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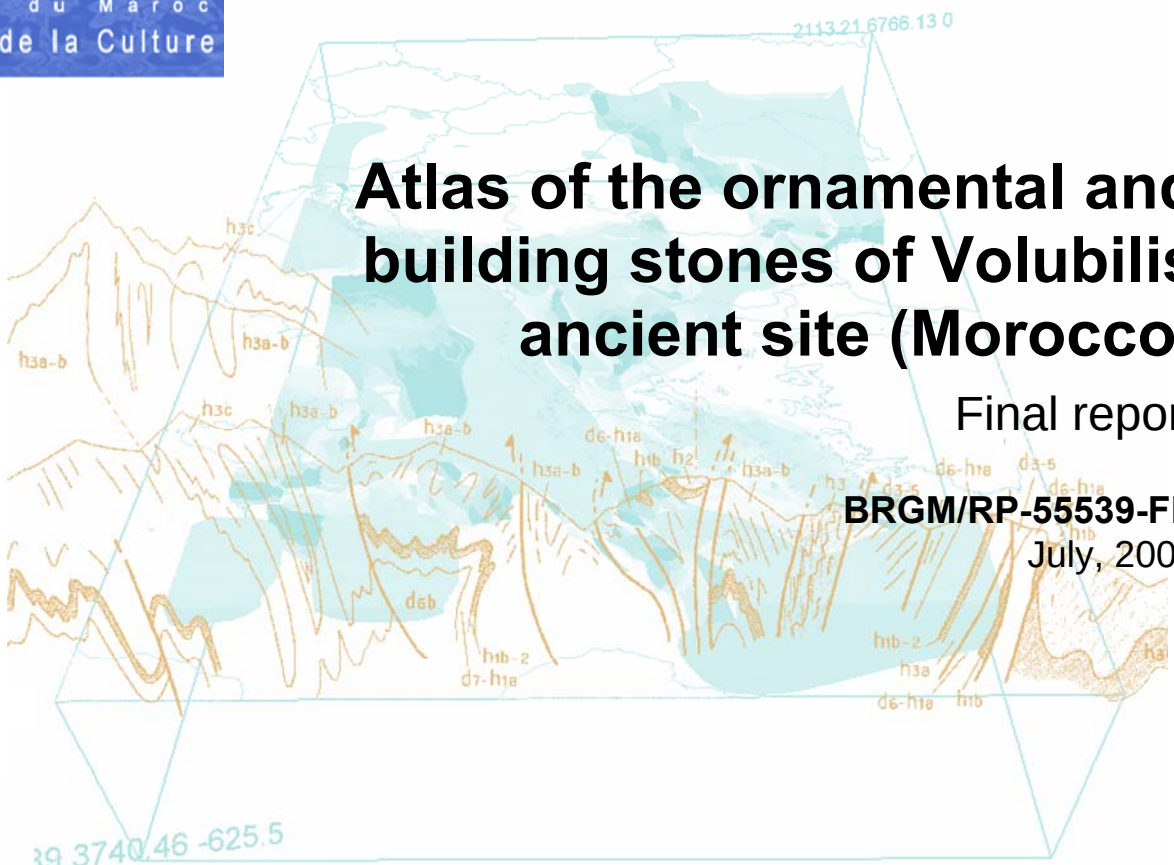
Atlas of the ornamental and building stones of Volubilis ancient site (Morocco)

Final report

BRGM/RP-55539-FR
July, 2008



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Laboratoire de Recherche des Monuments Historiques

Sixth Framework Programme

Geoscience for a sustainable Earth
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Atlas of the ornamental and building stones of Volubilis ancient site (Morocco)

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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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With the collaboration (in alphabetical order) of
F. Antonelli, R. Bouzidi, M. El Rhoddani, S. Kamel, L. Lazzarini, L. Leroux and M. Varti-Matarangas

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Synopsis

The present study titled “Atlas of the ornamental and building stones of Volubilis” 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 ancient site of Volubilis and to determine their provenance in terms of geographic areas (and of former quarry sites when possible). The obtained data and results are in an accessible form including photos and maps (so-called “Atlas”).

Concerning **ornamental stones**, a quite very limited amount of decorative stones and marble *s.s species* was observed *in situ* or accumulated as roving materials. All of the *in situ* detected marbles and other decorative stones were located in five buildings: House of the Ephebe, Palace of Gordian; Bath of Gallienus; House of Venus and House of Orpheus. In most cases they are in the form of small tiles or slab-fragments embedded in the mortar of floors and walls used for fixing prefabricated marble/mosaic panels.

Some other decorative stones and marbles objects are coming from the storeroom of Volubilis (erratic slab-fragments of white or colored marbles collected on the ground since the archaeological excavation until now by visitors and mainly by guardians) and the Archaeological Museum of Rabat (one column and a few statues of white marbles).

Although the imported stones and marbles in Volubilis are not present anymore in big quantities, the research revealed a significant relationship among this important Roman town of North-West Africa and the most famous marbles source areas of the central and eastern Mediterranean basin.

Four colored marbles *s.l.* belonging to the classical *marmora* used by Romans in the whole Mediterranean Basin were identified: Cipollino verde *(marmor carystium*) from Karystos (island of Eubea), Rosso antico (*marmor taenarium*) from the Mani peninsula; Verde antico (*marmor thessalicum*) from Larisa, Breccia di settebasi (*marmor scyreticum*) from the island of Skyros.

One other colored stone (a fossiliferous pinkish limestone), probably the most common decorative stone of the site was found. Its provenance is still unknown, but a local-Moroccan origin is presumed since its use was observed used in modern buildings.

Among the marbles *s.s.* identified in Volubilis, three categories were distinguished: white and pale grey marbles, grey striped and stained ones and a pinkish one:

→ Concerning white and pale grey marbles, the statues studied are sculpted in two fine-grained classical white marbles very appreciated and largely distributed during the Roman age: the *lunense* marble from Carrara (Italy) and the *pentelic* marble from Mount Pentelikon (Athens – Greece). Among the white marbles used for slab and architectural elements of Volubilis, besides the *pentelic* marble, four other marbles were identified: the dolomitic variety of the *Thasian* marble from the district of Vathy (island of Thasos - Greece), the *Parian* marble from Lakkoi (island of Paros, Cyclades - Greece), the *Proconnesian* marble from the island of Marmara (Turkey) and one unknown white fine-grained marble (most probably having a local origin).

→ About grey-striped or stained marbles quite abundant in the form of slabs, they macroscopically look like the type called "*greco scritto*" from Cap de Garde quarry (Annaba - Algeria), a graphitic medium-coarse grained marble with a white background drawn by thin grey-blackish veins or dark grey to bluish stains. Nevertheless, their petrographic parameters and isotopic compositions do not match with those measured for the classical Algerian *"greco scritto"* expressly sampled in the ancient quarry of Cap de Garde.

→ Concerning pinkish marbles, a stele dedicated to Venus and slab fragments were identified corresponding to the so-called *Portuguese pink*, an Hercynian marble outcropping at Vilaviçosa in the Estremoz Anticline (Portugal).

Concerning **building stones**, the systematic survey of each monument completed by petrographic-mineralogical characterisation and chemical analyses permitted to identify and classify the building stones of Volubilis into six main categories (referenced A to F). Therefore, the relative importance and the use of each of the six lithotypes was estimated and discussed.

As regards their relative importance of use, the lithotypes B and C are the most largely ones used as building stones on Volubilis site, representing over 90% of the total volume of building stones:

→ Lithotype B is a beige-yellowish calcarenite limestone (so-called molassa). Distributed on almost the whole monuments in a proportion ranging from 60 to 80%, it represents about 60% of the total volume of the building stones of Volubilis. In terms of uses, it is present as masonry stone-rubbles and linked to a relative softness as various carved and sculpted elements (column, chapiters…).

→ Lithotype C is a grey massive limestone representing about 31% of the total volume of the building stones of Volubilis. Distributed on the whole monuments in a proportion ranging from 5 to 20%, this hard stone is the only component of five public monuments (Capitol, Basilica, Public Fountain, Triumphal Arch and Door of Tangier). It is mainly used as architectonic elements as jamb, lintels, column and others structure carved blocks of significant size according to its mechanical strength. It is also observable as masonry stone-rubbles in limited proportion.

The four other lithotypes A, D, E and F are observable in a very low proportion representing less than 10% of the total volume of the building stones of Volubilis. Between those minor facies, lithotypes A and D seems to be slightly more represented.

→ Lithotype A is a beige-green marly limestone. Representing less than 3% of the total volume of building stones, it is distributed on almost the whole monuments in proportion ranging from less than 1% to 7%. In terms of uses, the marly limestone is present as medium-sized carved (and sometimes sculpted) architectonic elements (facilitated by their softness but at the origin of their important decays). It is also observable as masonry stone-rubbles in very limited proportion.

→ Lithotype D is an ochre-grey limestone rich in bivalvia and represents less than 3% of the total volume of building stones. It is distributed on almost the whole monuments in a proportion ranging from less than 1% to 10% and seems to be more represented in the monuments from the south and west parts than those from the north part. It is only present on the site as masonry medium-sized stone-rubbles.

→ Lithotype E is a coarse dolomite representing less than 2% of the total volume of building stones. It is distributed on almost the whole monuments in a proportion ranging from less than 1% to 5%. It is used mainly as masonry stone-rubbles. Many larger-sized blocks are also used as basement elements.

→ Lithotype F gathers together various continental limestones (including travertines) that represent about 1.5% of the total volume of building stones. They are distributed mainly on monuments from the medium part (south and west) of the site and almost absent in the north part. Their proportion ranges from less than 1% to 5%, except the Mausoleum for which it represents 80%. It is used as masonry stone-rubbles sometimes large-sized (notably travertine limestones) and also as basement elements.

After identifying the lithotypes of building stones of Volubilis, the search of their quarries of provenance was carried out, based on available bibliographic data and geological settings, then by sampling and in-laboratory characterisation of samples. Two main ancient quarries areas were located respectively near Aïn Schkor hill and on the upper part of Moulay Idriss Zerhoun city. Various outcrops were also investigated near Lakouar and Bou Assal villages, around Douar Ben Abdallah hill and also on the site of Volubilis itself. The considered quarries and outcrops are located in a five kilometer sector around Volubilis site. Their lithotypes were then compared to those (referenced A to F) from Volubilis ancient site:

→ Lithotypes A and B present as building stones in Volubilis correspond to the “upper molassa” formation (Miocene). Those lithotypes were observed especially in the extensive and hilly area called “Aïn Schkor”, enclosing numerous small to medium-sized quarries with indubitable trace of ancient extraction. They were also encountered in other outcrops showing more doubtful traces of quarrying altered by dissolution (Douar Ben Abdallah, Bou Assal).

→ Lithotype C was encountered in the upper part of Moulay Idriss Zerhoun city, in the Liasic (Domerian) geological formation. In this large area of quarrying, various ancient

architectonic elements remain (sculpted blocks, column fragments, frequent traces of wedges, etc). Despite of their hardness, the extraction of these limestones was facilitated by the stratification parallel to the slope and the thickness of strata (0.5 to 1m).

→ Lithofacies D was observed in various outcrops closed to « Lakouar » village. The corresponding formation (upper Lias, Aalenian) shows an alternance of ochre-grey limestone rich in bivalvia strata (0.1 to 0.4m of thickness) and marl layers. The outcrops show locally excaved area used to supply stone-rubbles. The extraction as stone–rubbles was facilitated by the topography (side of a hill), the thickness and the slope of the layers and as a consequence no significant trace of extraction is observable.

→ Provenance of lithofacies E (coarse dolomites) present in very low quantity at the ancient site was not yet precisely determined.

→ Lithofacies F (various continental limestones including travertines) corresponds to the bed-rock of Volubilis site itself. Usually covered by ancient constructions or excavation products, only few outcrops are nowadays visible. No significant trace of extraction was observed except weathered bedrock remains in a form of staircases and extracted blocks on the ground.

In final conclusion, the present study tried globally successfully to identify the stones of Volubilis 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 archaeology and conservation of the ancient site. Not undertaken in the framework of this project, future archaeological studies for example could focus on the relationship between spatial distribution of the types of stones and periods of constructions.

Contents

1. Introduction

The present study titled “Atlas of the ornamental and building stones of Volubilis” 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, the 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, of 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 Agess) 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 conditions.

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 (CSASCA, 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 (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, French Ministry of Culture, France).
- Small and Medium Enterprises (SME): LITHOS SNC (Italy), PONS-ASINI GmbH (Germany).

The "Atlas of the ornamental and building stones of Volubilis" 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. Fabrizio Antonelli, Geologist, specialist of ancient decorative stones, LAMA-IUAV University of Venice.
- Mr. Rachid Bouzidi, Archaeologist, Conservator of the Volubilis Site, Moroccan Ministry of Culture.
- Mr. Mohamed El Rhoddani, Doctorate student, University of Meknès.
- Prof. Said Kamel, Geologist, University of Meknès.
- Prof. Lorenzo Lazzarini, Geologist, specialist of ancient decorative stones, LAMA, University IUAV of Venice.
- Dr. Lise Leroux, Geologist, specialist of cultural heritage stones, LRMH, French Ministry of Culture.
- Dr. Myrsini Varti-Matarangas, Geologist, specialist of sedimentary rocks, IGME.

The first part of the atlas introduces the history of Volubilis and gives an overview of excavations and restoration works. In a second part, the question of identification and area of provenance of the ornamental stones (local or imported) of the site is addressed based mainly on characterization of representative samples and comparison to available databases. The third and last part deals with the study of the building stones and the search of corresponding quarries 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 Volubilis.

2. Overall presentation of Volubilis site

2.1. BRIEF HISTORY OF THE SITE

Located on a medium altitude plateau near Moulay Idriss Zerhoun City and about thirty kilometres north of Meknès, the famous ancient city of Volubilis is the most excavated and best preserved archaeological site of Morocco. Crossed by Oued Fertassa and bordered by Oued Khoumane, the city gradually stretched to attain a surface of forty hectares. Its name mentioned in ancient texts and roman letterings is presumed derived from the Berber word “Walili” signifying “rose-bay” a very profuse plant in those parts. In Arabic sources and on the early Arab coinage of the site the name was transformed into “Walila”. From the nineteenth century the ruins were known as “Ksar Faraoun”, the castle of the Pharaohs.

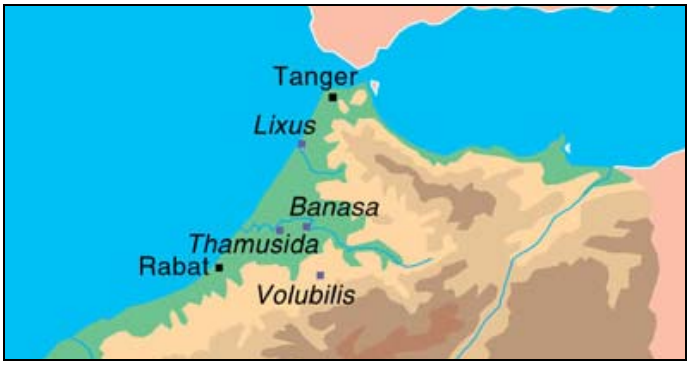


Figure 1 - Location map of Volubilis.

Volubilis perpetuated about thousand years from the 3rd century BC to the 7th century AD surviving between the 8th to the 11th century AD until Almoravide period.

From Mauretania Kingdom period (3rd century BC – 40 AD), Volubilis acquired a rampart for an estimated surface of twelve hectares (Figure 2 left: Mauretanian rampart). Most of the vestiges were subsequently destructed or recovered.

In 40 AD, after assassination of King Ptolemy by Emperor Caligula and rebellion against Roma of the freed slave Aedemon, the Roman army suppressed rebellion assisted by the Volubilis residents and built a fortress net. Volubilis was requited by the title of *Municipe* in the new Tingitan (from *Tingi* / Tangier city designation) province and fast reached its maximal expansion. Parallel to the construction of public monuments, temples and baths, the city comprised private houses, bakeries, various shops and many oil mills. In 168-169 AD under Marcus-Aurelius, Volubilis acquired the rampart presently observable made of eight monumental doors (Figure 2 left: Roman rampart of 2,6km long). From 218 AD under Septimus Severus dynasty, a new monumental centre was built comprising the Capitol, the Triumphal Arch, the Basilica and the re-planning of the Forum (Figure 2 right).

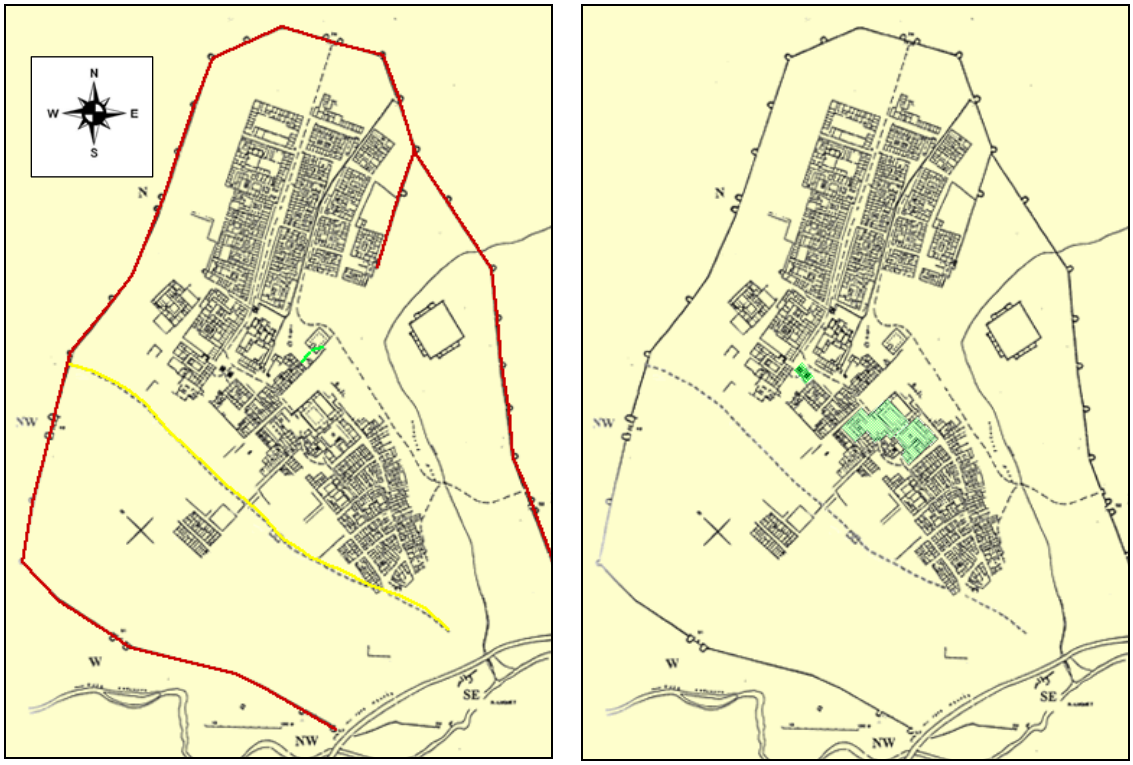


Figure 2 – Overall Maps of Volubilis site : (left) Ramparts: green = Mauretanian period, red = Roman period, yellow = post-Roman period; (right) Roman monumental centre comprising (green color) the Capitol, the Triumphal Arch, the Basilica and the re-planning of the Forum.

From 285 AD with accession of Dioclesius, the administration and the Roman army left the Tingitan province including Volubilis without well known reasons. Next, the Volubilis residents gathered together to the west part of the city after the aqueduct broke down and built a new district near to Oued Khoumane. A new rampart was constructed (fifth or sixth century AD) with blocks re-used from earlier constructions delimiting (Figure 2 left: post-Roman rampart) the later town from the early Roman city centre which was now occupied by cemeteries. The Triumphal Arch area became a Christian necropolis during a dated period from 599 to 655 AD. Funerary letterings testify the Christianization of the Roman-Berber population and the continuous use of the Latin language. Before accession of Idriss I, the Volubilis region was already islamized according to Arabic chronicles and coins. After a conflict between Abbasids and shiits, Idriss I escaped to Magrib and set up at “Walili” where he was acclaimed as headman of religious believers until his death in 791 AD. Then he was succeeded by his son Idriss II. Next, the ancient prosper city became a little town progressively abandoned by its residents until the Almoravide period and it remained only a few ruins at the Middle Ages.

Excavations (and parallel restoration works) of the archaeological site of Volubilis began in 1915. More than twenty hectares of the ancient city have been highlighted up till nowadays. As regards its millennium history, the site has been registered on the UNESCO World Heritage list since December 1997.

A simplified map of the site and a recapitulative list of the monuments (with their reference numbers) are presented in Figure 3 and Table 1. The reference monument numbers are useful for facilitating the location of each monument and the reading of the present atlas.

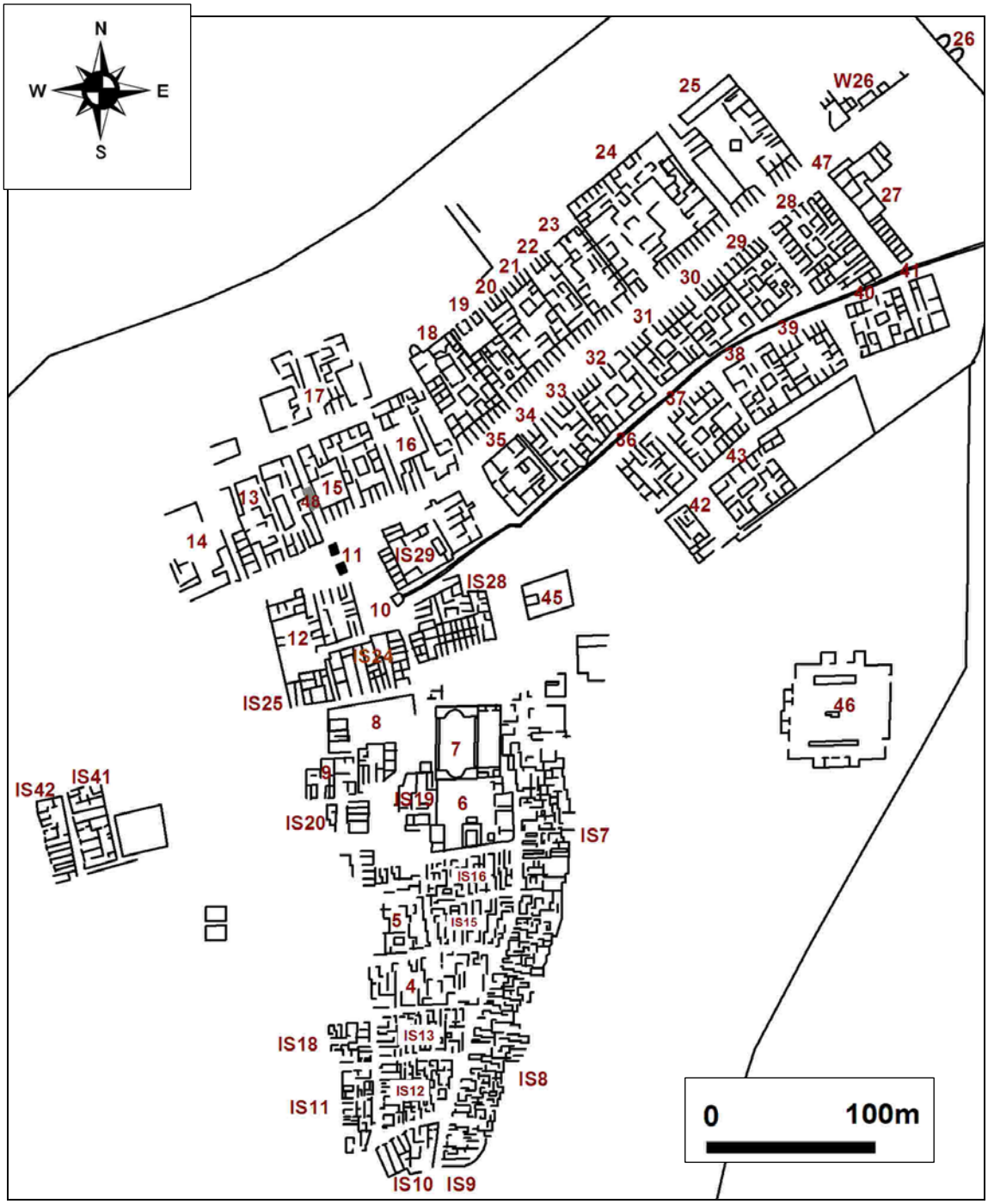


Figure 3 – Simplified map of Volubilis site figuring the reference number of the whole monuments.

Monument refrence number	Monument designation	Monument refrence number	Monument designation
4	House of Orpheus	**33**	House of the semi Columns
5	Baths of Gallienus	**34**	House of the Abside
6	Capitol	**35**	House of the Islamic Necropolis
7	Basilica	**36**	House of the gold ring
8	Forum	**37**	House of the Bronze Bust
9	Bakery	**38**	House of Venus
10	Public Fountain	**39**	House of the Portiques
11	Triumphal Arch	**40**	House of the Clover Basin
12	House of the Dog	**41**	House without peristyle
13	House of the Ephebe	**42**	House of the Crypt
14	House of the Compass	**43**	House of the big pilasters
15	House of the Columns	**48**	Mausoleum
16	House of the Rider	**IS7**	Insulae
17	House of the Cistern	**IS8**	Insulae
18	House of Hercules	**IS9**	Insulae
19	House of Flavius Germanus	**IS10**	Insulae
20	House of Dionysos and of four seasons	**IS11**	Insulae
21	House of the Baths of the Nymphs	**IS12**	Insulae
22	House of the Wild Beasts	**IS13**	Insulae
23	House at the West of Palace of Gordian	**IS15**	Insulae
24	Palace of Gordian	**IS16**	Insulae
25	House of the Discipline	**IS18**	Insulae
26	Door of Tangier	**IS19**	Baths of the Capitol
26W	House at the West of the Door of Tangier	**IS20**	Insulae
27	House at the West of the House of the Gold Coin	**IS24**	House of Desultor
28	House of the Gold Coin	**IS25**	Insulae
29	House of the Bacchus of marble	**IS28**	Insulae
30	House of the Sundial	**IS29**	Insulae
31	House of the two presses	**IS41**	Insulae
32	House of the Nereids	**IS42**	Insulae

Table 1– Recapitulative list of the considered monuments.

2.2. EXCAVATIONS AND RESTORATION WORKS

In 1721 an English traveller named Windus was the first person to report of the Volubilis site drawing the Triumphal Arch, the Basilica and the Door of Tangier (Figure 4) of which only traces were outcropping. One century later in 1830, the Austrian Baron Von Augustin noted a few letterings and drew the Triumphal Arch. In 1874 a French geographer Ch. Tissot undertook field works and identified the site as the Roman city of Volubilis.

The real and official beginning of excavations took place in Volubilis in 1915 ordered by the “Resident Général” of France in Morocco H. Lyautey and leaded by L. Chatelain.

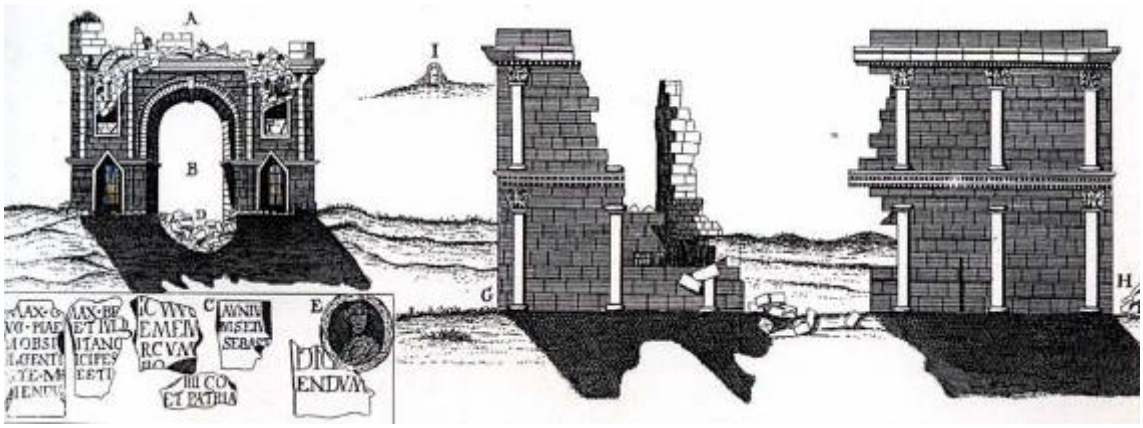


Figure 4 – Drawing of the Basilica, Triumphal Arch and Door of Tangier (Windus, 1721).

This one focused his researches on the roman period monuments and began with excavations of the monumental centre and some parts of the north and south districts (Chatelain, 1916, 1938). The works evolved with his successors during the colonial period. M. Euzennat established the first stratigraphic cut of an ancient Moroccan site including also pre-Roman archaeological levels (Euzennat, 1960). The next researches undertaken centred on Mauretanian period.

From 1980, the works focused on re-studying some badly excaved and misinterpreted monuments. Nowadays, one century after the beginning of excavations, half of the site still remains to be investigated.

The past excavations went with necessary restoration, consolidation and enhancing actions. The first restoration was undertaken in 1916 by a French engineer (Captain Hénissart) righting the north-east archway of the **Basilica** (Figure 5) using stone blocks available on the site.

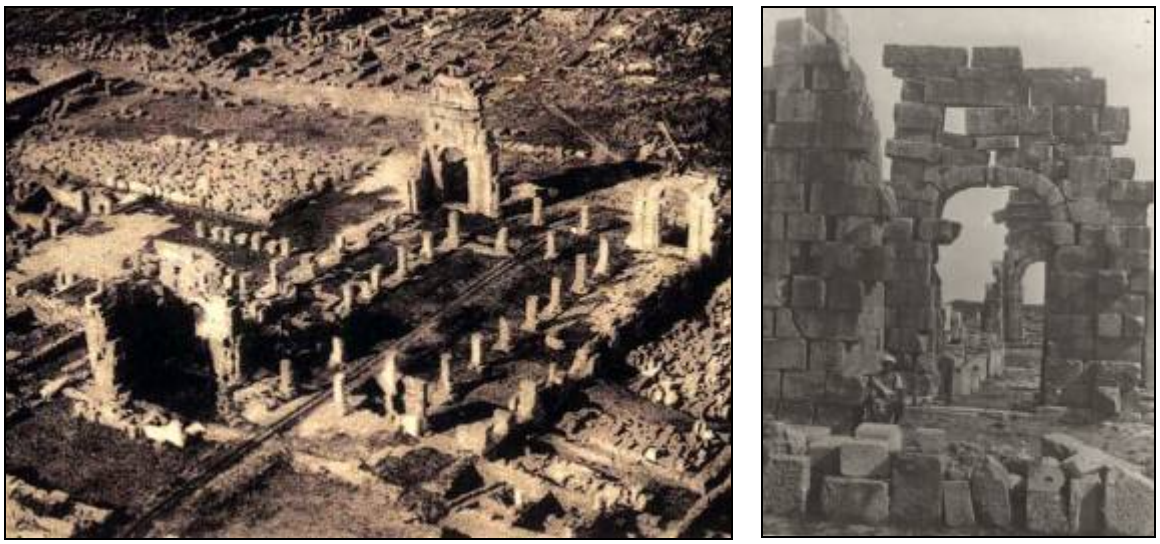


Figure 5 – (left) Overview of the Basilica before restoration; (right) North-East arch standing a chance of collapsing.

A restoration by anastylosis was carried out on the Basilica between 1965 and 1969 by A. Luquet after a detailed preliminary study based on available documents (reports, maps, drawings, photos…) and architectonic stone elements present in the area (Luquet, 1967).

Even incomplete (Figure 6), the works included a partial reconstruction of colonnade and archways of the west front (forum side) of the monument, using various architectonic blocks (bases, chapiters, cornices, architraves…) to render its entablature and elevation. The missing parts of the stone blocks and column elements were figured by a filling up of terra cotta bricks.

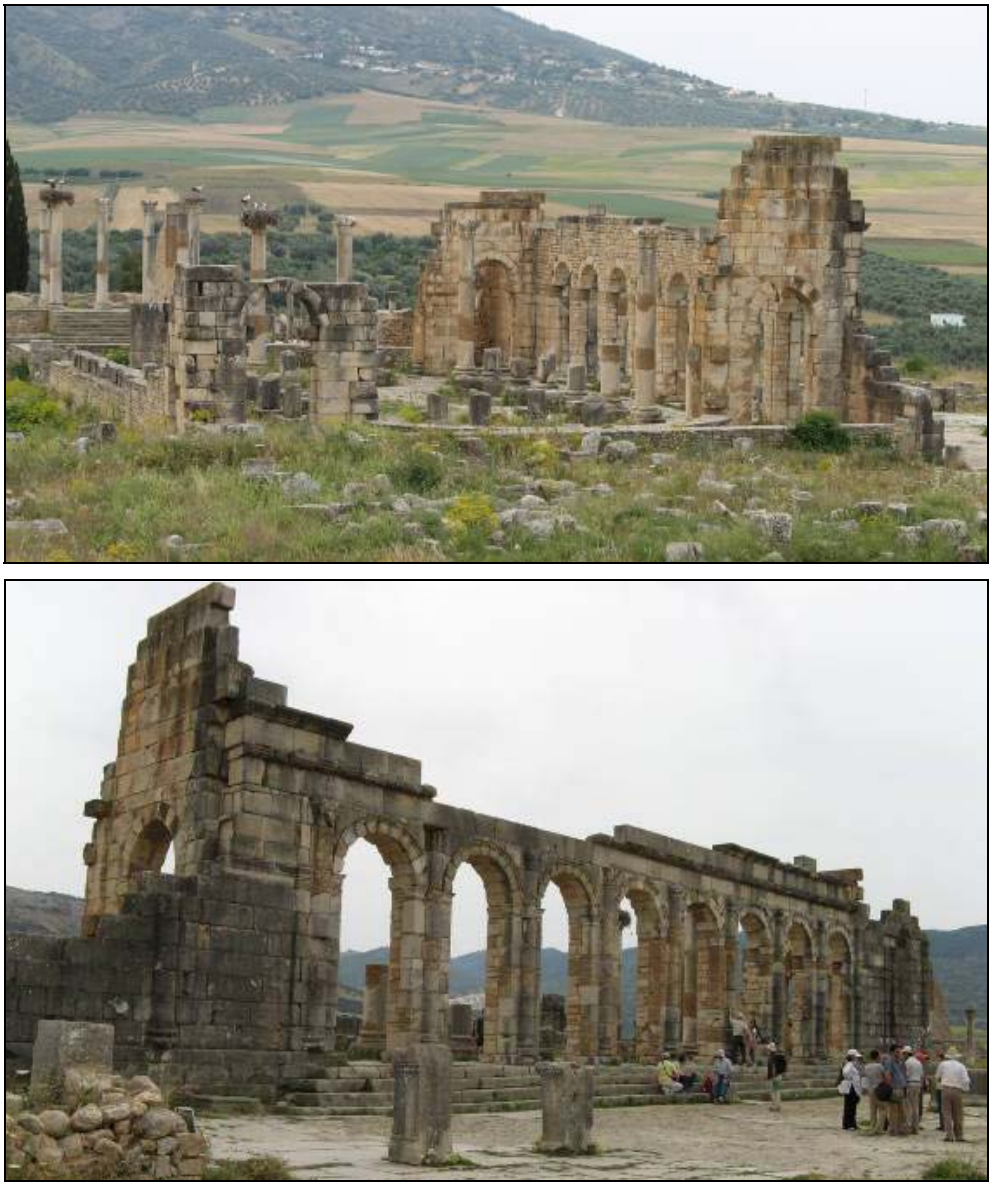


Figure 6 – Overviews of the Basilica nowadays after partial reconstitution.

The restitution of the **Triumphal Arch** (Figure 7) was a work leaded by the first searcher of Volubilis L. Chatelain from 1930 to 1936. Before the beginning of restoration works only the basement of the two pillars was visible and the other stone elements were dispersed all around on the ground.

Unfortunately, the works were relied on no preliminary study and comparison to similar arch in the Roman Empire. No anastylosis study was carried out. Many blocks found lying on the ground were not taken into account. Some other ones were re-cut before being used and cement was used cement to fill the missing parts.

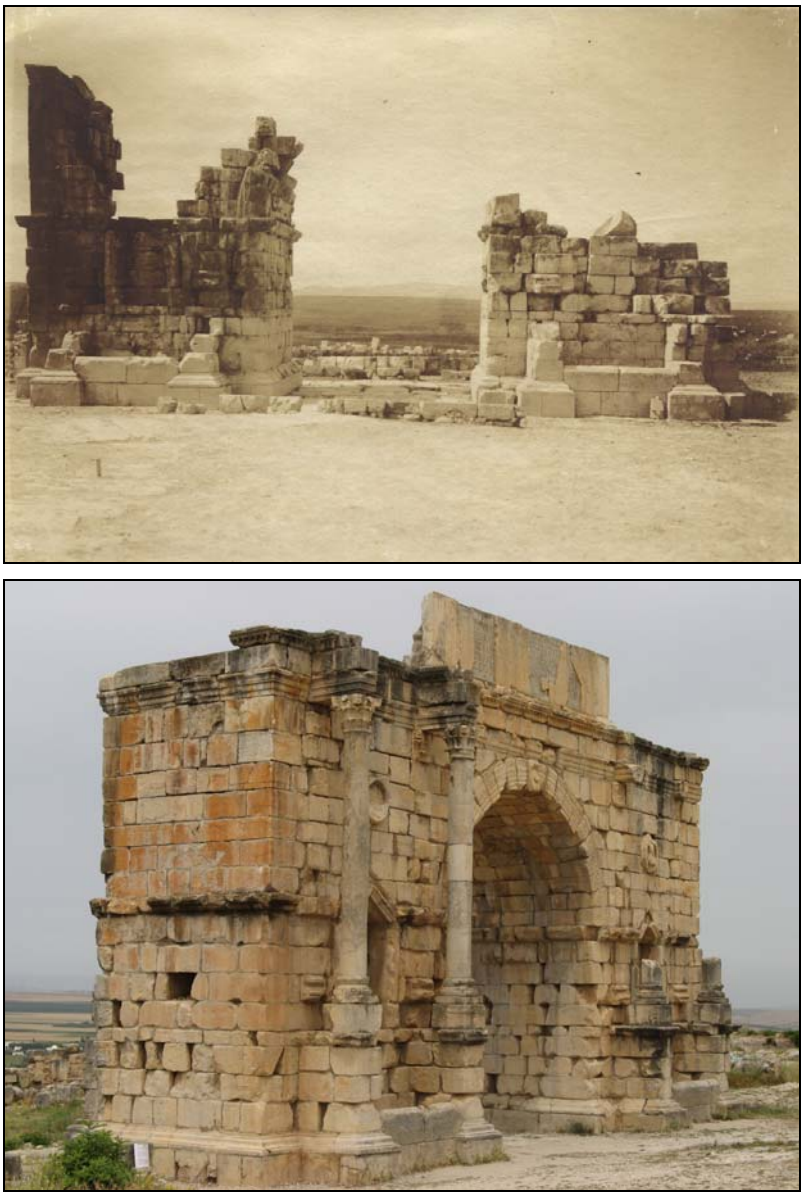


Figure 7 – Overview of the Triumphal Arch before (up) and after (down) after reconstitution.

Concerning the **Capitol**, only the basement remained and its reconstitution (Figure 8) was carried out by steps. In 1955, the portico around the temple was restored. Between 1958 and 1960, G. Hallier undertook a preliminary anastylosis study to reconstitute the west front. From 1962 to 1964, A. Luquet made a more detailed anastylosis study and undertook the restoration of the monument reconstructing the podium, the colonnade and the front stairs (Luquet, 1964). The missing parts of the columns were figured by a filling up of terra cotta bricks. This restoration is incomplete behind the columns and shows problems linked to the arrangement of certain structure compared to the ancient original state.

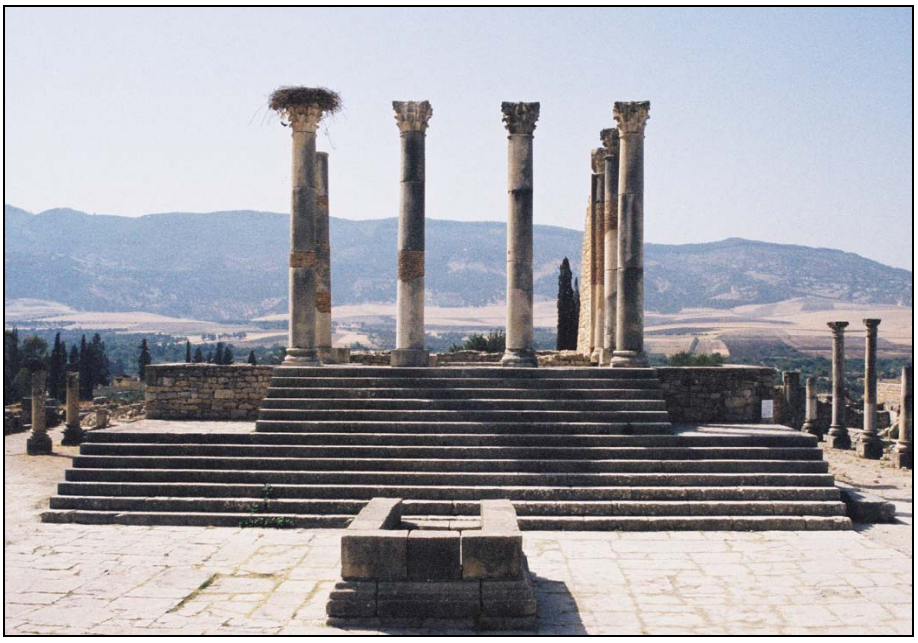


Figure 8 – Overview of the Capitole after partial reconstitution.

Concurrently to its works on the Capitol between 1962 and 1964, A. Luquet set up the paving of the **Forum** to its original position and gathered together the bases of statues once scattered according to a more or less coherent composition.

In addition to a partial restitution of the Roman monumental centre of Volubilis (including the Capitol, the Basilica and the Forum), many other restoration works were undertaken by A. Luquet: House of the Ephebe in 1955, House of the Columns (righting columns) and east door of the Roman rampart from 1958 to 1960, Door of Tangier (righting the two pillar) in 1960. From 1968, he restored the temples A and C, some edifices in the south district, the houses of the right side of Decumanus Maximus and finished by the House of the Nereids in 1972.

Maintenance and consolidation works never broke off and from 1990 the Department of Conservation of Volubilis has undertaken to restore a Roman bakery and an oil mill. With collaboration of foreign partners, it is also making restitution works on a part of the Islamic Baths.

3. Study of the ornamental stones

3.1. FIELD APPROACH, SAMPLING AND METHODOLOGY

All the excavated areas of *Volubilis* were carefully explored for the presence of imported colored stones (e.g. different from the local ones) and true marbles. Each single house and the whole important monuments were inspected.

The storeroom of Volubilis and the Archaeological Museum of Rabat were also investigated. One column and several statues made of white marbles were sampled for in-laboratory characterisation. Furthermore in the storeroom, numerous referenced erratic slab-fragments of white or colored marbles collected since the archaeological excavation until now (by visitors and mainly by guardians of the site) were examinated.

Colored stones were identified macroscopically on the basis of the specific knowledge of the Authors. Each one was described in a file including the essential data on the lithotype:

- picture of its most common *facies*;
- ancient designation (if known); commonly designation used and synonyms;
- petrographic classification;
- macroscopic aspect;
- name of the quarrying locality;
- period and typology of use;
- map of distribution of the lithotype in the provinces of the Roman Empire (the location of the quarries and Mediterranean sites are indicated by a number).

The maps were established with reference to a database including more than 6000 records of stone-occurrence in about 400 ancient sites (Lazzarini, 2004). They allow an immediate appreciation of the provinces reached by each lithotype, the concentration areas and the re-distribution of stones in the Middle Ages. The presence of a lithotype in a certain site was recorded as carefully as possible taking into account the inevitable constraints of the small scale of the reference maps used. Possible approximations are in any case offset by the list of numbered and named localities at the end of this report.

As regards the determination of the geological origin of the white and grey marbles as well as of stones of doubtful origin used for sculptures and architectural elements, in the site (and its storeroom) or currently conserved in the Archaeological Museum of Rabat, several samples were collected and later investigated by mineralogical-petrographic methods and isotopic analysis.

Small flakes (≅ 1 x 0.5 x 0.5 cm) were in fact detached with a small sharp chisel in hidden areas of artefacts. Each sample yielded a thin section for the purposes of petrographic investigation; another part of the same sample was finely ground and subjected to C & O isotopic measurements and XRD analysis. The thin sections were observed under the 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;
- 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.

The XRD analyses were performed with a PHILIPS PW 1840 diffractometer (CuKα/Ni: 40 KV & 20 mA) to evaluate the presence of a possible dolomitic fraction in marbles.

As regards the isotopic analyses, following the procedure of McCrea (1950), CO_2 was extracted from calcite by reaction with H_3PO_4 100% at 25°C using a high-vacuum line; the relative abundances of the C and O isotopic ratios were determined by a FINNIGAN Mat Delta E mass spectrometer. The values of isotopic composition are expressed in terms of $\delta^{13}C$ and $\delta^{18}O$, in ‰, relative to the international reference standard PDB (Craig, 1957), and then plotted in the updated diagrams proposed by Gorgoni *et al*. (2002).

3.2. RESULTS AND DISCUSSION

In general, a very limited amount of decorative stones and marble *s.s species* was observed *in situ* or accumulated as roving materials. All of the *in situ* detected marbles and other decorative stones were located in five buildings (Figure 9; monument reference number between parentheses):

- House of the Ephebe (13);
- Palace of Gordian (24);
- Bath of Gallienus (5) ;
- House of Venus (38);
- House of Orpheus (4).

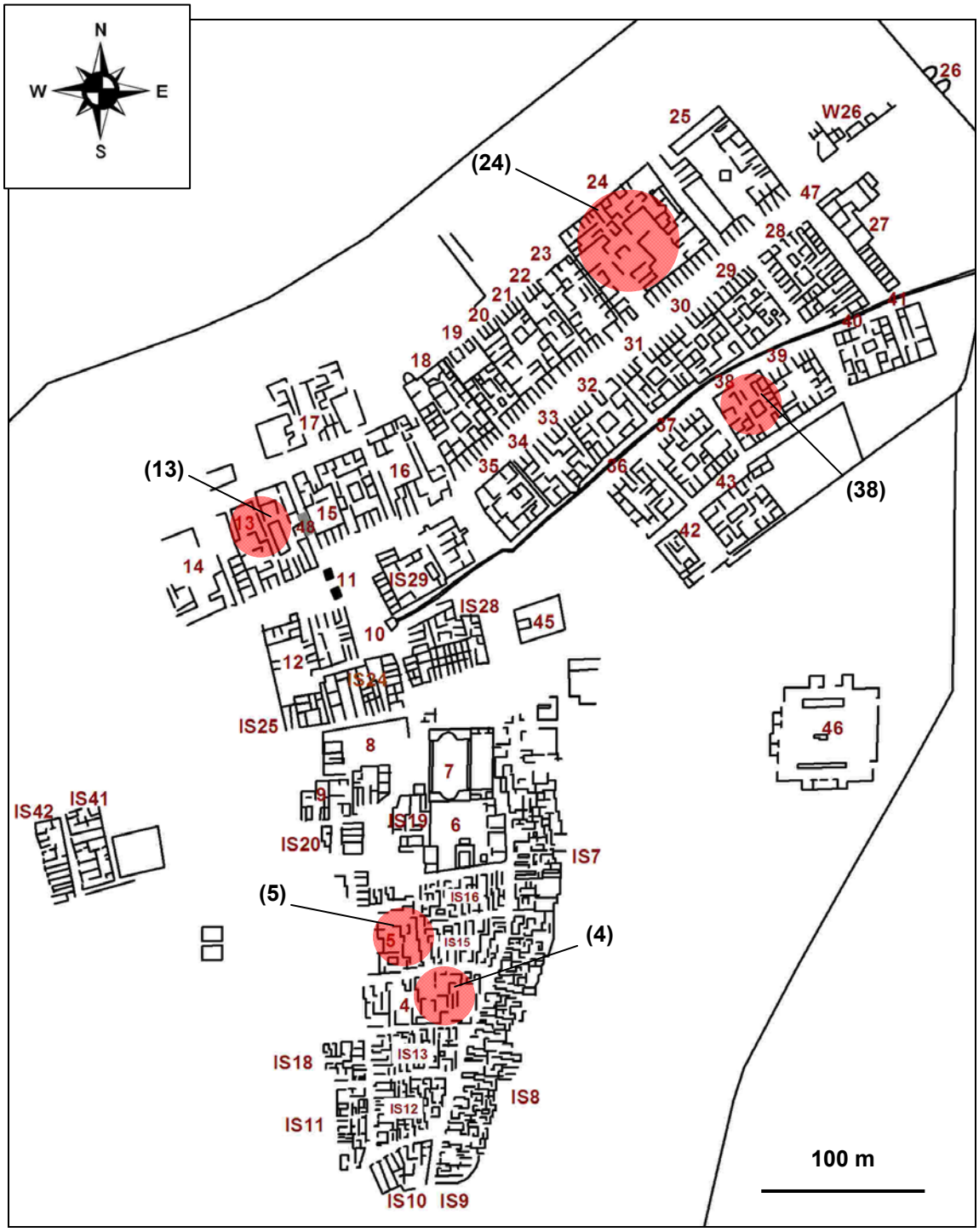


Figure 9 - Map of the Volubilis archaeological site with the location of the five buildings containing marbles.

In most cases they are in the form of small tiles or slab-fragments embedded in the mortar of floors and walls used for fixing prefabricated marble/mosaic panels (Figure 10, Figure 11, Figure 12 and Figure 13).

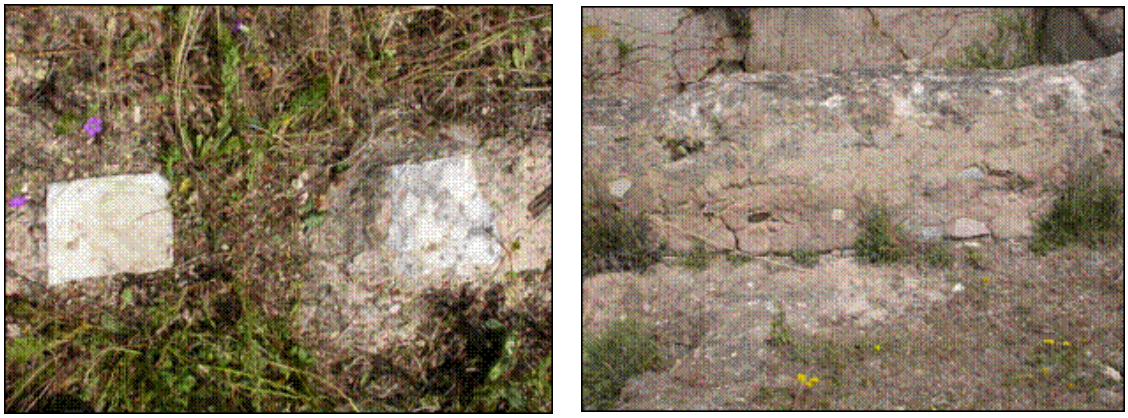


Figure 10 - (a): House of Venus (38): small slabs of white and greyish marbles embedded in the mortar of the floor; (b): Palace of Gordian (24): small slabs of exotic white and colored marbles embedded in a wall of the SE sector.

Figure 11 – Baths of Gallienus (5): small slab of white marble embedded in the wall.

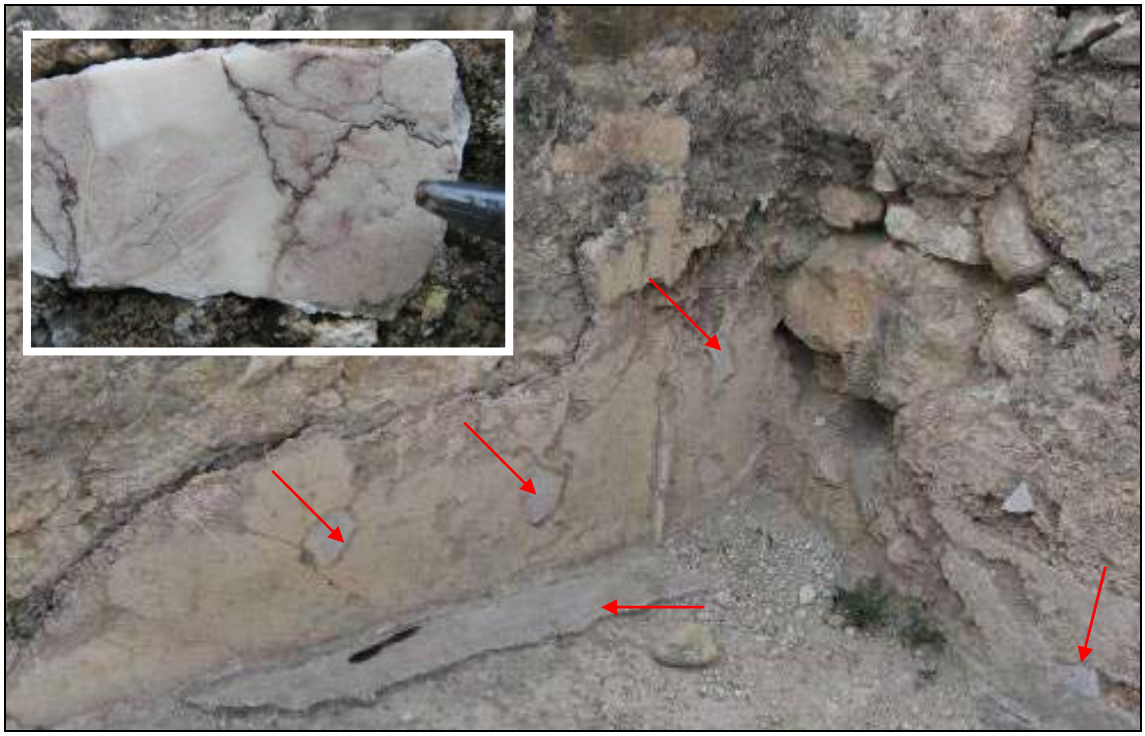
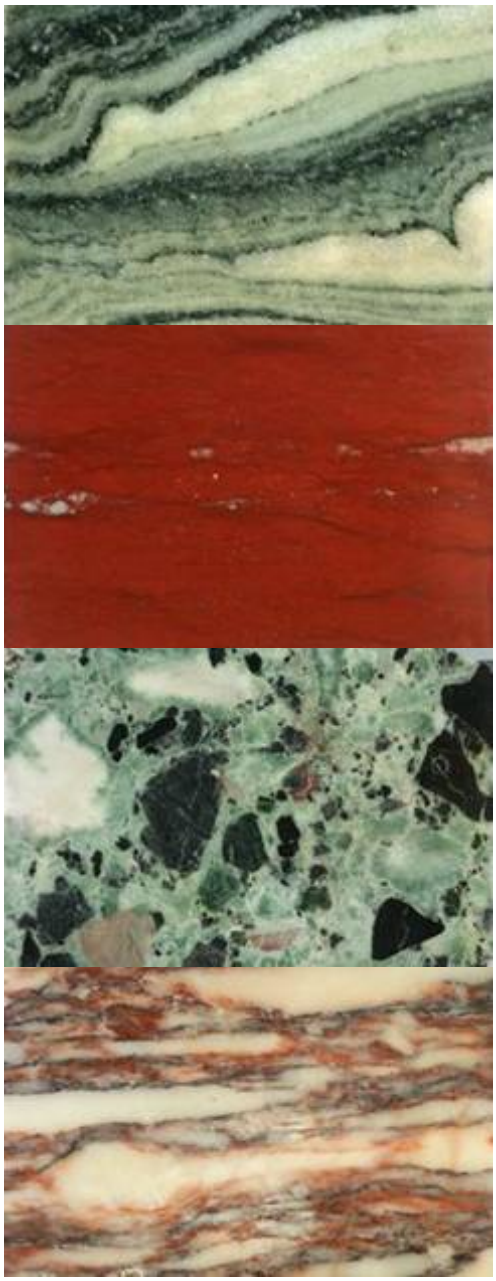


Figure 12 – Palace of Gordian (24): small slabs embedded in the walls and remain of a large slab on the floor of pinkish limestone.

Figure 13 – Bath of Gallienus (5): remains of large slabs of grey marble.

3.2.1. Colored marbles and stones

Among the classical colored marbles, four lithotypes imported from Greece were identified (Figure 14 - Figure 15). They are among the most common *marmora* used by Romans in the whole Mediterranean Basin. The relevant features of each lithotype are summarized in the files in Appendix 1.



Cipollino verde *(marmor carystium*) from Karystos (island of Eubea)

Rosso antico (*marmor taenarium*) from the Mani peninsula

Verde antico (*marmor thessalicum*) from Larisa

Breccia di settebasi (*marmor scyreticum*) from the island of Skyros

Figure 14 – References illustrations (samples from quarries) of the four colored Greek marbles identified in Volubilis site.

Figure 15 - Slab-fragments of colored Greek marbles from the Palace of Gordian (24) and the Baths of Gallienus (5).

One other colored stone, a pinkish fossiliferous limestone, probably the most common decorative stone of the site was found throughout the inspection (Figure 16 and Figure 17).

Figure 16 - (up) House of Orpheus (4): overall view of the basins including slabs of pinkish fossiliferous limestone; (down) House of Orpheus (5): detailed view of one slab (dimensions 30x30cm) among mosaics.

Figure 17 - Slab-fragments of a pinkish fossiliferous limestone resulted the most common colored stone in many houses of Volubilis.

The Volubilis archaeological objects made of pinkish fossiliferous limestones and sampled for in-laboratory determination are listed in Table 2.

Object and Location (monument reference number between parentheses)	Sample n°
Small slab *in situ* in the House of Orpheus (4)	MO3
Small slab in the Palace of Gordian (24): roving crust	PG1-3
Small slab in the Palace of Gordian (24): roving crust	PG2-2

Table 2 **–** List of the samples of pinkish fossiliferous limestone from Volubilis.

First, these unknown stone samples were submitted to a microscopic study aimed at supplying a correct petrographic classification. According to the most common classification systems the stone is a packed biomicrite (Folk, 1959; 1962) or a wackestone with spathic patches tending to packstone (Dunham, 1962). The allochems content is about 20-30% made of bioclasts, mainly bivalvia and echinoids (Figure 18 and Figure 19).

Figure 18 - Photomicrograph of the pinkish fossiliferous limestone (sample PG2.2): a bioclast of echinoid is visible in the centre of the field (N+, magnification x100).

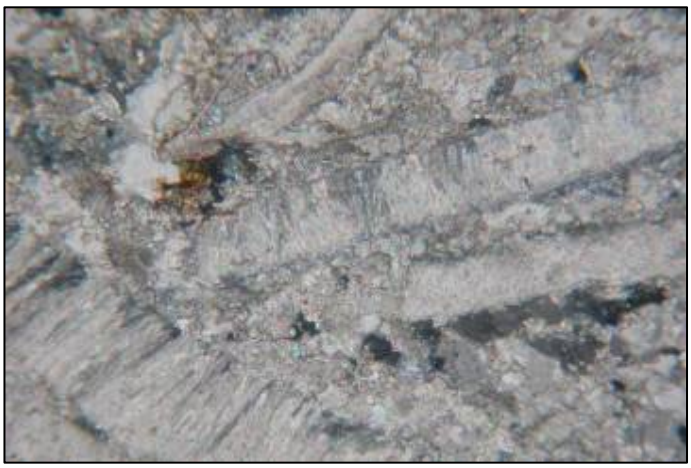


Figure 19 - Photomicrograph of the sample G2 showing presence of bivalvia (N+, magnification x100).

The detritic fraction is low made of monocrystalline quartz. Hematite, more or less diffused in the carbonated mass and concentrated in veins (Figure 20) is the pigment responsible for the variable pinkish color.

Figure 20 - Photomicrograph of the sample G2: shows abundant hematite concentrated along a small vein (N//, magnification x270).

For this fossiliferous pinkish limestone of unknown provenance, visually similar stones were observed used in modern buildings (Figure 21). Presumed local-Moroccan origin was investigated by means of marble stores inspection in Meknès City and two fossiliferous pinkish limestones nowadays extracted were sampled in the available stocks: the first type comes from a quarry near the city of Taroudant (east of Agadir) and the second from a quarry close to the city of Lakhssas (south-east of Tiznit).

The pinkish limestone from Taroudant (sample TA) is a fossiliferous grainstone (Dunham, 1962) or a biomicrosparite (Folk, 1959; 1962) with abundant hematite and silico-clasts dispersed and embedded in the carbonate mass (Figure 22). The latter (3-5%) is made of quartz ± chalcedony/opal ± feldspar grains. The bioclastic fraction contains bivalvia (filaments), echinoids and more rare ostracods and bryozoa. Rare, but characteristic is the presence of clasts of rounded glassy rocks (Figure 23).

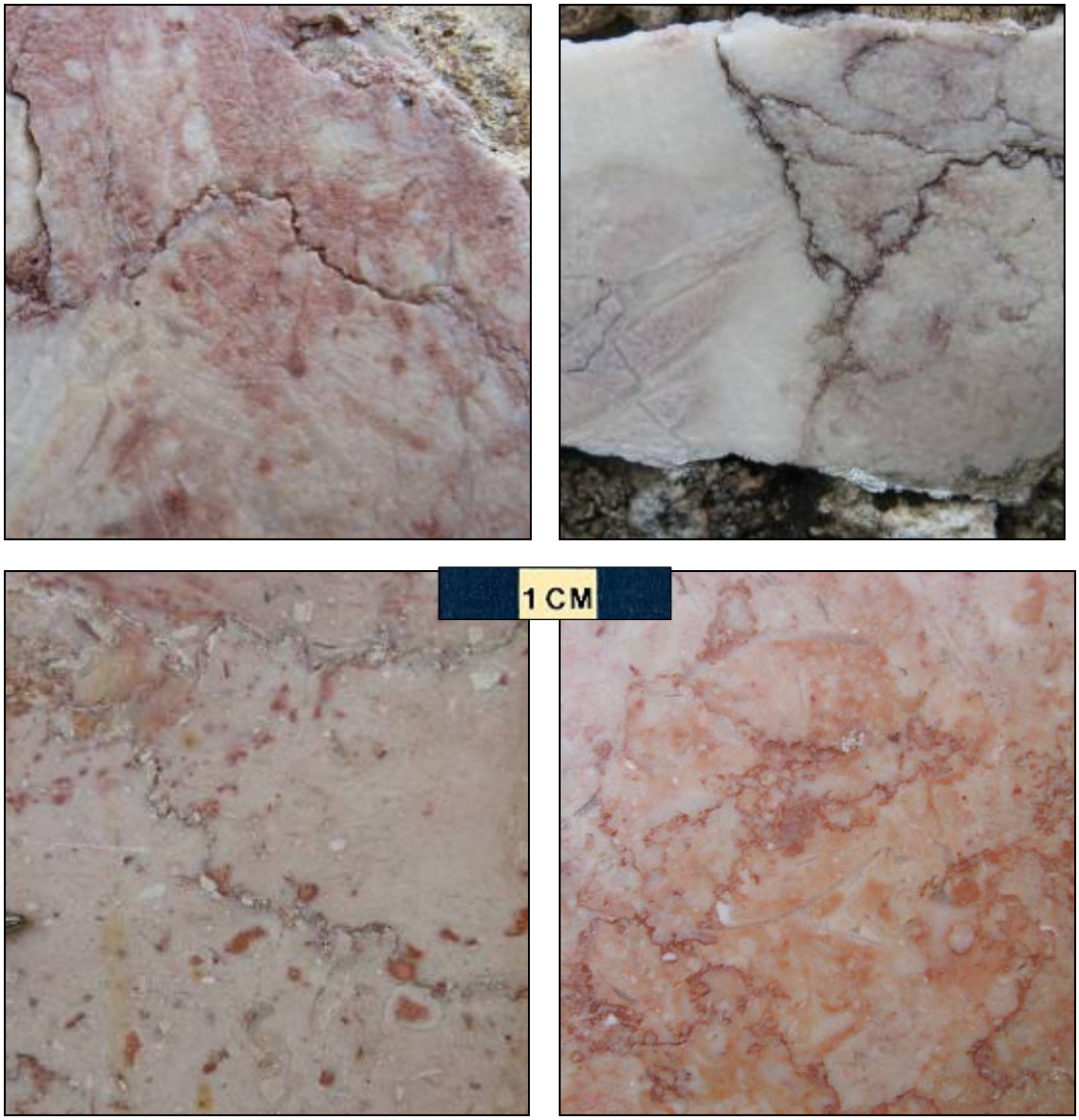


Figure 21 – Macroscopic views of fossiliferous pinkish limestones visually similar to the one of Volubilis and nowadays exploited: (up) Volubilis facies, (down left) Taroudant facies, (right) Lakhssas facies.

Figure 22- Photomicrograph of the fossiliferous pinkish limestone from Taroudant quarry (sample TA): biomicrosparite rich in silico-clasts (N+, magnification x4).

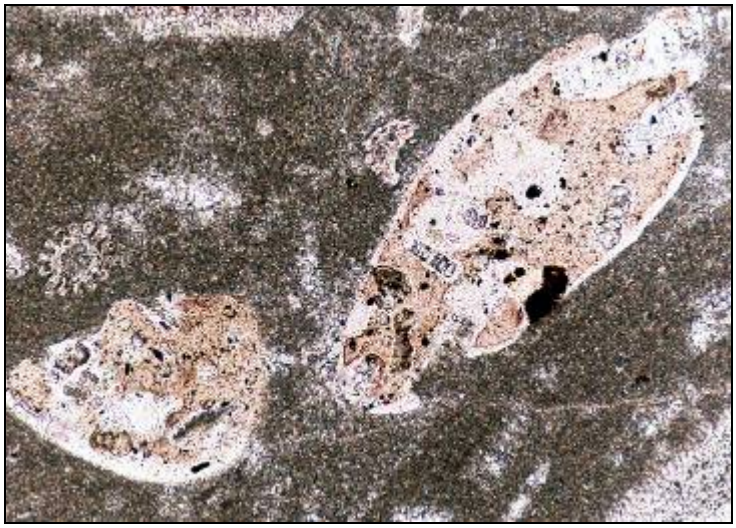


Figure 23 - Photomicrograph of the fossiliferous pinkish limestone from Taroudant quarry (sample TA): detail of two rounded glassy rock fragments (N//, magnification x16).

The pinkish limestone from Lakhssas (sample LA) is a fossiliferous packstone (Dunham, 1962) or biomicrite (tending to biomicrosparite) pigmented of pink by the presence of iron oxides dispersed in the carbonate mass or concentrated along spathic veins. The abundant bioclastic fraction is composed by calcareous algae (*dacycladaceae*), anellids, echinoids, bivalvia and rare bryozoa and foraminifera. The modest silico-clastic fraction includes quartz, chert and chalcedony (Figure 24).

Figure 24 - Photomicrograph of the the fossiliferous pinkish limestone from Lakhssas quarry (sample LA): biomicrite very rich of calcareous algae, bivalvia and anellids and serpulids (N+, magnification x4).

On the base of their petrographic features, these two pink fossiliferous limestones do not fit well with the one encountered in the archaeological site of Volubilis. This result is confirmed by their isotopic signatures, clearly different of the pinkish fossiliferous limestone one from the site (Figure 25).

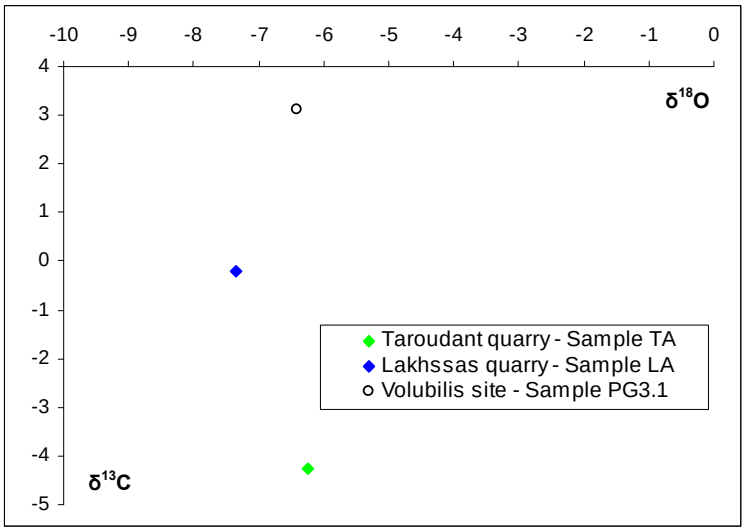


Figure 25 – Isotopic signature of pinkish fossiliferous limestones from Taroudant and Lakhssas quarries and comparison to the one from the pinkish fossiliferous limestone from Volubilis.

Therefore, the provenance of this pinkish fossiliferous limestone remains unknown although a local-Moroccan provenance is presumed.

3.2.2. White, pinkish and grey crystalline marbles

Among the marbles *s.s.* of Volubilis (observed *in situ* or conserved in the on-site storeroom and in the Archaeological Museum of Rabat), a preliminary macroscopic distinction based on the color features was done, classifying them into three categories:

- White and pale grey marbles;
- Grey striped and stained marbles,
- Pinkish marble.

A significant number of representative samples of the corresponding lithotypes was collected for petrographic-mineralogical and geochemical analyses with the aim to determine their geological nature and geographic provenance.

a. White and pale grey marbles

Several pure white marbles were found related to Volubilis site: slab-fragments on the site itself (Figure 26) and in its storeroom (Figure 27) or nowadays preserved in the Archaeological Museum of Rabat (Figure 28 - Figure 29).

Figure 26 - Small slab found in the palace of Gordian (5) rmade of a medium-grained marble from Thasos.

Figure 27 - (left) Statue of the “bibliothécaire” (librarian) made of *pentelic* marble (sample RV1 – storeroom of Volubilis) - (right) Base of a statue made of *lunense* marble (sample RV4 – storeroom of Volubilis).

Figure 28 – River divinity from Volubilis made of *pentelic* marble (sample MA2 - Archaeological Museum of Rabat).

Figure 29 - (left) Statue of imperial age made of *lunense* marble (sample MA3 - Archaeological Museum of Rabat) – (right) Column made of unknown (local?) marble (sample MA1 - Garden of the archaeological Museum of Rabat).

Some other pieces, showing dark or pale grey stripes and coarse grain seem macroscopically to be coming from the Turkish island of Proconnesos (now Marmara) (Figure 30).

Figure 30 **-** Slab of grey marble from the palace of Gordian (24) looking like the so-called and made of Proconnesian marble (sample PG1-5).

The Volubilis archaeological objects made of white and pale grey marbles and sampled for in-laboratory determination are listed in Table 3.

Object and Location (monument reference number between parentheses)	Sample n°
Small slab *in situ* in the House of Venus (38): floor's mortar	V1
Small slab *in situ* at the entry of the House of Venus (38)	V4
Small slab *in situ* from the base of the north column in the House of Orpheus (4)	MO1
Base of the south column of the fountain in the House of Orpheus (4)	MO2
Small slab in the Palace of Gordian (24)	PG1-1
Small slab in the Palace of Gordian (24)	PG1-2
Small slab in the Palace of Gordian (24)	PG1-5
Bottom of the column in the garden of the Archaeological Museum of Rabat	MA1
Statue of a river divinity in the Archaeological Museum of Rabat: back-side of the base	MA2
Statue of imperial age in the Archaeological Museum of Rabat: back-side of the base	MA3
Statue of the “bibliothécaire” (librarian) in the storeroom of Volubilis site	RV1
Statue (base) in the storeroom of Volubilis site	RV4

Table 3 **–** List of the samples of white and pale grey marbles from Volubilis.

The complete petrographic-mineralogical features and the isotopic signatures of the whole sampled white and grey marbles are shown in Table 4 and Figure 31.

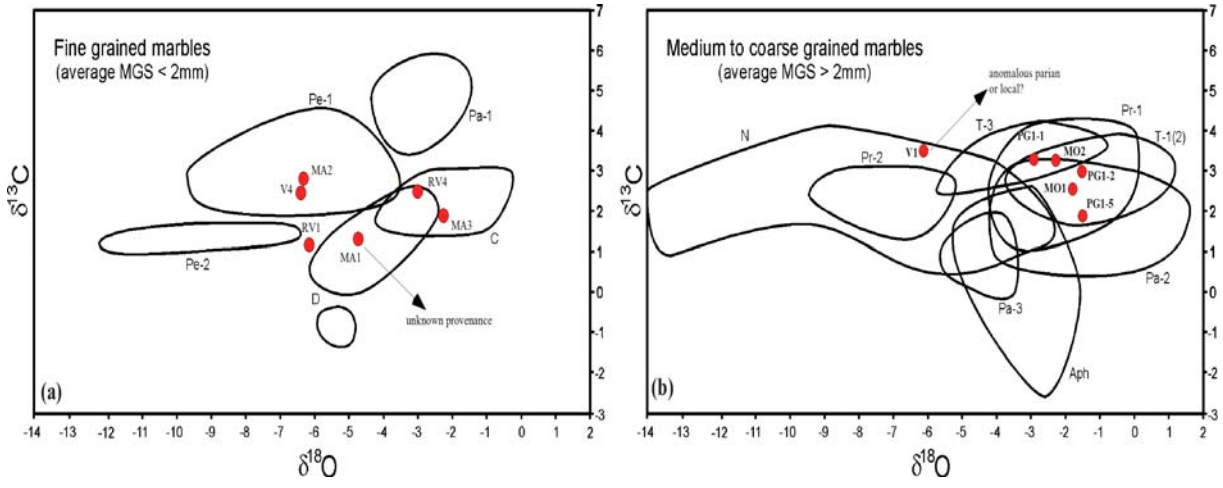


Figure 31 – Position of white marbles from Volubilis in the $\delta^{13}C$ vs $\delta^{18}O$ plot (isotopic fields from Gorgoni et al., 2002). (a) Pa1 = Paros Stefani; D = Dokimeion; Pe1-2 = Mount Pentelikon; C = Carrara. (b) N = Naxos; T1(2) = Thasos Aliki; T3 = Thasos Cape Vathy; Pr1-2 = Proconnesos; Aph = Aphrodisias; Pa2 = Paros Lakkoi; Pa3 = Paros Karavos.

According to the analytical results, the statues studied (four pieces) are sculpted in two fine-grained classical white marbles very appreciated and largely distributed during the Roman age:

- the *lunense* marble from Carrara (Italy);
- the *pentelic* marble from Mount Pentelikon (Athens – Greece).

Among the white marbles used for slab and architectural elements of Volubilis, the analyses indicate the presence of:

- the *pentelic* marble from Mount Pentelikon (Athens – Greece);
- the dolomitic variety of the *Thasian* marble from the district of Vathy, in the north-eastern sector of the island of Thasos (Greece);
- the *Parian* marble from Lakkoi (island of Paros, Cyclades - Greece);
- the *Proconnesian* marble from the island of Marmara (Turkey);
- One unknown white fine-grained marble, most probably having a local origin (cf. Figure 29b).

Concerning the latter, because of macroscopic similarities with the Filfila marble (northeast of Skikda, Algeria), its petrographic-mineralogical and geochemical features were compared with those of the Algerian marble. Unfortunately, their textures by optic microscopy are different (essentially homeoblastic for the Filfila marble, heteroblastic for our MA1 sample) and their isotopic signatures don't overlap (Figure 32). Therefore the provenance of this white marble remains unknown.

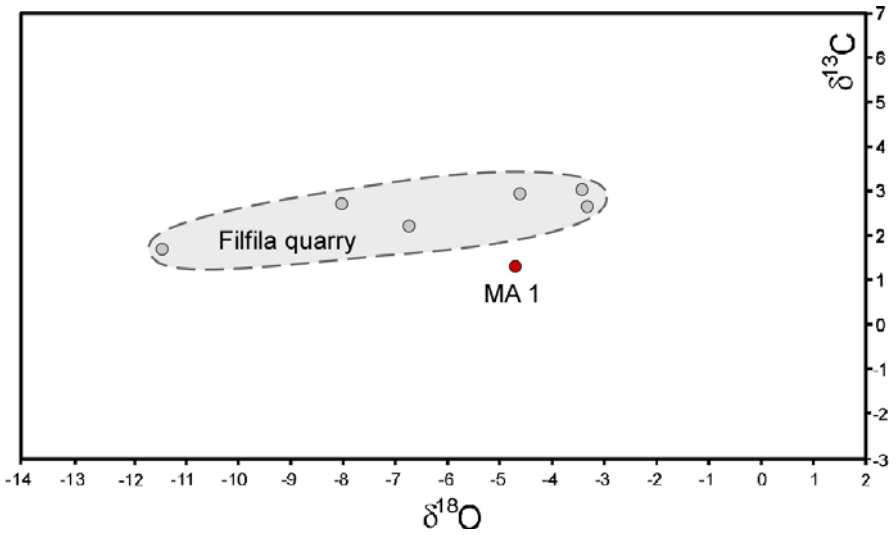


Figure 32 – The isotopic signature of Filfila quarry (Algeria) white marbles (sampled within the framework of the project) and of sample MA1 of unknown (local ?) orign.

Sample n°	Q	Ms	Chl	Ap	Gr	Ore min.	Fe oxy.	Tr	P	Ep	Dol*	MGS (mm)	Calcite crystals boundaries	Texture	Fabric	$\delta^{18}O$ (PDB)	$\delta^{13}C$ (PDB)	Origin
V1		±	±		+++		±			±		2.10	embayed. curved	HE	Mosaic	-6.1	3.6	Parian (Lakkoi) or Local
V4	+				+	±				±		1.95	sutured. embayed ± curved	HE	Mosaic. weakly lineated	-6.4	2.5	Pentelic
MO1					+++	±					±	2.88	sutured. embayed	HE	Mortar	-1.8	2.6	Proconnesian
MO2	±				++	±	±				±	2.50	embayed ± sutured	HE	Mosaic	-2.3	3.3	Parian (Lakkoi)
PG1-1		±		±	++	±	±			±	+++	2.55	sutured ± embayed	HE	Mosaic	-2.9	3.3	Thasos (Vathy)
PG1-2					++	±						2.15	embayed ± curved	HE	Mosaic	-1.5	3.0	Parian (Lakkoi)
PG1-5	±	+			++	±					±	2.80	sutured ± embayed	HE	Mortar	-1.5	1.9	Proconnesian
MA1		+	+	±		±		++				0.95	embayed. curved	HE	Mosaic	-4.7	1.3	Unknown /Local ?
MA2					++	±	±					0.75	curved. embayed	HE	Mosaic	-6.3	2.8	Pentelic
MA3					±	±						0.55	curved ± straight	HO	Mosaic. with rare triple points	-2.3	1.9	Lunense
RV1					++	±						1.16	embayed	HE	Mosaic	-6.1	1.2	Pentelic
RV4					±	±						0.76	embayed ± curved	HE	Mosaic	-3.0	2.5	Lunense

Table 4 – Petrographic-mineralogical and isotopic features of the samples of white and pale grey marbles from Volubilis.

b. Grey striped and stained marbles

The presence of grey-striped or grey-stained marbles is quite abundant in the richest houses and in the storeroom of the site. Most of them are medium-fine grained as illustrated by the slabs observable at the palace of Gordian and the baths of Gallienus (Figure 33).

Figure 33 - Slab-fragments from the Palace of Gordian (24) and the baths of Gallienus (5).

Macroscopically, they seem to belong to the type called “*greco scritto*” from Annaba, Algeria, a graphitic medium-coarse grained marble with a white background draw by thin grey-blackish veins or dark grey to bluish stains, at times remembering a sort of “black on white” writing.

The Volubilis archaeological objects made of grey striped and stained marbles and sampled for in-laboratory determination are listed in Table 5.

Object and Location (monument reference number between parentheses	Sample n°
Slab from the wall of the Palace of Gordian (24): roving crust	PG1-4
Slab from the Baths of Gallienus (5): roving crust	BG2.1
Slab from the wall of the Baths of Gallienus (5): roving crust:	BG2.2
Slab from the Palace of Gordian (24): roving crust	PG2-3
Slab from the wall of the Palace of Gordian (24): roving crust	PG2-1
Slab from the House of Venus (38): within the original mortar	V2
Slab from the House of Venus (38): within the original mortar	V3
Slab from the storeroom of the Volubilis site	RV6
Slab from the storeroom of the Volubilis site	RV7
Slab from the storeroom of the Volubilis site	RV8
Slab from the storeroom of the Volubilis site	RV9
Slab from the storeroom of the Volubilis site	RV10
Slab from the storeroom of the Volubilis site	RV11
Slab from the storeroom of the Volubilis site	RV12
Slab from the storeroom of the Volubilis site	RV13

Table 5 **–** List of the samples from Volubilis of grey stripped and stained marbles looking like "*greco scritto*".

The complete petrographic-mineralogical features and the isotopic signatures of the whole sampled grey stripped and stained marbles are shown in Table 6, Figure 34 and Figure 35).

Sample n.	Q	Ms	Chl	Ap	Gr	Ore min.	Fe oxy.	Tr	P	Ep	Dol*	MGS	Calcite crystals boundaries	Texture	Fabric	$\delta^{18}O$ (PDB)	$\delta^{13}C$ (PDB)	Origin
PG1-4	+++	±			++		±					0.54	embayed, straight	HO/HE	Mosaic, weakly lineated	–6.9	2.8	Unknown
BG2.1	++	±			+	+	±					0.22	straight, embayed	HO/HE	Mosaic, weakly lineated	–7.2	3.2	Unknown
BG2.2	++				+++		+++					0.62	embayed, straight	HO/HE	Mosaic, weakly lineated	–8.4	2.7	Unknown
PG2-3	++	±			+++	±					++	0.95	embayed ± straight	HE	Mosaic	–7.5	2.6	Unknown
PG2-1	±	±			+		±					2.20	straight ± embayed	HE	Mosaic	–2.9	2.5	Unknown
V2	++	±			+++	±					+	1.54	embayed ± sutured	HE	Mosaic	–3.1	2.4	Unknown
V3					+++							1.05	embayed ± sutured	HE	Mosaic	–2.9	3.3	Unknown
RV6	±				+++							0.48	straight ± curved	HO	Mosaic	–8.1	2.8	Unknown
RV7	+				++				±			1.27	sutured, embayed	HE	Mosaic	–6.5	0.8	Unknown
RV8	++	±			±						±	2.00	embayed ± curved ± sutured	HE	Mosaic	–6.6	0.9	Unknown
RV9	+++	++	±		++							0.42	sutured ± embayed	HE/HO	Mosaic	–7.0	3.0	Unknown
RV10	+++	+		±	++						±	0.84	sutured ± embayed	HE	Mosaic	–6.2	1.8	Unknown
RV11	±				++						±	0.39	straight, curved	HO	Mosaic	–8.2	2.2	Unknown
RV12	±				+++	+					±	2.62	sutured ± embayed ± curved	HE	Mosaic	–4.9	2.0	Unknown
RV13	+	±	+		++				±		+	1.05	embayed, curved	HE	Mosaic	–5.8	1.8	Unknown

Table 6 – Petrographic-mineralogical and isotopic features of the samples of grey striped and stained marbles from Volubilis.

As regards the grey stripped and stained marbles looking like the so-called "*greco scritto"*, both their petrographic parameters observed under the polarizing microscope and isotopic compositions do not match with those measured for the classical Algerian *"greco scritto"* that was expressly sampled in the ancient quarry of Cap de Garde close to Annaba (Algeria). In fact, the latter is characterized by higher MGS values (frequently > 2mm), different fabric and different accessory minerals.

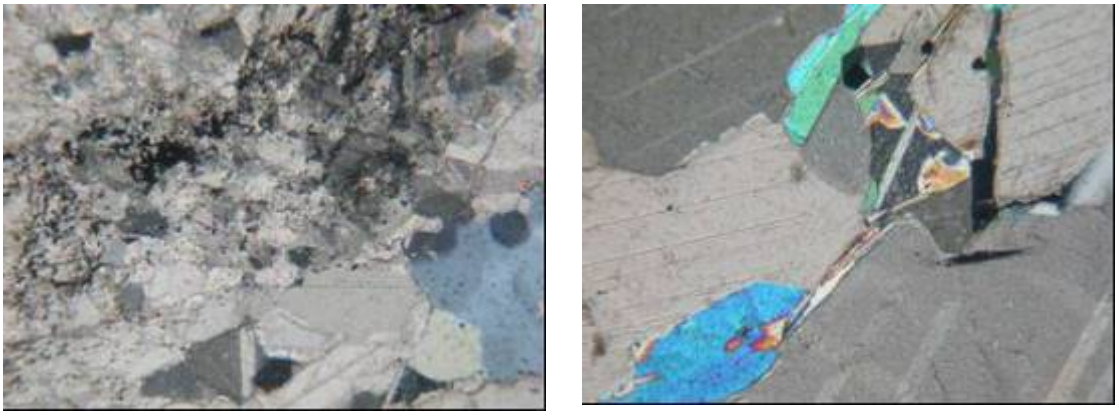


Figure 34 – Microfacies of the "*greco scritto*" from Volubilis (on the left; sample BG2-1) and from the ancient quarry of Cap de Garde (on the right), Annaba, Algeria. Samples show clearly different fabric, grain-size and accessory minerals (photomicrographs N+; magnification x9).

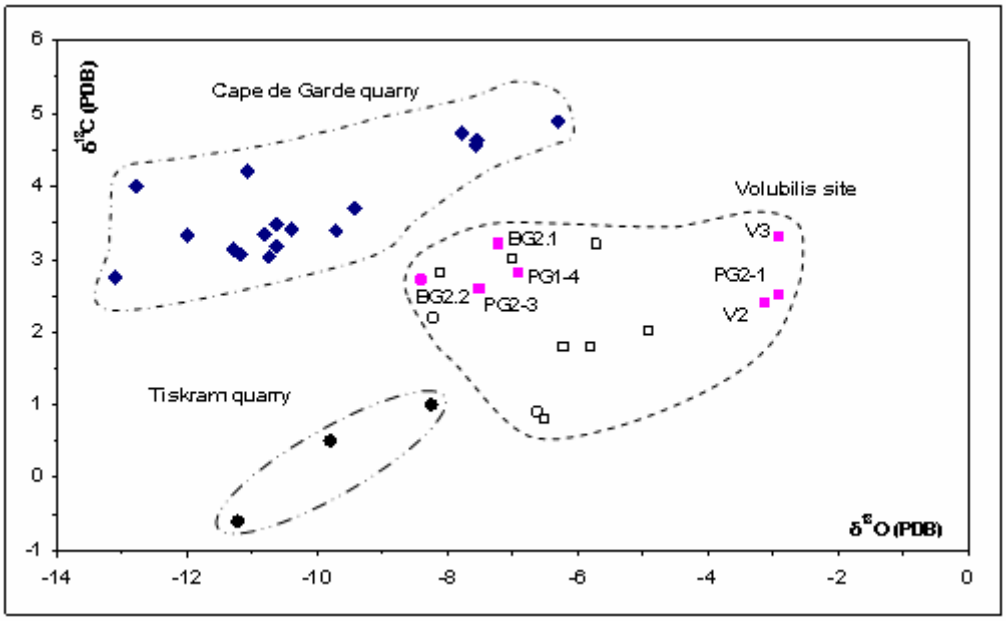


Figure 35 – The isotopic signature of the *greco scritto* found in Volubilis compared with both those of the *greco scritto* from Cap de Garde (Algeria) and the grey veined marbles from Tiskram (Moroccco).

Furthermore, a comparison with some grey veined white marbles extracted (for gravels at present) in the Tiskram area (Central Morocco, West of Khenifra city, about 120 km southern of Volubilis) was undertaken (Figure 36 - Figure 37) due to their relatively similar visual aspect with the so called *greco scritto*.

Unfortunately according to petrographic-mineralogical features and isotopic values (Figure 35), Volubilis site samples and those from Tiskram quarries area are different. The origin of these marbles remains unknown for the moment, nevertheless, a provenance of others Moroccan or Algerian regions is supposed.

Figure 36 – Overview of Tiskram quarries area supplying a grey veined white marble.

Figure 37 – Facies of grey veined white marble extracted in Tiskram quarries.

c. Pinkish marble

A pinkish marble was also observed in few elements during the inspection of the Volubilis site. First, a slab fragment is located in the wall of a room of the Gordian's Palace (Figure 38). It looks like the so-called *Portuguese pink*, an Hercynian marble outcropping at Vilaviçosa in the Estremoz Anticline (Portugal). The same pinkish marble was used for the stele dedicated to Venus exposed at the entry of the site (Figure 39).

Figure 38 - Slab-fragment of a pinkish marble on a wall of the Palace of Gordian (24).

Figure 39 - Stele dedicated to Venus made of portuguese pink (storerooms of the site).

Several slab fragments were also microscopically identified (no sampling performed) as *Portuguese pink* in the storeroom of the ancient site, without any information about their original location in buildings (Figure 40).

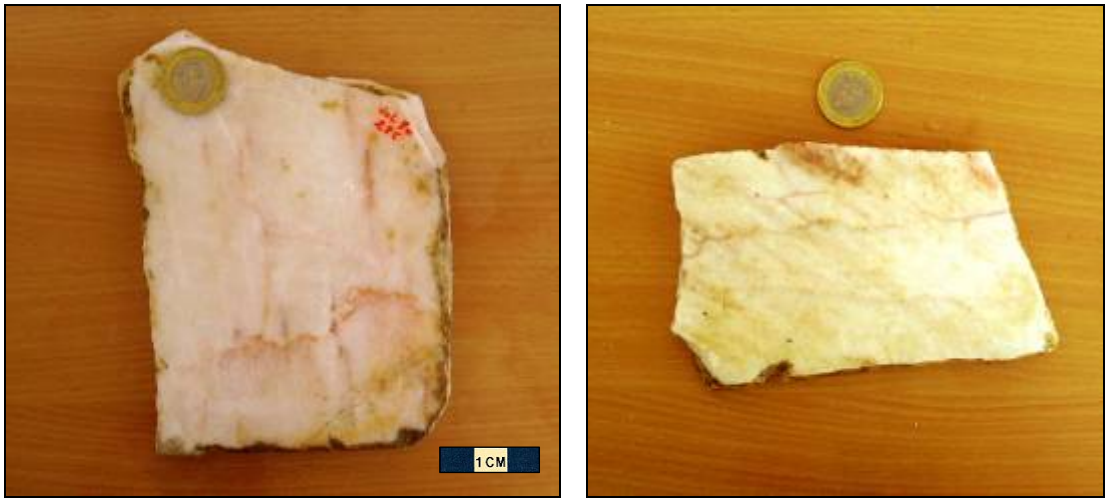


Figure 40 – Views of slab fragments of pinkish marble supposed to be *Portuguese pink*.

The three Volubilis archaeological objects made of pinkish marble and sampled for in-laboratory determination are listed in Table 7.

Object and Location	Sample n°
Slab from the base of the wall in room PG2, Palace of Gordian (24)	G1
Pinkish marble slab from the base of the wall in room PG2, Palace of Gordian (24)	G2
Stele dedicated to Venus in the storerooms of the site	Stele

Table 7 - List of the samples from Volubilis of pinkish marble.

The complete petrographic-mineralogical features and the isotopic signatures of the pinkish marbles are shown in Table 8 and Figure 41 to Figure 45.

Data obtained for G1 and G2 pinkish marble samples (Figure 41) were compared to available data from one sample of the classical *Portuguese pink* of secure provenance (Figure 42). as well as data from literature (Lapuente and Turi, 1995) concerning pinkish marbles outcropping in the Estremoz Anticline (Vilaviçosa, Portugal).

Sample n.	Q	Ms	Chl	Ap	Gr	Ore min.	Fe oxy.	Tr	P	Ep	Dol*	MGS	Calcite crystals boundaries	Texture	Fabric	$\delta^{18}O$ (PDB)	$\delta^{13}C$ (PDB)	Origin
G1	+++			+	±				±			4.45	sutured, embayed	HE	Mosaic/Mortar	-5.7	2.8	Estremoz, Portugal
G2	+++			+			++					2.45	sutured, embayed	HE	Mosaic/Mortar	-6.8	2.5	Estremoz, Portugal
Stele	++			±			+					2.85	sutured	He	Mosaic/Mortar	–5.9	3.0	Estremoz, Portugal

Table 8 – Petrographic-mineralogical and isotopic features of the samples of pinkish marble from Volubilis.

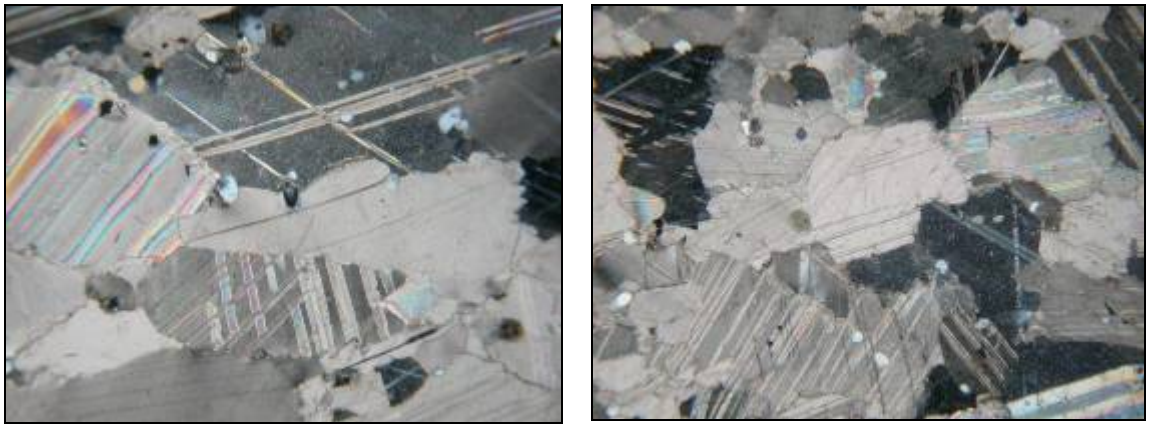


Figure 41 - Microfacies of the pinkish marble from Volubilis (slab samples from the base of the wall in room PG2, Gordian Palace) (photomicrographs N+; magnification x60; left: sample G1 ; right: sample G2).

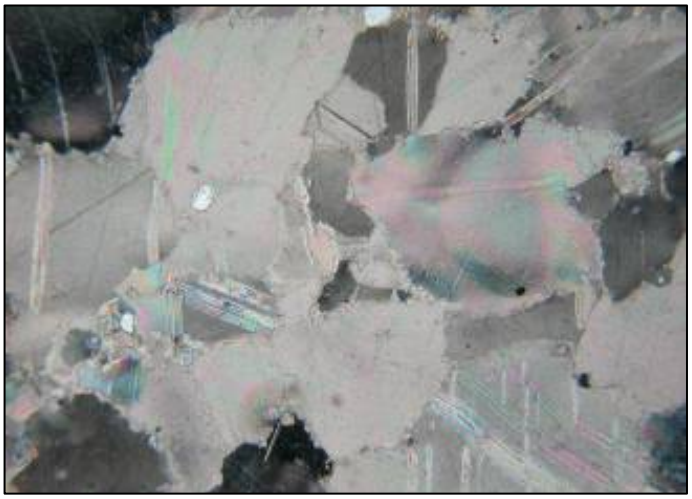


Figure 42 - Photomicrograph of a sample of " Portuguese pink" marble from Vilaviçosa, Portugal (polarized light, N+; magnification x35).

Both Volubilis samples were also compared to some of a relatively similar visual aspect Moroccan marble, extracted nowadays for decorative stone in Bou Acila (Central Morocco, West of Khenifra city, about 120 km southern of Volubilis - Figure 43 and Figure 44).

Figure 43 - Overview of one of the quarries of Bou Acila area supplying a white and pink marble.

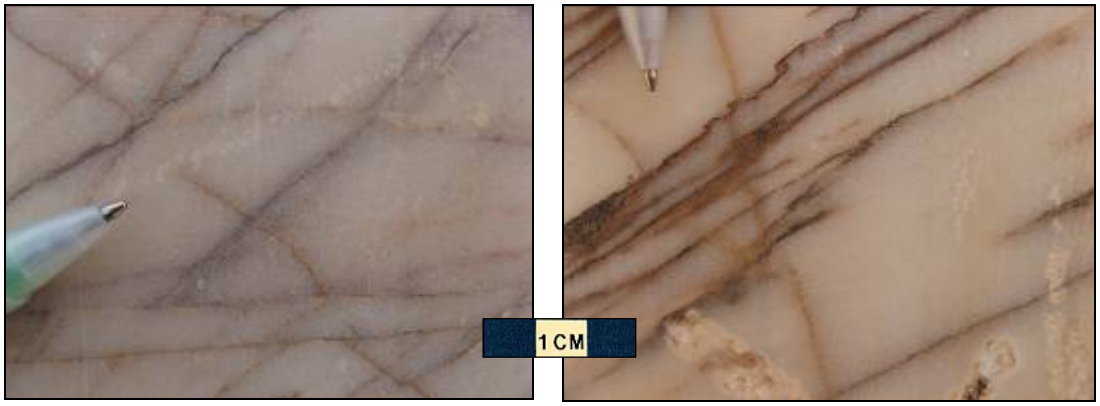


Figure 44 – Facies of Bou Acila quarries marble.

As shown in Figure 41 and

Figure 42, MGS (Maximum Grain Size), fabric, boundary shape of crystals and accessory minerals of both Volubilis pinkish marble samples and the one of *Portuguese pink* are very similar.

On the other hand, isotopic data (Figure 45) confirm a compatible provenance from Vilaviçosa in Portugal and exclude Bou Acila quarries i.e. a local provenance.

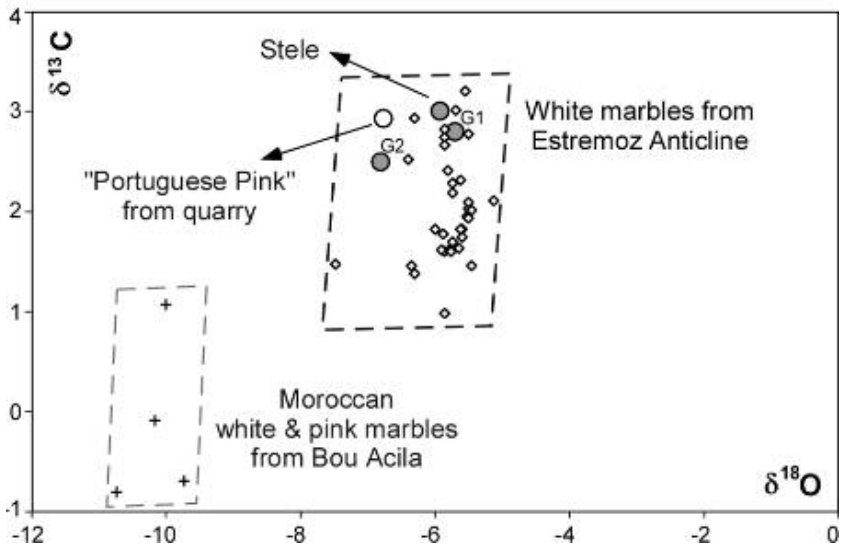


Figure 45 - $\delta^{18}O$ vs $\delta^{13}C$ isotopic diagram plotting pink and white marbles found in the Gordian Baths (samples G1, G2) versus Moroccan and Portuguese white & pink marbles.

4. Study of the building stones

In the past, the identification and the determination of origin of Volubilis building stones was not a priority research axis for archaeologists. Nevertheless, few investigations were carried out dealing with the study of Volubilis stones and the search of ancient quarries. Etienne (1950) made a preliminary description of limestone quarries located around Volubilis. Then, Feray and Paskoff (1960, 1966) gave few observations about origin and decay of Volubilis building stones. They supplied a detailed overview of quarries located around Volubilis, based on extraction and tool marks as well as petrographic visual description of the corresponding materials, and they proposed a classification of Volubilis building stones. Jodin (1969) discussed these previous results and reviewed the petrographic classification of Volubilis building stones. But in any case, the proposed classifications remained till now insufficient and sometimes arbitrary, limited by a petrographic description based only on visual criteria.

4.1. FIELD APPROACH, SAMPLING AND METHODOLOGY

Aiming to the determination of the building stone types and the locations of their origin in the regional areas of Volubilis monuments, the works described below were carried out.

4.1.1. Fieldworks

After a geological and archaeological review of bibliographic data available, a detailed macroscopic examination of the building stones of Volubilis (lithofacies analysis) and a very meticulous sampling of each type of stone visually observed were performed.

In parallel to these on-site investigations, a geological reconnaissance in the regional area was carried out for determining the location of the quarries of origin of the building stones observed on the ancient site and a sampling based on geological criteria and available historical data was done.

4.1.2. In-laboratory characterisation

Thin sections of samples collected both on monuments and quarries were prepared and examined by optical microscopy for determining their petrographic microfacies. Some of the samples were staining by Alizarin red-S and potassium hexacyanoferrate in order to distinguish the carbonate minerals from the others under the microscope. For determining their insoluble minerals fraction, some of the samples were submitted to dissolution by 10% solution of acetic acid and their insoluble residue was weighted. Then, their qualitative mineralogical composition was determined using an X-ray

diffractometer (Siemens D-500). Additional texture observations and chemical mapping by Scanning Electron Microscope (SEM) were also realized on selected samples.

Based on the above examinations, the following characteristics were inventoried for each sample: color, lithology, sedimentary structures, fractures, grains, matrix, fabric, fossils, porosity, cement types, stylolithes, and the amount and the mineralogical composition of non carbonate phases. These criteria characterize the lithofacies types ("type of stone") permitting a comparison between lithofacies types from monuments and quarries possibly ancient. They also control the endogenic decay factors of the stones.

Moreover, in order to complete the identification of the types of stones and facilitate their comparison, geochemical measurements were carried out on numerous samples after adequate preparations (drying, grinding). Major elements contents were determined by X-Ray Fluorescence (XRF) or by Inductively Coupled Plasma / Atomic Emission Spectrometry and Mass Spectrometry (ICP-AES) for some others. Trace elements contents were measured by ICP-AES. 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).

Furthermore, in order to characterise the building material quality of each type of stone and to achieve the knowledge of their identification parameters, some physical and mechanical tests were carried out on selected samples: total porosity and bulk density measurement (norm NF EN 1936), water absorption measurement (norm NF EN 13755) and measurement of uniaxial compressive strength (norm NF EN 1926) with a M.F.L. SYSTEM (O-200 KN) press.

4.2. DESCRIPTION OF THE TYPES OF BUILDING STONES

The systematic survey of each monument permitted to identify visually two main categories of building stones (referenced B and C): beige-yellowish calcarenite limestones so-called "molassa" (B) and grey massive limestones (C). Four other types (referenced A and D to F) present in quite low quantities were also observed: beige-green marly limestones (A), ochre-grey limestones rich in bivalvia (D), coarse dolomites (E) and continental limestones (F).

The in-laboratory study (notably petrographic observations by optic microscope using the usual classification systems (Folk, 1959, 1962; Dunham, 1962) of forty-eight representative samples (referenced VOL1 to VOL48) collected on monuments of each observed type resulted in the division of lithotypes B and C into sub-facies (referenced B1 to B3 and C1 to C3).

The detailed list of lithotypes of building stones encountered in Volubilis site is presented in Table 9. Each lithotype is described in the pages hereunder.

Lithofacies reference and simplified term	Lithological classification	Representative samples collected in Volubilis monuments (total number and reference)
A **Beige-green marly limestones**	Beige-green marly limestone (Silty wackestone/packstone) rich in pelagic fossils.	10 samples (ref. VOL03, 06, 10, 16, 19, 21, 28, 37, 46 and 48)
B **Beige-yellowish calcarenite limestones** **so-called "molassa"**	1. Beige- yellowish porous calcarenite rich in terrigenous material. 2. Beige-yellowish porous calcarenite rich in terrigenous material and large bioclasts 3. Beige-pink porous calcirudite rich in terrigenous material	15 samples (ref. VOL11,13, 15, 20, 23, 24, 25, 26, 32, 33, 34, 38, 39, 41 and 47)
C **Grey massive limestones**	1. Beige-grey peloid grainstone/packstone 2. Grey, coated bioclastic grainstone 3. Grey, ooid/ coated grainstone/packstone	18 samples (ref. VOL01, 02, 04, 07, 08, 09, 12, 14, 17, 18, 22, 27, 29, 30, 31, 36, 40 and 43)
D **Ochre-grey limestones rich in bivalvia**	Ochre-grey, bivalvia bioclastic limestone	1 sample (ref. VOL35)
E **Coarse dolomites**	Coarse dolomites	2 samples (ref. VOL5 and 42)
F **Continental limestones**	Travertines and lacustrine limestones	2 samples (ref. VOL44 and 45)

Table 9 – List of the building stones lithotypes from Volubilis site and the corresponding samples collected.

4.2.1. Lithotype A

The lithological term for lithotype A is **beige-green marly limestone**, classified as a “silty wackestone/packstone rich in pelagic fossils”. This facies largely used for the upper architectural members of the monuments suffers the greatest deterioration (loss of material) among the building stones. It is a poor quality limestone with light beige-green color, powdery, porous and silty in texture (Figure 46 and Figure 47).

Figure 46 – Macroscopic view of lithofacies A : block in “Palace of Gordian with fresh crack (a) and typical colored patina (b) due to lichens (location: Gordian Palace).

Figure 47 – Macroscopic view of lithofacies A : typical rounded weathering form with loss of material; location: Palace of Gordian (24).

The study of thin sections by optic microscopy reveals a content of pelagic fossils (Calcispaerulidis, Globigerinidae, Radiolarian, echinoid spine) (Figure 48 left) and rarely benthonic foraminifera (Figure 48 right) as well as sub-angular small clasts of quartz and probably feldspars. The groundmass is micritic calcite with very fine terrigenous admixture and grains of iron oxides / hydroxides. The porosity is primary and mainly secondary due to dissolutions.

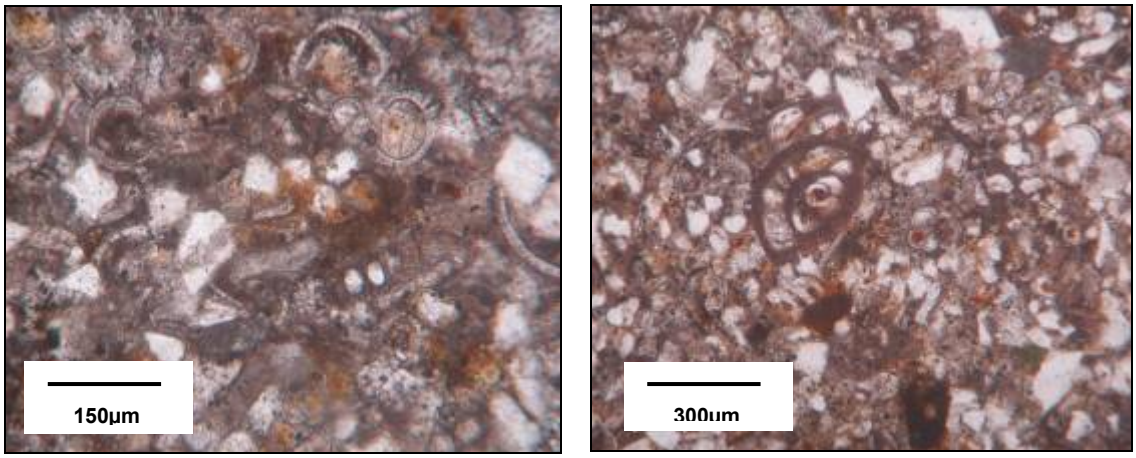


Figure 48 – Microscopic observations (N//) of lithofacies A (sample VOL21): (left) pelagic fossils (Calcisspaerulidis, Globigerinidae, Radiolarian, echinoid spine) and subangular small clasts of quartz, probably feldspars ; (right) benthonic foraminifera (rare).

The whole analytical data measured on the samples collected on Volubilis site and belonging to lithotype A (ten samples; ref. VOL03, 06, 10, 16, 19, 21, 28, 37, 46 and 48) are detailed in Table 10 and Table 11.

According to the obtained data, the lithotype A “beige-green marly limestone” corresponds to a soft stone (compressive strength below 24 MPa) correlated to a significant porosity ranging from 22 to 37% (30% in average) illustrating the heterogeneity of the stone in terms of variability and quality material.

In a mineralogical point of view, it is a carbonate (calcite content about 70% in average, reaching 80%) with a significant proportion of quartz (ranging from 15 to 28% considering both the petrographic microscopic observations and the silica content measured). Some samples also contain a few percents proportion of dolomite illustrating a beginning of dolomitisation of the stone. Besides quartz, accessory minerals are mainly traces of feldspars (albite), micas and clay minerals.

The major chemical elements of lithotype A are Calcium (average about 40%) and Silicium (23% in average). Concerning the trace chemical elements, the significant ones are Strontium with an average value 718 ppm, followed by order of importance by Zirconium (81 ppm in average), Barium (44 ppm), Zinc and Chromium (26 ppm) and Bore (24 ppm).

The isotopic signature of lithotype A “beige-green marly limestone” is illustrated in Figure 49.

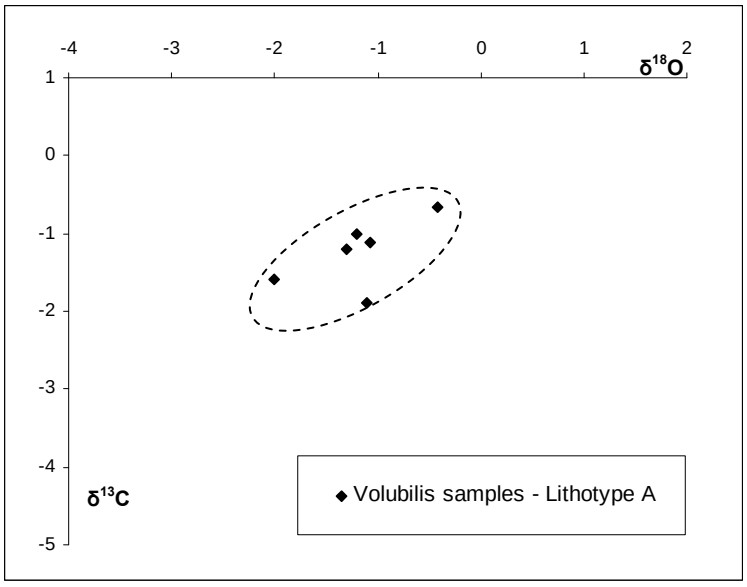


Figure 49 – Isotopic signature of lithotype A “beige-green marly limestone”.

Sample Reference	Samples Location on Volubilis site	Sub-lithotype	Petrographic description by optic microscopy	Mineralogical analysis by X-Ray Diffraction	Calcite content (%) by acid attack	Dolomite content (%) by acid attack	$\delta^{18}O$ ‰ vs PDB	$\delta^{13}C$ ‰ vs PDB	Uniaxial Compressive Strenght (MPa)	Total Water Porosity (%)	Solid Density	Bulk Density	Water Natural Saturation Degree
VOL03	House of Dyonisos (20)	A	X	-	66.1	9.9	-1.2	-1.0	23.7	25.5	2.68	2.00	0.70
VOL06	House of Orpheus (4)	A	X	-	-	-	-	-	-	-	-	-	-
VOL10	House of Gold Coin (28)	A	X	X	-	-	-	-	-	-	-	-	-
VOL16	House of Hercules (18)	A	X	X	-	-	-1.1	-1.9	-	-	-	-	-
VOL19	House of the Wild Beast Mosaic (22)	A	X	X	-	-	-1.3	-1.2	-	-	-	-	-
VOL21	House of the Wild Beast Mosaic (22)	A	X	X	-	-	-	-	-	-	-	-	-
VOL28	Palace of Gordian (24)	A	X	X	-	-	-	-	-	-	-	-	-
VOL37	Palace of Gordian (24) / West part	A	X	-	68.4	0.0	-1.1	-1.1	-	37.0	2.74	1.72	1.01
VOL46	House of the Sundial (30)	A	X	-	67.2	3.1	-2.0	-1.6	-	36.3	2.73	1.74	0.98
VOL48	Outdoor storage area	A	X	-	79.5	0.0	-0.4	-0.7	-	22.3	2.69	2.09	0.61
Min	-	-	-	-	66.1	0.0	-	-	-	22.3	2.68	1.72	0.61
Max	-	-	-	-	79.5	9.9	-	-	-	37.0	2.74	2.09	1.01
Av	-	-	-	-	70.3	3.3	-	-	23.7	30.3	2.71	1.89	0.82

Table 10 – Analytical data measured on the samples from Volubilis site belonging to lithotype A.

Sample Reference	Al_2O_3 (%)	CaO (%)	Fe_2O_3 (%)	K_2O (%)	MgO (%)	MnO (%)	P_2O_5 (%)	SiO_2 (%)	TiO_2 (%)	LOI (%)	Co (ppm)	Pb (ppm)	As (ppm)	Sr (ppm)	Zn (ppm)	B (ppm)	V (ppm)	Cr (ppm)	Ba (ppm)	Ag (ppm)	Ce (ppm)	Zr (ppm)
VOL03	1.9	38.4	1.16	0.49	2.0	<0.01	0.37	22.7	0.16	32.5	<5	<10	21	719	24	17	11	37	40	<0.2	<10	66
VOL06	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
VOL10	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
VOL16	3.0	43.5	1.3	0.8	2.1	0.01	0.69	26.8	0.22	-	6	15	<20	816	39	38	22	44	67	<0.2	29	112
VOL19	3.2	41.1	1.3	0.8	2.2	0.01	0.67	27.8	0.23	-	5	10	<20	755	33	37	24	41	73	<0.2	27	116
VOL21	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
VOL28	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
VOL37	2.2	38.1	0.95	0.49	1.3	<0.01	0.74	21.5	0.16	33.3	<5	<10	<20	796	29	24	<10	24	49	0.3	27	103
VOL46	2.5	36.9	1.32	0.58	2.6	<0.01	0.46	21.9	0.19	32.9	<5	<10	<20	619	33	28	<10	27	54	<0.2	27	100
VOL48	1.5	43.3	0.61	0.39	0.7	<0.01	0.82	15.9	0.09	35.6	<5	<10	22	737	18	14	<10	16	32	0.5	23	54
Min	1.5	36.9	0.61	0.39	0.7	-	0.37	15.9	0.09	32.5	-	-	-	619	18	14	-	16	32	-	-	54
Max	3.2	43.5	1.32	0.80	2.6	0.01	0.82	27.8	0.23	35.6	6	15	22	816	39	38	24	44	73	0.5	29	116
Av	2.4	40.2	1.11	0.59	1.8	-	0.63	22.8	0.18	33.6	-	-	-	718	26	24	-	26	44	-	-	81

Table 11 – Analytical data measured on the ten samples from Volubilis site belonging to lithotype A (LOI = Lost Of Ignition).

4.2.2. Lithotype B

The lithological term for lithotype B is **beige-yellowish calcarenite limestones** (so-called “Molassa”).

According to petrographic observations by optic microscope using the usual classification systems; Folk, 1959, 1962; Dunham, 1962), the lithotype B was finally divided into three sub-facies referenced B1 to B3.

⇨ **Lithofacies B1 “beige-yellowish porous calcarenite rich in terrigenous material”:** This lithotype is a poor calcarenite, beige-light yellowish in color, locally porous and sandy in texture (Figure 51). According to microfacies analysis (Figure 50) it consists of sub-rounded echinoderm (crinoids) fragments showing typical characteristic of echinoderms grain-single-crystal extinction and neretic foraminifera as well as terrigenous clasts. The presence of terrigenous material is characteristic and corresponds mainly to sub-angular clasts of quartz, feldspars and very rare lithoclasts. The grain size is 0.3 to 0.5 mm and their sorting is good. The cement is predominately syntaxial (“rim cement”) around the clasts of crinoids in optical continuity with the original grain and micritic. The proportion of cement is lower than that of grains.

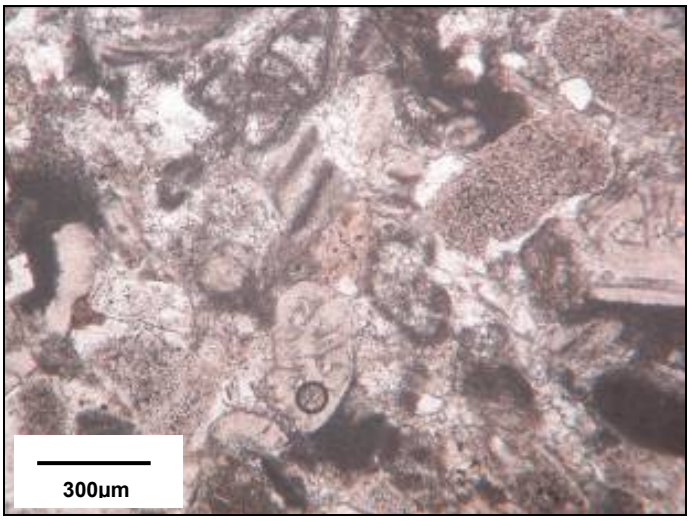


Figure 50 – Microscopic observation (N//) of lithofacies B1 (sample VOL20): sub-rounded echinoderm (crinoids) fragments, neretic foraminifera and terrigenous clasts of quartz and feldspars; good sorting.

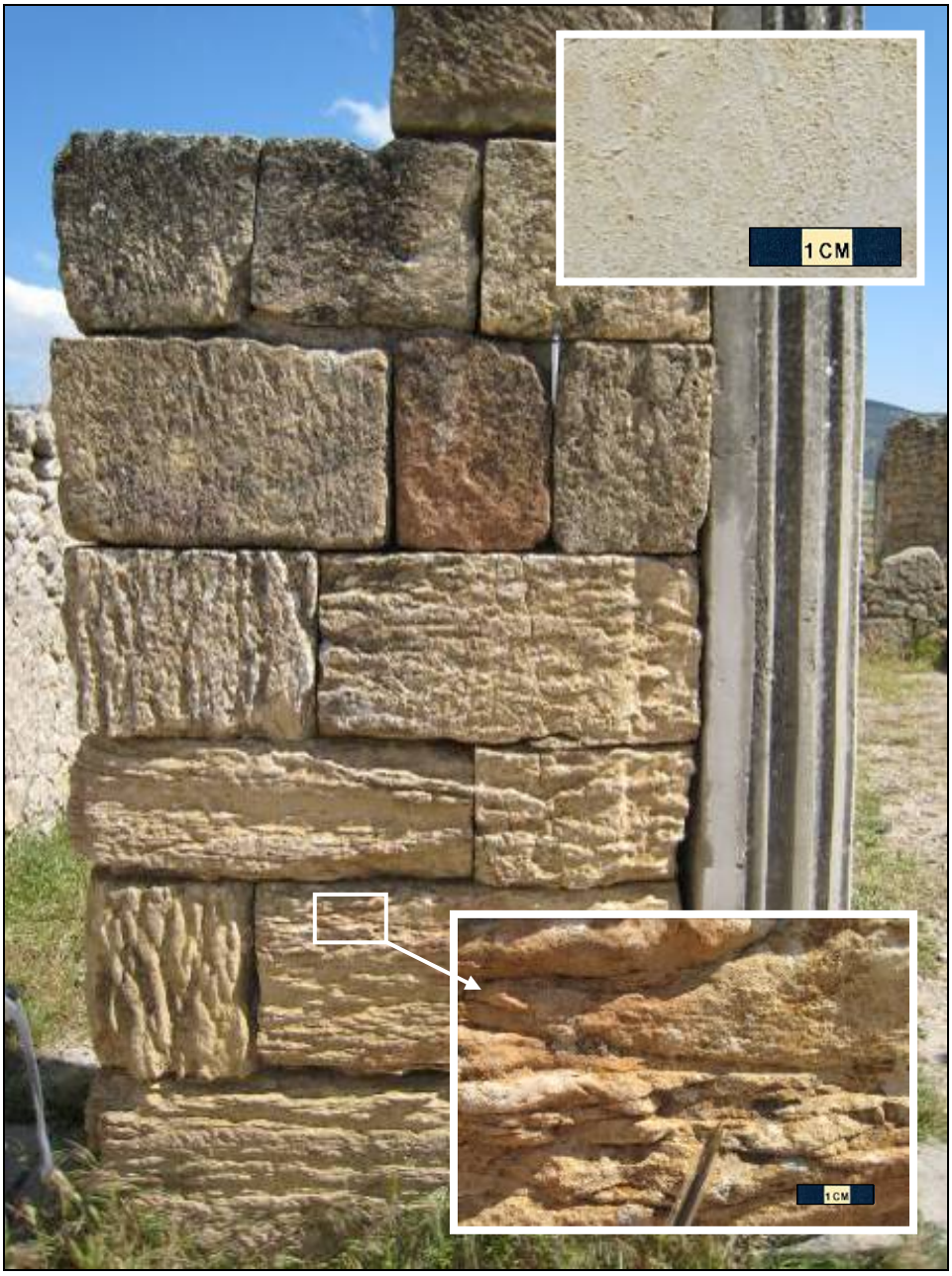


Figure 51 – Macroscopic view of lithofacies B1: poor calcarenite, beige-light yellowish in color, locally porous and sandy in texture; typical sandy desagregation and alveolisation weathering form (location: House of the Column (15)) and texture of a cut face.

⇨ **Lithofacies B2 "beige-yellowish porous calcarenite rich in terrigenous material and large bioclasts":** This lithotype is yellowish-beige in color, slightly friable and porous and sandy in texture with large fossils (Figure 53 and Figure 54). Its microfacies characteristics are similar to those from B1 one but in this group, large (centimetric) bioclasts and planktonic foraminifera are also present (Figure 52).

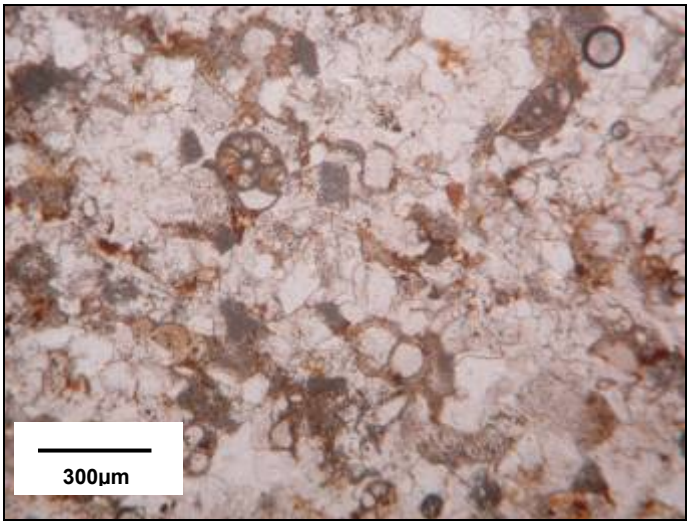


Figure 52 – Microscopic observation (left: N//) of lithofacies B2 (sample VOL25): bentonic foraminifera, sub rounded echinoderm (crinoids) fragments, planktonic foraminifera and terrigenous clasts of quartz and feldspars ; good sorting.

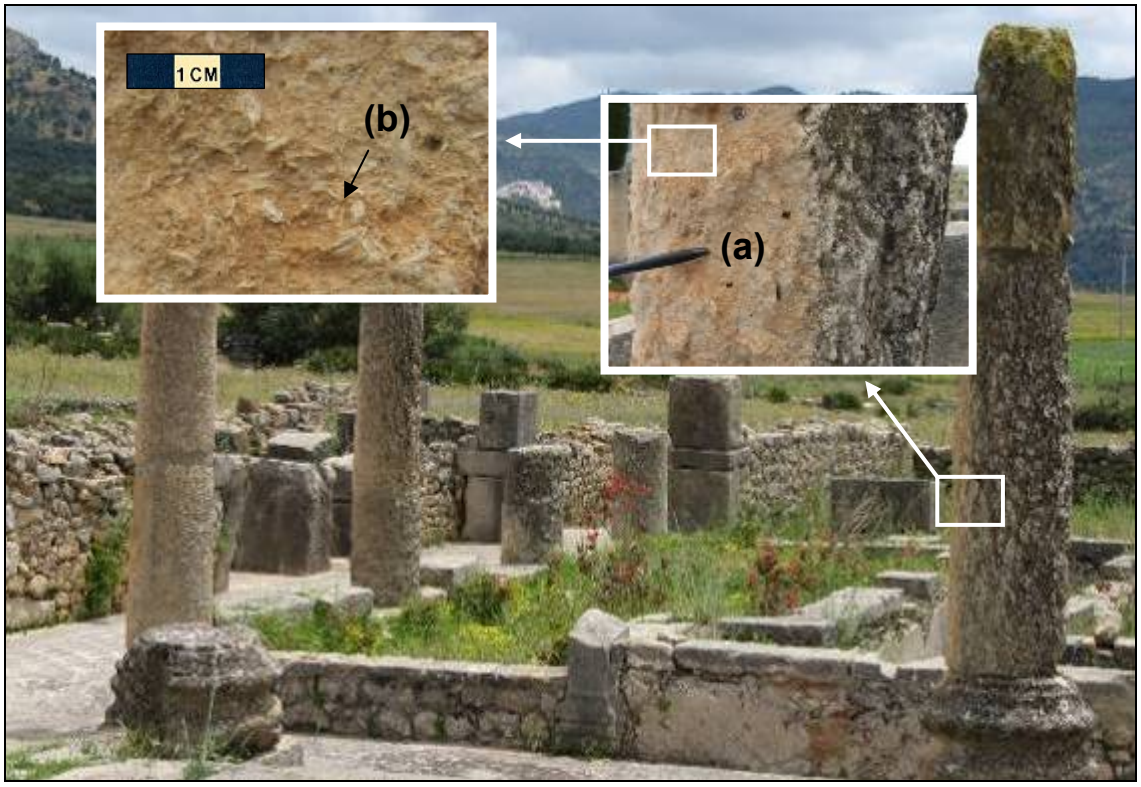


Figure 53 – Macroscopic view of lithofacies B2: (a) Column with typical sandy desagregation and alveolisation erosion forms - (b) Detail of large bioclats; location: House of Venus (38).

Figure 54 – Macroscopic view of lithofacies B2: door jamb of a house (west of Palace of Gordian (24) on Decumanus Maximus) with greyish biological patina.

⇨ **Lithofacies B3 "beige-pink porous calcirudite rich in terrigenous material":** This lithotype is a calcirudite, yellowish to brownish-reddish in color, porous, coarse sandy in texture (Figure 56). Based on microfacies analysis (Figure 55) their particles (grains) are mainly clasts of red algae, echinoderms, brachiopods and others, large benthonic foraminifera. In minor amount, sub-angular clasts of quartz and feldspars participate as well as iron-oxides-hydroxides. The size of the particles are higher than 0.5 mm and their sorting is very to extremely poor. The cement is granular calcite and syntaxial one in inter and intra-particle pores.

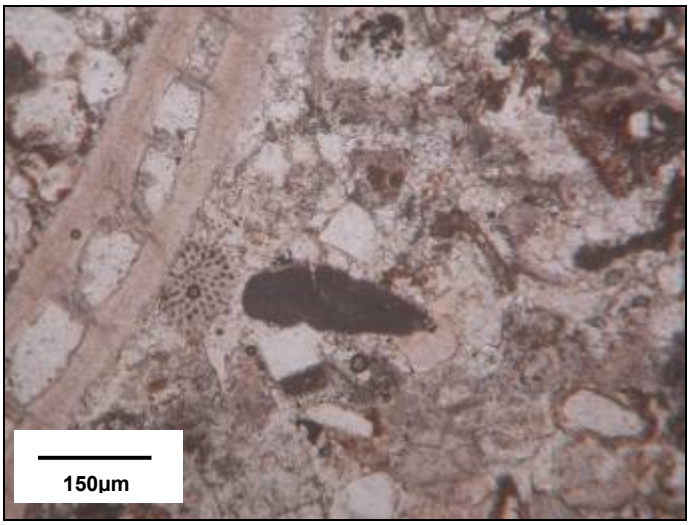


Figure 55 – Microscopic observations (N//) of lithofacies B3 (sample VOL15): clasts of red algae, echinoderms and brachiopods are distinguishable as well as the subangular clasts of quartz and probably feldspars; very to extremely poor sorting.

The typical characteristics for this facies are macroscopically the ochre–yellowish color and larger pores (Figure 56) and microscopically the very poor sorting of the grains (Figure 55).

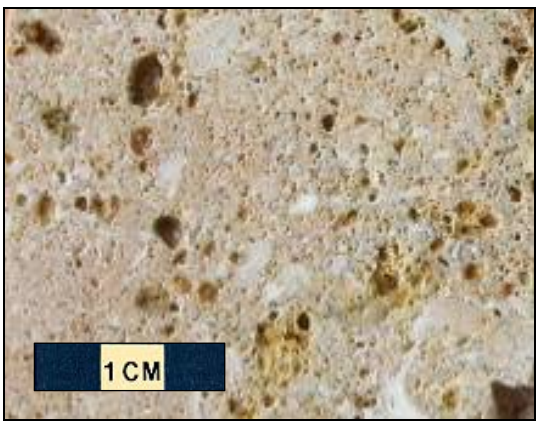


Figure 56 – Macroscopic view of lithofacies B3: texture of cut face (sample VOL39).

The whole analytical data measured on the samples collected on Volubilis site and belonging to lithotype B (fifteen samples; ref. VOL11,13, 15, 20, 23, 24, 25, 26, 32, 33, 34, 38, 39, 41 and 47) are detailed in Table 12 and Table 13.

According to the obtained data, the lithotype B “Beige-yellowish calcarenite limestones” corresponds to a quite soft stone with a porosity ranging from 15 to 26% (21% in average) illustrating the heterogeneity of the “Molassa” series in terms of variability and quality material. The water natural saturation degree shows a quite low average value (0.59). The very low value (0.32) of sample VOL39 belonging to lithotype B3, linked to its macroporous medium, is noteworthy.

In a mineralogical point of view, it is a carbonate (calcite content about 86% in average, reaching 95%) with a variable proportion of quartz ranging from 5 to 21% (considering both the petrographic microscopic observations and the silica content measured). Besides quartz, accessory minerals are mainly traces of micaceous minerals (illite, muscovite) and of clay minerals (smectites, kaolinite).

As a consequence, the major chemical elements of lithotype B are Calcium (average about 49%) and Silicium (about 13% in average). Concerning the trace chemical elements, the significant ones are Strontium with an average value 291ppm, followed by order of importance by Barium (32 ppm in average), Cerium (17 ppm) and Zinc (15 ppm). A few samples contain Zirconium in a notable content (80-90 ppm).

The isotopic signature of lithotype B “Beige-yellowish calcarenite limestones” is illustrated in Figure 57.

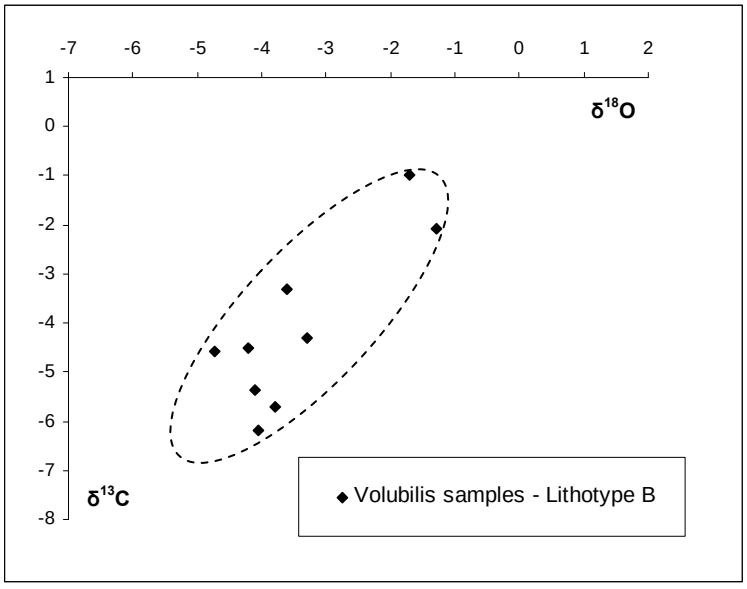


Figure 57 – Isotopic signature of lithotype B “Beige-yellowish calcarenite limestones”.

Sample Reference	Samples Location on Volubilis site	Sub-lithotype	Petrographic description by optic microscopy	Mineralogical analysis by X-Ray Diffraction	Calcite content (%) by acid attack	Dolomite content (%) by acid attack	$\delta^{18}O$ ‰ vs PDB	$\delta^{13}C$ ‰ vs PDB	Uniaxial Compressive Strenght (MPa)	Total Water Porosity (%)	Solid Density	Bulk Density	Water Natural Saturation Degree
VOL11	House of the Columns (15)	B2	X	X	-	-	-	-	-	-	-	-	-
VOL13	House of the Columns (15)	B2	X	X	-	-	-1.7	-1.0	-	-	-	-	-
VOL15	House of the Columns (15)	B3	X	X	-	-	-	-	-	-	-	-	-
VOL20	House of the Wild Beast Mosaic (22)	B1	X	X	-	-	-3.8	-5.7	-	-	-	-	-
VOL23	House of two presses (31)	B2	X	X	-	-	-	-	-	-	-	-	-
VOL24	House of Sundial (30)	B2	X	X	-	-	-4.2	-4.5	-	-	-	-	-
VOL25	House of Sundial (30)	B2	X	X	-	-	-	-	-	-	-	-	-
VOL26	House of the Bacchus of marble (29)	B2	X	X	-	-	-	-	-	-	-	-	-
VOL32	Door of Tangier (26)	B3	X	X	-	-	-	-	-	-	-	-	-
VOL33	House of Venus (38)	B2	X	X	-	-	-3.6	-3.3	-	-	-	-	-
VOL34	House of the Bacchus of Marble (29)	B1	X	-	86.8	0.0	-3.3	-4.3	-	15.1	2.69	2.28	0.65
VOL38	House of the Bacchus of Marble (29)	B2	X	-	74.6	0.0	-4.7	-4.6	-	25.9	2.68	1.99	0.81
VOL39	House at the West of the House of the Gold Coin (27)	B3	X	-	94.9	0.0	-4.1	-5.4	-	17.3	2.69	2.23	0.32
VOL41	House of the Clover Basin (40)	B2	X	-	82.9	0.0	-4.0	-6.2	-	24.0	2.69	2.05	0.57
VOL47	House of the Gold Coin (28)	B1	X	-	93.2	0.0	-1.3	-2.1	-	-	-	-	-
Min	-	-	-	-	74.6	0.0	-	-	-	15.1	2.68	1.99	0.32
Max	-	-	-	-	94.9	0.0	-	-	-	25.9	2.69	2.28	0.81
Av	-	-	-	-	86.5	0.0	-	-	-	20.6	2.69	2.14	0.59

Table 12 – Analytical data measured on the fifteen samples from Volubilis site belonging to lithotype B.

Sample Reference	Al_2O_3 (%)	CaO (%)	Fe_2O_3 (%)	K_2O (%)	MgO (%)	MnO (%)	P_2O_5 (%)	SiO_2 (%)	TiO_2 (%)	LOI (%)	Co (ppm)	Pb (ppm)	As (ppm)	Sr (ppm)	Zn (ppm)	B (ppm)	V (ppm)	Cr (ppm)	Ba (ppm)	Ag (ppm)	Ce (ppm)	Zr (ppm)
VOL11	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
VOL13	<1	56.8	<1	<0.5	<1	0.01	0.70	8.5	0.04	-	<5	12	<20	485	14	13	<10	13	24	0.3	18	32
VOL15	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
VOL20	1.2	52.3	<1	<0.5	<1	0.01	0.30	14.9	0.03	-	<5	12	<20	303	15	<10	<10	11	29	<0.2	17	<20
VOL23	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
VOL24	2	51.2	<1	0.7	<1	0.01	0.70	20.6	0.12	-	<5	13	<20	203	21	15	11	17	57	<0.2	21	82
VOL25	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
VOL26	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
VOL32	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
VOL33	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
VOL34	1.2	46.7	0.26	0.39	<0.2	<0.02	0.21	12.4	<0.05	37.3	<5	<10	<20	256	9	<10	<10	<10	25	<0.2	12	<20
VOL38	2	40.6	0.77	0.63	0.3	<0.02	0.60	21.4	0.13	32.8	<5	<10	20	165	22	14	<10	13	53	0.2	24	92
VOL39	0.8	50.6	0.25	0.19	<0.2	<0.02	0.24	4.7	<0.05	40.8	<5	<10	20	129	11	<10	<10	<10	12	0.4	13	20
VOL41	1	46.4	0.65	0.32	0.2	<0.02	0.39	13.9	<0.05	36.7	<5	<10	<20	258	15	<10	<10	<10	31	0.3	17	<20
VOL47	0.5	50.7	0.47	0.15	0.2	<0.02	0.18	6.9	<0.05	40.4	<5	<10	21	530	9	<10	<10	<10	21	0.3	13	<20
Min	-	40.6	-	-	-	-	0.18	4.7	-	32.8	-	-	-	129	9	-	-	-	12	-	12	-
Max	2	56.8	<1	0.7	<1	<0.02	0.70	21.4	0.13	40.8	<5	13	21	530	22	15	11	17	57	0.4	24	92
Av	-	49.4	-	-	-	-	0.42	12.9	-	37.6	-	-	-	291	15	-	-	-	32	-	17	-

Table 13 – Analytical data measured on the fifteen samples from Volubilis site belonging to lithotype B (LOI = Lost Of Ignition).

4.2.3. Lithotype C

The lithological term for lithotype C is **grey massive limestone**.

According to petrographic observations by optic microscope using the usual classification systems (Folk, 1959, 1962; Dunham, 1962), the lithotype C was finally divided into three sub-facies referenced C1 to C3.

⇨ **Lithofacies C1 "beige-grey peloid grainstone / packstone":** This facies is largely widespread among the monuments of the archaeological site of Volubilis and shows rather good resistance. The blocks use sedimentary surfaces of the stone. It is limestone with beige-grey color (grey to dark grey patina, beige when freshly cut or washed by rain), massive texture, conchoidal fracture and sedimentary surface. Few fossils are observed (belemnites, ammonoids, gastropods, etc) as well as fissures filled by calcite and stylolithes (Figure 58 to Figure 61). Based on microfacies analysis of the samples, the grains are dominants. They are peloids and rarely benthonic foraminifera, coated bioclasts (echinoderms, gastropods, etc), oncoids. The sorting is good to very good. The cement of the grains is either made of granular calcite (cement B) or micrite-microsparite and locally syntaxial (Figure 62). The age of this limestone according to the foraminifera (*ophthalmidium martanum)* is liasic. The depositional environment is a shallow carbonate platform.

Figure 58 – Macroscopic view of lithofacies C1: : paving stone in the Palace of Gordian (24) including a belemnite.

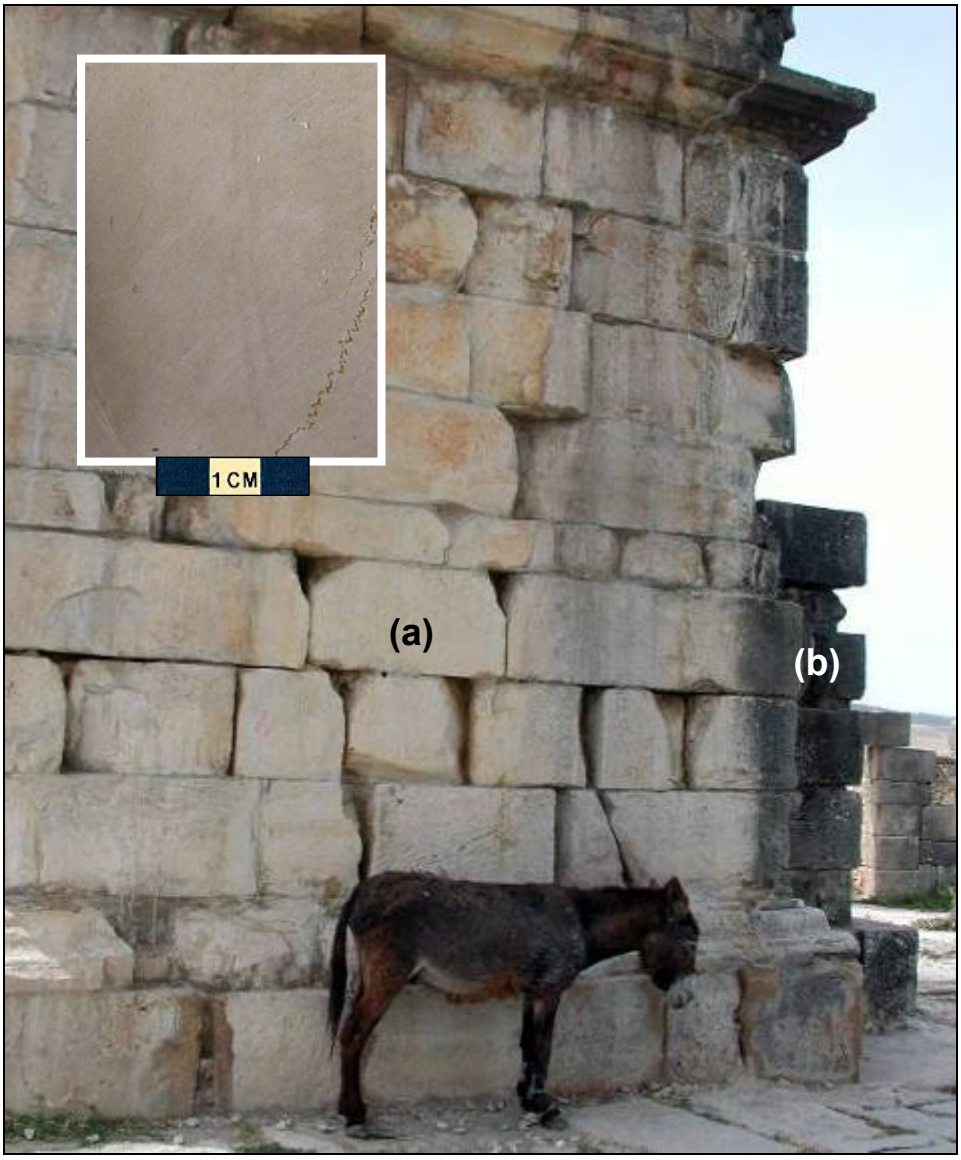


Figure 59 – Macroscopic view of lithofacies C1: North side of the Triumphal Arch (Caracalla Arch) with beige blocks washed by rain (a) and dark grey patina on the right exposed part (b) ; detail of color of cut face (sample VOL36).

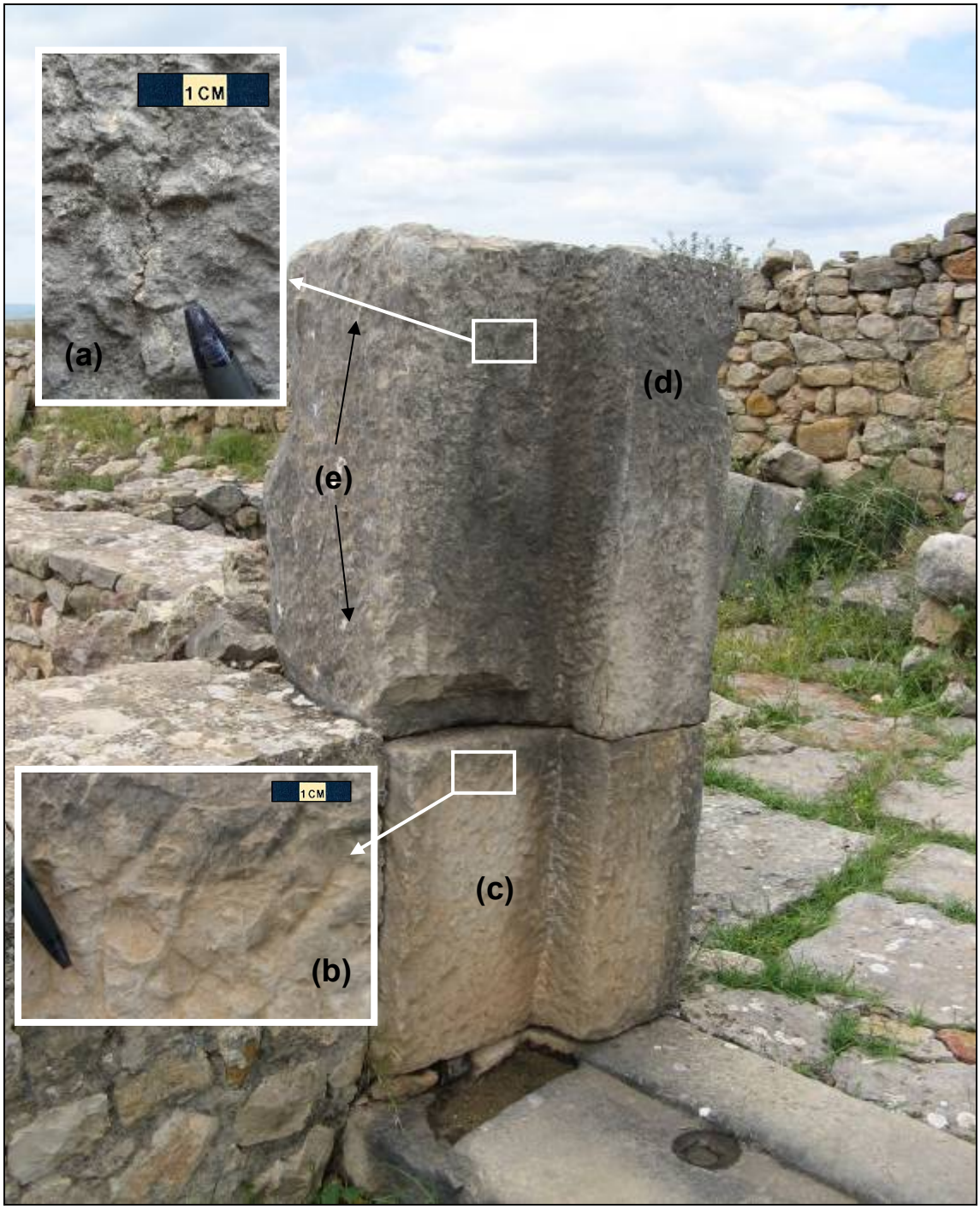


Figure 60 – Macroscopic view of lithofacies C1: door jamb blocks in the House of Venus (38) with typical conchoïdal fractures (a and b) and stylolithes (a), beige color (c) and grey patina (d), sedimentary surface (e).

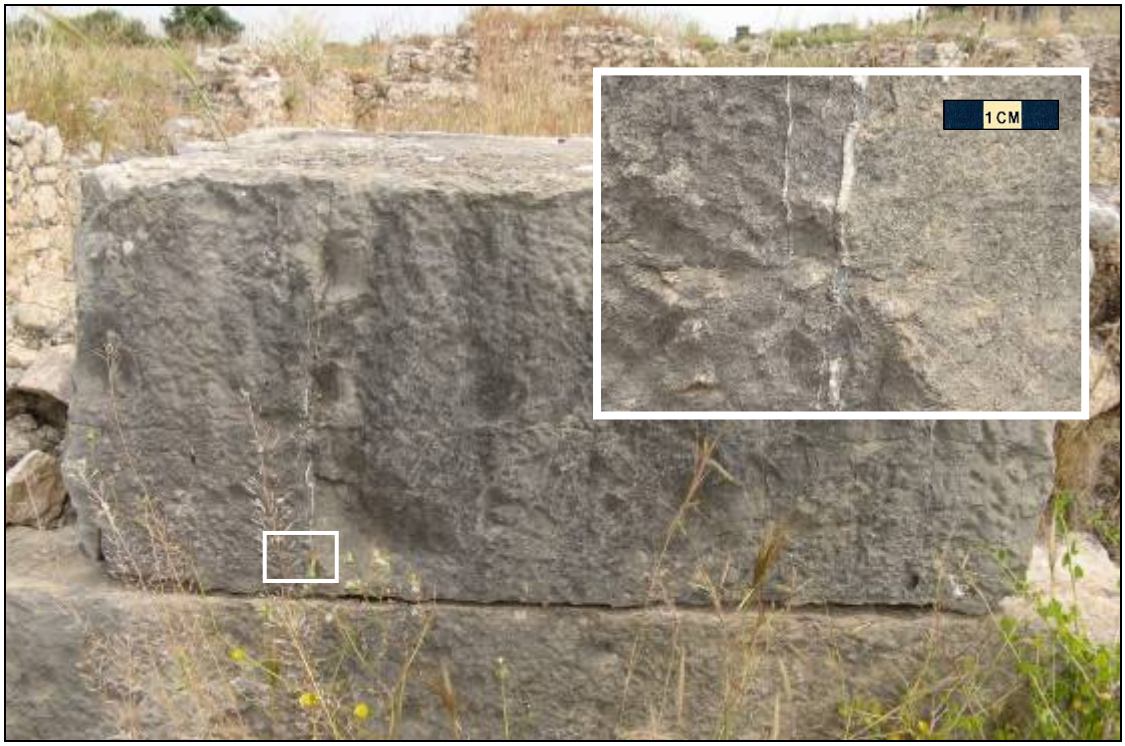


Figure 61 – Macroscopic view of lithofacies C1: Typical calcite filled fissures.

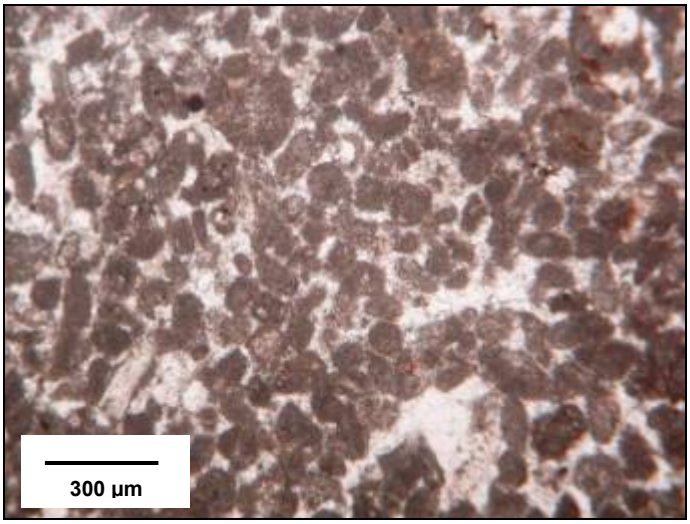


Figure 62 – Microscopic observations (N//) of lithofacies C1 (sample VOL30): grains are dominated by peloids and rarely benthonic foraminifera, coated bioclasts (echinoderms, gastropods, etc.), oncoids with good to very good sorting.

⇨ **Lithofacies C2 "grey coated bioclastic grainstone":** This facies is a limestone with grey color and massive texture (Figure 64). Based on microfacies analysis of the samples the grains are dominants and they are bioclasts coated by micrite envelopes or biogenic encrustations and correspond to cortoïds and oncoïds. In minor amount are found peloids, intraclasts, aggregate grains and ooids. Some of the grains are strongly micritized and are associated with few benthonic foraminifera. The bioclasts are mollusk shells, echinoderms, algae, etc. (Figure 63). The presence of idiomorphic crystals calcite as well as very small pyrite grains and grapes of them is characteristic. The spaces in the grain–supported fabric are in-filled by micritic calcite and small peloids but also are occluded by calcitic drusy mosaic cement. The bigger intra-particles pores are filled by calcitic drusy mosaic cement with larger crystals. Its depositional environment is a very shallow open platform.

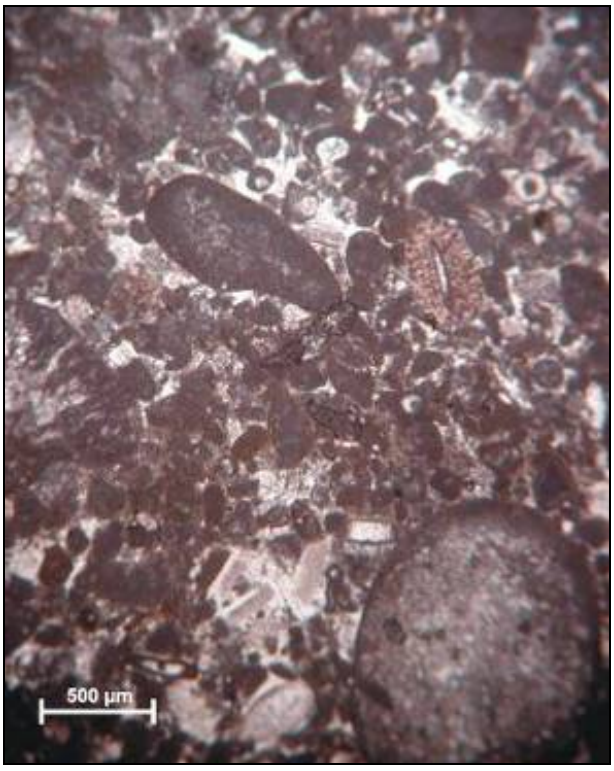


Figure 63 – Microscopic observations (N//) of lithofacies C2 (sample VOL1): coated bioclasts and minor amount of peloids, intraclasts, aggregate grains and ooids are participated.

Figure 64 – Macroscopic view of lithofacies C2: Basement blocks in the Palace of Gordian (24).

⇨ **Lithofacies C3 "grey ooïd / coated grainstone / packstone":** This lithofacies is a limestone with beige-grey color and massive in texture (Figure 65 and Figure 66). It consists mainly of ooids, strongly micritized, coated grains, and bioclasts of Echinoderms, corals, green algae, cyanobacteria. The sorting of them is poor and only locally good to very good. The ooids which are radial and radial/tangential and the others grains are cemented by granular, rarely by syntaxial calcite crystals and locally are with micrite matrix (Figure 67). The depositional environment of this rock is a very shallow, sea with high energy.

Figure 65 – Macroscopic view of lithofacies C3 : Columns of the “Decumanus Maximus” in front of the Palace of Gordian (24) with stylolithes.

Figure 66 – Macroscopic view of lithofacies C3 : Columns in the House of Dyonisos (20).

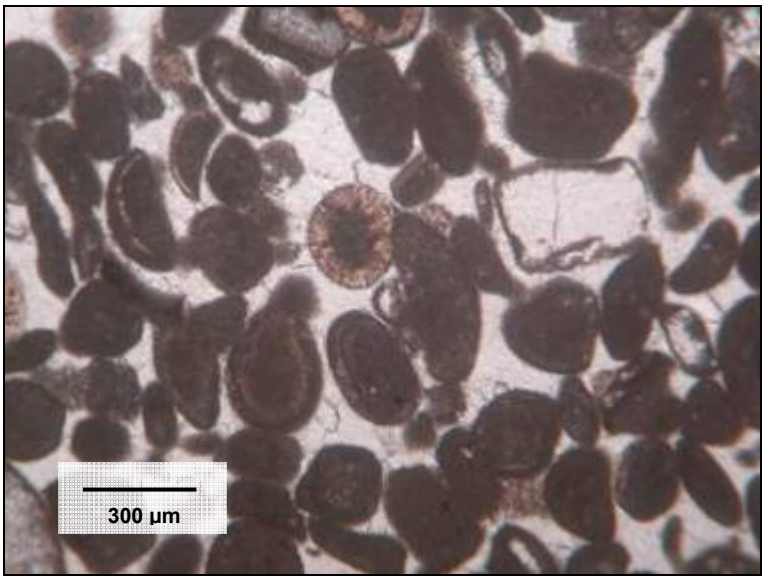


Figure 67 – Microscopic observations (N//) of lithofacies C3 (sample VOL22): ooids (radial and radial/tangential), strongly micritized, coated grains, and bioclast ; grains are cemented by granular, rarely by syntaxial calcite crystals and locally with micrite matrix.

The whole analytical data measured on the samples collected on Volubilis site and belonging to lithotype C (eighteen samples; ref. (ref. VOL01, 02, 04, 07, 08, 09, 12, 14, 17, 18, 22, 27, 29, 30, 31, 36, 40 and 43) are detailed in Table 14 and Table 15.

According to the obtained data, the lithotype C "**grey massive limestones**" corresponds to a hard stone (one compressive strength measure of about 86 MPa) with a low porosity ranging from 2.5 to 4.9% (3.5% in average) illustrating its good quality of building material. Its natural water saturation degree is high with an average value about 0.88.

In a mineralogical point of view, it is a pure carbonate (calcite content about 95% in average) with a few percents (2.5% in average) of quartz (considering both the petrographic microscopic observations and the silica content measured). Besides quartz, accessory minerals are mainly traces of micas (illite, muscovite) and clay minerals (kaolinite, palygorskite).

The major chemical elements of lithotype C is Calcium with an average content of 56%. Among trace chemical elements, the significant one is Strontium with an average value of 309 ppm. Zinc (15 ppm in average) is also present in the whole samples.

The isotopic signature of lithotype C "grey massive limestones" is illustrated in Figure 68.

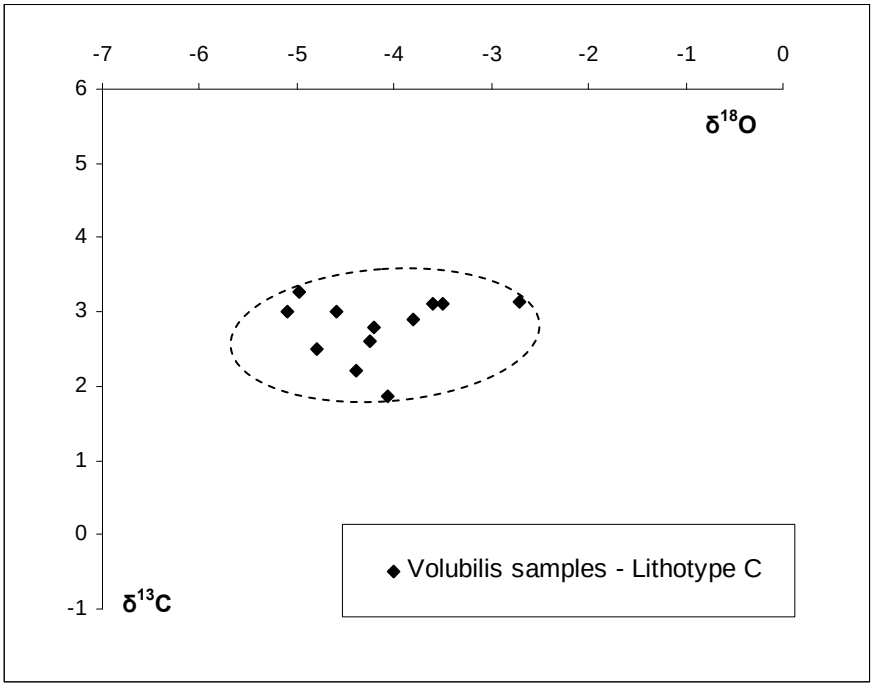


Figure 68 – Isotopic signature of lithotype C "Grey massive limestones".

Sample Reference	Samples Location on Volubilis site	Sub-lithotype	Petrographic description by optic microscopy	Mineralogical analysis by X-Ray Diffraction	Calcite content (%) by acid attack	Dolomite content (%) by acid attack	$\delta^{18}O$ ‰ vs PDB	$\delta^{13}C$ ‰ vs PDB	Uniaxial Compressive Strenght (MPa)	Total Water Porosity (%)	Solid Density	Bulk Density	Water Natural Saturation Degree
VOL01	Palace of Gordian (24)	C2	X	-	-	-	-3.5	3.1	-	-	-	-	-
VOL02	Aqueduct / re-employed column in the masonry	C	X	-	-	-	-4.4	2.2	-	-	-	-	-
VOL04	House of Flavius Germanus (19)	C1	X	X	94.6	0.0	-4.3	2.6	86.0	3.7	2.71	2.61	0.85
VOL07	Basilica (7)	C1	X	X	-	-	-4.2	2.8	-	-	-	-	-
VOL08	Basilica (7)	C1	X	X	-	-	-	-	-	-	-	-	-
VOL09	House of Golden Coins (28)	C1	X	X	-	-	-	-	-	-	-	-	-
VOL12	House of Columns (15)	C1	X	X	-	-	-4.6	3.0	-	-	-	-	-
VOL14	House of Columns (15)	C1	X	X	-	-	-	-	-	-	-	-	-
VOL17	House of Hercules (18)	C1	X	X	-	-	-4.8	2.5	-	-	-	-	-
VOL18	House of Flavius Germanus (19)	C	X	X	-	-	-	-	-	-	-	-	-
VOL22	House of Dyonisos (20)	C3	X	X	-	-	-3.8	2.9	-	-	-	-	-
VOL27	House of Bacchus Marble (29)	C1	X	X	-	-	-	-	-	-	-	-	-
VOL29	Palace of Gordian (24)	C2	X	X	-	-	-3.6	3.1	-	-	-	-	-
VOL30	Gate of Tanger (26)	C1	X	X	-	-	-5.1	3.0	-	-	-	-	-
VOL31	Gate of Tanger (26)	C1	X	X	-	-	-	-	-	-	-	-	-
VOL36	House of Clover Basin (40)	C1	X	-	94.9	0.0	-5.0	3.3	-	4.9	2.70	2.57	0.86
VOL40	House of Clover Basin (40)	C1	X	-	94.9	0.0	-2.7	3.1	-	2.5	2.69	2.63	0.95
VOL43	House of Clover Basin (40)	C1	X	-	94.0	0.0	-4.1	1.9	-	2.8	2.71	2.63	0.87
Min	-	-	-	-	94.0	0.0	-	-	-	2.5	2.69	2.57	0.85
Max	-	-	-	-	94.9	0.0	-	-	86.0	4.9	2.71	2.63	0.95
Av	-	-	-	-	94.6	0.0	-	-	-	3.5	2.70	2.61	0.88

Table 14 – Analytical data measured on the eighteen samples from Volubilis site belonging to lithotype C.

Sample Reference	Al_2O_3 (%)	CaO (%)	Fe_2O_3 (%)	K_2O (%)	MgO (%)	MnO (%)	P_2O_5 (%)	SiO_2 (%)	TiO_2 (%)	LOI (%)	Co (ppm)	Pb (ppm)	As (ppm)	Sr (ppm)	Zn (ppm)	B (ppm)	V (ppm)	Cr (ppm)	Ba (ppm)	Ag (ppm)	Ce (ppm)	Zr (ppm)
VOL01	1.1	50.8	0.52	0.07	0.8	<0.01	0.06	3.2	0.06	42.0	<5	<10	21	305	9	<10	<10	12	11	<0.2	<10	<20
VOL02	<1	51.7	<1	<0.5	<1	<0.01	0.07	1.8	<0.05	-	<5	<10	20	227	14	<10	<10	<10	<10	<0.2	<10	<20
VOL04	0.7	52.6	0.45	0.13	0.7	<0.01	<0.05	3.1	<0.05	41.7	<5	<10	24	263	25	<10	<10	<10	<10	<0.2	<10	<20
VOL07	1	59.6	<1	<0.5	<1	0.01	0.07	3.6	0.05	-	<5	<10	<20	252	22	<10	<10	12	<10	<0.2	14	<20
VOL08	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
VOL09	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
VOL12	<1	58.0	<1	<0.5	<1	0.01	0.06	2.9	0.03	-	<5	<10	<20	264	15	<10	<10	<10	<10	0.2	14	<20
VOL14	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
VOL17	<1	60.6	<1	<0.5	<1	<0.01	0.05	1.6	0.02	-	<5	10	<20	200	22	<10	<10	<10	<10	0.3	13	<20
VOL18	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
VOL22	<1	60.7	<1	<0.5	1	<0.01	0.02	<1	0.01	-	<5	<10	<20	366	5	<10	<10	<10	<10	0.3	14	<20
VOL27	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
VOL29	<1	60.7	<1	<0.5	<1	0.01	0.06	2.7	0.04	-	<5	<10	<20	349	7	<10	<10	10	<10	0.3	16	<20
VOL30	<1	58.9	<1	<0.5	<1	<0.01	0.04	1.5	0.02	-	<5	13	<20	209	32	<10	<10	10	<10	0.2	14	<20
VOL31	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
VOL36	0.5	54.0	0.21	0.07	0.4	<0.01	<0.05	1.6	<0.05	42.9	<5	<10	22	238	36	<10	<10	<10	<10	0.5	13	<20
VOL40	0.9	51.5	0.35	0.16	0.7	<0.01	<0.05	3.3	<0.05	42.0	<5	<10	22	819	13	<10	<10	<10	<10	0.3	15	<20
VOL43	1	52.3	0.59	0.14	0.6	<0.01	<0.05	2.5	<0.05	42.4	<5	16	25	220	9	<10	<10	<10	17	0.6	16	<20
Min	-	50.8	-	-	-	-	-	-	-	41.7	-	-	-	200	5	-	-	-	-	-	-	
Max	1.1	60.7	<1	<0.5	1	0.01	0.07	3.6	0.06	42.9	<5	16	25	819	36	<10	<10	12	17	0.6	16	<20
Av	-	56.0	-	-	-	-	-	-	-	42.2	-	-	-	309	17	-	-	-	-	-	-	-

Table 15 – Analytical data measured on the eighteen samples from Volubilis site belonging to lithotype C (LOI = Lost Of Ignition).

4.2.4. Lithotype D

The lithological term for lithotype D is **ochre-grey bioclastic limestone rich in bivalvia**.

This lithofacies is a limestone with ochre to ochre-grey color and quite massive in texture (Figure 69 and Figure 70). It presents pluri-centimetres shells of bivalve and the blocks use the sedimentary surfaces of the stone. Based on facies analysis (Figure 71), the large bivalve bioclasts are predominated with sub-parallel arrangement of them. Also significant is the presence of benthic foraminifera and rarely dacycladaceae algae and clasts of echinoderms. The matrix (groundmass) is micritic to microsparitic calcite (due to recrystallization with smaller bioclasts and small (until 0.15 mm) detritic clasts of quartz and feldspars. The presence of grains iron-oxides / hydroxides is significant in the matrix, giving the ochre color to the stone.

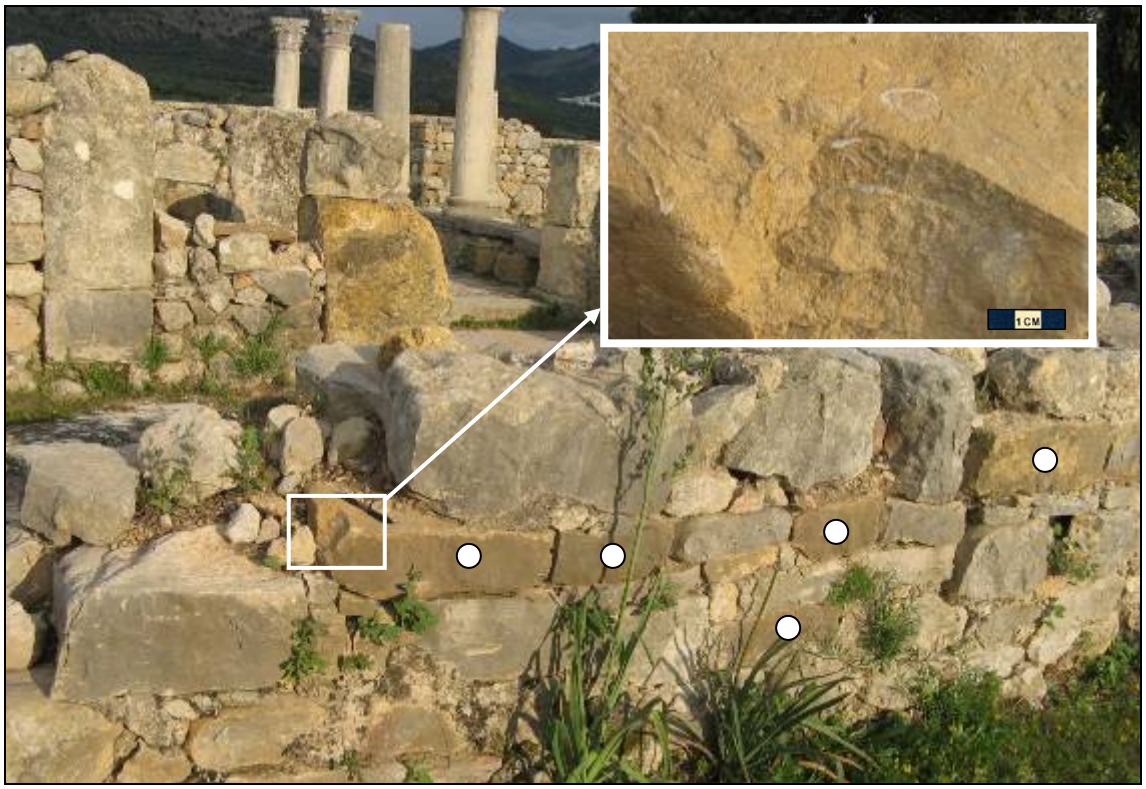


Figure 69 – Macroscopic view of lithofacies D : stone-rubbles (white spots) in the House of Orpheus (4) with typical large bivalvia shells and ochre dominant color.

Figure 70 – Macroscopic view of lithofacies D : stone-rubble in the House of Orpheus (4) with typical large bivalvia shells and ochre-grey dominant color; view of a cut face (sample VOL35).

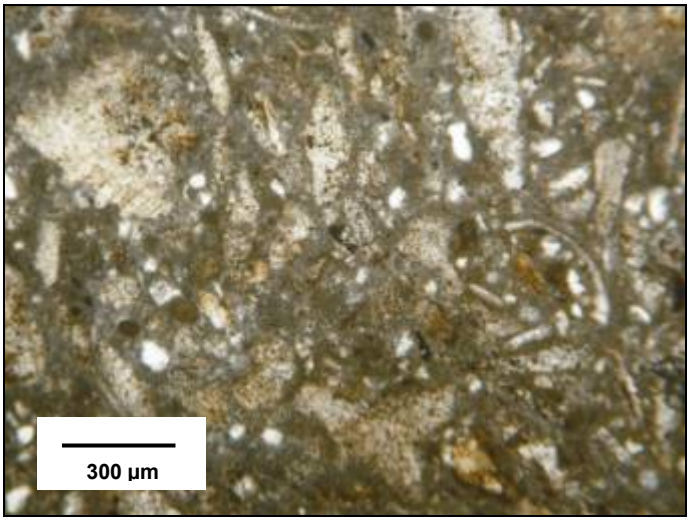


Figure 71 – Microscopic observations (N//) of lithofacies D (sample VOL35): different size clasts of bivalvia, brachiopods; presence of benthic foraminifera and rarely dacycladaceae algae and clasts of echinoderms; micritic to microsparitic calcite matrix with smaller bioclasts and small detritus clasts of quartz and feldspars.

The analytical data measured on sample VOL35 collected on Volubilis site and belonging to lithotype D are detailed in Table 16 and Table 17.

According to the few measurements, the lithotype D “ochre-grey bioclastic limestone rich in bivalvia” corresponds to a quite hard stone with a low porosity about 5%. Its water natural saturation degree is high (0.87).

In a mineralogical point of view, it is a carbonate (calcite content about 86%) with a proportion about 10% of quartz and feldspar (albite) considering both the petrographic microscopic observations and the silica and alumina contents measured).

The major chemical elements of lithotype D are logically Calcium (46%) and Silicium (about 9% in average). Iron oxides are also present (about 2%) participating to the greyish to yellowish color of this stone. Within the trace chemical elements, the significant ones are Strontium (554 ppm), followed by order of importance by Zirconium (48 ppm), Barium (41 ppm), Arsenic (35 ppm), Cerium (30), Zinc (28) and Chromium (26 ppm).

The values of isotopic composition of lithotype D “ochre-grey bioclastic limestone rich in bivalvia” in terms of $\delta^{13}C$ and $\delta^{18}O$ (in ‰ relative to the international reference standard PDB) are respectively of -2.6 and -5.5 (from one sample).

4.2.5. Lithotype E

The lithological term for lithotype E is a **coarse dolomite**.

The lithotype is a dolomite with pink and locally yellowish colour, pseudo-brecciated in texture (Figure 72 and Figure 73).

Figure 72 – Macroscopic view of lithofacies E: pinkinsh dolomite stone-rubble in a wall of the Palace of Gordian (24).

Figure 73 – Macroscopic views of lithofacies E: (a) (b) yellowish dolomite block used as a bottom element in the House of the Islamic Necropolis (35); (c) cut face of a sample (VOL42).

Sample Reference	Samples Location on Volubilis site	Sub-lithotype	Petrographic description by optic microscopy	Mineralogical analysis by X-Ray Diffraction	Calcite content (%) by acid attack	Dolomite content (%) by acid attack	$\delta^{18}O$ ‰ vs PDB	$\delta^{13}C$ ‰ vs PDB	Uniaxial Compressive Strenght (MPa)	Total Water Porosity (%)	Solid Density	Bulk Density	Water Natural Saturation Degree
VOL35	House at the West oh the House of the Gold Coin (27)	D	X	X	86.0	0.0	-5.5	-2.6	-	5.8	2.68	2.53	0.87
VOL05	House of the Gold Coin (28)	E	X		-	-	-	-	-	-	-	-	-
VOL42	House of the Clover Basin (40)	E	X	X	58.1	41.7	-4.7	-5.2	-	3.9	2.78	2.67	0.85
VOL44	East-side of Basilica (7) / Outdoor storage area	F	X	X	91.5	0.0	-6.0	-9.2	-	32.8	2.65	1.78	0.66
VOL45	East-side of Basilica (7) / Outdoor storage area	F	X	X	88.0	0.0	-5.1	-8.5	-	15.7	2.73	2.30	0.84

Table 16 – Analytical data measured on the five samples from Volubilis site belonging to lithotypes D, E and F.

Sample Reference	Al_2O_3 (%)	CaO (%)	Fe_2O_3 (%)	K_2O (%)	MgO (%)	MnO (%)	P_2O_5 (%)	SiO_2 (%)	TiO_2 (%)	LOI (%)	Co (ppm)	Pb (ppm)	As (ppm)	Sr (ppm)	Zn (ppm)	B (ppm)	V (ppm)	Cr (ppm)	Ba (ppm)	Ag (ppm)	Ce (ppm)	Zr (ppm)
VOL35	2.2	46.3	2.07	0.42	0.6	0.04	0.07	9.4	0.16	38.2	<5	12	35	554	28	15	19	26	41	0.4	30	48
VOL05	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
VOL42	0.4	39.6	0.29	<0.05	12.5	<0.02	<0.05	0.7	<0.05	44.9	<5	<10	<20	35	27	<10	<10	<10	<10	<0.2	<10	<20
VOL44	0.9	51.6	0.37	0.1	0.4	<0.02	0.26	2.9	0.05	42.4	<5	<10	20	348	27	<10	<10	<10	43	0.4	12	<20
VOL45	0.8	47.5	4.69	0.16	0.2	0.11	0.14	6.2	<0.05	39.1	9	<10	104	89	12	<10	97	<10	67	0.6	15	24

Table 17 – Analytical data measured on the five samples from Volubilis site belonging to lithotypes D, E and F (LOI = Lost Of Ignition).

Thin section studies show that it is an early diagenetic dolomite with primary features such as corals and others (Figure 74).

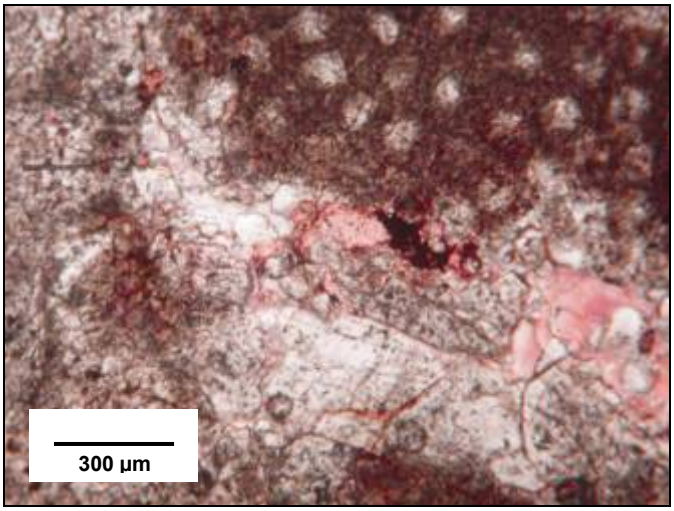


Figure 74- Microscopic observations (N//) of lithofacies E (sample VOL42): primary features such as corals.

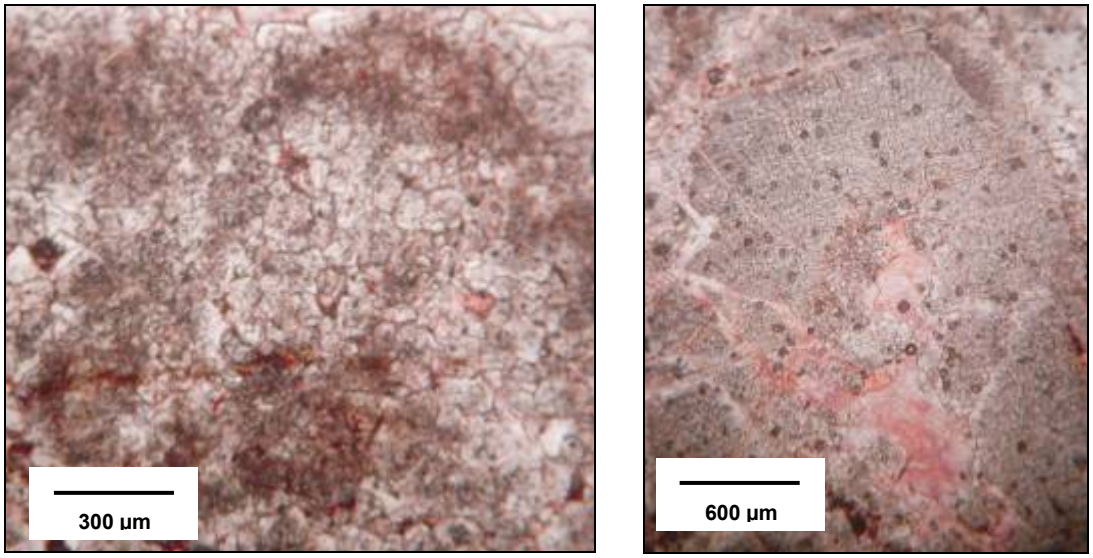


Figure 75 - Microscopic observations (N//) of lithofacies E (sample VOL42): hypidiotropic fabric of dolomite crystals (left) and saddle dolomite crystal (right).

The hypidiotropic fabric (Figure 75 left) of dolomite crystals indicates recrystallization during the burial stage. The presence of saddle dolomite (Figure 75 right) is most likely associated to sulphide mineralization or hydrothermal activity. The dolomitisation is significant and took place during the burial stage. Calcite veins are transecting the rock. Small quartz grains (0.03 to 0.06 mm), albite and probably anhydrite are also present.

The analytical data measured on the two samples VOL05 and VOL42 collected on Volubilis site and belonging to lithotype E are presented in Table 16 and Table 17.

According to the few measurements, the lithotype E “Coarse dolomites” corresponds to a hard stone with porosity smaller than 4%. Its water natural saturation degree is high (0.85). In a mineralogical point of view, it is a pure carbonate (calcite content about 58% and dolomite one about 42%). Accessory minerals correspond to traces of quartz and feldspars (albite) and rare clay minerals (kaolinite and illite). The major chemical elements of lithotype E are Calcium (40%) and Magnesium (13%). Trace chemical elements are rare (Strontium and Zinc) and in non significant content (respectively 35 and 27 ppm). The values of isotopic composition of lithotype E “Coarse dolomites” in terms of $\delta^{13}C$ and $\delta^{18}O$ (in ‰ relative to the international reference standard PDB) are respectively of -5.2 and -4.7 (from one sample).

4.2.6. Lithotype F

The lithological term for lithotype F is **Continental limestones**, gathering together several continental facies.

⇨ The first one is a travertine (freshwater limestone) of beige-grey color, very porous and cavernous (Figure 76). According to thin sections study (Figure 77), this limestone presents a microsparitic to sparitic matrix (wackestone texture) with a few disseminated grains of quartz (20-40 µm in diameter). The insoluble residue (IR) is constituted only of quartz. No clay mineral is observed by X-ray diffraction.

Figure 76 – Macroscopic views of lithotype F : (a) Blocks (white spots) of cavernous beige-grey travertine in Mausoleum (48) beside the House of the Ephebe (13); (b) cut face of a sample (VOL44).

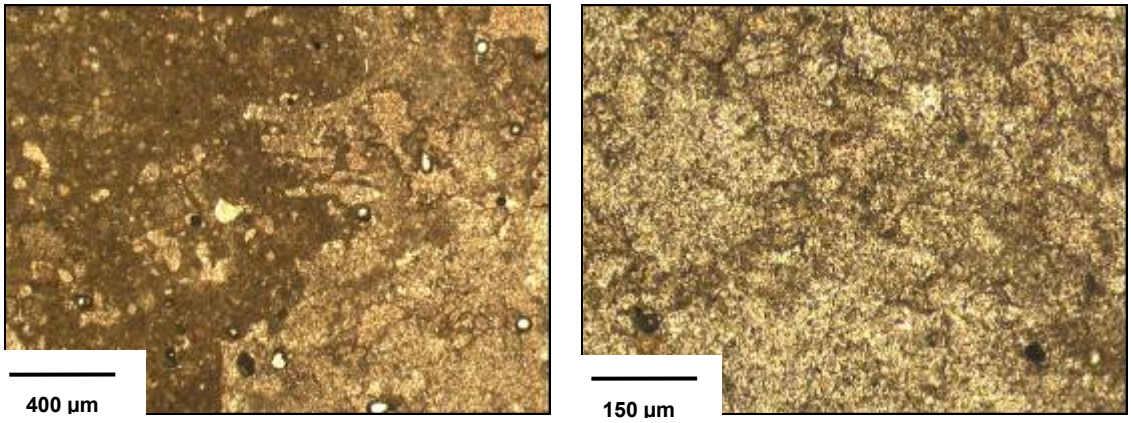


Figure 77 – Microscopic observations (N//) of lithotypes F: beige-grey cavernous travertine (sample VOL44); microsparitic to sparitic matrix with a few disseminated grains of quartz.

⇨ The second continental facies corresponds to a quite compact yellowish travertine limestone with large opened fissures filled of calcite facilitating its decays (Figure 78). According to thin sections study, this limestone presents a sparitic matrix (wackestone texture) with a few grains of quartz (50-100 µm in diameter). Besides quartz, the insoluble residues (IR) are clay minerals (mainly smectites, rare kaolinite) also contributing by swelling to the high decays of the stone (Figure 79).

Figure 78 – Macroscopic view of lithofacies F: Blocks (white spots) of yellowish travertine in the House of Orpheus (4) with typical large opened fissures filled of calcite facilitating the weathering.

Figure 79 – Macroscopic view of lithofacies F: Block of yellowish travertine limestone in the House of the Islamic Necropolis (35) with important decays facilitated by swelling clays (smectites) content.

⇨ The third continental facies is a more or less conglomeratic and knobly beige-yellowish lacustrine limestone. It is constituted by centimetric to pluricentimetric hard lithic components (ooliths, oncoliths and other lithoclasts) in yellowish carbonate softer

cement (Figure 80). This facies shows important weathering forms highlighting its hardest parts (differential erosion). According to thin sections study, it presents a micritic to microsparitic matrix (wackestone texture) with large calcitic ooliths and oncolithes, and rounded grains of quartz (200-300 µm in diameter). Besides quartz, the insoluble residues (IR) are traces of goethite and microcline (Figure 81).

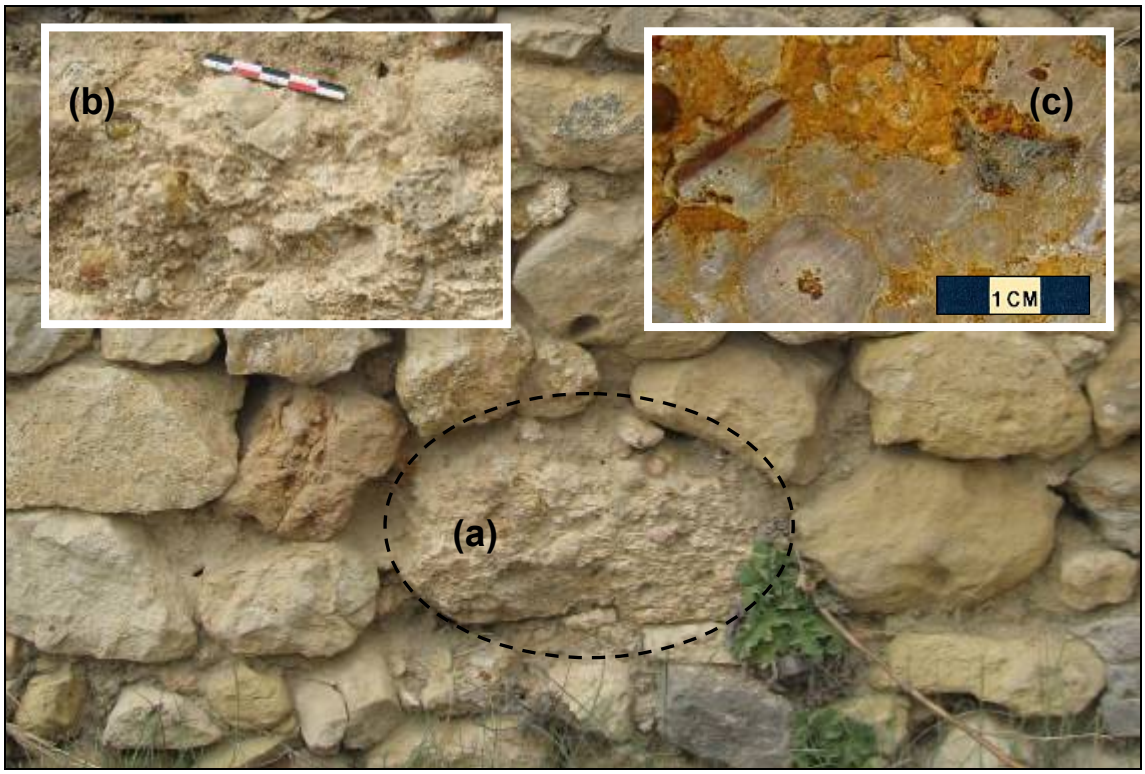


Figure 80 – Macroscopic views of lithotypes F; (a) stone-rubble of lacustrine limestone in the Palace of Gordian (24) with beige-whitish patina; (b) weathered surface with highlight hard lithic components and dissolution of the carbonated cement; (c) cut face of a sample (VOL45) with oolithes, oncolithes and other lithoclasts.

The analytical data measured on the two samples VOL44 and VOL45 collected on Volubilis site and belonging to lithotype F are presented in Table 16 and Table 17.

On the basis of the few measured data, the travertine is as expected more porous (32.8%) than the lacustrine limestone (15.7%). Its water natural saturation degree is quite low due to its large vacuoles and smaller than the ones of the lacustrine limestone (0.66 against 0.84).

In a mineralogical point of view, they are both quite pure carbonates (calcite content about 90%). Their accessory minerals correspond mainly to a few percents of quartz and also iron oxides / hydroxides for the lacustrine limestone, and to traces of clay minerals.

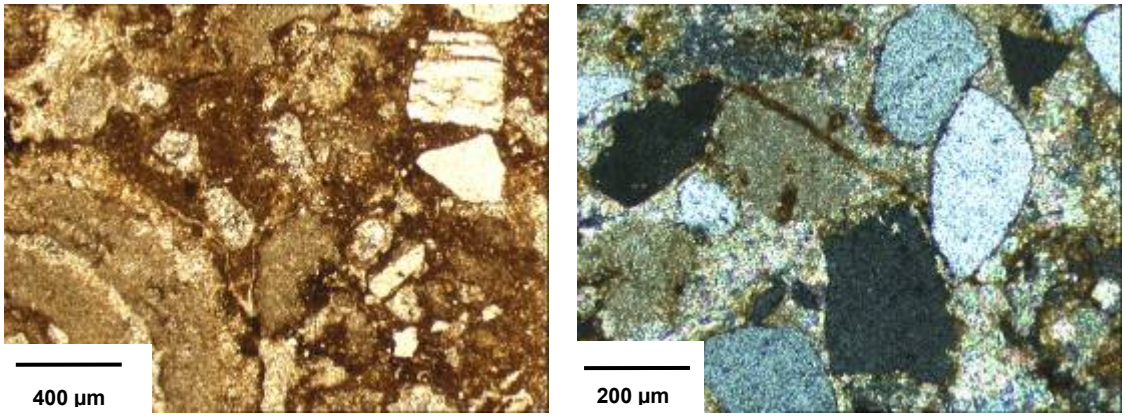


Figure 81 – Microscopic observations (left:N//; right: N+) of lithotype F: beige-yellowish lacustrine limestone (sample VOL45); larges oolithes and lithoclats (mainly quartz ones) in a microsparitic to sparitic matrix.

The major chemical elements are Calcium (48 to 52%) and Silicium (3% for the travertine, more than 6% for the lacustrine limestone). Among the trace chemical elements, the lacustrine limestone contains Arsenic (104 ppm) and Barium (67 ppm). Its Strontium value (89 ppm) is quite smaller to the one of the travertine (348 ppm) that also contains traces of Barium (43 ppm) and Zinc (27). The isotopic signature of lithotype F “continental limestones” (from two samples) is illustrated in Figure 82.

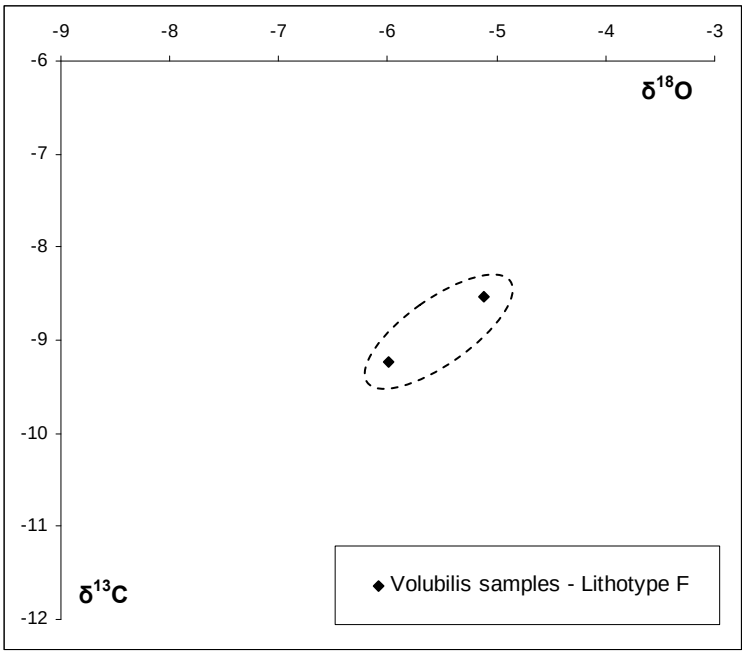


Figure 82 – Isotopic signature of lithotype F “Continental limestones”.

4.3. DISCUSSION ABOUT THE USES OF THE LITHOTYPES

The relative importance of each of building stones six lithotypes (A to F) was estimated for each monument and for the whole site according to the following procedure:

- visual evaluation of the Proportion (P) of a considered lithotype on the monument “m” (expressed as a percentage of the total volume of building stones of the monument);

- estimation of the Surface (S) occupied by the monument “m” (expressed in square metres) and calculation of the surface occupied only by its various architectonic stone elements (mainly walls, also columns, sometimes basins…) using a ratio of 5% of the estimated total surface (5% x S);

- estimation of the average height (H) (expressed in metres) of the whole architectonic elements of the monument “m”;

- calculation of the Volume (V) of the whole architectonic elements of the monument “m” (V = 5% x S x H) expressed in cube metres;

- calculation of the estimative Total Volume (TV) of each lithotype on the whole site (TV = $Vm_1+Vm_2+…+Vm_i$) expressed in cube metres;

- calculation of the total percentage of each lithotype on the whole site.

Important remarks: The estimations don’t take into account the numerous blocks till nowadays scattered on the ground or stored in various outdoor places of the ancient site.

The corresponding results are presented for the whole site in Table 18 and monument by monument in Appendix 2.

Lithotype reference and simplified term	Total volume (m^3)	Relative proportion (%)
A - Beige-green marly limestones	130	2.6*
B - Beige-yellowish calcarenite limestones so-called “Molassa”	3006	60.2*
C - Grey massive limestones	1570*	31.4*
D - Ochre-grey limestones rich in bivalvia	129	2.6*
E - Coarse dolomites	86	1.7*
F – Continental limestones	75	1.5*

Table 18 – Relative importance (expressed as a percentage of the total volume) of the lithotypes of Volubilis building stones; *Values without considering the Triumphal Arch (11) almost completely rebuilt that represents a volume of stone (lithotype C) of about 750 m^3

The spatial distribution of the lithotypes of building stone are also illustrated by maps (one per lithotype) in Appendix 3.

As regards their relative importance of use, the lithotypes B (so-called “molassa”) and C (grey massive limestones) are the most largely ones used as building stones on Volubilis site, representing over 90% of the total volume of building stones.

⇨ The lithotype B represents about 60% of the total volume of building stones; it is distributed on almost the whole of the monuments, except in five ones where it is completely absent: Capitol (6), Basilica (7), Public Fountain (8), Triumphal Arch (11) and Door of Tangier (26). In the fifty-five other monuments considered, its proportion ranges from 60 to 80% (average about 70% per monument) except in the Mausoleum (M48) composed only by 15% of the type of stone. In terms of uses, the “molassa” are present as masonry stone-rubbles, and on account of their relative softness, as various carved and sculpted elements (column, chapiters…).

⇨ The lithotype C represents (without considering the Triumphal Arch (11) almost completely rebuilt) about 31% of the total volume of building stones; it is distributed on the whole of the monuments, in variable proportions. Five monuments (Capitol (6), Basilica (7), Public Fountain (8), Triumphal Arch (11) and Door of Tangier (26)) are exclusively constituted by this type of hard stone. In the fifty-five other monuments considered, its proportion ranges from 5 to 30% (average about 20% per monument). About its uses Lithotype C (grey massive limestones) constitutes architectonic elements as jamb, lintels, column and others structure carved blocks of significant size according to its mechanical strength. It is also observable as masonry stone-rubbles (in very limited proportion).

The four other lithotypes A, D, E and F represents a very low proportion of the total volume of Volubilis building stones. Between those minor facies in terms of a use, lithotypes A and D seem to be the most represented:

⇨ The lithotype A (beige-green marly limestones) represents less than 3% (calculated value 2.6%) of the total volume of building stones; it is distributed on almost the whole of the monuments, except in six ones where it is completely absent: Capitol (6), Basilica (7), Public Fountain (8), Triumphal Arch (11), Door of Tangier (26) and Mausoleum (48). In the fifty-four other monuments considered, its proportion ranges from less than 1% to 7% (House of the Sundial 30) for an average proportion about 2,6% per monument. In terms of uses, the marly limestones are present as medium-sized carved (and sometimes sculpted) architectonic elements (facilitated by their softness but at the origin of their important decays). They are also observable as masonry stone-rubbles (in very limited proportion).

⇨ The lithotype D (ochre-grey limestones rich in bivalvia) represents less than 3% (calculated value 2.6%) of the total volume of building stones; it is distributed on almost the whole of the monuments and seems to be more represented in the monuments from the south and west part than those from the north part. It is also completely absent in the five monuments built only with grey massive limestone (Capitol (6), Basilica (7), Public Fountain (8), Triumphal Arch (11) and Door of Tangier (26)). In the fifty-five other monuments considered, its proportion ranges from less than 1% to 10% (House of Desultor 11 and Insulae I7) for an average proportion of about 3% per monument. Lithotype D is only present on the site as masonry medium-sized stone-rubbles.

⇨ The lithotype E (coarse dolomites) represents less than 2% (calculated value 1.7%) of the total volume of building stones; it is distributed on almost the whole of the monuments, except six ones where it is completely absent: Capitol (6), Basilica (7), Public Fountain (8), Triumphal Arch (11), Door of Tangier (26) and Mausoleum (M48). In the fifty-four other monuments considered, its proportion ranges from less than 1% to 5% (House of the Rider 16, House of Dionysos 20 and House of the Crypt 42) for an average proportion of about 2% per monument. Lithotype E is used mainly as masonry stone-rubbles. Many larger-sized blocks are also used as basement elements.

⇨ The lithotype F (various continental limestones) represents about 1.5% of the total volume of building stones; it is distributed mainly on monuments from the medium part (south and west) of the site and it is almost absent of the north one. It is also completely absent in the four monuments: Capitol (6), Basilica (7), Public Fountain (8) and Door of Tangier (26) built only with grey massive limestone (lithotype C). On the opposite, it represents about 80% of the Mausoleum (48). It is also present in a significant proportion (10%) in the Bakery (9). For the fifty-three other monuments considered, the proportion ranges from less than 1% to 5% for an average proportion of about 1.6% per monument. In terms of uses, lithotype F is used as masonry stone-rubbles sometimes large-sized (notably travertine limestones) and also as basement elements.

Not undertaken in the framework of the project, some future archaeological studies could logically focus on the relationship between spatial distribution of the types of stones as highlighted here above and periods of constructions.

To illustrate the juxtaposition of the different lithotypes on monuments, the lithofacies of a few walls were mapped (Figure 83):

- Wall 1 (Figure 84): masonry stone-rubbles wall in the House at the West of the Door of Tangier (26W) selected for its great diversity of type of stones; its width is 1.5 metres and its maximum height about 1.8 m.

- Wall 2 (Figure 86) in the House of Venus (38): the mapped wall is in place and does not present any trace of restoration; its width is 3 metres and its maximum height about 0.8 m.; the molassa is the main type of stone-rubbles. On the West side, a large dimension block of grey massive limestone constitutes a jamb of a door.

- Wall 3 (Figure 85) in the House of the Ephebe (13): the mapped wall (height 2.6 m; width 2.5 m) presents mainly molassa and then coarse dolomite rubbles well arranged according the bedding. Few rubbles of the others types of stones are observable.

- Wall 4 (Figure 87) in the Insulae (IS8): the mapped wall (height 1.2 m; width 3.5 m) is in place and contains an obvious re-used block on its south part (probable a wine press weight-against). The molassa is the main type of the stone-rubbles; some of them are well carved and present a rectangular form (notably in the north side).

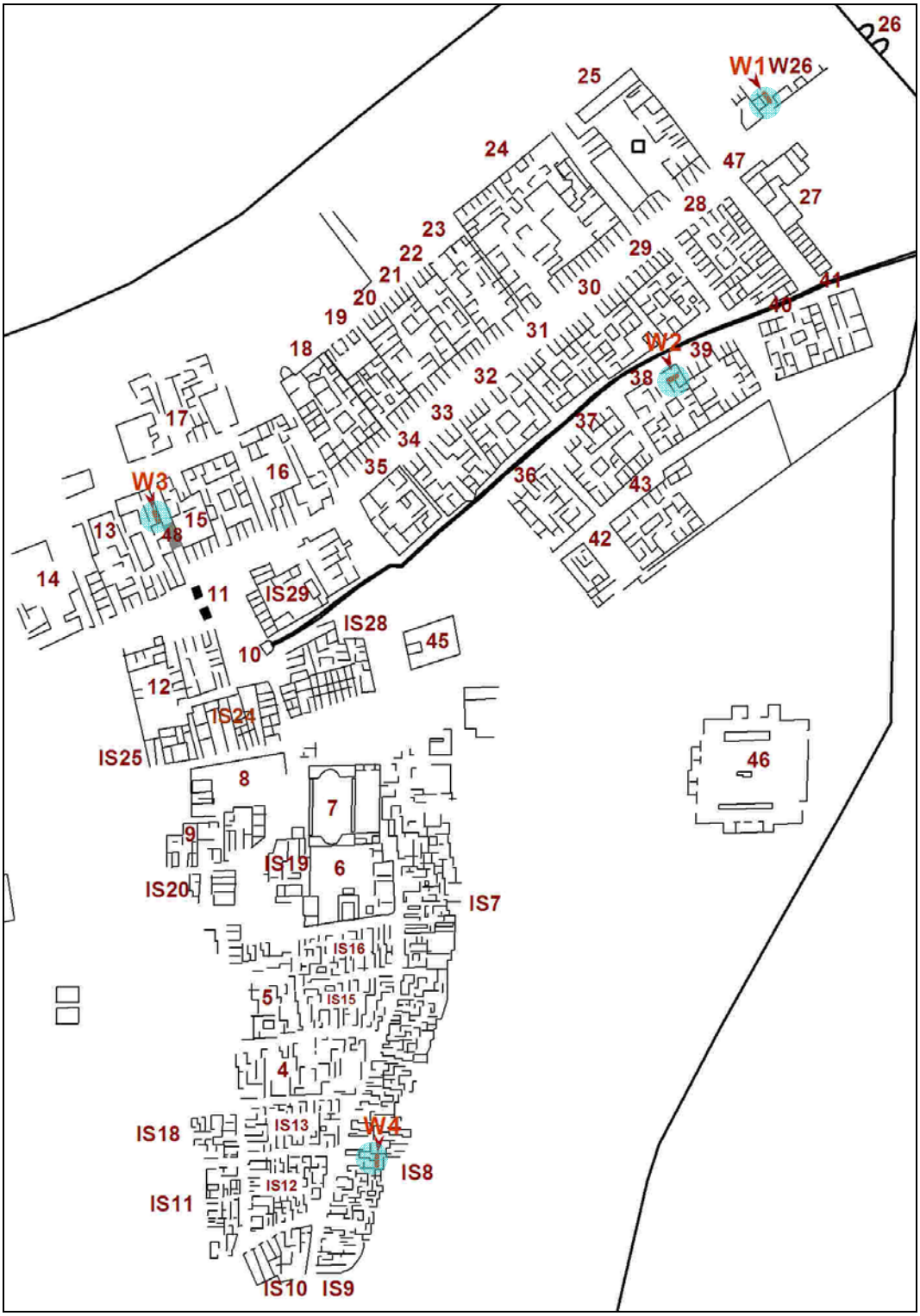


Figure 83 – Location of the mapped few walls of Volubilis.

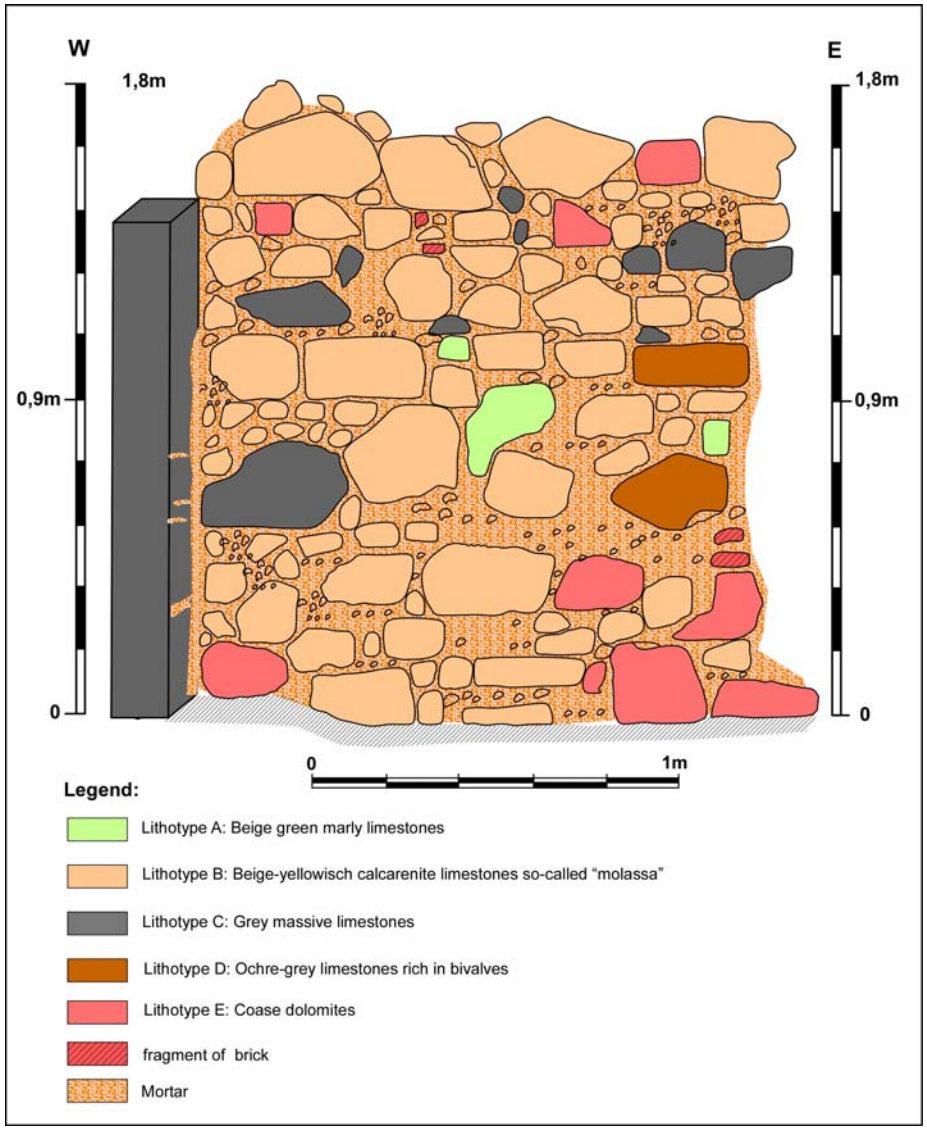


Figure 84 - Lithofacies map (right; drawing by Mr. Alilou, Conservation of Volubilis) and comparison to the photographic view (left): Wall 1 in the House at the West of the Door of Tangier (26W).

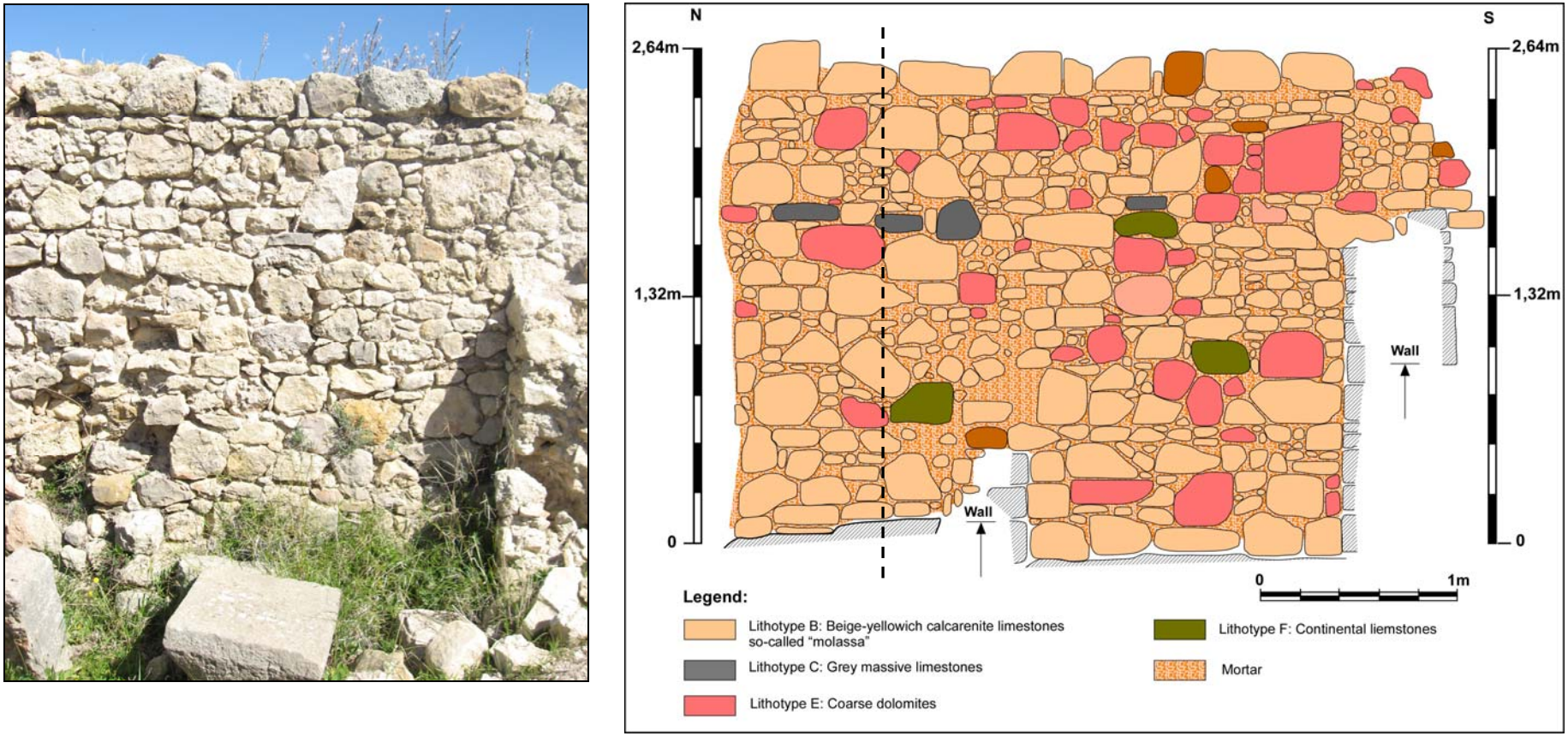


Figure 85 - Lithofacies map (right; drawing by Mr. Alilou, Conservation of Volubilis) and comparison to the photographic view (left): Wall 3 in the House of the Ephebe (13).

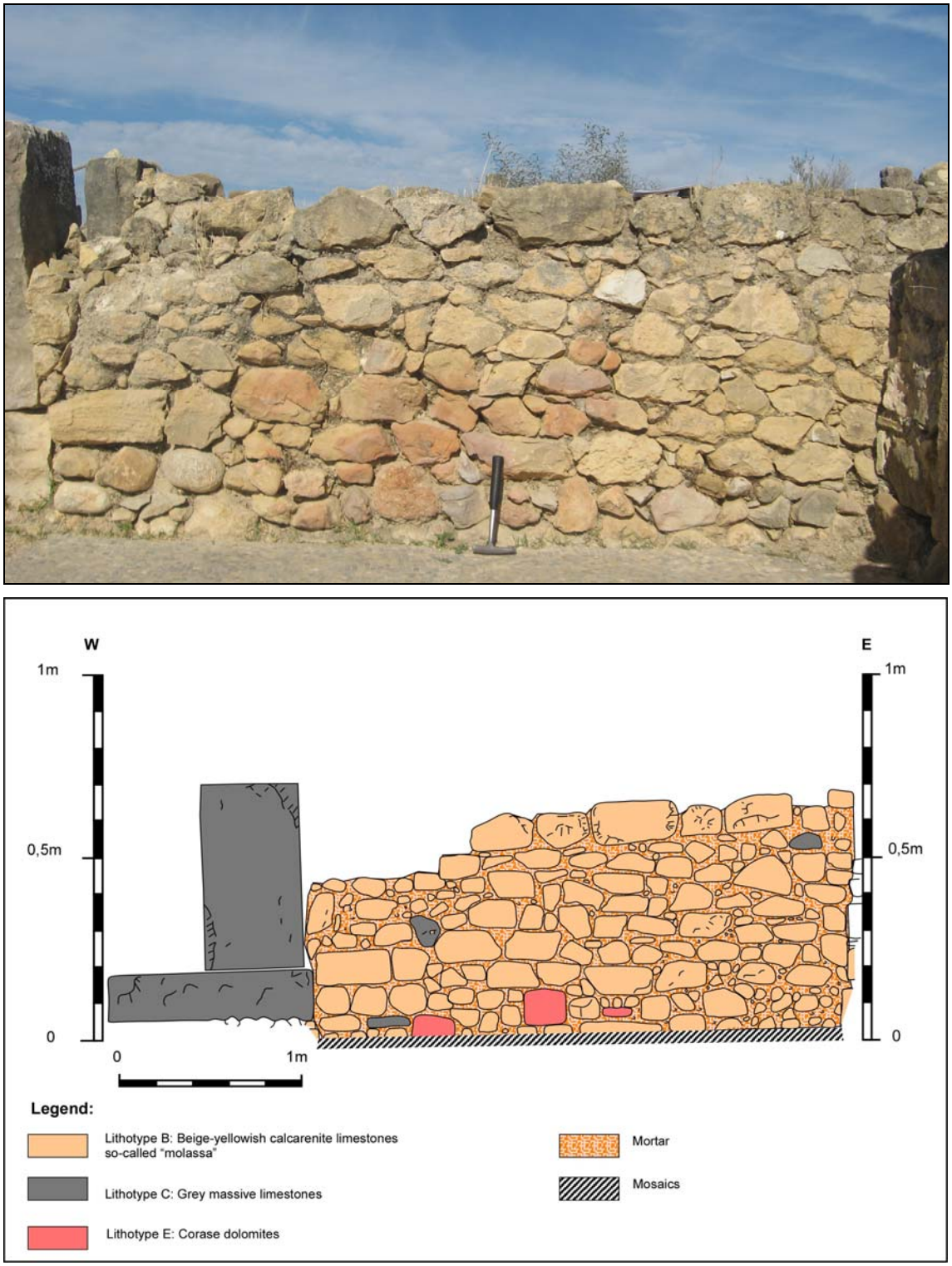


Figure 86 – Lithofacies map (down; drawing by Mr. Alilou, Conservation of Volubilis) and comparison to the photographic view (up): Wall 2 in the House of Venus (38).

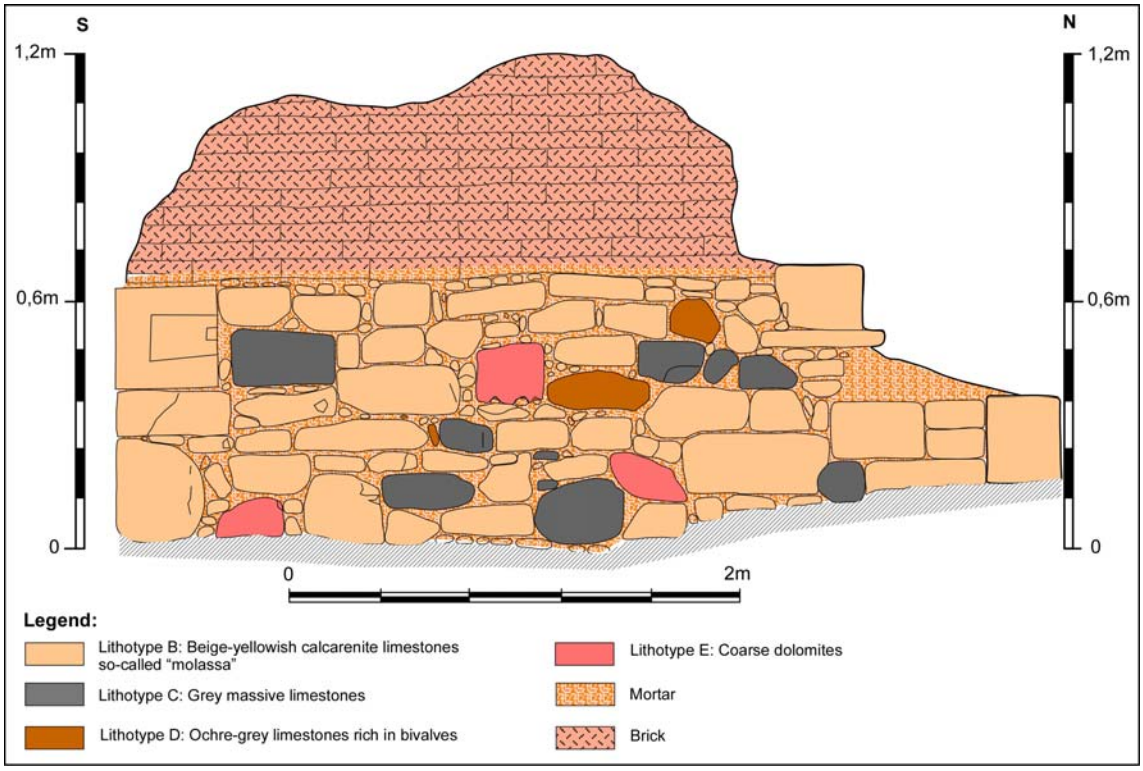


Figure 87 - Lithofacies map (down; drawing by Mr. Alilou, Conservation of Volubilis) and comparison to the photographic view (up): Wall 4 in the Insulae (IS8).

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4.4. REFERENCE QUARRIES AND OUTCROPS

As already said in the introduction of this chapter, the identification and determination of origin of Volubilis building stones was not in the past a priority research for archaeologists. Few investigations were carried out dealing with the search of ancient quarries. Etienne (1950) made a preliminary description of limestone quarries located around Volubilis. Then, Feray and Paskoff (1966) supplied a detailed overview of quarries located around Volubilis, based on extraction and tool marks as well as petrographic visual description of the corresponding materials. Unfortunately, the previous studies results remained insufficient and sometimes arbitrary.

Therefore, a further geological survey of the area around Volubilis based on the previous available bibliographic and geological setting data was carried out in order to check or find the quarries of provenance of Volubilis building stones and to improve the knowledge of the characteristics of their lithofacies.

The reconnaissance of ancient quarries was first of all based on observations of traces of tools used for the extraction of blocks. In some sites, these extraction traces are numerous and indubitable (traces of wedges, holes, step faults, blocks ready to be loosened, dimension stones abandoned), whereas other outcrops present more doubting traces of quarrying altered by dissolution.

Two main quarries areas were located respectively near Aïn Schkor hill and on the upper part of Moulay Idriss Zerhoun city. The search of provenance of the stones was completed by the study of various outcrops near Lakouar and Bou Assal villages, around Douar Ben Abdallah hill and also on the site of Volubilis itself.

The considered quarries and outcrops are located in a five kilometres sector around Volubilis site (Figure 88). They were investigated and sampled for in-laboratory analysis, their corresponding lithotypes were characterised and identified and then compared to those (referenced A to F) from Volubilis ancient site.

The corresponding whole results are presented in the paragraphs below.

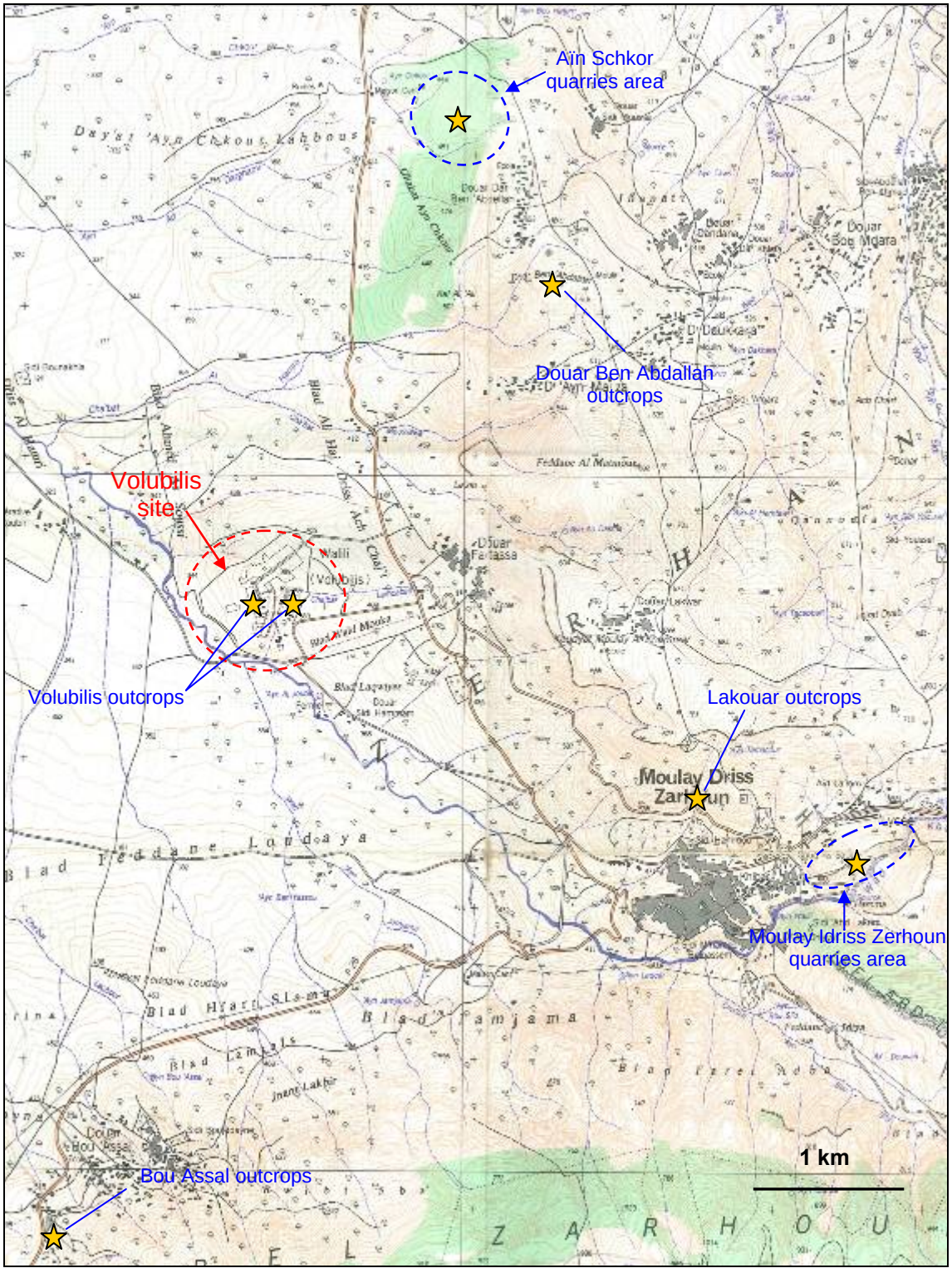


Figure 88 – Location map of ancient quarries and outcrops considered.

4.4.1. "Aïn Schkor" quarries area

Various small to medium-sized quarries can be observed in the extensive and hilly area called "Aïn Schkor" (Figure 89). They are distributed from the basis to the top of the hill into three main parts (Figure 90): a low level and an intermediate one blocked off by vegetation (recent forest of pines) and an upper level corresponding to a meadow area.

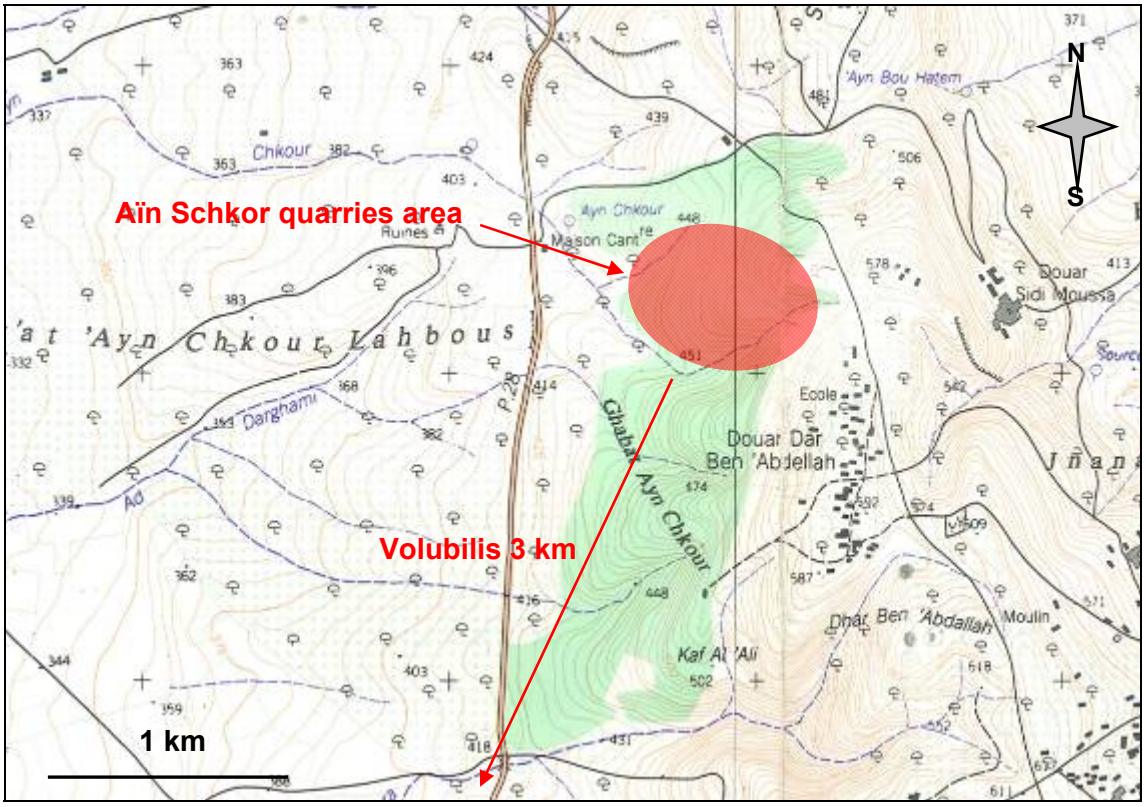


Figure 89 – Location map of Aïn Schor quarries area.

The most important quarries in terms of extension and thickness of exploited bank (three to four metres) correspond to the intermediate part (Figure 91) and the upper part (Figure 92) of Aïn Schkor area. These two parts have probably supplied few metres long block used for squared blocks and architectonics elements like columns. At the contrary, smaller elements (few decimetres thick) were extracted from the lower part (Figure 93) and used for stone-rubbles walls.

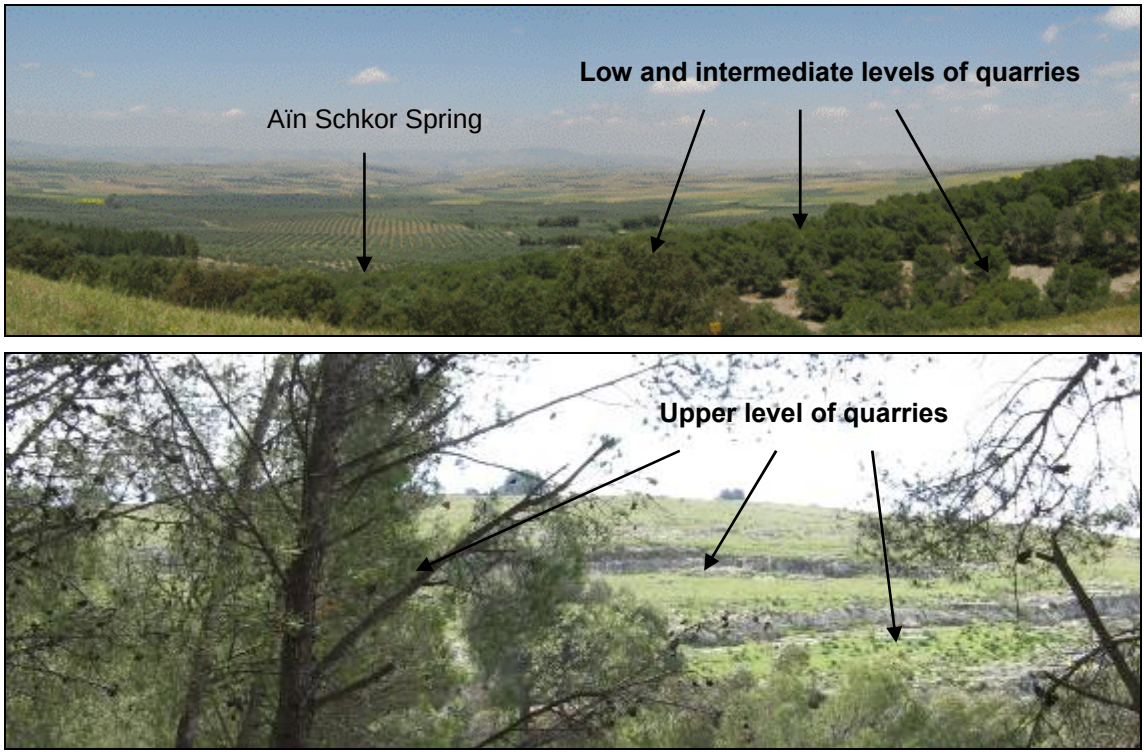


Figure 90 - Overviews of the three main levels of Aïn Schkor quarries area.

Figure 91 - View of one of the most important quarries in the intermediate part of Aïn Schkor area; thickness of the exploited bank about three metres.

Figure 92 – Views of the most important quarries in the upper part of Aïn Schkor area; thickness of the exploited bank until 4 metres.

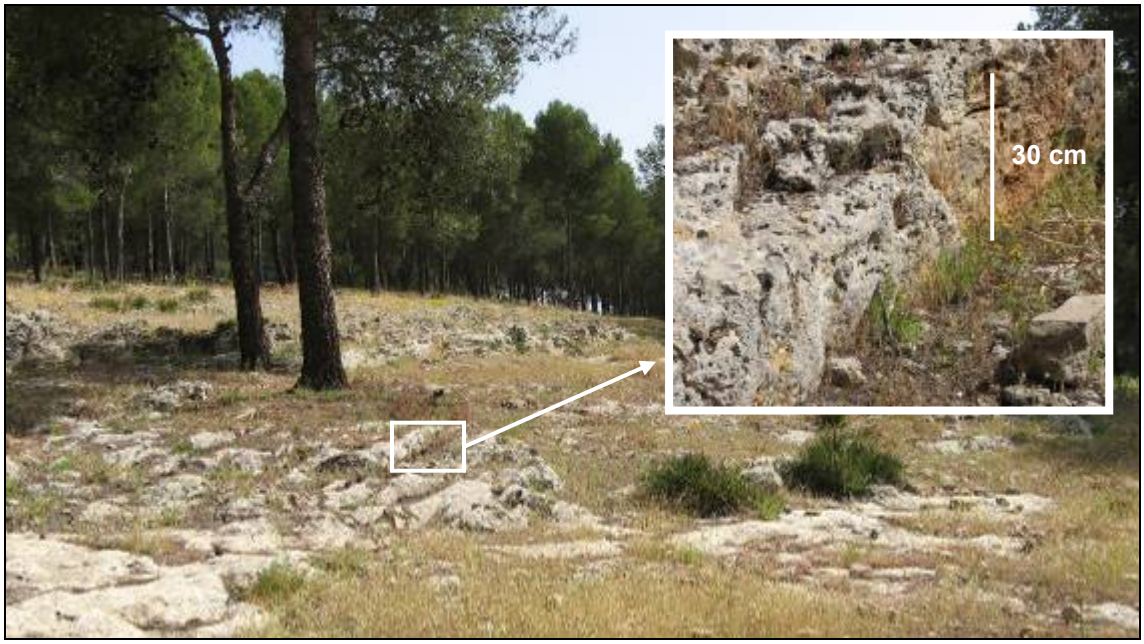


Figure 93 – Overview of the most important quarry in the lower part of Aïn Schkor area; thickness of the exploited bank about few decimetres thick.

Figure 94 – (Left) Abandoned detached block and (right) cutting traces in the intermediate part of Aïn Schkor quarries area.

Figure 95 – Traces of extraction of large-sized squared blocks in the upper part of Aïn Schkor quarries area.

Corresponding ancient exploitation signs are numerous (Figure 94 and Figure 95): cutting faces, holes; step faults, blocks ready to be detached, big squared and abandoned stones.

According to geological setting (Faugères, 1978), the Aïn Schkor quarries area is located in the Miocene “Upper molassa” formations (Figure 96). The “Upper molassa” formation is stratigraphicaly above the “White marls” formation, and their limit is not well observable on the field. In a lithological point of view, the “Upper molassa” corresponds to a few metres thickness of white marly-limestones under a thick (about 80 metres) continuous formation of limestones more or less bioclastic and rich in terrigenous materials, with a dip oriented 10° NW. The thickness of its layers ranges from one to over ten metres for the thickest ones. This variation is a determining factor for the size of extracted building stones.

Fourteen samples referenced AS01 to AS14 were collected in Aïn Schkor quarries area, characterised in laboratory and compared to those from Volubilis monuments.

According to the analytical results (Table 19 and Table 20), the stones from Aïn Schkor quarries area correspond to a medium soft stone (average compressive strength about 25 MPa). The amplitude of total porosity from quite low value (7.5%) to more than 25% (corresponding to porous materials) illustrates the heterogeneity of the “molassa” series. In a mineralogical point of view, it is a carbonate (calcite content of about 88% in average) with a significant proportion of quartz (about 10% considering the silica proportion measured). Some samples also contain a small proportion of dolomite illustrating a beginning of dolomitisation of the stone. Besides quartz, accessory minerals are mainly traces of feldspars and of clay minerals.

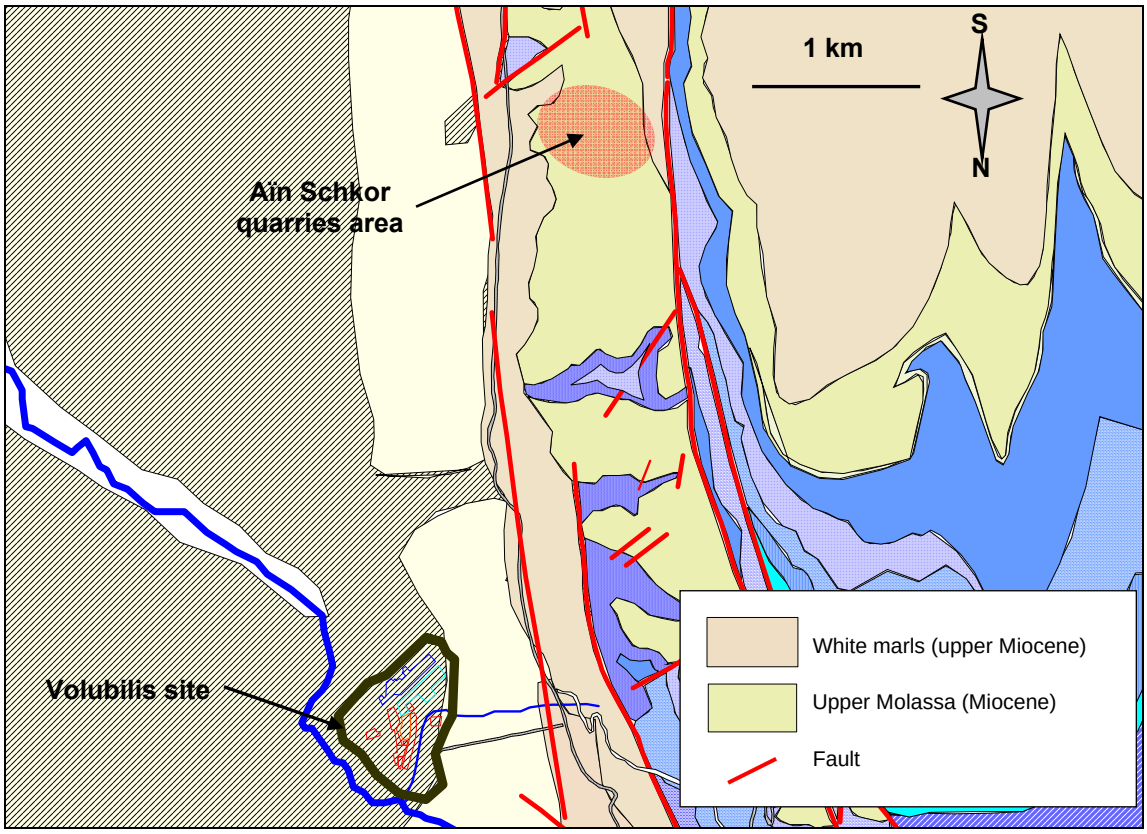


Figure 96 – Geological map including Ain Schkor area (Faugères, 1978; modified).

The major chemical elements of this type of stone are Calcium (average about 50%), and Silicium (more than 10% in average). Concerning trace chemical elements, the significant ones are Strontium (258 ppm en average) and Barium (47 ppm). Some samples also contain Zirconium (about 25 ppm).

According to their petrographic description by optic microscope (Figure 97) and their mineralogical qualitative analysis by XRD (Figure 98), samples AS12 and 14 are similar to those from Volubilis site belonging to the lithotype A “Beige-green marly limestones”.

Sample Reference	Sub-lithotype	Petrographic description by optic microscopy	Mineralogical analysis by X-Ray Diffraction	Calcite content (%) by acid attack	Dolomite content (%) by acid attack	$\delta^{18}O$ ‰ vs PDB	$\delta^{13}C$ ‰ vs PDB	Uniaxial Compressive Strenght (MPa)	Total Water Porosity (%)	Solid Density	Bulk Density	Water Natural Saturation Degree
AS01	B2	X	X	87.7	1.6	-2.9	-3.1	33.4	15.6	2.69	2.27	0.63
AS02	B2	X	X	84.2	4.8	-3.4	-3.8	19.5	20.7	2.70	2.13	0.75
AS03	B1	X	X	-	-	-1.7	-2.2	-	-	-	-	-
AS04	B3	X	X	-	-	-	-	-	-	-	-	-
AS05	B2	X	-	89.8	0.0	-0.6	-1.1	-	7.5	2.69	2.49	0.59
AS06	B2	X	-	89.7	1.6	-2.7	-2.6	-	26.3	2.69	1.98	0.91
AS07	B2	X	-	87.6	0.0	-2.8	-2.6	-	16.7	2.68	2.23	0.79
AS08	B2	X	X	-	-	-2.5	-3.1	-	-	-	-	-
AS09	B2	X	X	-	-	-3.0	-3.0	-	-	-	-	-
AS10	B1	X	X	-	-	-	-	-	-	-	-	-
AS11	B3	X	X	-	-	-1.2	-1.3	-	-	-	-	-
AS12	A	X	X	-	-	-2.7	-2.8	-	-	-	-	-
AS13	B2	X	X	-	-	-3.6	-3.6	-	-	-	-	-
AS14	A	X	X	-	-	-1.3	-1.8	-	-	-	-	-
Min	-	-	-	84.2	0.0	-	-	19.5	7.5	2.68	1.98	0.59
Max	-	-	-	89.8	4.8	-	-	33.4	26.3	2.70	2.49	0.91
Av	-	-	-	87.8	1.6	-	-	26.5	17.4	2.69	2.22	0.74

Table 19 – Analytical data measured on the fourteen samples from Aïn Schkor quarries.

Sample Reference	Al_2O_3 (%)	CaO (%)	Fe_2O_3 (%)	K_2O (%)	MgO (%)	MnO (%)	P_2O_5 (%)	SiO_2 (%)	TiO_2 (%)	LOI (%)	Co (ppm)	Pb (ppm)	As (ppm)	Sr (ppm)	Zn (ppm)	B (ppm)	V (ppm)	Cr (ppm)	Ba (ppm)	Ag (ppm)	Ce (ppm)	Zr (ppm)
AS01	1.2	46.8	0.30	0.47	0.4	<0.02	0.24	13.1	0.05	37.2	<5	<10	<20	251	11	<10	<10	<10	103	0.6	<10	22
AS02	1.1	47.5	0.40	0.34	0.4	<0.02	0.36	12.1	0.07	37.4	<5	<10	<20	235	11	<10	<10	<10	86	0.2	<10	32
AS03	<1	57.4	<1	<0.5	<1	0.01	0.25	9.8	0.02	-	<5	10	<20	181	6	<10	<10	<10	27	<0.2	12	<20
AS04	-	-	-	-	-	-	-	-	-	-												
AS05	0.8	49.7	0.12	0.35	0.2	<0.02	0.32	8.5	<0.05	39.2	<5	<10	22	311	8	<10	<10	<10	23	1.3	16	27
AS06	1	49.4	0.49	0.24	0.2	<0.02	0.40	9.1	0.07	38.9	<5	<10	21	290	14	<10	<10	<10	20	0.7	18	34
AS07	1.1	47.7	0.30	0.34	<0.2	<0.02	0.44	11.6	<0.05	37.8	<5	<10	21	283	10	<10	<10	<10	26	<0.2	15	<20
AS08	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
AS09	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
AS10	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
AS11	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
AS12	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
AS13	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
AS14	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Min	-	46.8	-	-	-	-	0.24	8.5	-	37.2	-	-	-	181	6	-	-	-	20	<0.2	<10	-
Max	1.2	57.4	<1	<0.5	<1	<0.02	0.44	13.1	0.07	39.2	<5	<10	22	311	14	<10	<10	<10	103	1.3	18	34
Av	-	49.8	-	-	-	-	0.34	10.7	-	38.1	-	-	-	258	10	-	-		47	0.7	-	-

Table 20 – Analytical data measured on the fourteen samples from Aïn Schkor quarries (LOI = Lost Of Ignition).

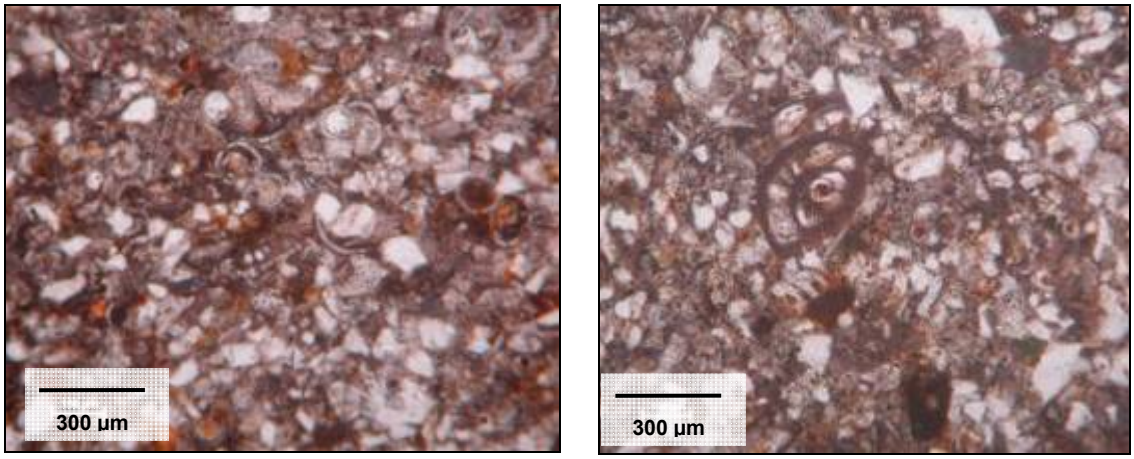


Figure 97 - Microscopic observations (N//) of lithofacies A: (left) sample AS14 from Aïn Schkor quarries area; (right) sample VOL21 from Volubilis; obvious similarity of microfacies characteristics between both.

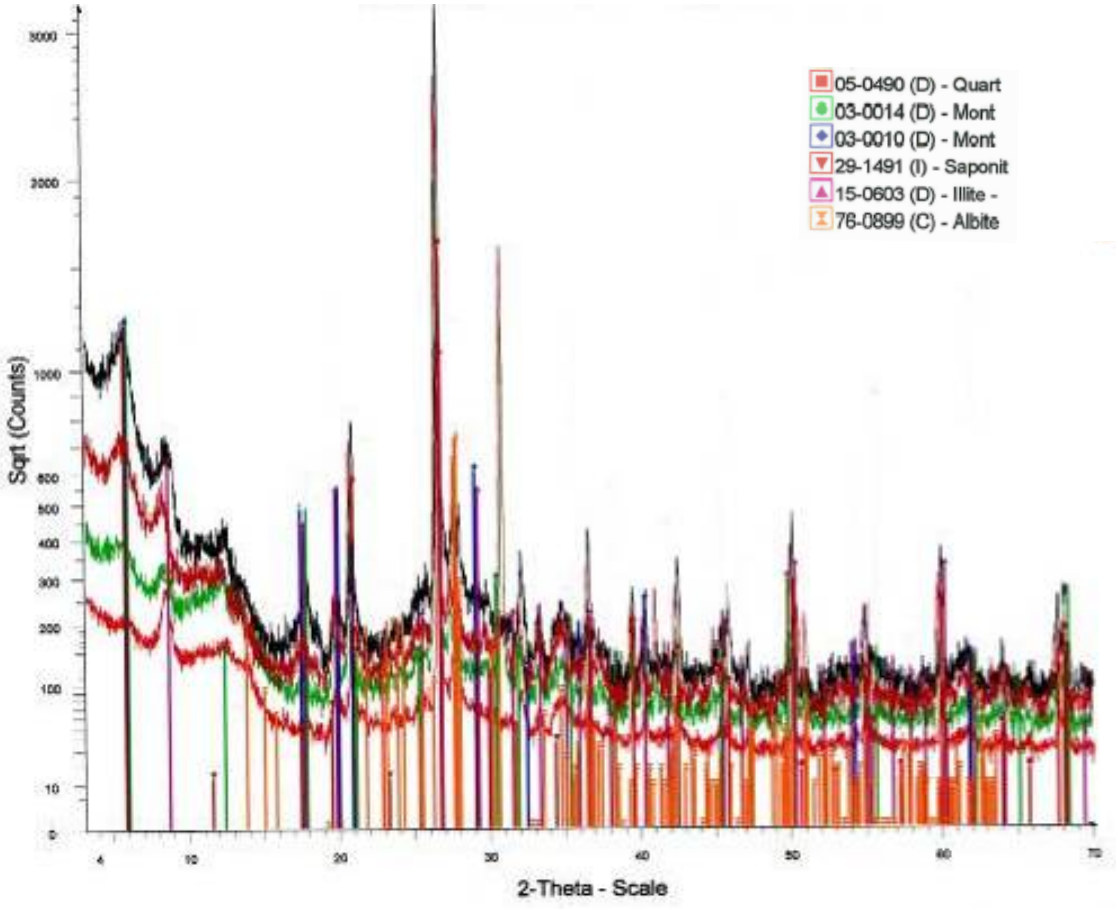


Figure 98 – Similar mineralogical qualitative analysis of the insoluble residue between lithofacies A samples from Volubilis and Aïn Sckhor quarries area: mainly of quartz, clays (especially smectites), feldspars (albite), mica group.

The twelve other quarries samples from Aïn Schkor area (Figure 99 to Figure 101) are similar to those from Volubilis site belonging to the lithotype B “beige-yellowish calcarenite limestones” (so-called “molassa”); more precisely:

- samples AS03 and 10 belong to B1 sub-lithotype “Beige-yellowish microporous calcarenite rich in terrigenous material;

- samples AS01, 02, 05, 06, 07, 08, 09 and 13 belong to B2 sub-lithotype” Beige-yellowish microporous calcarenite rich in terrigenous material and large bioclasts (Figure 102);

- samples AS04 and 11 belong to B3 sub-lithotype “Beige-pink macroporous calcirudite rich in terrigenous material (Figure 103).

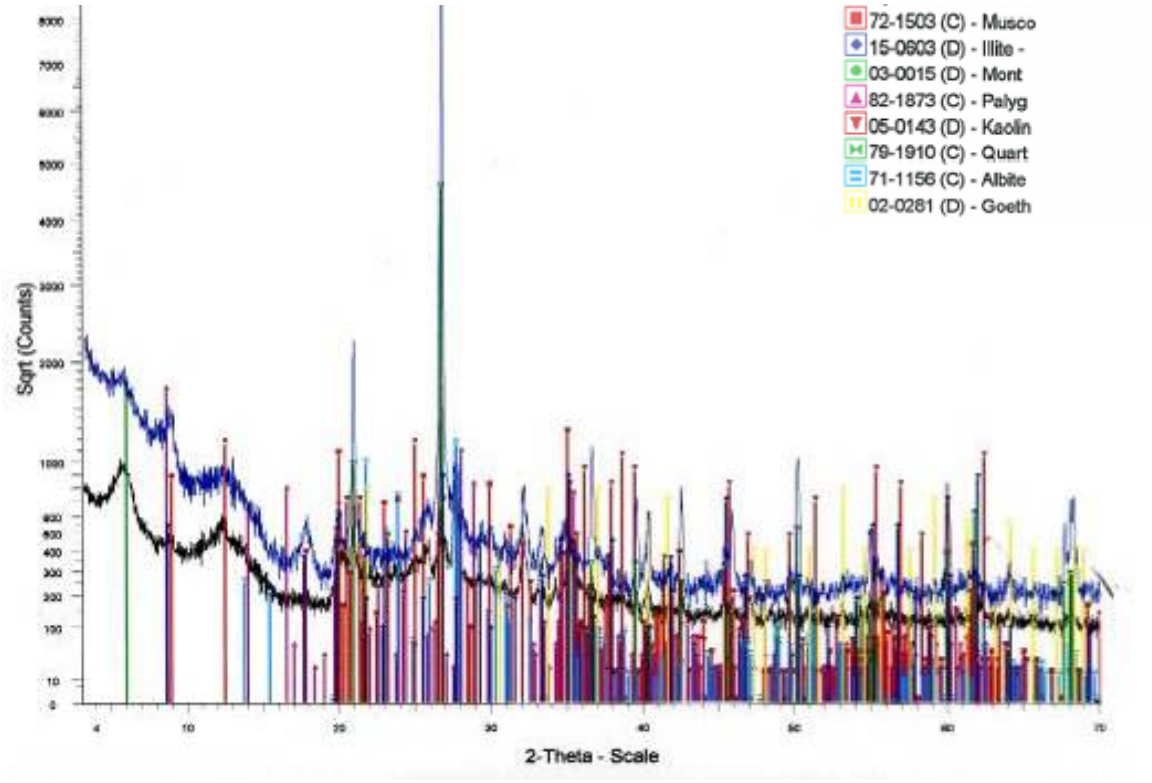


Figure 99 - Similar mineralogical qualitative analysis of the insoluble residue between lithofacies B1 samples from Volubilis and Aïn Sckhor quarries area: mainly of clay minerals (smectites, kaolin), micas (illite, muscovite) and quartz.

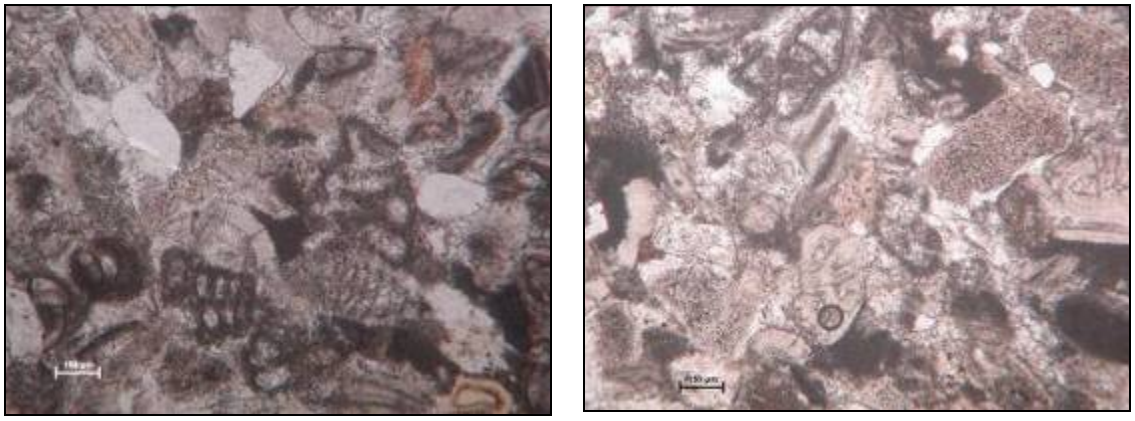


Figure 100 - Microscopic observations (N//) of lithofacies B1: (left) sample AS3 from Aïn Schkor quarries area; (right) sample VOL20 from Volubilis; obvious similarity of microfacies characteristics between both.

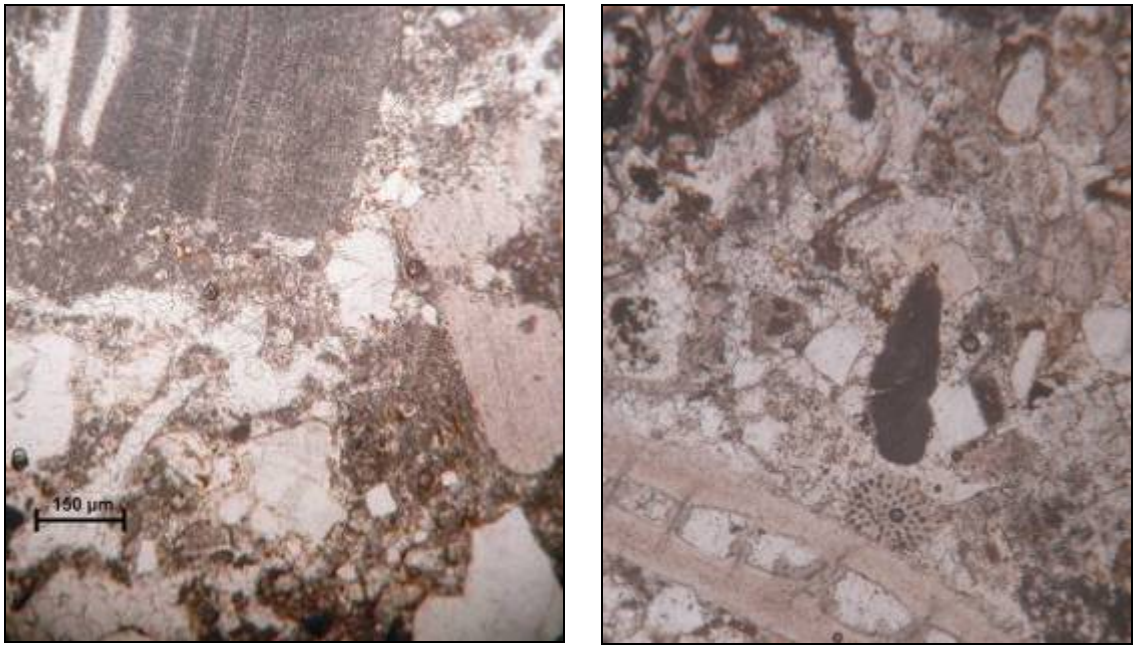


Figure 101 - Microscopic observations (N//) of lithofacies B3: (left) sample AS4 from Ain Schkor quarries are; (right) sample VOL15 from Volubilis: obvious similarity of microfacies characteristics between both (notably very to extremely poor sorting).

Figure 102 – Macroscopic observations of lithotype B2 in Aïn Schkor quarries area; typical terrigenous material and large bioclasts.

Figure 103 – Macroscopic observations of lithotype B3 in Aïn Schkor quarries area; typical macroporosity.

On the basis of isotopic signature, the comparison of Aïn Schkor quarries samples to those from Volubilis monuments confirms (Figure 104) that Aïn Schkor quarries area is one of the areas (probably the main) of supply of Volubilis building stones belonging to lithotypes A and B.

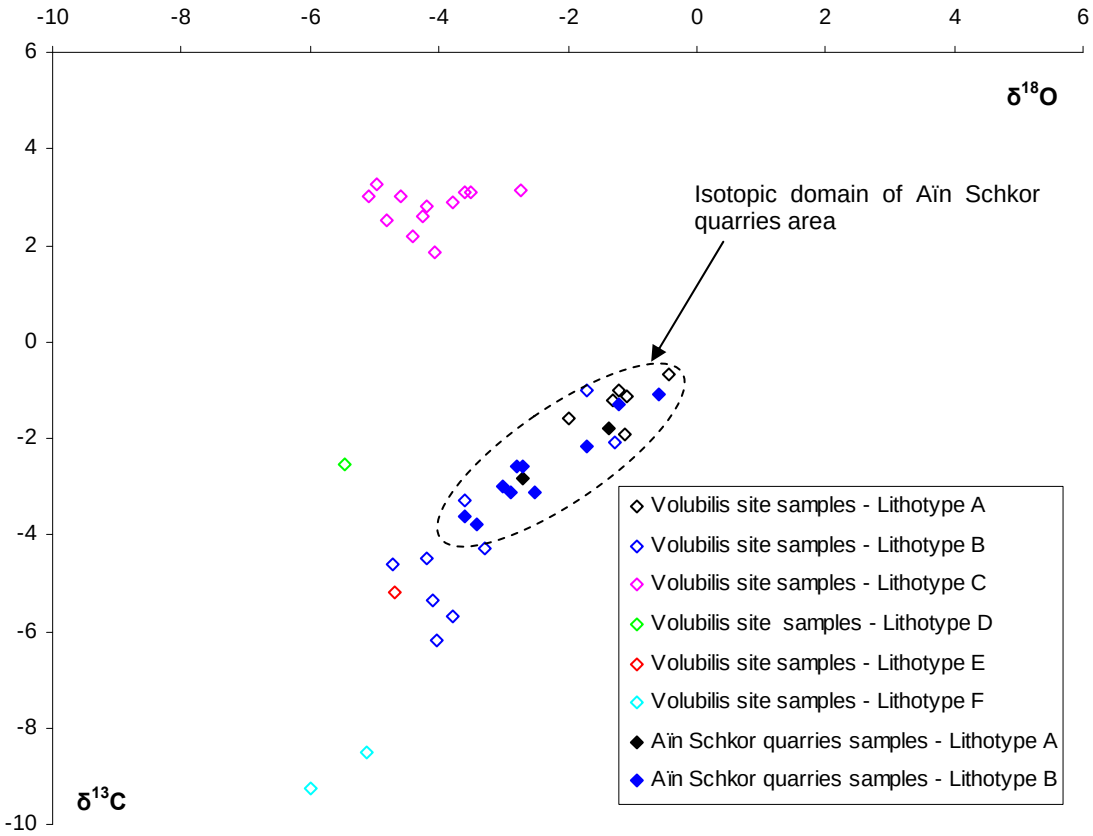


Figure 104 – Isotopic signature of the samples from Aïn schkor quarries and comparison to those from Volubilis site

4.4.2. "Moulay Idriss Zerhoun" quarries area

Moulay Idriss Zerhoun quarries are located in the upper part of the city under a large inclined to the north plateau, 500 metres long by 100 metres large, limited to the south by high cliffs (Figure 105 to Figure 107). Nowadays, the area is used for pasture, free of other activities, except the presence of a water tower (white building on Figure 107) and an intermittent "modern" quarry along the road (at the west base of the plateau). Some disseminated houses are also present at the eastern foot of the plateau.

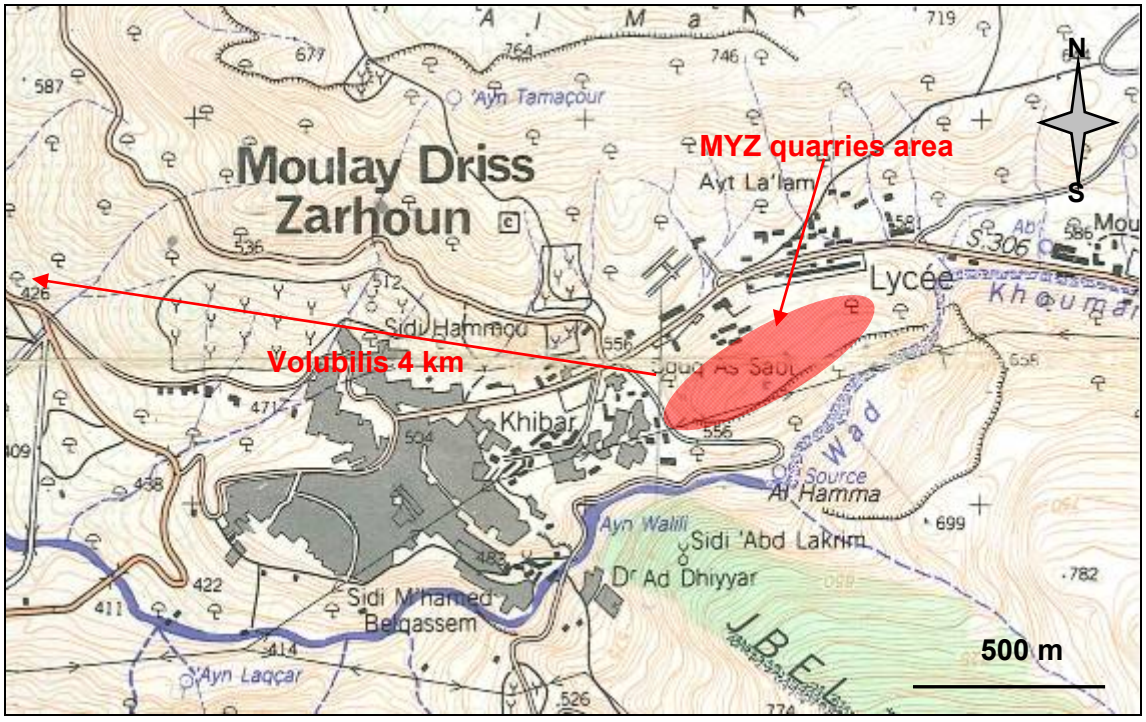


Figure 105 – Location map of Moulay Idriss Zerhoun (MIZ) quarries area.

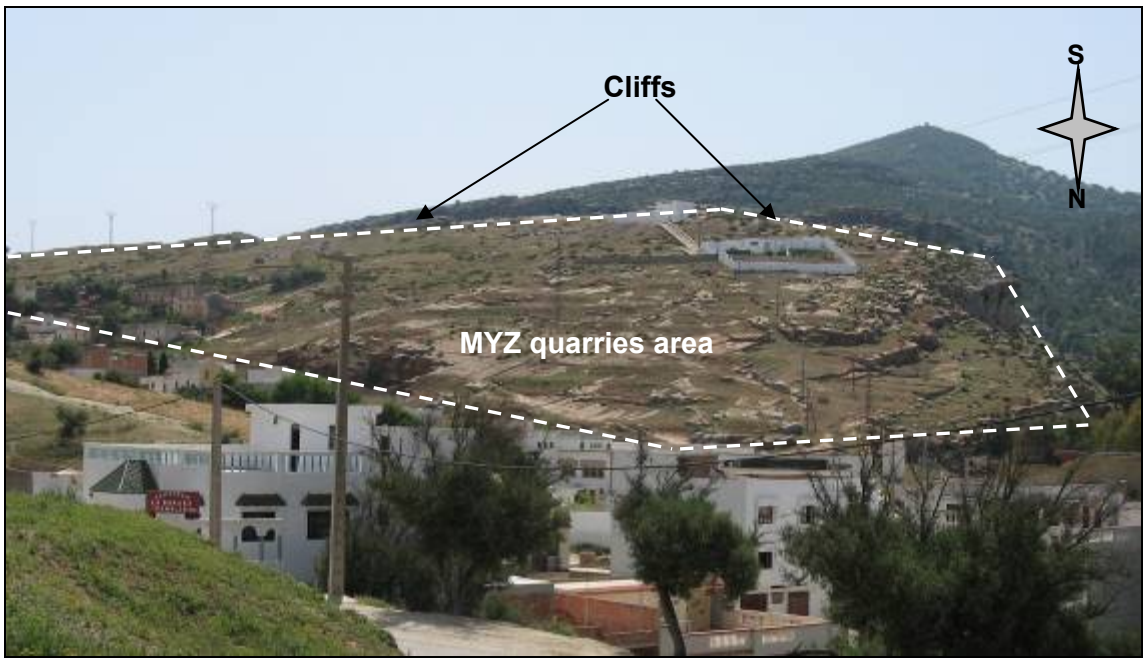


Figure 106 –Overview of Moulay Idriss Zerhoun (MIZ) quarries located in the upper part of the city.

Figure 107 – View of the upper part of Moulay Idriss Zerhoun (MIZ) limited by South high cliffs.

From the west to the east along the cliffs, the area of extraction is continuous, showing a succession of small to medium quarries with corresponding workshops (Figure 108 and Figure 109). From the north (down) to the south (up), the presence of wedge holes indicates that the whole surface of the plateau was anciently exploited. The extracted stone is a massive grey limestone (with conchoïdal fractures and sedimentary surfaces; Figure 109), separated by thin marly layers (Figure 110). Stylolithes and some macrofossils as belemnite are observable (Figure 111). The stone presents a typical greyish patina with white and black pluricentimetric lichens (Figure 112).

Despite the hardness of the stone, the blocks extraction was facilitated by the existence of stratification plans (lightly inclined) and the thickness of the strata, easily supplying stone pieces about several metres long for a thickness varying from fifty centimetres in average to one meter (Figure 113).

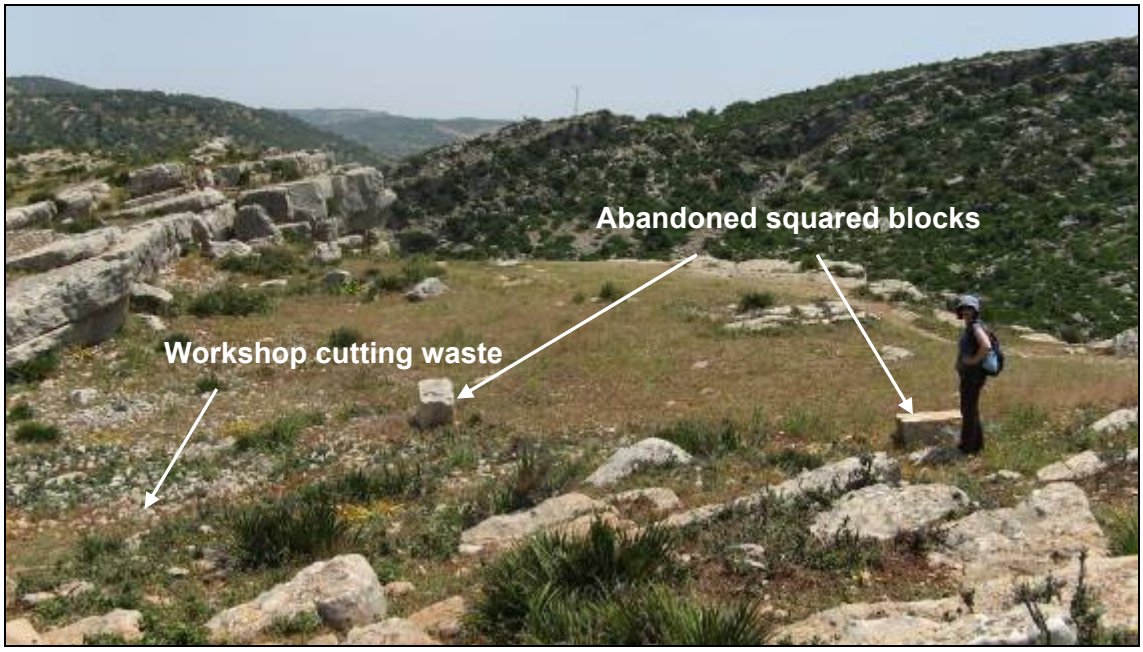


Figure 108 – One of the quarries located along the cliffs with abandoned squared blocks and cutting workshop.

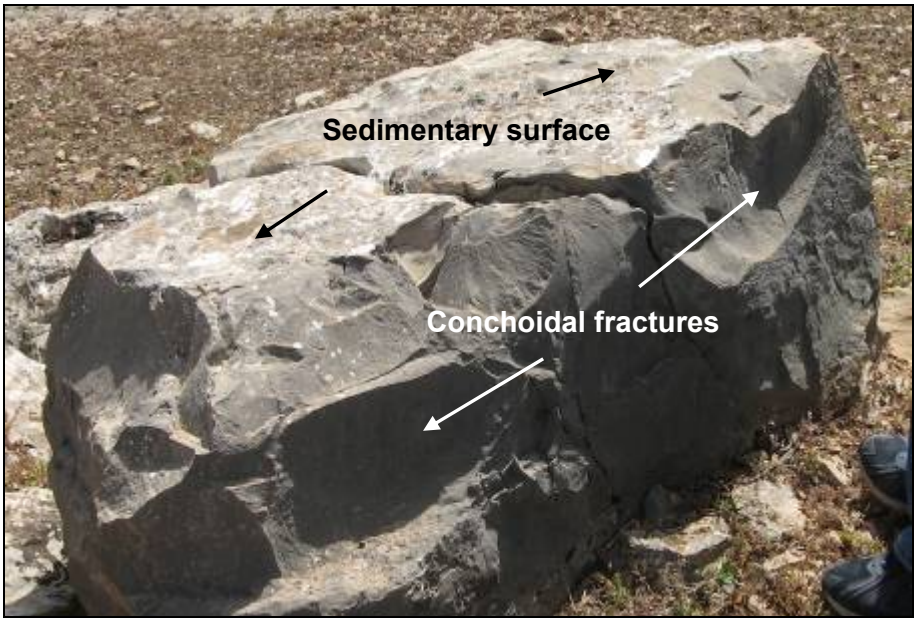


Figure 109 – Macroscopic observations of the exploited grey massive limestone: sedimentary surface and grey colored fresh conchoidal fractures.

Figure 110 – Thin marly layer (few centimetre thick) between two strata of grey massive limestone.

Figure 111 – Macroscopic observations of grey massive limestone of MYZ quarries: Belemnite fossil in an abandoned column fragment.

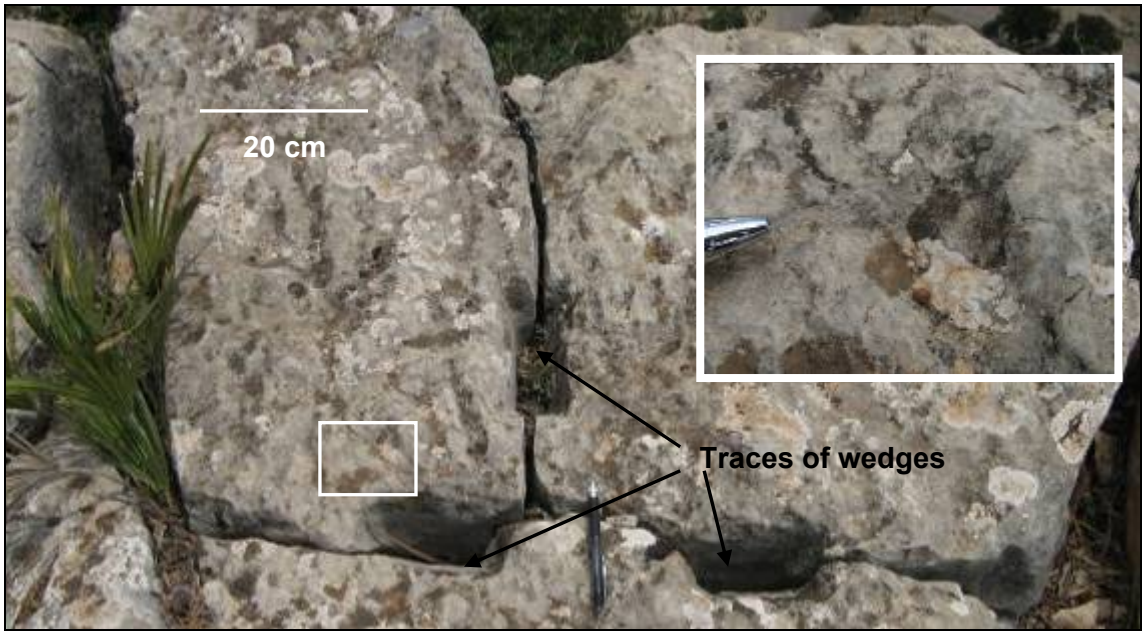


Figure 112 –Macroscopic observations of grey massive limestone of MYZ quarries: typical light grey patina with pluricentimetric black and white lichens; traces of wedges illustrating the technique of separation of blocks on a same strata.

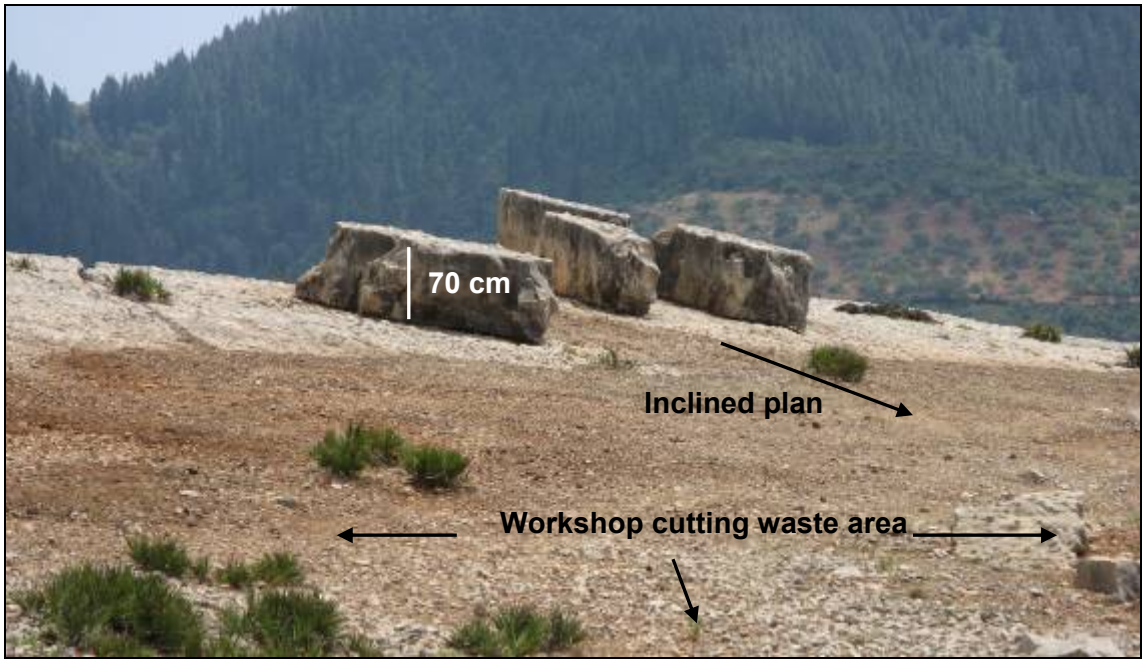


Figure 113 – Remains of a stratum on the upper part of the quarries area illustrating its thickness (and as a consequence the size of extracted piece) and the (relative) easiness of extraction linked also to the inclination of the strata.

The various ancient architectonic elements remains (sculpted blocks, column fragments, etc) as well as frequent traces of wedges observable (Figure 114 to Figure 116) under the whole quarries area, testify the Roman period of the exploitation.

Figure 114 – Abandoned column fragments and raw blocks in a cut workshop area.

Figure 115 – Typical traces of block extraction: wedges using stratification plan and natural fracturation to detach the element.

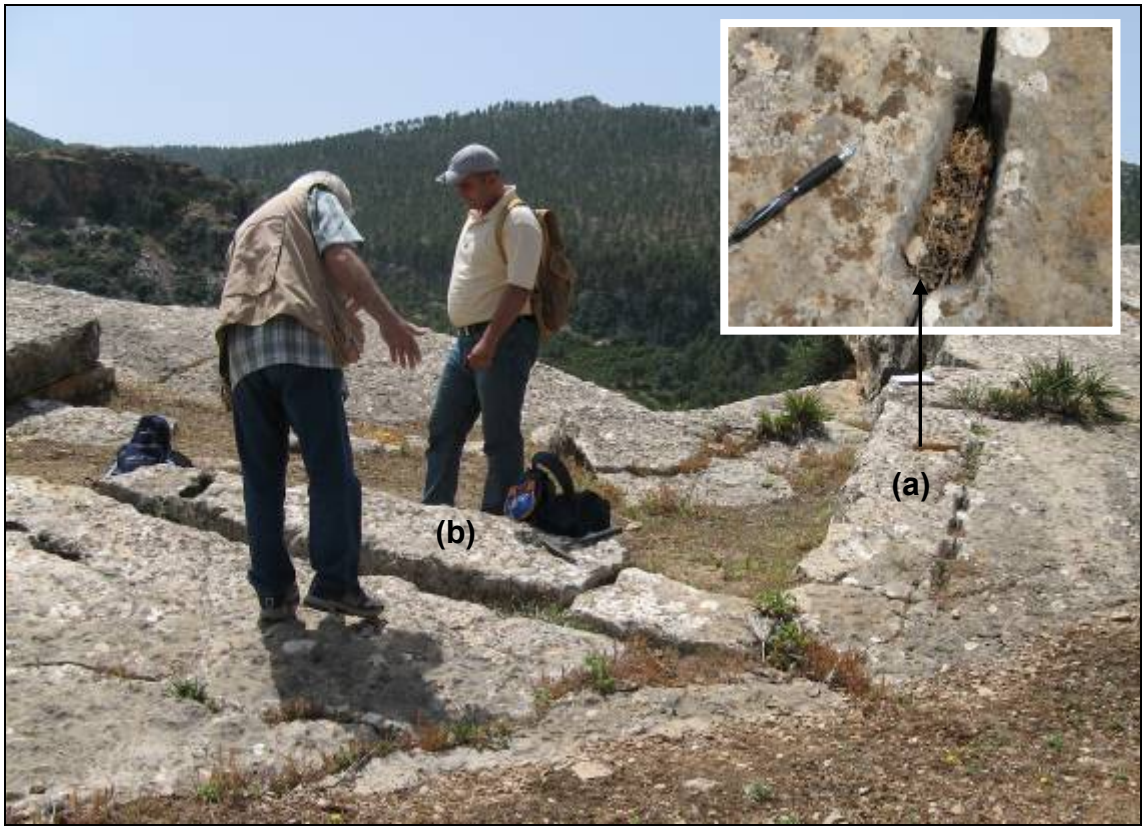


Figure 116 – Typical traces of blocks extraction (length of the pieces around 2 metres): (a) the wedge insertion brings about fracturation; (b) the block is moved away from the rest of the strata.

As concerns their geological setting (Faugères, 1978), the Moulay Idriss Zerhoun quarries are located in the medium Lias (medium and inferior Domerian) formation named “Bedded limestones” (Figure 117).

Stratigraphicaly located over a Carixian formation of siliceous limestones, the Domerian formation is mainly composed by marly-limestones (150 metres thick series) including the exploited “Bedded limestones”. This Domerian limestones are surmounted by a thick series of upper Lias (lower Toarcian = marly series with limestones at the top – Toarcian = sandy marly-limestones). These Jurassic series are surmounted in discordance by Miocene carbonates and marls.

In the Moulay Idriss Zerhoun quarries area, the Domerian layers of “Bedded limestones” present a whole thickness about 100 metres (thickness of each bed lower than one metre, fifty centimetres in average) and a quite important dip (slope 20-30° from the West part to the East one - Strike N30 to N60 from the West to the East). They form a well released bar in the relief, affected by various faults. As a consequence, these fields are affected by fracturing useful for an easier extraction as well as the stratification plan underlined by thin marly levels.

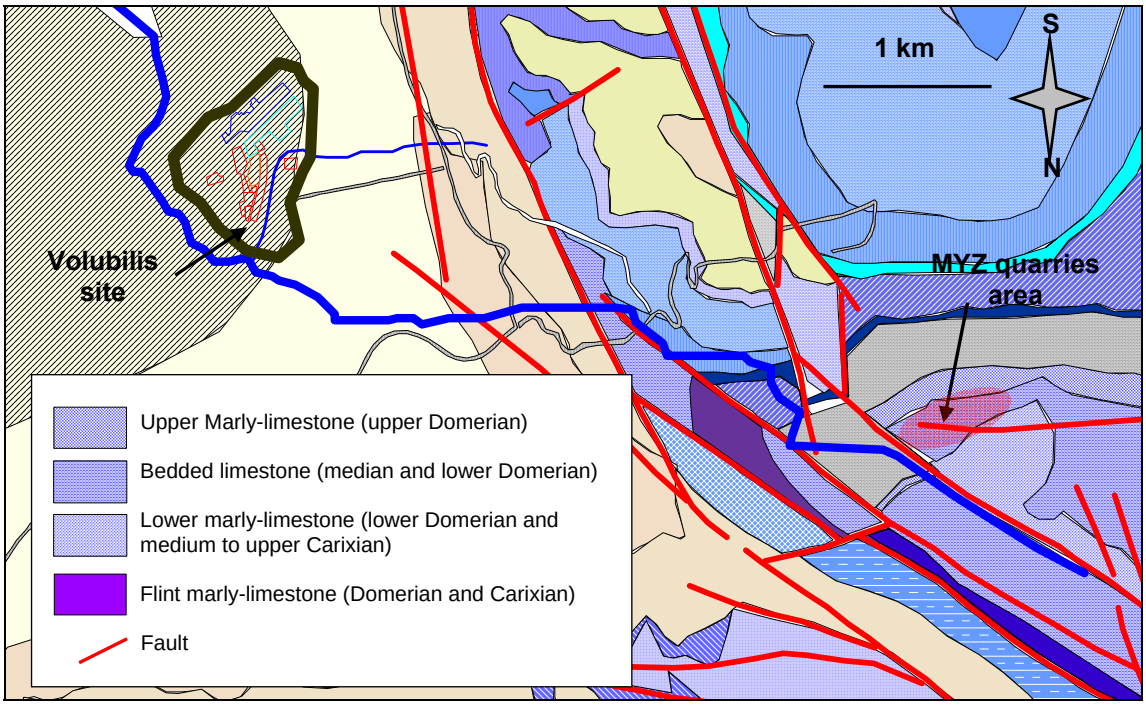


Figure 117 – Geological map including Moulay Idriss Zerhoun quarries area (Faugères, 1978; modified).

Twelve samples referenced MZ01 to MZ12 were collected in Moulay Idriss Zerhoun quarries area, characterised in laboratory and compared to those from Volubilis monuments.

According to the analytical results (Table 21 and Table 22) the stones from Moulay Idriss Zerhoun quarries area correspond to a hard stone (average compressive strength under 70 MPa) linked with a low total porosity (5% in average). Its water natural water saturation degree is high (average of 0.84).

In a mineralogical point of view, it is a quite pure carbonate with a calcite content of about 97% in average. Some samples also present a low proportion of dolomite illustrating a beginning of dolomitisation of the stone. The other accessory minerals are mainly quartz and also traces of clay minerals. As a consequence, the major chemical elements of this type of stone are Calcium (average about 57%) and Silicium (until 2.5%). Concerning trace chemical elements, the significant ones are Strontium (average of 199 ppm) and Zinc (17 ppm in average ranging from 5 to 51 ppm). Some samples also contain Arsenic.

According to their petrographic description by optic microscope (Figure 118) and their mineralogical qualitative analysis by XRD (Figure 119), the whole of the samples are similar to those from Volubilis site belonging to the lithotype C “grey massive limestones”. More precisely, samples MZ01 to MZ08 and MZ12 belong to C1 sub-lithotype “beige-grey peloid grainstone / packstone” and samples MZ09 to MZ11 belong to C2 sub-lithotype “grey, coated bioclastic grainstone”.

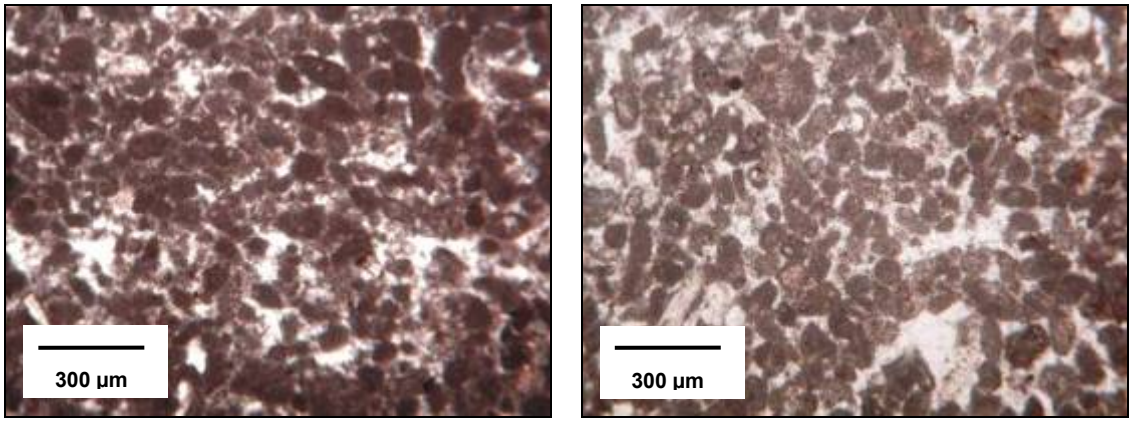


Figure 118 - Microscopic observations (N//) of lithofacies C1: (left) sample MZ05 from Moulay Idriss Zerhoun Quarries quarries; (right) sample VOL30 from Volubilis: obvious similarity of microfacies characteristics between both (notably peloids and rarely benthonic foraminifera, coated bioclasts, oncoids with good to very good sorting).

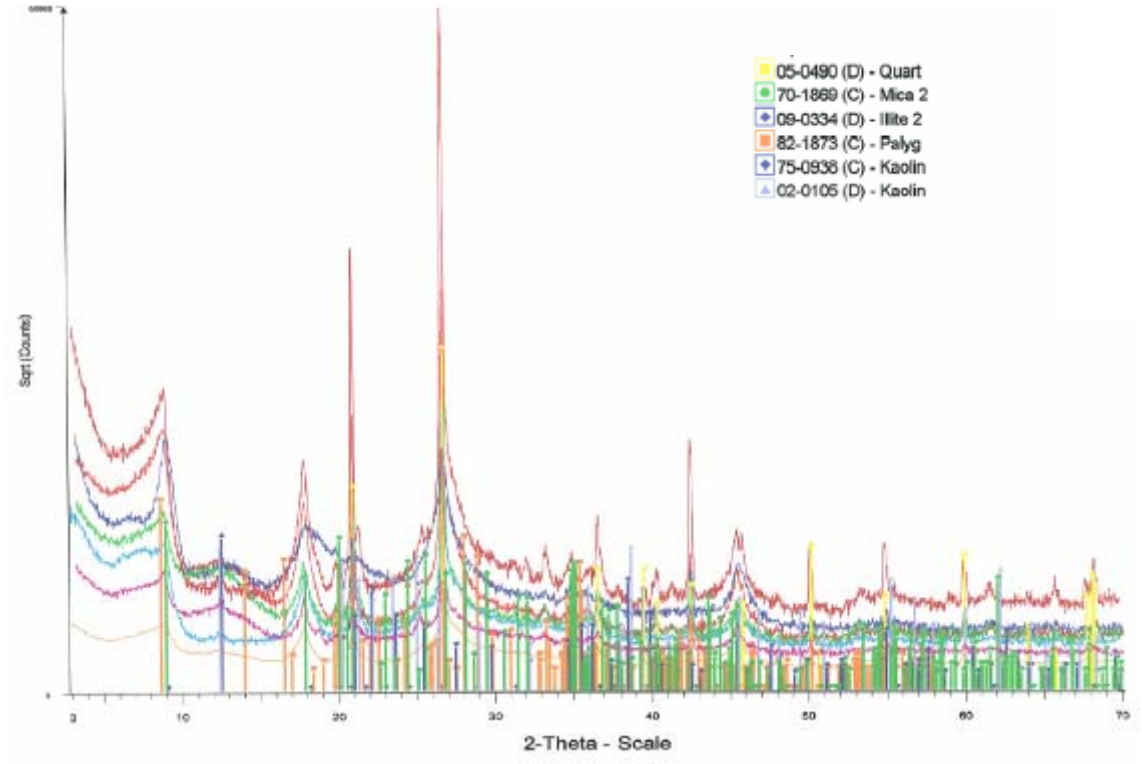


Figure 119 - Similar mineralogical qualitative analysis of the insoluble residue between lithofacies C1 samples from Volubilis and samples from Moulay Idriss Zerhoun quarries area: mainly mica, illite, kaolin, quartz and palygorskite.

Sample Reference	Sub-lithotype	Petrographic description by optic microscopy	Mineralogical analysis by X-Ray Diffraction	Calcite content (%) by acid attack	Dolomite content (%) by acid attack	$\delta^{18}O$ ‰ vs PDB	$\delta^{13}C$ ‰ vs PDB	Uniaxial Compressive Strenght (MPa)	Total Water Porosity (%)	Solid Density	Bulk Density	Water Natural Saturation Degree
MZ01	C1	X	X	98.2	0.0	-4.6	2.8	80.7	6.0	2.72	2.55	0.85
MZ02	C1	X	X	98.2	0.0	-4.7	3.0	65.9	5.6	2.71	2.56	0.85
MZ03	C1	X	X	94.6	3.3	-4.6	2.9	72.6	2.9	2.71	2.63	0.80
MZ04	C1	X	X	98.2	1.6	-5.1	2.9	69.1	5.8	2.71	2.55	0.87
MZ05	C1	X	X	-	-	-4.4	2.7	-	-	-	-	-
MZ06	C1	X	X	-	-	-5.1	2.9	-	-	-	-	-
MZ07	C1	X	X	-	-	-4.6	3.0	-	-	-	-	-
MZ08	C1	X	X	-	-	-3.7	3.0	-	-	-	-	-
MZ09	C2	X	-	96.6	0.0	-4.7	2.9		6.7	2.71	2.53	0.83
MZ10	C2	X	-	-	-	-	-	-	-	-	-	-
MZ11	C2	X	-	-	-	-	-	-	-	-	-	-
MZ12	C1	X	-	-	-	-	-	-	-	-	-	-
Min	-	-	-	94.6	0.0	-	-	65.9	2.9	2.71	2.53	0.80
Max	-	-	-	98.2	3.3	-	-	80.7	6.7	2.72	2.63	0.87
Av	-	-	-	97.2	1.0	-	-	72.1	5.4	2.71	2.56	0.84

Table 21 – Analytical data measured on the twelve samples from Moulay Idriss Zerhoun quarries.

Sample Reference	Al_2O_3 (%)	CaO (%)	Fe_2O_3 (%)	K_2O (%)	MgO (%)	MnO (%)	P_2O_5 (%)	SiO_2 (%)	TiO_2 (%)	LOI (%)	Co (ppm)	Pb (ppm)	As (ppm)	Sr (ppm)	Zn (ppm)	B (ppm)	V (ppm)	Cr (ppm)	Ba (ppm)	Ag (ppm)	Ce (ppm)	Zr (ppm)
MZ01	0.3	54.0	0.24	0.05	0.6	<0.02	<0.05	1.1	<0.05	42.9	<5	<10	36	194	25	<10	<10	<10	<10	<0.2	<10	<20
MZ02	0.3	54.5	0.24	<0.05	0.6	<0.02	<0.05	1.1	<0.05	42.8	<5	<10	28	188	6	<10	<10	<10	<10	<0.2	<10	<20
MZ03	0.4	53.8	0.32	<0.05	0.7	<0.02	<0.05	2.2	<0.05	42.2	<5	<10	24	206	7	<10	<10	<10	<10	<0.2	<10	<20
MZ04	0.3	54.4	0.22	<0.05	0.6	<0.02	<0.05	1	<0.05	42.8	<5	<10	26	180	20	<10	<10	<10	<10	<0.2	<10	<20
MZ05	<1	61.2	<1	<0.5	<1	<0.01	0.03	1	0.01	-	<5	<10	<20	185	51	<10	<10	<10	<10	0.3	12	<20
MZ06	<1	60.7	<1	<0.5	<1	<0.01	0.04	1.6	0.02	-	<5	<10	<20	191	17	<10	<10	<10	<10	0.2	13	<20
MZ07	<1	59.5	<1	<0.5	<1	<0.01	0.07	2.5	0.03	-	<5	<10	<20	232	11	<10	<10	<10	<10	0.3	14	<20
MZ08	<1	62.6	<1	<0.5	<1	<0.01	0.05	1	0.01	-	<5	<10	<20	215	8	<10	<10	<10	<10	0.3	13	<20
MZ09	0.4	53.8	0.44	<0.05	0.4	<0.02	<0.05	0.7	<0.05	43.3	<5	<10	23	197	5	<10	<10	<10	<10	0.4	12	<20
MZ10	-	-	-	-	-	-	-	-	-	-	<5	<10	36	194	25	<10	<10	<10	<10	<0.2	<10	<20
MZ11	-	-	-	-	-	-	-	-	-	-	<5	<10	28	188	6	<10	<10	<10	<10	<0.2	<10	<20
MZ12	-	-	-	-	-	-	-	-	-	-	<5	<10	24	206	7	<10	<10	<10	<10	<0.2	<10	<20
Min	-	53.8	-	-	-	-	-	0.7	-	42.2	-	-	-	180	5	-	-	-	-	-	-	-
Max	<1	62.6	<1	<0.5	<1	<0.02	0.07	2.5	<0.05	43.3	<5	<10	36	232	51	<10	<10	<10	<10	0.4	14	<20
Av	-	57.2	-	-	-	-	-	1.3	-	42.8	-	-	-	199	17	-	-	-	-	-	-	-

Table 22 – Analytical data measured on the twelve samples from Moulay Idriss Zerhoun quarries (LOI = Lost Of Ignition).

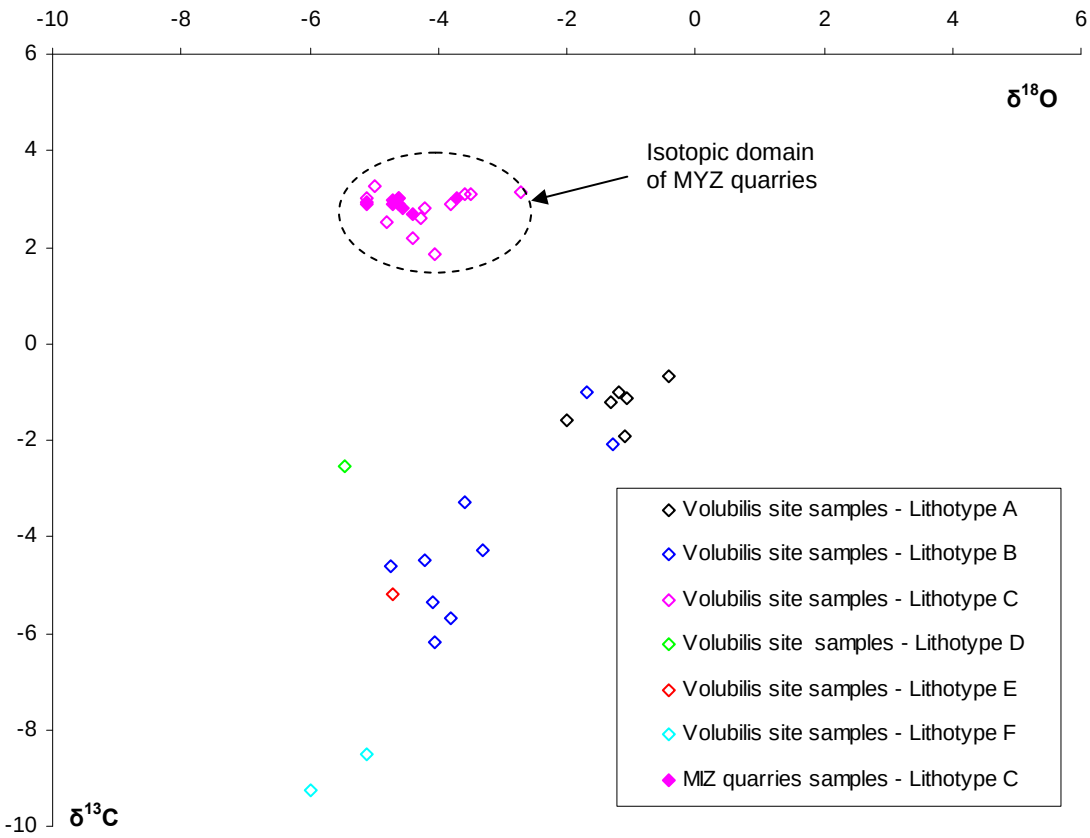


Figure 120 – Isotopic signature of the samples from Moulay Idriss Zerhoun quarries and comparison to those from Volubilis site.

On the basis of the isotopic signature, the comparison of Moulay Idriss Zerhoun quarries samples to those from Volubilis monuments confirms (Figure 120) that Moulay Idriss Zerhoun quarries are the area of provenance of Volubilis building stones belonging of the lithotype C.

4.4.3. Lakouar outcrops

Underneath Douar Lakouar, along the upper part of the road from Fertassa Village to Moulay Idriss Zerhoun City occurs in various points a geological formation constituted by the alternance of grey-yellowish sandy limestones layers (average thickness about thirty centimetres) and thinner grey marly levels (Figure 121). According to the geological setting (Faugères, 1978), the geological age of this formation is upper liasic (lower Bajocian). The grey-yellowish sandy limestones are characterised by an ochre-yellowish patina and the presence of many large bivalvia shells (Figure 122).

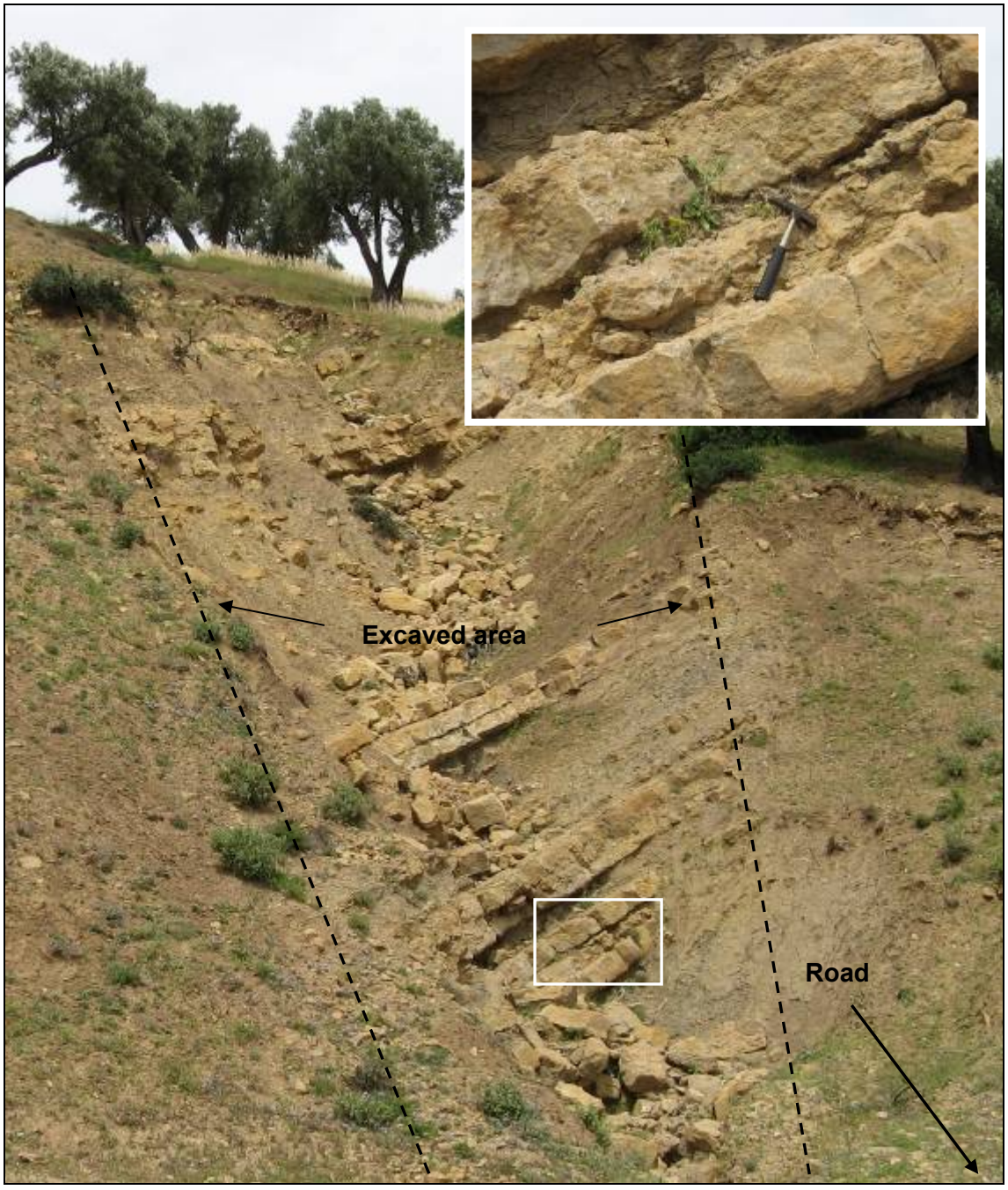


Figure 121 - Excaved area showing an alternance of greyish sandy limestones layers and thinner greyish marly levels

Figure 122 – Block of Ochre-grey limestone very rich in bivalvia shells: (a) sedimentary surface with highlighted shells.

The outcrops show locally excavated area used to supply stone-rubbles. The extraction was facilitated by the topography (side of a hill), the thickness and the slope of the layers and as a consequence no significant trace of extraction is observable.

Two samples referenced LK01 and LK02 were collected in Lakouar outcrops, characterised in laboratory and compared to those from Volubilis monuments.

According to the analytical results (Table 23 and Table 24), the stone from Lakouar outcrops corresponds to a hard stone (compressive strength about 86 MPa). Its total porosity is low (2,5% in average) and its water natural saturation degree quite high (average 0,76).

In a mineralogical point of view, it is a carbonate (calcite content about 84% in average ranging from 73 to more than 95%; sometime partially dolomitised) with a variable proportion of quartz (ranging from a few percents to about 10% considering the silica proportion measured). Besides quartz, accessory minerals are mainly traces of feldspars (albite) and of clay minerals (smectites, illite and kaolinite).

The major chemical elements of this type of stone are Calcium (average about 45%), and Silicium (11% in average). Al_2O_3 and iron oxides (giving the ochre patina color) are also present. Concerning trace chemical elements, the significant ones are Strontium (516 ppm en average) and Zirconium (103 ppm). Traces of Barium (37 ppm), Arsenic (26 ppm), Zinc and Cerium (23 ppm) are also present.

According to their megascopic appearance, petrographic description by optic microscope (Figure 123) and mineralogical qualitative analysis by XRD (Figure 124), the two samples are similar to those from Volubilis site belonging to the lithotype D “Ochre-grey limestone rich in large bivalvia.

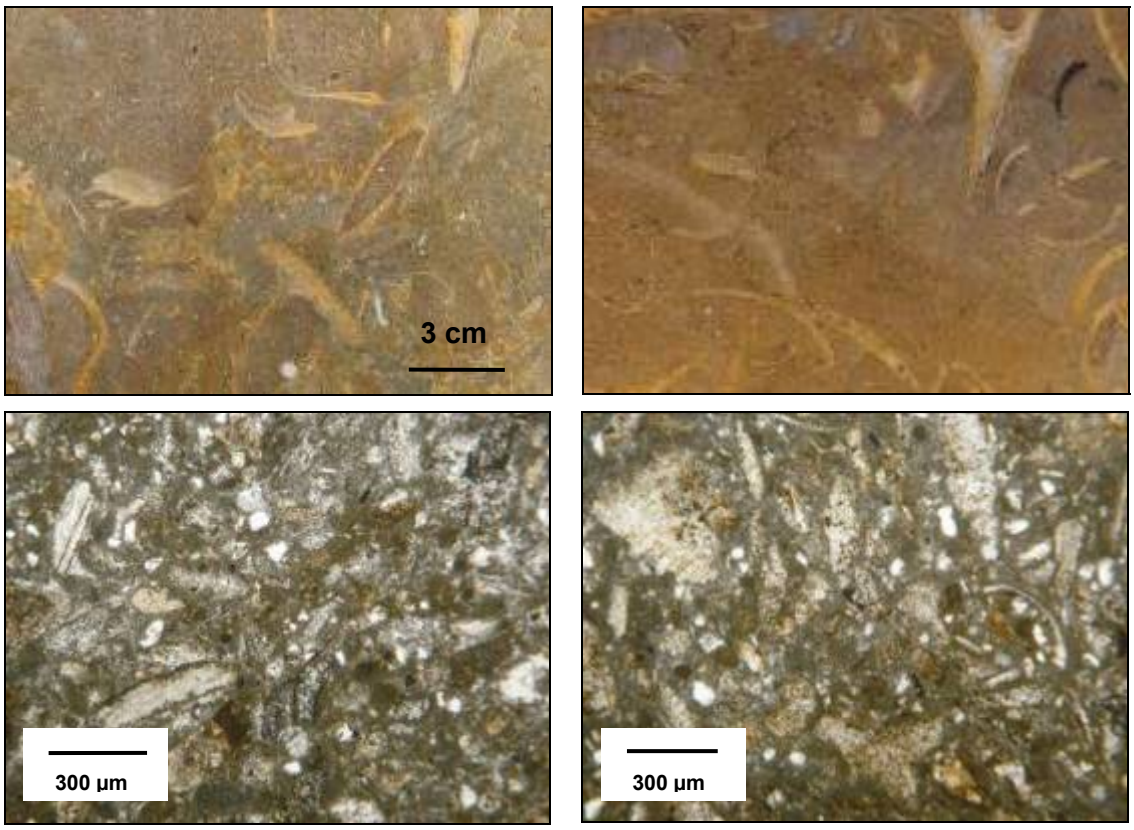


Figure 123 – Macroscopic and microscopic observations (N//) of lithofacies D: (left) sample LK01 from Lakouar outcrops; (right) sample VOL35 from Volubilis: obvious similarity of microfacies characteristics between both (notably different size clasts of bivalvia, brachiopods; micritic to microsparitic calcite matrix with smaller bioclasts and small detritic clasts of quartz and feldspars).

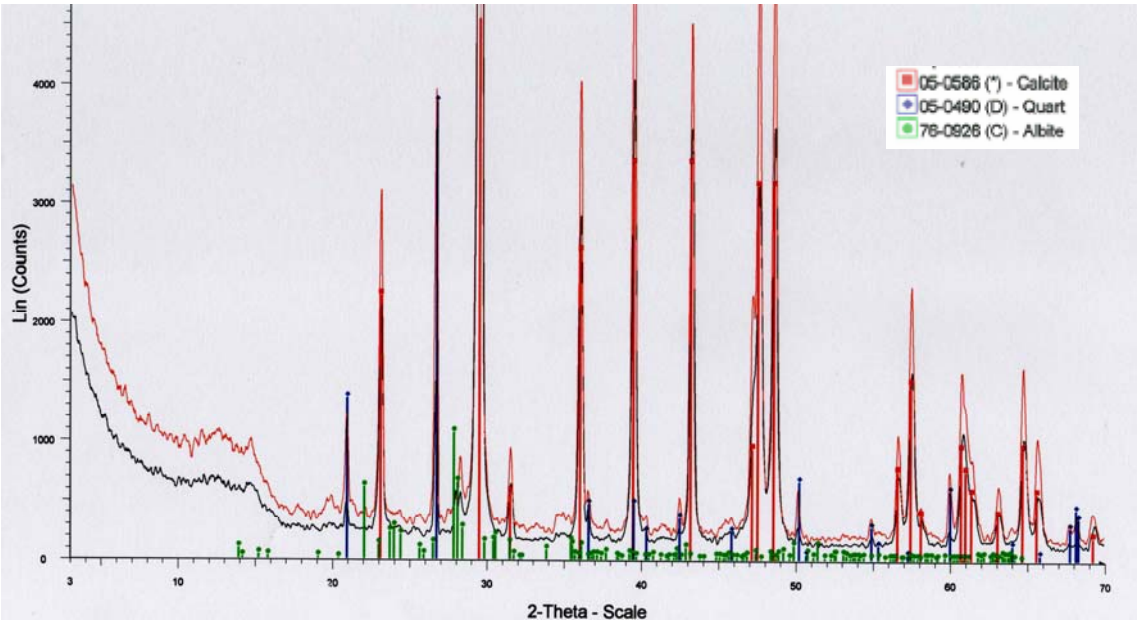


Figure 124 – Similar mineralogical qualitative analysis of the insoluble residue between lithofacies D sample from Volubilis (VOL35; red line on the graph) and sample from Lakouar outcrops (LK01; dark line) consisting mainly of calcite, quartz and albite.

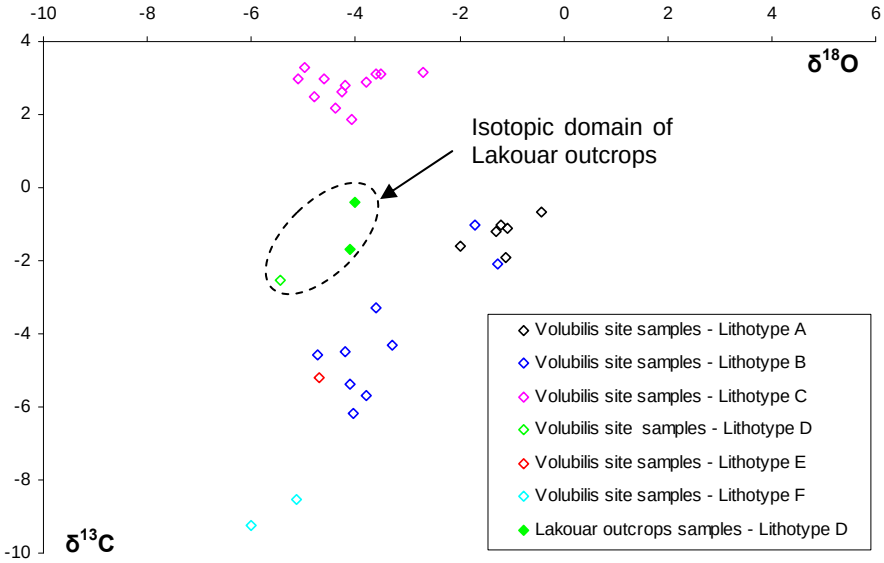


Figure 125 – Isotopic signature of the samples from Lakouar outcrops and comparison to those from Volubilis site.

On the basis of isotopic signature, the comparison of Lakouar outcrops samples to the one from Volubilis monuments (Figure 125) confirms that Lakouar outcrops is an area of provenance of Volubilis building stones belonging of the lithotype D.

Sample Reference	Petrographic description by optic microscopy	Mineralogical analysis by X-Ray Diffraction	Calcite content (%) by acid attack	Dolomite content (%) by acid attack	$\delta^{18}O$ ‰ vs PDB	$\delta^{13}C$ ‰ vs PDB	Uniaxial Compressive Strenght (MPa)	Total Water Porosity (%)	Solid Density	Bulk Density	Water Natural Saturation Degree
LK01	X	X	95.6	0.0	-4.1	-1.7	-	1.9	2.66	2.60	0.78
LK02	X	X	73.2	3.3	-4	-0.4	86.4	3.1	2.69	2.61	0.75
Av	-	-	84.4	1.7	-	-	-	2.5	2.67	2.61	0 .76

Table 23 – Analytical data measured on the two samples from Lakouar outcrops.

Sample Reference	Al_2O_3 (%)	CaO (%)	Fe_2O_3 (%)	K_2O (%)	MgO (%)	MnO (%)	P_2O_5 (%)	SiO_2 (%)	TiO_2 (%)	LOI (%)	Co (ppm)	Pb (ppm)	As (ppm)	Sr (ppm)	Zn (ppm)	B (ppm)	V (ppm)	Cr (ppm)	Ba (ppm)	Ag (ppm)	Ce (ppm)	Zr (ppm)
LK01	0.9	50.7	1.26	0.09	0.8	0.05	<0.05	3.9	0.07	41.4	<5	<10	33	440	25	<10	<10	10	14	0.3	20	31
LK02	2.8	40.7	1.86	0.54	1	0.04	<0.05	18.6	0.27	33.4	<5	<10	20	591	21	18	23	24	61	<0.2	26	175
Av	1.8	45.7	1.56	0.32	0.9	0.05	-	11.2	0.17	37.4	<5	<10	26	516	23	-	-	17	37	-	23	103

Table 24 – Analytical data measured on the two samples from Lakouar outcrops (LOI = Lost Of Ignition).

4.4.4. Volubilis bedrock

The bedrock of the archaeological site is still nowadays observable in two main areas:

⇨ Close to the modern entrance and near “Oued Fertassa” (river): because of the recovering and the remodelling of the area during the past excavations, only few outcrops are nowadays visible (Figure 126) and no significant trace of extraction was observed except weathered bedrock remains in a form of staircases and extracted blocks on the ground (Figure 127).

Figure 126 – Overview of Volubilis outcrops area near “Oued Fertassa”: recovering and remodelling of the area during past excavations works; extracted blocks on the ground.

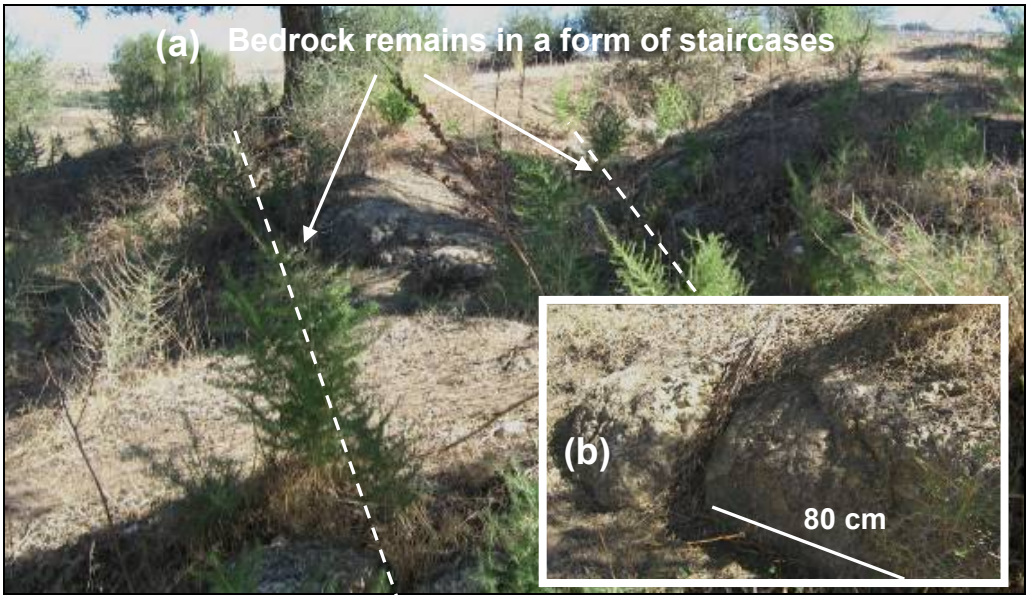


Figure 127 – View of Volubilis outcrops near “Oued Fertassa”: (a) remains of a staircase structure of the area; (b) typical weathered outcropping layer of a conglomeratic beige-yellowish macroporous travertine.

The outcrops show a more or less conglomeratic beige-yellowish macroporous travertine in the form of weathered blocks of until fifty centimetre of thickness. This geological formation is a terrestrial freshwater limestone.

⇨ At the west limit of the south part of the archaeological excavation of the site (between the bakery (9) and the Insula 25): a few outcrops are nowadays visible (Figure 128) hid by the ancient constructions and also recovered by the excavated materials. The outcrops show a highly weathered in surface conglomeratic beige limestone. This geological formation is a terrestrial (lacustrine) limestone. Two samples referenced VQ01 (Figure 129) and VQ02 were collected in the bedrock of Volubilis near “Oued Fertassa” (VQ01) and at west limit of the south part of the site (VQ02), characterised in laboratory and compared to those from Volubilis monuments.

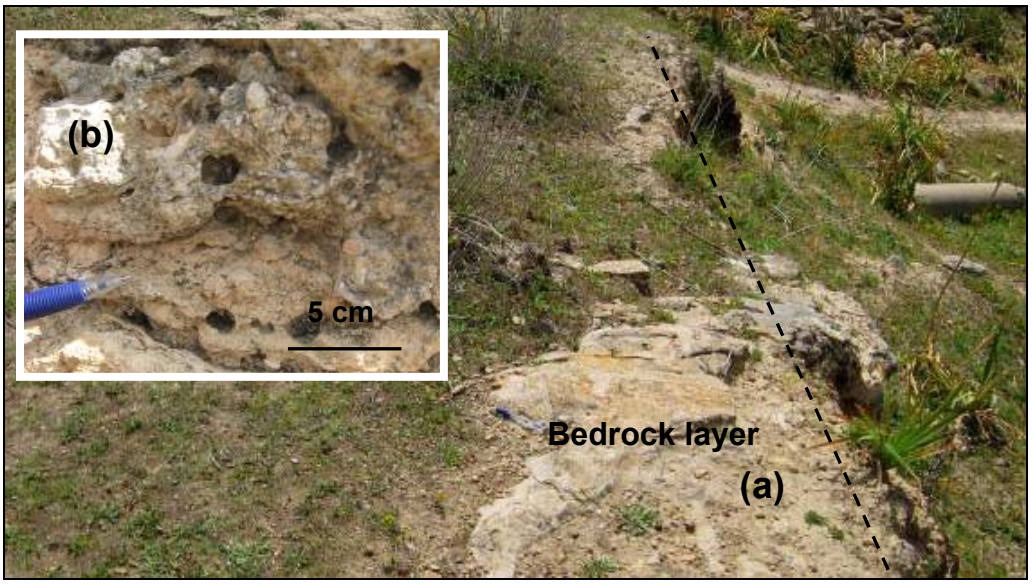


Figure 128 - View of Volubilis outcrops at the west limit of the south part of the site: (a) conglomeratic beige lacustrine limestone layer with a weathering powdered white crust; (b) highlight of the hardest elements under the weathered white surface.

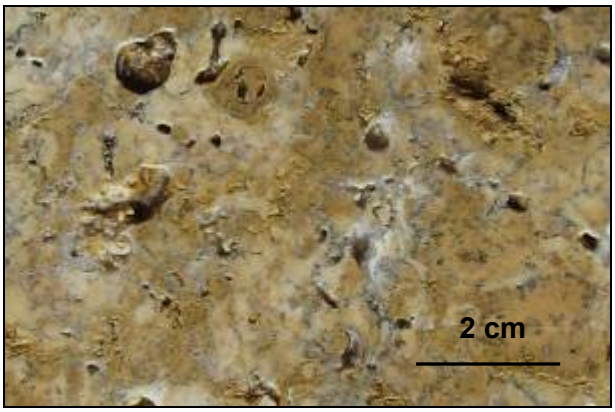


Figure 129 – Macroscopic view of conglomeratic beige-yellowish macroporous travertine (sample VQ01) from Volubilis outcrops near “Oued Fertassa”.

Based on geological settings (Faugères, 1978) these continental limestones more or less conglomeratic belong to the undifferentiated Plio-Quaternary.

By comparing macroscopic and microscopic observations, the travertines and lacustrine limestones from the Volubilis bedrock outcrops are similar to those from the site, belonging to the lithotype F “continental limestones”.

According to the analytical results (see Table 25), the stone from Volubilis outcrops corresponds to a quite hard stone with a quite low porosity (8,5%) and a medium water natural saturation degree linked to its macroporosity (average 0,69). In a mineralogical point of view, it is a rather pure carbonate (calcite content ranging from 88 to 91%) with a few percents of quartz (about 5% considering the silica proportion measured). Besides quartz, accessory minerals are mainly clay minerals (smectites and rare kaolinite). The major chemical elements of this type of stone are Calcium (about 50-51%) and Silicium (about 5%). Concerning trace chemical elements, no one is measured in significant quantity: only traces of Arsenic (32 ppm), Strontium (29 ppm), Barium (28 ppm) and Cerium (13 ppm).

On the basis of isotopic signature, the comparison of Volubilis outcrops samples to those from Volubilis monuments confirms (Figure 130) that the bed-rock of Volubilis site is an area of provenance of building stones, precisely those belonging of the lithotype F.

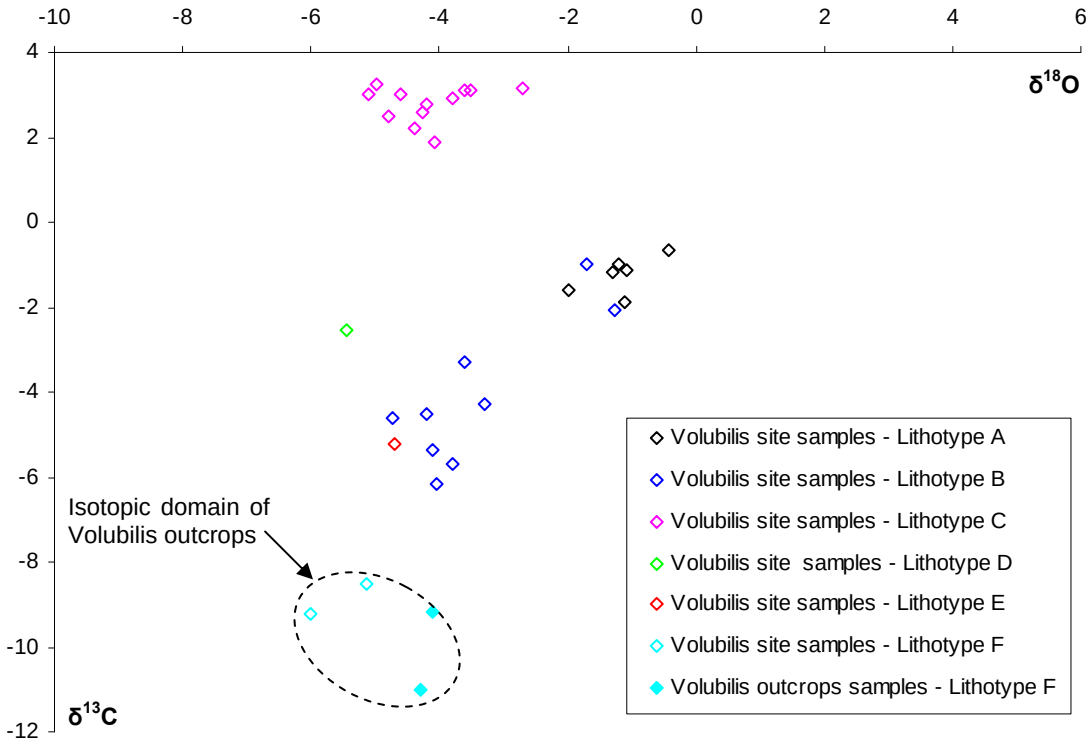


Figure 130 – Isotopic signature of the samples from Volubilis outcrops and comparison to those from Volubilis site.

Sample Reference	Petrographic description by optic microscopy	Mineralogical analysis by X-Ray Diffraction	Calcite content (%) by acid attack	Dolomite content (%) by acid attack	$\delta^{18}O$ ‰ vs PDB	$\delta^{13}C$ ‰ vs PDB	Uniaxial Compressive Strenght (MPa)	Total Water Porosity (%)	Solid Density	Bulk Density	Water Natural Saturation Degree
VQ01	X	-	90.6	0.0	-4.1	-9.2	-	8.5	2.70	2.47	0.69
VQ02	X	-	87.7	0.0	-4.3	-11.0	-	-	-	-	-

Sample Reference	Al_2O_3 (%)	CaO (%)	Fe_2O_3 (%)	K_2O (%)	MgO (%)	MnO (%)	P_2O_5 (%)	SiO_2 (%)	TiO_2 (%)	LOI (%)	Co (ppm)	Pb (ppm)	As (ppm)	Sr (ppm)	Zn (ppm)	B (ppm)	V (ppm)	Cr (ppm)	Ba (ppm)	Ag (ppm)	Ce (ppm)	Zr (ppm)
VQ01	1.2	50.3	0.94	0.08	0.3	0.04	<0.05	4.6	0.06	41.0	<5	<10	32	29	10	<10	<10	<10	28	0.4	13	<20
VQ02	1.5	51.0	0.61	0.08	0.4	< 0.02	0.06	4.7	0.08	41.2	-	-	-	-	-	-	-	-	-	-	-	-

Table 25 – Analytical data measured on the two samples from Volubilis bedrock.

4.4.5. Other outcrops

Besides Aïn Schkor quarries area, outcrops of the so-called “molassa” and marly limestones formations (Miocene, “Upper molassa” series according to Faugères, 1978) are observable in many areas near Volubilis site (less than five kilometres around): at the East of the site on the hills between Aïn Schkor and Moulay Idriss Zerhoun (Douar Ben Abdallah, Fertassa village, etc); at the south of the site on the lower part of the hills around Bou Assal village.

The outcropping areas present sometimes traces of extraction more or less doubtful due notably to weathering. Nevertheless, according to their closeness to Volubilis site and their easiness of extraction, these molassa outcrops have probably supplied some building stones (notably stone-rubbles).

Among the various surveyed areas, the sampling focused on two representative ones: Douar Ben Abdallah and Bou Assal village.

⇨ **Douar Ben Abdallah outcrops area** (Lambert coordinates: X=487,3 - Y=387,8 - Z=600): The area located near Douar Ben Abdallah about one kilometre to the south of Ain Schkor quarries includes many outcropping levels in staircases steps along the hill (Figure 131). The thickness of the outcropping layers is usually ranging from less than fifty centimetres to more than two metres.

Figure 131 – Overview of Douar Ben Abdallah outcrops area: many levels in staircases steps; detail of a cut face of the extracted stone (sample DBA01).

⇨ **Bou Assal outcrops area** (Lambert coordinates X=484.3 - Y=382.5 - Z=525m): The area located close to Bou Assal Village along the road to Moulay Idriss Zerhoun presents some exploitation traces (Figure 132) partially masked by the modern road.

Figure 132 – Views of Bou Assal outcrops and traces of extraction: cut faces and blocks almost detached.

One sample from Douar Ben Abdallah area (ref. DBA01) and three from Bou Assal area (ref. BA01 to BA03) were collected, characterised in laboratory and compared to those from Volubilis monuments.

According to the analytical results (Table 26 and Table 27), the stones from Douar Ben Abdallah and Bou Assal outcrops corresponds to quite porous stones (average porosity about 15% ranging from about 11 to 22%) with a quite low water natural saturation degree (0.65 in average).

In a mineralogical point of view, they are carbonates (calcite content about 80% in average) with a significant proportion of quartz (ranging from 10 to 38% for samples BA02 considering the silica proportion measured). Besides quartz, accessory minerals are mainly traces of clay minerals (illite, palygorskite and kaolinite). The major chemical elements are Calcium (42% in average) and Silicium (about 22% in average). Concerning trace chemical elements, the significant one is strontium (average 383 ppm); traces of Zirconium (94 ppm in average with a maximum of 208 ppm for sample BA03), Barium (46 ppm), Cerium (24 ppm), Zinc (21 ppm) and Chromium (19 ppm) are also measured. The variability of the above physical and chemical parameters illustrates that of the "upper molassa" series (so-called "molassa" and marly limestones) in general.

According to their petrographic description by optic microscope and their mineralogical composition, DBA01, BA01 and BA02 samples are similar to those from Volubilis site belonging to the lithotype B "Beige-yellowish calcarenite limestones" (so-called "molassa"). Concerning BA03 sample, it corresponds to the lithotype A "Beige-green marly limestones" found in Volubilis.

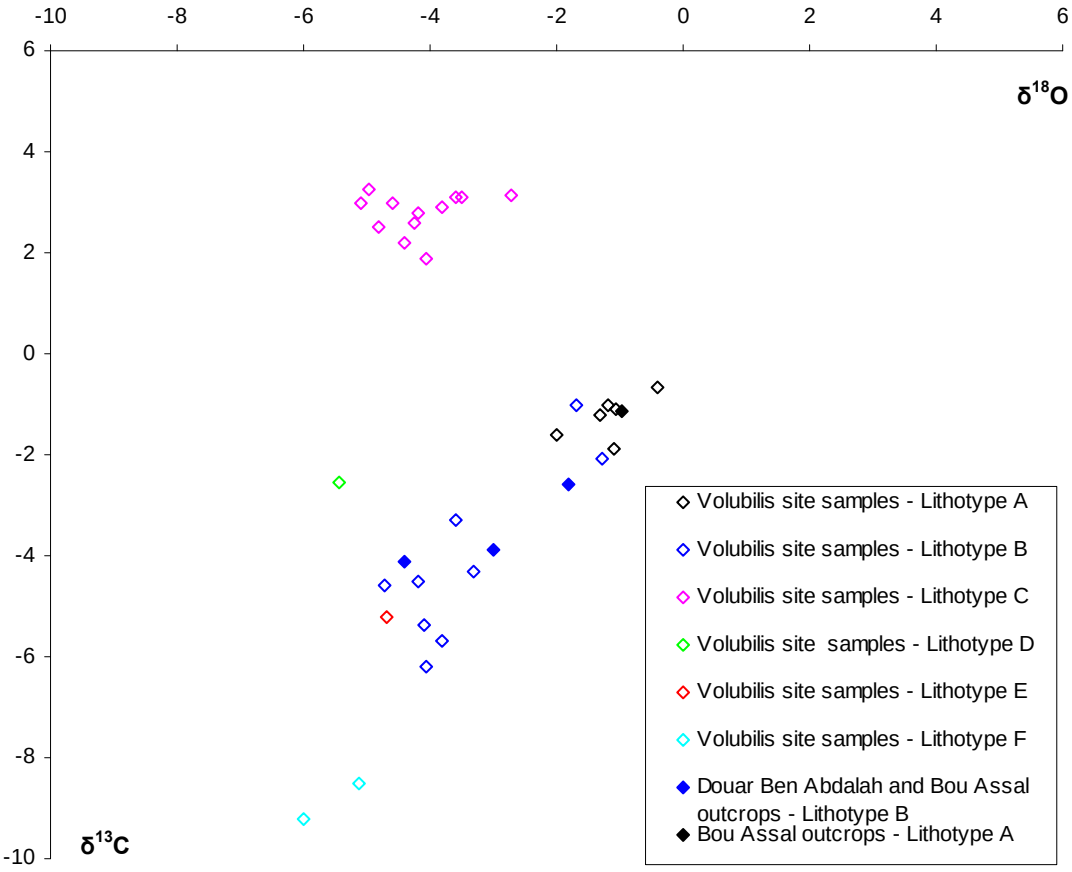


Figure 133 – Isotopic signature of the samples from Douar Ben Abdalah and Bou Assal outcrops and comparison to those from Volubilis site.

Sample Reference	Petrographic description by optic microscopy	Mineralogical analysis by X-Ray Diffraction	Calcite content (%) by acid attack	Dolomite content (%) by acid attack	$\delta^{18}O$ ‰ vs PDB	$\delta^{13}C$ ‰ vs PDB	Uniaxial Compressive Strenght (MPa)	Total Water Porosity (%)	Solid Density	Bulk Density	Water Natural Saturation Degree
DBA01	X	X	83.9	0.0	-4.4	-4.1	-	22.4	2.69	2.09	0.53
BA01	X	X	83.9	0.0	-3	-3.9	-	10.8	2.69	2.40	0.65
BA02	X	X	83.1	0.0	-1.8	-2.6	-	12.7	2.69	2.35	0.79
BA03	X	X	70.3	0.0	-1.0	-1.1	-	-	-	-	-
Min	-	-	70.3	0.0	-	-	-	10.8	2.69	2.09	0.53
Max	-	-	83.9	0.0	-	-	-	22.4	2.69	2.40	0.79
Av	-	-	79.1	0.0	-	-	-	15.3	2.69	2.28	0.65

Table 26 – Analytical data measured on the samples from Douar Ben Abdallah and Bou Assal outcrops.

Sample Reference	Al_2O_3 (%)	CaO (%)	Fe_2O_3 (%)	K_2O (%)	MgO (%)	MnO (%)	P_2O_5 (%)	SiO_2 (%)	TiO_2 (%)	LOI (%)	Co (ppm)	Pb (ppm)	As (ppm)	Sr (ppm)	Zn (ppm)	B (ppm)	V (ppm)	Cr (ppm)	Ba (ppm)	Ag (ppm)	Ce (ppm)	Zr (ppm)
DBA01	1.4	47.0	0.45	0.44	0.3	<0.01	0.31	12.1	0.06	37.5	<5	<10	<20	247	15	<10	<10	10	31	<0.2	14	27
BA01	1.2	44.9	0.93	0.39	0.4	<0.01	0.41	13.4	0.06	36.9	<5	<10	20	312	23	11	<10	13	30	<0.2	19	35
BA02	1.8	38.0	0.67	0.46	0.5	<0.01	0.57	25.5	0.14	31.2	<5	<10	22	439	20	20	<10	14	44	0.6	29	106
BA03	2.4	36.9	1	0.9	1	0.01	0.9	38.5	0.23	-	5	13	<20	533	24	39	17	37	77	<0.2	35	208
Min	1.2	36.9	0.45	0.39	0.3	0.01	0.31	12.1	0.06	31.2	-	-	-	247	15	-	-	10	30	-	14	27
Max	2.4	47.0	1	0.9	1	0.01	0.9	38.5	0.23	37.5	5	13	22	533	24	39	17	37	77	0.6	35	208
Av	1.7	41.7	0.76	0.55	0.5	0.01	0.55	22.4	0.12	35.2	-	-	-	383	21	-	-	19	46	-	24	94

Table 27 – Analytical data measured on the samples from Douar Ben Abdallah and Bou Assal outcrops.

On the basis of isotopic signature, the comparison of both outcrops samples to those from Volubilis monuments confirms (Figure 133) that these other “Upper molassa” areas could have provided Volubilis building stones belonging of the lithotypes A (beige-green marly limestones) and B (beige-yellowish calcarenite limestones so-called “molassa”).

5. Conclusion

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

Concluding about **ornamental stones**, a quite very limited amount of decorative stones and marble *s.s species* was observed *in situ* or accumulated as roving materials. All of the *in situ* detected marbles and other decorative stones were located in five buildings: House of the Ephebe, Palace of Gordian, Bath of Gallienus, House of Venus and House of Orpheus. In most cases they are in the form of small tiles or slab-fragments embedded in the mortar of floors and walls used for fixing prefabricated marble/mosaic panels.

Some other decorative stones and marbles objects are coming from the storeroom of Volubilis (erratic slab-fragments of white or colored marbles collected on the ground since the archaeological excavation until now by visitors and mainly by guardians) and the Archaeological Museum of Rabat (one column and a few statues of white marbles).

As shown in Figure 134, although the imported stones and marbles in Volubilis are not present anymore in big quantities, the research revealed a significant relationship among this important Roman town of North-West Africa and the most famous marbles source areas of the central and eastern Mediterranean basin.

Four colored marbles *s.l.* belonging to the classical *marmora* used by Romans in the whole Mediterranean Basin were identified: Cipollino verde *(marmor carystium*) from Karystos (island of Eubea), Rosso antico (*marmor taenarium*) from the Mani peninsula; Verde antico (*marmor thessalicum*) from Larisa, Breccia di settebasi (*marmor scyreticum*) from the island of Skyros.

One other colored stone (a fossiliferous pinkish limestone), probably the most common decorative stone of the site, was found. Its provenance is still unknown, but a local-Moroccan origin is presumed since its use was observed in modern buildings.

Among the marbles *s.s.* identified in Volubilis, three categories were distinguished: white and pale grey marbles, grey striped and stained ones and a pinkish one:

→ Concerning white and pale grey marbles, the statues studied are sculpted in two fine-grained classical white marbles very appreciated and largely distributed during the Roman age: the *lunense* marble from Carrara (Italy) and the *pentelic* marble from Mount Pentelikon (Athens – Greece). Among the white marbles used for slab and architectural elements of Volubilis, besides the *pentelic* marble, four other marbles were identified: the dolomitic variety of the *Thasian* marble from the district of Vathy

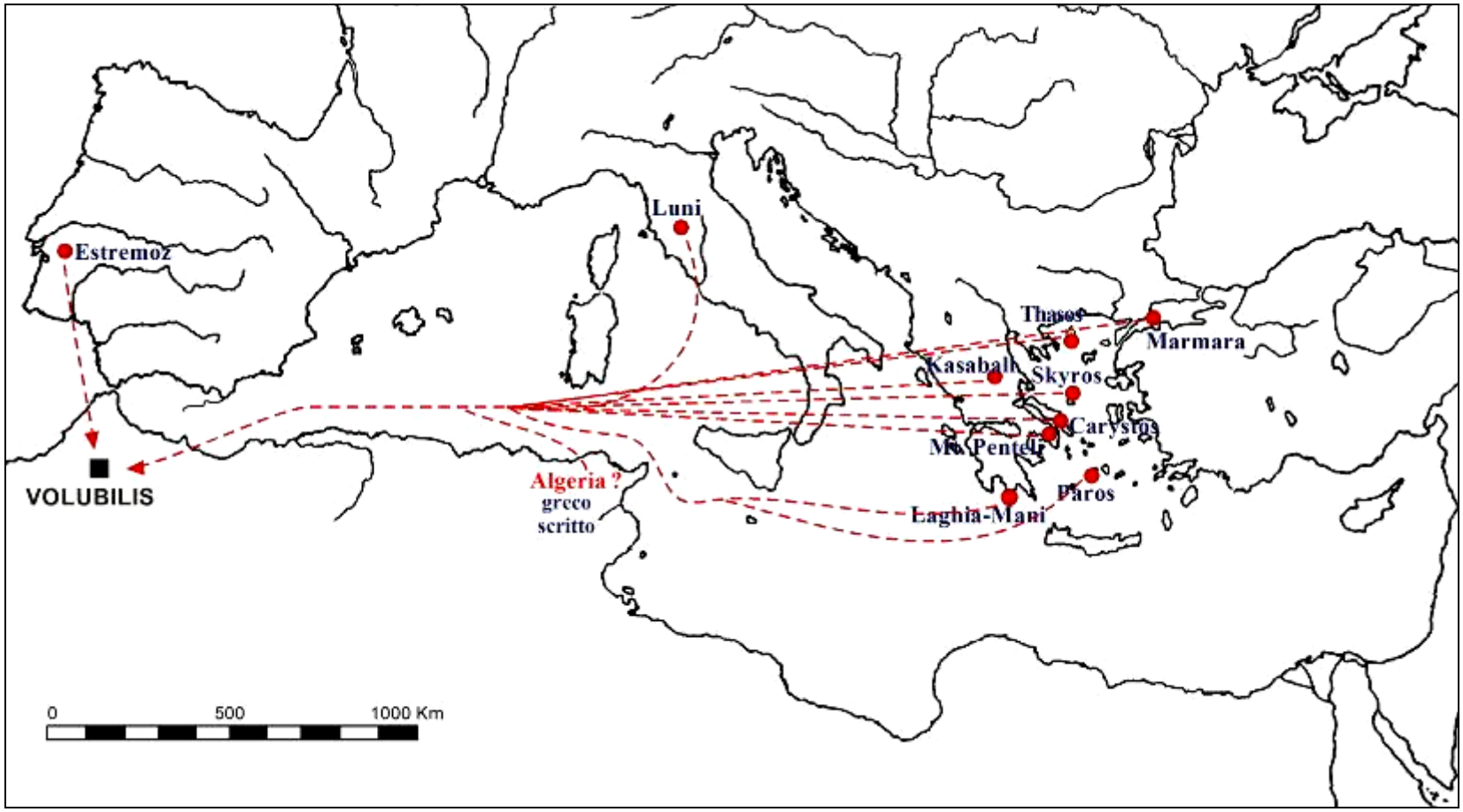


Figure 134 - Provenance of the imported white and colored marbles of Volubilis.

(island of Thasos - Greece), the *Parian* marble from Lakkoi (island of Paros, Cyclades - Greece), the *Proconnesian* marble from the island of Marmara (Turkey) and one unknown white fine-grained marble (most probably having a local origin).

→ About grey-striped or stained marbles quite abundant in the form of slabs, they macroscopically look like the type called "*greco scritto*" from Cap de Garde quarry (Annaba - Algeria), a graphitic medium-coarse grained marble with a white background drawn by thin grey-blackish veins or dark grey to bluish stains. Nevertheless, their petrographic parameters and isotopic compositions do not match with those measured for the classical Algerian *"greco scritto"* expressly sampled in the ancient quarry of Cap de Garde.

→ Concerning pinkish marbles, a stele dedicated to Venus and slab fragments were identified corresponding to the so-called *Portuguese pink*, an Hercynian marble outcropping at Vilaviçosa in the Estremoz Anticline (Portugal).

Concluding about **building stones**, the systematic survey of each monument completed by petrographic-mineralogical characterisation and chemical analyses permitted to identify and classify the building stones of Volubilis into six main categories (referenced A to F). Therefore, the relative importance and the use of each of the six lithotypes was estimated and discussed.

As regards their relative importance of use, the lithotypes B and C are the most largely ones used as building stones on Volubilis site, representing over 90% of the total volume of building stones:

→ Lithotype B is a beige-yellowish calcarenite limestone (so-called molassa). Distributed on almost the whole of the monuments in a proportion ranging from 60 to 80%, it represents about 60% of the total volume of the building stones of Volubilis. In terms of uses, it is present as masonry stone-rubbles and linked to a relative softness as various carved and sculpted elements (column, chapiters…).

→ Lithotype C is a grey massive limestone representing about 31% of the total volume of the building stones of Volubilis. Distributed on the whole of the monuments in a proportion ranging from 5 to 20%, this hard stone is the only component of five public monuments (Capitol, Basilica, Public Fountain, Triumphal Arch and Door of Tangier). It is mainly used as architectonic elements as jamb, lintels, column and others structure carved blocks of significant size according to its mechanical strength. It is also observable as masonry stone-rubbles in limited proportion.

The four other lithotypes A, D, E and F are observable in a very low proportion representing less than 10% of the total volume of the building stones of Volubilis. Between those minor facies, lithotypes A and D seems to be slightly more represented.

→ Lithotype A is a beige-green marly limestone. Representing less than 3% of the total volume of building stones, it is distributed on almost the whole of the monuments in proportion ranging from less than 1% to 7%. In terms of uses, the marly limestone is

present as medium-sized carved (and sometimes sculpted) architectonic elements (facilitated by their softness but at the origin of their important decays). It is also observable as masonry stone-rubbles in very limited proportion.

→ Lithotype D is an ochre-grey limestone rich in bivalvia and represents less than 3% of the total volume of building stones. It is distributed on almost the whole of the monuments in a proportion ranging from less than 1% to 10% and seems to be more represented in the monuments from the south and west parts than those from the north part. It is only present on the site as masonry medium-sized stone-rubbles.

→ Lithotype E is a coarse dolomite representing less than 2% of the total volume of building stones. It is distributed on almost the whole of the monuments in a proportion ranging from less than 1% to 5%. It is used mainly as masonry stone-rubbles. Many larger-sized blocks are also used as basement elements.

→ Lithotype F gathers together various continental limestones more or less conglomeratic (including travertines) of undifferentiated Plio-Quaternary age that represent about 1.5% of the total volume of building stones. They are distributed mainly on monuments from the medium part (south and west) of the site and almost absent in the north part. Their proportion ranges from less than 1% to 5%, except the Mausoleum for which it represents 80%. It is used as masonry stone-rubbles sometimes large-sized (notably travertine limestones) and also as basement elements.

After identifying the lithotypes of building stones of Volubilis, the search of their quarries of provenance was carried out, based on available bibliographic data and geological settings, then by sampling and in-laboratory characterisation of samples. Two main ancient quarries areas were located respectively near Aïn Schkor hill and on the upper part of Moulay Idriss Zerhoun city. Various outcrops were also investigated near Lakouar and Bou Assal villages, around Douar Ben Abdallah hill and also on the site of Volubilis itself. The considered quarries and outcrops are located in a five kilometres sector around Volubilis site as shown in Figure 135. Their lithotypes were then compared to those (referenced A to F) from Volubilis ancient site:

→ Lithotypes A and B present as building stones in Volubilis correspond to the “Upper molassa” formation (Miocene). Those lithotypes were observed especially in the extensive and hilly area called “Aïn Schkor”, enclosing numerous small to medium-sized quarries with indubitable trace of ancient extraction. They were also encountered in other outcrops showing more doubtful traces of quarrying altered by dissolution (Douar Ben Abdallah, Bou Assal).

→ Lithotype C was encountered in the upper part of Moulay Idriss Zerhoun city, in the Middle Liasic (Domerian) geological formation called “Bedded limestones”. In this large area of quarrying, various ancient architectonic elements remain (sculpted blocks, column fragments, frequent traces of wedges, etc). Despite their hardness, the extraction of these limestones was facilitated by the stratification parallel to the slope and the thickness of strata (0.5 to 1m).

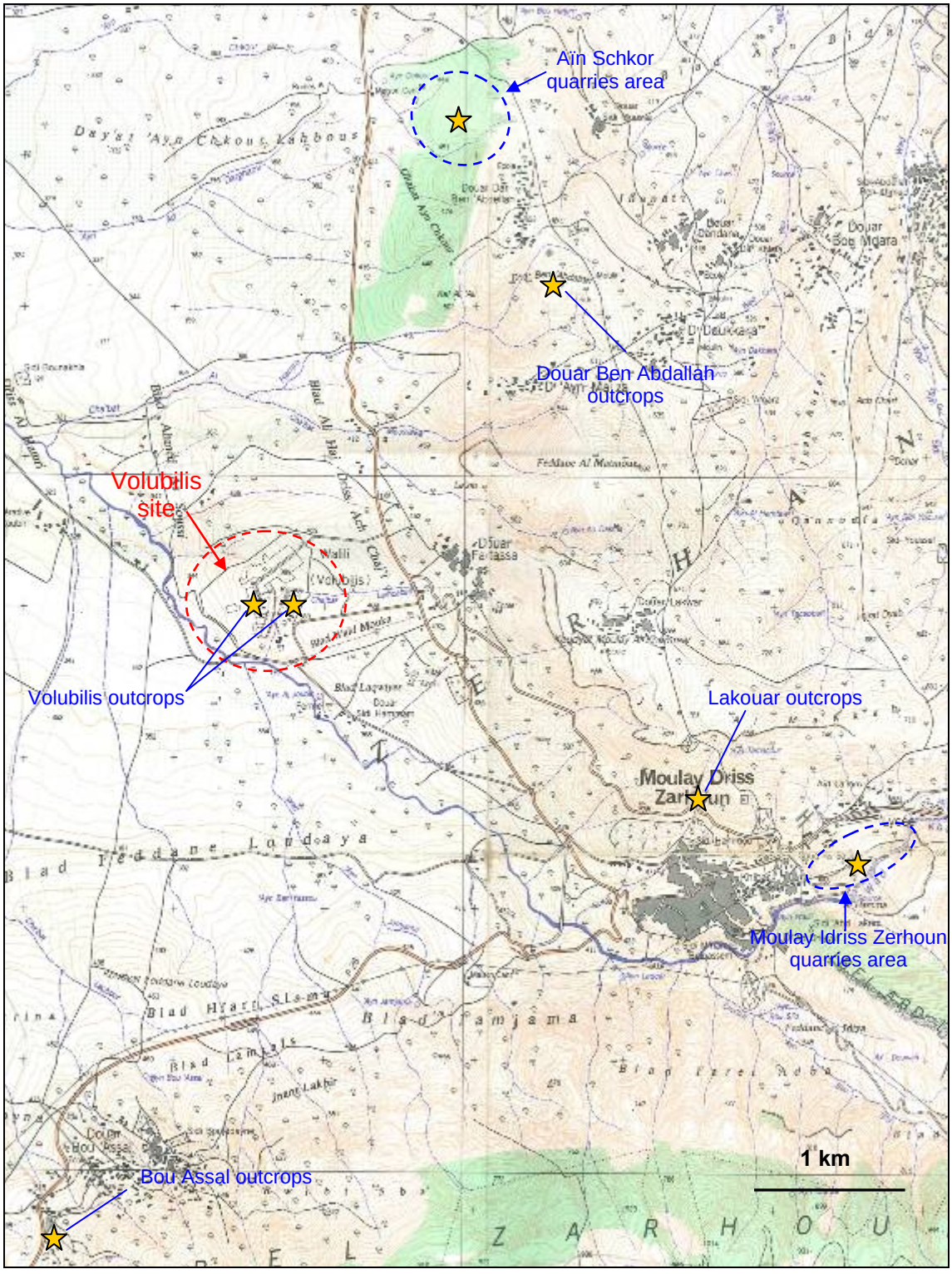


Figure 135 – Location map of ancient quarries of building stones of Volubilis and others considered outcrops.

→ Lithofacies D was observed in various outcrops closed to « Lakouar » village. The corresponding formation (Upper Lias, Lower Bajocian) shows an alternance of ochre-grey limestone rich in bivalvia strata (0.1 to 0.4m of thickness) and marl layers. The outcrops show locally excavated area used to supply stone-rubbles. The extraction as stone-rubbles was facilitated by the topography (side of a hill), the thickness and the slope of the layers and as a consequence no significant trace of extraction is observable.

→ Provenance of lithofacies E (coarse dolomites - present in very low quantity at the ancient site) was not yet precisely determined.

→ Lithofacies F (various continental limestones including travertines) correspond to the bed-rock of Volubilis site itself (Upper Pliocene). Usually covered by ancient constructions or excavation products, only few outcrops are nowadays visible. No significant trace of extraction was observed except weathered bedrock remains in a form of staircases and extracted blocks on the ground.

In final conclusion, the present study tried globally successfully to identify the stones of Volubilis and determine their provenance areas (Table 28). Besides the accomplishment of this objective, the whole of the gained data constitutes a knowledge improvement available for further investigations and studies dealing with archaeology and conservation of the ancient site. Not undertaken in the framework of this project, future archaeological studies for example could focus on the relationship between spatial distribution of the types of stones and periods of constructions.

Lithotype observed on Volubilis		Use of the lithotype as building stone on the whole site			Reference quarries and outcrops of provenance of the lithotype	
Ref.	*Simplified designation*	*Proportion (%)*	*Types of use*	*Distribution in the monuments*	*Name*	*Geological formation and age*
A	**Beige-green marly limestones**	2.6	Medium-sized carved (and sometimes sculpted) architectonic elements Masonry stone-rubbles in very limited proportion	1-7% in almost all monuments	Aïn Schkor quarries area	Upper molassa, Miocene
B	**Beige-yellowish calcarenite limestones (so-called "molassa")**	60.2	Masonry stone-rubbles and various carved and sculpted elements (column, chapiters…)	60-80% in all monuments	Aïn Schkor quarries area, Douar Ben Abdallah and Bou Assal outcrops	Upper molassa, Miocene
C	**Grey massive limestones**	31.4	Architectonic elements (jamb, lintels, column, carved blocks of significant size Masonry stone-rubbles in limited proportion	100% in Capitol, Basilica, Public Fountain, Triumphal Arch and Door of Tangier, 5-20% in other monuments	Moulay Idriss Zerhoun quarries area	Bedded limestones, Middle Lias (Domerian)
D	**Ochre-grey limestones rich in bivalvia**	2.6	Masonry medium-sized stone-rubbles only	1-10% in almost all monuments More present in south and west parts	Lakouar outcrops	Grey marls and sandy limestones, Upper Lias (Bajocian)
E	**Coarse dolomites**	1.7	Masonry stone-rubbles mainly Many larger-sized blocks also used as basement elements.	1-5% in all monuments	Indeterminate	Indeterminate
F	**Continental limestones**	1.5	Masonry stone-rubbles sometimes large-sized Basement elements.	80% in Mausoleum 1-5% in all other monuments	Volubilis bedrock	More or less conglomeratic limestones, undifferentiated Plio-Quaternary

Table 28 – Results synthetic restitution of Volubilis building stones study.

6. References

Bouzidi R. (2001) - Recherches archéologiques sur le quartier du tumulus (Volubilis), Thèse de doctorat de 3ème cycle de l'Institut National des Sciences de l'Archéologie et du Patrimoine, Rabat.

Chalouan, A., Galindo-Zaldívar, J., Bargach, K., Ruano, P., Akil, M., Chabli, A., Jabaloy, A., Ahmamou, M. et Sanz de Galdeano, C. (2003). Evolution tectonique du front de la Chaîne du Rif et de son avant-pays Meseto-Atlasique dans un modèle d'un coin expulsé vers le SW**.** *Third Regional Commitee on Atlantic Neogene Stratigraphy Congress*. 19-25 Septiembre, Tetuán (Marruecos).

Chatelain L. (1916). Les fouilles de Volubilis (Ksar-Faraoun, Maroc). BCTH, p. 70-92.

Chatelain L. (1938). Les origines des fouilles à Volubilis. PSAM 3, p. 5-9.

Chatelain L. (1938). L'arc de triomphe de Caracalla'. PSAM 3, p. 11-21.

Craig H. (1957). Isotopic standards for carbon and oxygen and correction factor for mass-spectometric analyses of carbon dioxide. Geochim Cosmochim. Acta, 12, 133-149.

Dunham R.J. (1962). Classification of carbonate rocks according to depositional texture. In W. E. Hamm (Ed.), *Classification of carbonate rocks*. *Am. Assoc. Petrol. Geol. Mem. 1*, 108-121.

Etienne R. (1950). Les carrières de calcaire dans la région de Volubilis (Maroc). BCTH, p. 23-32.

Euzennat M. (1957). L'archéologie marocaine de 1955 à1957. BAM 2, p. 199-229.

Euzennat M. (1960). L'archéologie marocaine de 1958 à 1960. BAM 4, p. 559.

Faugères J.C (1978). Les rides sud-rifaines. Evolution sédimentaire et structurale d'un bassin atlantico-mésogéen de la marge africaine. Thèse doct. Etat, Univ. Bordeaux I 480p.

Feray G., Paskoff R. (1960). Volubilis: quelques observations sur l'origine et l'altération des matériaux de construction. B.A.M., tome IV, 481-487.

Feray G., Paskoff R. 1966). Recherches sur les carrières romaines des environs de Volubilis. B.A.M., tome VI, 279-300.

Folk, R. L. (1959). Practical petrographic classification of limestone types. *Bull*. *Am. Assoc. Petrol. Geol.* 43, 1-38.

Folk, R. L. (1962). Spectral subdivision of limestone types. In W. E. Hamm (Ed.), *Classification of carbonate rocks*. *Am. Assoc. Petrol. Geol. Mem. 1*, 62-84.

Gnoli R. (1988). Marmora Romana. Ed. Dell'Elefante, 289 p.

Gnoli R., Ortolani G. And Pensabene P. (1989) – Marmi antichi. Ed. De Luca, Roma, 319 p.

Gorgoni C., L. Lazzarini, P. Pallante, B. Turi (2002). An updated and detailed mineropetrographic and C-O stable isotopic reference database for the main Mediterranean marbles used in antiquity. In J.J.Herrmann, N.Herz, R.Newman (eds).

Jodin A. (1987). Contribution à l'étude des civilisations du Maroc antique préclaudien. Centre nationale de la recherche scientifique, Paris.

Jodin A. (1972). Remarques sur la pétrographie de Volubilis. BAM 8, p. 127-177.

Lapuente P., Turi B. (1995). Marbles from Portugal: petrographic and isotopic characterization. *Science and technology for cultural heritage,* 4 (2), 33-42.

Lazzarini L., Moschini G. and Stievano A. (1980). A contribution to the identification of Italian, Greek and Anatolian marbles through a petrographical study and the evalution of Ca/Sr ratio, *Archaeometry*, 22, 173-183.

Lazzarini L. (2006) – I marmi colorati della Grecia Antica. Ed. Fabrizio Serra, Pisa, Roma, 285 p.

Luquet A. (1964) - Volubilis, Restauration du Capitole. BAM 5, p. 351-356

Luquet A. (1967) - La basilique judiciaire de Volubilis. BAM7, p. 407-442.

McCrea J.M. (1950). On the isotopic chemistry of carbonates and a paleotemperature scale. *Journal of Chemistry and Physics.* 18, 849-857.

Moens L., Roos P., De Rudder J., De Paepe Van Hende J., Waelkens M. (1988). A multi-method approach to the identification of white marbles used in ancient artefacts, in N. Hertz & Waelkens M. (eds), "*Classical Marble: Geochemistry, Technology, Trade"*, NATO ASI series, 153, 243-250.

Moens L., De Paepe P., Waelkens M., (1992). Multidisciplinary research and cooperation: keys to a successful provenance determination of white marble, in M. Waelkens, N. Herz, L. Moens (eds), "*Ancient Stones: Quarrying, Trade and Provenance"*, *Acta Archaeologica Lovaniensia,* Monographiae 4, Leuven University Press, 247-255.

Pensabene P. And Lazzarini L. (editors) (2006). I marmi colorati della Roma imperiale. Ed. Marsilio, Venezia, 643 p.

Rapport SCP (1996). Synthèse géologique, géophysique et pétrolieres des rides prérifaines. Office national des Recherches et d'Exploitation Pétroliers (ONAREP).

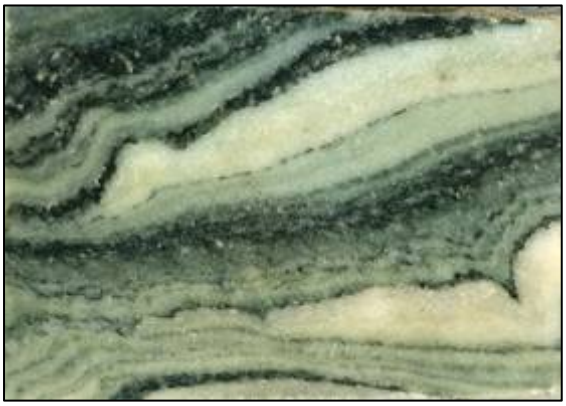
Scolari G., Lille R. (1973) - Nomenclature et classification des roches sédimentaires. *Bull. B.R.G.M.* n°2, IV, 125 p.

Appendix 1 - Files of imported colored marbles identified in Volubilis

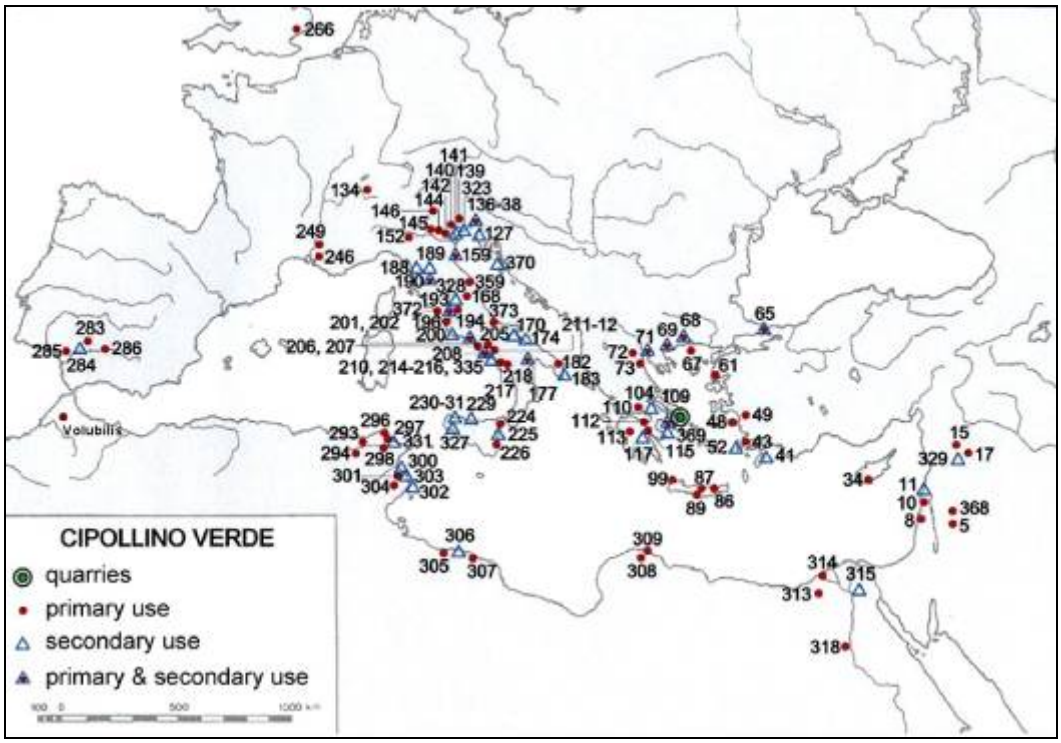
MARMOR CARYSTIUM

or MARMOR STYRIUM

or *CIPOLLINO VERDE*



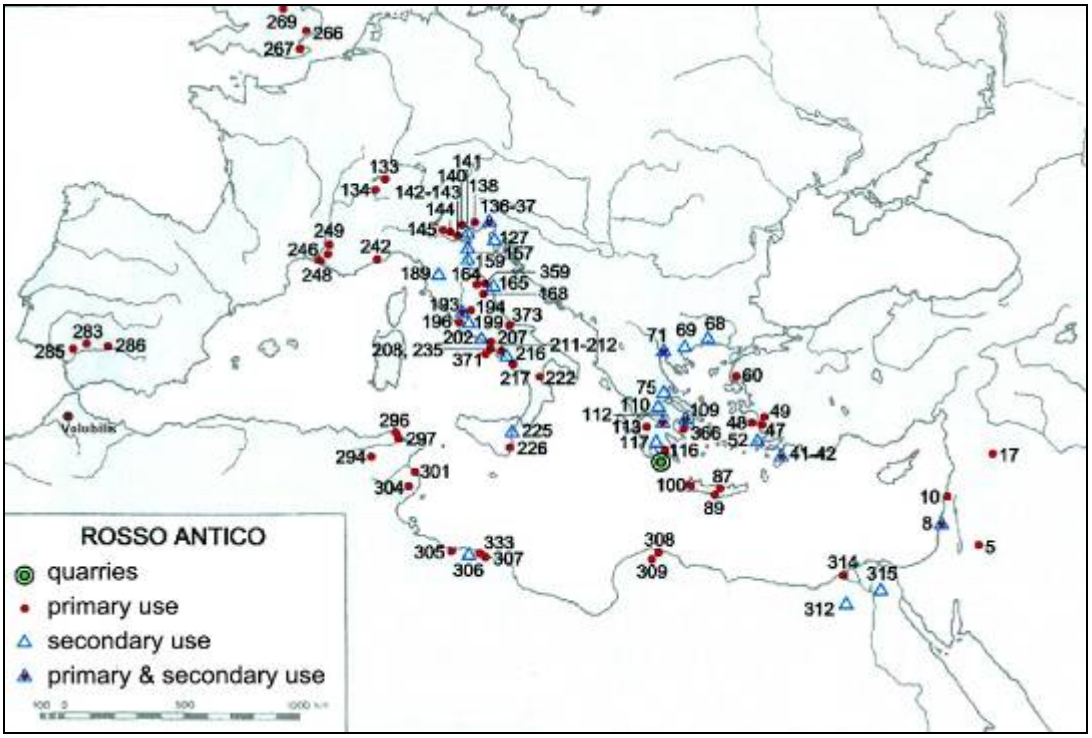
PETROGRAPHIC CLASSIFICATION	Impure chlorite-marble
ASPECT	Light green or gray background with veins of similar darker colors. The schistosity may be straight or wavy.
QUARRY LOCALITY	Southern Euboea, in the Styra-Karystos area (Mount Ochi).
PERIOD OF USE	Imported to Rome at the beginning of the I century B.C.; distributed in the whole Empire, especially in the Hadrianic-Antonine periods; quarried also in the Early Byzantine period.
TYPOLOGY OF USE	Columns. Facing slabs in walls and floors, sculptures and tubs.



MARMOR TAENARIUM

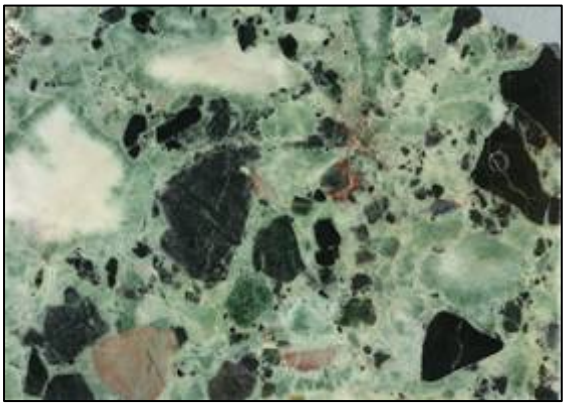
or ROSSO ANTICO

PETROGRAPHIC CLASSIFICATION	Impure hematite-marble
ASPECT	There exist several varieties with uniform dark-to-pale red or with white-grey patches, stains, veins, sometimes with thin black veins.
QUARRY LOCALITY	Mani Peninsula. Various localities: Paganea, Prophitis Elias, Kokkinoghia, Laghia, Mianes.
PERIOD OF USE	First use in the Minoan times (M. M. III ≅1700 B.C.), then from the Ist century B.C. on. Much sought during the Middle Ages and later on for its purplish color.
TYPOLOGY OF USE	Statuary, especially of Dyonisiac subject, wall and floor facing, cornices, columns and chapiters.

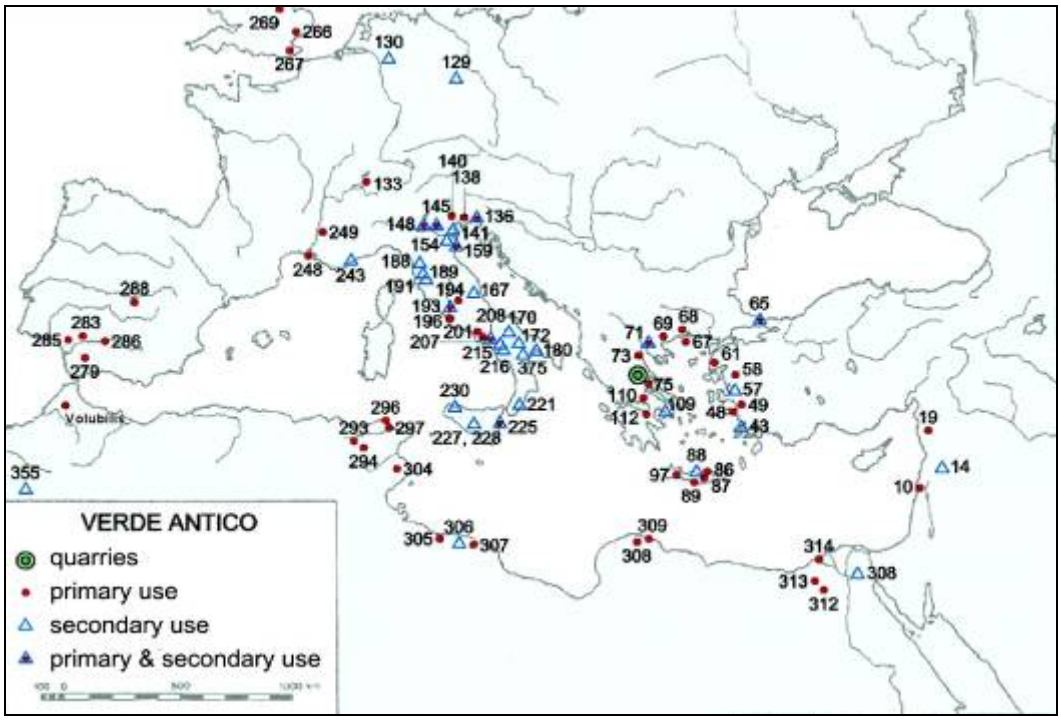


MARMOR THESSALICUM

or VERDE ANTICO



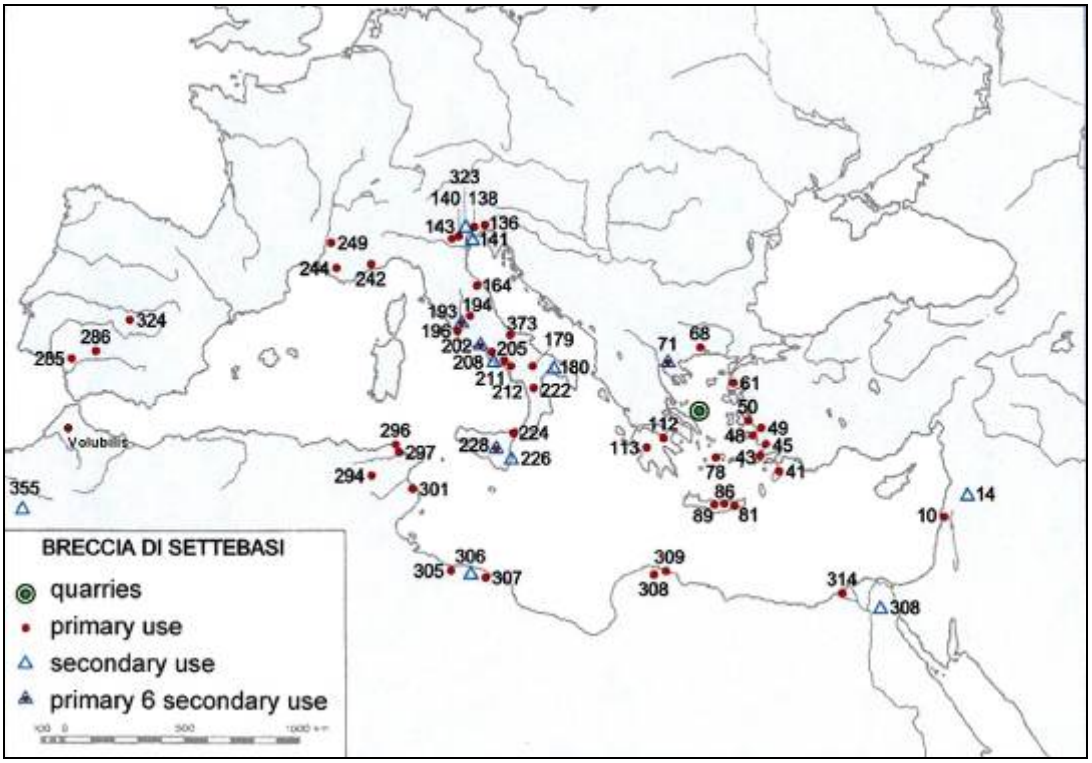
PETROGRAPHIC CLASSIFICATION	Ophicarbonate breccia with black-antigorite and white-calcite clasts.
ASPECT	Emerald-green background with dark-green/black and white, sometimes grey stains.
QUARRY LOCALITY	Mount Mopsion, North-East of Larisa, Thessaly
PERIOD OF USE	Quarried starting from the II century AD till the Middle Byzantine.
TYPOLOGY OF USE	Columns, wall and floor facing, tubs, sarcophagi, baptismal fonts, altar table tops.



MARMOR SCYRETICUM

or BRECCIA DI SETTEBASI

PETROGRAPHIC CLASSIFICATION	Calcareous metaconglomerate (breccia)
ASPECT	Brown or white background with polichrome clasts (red, pink, brown and yellow).
QUARRY LOCALITY	Various localities in the islands of Skyros (Aghios Panteleimon, Treis Boukes, Kourisies), Valaxa and Reulia.
PERIOD OF USE	Introduced to Rome in the Ist century B.C., used until the IV century AD.
TYPOLOGY OF USE	Wall and floor facings, columns, more rarely for statuary and tubs.



LIST OF THE LOCALITIES REPORTED ON THE PREVIOUS MAPS

1. St. Caterine (Sinai)
2. Ascalona (Ascalon)
3. Petra
4. Col.Nova Traiana (Bosra)
5. Gerasa (Jerash)
6. Col. Aelia Capitolina (Jerusalem)
7. Philadelphia (Amman)
8. Caesarea Maritima
9. Ake Ptolemais (Akko)
10. Tyrus (Tyre)
11. Sidon
12. Berytus (Beirut)
13. Byblos
14. Damascus
15. Heliopolis (Baalbek)
16. Aradus (Aruad)
17. Hadrianopolis (Palmira)
18. Emesa (Hama)
19. Apamea Syriae
20. Laodicea Syriae (Latakia)
21. Antiochia (Antioch)
22. Anazarbo
23. Hierapolis Castabala
24. Mopsuestia (Yakapinar)
25. Adana
26. Tarsus
27. Diocesarea (Uzuncaburç)
28. Seleucia (Silifke)
29. Anemurium (Anamur)
30. Salamina (Cyprus)
31. Kition
32. Amathus
33. Kirynia (Kirenia)
34. Kourion
35. Paphos
36. Side
37. Aspendos (Belkis)
38. Perge (Murtana)
39. Attalea (Antalya)
40. Myra (Demre)
41. Ialysos (Rodes)
42. Rhodus
43. Kos
44. Halicarnassus (Bodrum)
45. Iasos (Kiyikislacik)
46. Hierapolis (Pamukkale)
47. Miletos (Balat)
48. Pitagorion (Samos)
49. Ephesus
50. Teos (Sigacik)
51. Kios
52. Patmos
53. Smyrna (Izmir)
54. Sardis (Sart)
55. Magnesia ad S. (Manisa)
56. Tyatira (Akhisar)
57. Phokaea (Focea)
58. Pergamum (Bergama)
59. Mitilenae (Lesbos)
60. Assos (Behramkale)
61. Alexandria Troas (Eski Istanbul)
62. Ilion (Truva)
63. Cyzicus (Erdek)
64. Prusa ad O. (Bursa)
65. Constantinopolis (Istanbul)
66. Neapolis Macedoniae (Kavala)
67. Thasos (Is. di Taso)
68. Philippi
69. Amphipolis
70. Olinthus
71. Tessalonica (Salonika)
72. Beroea (Veria)
73. Dion
74. Larissa (Larisa)
75. Pyrasos (Nea Anchialos)
76. Tinos
77. Delos
78. Paros
79. Naxos
80. Itanos (Crete)
81. Praisos
82. Ierapitna (Ierapetra)
83. Lyktos
84. Inatos
85. Priansos
86. Chersonesos (Cherson)
87. Knossos
88. Candia (Iraklion)
89. Gortina (Gortyn)
90. Zaros
91. Lebena (Lendas)
92. Matala
93. Eleutherna
94. Soulia
95. Rhithymna (Rethimno)
96. Kydonia (Chania)
97. Keraia
98. Diktynnaion
99. Kysamos (Kasteli)
100. Polyrrenia
101. Makryialos
102. Lenke
103. Phalasarna
104. Delfi (Delphos)
105. Tebae (Thyva)
106. Skyros
107. Volos
108. Calcide
109. Atene (Athens)
110. Hosios Loukas
111. Egina
112. Corinthus (Corinth)
113. Olimpia
114. Nauplia
115. Argos
116. Sparta
117. Mistrà
118. Ghitio
119. Parga
120. Dyrrachium (Durres)
121. Salona (Split)
122. Traù (Trogir)
123. Sebenico
124. Zara
125. Pola
126. Rovinium (Rovigno)
127. Parentium (Parenzo)
128. Praga (Prague)
129. Magdeburgo
130. Aquisgrana (Aachen)
131. Treviri (Trier)
132. Ingelheim
133. Col. Aventicum (Avenches)
134. Orbe-Bosceaz
135. Tergeste (Trieste)
136. Aquileia
137. Grado
138. Iulia Concordia (Portogruaro)

139. Opitergium (Oderzo)
140. Altinum (Quarto d'Altino)
141. Venezia (Venice)
142. Patavium (Padua)
143. Ateste (Este)
144. Vicetia (Vicenza)
145. Verona
146. Tridentum (Trento)
147. Sirmione
148. Brixia (Brescia)
149. Mediolanum (Milan)
150. Monza
151. Augusta Taurinorum (Turin)
152. Ticinum (Pavia)
153. Mantua (Mantua)
154. Ferrara
155. Mutina (Modena)
156. Bononia (Bologna)
157. Pomposa
158. Faenza
159. Ravenna
160. Ariminum (Rimini)
161. Pisaurum (Pesaro)
162. Fanum Fortunae (Fano)
163. Forum Sempronii (Fossonbrone)
164. Urvinum Mataurense (Urbino)
165. Ancona
166. Fossacesia
167. Firmum Picenum (Fermo)
168. Urb Salvia (Urbisaglia)
169. Assisi
170. Luceria (Lucera)
171. Sipontum (Siponto)
172. Canusium (Canosa)
173. Barletta
174. Trani
175. Troia Apula
176. Bitonto
177. Venusia (Venosa)
178. Barium (Bari)
179. Melfi
180. Tarentum (Taranto)
181. Brundisium (Brindisi)
182. Lupia (Lecce)
183. Otranto
184. Augusta Pretoria (Aosta)
185. Genua (Genoa)
186. Luna (Luni)
187. Luca (lucca)
188. Pisa
189. Florentia (Florence)
190. Arretium (Arezzo)
191. Siena
192. Lucus Feroniae
193. Roma (Rome)
194. Tibur (Tivoli)
195. Grottaferrata
196. Ostia
197. Viterbium (Viterbo)
198. Praeneste (Palestrina)
199. Anagni
200. Terracina
201. Minturnae
202. Suessa Aurunca (Mondragone)
203. Teanum Sidicinum (Teano)
204. Cales (Calvi Risorta)
205. Capua
206. Cumae
207. Puteoli (Pozzuoli)
208. Neapolis (Naples)
209. Nola
210. Cimitile
211. Herculaneum (Ercolano)
212. Pompeii (Pompeii)
213. Villa Oplontis (Oplonti)
214. Amalfi
215. Ravello
216. Salerno
217. Paestum
218. Velia (Marina di Ascea)
219. Hipponium (Vibo Valenza)
220. Regium (Reggio Calabria)
221. Gerace
222. Copia Thurii
223. Messana (Messina)
224. Tauromenium (Taormina)
225. Catana (Catania)
226. Siracusa (Syracuse)
227. Henna (Enna)
228. Philosophiana (Piazza Armerina)
229. Cehaloedium (Cefalù)
230. Panhormus (Palermo)
231. Monreale
232. Drepanum (Trapani)
233. Lilybaeum (Marsala)
234. Mazara
235. Thermae Selin. (Sciacca)
236. Agrigento
237. Ragusa Ibla
238. Modica
239. Noto
240. Caralis (Cagliari)
241. Albintimilium (Ventimiglia)
242. Caemenelum (Nice)
243. Col. Forum Iulii (Frejus)
244. Arelate (Arles)
245. Lugdunum (Lyons)
246. Aix en Provence
247. Nemausus (Nimes)
248. Massalia (Marseilles)
249. Arausio (Orange)
250. Augustonemetum (Clermont-Ferrand)
251. Antricum (Chartres)
252. Lutetia P. (Paris)
253. Burgundy
254. Lillebonne
255. Le Havre
256. Noviodunum (Jublains)
257. Poitiers
258. Augustoritum (Limoges)
259. Burdigala (Bordeaux)
260. Col. Augusta Narbonensis (Narbonne)
261. Divona (Cahors)
262. Rodez
263. Toulouse
264. Lugdunum Convenarum (St.Bertrand de Comminges)

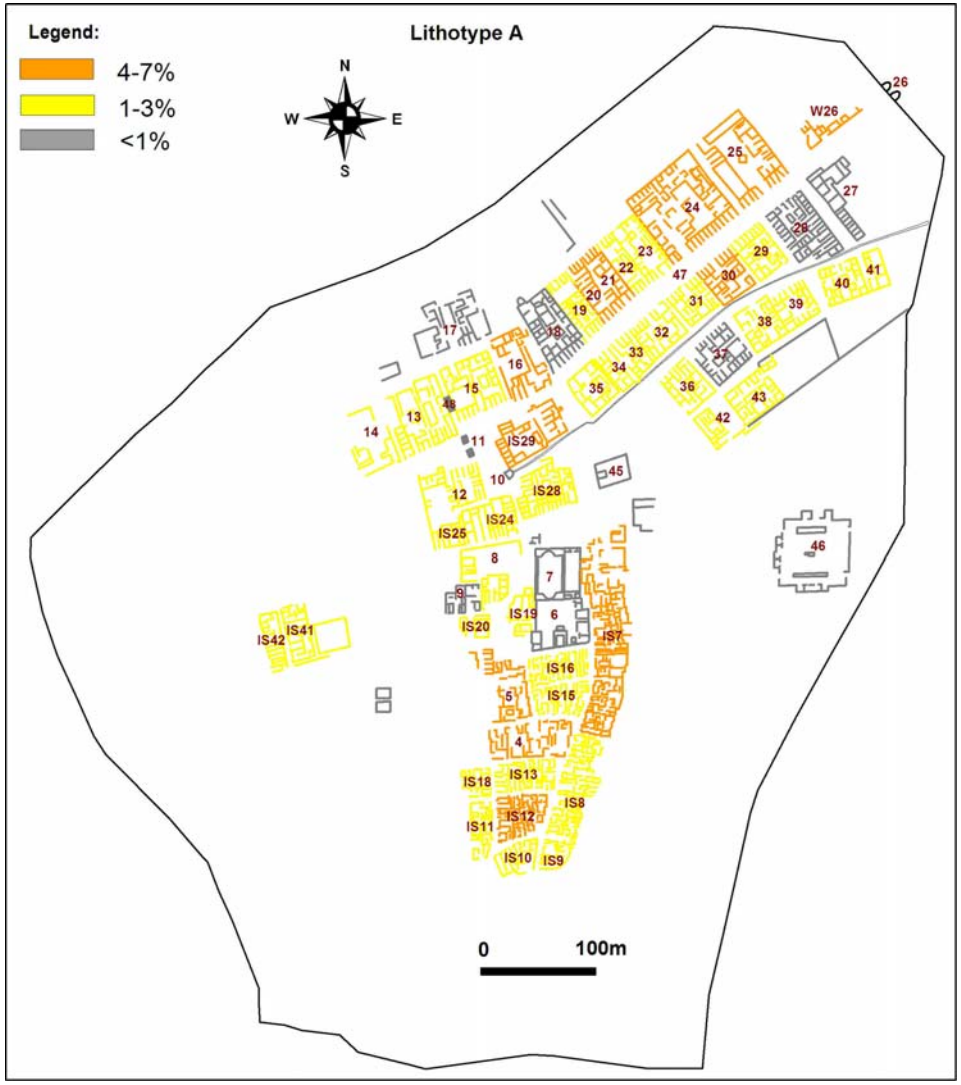
265. Londinium (London)
266. Col. Camulodumum (Colchester)
267. Canterbury
268. Fishbourne
269. Colonia Lindum (Lincoln)
270. Emporiae (Ampurias)
271. Baetulo (Badalona)
272. Barcino (Barcelona)
273. Tarraco (Tarragona)
274. Dertosa (Tortosa)
275. Sagunto
276. Alicante
277. Elche
278. Carthago Nova (Cartagena)
279. Singili Barba (Cortijo de El Castillon – Antequera)
280. Malaga
281. Gades (Cadiz)
282. Marrakesh
283. Munigua
284. Siviglia (Seville)
285. Italica (Santiponce)
286. Corduba (Cordova)
287. Emerita Augusta (Merida)
288. Carranque (S.Maria de Abajo)
289. Segovia
290. Caesaraugusta (Zaragoza)
291. Hippo Regius (Ippona)
292. Simitthus (Chemtou)
293. Bulla regia
294. Thugga (Douggha)
295. Hippo Diarrhytus (Biserta)
296. Utica
297. Carthago (Carthage)
298. Thuburbo Maius
299. Kairouan
300. Sousse
301. Leptis Minor
302. Mahdia
303. Monastir
304. Thysdrus (El Djem)
305. Sabratha
306. Oea (Tripolis)
307. Leptis Magna (Lebda)
308. Cirene
309. Apollonia
310. Darnis (Derna)
311. Cherronesos
312. Uadi Natrun
313. Abu Mina
314. Alexandria
315. Heliopolis Ae. (Cairo)
316. Menphis
317. Oxyrhyncus
318. Hermopolis Magna
319. Thebai
320. Syene
321. Volaterrae (Volterra)
322. Reggio Emilia
323. Treviso
324. Toledo
325. Modone (Methoni)
326. Jublè
327. Castelvetrano
328. Spoleto
329. Aanjar
330. Samaria Sebaste
331. Tunisi (Tunis)
332. Petelia
333. Silin (villa)
334. Augusta Pretoria (Aosta)
335. S.Angelo in Formis
336. Barletta
337. Arta
338. Alika
339. Cossura (Pantelleria)
340. Montescaglioso
341. Rieti
342. Equilium (Jesolo)
343. Merbaka
344. Napoli di Romania (Nauplia)
345. Aleppo
346. Dafnì
347. Lampsacus (Lapseki)
348. Abidus (çanakkale)
349. Hamaxitos
350. Tebe (Thebes)
351. Ankyra (Ankara)
352. Mazara del Vallo
353. Nazaret (Nazareth)
354. Andravida
355. Marrakesh
356. Hadrianopolis (Edirne)
357. Nicopolis
358. Delfi (Delphos)
359. Suasa
360. Chiusi
361. Peparetos (Scopelos)
362. Tripolis (Tripoli)
363. Torre di Pordenone (villa)
364. Macerata
365. Carrara S.Stefano
366. Egina
367. S.Demetrio Corone
368. Bosra
369. Trezene
370. Arba (Rab)
371. Capri
372. Tarquinia
373. Chieti
374. Metaponto
375. Matera
376. Agliate
377. Amathus (Ciprus)

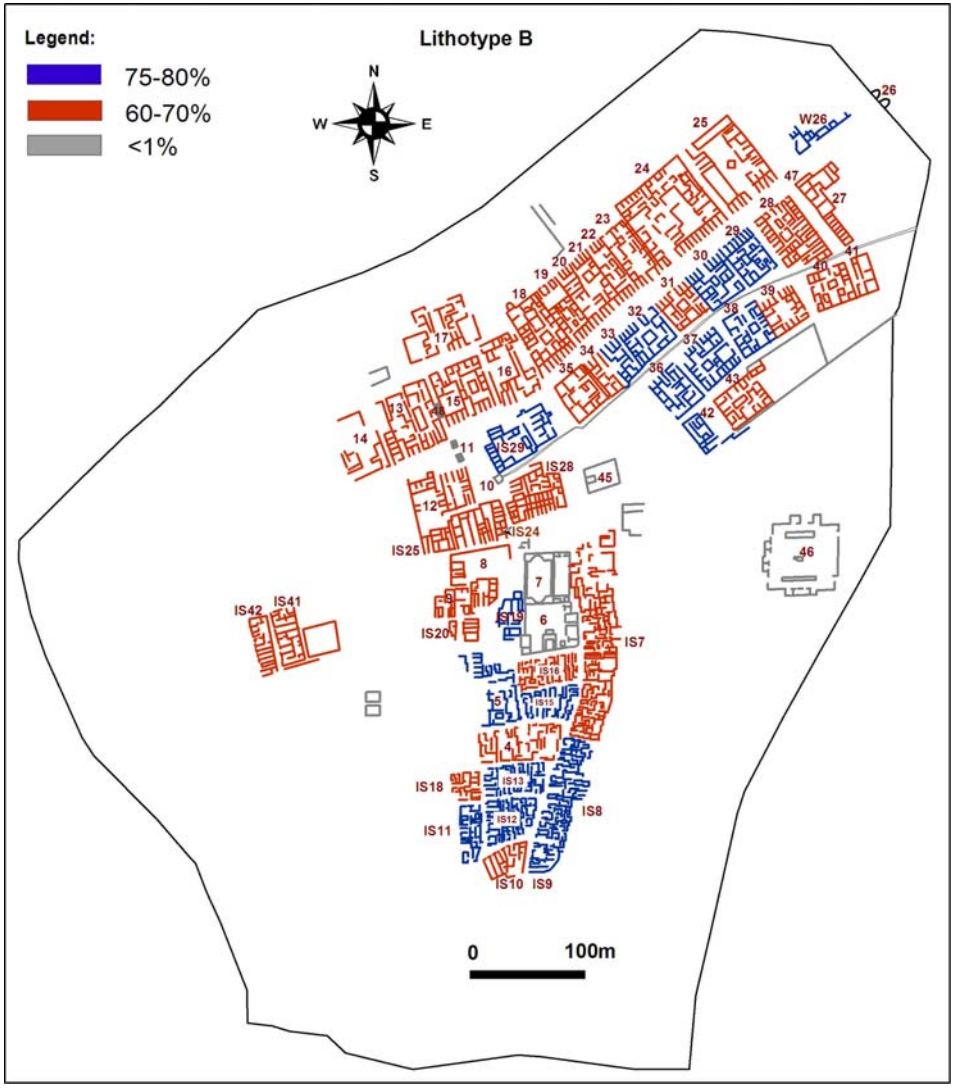
Appendix 2 - Estimation of the volume of building stones and of the proportion of each lithotype in the monuments of Volubilis

Monument refrerence	Monument designation	Surface (S) of the monument (m^2)	Average Height (H) of building stone elements (m)	Volume (V) of building stone elements (m^3)	Proportion (P) of each lithotype (% of the total volume of building stone of the monument) evaluated visually					
					A	B	C	D	E	F
4	House of Orpheus	1632	1.5	122.4	5	65	20	5	3	2
5	Baths of Gallienus	1800	2	180	6	80	10	<1	<1	4
6	Capitol	1600	3	240	0	0	100	0	0	0
7	Basilica	1600	6	480	0	0	100	0	0	0
8	Forum	2500	1	125	1	70	20	1	3	5
9	Bakery	600	1.5	45	0.5	65	20	<1	4	10
10	Public Fountain	100	0.5	2.5	0	0	100	0	0	0
11	Triumphal Arch	92	11	750	0	0	100	0	0	0
12	House of the Dog	1500	2	150	2	70	20	5	2	1
13	House of the Ephebe	1344	1.5	100.8	3	70	20	1	1	5
14	House of the Compass	672	2	67.2	3	70	25	<1	1	<1
15	House of the Columns	2000	2.5	250	2	70	20	5	2	1
16	House of the Rider	1904	0.5	47.6	6	70	15	3	5	1
17	House of the Cistern	1600	2.5	200	<1	70	20	6	3	<1
18	House of Hercules	2160	1	108	<1	70	25	<1	3.5	<1
19	House of Flavius Germanus	1160	1	58	1	70	25	<1	3	<1
20	House of Dionysos and of four seasons	896	1.5	67.2	4	70	20	<1	5	<1
21	House of the Baths of the Nymphs	728	2	72.8	1	70	25	<1	3	<1
22	House of the Wild Beasts	1296	1.5	97.2	1	70	25	<1	3	<1
23	House at the West of Palace of Gordian	1248	1.5	93.6	4	70	20	1.5	4	<1
24	Palace of Gordian	4480	1.5	336	5	60	30	2	1	2
25	House of the Discipline	2904	2.5	363	5	70	20	2.5	2	<1
26	Door of Tangier	0		0	0	0	100	0	0	0
26W	House at the West of the Door of Tangier	1104	0.5	27.6	4	75	15	2.5	3	<1
27	House at the West of the House of the Gold Coin	1400	0.2	14	<1	65	30	2	2	<1
28	House of the Gold Coin	2016	0.5	50.4	<1	65	30	2	2	<1
29	House of the Bacchus of marble	1120	1	56	5	75	15	2.5	2	<1
30	House of the Sundial	1224	1	61.2	7	75	15	2	<1	<1
31	House of the two presses	1080	1	54	2	70	25	2	<1	<1
32	House of the Nereids	960	1.5	72	2	75	20	1	1.5	<1
33	House of the semi Columns	448	1	22.4	1	75	20	2	1.5	<1
34	House of the Abside	448	0.4	8.96	3	70	20	3	1	3

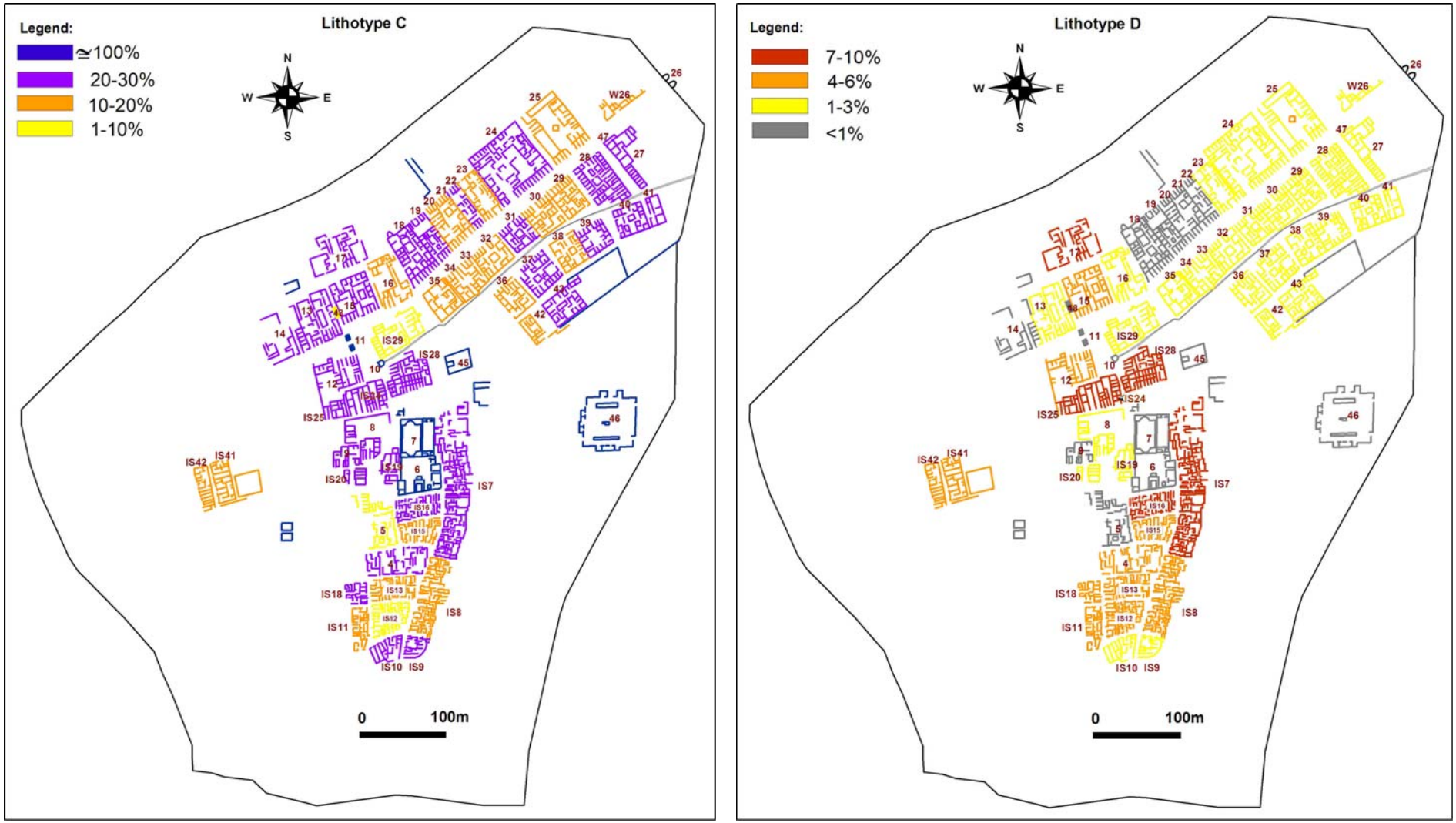
Monument refrerence	Monument designation	Surface (S) of the monument (m^2)	Average Height (H) of building stone elements (m)	Volume (V) of building stone elements (m^3)	Proportion (P) of each lithotype (% of the total volume of building stone of the monument) evaluated visually					
					A	B	C	D	E	F
35	House of the Islamic Necropolis	1200	0.2	12	1	70	20	1	3	5
36	House of the gold ring	1064	1	53.2	3	75	15	3	3	1
37	House of the Bronze Bust	1368	1.5	102.6	<1	75	20	1	3	<1
38	House of Venus	1080	1.5	81	2	75	15	3	4	1
39	House of the Portiques	1152	1	57.6	1	70	25	3	<1	<1
40	House of the Clover Basin	832	0.5	20.8	2	65	30	2	<1	<1
41	House without peristyle	576	0.6	17.28	2	70	20	3	4	<1
42	House of the Crypt	448	2	44.8	1	75	15	3	5	1
43	House of the big pilasters	1216	1.5	91.2	2	70	25	2	<1	<1
48	Mausoleum	60	1	3	0	15	5	0	0	80
IS7	Insulae	3360	0.8	134.4	4	60	20	10	1	5
IS8	Insulae	2160	1	108	1	75	15	5	1	3
IS9	Insulae	400	0.5	10	2	75	20	2	<1	<1
IS10	Insulae	720	0.5	18	2	70	25	2	<1	<1
IS11	Insulae	736	1	36.8	2	75	15	5	1	2
IS12	Insulae	1200	0.8	48	5	75	10	5	3	2
IS13	Insulae	1100	0.8	44	3	75	15	5	1	1
IS15	Insulae	1056	1	52.8	2	75	15	4	1	3
IS16	Insulae	1000	0.6	30	3	65	20	7	2	3
IS18	Insulae	484	0.8	19.36	2	70	20	5	1	2
IS19	Baths of the Capitol	600	0.5	15	3	75	20	1	<1	<1
IS20	Insulae	384	0.5	9.6	1	70	25	3	<1	<1
IS24	House of Desultor	1200	0.3	18	3	60	20	10	2	5
IS25	Insulae	480	1	24	1	70	20	5	1	3
IS28	Insulae	920	1	46	3	65	20	6	3	3
IS29	Insulae	2160	2	216	5	80	10	3	1	1
IS41	Insulae	828	1.5	62.1	3	70	15	5	2	5
IS42	Insulae	644	1.5	48.3	3	70	15	5	2	5

Appendix 3 - Spatial distribution maps of the building stone lithotypes in Volubilis

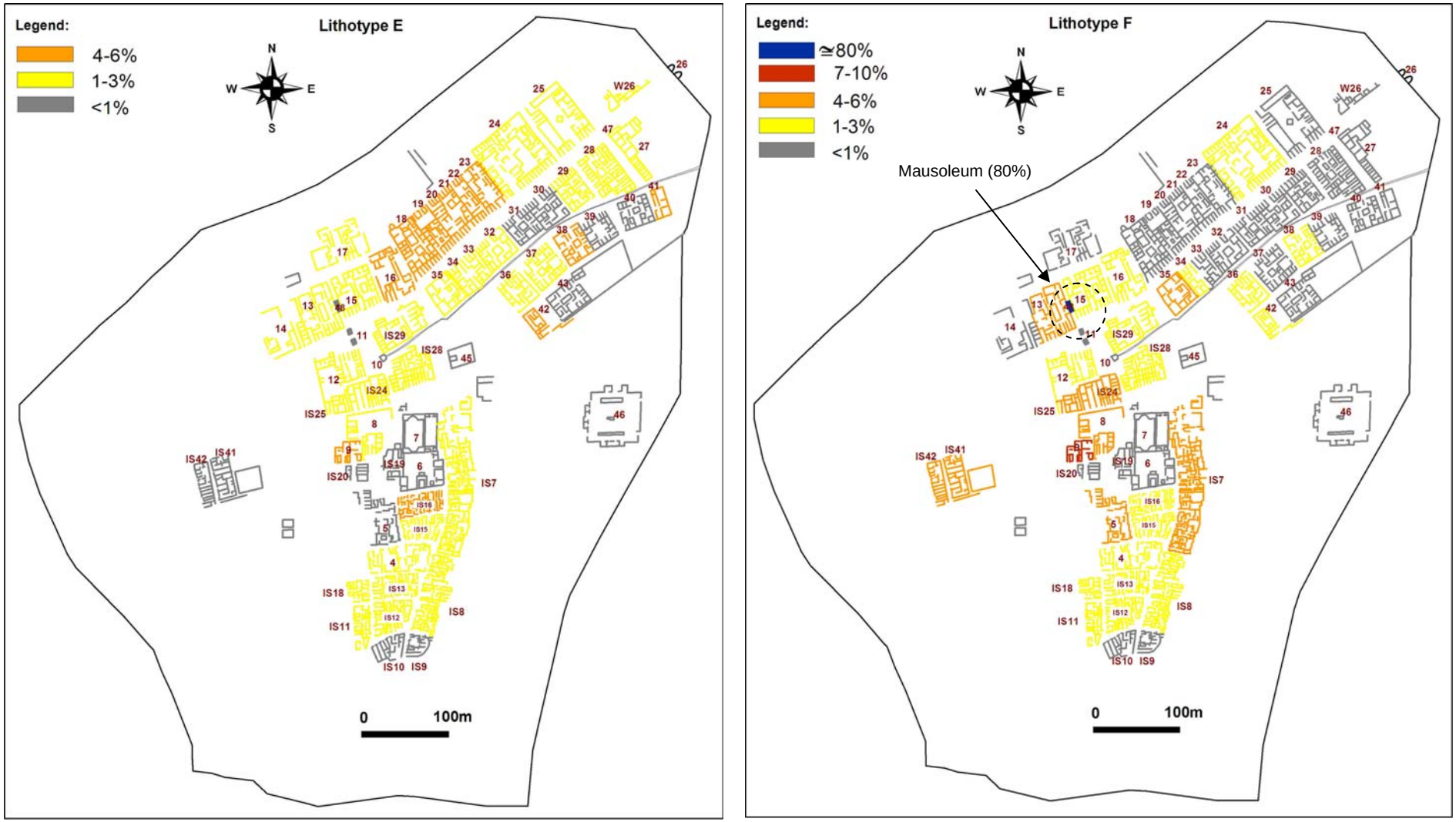




Spatial distribution (% monument per monument) maps of the lithotypes A and B.



Spatial distribution (% monument per monument) maps of the lithotypes C and D.



Spatial distribution (% monument per monument) maps of the lithotypes E and F.

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