Microcline ranges from anhedral to subhedral crystals, fresh and showing cross-hatching (Figure 73 left). Plagioclase tends to be platy and ranges from subhedral to anhedral crystals showing lamellar twinning. Some plagioclase crystals are slightly altered to sericite and muscovite especially towards centre of crystals (Figure 73 right). Quartz is usually granular with irregular outlines showing waving extinction. Myrmekitic intergrowths of vermicular quartz in plagioclase are occasionally present. Ferromagnesian minerals are essentially represented by dark brown pleochroic biotite flakes and occasionally in green color. Some biotite flakes are slightly altered to chlorite and iron oxides especially along cleavage planes.

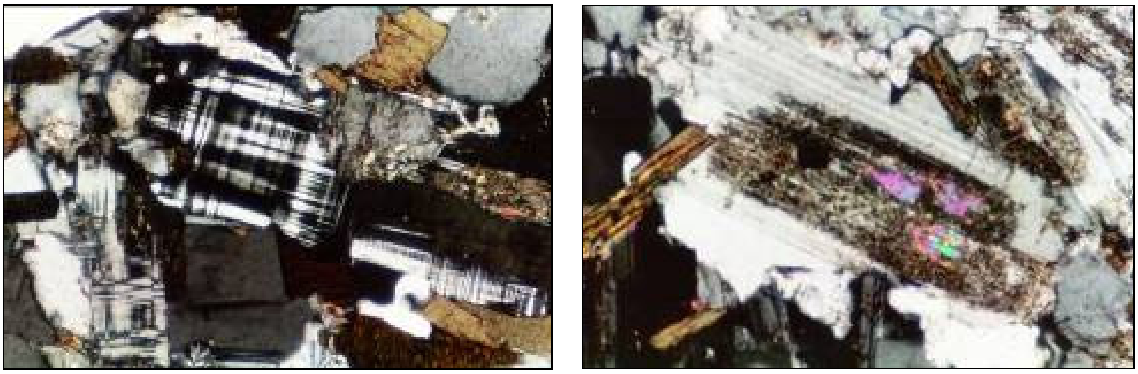

Figure 73 – Microscopic observations (N+; magnification x110) of fine granite - type (d) - samples from Aswan quarries: (left) Microcline subhedral crystals showing cross-hatching; (right) Plagioclase crystal altered to sericite and muscovite.

The petrographic observations by polarizing optic microscope revealed that the samples from the above mentioned quarries are to great extent similar in mineralogical composition and texture to those collected on archaeological objects from Alexandria Lighthouse.

After their petrographic description, two samples of coarse pink granite - type (a) - from El Shellal Road (quarries III and IV) and two samples of granodiorite – type (b) - from Gebel Ibrahim Pasha (quarries IX and X) were also ranked as an example adopting IUGS classification (Streckeisen, 1976; Le Maitre et al., 1989). This petrographic-mineralogical classification is based on the relative amounts of quartz, alkali feldspars (orthoclase and microcline) and plagioclase recalculated to 100% and plotted on a ternary diagram. The proportion of considered minerals is obtain by counting (about 2000 points per sample) on representative thin-sections examinated by polarizing optic microscope (equipped with a mechanical point counting stage). The method was also applied to one archaeological sample of sufficient volume (A30 – Right jamb of a gigantic door stored on the Eastern harbour platform of Alexandria).

The corresponding results (thin–section point–count data and IUGS ternary diagram) are presented in Table 8 and Figure 74. As results, the whole coarse pink granites samples (from Aswan quarries and Alexandria Lighthouse) are plotted in the syenogranite field and the granodiorite samples in the granodiorite field.

Minerals	Samples of coarse pink granite - type (a) - from El Shellal Road quarries		samples of granodiorite – type (b) - from Gebel Ibrahim Pasha quarries		Sample A30 Right Jamb
	III	IV	IX	X	
Quartz	28.74	23.49	20.26	23.50	28.20
Orthoclase	12.74	13.97	1.88	3.40	13.67
Microcline	28.74	36.87	12.51	8.02	28.40
Plagioclase	18.88	17.69	37.06	37.26	17.80
Hornblende	4.00	2.38	12.80	9.48	3.78
Biotite	5.60	3.88	12.54	14.52	5.80
Accessory minerals*	1.60	1.72	2.95	3.82	2.35
Total	100	100	100	100	100
IUGS Classification	**Syenogranite**	**Syenogranite**	**Granodiorite**	**Granodiorite**	**Syenogranite**

Table 8 – Thin–section point–count data of four granitoïd samples from Aswan quarries and one granitoïd sample from Alexandria Lighthouse (*Accessory minerals = sphene, epidote, apatite, zircon, magnetite and ilmenite).

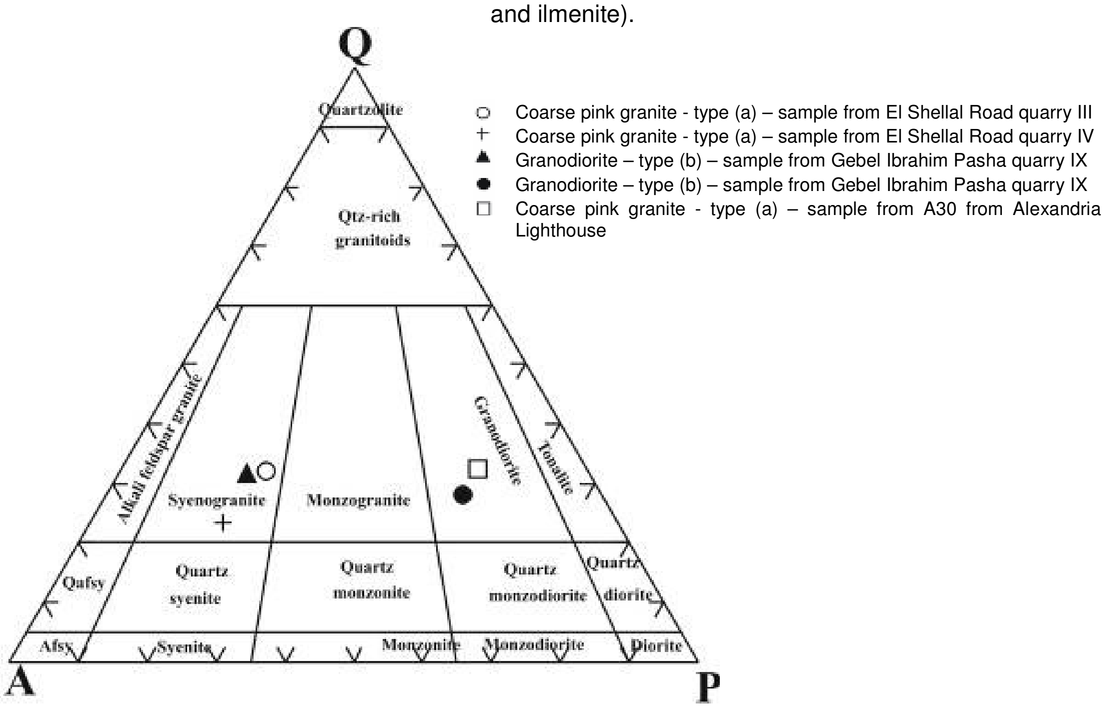

Figure 74 – IUGS classification of granitoïd samples from Aswan quarries and Alexandria Lighthouse object based on thin–section point–count data (*Accessory minerals = sphene, epidote, apatite, zircon, magnetite and ilmenite).

From a geochemical point of view (whole chemical data in Appendix 2) using the total alkalis versus silica (TAS) diagram for plutonic rocks proposed by Wilson (1989), the whole granitoïd samples from Aswan quarries area are oversaturated rocks grouped together in the granite, alkali granite and diorite (± granodiorite ± syenogranite) fields (Figure 75) and match to those from Alexandria Lighthouse objects.

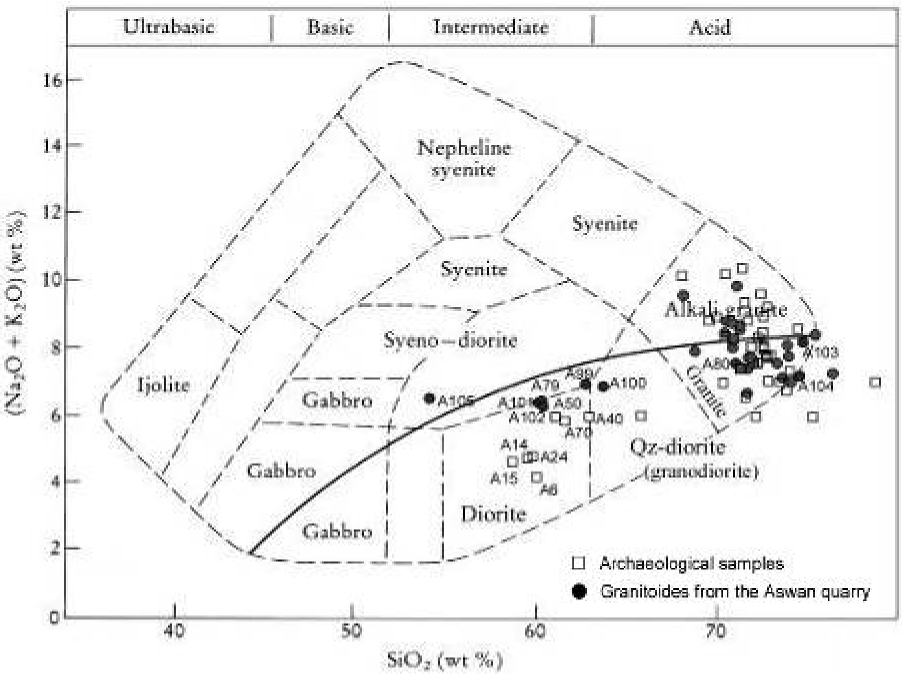

Figure 75 - Classification of granitoïd samples from Aswan quarries area and comparison to those from Alexandria Lighthouse objects (according to total alkalis versus silica diagram for plutonic rocks proposed by Wilson 1989).

According to the chemical classification scheme proposed by De la Roche et al. (1980), the considered Aswan quarries granitoïd samples are mostly grouped together in the monzogranite (± syenogranite) and tonalite (± granodiorite) fields (Figure 76).

This later aspect is well highlighted by a general comparison of chemical data listed in Appendix 2 as well as other possible bivariate oxide-oxide major element plots (Figure 77) that shows clear distinction between granites and tonalites/granodiorites and confirms a common origin (Aswan quarries area) for all the sampled objects from the Alexandria Lighthouse.

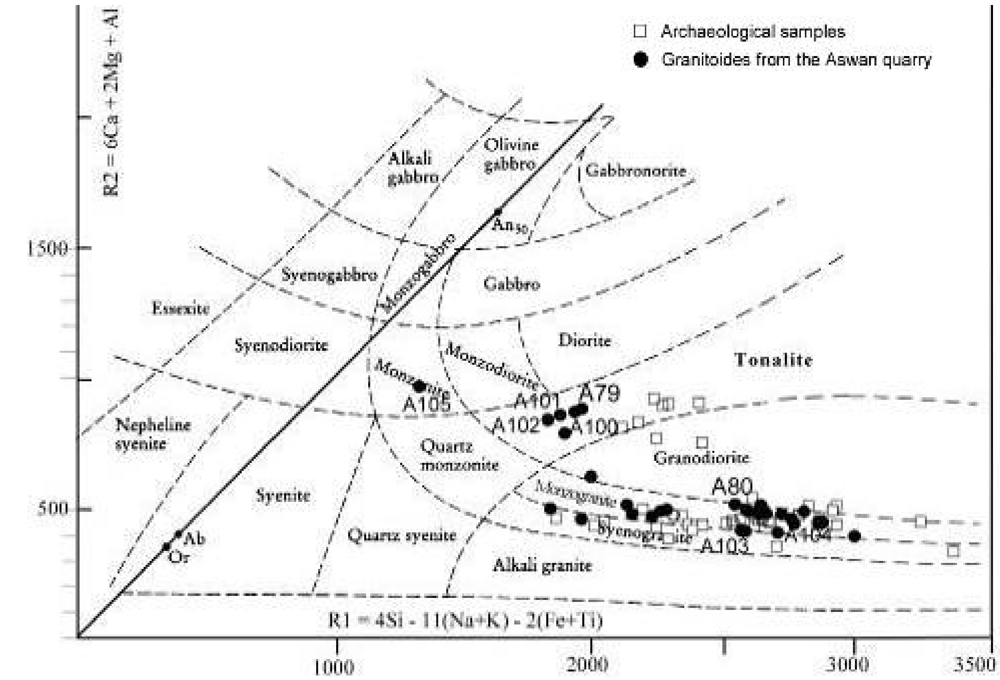

Figure 76 **-** Classification of granitoïd samples from Aswan quarries area and comparison to those from Alexandria Lighthouse objects (according to De La Roche et al., 1980); R1 = 4Si – 11(Na + K) – 2(Fe + Ti); R2 = 6Ca + 2Mg + Al; R1 and R2 are calculated from millication proportions.

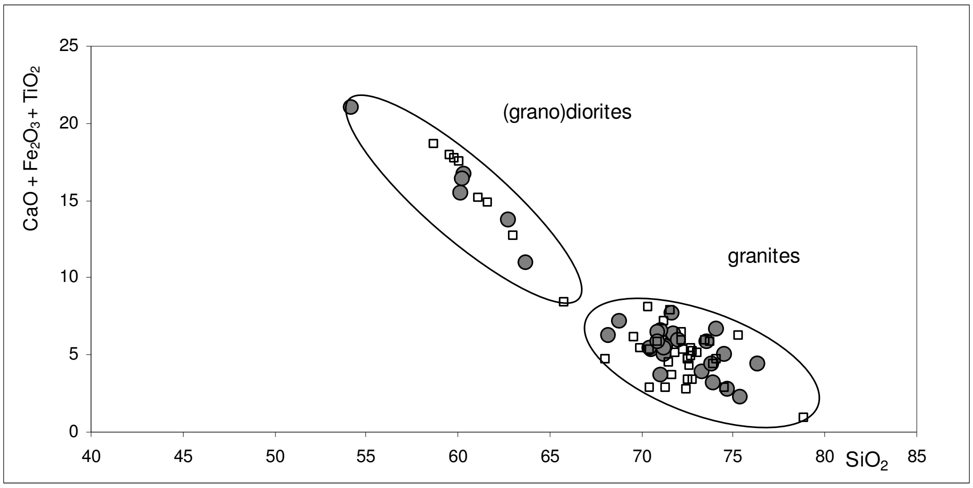

Figure 77 - SiO_2 vs (CaO+Fe_2O_3+TiO_2) variation diagram showing the separation between granite and tonalite (± granodiorite) groups and a good correspondence between quarry and archaeological samples; full circles: quarry samples; empty squares: archaeological samples.

Parallel to chemical characterisation and classification, the determination of total water porosity (and densities) of a few Aswan granitoïds samples was undertaken. Synthetic results are presented per type of granitoïd in Table 9, showing as expected for that kind of stones very low values. The maximum value of about 5% for coarse pink granites is probably due to a weathered state of the corresponding sample.

Type	Total water porosity (%)	Solid density (g/cm^3)	Bulk density (g/cm^3)
(a) Coarse pink granite 20 samples	0,5 / 4,5 / 1,1	2,65 / 2,77 / 2,69	2,56 / 2,74 / 2,66
(b) Granodiorite 7 samples	0,3 / 0,6 / 0,4	2,68 / 2,91 / 2,84	2,67 / 2,90 / 2,82
(c) Fine pink granite 5 samples	0,3 / 1,4 / 0,8	2,63 / 2,69 / 2,65	2,61 / 2,61 / 2,63

Table 9 – Total water porosity (and densities) of Aswan quarries granitoïds samples: Mininum / Maximim / Average values.

In intermediate conclusion, on the basis of petrographic observations and chemical measurements (notably major elements contents), the granitoïd (megascopically coarse pink granites and dark-grey granodiorite) samples from Aswan quarries are monzogranite (± syenogranite) and tonalite (± granodiorite) as those from archaeological objects. Then in accordance with bibliography **Aswan granitoïd quarries** are the provenance area of the stone of the whole studied archaeological objects made of coarse pink granite or dark-grey granodiorite from Alexandria Lighthouse.

4.2. SILICEOUS SANDSTONES

Among the sixty-seven stone samples collected from monuments and artefacts of Alexandria Lighthouse, nine (referenced A8, A10, A11 and A12, A54, A59, A62, A64 and A66) are siliceous sandstones that megascopically can be described as fine-grained to coarse-grained (almost conglomeratic) more or less bedded materials with beige-yellowish to ochre-brownish color.

4.2.1. Investigated quarries

According to bibliography (De Putter et Karlshausen, 1992, Klemm et Klemm, 1993, Ashton et al., 2000), the siliceous sandstones used in ancient times are commonly reputed coming from two specific areas of Egypt: Gebel Ahmar deposit located in the eastern suburb of Cairo and nowadays covered by the new town of Nasr City and in vicinity of Gebel Tingar, Gebel Gulab area on the western bank of the Nile river opposite Aswan.

The **Gebel Ahmar siliceous sandstone deposit** (coordinates: N30°3.15' - E31°17.8') belongs to the “Gebel Ahmar Formation” (Oligocene) and was exploited from the Old Kingdom to the Roman period. It supplied (Harrel et al., 1996) a light grey or red to mainly various shades of brown (Figure 78), medium- to coarse-grained, commonly pebbly, quartz- cemented stone (orthoquartzite).

The **Gebels Gulab and Tingar siliceous sandstone deposits** (coordinates: N24°6.4’ - E32°52.6’) belongs to the “Umm Barmil Formation” of the Nubia Group (Upper Cretaceous) and was exploited from the New Kingdom period to the Roman period. They supplied according to Harrel (1996) a light grey to mainly various shades of brown, rarely purplish red (Figure 79), fine to medium-grained and occasionally pebbly, quartz-cemented stone (orthoquartzite).

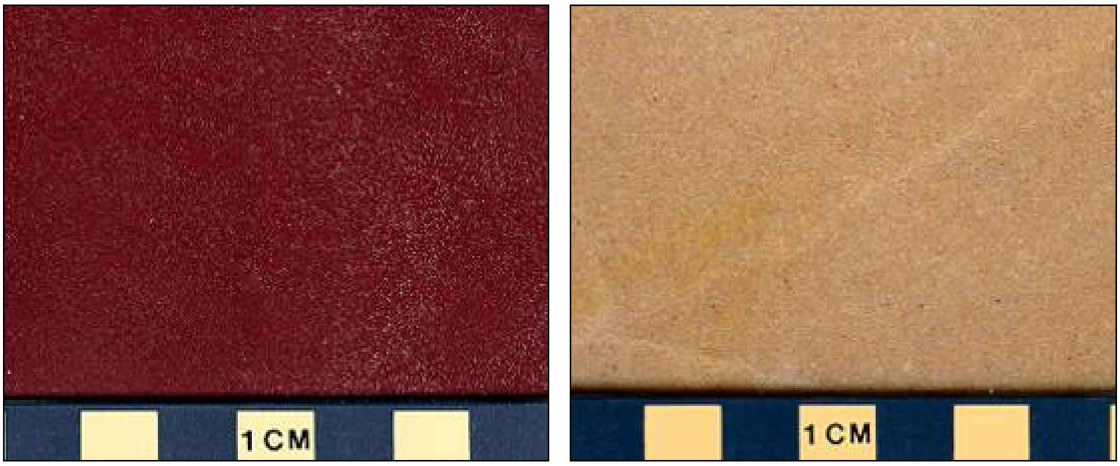

Figure 78 - Megascopic views of Gebel Ahmar siliceous sandstones (from J.A. Harrel, modified, http://www.eeescience.utoledo.edu/Faculty/Harrell/Egypt/Quarries/Quarries_Menu.html).

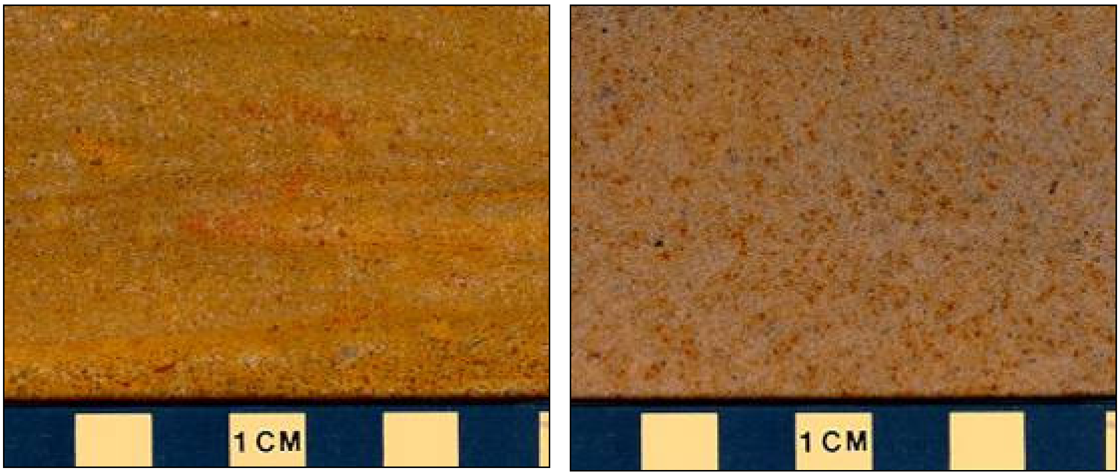

Figure 79 - Megascopic views of Gebels Gulab and Tingar siliceous sandstones (from J.A. Harrel, modified, http://www.eeescience.utoledo.edu/Faculty/Harrell/Egypt/Quarries/Quarries_Menu.html).

According to Ashton et al. (2000), the various colors for both quarries areas are linked to variable contents of iron oxides (hematite and goethite) in the quartz cement and the purplish one is caused probably by manganese oxides.

Based on bibliography, the survey of both areas was carried out and representative samples were collected.

Gebel Ahmar quarries area survey:

The “Gebel Ahmar” ancient quarries mentioned in the bibliography have unfortunately been destroyed during last years due to the extension of Cairo city. Their outcropping area is nowadays occupied by buildings and only two siliceous sandstone outcrops were encountered, investigated and sampled (Figure 80).

Figure 80 – Overview (Google Earth) of Gebel Ahmar area: location of the two sampled sandstone outcrops (and detail of their geographic coordinates).

The first outcrop (Figure 81) lies close to “Autostrad Road” and near the gate of the “Arab Contractors Club”. It corresponds to the remains of a small hill and is constituted of many sandstone blocks distributed in an area about one hundred metres long. The sandstones present different colors ranging from yellowish to red-brownish. They look hard, silicified and contain pebble fragments (pebbly sandstone).

Figure 81 – Views of the first sandstone sampled outcrop of Gebel Ahmar.

The second outcrop (Figure 82) lies in the back side of the “Arab Contractor Club” forming sequence (about 50 metres of thickness) of vary colored, yellow, red, dark red and yellowish white, bedded sandstones with some conglomerate intercalations containing flint pebbles and silicified wood fragments.

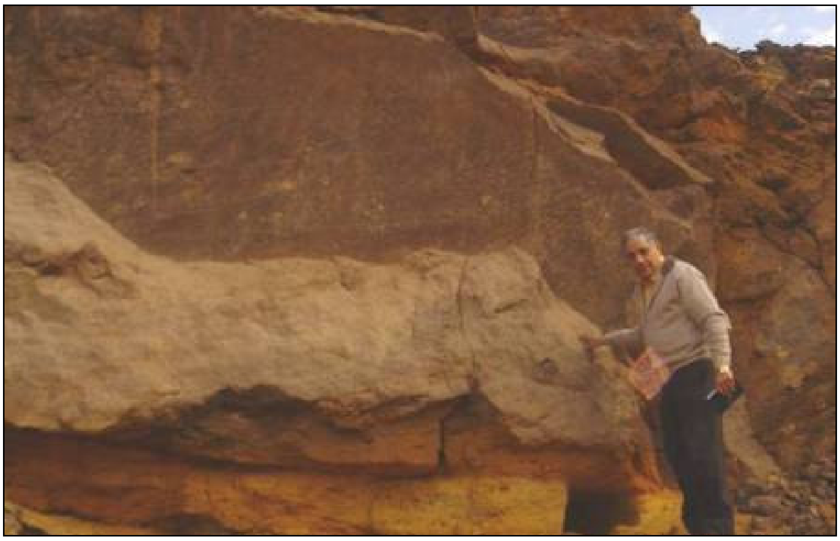

Figure 82 – View of the second sandstone sampled outcrop of Gebel Ahmar.

Gebel Gulab quarries area survey:

The ancient siliceous sandstones quarries lay in the vicinity of Gebel Gulab area opposite to Aswan city on the west bank of the Nile River (Figure 83; Klemm et Klemm, 1993, Bloxam et al., 2007). The Gebel Gulab silicified sandstones quarries correspond to a specific restricted area showing high silicified facies ranging in color from beige to brownish, pinkish to reddish (Figure 84).

The sandstones of the studied area are related to the upper part of Nubia Formation (Upper Cretaceous age) and more precisely to the Um Barmil (Taref sandstones) formation (Klitzsch, 1990, Isawi et al, 1999). The Taref sandstones (Coniacian and / or Santonian age) are mainly formed of about one hundred metres of cross bedded sandstones showing every kind of lithological variations: silicified, quartzitic, quartzose, more or less ferruginous, magniferous, soft to hard well cemented, fine to coarse-grained, moderately sorted and partially conglomeratic (Figure 84).

Traces of ancient exploitation are numerous on a large area (Figure 85) about five hundred metres long.

Figure 83 – Location map of the Gebel Gulab silicified sandstones quarries located north Aswan city (from Klemm et Klemm, 1984).

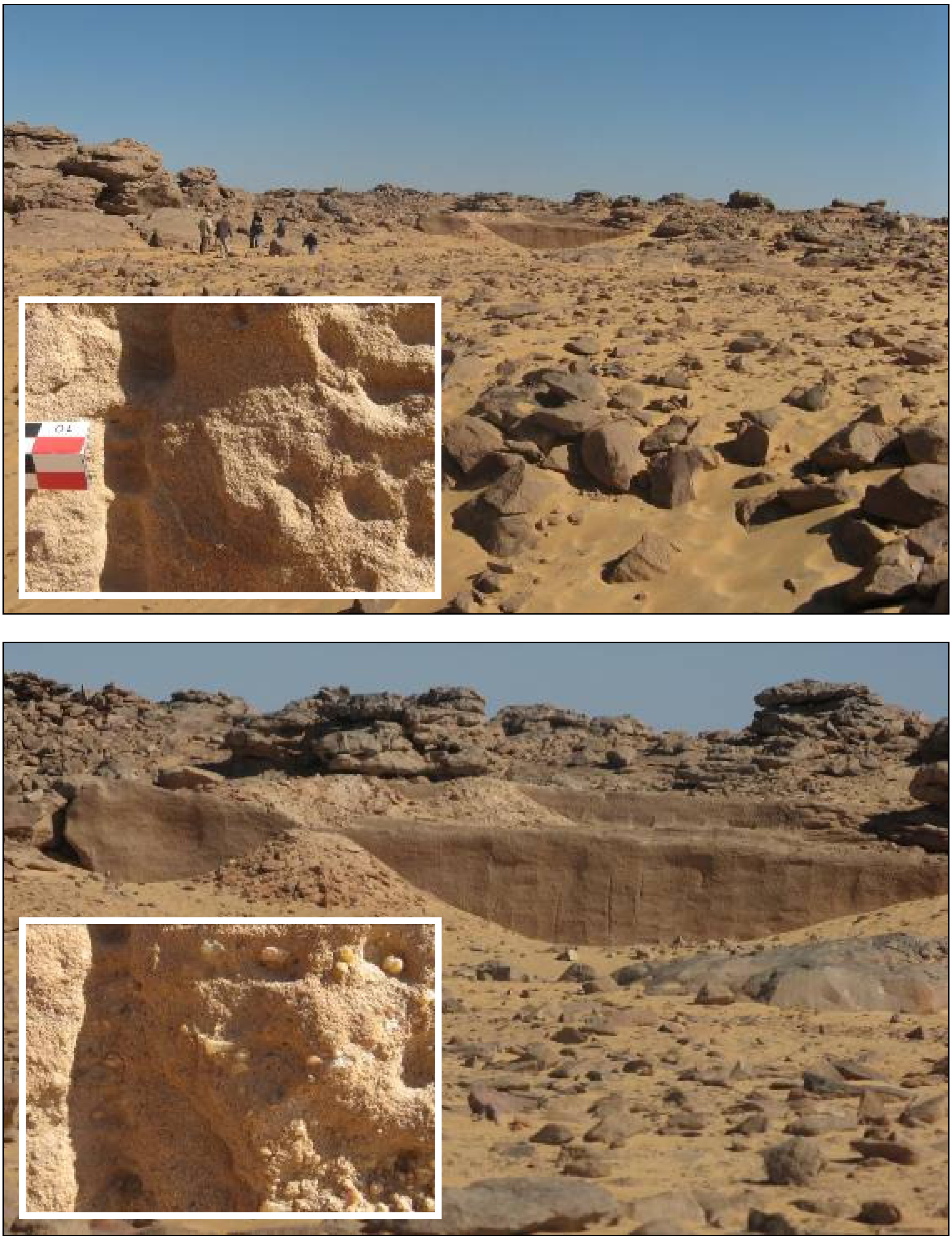

Figure 84 – Overviews of one silicidfied sandstone quarry in Gebel Gulab area with megascopic views of variation of facies (from fine to coarse-grained, moderately sorted).

Figure 85 – Traces of ancient exploitation in Gebel Gulab quarries area: (up) remain of an unfinished obelisk and (down) traces of tools (pick).

4.2.2. Characterisation of the stones and comparison to those from monuments and artefacts

Four siliceous sandstone samples from Gebel Ahmar area (ref. A117 and A 119 to A121) and eight from Gebel Gulab area (ref. A122 to A129) were collected and submitted to the same procedure of chemical analyses than those collected on Alexandria Lighthouse objects (cf.3.3.2).

The whole analytical data measured on these samples are detailed in Appendix 3. According to microscopic observations and sedimentary rocks usual classifications, the samples from both provenance areas can be characterized as **quartzarenites** (Scolari et Lille, 1973) or **orthoquartzite** (Folk, 1954).

Gebel Ahmar sandstones:

Petrographically (Figure 86 and Figure 87), the studied siliceous sandstones are composed mainly of quartz grains (>95% of the framework) moderately to well sorted, medium to coarse and sub-rounded to rounded. The grains are mostly monocrystalline (rarely polycrystalline), some show waving extinction and other inclusions of zircon or rutile. The other detrital grains are represented by feldspars and chert fragments that are the main lithic fragments. Most of 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 the whole studied samples. These overgrowths are separated from detrital core by a thin line of impurities represented by clayey material but mainly by iron oxide which stained the quartz detrital grains before enlargement. Quartz grains are highly packed and interlocked forming mosaic texture.

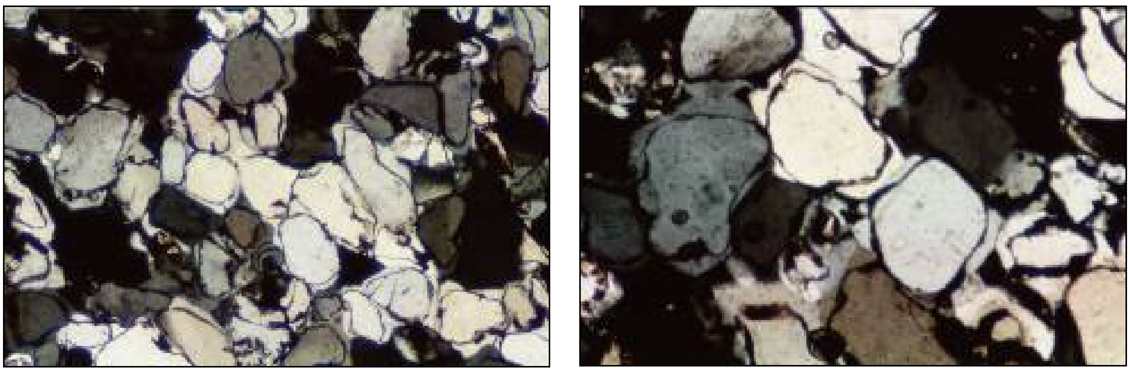

Figure 86 - Microscopic observations (N+; magnification x70 and x110) of siliceous sandstone sample (A119) from Gebel Ahmar: orthoquartzite with interlocked grains forming mosaic texture and quartz overgrowth.

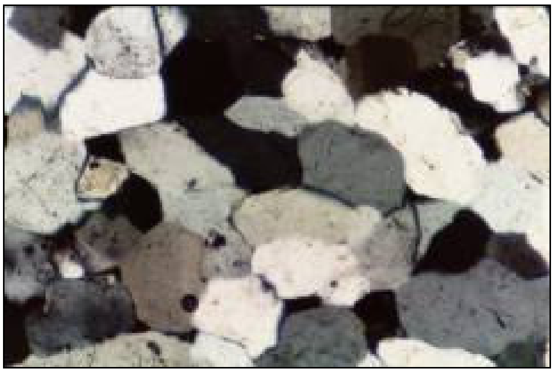
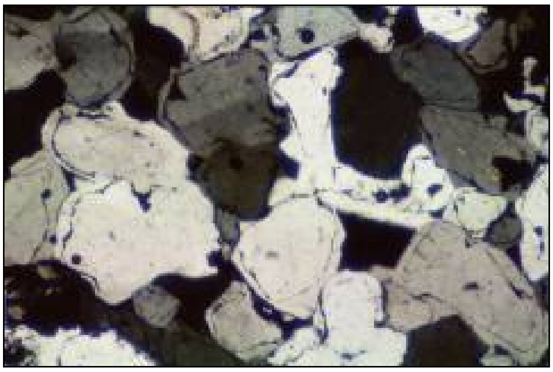

Figure 87 - Microscopic observations (N+; magnification x70 and x110) of siliceous sandstone samples (left: A119; right: A121) from Gebel Ahmar: orthoquartzite with interlocked grains forming mosaic texture and quartz overgrowth.

Gebel Gulab sandstones:

Petrographically, the samples are orthoquartzite composed mainly of sub-angular to sub-rounded quartz grains, interlocked forming a mosaic texture and slightly to moderately sorted (Figure 88). In some samples, quartz grains display a slight sedimentary syntaxial overgrowth (Figure 89).

Figure 88 - Microscopic observation (N+; magnification x110) of silicified sandstone sample (A125 = unfinished obelisk) from Gebel Gulab: orthoquartzite with interlocked grains slightly silificified.

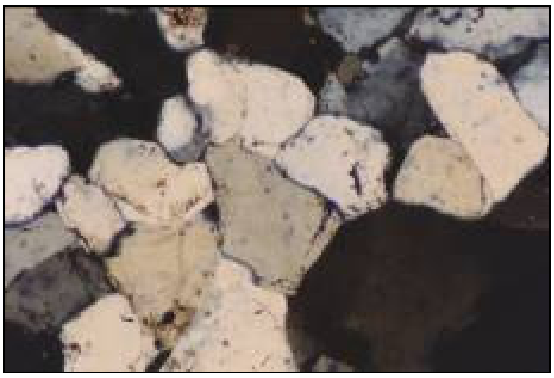


Figure 89 - Microscopic observations (N+; magnification x110) of silicified sandstone samples (left: A131; right: A129) from Gebel Gulab: quartz grains showing slight sedimentary syntaxial overgrowth.

According to microscopic observations, the sandstones samples from Gebel Ahmar are very similar to those from Gebel Gulab. Both are orthoquartzites made of more than 90% of coarse to medium-size quartz grains. One slight difference is the roundness of their grains, more rounded (sub-rounded to rounded) in the samples from Gebel Ahmar than in the Gebel Gulab ones (sub-angular to sub-rounded). Another discriminatory parameter is the presence of chert grains in Gebel Ahmar samples. These results are conformed to bibliographic data (Aston et al., 2000): the quartzites from the two areas are usually indistinguishable megascopically and in thin section, they differ mainly in the roundness of their grains. Chert pebbles (when present) also permit to identify microscopically (and megascopically) Gebel Ahmar sandstones.

The presence of chert pebbles and the roundness (sub-rounded to rounded) of quartz grains in the samples collected on Alexandria Lighthouse objects (samples A8, A10, A12 and A13 from outer exhibited objects and A54, A59, A62, A64 and A66 from still underwater objects) seem to indicate that **Gebel Ahmar** was the area of provenance of these stones.

From a geochemical point of view (whole chemical data in Appendix 3), the samples from Gebel Ahmar are also very similar to those from Gebel Gulab and no chemical element seems to discriminate the two considered quarries areas. As any quartzarenite, the whole samples contain a high proportion of Siliciium (average about 91% ranging from 88% to 96%). No other major element is detected in significant proportion and K_2O, MgO and MnO are not detected at all. In terms of chemical signature, the one major element present in the whole samples is Titanium (Figure 90) that seems to be present in higher content in Gebel Gulab samples. Nevertheless according to the limited number of samples, this result cannot be considered as definitive.

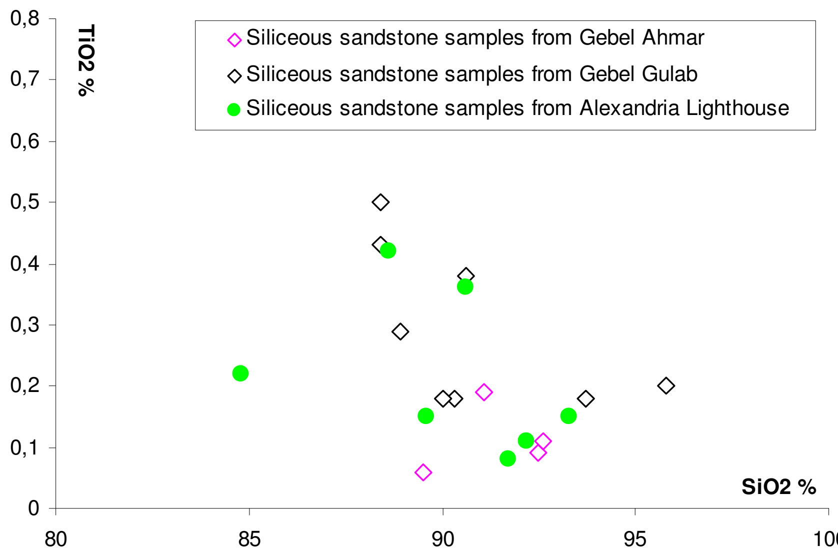

Figure 90 - Covariation of major element TiO_2 versus SiO_2 for the siliceous sandstone samples of Gebel Ahmar and Gebel Gubab; comparison to the samples from Alexandria Lighthouse.

By comparing the major elements contents measured on samples from both quarries areas to those from Alexandria lighthouse objects made of siliceous sandstones (samples A8, A10, A12 and A13 from outer exhibited objects and A54, A59, A62, A64 and A66 from still underwater objects), similar values are observed.

About trace chemical elements, the most significant ones are Zirconium and Strontium with average contents of 97 and 20 ppm for Gebel Ahmar samples and 89 and 19 ppm for Gebel Gulab samples (Figure 91). Traces of Barium, Chromium, Nickel, Zinc and Vanadium are also detected in many samples.

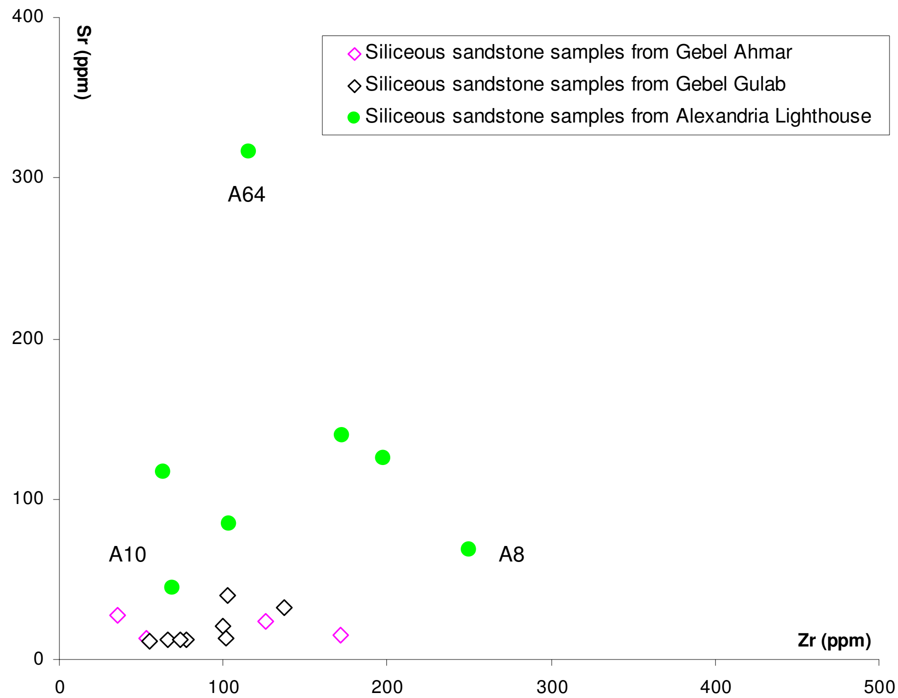

Figure 91 – Zirconium versus Strontium contents diagram of the samples from Gebel Ahmar and Gebel Gulab quarries areas and comparison to those from Alexandria Lighthouse objects.

Zirconium and Strontium values measured on Gebel Ahmar and Gulab quarries samples are compatible to those measured by Klemm et al. (1984, 1993) on other series of samples collected in the same quarries areas (Zirconium ranging from 10 to 130 ppm for Gebel Ahmar and 15 to 110 ppm for Gebel Gulab; Strontium ranging from 3 to 19 ppm for Gebel Ahmar and 3 to 18 ppm for Gebel Gulab).

Zirconium content in archaeological samples (ranging from 35 to 172 ppm) is rather similar to the one measured on both quarries areas. On the other hand, Strontium content is slightly (for samples A8 and A10) to clearly higher (for samples A59, A62, A64 and A66) to the one from both quarries areas (Figure 91). The measured values range from 45 to 316 ppm with an average content of 128 ppm. A first explanation could be another provenance area still unknown for the siliceous sandstone constituting these objects. Nevertheless, the most probable explanation is the underwater impact on archaeological objects by presence of remains in the samples of

marine concretions rich in Strontium (by memory, the sea water contains about 8 mg of Strontium per litre).
This hypothesis seems to be confirmed by the two samples A8 and A10 collected on cleaned and desalinated objects that show lower values of Strontium than the still “raw” underwater objects samples.

Concerning other trace elements detected on many samples (Chromium, Nickel, Zinc and Vanadium, present in very limited contents) from Gebel Ahmar and Gebel Gulab quarries they are confronted to those from Alexandria lighthouse samples in Figure 92. According to this graph, many quarries samples show more non detected trace elements than the archaeological objects ones.

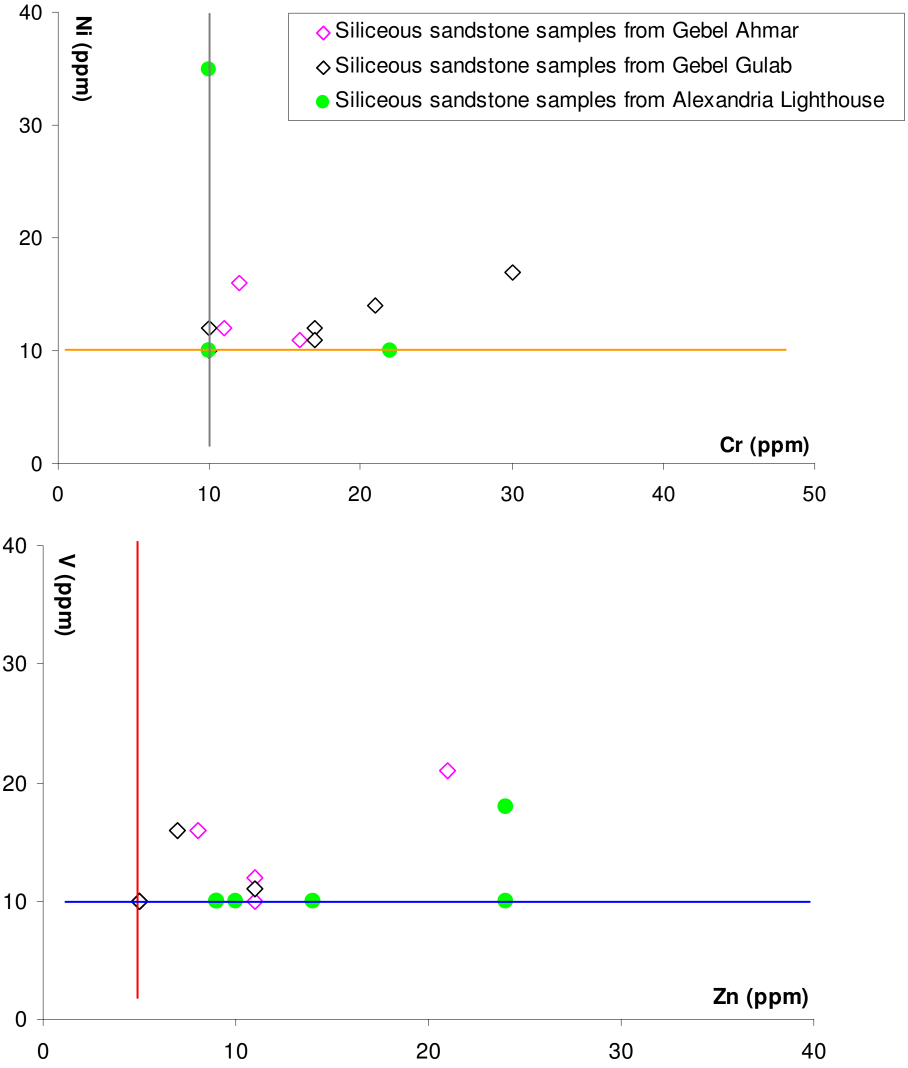

Figure 92 – Zirconium versus Strontium contents diagram of the samples from Gebel Ahmar and Gebel Gulab quarries areas and comparison to those from Alexandria Lighthouse objects (orange line = limit of detection of Ni; grey line = LD of Cr; red line = limit of detection of Zn; blue line = limit of detection of V).

Klemm et al. (1984) tried a discrimination of both areas using trace elements contents plotted in bivariable (Rb/Sr, Sr/Zr) or trivariable diagrams (2xPb/2xCu/Zn or 20xNi/10xCo/Mn) but the results are moderately convincing.

In intermediate conclusion, on the basis of petrographic observations the siliceous sandstone samples from Gebel Ahmar and Gebel Gulab quarries areas are both orthoquartzites made of about 90% of coarse to medium-size quartz grains and are similar to those from Alexandria Lighthouse objects. Concerning chemical measurements (major and trace elements contents) the obtained values from both quarries samples are similar and compatible to those from the archaeological objects without highlighting any discriminatory parameter of provenance. Only the presence of chert pebbles and the roundness (sub-rounded to rounded) of quartz grains in the whole archaeological samples (A8, A10, A12 and A13 from outer exhibited objects and A54, A59, A62, A64 and A66 from still underwater objects) as in Gebel Ahmar quarries ones seem to indicate in accordance with bibliography that **Gebel Ahmar silicified sandstone quarries** (near Cairo) are the provenance area of the stone of these archaeological objects from Alexandria Lighthouse.

4.3. WHITE MARBLES

Among the sixty-seven samples collected on monuments and artefacts from Alexandria Lighthouse, two ones (samples A16 and A71) are marbles *sensu stricto* (pure white crystalline marbles)

According to analytical results (cf. Paragraph 3.3.3), the two studied objects are sculpted in two imported medium to coarse grained classical white marbles very appreciated and largely distributed during the Roman age: the Thasian marble from Vathy (Greece) and the proconnesian marble from Turkey.

As a consequence, no search and study of local marbles was necessary to undertake. Nevertheless, it is interesting to introduce the question of Egyptian white marbles. The most important and one well-attested ancient Egyptian marble deposit (Harrel et al., 1996) is located at Gebel Rokham near Wadi Mia, Eastern Desert (coordinates: N25°17.95' - E33°57.85') and was exploited from the New Kingdom period to the Roman period. Nowadays, the ancient workings have been destroyed by modern quarrying but the original tailings still exist (Brown and Harrel, 1995).

According to Ashton et al. (2000), the marble extracted (Precambrian basement aged) is variously colored and banded to mainly white, fine-grained; calcitic with minor brucite and dolomite and rare quartz. Isotopic signature of Gebel Rokham marble (Brown et Harrel, 1995) expressed in terms of $\delta^{13}C$ and $\delta^{18}O$ values in ‰ relative to the international reference standard PDB (Craig, 1957) is +3,45 and +11,91.

Other marble deposits are known in Egypt in the same part of the Eastern Desert and also in the desert at the West and East of Kerma (De Putter et Karlshausen, 1992).

4.4. GREYWACKES

Among the sixty-eight stone samples collected on monuments and artefacts from Alexandria Lighthouse, two ones (samples A9 and A69) are greywackes (cf. paragraph 3.3.4 for the whole corresponding data). Any *in situ* investigation was carried and the search of the provenance of the greywacke was restricted to the phase of bibliography study.

4.4.1. Investigated quarries

Various authors (Klemm et Klemm, 1993; Harrel et al., 1996; Ashton et al., 2000) indicate that the most important ancient greywacke deposit is located in the Wadi Hammamat, Eastern Desert (coordinates: N25°59.4' - E33°34.05') and was exploited from the Early Dynastic period to the Roman period. Other authors (De Putter et Karlshausen, 1992) specify that Wadi Hammamat is not the one greywacke outcrop in the Eastern Desert and indicate other workable outcrops in an area comprised between N25 to 28° and E33 to 34°.

The greywacke deposit (Precambrian basement age) range from dark greenish-grey to mainly greyish-green in color and from medium to very fine-grained (Figure 93), occasionally pebbly, and talk about chloritic greywacke metasandstone to coarse-grained metasiltstone (the prefix 'meta' means "slightly metamorphosed").

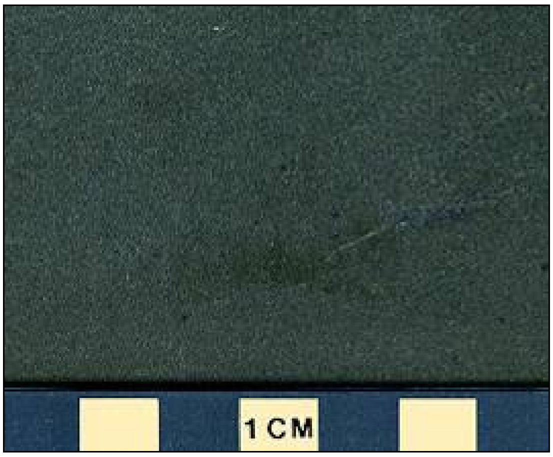

Figure 93 - Megascopic views of Wadi Hammamat Greywackes (from J.A. Harrel, modified, http://www.eeescience.utoledo.edu/Faculty/Harrell/Egypt/Quarries/Quarries_Menu.html).

The ancient quarries in the Wadi Hammamat area (Figure 94) occur along a stretch of the Wadi just over one kilometer in length, containing grey siltstones and greywackes, recovered by many inscriptions (Figure 95 left). Numerous tool traces are also observable (Figure 95 right). In accordance with Ashton et al. (2000), siltstone and greywacke are distinguishable by the granular nature of the greywacke visible to naked eye whereas siltstone has a fine appearance with small grains not distinguishable without microscope.

Figure 94 - Views of Wadi Hammamat Greywackes ancient quarries area.

Figure 95 – Megascopic views of Wadi Hammamat greywackes ancient quarries area: inscriptions and tool traces.

4.4.2. Characterisation of the stones and comparison to those from monuments and artefacts

Six greywacke samples from Wadi Hammamat area (ref. A131 to A136) were collected and submitted to the same procedure of chemical analyses than those collected on monuments and artefacts from Alexandria Lighthouse (cf. 3.3.4). The whole analytical data measured on these samples are detailed in Appendix 5.

According to microscopic observations and sandstones usual classifications (Pettijohn et al., 1987), the collected samples can be classified as metamorphosed siltstone (meta-siltstone) and greywacke metasandstone.

The siltstone sample (A136) is built up mainly of rather well-sorted silt-size grains (0.02 to 0.05mm) giving a fine homogeneous appearance. The grains are formed of quartz with minor plagioclase in a fine-grained matrix made of quartz and muscovite, plus rare epidote, chlorite and sericite (Figure 96).

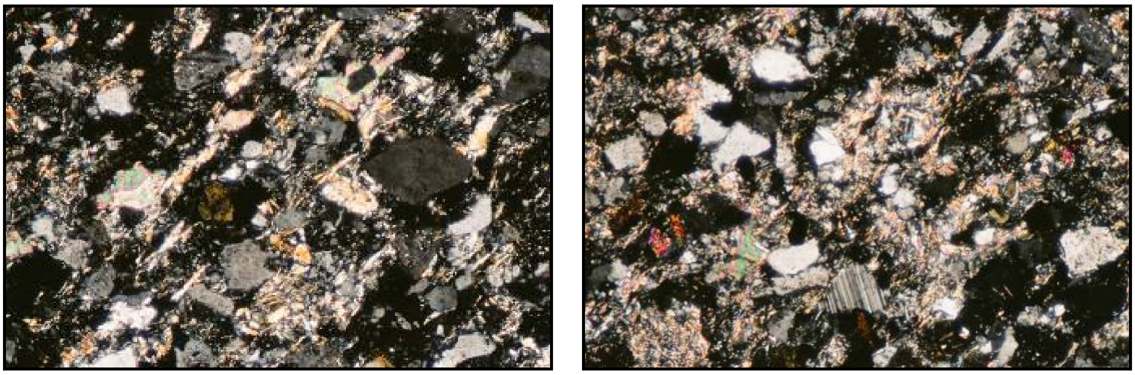

Figure 96 - Microscopic observations (N+; magnification x110) of metasiltstone sample (A136) from Wadi Hamamat quarries area (left = sort of foliation).

Greywacke samples (other samples than A136) are formed of fine to medium poorly sorted sub-rounded grains (0.05 to 0.15 mm) consisting mainly of quartz and plagioclase, lithic fragments and rare muscovite (Figure 97). The grains are lightly cemented by a matrix (representing more than 40% of the rock volume) formed mainly silt and clay-sized grains of quartz and feldspar, chlorite and sericite, and calcite and epidote as minor minerals.

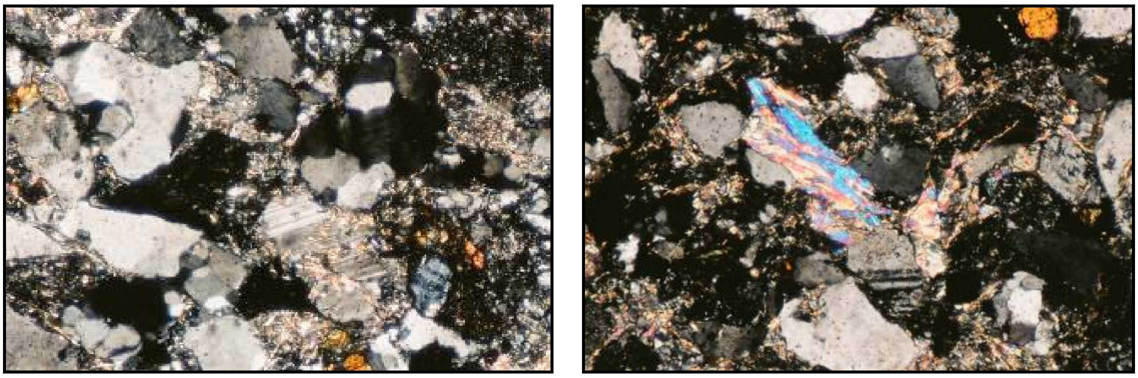

Figure 97 - Microscopic observations (N+; magnification x110) of greywacke samples (left: A133; right: A135) from Wadi Hamamat quarries area (right = muscovite and plagioclase crystals).

According to microscopic observations, the greywacke *s.l* (greywacke *s.s* and metasiltstone) samples from Wadi Hammamat are very similar to those from Alexandria lighthouse objects (greywacke *s.s* sample A9 from outer exhibited objects and metasiltstone A69 from still underwater objects).

From a geochemical point of view (whole chemical data in Appendix 5), the major element contents measured on two samples from Wadi Hammamat (samples A133 and A136) are Siliciium (72.3 and 65.5%), Aluminium (12.1 and 14.1%) and Iron (4.2 and 5.5%). These results are conformed to those obtained by Holail and Moghazi (1998) under a series of greywacke and siltstone samples chosen to cover variations in color and grain size among siltstone and greywacke beds of Wadi Hammamat area (Figure 98). NaO_2 was not determined but an average value about 3% was determined by the same authors.

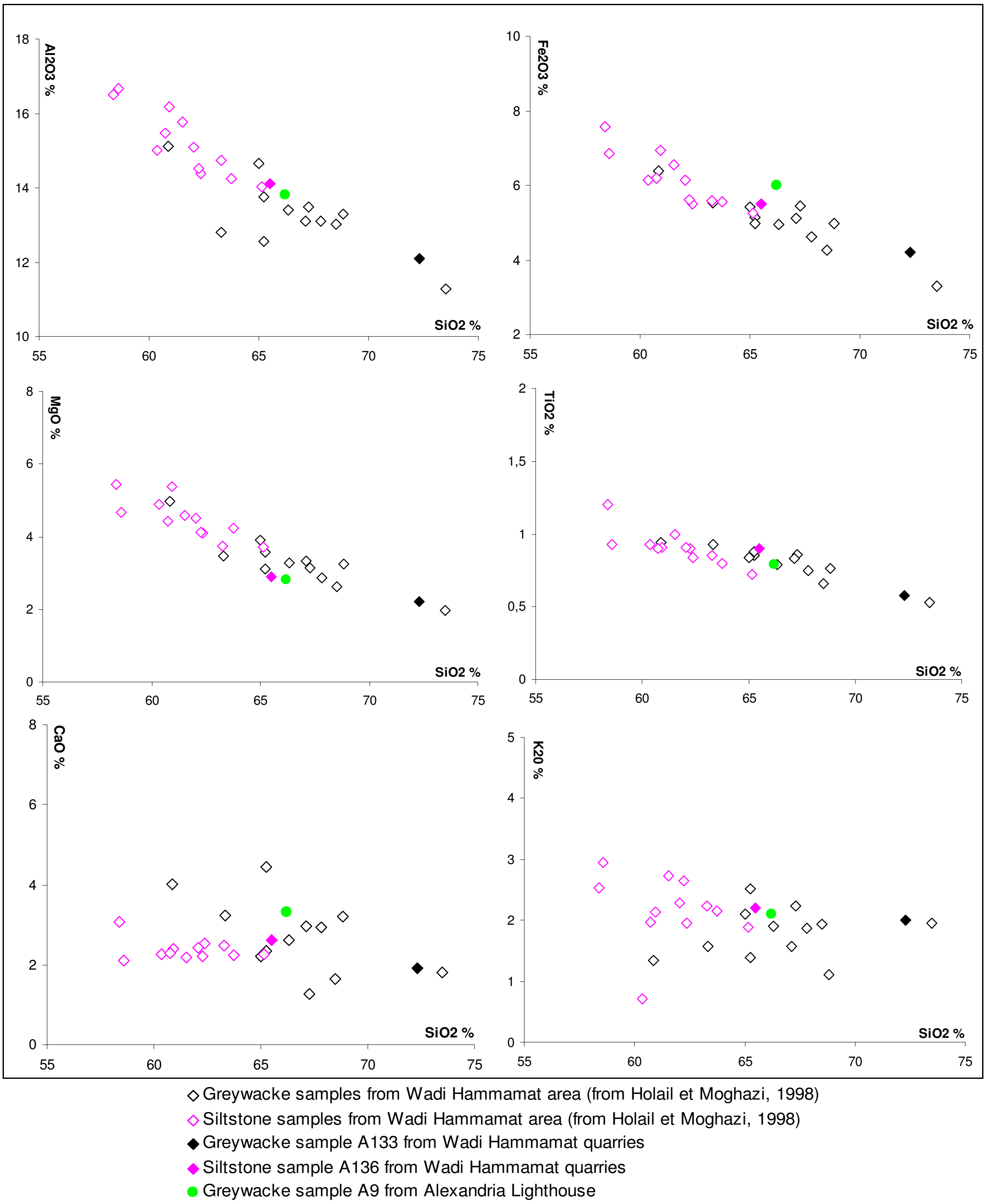

Figure 98 – Covariation of major elements versus SiO_2 for the greywackes and siltstones of Wadi Hammamet (from Holail et Moghazi, 1998, modified); comparison to quarries samples (A133 and A139) and sample A9 from Alexandria Lighthouse; notice the negative correlations of SiO_2 versus TiO_2, Al_2O_3, Fe_2O_3 and MgO.

Concerning the trace elements values, the most significant ones measured on both samples (A133 and A136) from Wadi Hammamat are Barium (607 and 538 ppm), Strontium (305 and 278 ppm), Zirconium (118 and 226 ppm), Chromium (104 and 144 ppm), Vanadium (100 and 116 ppm), Zinc (59 and 84 ppm), Nickel (63 and 60 ppm) and Cerium (39 and 55 ppm). As major elements, these data are conformed to those obtained by Holail and Moghazi (1998) under a series of greywacke and siltstones samples from the Wadi Hammamat area (Figure 99).

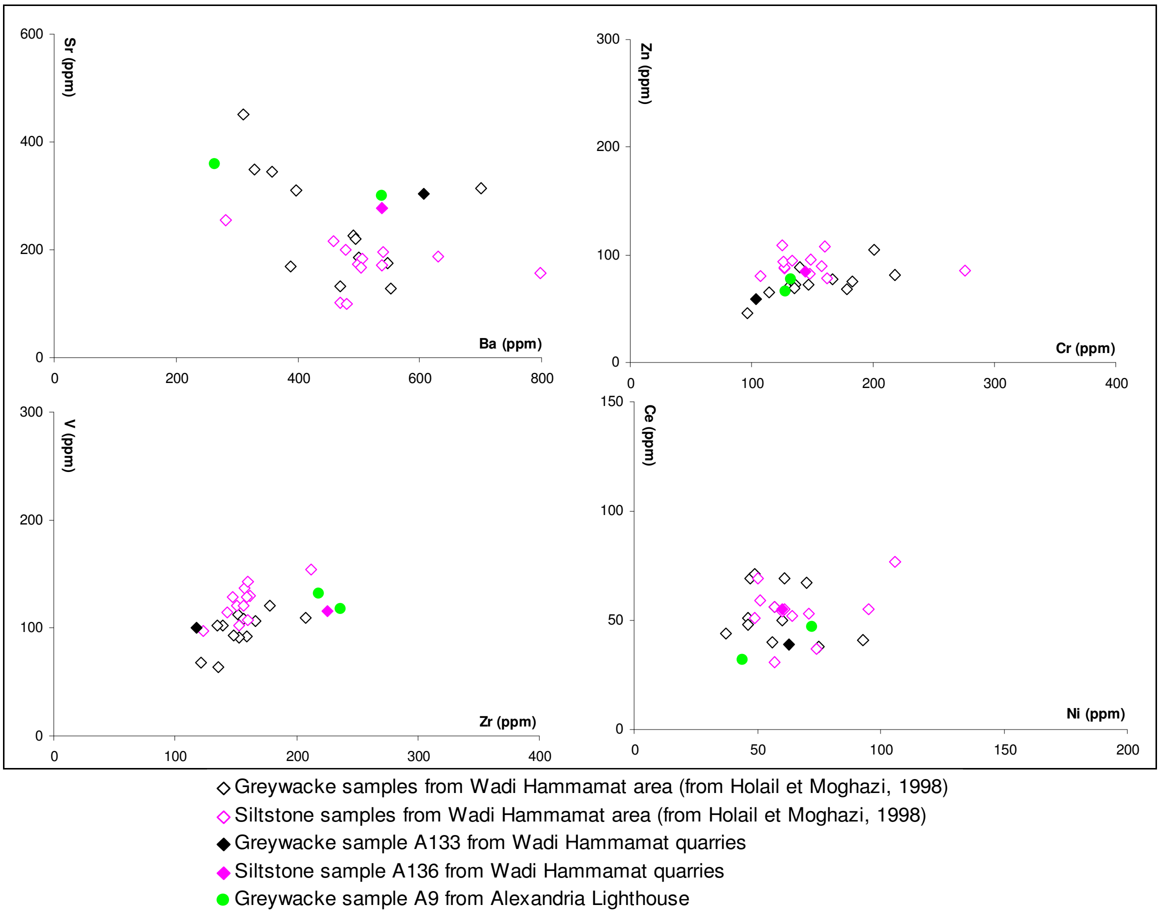

Figure 99 – Plots of Ba/Sr, Cr/Zn, Zr/V and Ni/Ce illsutrating the chemical signature of the greywackes and siltstones of Wadi Hammamet (from Holail et Moghazi, 1998, modified); comparison to quarries samples (A133 and A139) and samples A9 and A69 from Alexandria Lighthouse.

By comparing the chemical data measured on the whole samples from Wadi Hammamat area to those from Alexandria lighthouse objects (greywacke *s.s* sample A9 from outer exhibited objects and metasiltstone A69 from still underwater objects), similar values are observed (Figures 98 and 99).

In intermediate conclusion, the previous petrographic observations and chemical measurements (major and trace elements contents) testify that Wadi Hammamat quarries are the provenance area of graywacke (s.l.) constituting the two sampled Alexandria lighthouse objects.

4.5. LIMESTONES

Among the sixty-seven stone samples collected on monuments and artefacts from Alexandria Lighthouse, three ones are limestones of light-color (samples A3 and A4) or dark-color (sample A68). Collected on blocks constituting the base of Qaitbay Fortress (according to the hypothesis that the fortress is located in the same place than the Alexandria Lighthouse using its ruins), samples A3 and A4 belong to a same geological formation different than the one of Qaitbay bedrock (sample A5; cf. Paragraph 3.3.5). Sample A68 was kept from an archaeological object (part of prism) still underwater.

4.5.1. Investigated quarries

It is useful to remind that the provenance area of the building stones (because of the considered volumes to carry) 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 under long distance because of their high value and more limited volumes ordered. In the present case, the coastal position of outcrops could facilitate the carriage by the Mediterranean sea of the stones toward Alexandria and also farer destinations. Other farther coastal or located on Nile river banks ancient quarries could have easily supplied building materials to Alexandria City.

According to literature first, the only referenced ancient quarries near Alexandria (exploited from Ptolemaic period to Roman period) are located at the west of the City on both sides of Mariut marsh (Harrel et al., 1996) between the villages of Abu Sir (coordinates: N30°56.8’ - E29°30.0’) and Burg el-Arab (N30°55.0’ – E29°32.7’) to the South-West and El Mex (N31°9.25’ – E29°50.6’) to the North-East (Figure 100). The corresponding limestones are light-colored and their deposits belong to the Alexandria Formation of Pleistocene age. They correspond to calcarenite limestone, described by Harrel (1996) as following: fine-grained, occasionally silty/sandy (quartzose), friable, highly porous packstones to mainly grainstones (calcarenites) with mostly non skeletal carbonate grains (especially ooliths and coated grains), containing until a few percents of dolomite.

About Dark-grey limestone (sample A68) provenance, no ancient quarry is referred near Alexandria as supplying dark-colored stones. The one encountered reference (Harrel et al., 1996) deals with light to dark grey and black limestones (without supplying more petrographic details) quarrying at Wadi Abu Mu'aymil near St. Antony Monastery, in the Wadi Arab area, Eastern Desert (coordinate: N28°53.9’ - E32°19.5’) without knowledge of the period of activity. The stone belongs to the Mokattam Formation of Middle Eocene age (Lutetian stage), that supplied “silty/sandy, occasionally clayey mudstones” (Harrel, 1992, Harrel et al., 1996). By memory, sample A68 is also a mudstone containing silt-size grains of quartz and micaceous clays according to petrographic study (cf. 3.3.5). Nevertheless on the basis of few available data, it is not possible to conclude about the provenance of the dark grey-bluish limestone sample A68 even though Wadi Abu Mu'aymil quarry remains a possible provenance area, and no further investigation was undertaken for this single sample.

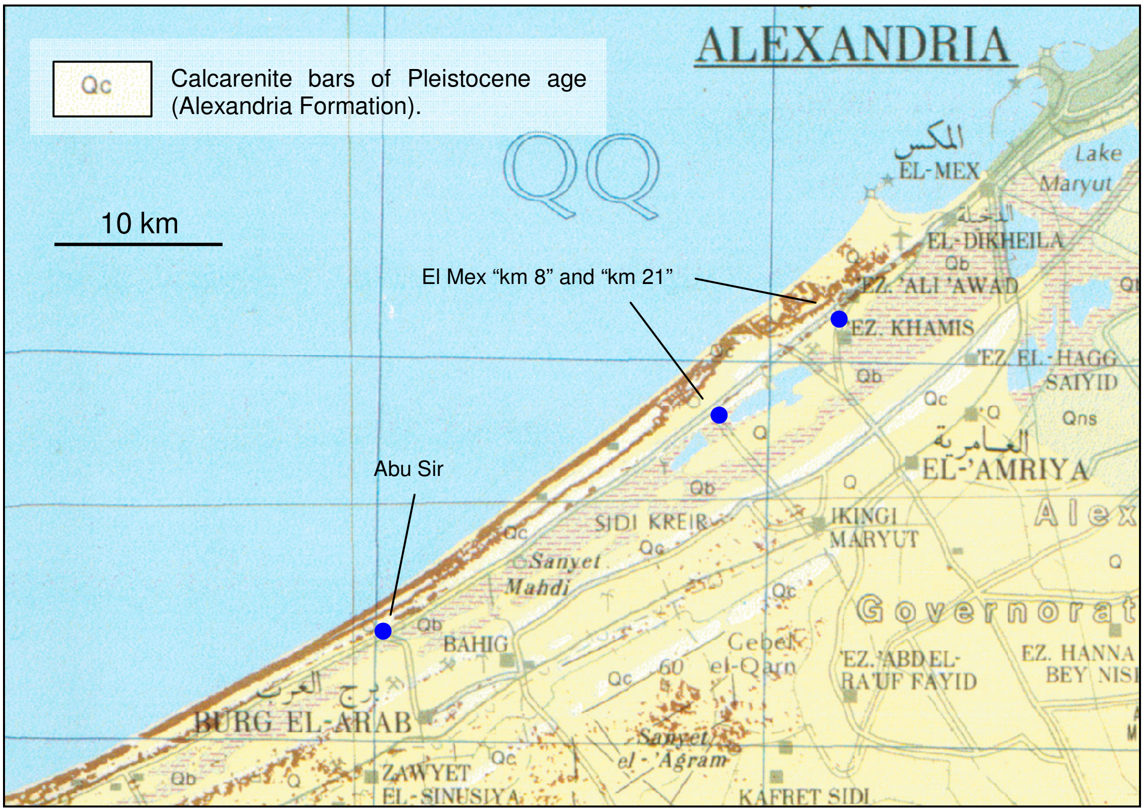

Figure 100 – Location map of the limestone quarries areas near Alexandria (from Conoco Coral, Geological map of Egypt 1:5000 000, 1986) limited to the calcarenite bars of Pleistocene age (Alexandria Formation; Qc).

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.

El Mex area is located close to Alexandria city (Figure 100). The area is nowadays occupied by many buildings and most of the quarries have been damaged due to building activities. Remains of small outcrops formed of fine grained, white chalky limestone are present in some free of construction areas (kilometer 8, Marsa Matrouh road, Alexandria; Figure 101). Moreover, some ancient (Figure 103) and recent quarries (Figure 102) are observables at kilometer 21 of Marsa Matrouh Road, Alexandria. Megascopically, the whole stones are whitish to light-beige pure limestones (carbonate content measured about 95% in average), porous to very porous (total porosity measured ranging from about 24% to over 39%), very friable, and sandy in texture. They are also weathered in surface.

Figure 101 – « km 8 » El Mex area: outcrop of whitish to light-beige porous limestone.

Figure 102 – « km 21 » El Mex area: modern quarries of whitish to light-beige porous limestone.

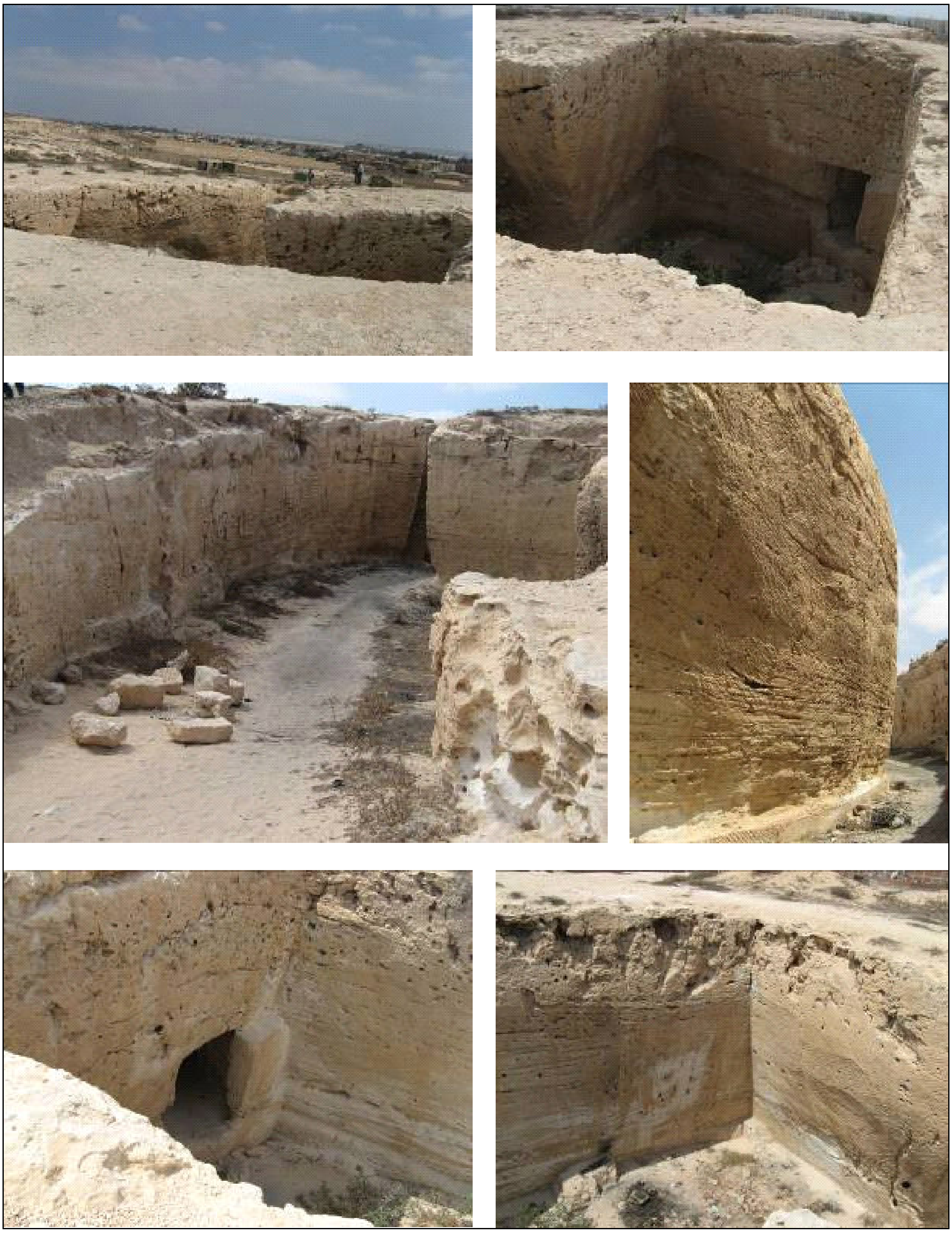

Figure 103 - « km 21 » El Mex area: ancient quarries of whitish to light-beige porous limestone.

Abu Sir ancient quarries lie about 45km to the south-west of Alexandria city (Figure 100). The main quarry corresponds to a very big and impressive one with many quarrying fronts and hosting a sedimentary lithological formation of great thickness and expanse (Figure 104). The presence of cross–bedding is very characteristic (Figure 105 up). It is a porous calcarenite limestone, light beige (unweathered surface) to beige (weathered surface; Figure 105 down), laminated or not and sandy in texture.

Figure 104 – Overview of the main quarry of Abu Sir quarries area: beige porous limestone.

Figure 105 – Views of the main quarry of Abu Sir area: beige porous calcarenite limestone with (up) typical cross-bedding and (down) intense weathering form (alveolisation).

4.5.2. Characterisation of the stones and comparison to those from monuments and artefacts

Six samples from El Mex and Abu Sir quarries areas (ref. A33 to A38) were collected and submitted to the same procedure of chemical analyses than those collected on monuments and artefacts from Alexandria Lighthouse (cf. 3.3.5). The whole analytical data measured on these samples are detailed in Appendix 6.

Microscopic examination of thin sections of **Abu Sir quarries samples** (A36 to A38) shows that they predominately calcarenite, ooid grainstone to wackestone or oosparite, consisting of ooids, well sorted, 0.2 to 0.3 mm in size and rarely of foraminifera, gastropods and skeletal fragments (Figure 106). Ooids are tangential and aragonitic. Except the tangential, micritized, superficial and complex type of ooids, very often is the presence of molds which are dissolved ooids due to their aragonitic composition during sub-aerial exposure. The degree of cementation is low. The types of cement are dog-tooth cement or micritic one in periphery of grains and meniscus cement.

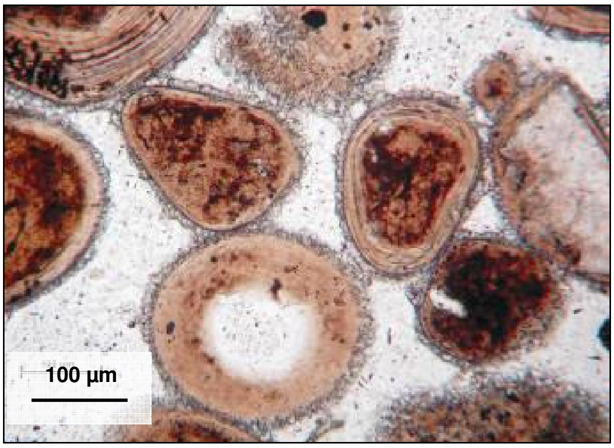

Figure 106 – Microscopic view (N//) of the Abu Sir quarry limestone (sample A37): oocalcarenite consisting of well sorted, tangential and aragonotic ooids; dog-tooth cement or micritic one in the periphery of the grains and meniscus one.

Microscopic examination of thin sections of **El Mex quarries and outcrop** samples (A33 to A35) shows that they predominately consist of ooids, well sorted, with mean size about 0.2mm and rarely of foraminifera and skeletal fragments (mainly echinoderms and red algae). Nuclei of them are mostly microcrystalline carbonate grains and less are skeletal fragments and siliclastic grains. Cortex consists of tangential predominately aragonitic lamellae. Some ooids are superficial (very few lamellae around the nuclei) and few of them are complex and oomolds. Many of ooids are micritized. Ooids are cemented by dog-tooth cement which is growing perpendicular to them and the pores are filling by granular mosaic cement (Figure 107).

Their petrographic characteristics are similar (ooid grainstone to wackestone, oosparite) to those of Abu Sir quarry samples and they are also oocalcarenite limestone. The slight differentiation concerns mainly the type of cementation: the observed types of cement are dog-tooth and granular calcitic ones.

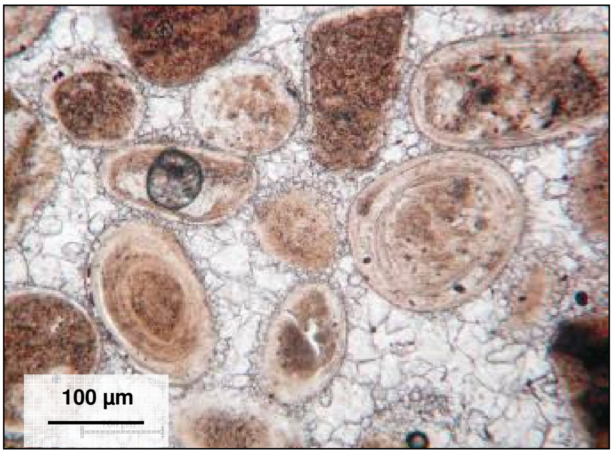

Figure 107 – Microscopic view (N//) of the El Mex quarries limestones (sample A34): oocalcarenite; dog-tooth cement or granular calcitic one.

Mineralogical analyses by X-Ray diffraction of the samples (example in Figure 108) confirm that they are pure calcium carbonates in the form of calcite and also aragonite.

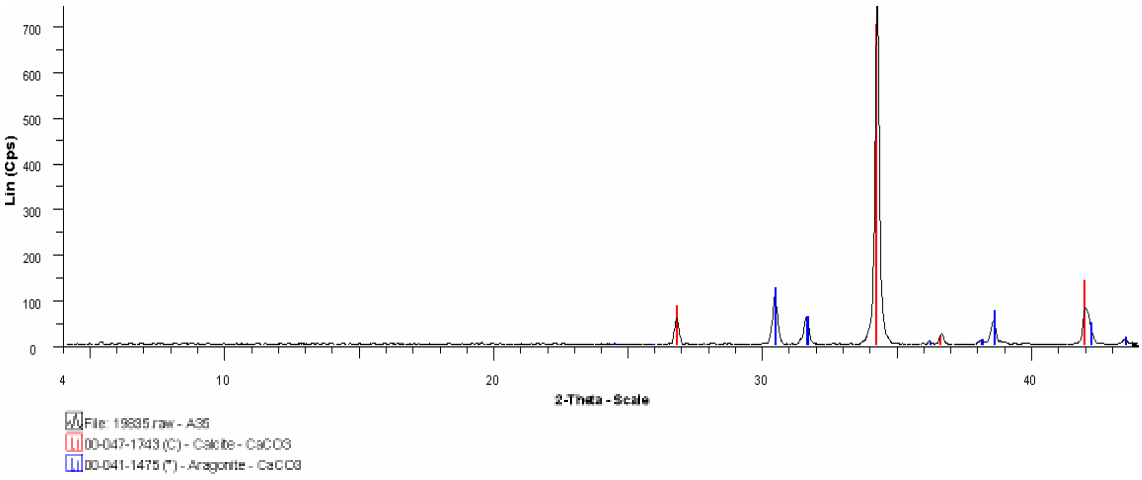

Figure 108 – X-Ray diffractogram of the limestone sample A35.

Isotopic signature of the El Mex quarries samples A33 to A35 (expressed in terms of $\delta^{13}C$ and $\delta^{18}O$ in ‰ relative to the international reference standard PDB; Craig, 1957) is plotted in Figure 109 and compared to both (A3 and A4) collected on the basement of QaitBay Fortress.

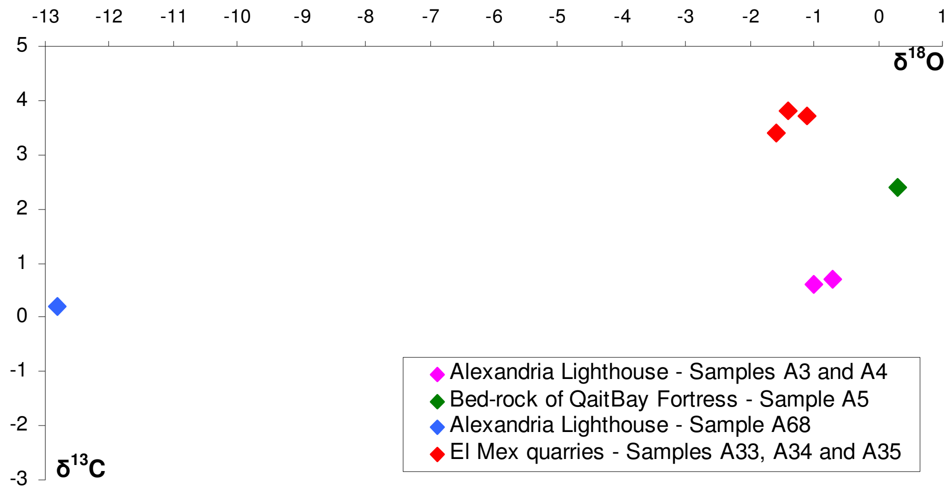

Figure 109 – Isotopic signature and comparison of the ligh-colored limestone samples from El Mex quarries (Alexandria Formation) to those from Alexandria Lighthouse (A3, A4); samples A68 (underwater object) and A5 (bedrock of Qaitbay Fortress) also plotted.

The comparison of analytical data (petrographic description and chemical results) measured on both archaeological samples A3-A4 to those of quarries samples A33 to A38 clearly indicates that El Mex and Abu Sir quarries (and more generally the Alexandria Formation) are not the provenance area of the light-colored stones nowadays constituting the basement of Qaitbay Fortress (and supposed to correspond to the ruins of the Alexandria Lighthouse).

The archaeological samples A3 and A4 are fine sandstones with dolomitic cement to sandy dolostones characterized by a calcite content ranging from 30 to almost 70% and (by difference) a high to major quartz content from 60-70 to 20-30% while El Mex and Abu Sir quarries supply almost pure calcarenite made of more than 90% of calcite. By comparing these data with those obtained by Harrel et al. (1992, 1996) on the various Egyptian limestone formations (Mokattam, Samalut, Minia, Drunka, Serai and Tarawan) used for quarrying, no lithological and mineralogical correlation was either found.

5. Conclusion

The present study titled “Atlas of the stones of Alexandria Lighthouse” was performed in the framework of the project MEDISTONE (“Preservation of ancient MEDIterranean sites in terms of their ornamental and building STONE: from determining stone provenance to proposing conservation/restoration techniques”) supported by the European Commission (research program FP6-2003-INCO-MPC-2 / Contract n° 015245).

Its scientific objective was to identify the stones (ornamental and building ones) of the Lighthouse and to determine their provenance in terms of geographic areas (and of former quarry sites when possible). The obtained data and results in an accessible form including photos and maps (so-called “Atlas”).

First of all, one should remember that the Alexandria Lighthouse was toppled into the sea. The archaeological site is nowadays essentially underwater just off the coast of Alexandria. Its ruins consist of about three-thousand architectonic blocks and statues lying on the seabed at depths between six to eight meters.

Until the beginning of modern underwater excavations only few and contradictory informations about the building materials of the Pharos were available. Some authors mentioned the Lighthouse was build of white stone whereas others indicated the presence of marble, limestone and bronze for the decorated statues. Various theories followed one another talking about local limestone, nummulitic limestone, granite, alabaster, white marble…

According to new results following many underwater excavations from 1994, Jean-Yves Empereur (Centre d’Etude Alexandrine) first made scientific and systematic investigation and review of the materials constitutive of the blocks, encountering granites essentially and sandstones as well as few graywacke, marble and limestones. The archaeologist explained the relative lack of limestone and marble blocks by three reasons: these softer stones are difficult to identify underwater after having been eroded over the centuries by marine flora and fauna, the need for chalk to manufacture cement for Alexandria city, these stones are much easier worked and therefore were taken to be re-employed in later constructions such as the fortress itself and the adjacent Ottoman tower.

Up till nowadays, the various undersea excavations in QaitBay extracted from under the sea about fifty blocks of different sizes (architectonic blocks and statues). Therefore, guided by Centre d’Etude Alexandrine (special acknowledgement to Mrs. Isabelle Hairy), an overall examination of the sites of exhibition and / or storage of these blocks reputed coming from the collapsed Alexandria Lighthouse was undertaken. A detailed study of the blocks was performed to inventory megascopically the main types of stones related to the Pharos and a first series of thirty-two samples were collected. As most of the stones related to the lighthouse are still occurring underwater, a second series of thirty-five samples was collected by diving from still underwater architectonic blocks.

The whole sixty-six archaeological samples were described megascopically and characterized in laboratory in terms of their petrographic types of stone and physical-chemical properties, classified as follows:

Fifty samples are granitoïds (forty-two coarse pink granites and eight dark-grey granodiorites) mostly grouped together in monzogranite (± syenogranite) and tonalite (± granodiorite) fields (according to chemical classification of De la Roche et al., 1980).

Nine are megascopically beige-yellowish to ochre-brownish siliceous sandstones made of fine-grained to coarse-grained (almost conglomeratic) more or less bedded materials with color and classified as orthoquartzites (according to Folk, 1954).

Two samples are medium to coarse grained pure whitish crystalline marbles.

Two look like greywackes of dark-grey color and slightly oriented texture (foliation) megascopically, classified under microscope as metasandstone and coarse-grained metasiltstone (according to Pettijohn et al., 1987).

One sample is a fine dark grey-bluish limestone, corresponding to a lime-mudstone (micrite) containing a few silt-size grains of quartz and micaceous clays.

Two samples looking like light-colored limestones megascopically are classified as fine sandstones with dolomitic cement to sandy dolostones. Contrary to the others, both were not collected on underwater archaeological objects but on blocks constituting the basement of Qaitbay Fortress according to the hypothesis that the fortress was located in the same place than the Alexandria Lighthouse using its ruins.

The search of reference quarries of the various petrographic types of stones constituting the archaeological samples was relied on bibliographic data and field investigations and sampling. Collected quarries representative samples were described megascopically and studied in laboratory before being compared to the archaeological samples.

Concerning granitoïds in accordance with bibliography, quarries were located in Aswan City area. A geological survey of modern and ancient ones was performed and thirty-two samples were collected. On the basis of their petrographic observations and chemical measurements (notably major elements contents), the granitoïds from Aswan quarries (Neoproterozoic age) are monzogranite (± syenogranite) and tonalite (± granodiorite) as the archaeological objects. Then Aswan granitoïd quarries are the provenance area of the stone of the whole studied archaeological objects made of coarse pink granite or dark-grey granodiorite from Alexandria Lighthouse.

About siliceous sandstones, the bibliography focused the quarries investigations on quarries areas of Gebel Ahmar (from “Gebel Ahmar Formation”; Oligocene age) near Cairo and Gebel Gulab (from “Umm Barmil Formation” of the Nubia Group; Upper Cretaceous age) near Aswan. Based on petrographic observations on fourteen samples collected, the siliceous sandstones from Gebel Ahmar and Gebel Gulab areas are both orthoquartzites made of about 90% of coarse to medium-size quartz grains and resemble to those from Alexandria Lighthouse. Concerning chemical measurements (major and trace elements contents) the obtained values from both quarries samples are similar and compatible to those from the archaeological objects without nevertheless highlighting any discriminatory parameter of provenance. Only the presence of chert pebbles and the roundness (sub-rounded to rounded) of quartz grains in the nine archaeological samples as in Gebel Ahmar quarries ones seem to indicate in accordance with bibliography that Gebel Ahmar silicified sandstone quarries are the provenance area of the stone of these archaeological objects from Alexandria Lighthouse.

Concerning white marbles, no search and study of local marbles was necessary. Indeed according to analytical results (specific mineralogical-petrographic methods and isotopic analysis), both samples (and their source archaeological objects) are made of two imported classical white marbles very appreciated and largely distributed during the Roman age: the Thasian marble from Vathy (Greece) and the Proconnesian marble from Turkey.

For greywackes in accordance with bibliography, quarries were located in Wadi Hammamat area (Precambrian basement age) in Eastern Desert. Fields controls were performed and six samples were collected. As the two archaeological ones, the quarries samples correspond petrographically to metasiltstone and greywacke metasandstone. According to this petrographic similarities and also concordant chemical measurements (major and trace elements contents) Wadi Hammamat quarries are confirmed as the provenance area of graywacke (s.l.) constituting the two sampled Alexandria lighthouse objects.

About the fine dark-grey limestone provenance (one single sample of lime-mudstone – micrite - containing a few silt-size grains of quartz and micaceous clays), the only ancient quarry referred in bibliography as supplying dark grey and black limestones is located at Wadi Abu Mu'aymil (Eastern Desert). Belonging to the Mokattam Formation (late Middle Eocene age), theses stones are described as “silty/sandy, occasionally clayey mudstones” (Harrel et al., 1996). On the basis of few available data and no field control undertaken for a single sample, it was not possible to conclude about the provenance of the archaeological sample even though Wadi Abu Mu'aymil quarry remains a possible provenance area.

Finally, the search of provenance of fine sandstones with dolomitic cement to sandy dolostones (two blocks nowadays constituting the basement of Qaitbay Fortress and supposed to correspond to the ruins of the Alexandria Lighthouse; resembling megascopically resembling to light-colored limestones”) focused on two quarries areas El Mex and Abu Sir (from the “Alexandria Formation”; pleistocene age) near Alexandria City. Based on petrographic observations on six samples collected, both areas supply calcarenite made of more than 90% of calcite clearly indicating that El Mex and Abu Sir quarries are not the provenance area of the current basement blocks of Qaitbay Fortress. By comparing with available data for other Egyptian limestone formations (Mokattam, Samalut, Minia, Drunka, Serai and Tarawan) used for quarrying, no lithological and mineralogical correlation was either found and the fine sandstones with dolomitic cement to sandy dolostones provenances remains still unknown.

In final conclusion, the present study tried successfully to identify the stones of the Alexandria Lighthouse and determine their provenance areas. Moreover the accomplishment of this objective, the whole gained data constitutes a knowledge improvement available for further investigations and studies dealing with Egyptian stones.

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