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# The building stone of the Roman city of Lixus (NW Morocco): provenance, petrography and petrophysical characterization

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## | A B S T R A C T |

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The characterization of building materials is a key tool to assess deterioration processes and improve potential restoration works of archaeological sites. The aim of this paper is to identify and characterize the most important building stones used in the construction of the Roman city of Lixus (Larache, Morocco) by means of petrographic and petrophysical techniques. Based on the visual analysis of the monuments, three major building stones (i.e. lithotypes) have been identified: i) Oligocene sandstones, ii) Quaternary sandstones and iii) Quaternary conglomerates. Based on the analysis of the regional geology and exploitation marks, these three lithotypes have been recognised to crop out in the surroundings of Lixus and the quarries, presumably Roman in origin, recognized. The Oligocene sandstone is the primary building stone in Lixus as it forms and crops out extensively in the Tchemmis hill, at the top of which the city is settled. The Quaternary sandstones and conglomerates, which represent nearshore deposits and eolianites, crop out along the Atlantic coast where they form part of the cliffs next to Larache.

Petrographic results indicate that lithotypes differ notably in grain size, ratio of detrital to allochemical components, and the configuration of their porous system. Mechanical analysis shows that the Oligocene sandstones are more resistant to compression than the Quaternary sandstones and conglomerates, the latter exhibiting relatively low compressive strength. The Oligocene sandstones, which display scarce porosity and permeability, show a hydric behaviour characterized by a very low degree of absorption and desorption water, likely resulting from a poor connectivity of the pore network. Contrary to the latter lithotype, the Quaternary sandstones, which exhibit very high porosity and permeability, display a hydric behaviour characterized by high degree of both absorption and desorption of water. This is attributed to the low degree of cementation compared to porosity of this lithotype and the excellent connectivity of the porous network. Finally, Oligocene and Quaternary sandstones do not show a significant weight loss after the accelerated artificial aging test, indicating that both are slightly affected by salt crystallization and presumably ice formation. Results indicate that the relatively fine state of conservation of the building rocks of Lixus is linked to intrinsic factors such as mineralogy and petrophysical characteristics together with the favourable effect of the climatic condition of the study area.

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**KEYWORDS** | Building stone. Lixus. Petrography. Petrophysics. Durability.

## INTRODUCTION

Alteration and preservation of architectural heritage is challenging both culturally and scientifically (Beck *et al.*, 2003). The restoration of ancient monuments is usually done by replacing the most damaged rock material. Whenever possible, the building stones used in restoration should be of the same rock type or have similar petrophysics characteristics than the replaced ones. Unfortunately, the number of quarries that can provide restoration sites are limited compared to the variety of stones originally used. In this regard, the juxtaposition of stones of similar appearance but of different petrophysical nature on a monument can accelerate the degradation of one of them or both (Beck *et al.*, 2003; Beck and Al-Mukhtar, 2005; Derbez and Lefèvre, 2003). Therefore, a major issue that arises during restoration processes is the compatibility between the original building stones and the rock types used as a replacement.

The identification and characterization of building stones used in the construction of archaeological sites is a key tool to evaluate deterioration processes and improve future restoration works (Zoghlami *et al.*, 2017). Deterioration of building stones by weathering is a natural process that occurs in all type of rocks exposed to atmospheric environment (Siedel and Siegesmund, 2014). In this regard, the description and interpretation of the diverse types of rock weathering, and the driving forces behind them, have been a subject of interest in geosciences such as geomorphology and physical geography for many years (Robinson and Williams, 1994; Turkington and Paradise, 2005). The degree of weathering is strongly related to petrophysics properties of the rock as well as environmental conditions. Common alteration features on rock materials are typically characterized by an increase in porosity of the altered rock, a process that has been accentuated in the last century by the rapid development of atmospheric pollution and by the aggressiveness of the environment (Beck *et al.*, 2003; Price, 1995). In this regard, water commonly is the main driving force of weathering and it can affect the rock directly (by the effect of ice and mineral dissolution, among others) and indirectly (transport of soluble salts and favouring biological activity, among others) (Andriani and Walsh, 2007; Ruedrich *et al.*, 2007). Most rock alteration processes involve water and salts and use to develop in close association with the flow of fluids through the pore system. Among weathering agents, the soluble salts play a major role in the degradation of the stones used in construction. Halite (NaCl) and gypsum (CaSO<sub>4</sub> 2H<sub>2</sub>O) are the most common and most destructive salts. Thus, many alteration studies have been carried out in the laboratory to observe the behaviour of building stones to diverse weathering agents (Benavente, 2011; Goudie, 1999). Rock alteration studies have focused over the last decades on sedimentary

rocks, and most particularly on limestones and arenites (Dessandier *et al.*, 1997; Martínez-Martínez *et al.*, 2017a, b; Zoghlami *et al.*, 2017).

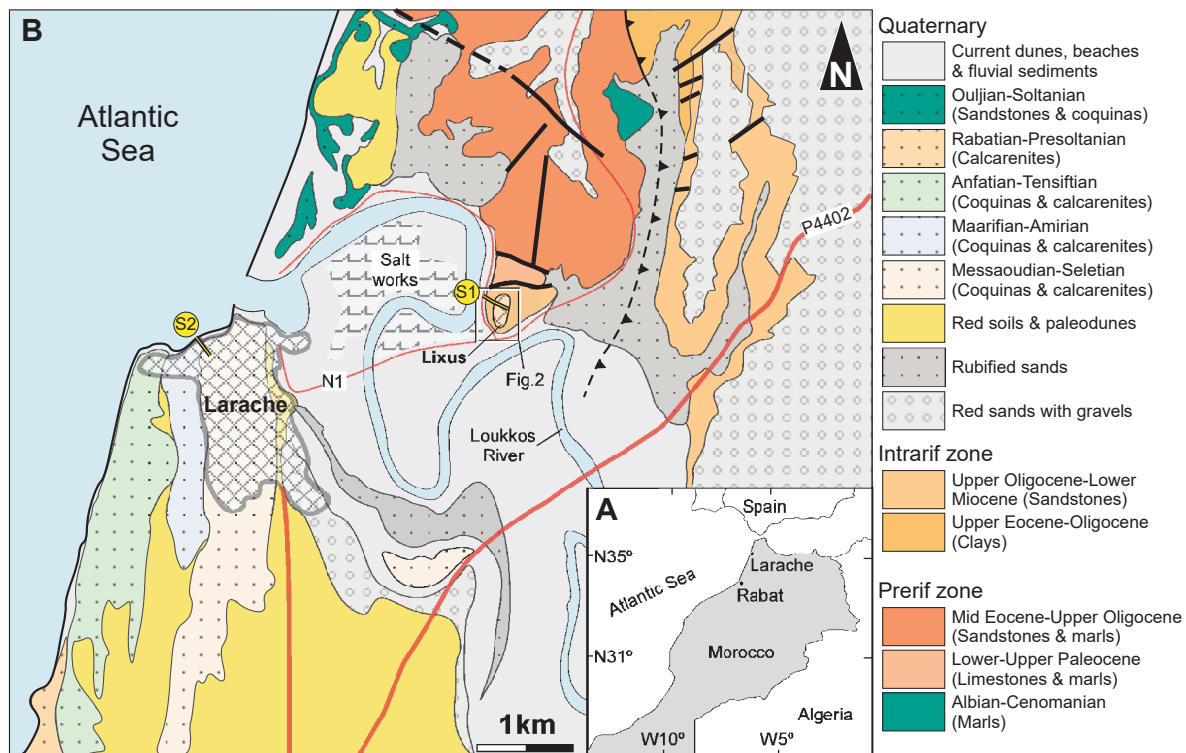
The Quaternary nearshore deposits that crop out along the coastal areas of the Mediterranean countries are typically used in the construction of most important historic monuments (*e.g.* El Djem and the cities of Utica and Cartago in Tunisia) due to the facility to quarry and shape such rocks. Within these Tyrrhenian deposits many historic quarries were opened to supply building stones to a large number of monuments of cities in Tunisia (*e.g.* Bizerte, Tunis and Monastir), in Sicily (*e.g.* Palermo, Marsala) and in Balearic Islands. However, the study of this type of rock is not abundant in the literature and their characterization needs proper attention. These Quaternary sediments are common building rocks in the construction of classic monuments both in the NW of Morocco as Benasa and Thamusida (Ouacha *et al.*, 2013), and in Rabat as Roman challah (Zaouia *et al.*, 2014). In this regard, the Quaternary (Tyrrhenian) sandstones and conglomerates of the Atlantic coast of Larache, together with the Tchemmis Oligocene sandstones, are the most common building stones used in the ancient City of Lixus (Morocco). Therefore, the study of Lixus gives a great opportunity to increase our knowledge of this type of rock.

Potential restoration works of Lixus will need abundant and diverse information regarding the origin and characteristics of the building rocks for a correct replacement process. Such characterization includes the determination of the petrographic, hydric and mechanical properties, together with the accelerated artificial aging test (Borrelli and Urland, 1999; De Kock *et al.*, 2015; Esbert and Marcos, 1983; Esbert *et al.*, 2008; Gauri and Punuru, 1989; Lazzarini and Laurenzi Tabasso, 1986; López-Arce *et al.*, 2009; Ordoñez *et al.*, 1997; Villegas and Vale, 1993; Winkler, 1975).

The goal of this paper is to identify and characterize most important building stones used in the construction in the city of Lixus (NW Morocco). Specifically, the objectives are: i) to identify the main lithotypes used, ii) to recognize the rock formations and specific sites from where the lithotypes were quarried, iii) to characterize the petrology of the lithotypes and iv) to characterize the petrophysics properties of the lithotypes.

## GEOGRAPHIC LOCATION AND CLIMATE

Lixus is an archaeological site located about 3km NE of Larache (NW Morocco), on the right bank of the Loukkos River (Figs. 1; 2; 3A-B). Lixus is considered one of the oldest cities of the West Roman Empire together with Cadix



**FIGURE 1.** A) Map of Morocco showing the location of Larache. B) Geological map of the Larache area showing the location of the Roman City of Lixus (Modified from Haddane, 1997). The location of the studied stratigraphic sections are noted as S1 (Tchemmis section) and S2 (Larache Cliff section).

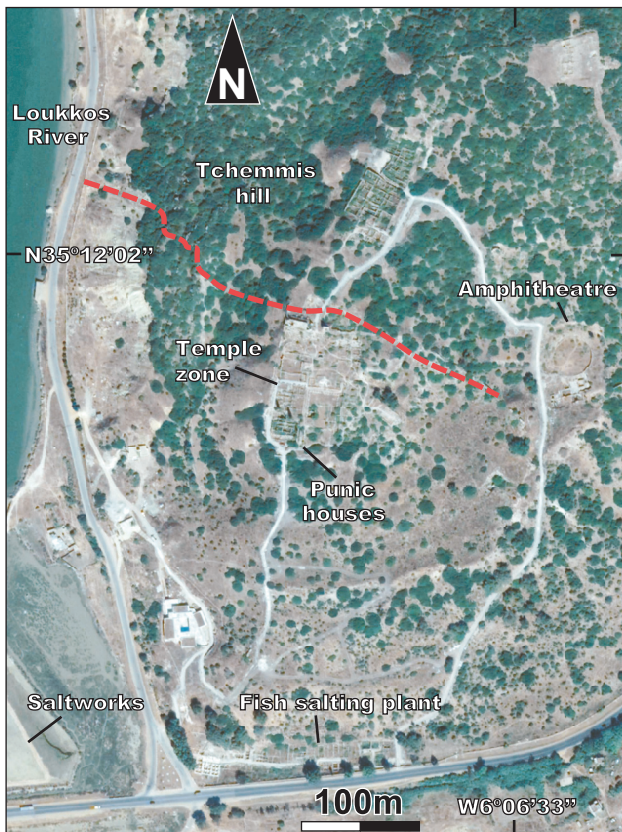
(Spain) and Utica (Tunisia) (Ponsich, 1966). The ruins of the city represent the pass of diverse civilizations, starting as Phoenician and followed by Punic, Mauritanian, Roman, and finally Islamic (Ouacha *et al.*, 2013). The city is endowed with several public monuments such as an amphitheatre, temple area and private baths richly decorated with frescoes and mosaics of good quality (Fig. 3). In addition, the city has a large industrial complex for the elaboration of salted brine and salted fish (Fig. 3F), being the salt produced in a work complex located in the vicinity of the city (Figs. 2; 3A-B). Most Lixus buildings are partially to completely ruined and numerous original rock elements are broken or disappeared (Figs. 3B-F; 4A). Moreover, the remaining building rocks frequently present alteration patterns such as fissures, surface erosion, fragmentation and biological colonization (Fig. 3B-F).

Regarding the climate of the studied area, the region of Larache is located in the Atlantic coast of northwest of Morocco (Fig. 1). Lixus has a warm-temperature Mediterranean climate, with a hot and dry summer, classified as Csa according to the Köppen-Geiger climate system (Kottek *et al.*, 2006). The average annual temperature is 17.9°C, with a minimum average value of 13.5°C and a maximum average value of 25.5°C and a strong seasonality, with monthly temperature variations ranging between 9°C in January and 30°C in August. The annual average rainfall

of the area is approximately 650mm. The climate is sub-humid and characterized by two very different seasons. From October to April, the climate is humid and cool, and concentrates up to 90% of the annual rainfall. From May to September the climate is dry and hot, being the rainfall virtually zero in the month of July (Bouhmadi *et al.*, 1995). The wind regime on the western coast of Morocco is closely related to the Azores anticyclone and the North Atlantic depressions (El Gharbaoui, 1981; El Moutchou *et al.*, 2014). Therefore, the prevailing winds in the Larache area come from the west (Atlantic Ocean) with average wind speed above 15km/h. During the summer, these winds alternate near the coast with the East Chergui wind of continental origin (El Mekadem and Moutchou, 2016). The relative humidity is relatively high due to the proximity to the Atlantic Ocean, ranging between 66-70% in winter and 55% in summer. The River Loukkos, which is about 180km long and has a basin area of 3750km<sup>2</sup>, flows into Larache developing an extensive fluvial plain with channels and meanders at the foot of the Tchemmis hill.

## GEOLOGICAL SETTING

The region of Larache belongs to the Hapt Atlantique Intrarif unit, which is exposed in the western part of the



**FIGURE 2.** Google Earth image of the Tchemmis hill showing the aerial view of Lixus (See location in Figure 1). The red dashed line denotes the trace of the Tchemmis section.

Rif Chain in the northwest of Morocco (Lespinasse, 1975; Samaka *et al.*, 1997) (Fig. 1). This area constitutes the western termination of the Maghrebian Alpine Chain that extends along the Mediterranean coast of North Africa from Calabria to the Arch of Gibraltar (Chalouan *et al.*, 1990, 2001; Didon *et al.*, 1973; Durand Delga, 1964). Specifically, the study area is located in the external domain of the Rif Chain and it is affected by the Hapt nappe.

The Hapt Unit has been the subject of several studies since middle last century (Abdelkhaliki, 1997; Cazzola and Critelli, 1987; Morley, 1987; Samaka *et al.*, 1997; Suter, 1986; Suter and Fiecher, 1966; Tejera de León *et al.*, 1995). Structurally, it belongs to the external domain of the Rif Chain, and is bounded in the west by the internal Prerif and in the east by the Tangier Unit series. The Hapt Unit is Eocene to Middle Miocene in age and is made of gravity deposits representing the filling of deep submarine cones at the trough of the syn-orogenic depression (Abdelkhaliki, 1997). The general stratigraphic succession is organized in three superimposed formations (Tejera de León *et al.*, 1995): i) the Upper Eocene-Oligocene clays of the Sahel Fm. ii) the Upper Oligocene-Lower Miocene sandstones and clays of the Asilah Fm. and iii) the Middle Miocene

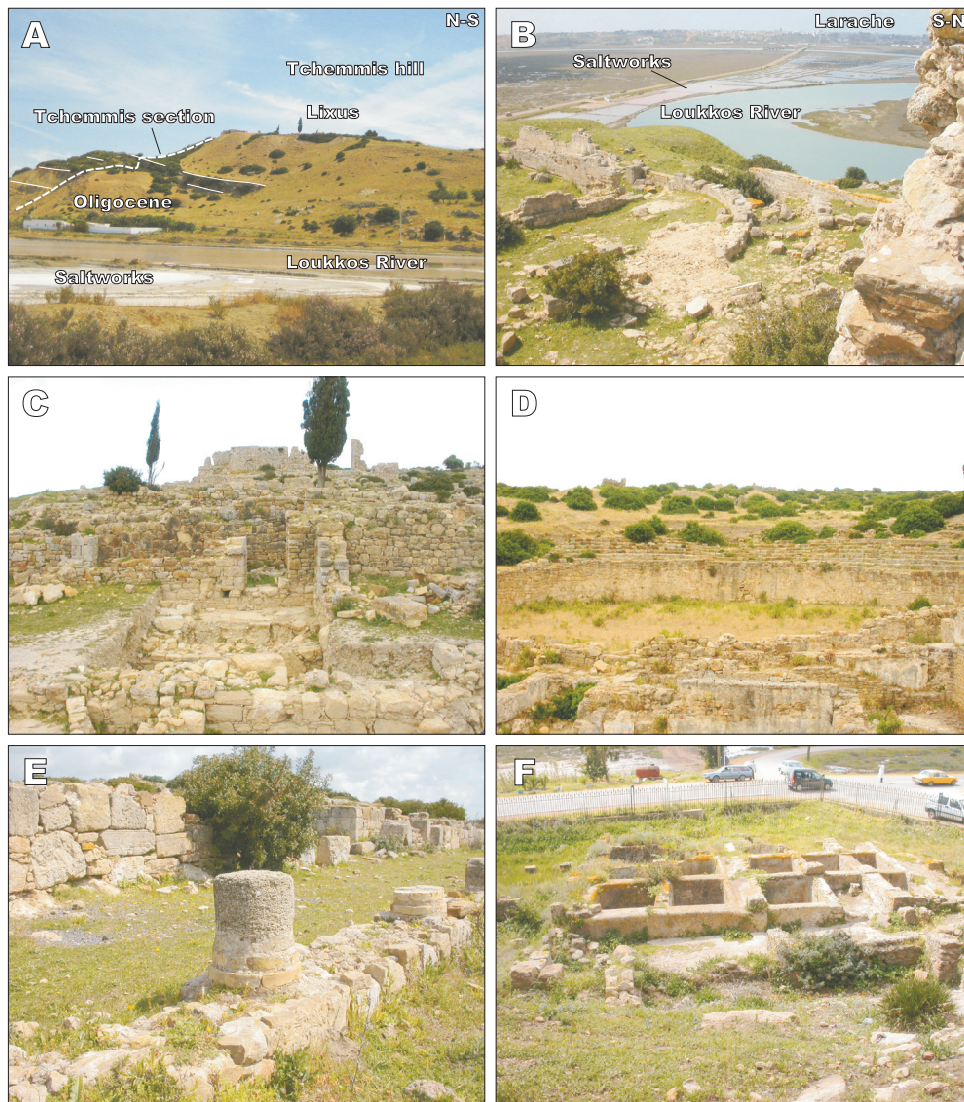
marls of the Sidi Moussa Fm., The Asilah Fm. form and crops out in the Tchemmis hill, where the Roman City of Lixus is located, being the most used building stone in its construction.

The Quaternary deposits that crop out along the Atlantic coast of Morocco, which are irregularly distributed, have been widely reported in the literature (Aboumaria *et al.*, 2009; Akil and Gayet, 1988; Beaudet, 1971; Chabli *et al.*, 2014; Chouber and Roche, 1956; Gigout, 1947; Ouadia, 2015). These deposits are mainly made of conglomerate, sandstones and bioclastic limestones (*i.e.* coquinas) that are the result of successive Quaternary marine transgressions (Akil and Gayet, 1988). The conglomerates are frequently made of abundant broken to fully preserved shells of marine molluscs mixed with clastic sediments. They commonly show flat or slightly oblique lamination to the sea indicating medium to strong energy of deposition. The Quaternary sandstone deposits are the result of the wave and wind action witnessed by the abundance of round quartz grains and rock fragments. In the coast of Larache the Quaternary sediments show an evolution from intertidal foreshore marine to backshore or dune aeolian deposits.

## MATERIALS AND METHODS

The characterization of the building stone used in the construction of the Roman City of Lixus was accomplished in two steps. Firstly, the buildings were recognized by visual analysis and major rock types (*i.e.* lithotypes) were identified based on lithology and abundance (Figs. 3; 4). Small pieces of the selected lithotypes up to 5cm long have been sampled from the monuments, mostly from loose and broken blocks, in order to perform thin sections for the petrographic study described below. Secondly, the geology of the region surrounding Lixus was analysed in order to identify potential exposures of the rocks that were the origin of such lithotypes. In addition, two stratigraphic sections of such exposures were logged in order to identify and locate the strata that provided these lithotypes (*i.e.* Roman quarries). The first stratigraphic section was measured at the Tchemmis hill where the Oligocene sandstone crop out under the city of Lixus (Figs. 1; 2; 3; 4). The second stratigraphic section was measured at the Larache cliff, near the Sidi Abdelah cemetery, where the Quaternary sandstones, conglomerates and coquinas crop out extensively (Figs. 1; 3; 4). The selected lithotypes have been sampled directly from the quarries in order to perform the petrophysical and the accelerated artificial aging analyses described below.

The petrographic study was carried out by analysing standard thin sections in an optical microscope in accordance with the standard test UNE-EN 12407



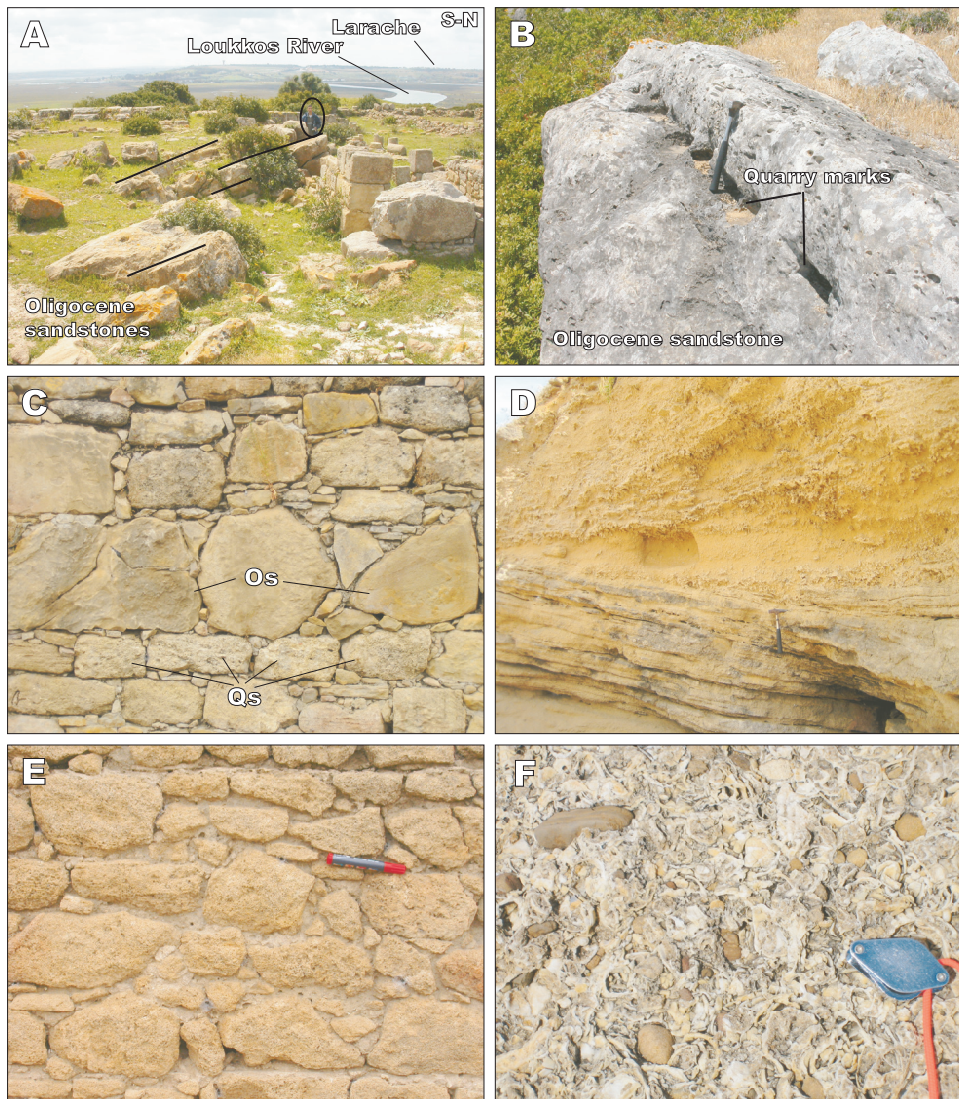
**FIGURE 3.** Field views of Lixus showing: A) The Tchemmis hill and the trace of the Tchemmis section following the structural steps related to the exposure of the Oligocene sandstones. B) The Tchemmis Hill west view with the Loukkos River and the city of Larache in the background. C) The Temple district. D) The Amphitheater. E) The Quarter of the temples with partially ruined columns made of Quaternary sandstones. F) The complex for the production of salted fish.

(2007). Microscopic observations allow recognizing rock components (qualitative and quantitative mineralogy, and textural relationship between components) and the pore system (qualitative and quantitative porosity, and relationship between voids and components). Comparison between thin sections from both monument and quarry was done in order to confirm that the petrographic characteristics, and thus lithotypes, are the same.

The petrophysical properties, which include total open porosity, water absorption and desorption, compressive strength, and accelerated artificial aging, were determined by standard tests. These tests are typically used to determine the durability of building materials and to test their resistivity against various deterioration factors (Zoghlami

*et al.*, 2004). Measurements were carried out in 5x5x5cm cubes (six cubs for each lithotype). Due to the difficulty of shaping such cubes from the Quaternary conglomerates, which is related to the high degree of porosity and the presence of large lithic and skeletal fragments, water and durability tests have been only performed in the Oligocene and Quaternary sandstones.

The total open porosity of the Oligocene and Quaternary sandstones was measured by the vacuum absorption test (UNE-EN 1936, 2007). By contrast, the vacuum absorption test was not performed in the Quaternary conglomerate due to the large pore diameter (5 to 12mm). According to the method described by Beck and Al-Mukhtar (2005), the total open porosity of the Quaternary conglomerate was



**FIGURE 4.** Field views of the building rocks used in the construction of Lixus. A) Top of the Tchemmis Hill showing Oligocene sandstone strata cropping out within the city. Note how the strata is used as part of the walls. B) Oligocene sandstone exposures in the side of the Tchemmis hill showing marks of extraction, presumably roman in origin. C) Wall of the amphitheatre showing blocks of the Oligocene sandstone (Os) and Quaternary sandstone (Qs) lithotypes. (D) Detail of the Larache cliff section showing Quaternary sandstones both well cemented (bottom) and poorly cemented (top). E). Detail of the wall of the amphitheatre showing abundant blocks of Quaternary sandstone. F) Shell-rich conglomerate in the Larache cliff.

determined taken into account the apparent density ( $\rho_a$ ), which represents the mass of minerals relative to the total volume of the stone, and the density of the solid skeleton ( $\rho_s$ ), which represents the mass of minerals relative to the total volume of grains.

The hydric tests that have been performed include water desorption and water absorption. The water desorption test allows determining the percentage of water retention ( $Se$ ) carried out under 40% moisture conditions and at a temperature of 20°C, according to the standard test of [NORMAL 29/88 \(1988\)](#). The water absorption test allows determining the Capillary Absorption Coefficient  $c.A.C$

( $kg/(m^2 \cdot h^{1/2})$ ), which indicates the rate of water suction by capillarity in accordance with the standard test [UNE-EN 1925 \(1999\)](#). Both hydric tests have been performed on six cubes for each lithotype although the reported data correspond to most significant values.

The mechanical properties are based on the compressive strength test according to the standard [UNE-EN 1926 \(2007\)](#). The test has been performed in 6 cubes for each lithotype, being the presented value the average one. The accelerated artificial aging was performed in order to determine the durability or degree of alteration of the rock by salt crystallization. It consists of 12 cycles of immersion

in a solution saturated in sodium sulphate followed by drying in oven at 100°C in accordance with the standard test UNE-EN 12370 (1999). The test favours the crystallization of the salt in the pore system and allows determining the associated increase or decrease of mass. The sodium sulphate was the salt chosen to this experiment because it is considered the most aggressive alteration agent on rocks as suggested by Zehnder and Arnold (1989).

## RESULTS

### Identification of major building stones

Visual analysis of the building stone of Lixus allows recognizing three major lithotypes used in the construction of the city: i) Oligocene sandstone, ii) Quaternary sandstone and iii) Quaternary conglomerate. The Oligocene sandstone is by far the most common lithotype and is specially used as large blocks for the construction of the walls of temples and houses (Figs. 3C-D; 4A-C). The Quaternary sandstone, especially fine to medium-grained bioclastic sandstones, is mainly used in the construction of columns as well as in the construction of the walls of houses and temples (Fig. 4E). The Quaternary conglomerate, especially microconglomeratic facies, is dominantly used in the construction of the base of the columns (Fig. 3E).

### Petrological characterization of quarry rocks

Field logging and sampling of the Lixus and Larache cliff sections allows identify the cropping areas and most important macroscopic characteristics of the Oligocene and Quaternary lithotypes used in the construction of the Roman city of Lixus.

The Oligocene sandstones crop out extensively along the sides and on top of the Tchemmis hill (Fig. 2), being the strata frequently incorporated as part of the walls in the city buildings (Fig. 4A). The Lixus section is 216m thick and represents the above-mentioned exposures starting in the base of the hill next to the Loukkos River and ending close to the amphitheatre (Figs. 2; 3A; 5). It is made of green to grey colour marls and marly limestones interbedded with carbonate sandstones (Fig. 4B). The sandstones form bed sets with individual beds around 1 to 5m thick, showing erosive bases and channel-shaped geometry. The sandstones are medium to fine grained in the base and very fine grained, and even silt sized, towards the top. They show cross-lamination that appear slightly disturbed probably associated with the escape of water during compaction. The sandstones are generally well cemented, which makes them optimal as construction rock. The exploitation of the sandstones directly from these exposures is noted by the presence of

block extraction marks, presumably Roman in origin, in some of the sandstone beds in the hill sides (Fig. 4B).

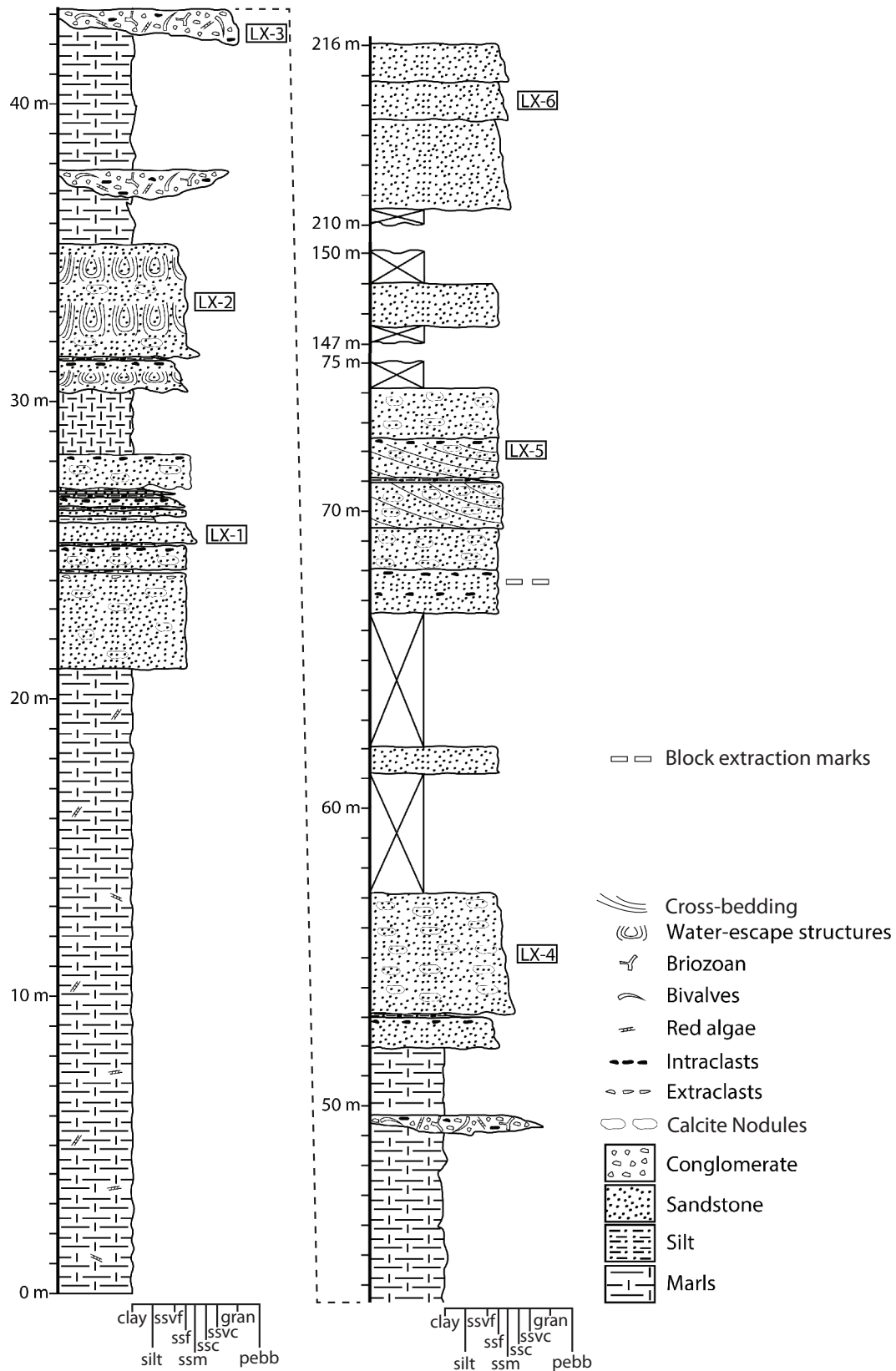
The Quaternary sandstones and conglomerates used in the construction of Lixus were recognized to crop out in the coastal cliffs surrounding Larache. The Larache cliff section is 30m thick and show two main units (Fig. 6). The lower unit is about 15m thick and constitutes an alternation of decimetre thick beds of sandstones and conglomerates bounded by erosive bases. Sandstone beds are bioclastic-rich, medium to very coarse grained and frequently show scoured surfaces and medium-scale cross-stratification. The conglomerate and microconglomerate beds are constituted by extrabasinal clasts mainly made of brown colour Eocene sandstones and quartz, together with minor intraformational pebbles of Quaternary sandstones. A shell-rich layer (*i.e.* coquina) occurs towards the top of the lower unit and consists of a 1.5m thick bed of coarse-grained limestone mainly composed of shells and shell fragments of bivalves and gastropods (Fig. 4F). The lower unit is interpreted to have been deposited in a very energetic nearshore beach environment (shoreface-foreshore settings) near the shoreline.

The upper unit of the Larache cliff section, which overlay the shell-rich conglomeratic layer, is 15m thick. It is made of highly porous and medium-grained sandstones (Figs. 4D; 6). Individual beds range between 5 and 8m thick and show low angle cross-lamination and plane lamination parallel to the beach face and limited by scoured surfaces. To the top of the section shows large scale and high angle crossbedding representing the major foreset of aeolian dunes only disturbed by bioturbation marks made by root plants (rhizoliths). This upper unit is interpreted to represent a coastal dune setting (foreshore-backshore transition upwards) associated with sandy beaches represented by the lower unit.

The beds or bed sets that have similar petrographic characteristics to the three lithotypes identified in Lixus have been located in the logged sections (Figs. 5; 6). These beds have been sampled for petrophysical characterization both in terms of mechanical and hydric behaviour.

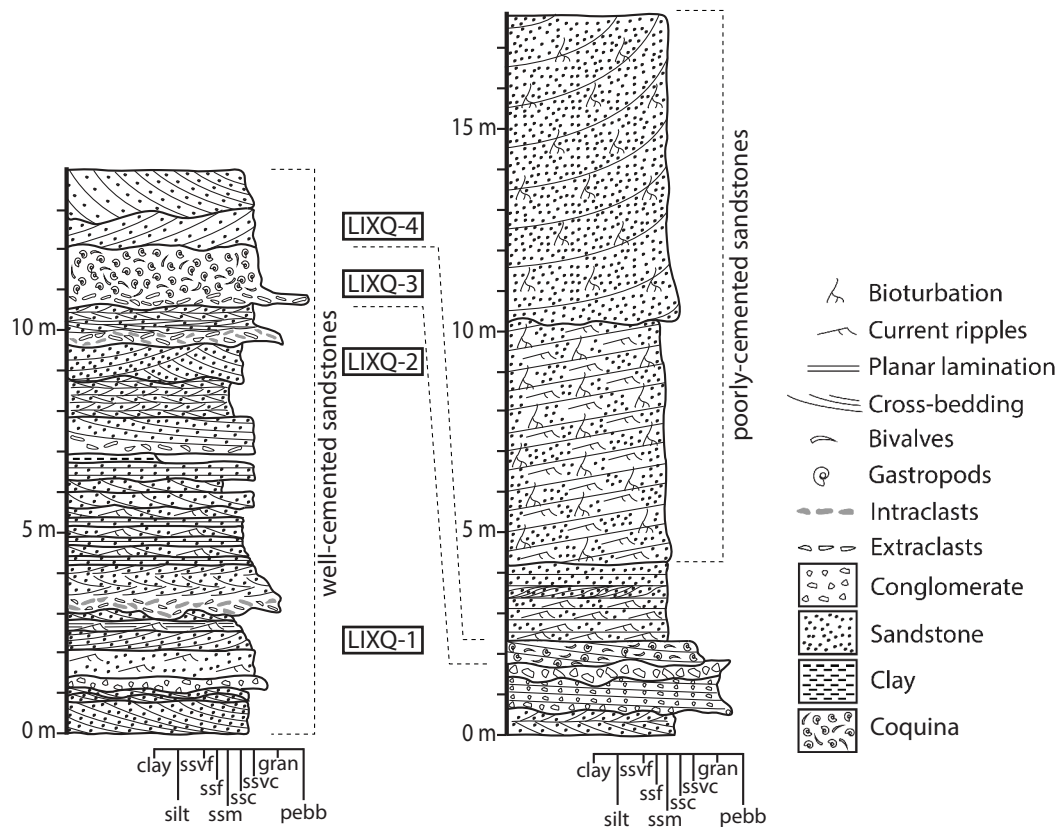
### Petrography of lithotypes

The Oligocene sandstone is made up of very well sorted and rounded to sub-rounded grains, with an average diameter of 350µm (Fig. 7A; Table 1). The intrabasinal carbonate grains (44.8%), which area dominated by red algae, foraminifera and bryozoan, are more abundant than the extrabasinal grains (32.1%), which are largely dominated by monocrystalline quartz. The sandstone is well cemented by calcite (21.2%). The porosity observable with this technique is very low (1.9%), being the pores



**FIGURE 5.** Stratigraphic section of the Tchemmis Hill showing the most important lithological characteristics of the Oligocene sediments and the location of the mined strata noted by block extraction marks.





**FIGURE 6.** Stratigraphic section of the Larache cliff showing the most important lithological characteristics of the Quaternary sediments.

generally isolated and ranging between 50 and 250 $\mu$ m in diameter.

The Quaternary sandstone is made up of well sorted, and very well-rounded grains, with an average diameter between 0.3 and 1mm (Fig. 7B; Table 1). The extrabasinal grains (16.9%), which are dominated by monocrystalline quartz, are more abundant than the intrabasinal carbonate grains (13.2%), which are dominated by bioclasts (8.8%). Both the calcite cement (26.2%) and the porosity (26.8%) are very abundant. The pores show diameters ranging between 1 and 5mm.

The Quaternary conglomerate is a shell-bearing rock characterized by a very porous and relatively poorly cemented texture (Fig. 7C; Table 1). It is composed of coarse sized (5 to 12mm), poorly sorted, and well-rounded grains. The extrabasinal grains (18.6%), which are dominated by monocrystalline quartz, are more abundant than the intrabasinal carbonate grains (15.2%), which are dominated by bivalves and gastropods. The calcite cement is relatively poor (15.2%) relative to porosity, which is very high and reaches up to 45.2%, being the pores considerably bigger (5 and 12mm) than in other lithotypes.

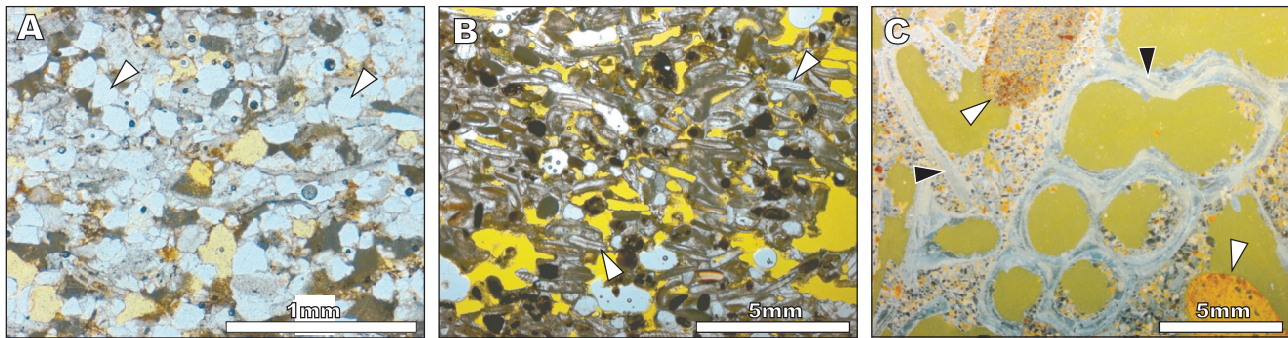
### Water porosity

The Oligocene sandstone shows a very low value of porosity accessible to water (0.9%) compared to the Quaternary sandstones (30.9%) (Table 2). These results are in agreement with the difference in apparent density of both lithotypes, being 2.65g/cm<sup>3</sup> for the Oligocene sandstone and 1.87g/cm<sup>3</sup> for the Quaternary sandstone. However, the relative density of the two lithotypes is very similar, being 2.68g/cm<sup>3</sup> for the Oligocene sandstone and 2.71g/cm<sup>3</sup> for Quaternary sandstone.

The total porosity of the Quaternary conglomerate based on real and apparent densities is relatively high (35.67%), although it corresponds to a minimum value as most of the water was lost before carrying out the measurement. Therefore, the real value of porosity should be much higher, which agrees with the value reported from the petrographical description under the microscope (45.2%; Table 1).

### Hydric and mechanical properties

The water and durability tests have been performed only in the Oligocene sandstone and Quaternary sandstone



**FIGURE 7.** Photomicrographs of the studied lithotypes. A) Oligocene sandstone showing abundant quartz grains (arrows). B) Quaternary sandstone showing abundant fragments of bivalves (arrows). C) Quaternary conglomerate showing fragments of bivalves and gastropods (black arrows) and sedimentary rock fragments (white arrows). Note the abundant inter- and intragranular porosity (green colour).

lithotypes. By contrast, the large pore size of the Quaternary conglomerate makes the capillary tension very low and the hydric tests cannot be performed (Fort *et al.*, 2002; Grossi and Esbert, 1994; Ordoñez *et al.*, 1997). The Oligocene sandstone shows a maximum content of absorbed water that is considered very low (0.35%) (Table 3). The capillary absorption coefficient is also very small (0.04kg/m<sup>2</sup>.h<sup>1/2</sup>) as indicated in the capillary water suction curves (Fig. 8A). The rate of water absorption by capillarity is slow and the degree of capillary saturation (Si) is small (25.2%). Desorption curves show that the Oligocene sandstone

preserves a significant water content after 100 hours, which approximately reaches 41% (Fig. 8B).

The Quaternary sandstone is characterized by a very high value of water absorption under vacuum conditions (16.6%) (Table 3). This lithotype absorb water by capillarity very quickly under ambient conditions, with a capillary absorption coefficient of 19Kg/m<sup>2</sup>h<sup>1/2</sup> (Fig. 8A). The degree of saturation of water by capillarity remains relatively low by an average of 54.3%. Desorption curves, however, show that the water content after 100 hours is approximately 4.7% (Fig. 8B).

**TABLE 1.** Composition, grain size and sorting of the three lithotypes based on the petrographic analysis by optical microscopy. RF: Rock Fragment

	Oligocene sandstone	Quaternary sandstone	Quaternary conglomerate
Extrabasinal grains (%)	32.1	16.9	18.6
Quartz – monocystal.	19.9	9.1	10.4
Quartz – coarse polycrystal.	3.6	2.9	1.0
Quartz – fine polycrystal.	1.8	-	1.0
Detrital K-feldspar	3.4	-	-
K-feldspar in plutonic RF	0.3	-	-
Sandstone RF	-	3.3	3.9
Metamorphic RF	0.6	-	-
Chert fragment	0.9	-	0.9
Micritic mudstone RF	1.6	1.6	1.4
Intrabasinal grains (%)	44.8	13.2	15.2
Bioclasts	-	8.8	1.9
Bryozoans	18.6	0.8	-
Gastropods	-	-	5.4
Echinoderms	2.3	1.6	-
Bivalves	3.3	-	7.9
Red algae	20.6	2.0	-
Cement (%)	21.2	26.2	15.2
Intergranular calcite	5.9	34	15.3
Intergranular micritic calcite	0.6	-	-
Calcite replacing detrital grains	7.8	-	-
Calcite overgrowths	6.9	9.1	3.3
Intragranular calcite in	-	-	2.4
Porosity (%)	1.9	26.8	45.2
Intergranular	1.6	26.3	34.8
Intragranular	0.3	0.5	10.4
Grain size (mm)	0.2-0.5	0.3-1.0	5-12
Sorting	Very well sorted	Well sorted	Poorly sorted

Regarding the compressive strength, the Oligocene sandstone is the more resistant lithotype to compression (1.17MPa), showing considerably higher values than the Quaternary sandstone (0.12MPa) and Quaternary conglomerate (0.06MPa) (Table 4).

### Accelerated artificial aging

The visual inspection of the tested rock cubes before and after the accelerated artificial aging indicates that the Oligocene and Quaternary sandstones are slightly affected by such test in terms of colour change, fissures, exfoliation, etc. (Fig. 9). Moreover, the results of test indicate that both lithotypes are quite resistant to saline attack as there is not a significant loss of mass (Figs. 9; 10). The loss of mass at the end of the test is very similar in both cases being on average 1.7% for the Oligocene sandstone and 1.12% for the Quaternary sandstone. These values are related to the initial and final weight, and thus represent an effective loss of mass.

Despite the similar loss of mass, the absorption dynamics of the salt solution of the studied lithotypes is significantly different (Fig. 10). The Oligocene sandstone absorbs less saline solution than the Quaternary sandstones (maximum water content (Ws) of 0.35% and 16.6%,

respectively). Therefore, the absorption of the saline solution occurs at higher rate for the Quaternary sandstone as is also indicated by the capillary absorption coefficient of  $19\text{Kg/m}^2\text{h}^{1/2}$  for the Quaternary versus  $0.04\text{Kg/m}^2\text{h}^{1/2}$  for the Oligocene.

## DISCUSSION

### Origin of the building stones

The Oligocene succession, which includes sandstones and marls, form the Tchemmis hill on top of which the city of Lixus was built. Therefore, these sandstones constitute the local building stone, and thus was the most used lithotype in the construction of the city (Figs. 2; 3A; 5). The location of the historical stone quarries in the Tchemmis hill, probably roman in origin, is evidenced by the presence of extraction marks still preserved in the rock (Fig. 4B). According to the lithostratigraphic section, the largest blocks found in the base of the walls of most important buildings of the city were taken from the second morphological step of the hill (Fig. 3A), corresponding in the log to the stretch between 67 to 74m (Fig. 5).

The Quaternary sandstone and conglomerate lithotypes are relatively recent coastal deposits that crop out along the Atlantic coast of Larache. The exact location of the quarries has not been identified although they were most probably exploited from the Larache cliff where equivalent sandstones and conglomerates have been observed (Fig. 6). This location is very close to the harbour and around 4km far from Lixus, suggesting that the transport of the building rocks until the site was most probably done by boat along the river Loukkos. Most important characteristic of both the

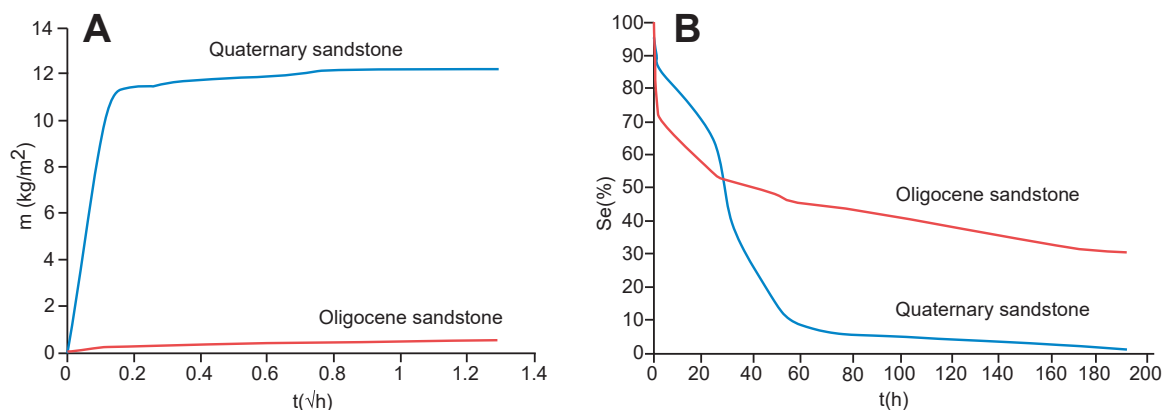
**TABLE 2.** Apparent density, relative density and total accessible porosity of the Oligocene and Quaternary sandstones. Values represent an average of six measurements for each lithotype

Lithotype	Apparent density ( $\text{g/cm}^3$ )	Relative density ( $\text{g/cm}^3$ )	Water accessible porosity (%)
Oligocene sandstone	$2.65 \pm 0.01$	$2.68 \pm 0.01$	$0.9 \pm 0.02$
Quaternary sandstone	$1.87 \pm 0.05$	$2.71 \pm 0.01$	$30.9 \pm 3.6$

Quaternary sandstone and the Quaternary shell-rich conglomerate cropping out in the Larache cliff section is the high degree of porosity typical of shoreline recent deposits, which likely facilitated the mining and shaping of the rock.

### Rock quality

Analytical results indicate that the Oligocene sandstone, which is definitely the most used lithotype, is a high-quality rock in terms of the potential alteration by water (*i.e.* hydric properties) and resistance to compressive efforts (*i.e.* mechanical properties). Firstly, the results of the hydric tests evidence that the Oligocene sandstones absorb water with difficulty (Fig. 8A), and thus the deterioration of the rock matrix associated with the flow of water in the pore network is not significant. This behaviour is attributed to the low percentage of porosity and poor communication between pores as well as the absence of clay minerals (Navarro, 1993; Zoghalmi, 2004; Zoghalmi and Gómez-Gras, 2009) (Figs. 7A; Table 2). Moreover, the rate of desorption is slow and shows interruptions as indicated by the shape of the curve (Fig. 8B), confirming a poor communication within the pore system.



**FIGURE 8.** Hydric properties of the Oligocene sandstone (red) and Quaternary sandstone (blue). A) Capillary absorption curves showing very significant differences in the absorption of water between both lithotypes. B) Desorption curves of the Oligocene sandstone (red) and Quaternary sandstone (blue) showing the difference in water loss between both lithotypes. Values represent an average of six measurements for each lithotype.

**TABLE 3.** Hydric parameters of the Oligocene and Quaternary sandstone lithotypes. Ws: water saturation under vacuum; c.A.C: coefficient water capillary absorption; Si: capillary saturation degree; Se: final water content at the end of the dry process. Values represent an average of six measurements for each lithotype

Lithotype	Ws (%)	c.A.C (kg/(m <sup>2</sup> *h <sup>1/2</sup> ))	Si (%)	Se (%)
Oligocene sandstone	0.35 ±0.07	0.04 ±0.02	25.2 ±3.4	41 ±1.7
Quaternary sandstone	16.6 ±2.8	19 ±3.5	54.3 ±4.4	4.7 ±1.6

Secondly, analytical results indicate that the Oligocene sandstone is considerably more resistant to compression than the Quaternary sandstones, and presumably than conglomerates too, and thus its capacity to support the weight of architectural elements is the highest of the three lithotypes (Table 4). Such a high resistance is attributed to the effect of diverse rock characteristics like grain size distribution, rock fabric, degree of cementation, and porosity (Siegesmund, 1996; Zoghalmi *et al.*, 2004).

#### Deterioration related to climatic conditions

This section analyses the climate conditions of the studied area and its potential influence in the low level of rock alteration observed in the building stone used in the construction of Lixus. Rock damage caused by weather conditions typically includes the effect of water, ice, moisture, soluble salts, and air pollutants, among others (Graue *et al.*, 2013). Firstly, the moderate temperatures and low rates of precipitation typical of Lixus most probably prevented a significant weathering of both mechanical and chemical types of the building rock. Accordingly, the plot of the climate characteristics of Lixus in the Peltier diagram, which relates temperature and precipitation with weathering, predict a low degree of weathering (Nagel, 2000). Secondly, and despite the lack of analytical data, air pollution in Lixus is not relevant due to its location in a rural area with low density of population. In this regard, Lixus is around

**TABLE 4.** Compressive strength of the three lithotypes. Note that all values represent an average of six measures for each lithotype

Lithotype	Compressive Strength (MPa)
Oligocene sandstone	1.17 ±0.11
Quaternary sandstone	0.12 ±0.06
Quaternary conglomerate	0.06 ±0.11

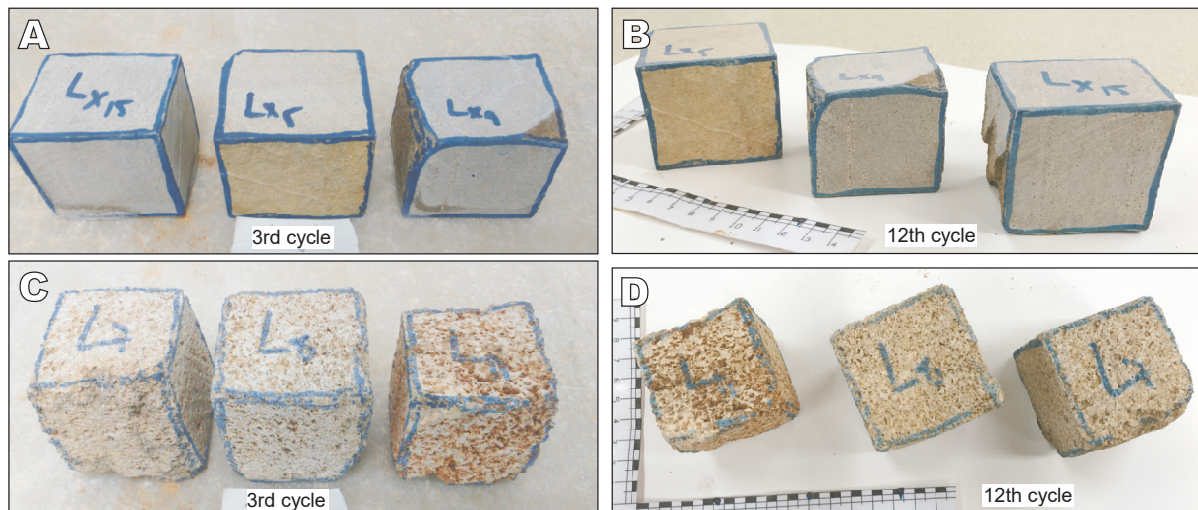
4km far from the city of Larache (125000 inhabitants) where major activities are fishing and agriculture. Finally, a potentially important factor in the alteration of the building stone of Lixus could be associated with the presence of salt (NaCl) in the environment, which is related to its location in the proximity of the Atlantic coast (Cardell *et al.*, 2003, 2008; Colston *et al.*, 2001; Ouacha *et al.*, 2013; Silva and Simão, 2009; Urosevic *et al.*, 2013). Accordingly, the results of the accelerated artificial aging test of the lithotypes in Lixus indicate a slight increase in the mass after the test, which is interpreted to result from the crystallization of salt inside the pore network (Figs. 9; 10). However, the disruptive action of the salt crystallisation within the rock mass is not significant as the real loss of mass is approximately 1% for the two lithotypes. According to Arnold and Zehender (1989), the alteration associated with salt tend to be more intense with increasing porosity and pore diameter, and thus the Oligocene lithotypes is supposed to be less ready to alteration than the Quaternary one.

In the case of the Oligocene sandstone, the low porosity (0.9%) and low saturation rate (Ws) is interpreted to prevent the circulation of fluids and to avoid salt crystallisation inside the rock (see Arnold and Zehender, 1989; Van *et al.*, 2007). Accordingly, the high resistance to salt crystallization during the aging test is attributed to the small pore size of this lithotype (Figs. 9; 10). The high compressive strength and hydric properties, which are characterized by high dry rate and low retention, play a key role in conferring such resistance to the rock against salt action (Ruedrich and Siegesmund, 2007).

The Quaternary sandstones and conglomerates, which are characterized by a very high porosity (30.9% and 45.2%, respectively), have a very well communicated pore network. The Quaternary sandstone absorb water very rapidly under ambient conditions, which is attributed to the high porosity with a very large access diameter (Fig. 8; Tables 2; 3). Therefore, the saline solution goes in and out easily from the rock, resulting in an increase of resistivity against salt impairment as well as ice crystallisation (Navarro, 1993). This is even more evident in the case of the Quaternary conglomerate that shows the highest porosity together with the largest pore radius, which avoids significant crystallization stresses.

#### CONCLUSIONS

The study of the building stones used in the construction of the Roman city of Lixus (Larache, Morocco) allows the identification of three major rock types (*i.e.* lithotypes) labelled as i) Oligocene sandstone, ii) Quaternary



**FIGURE 9.** Detail view of the cubes used for the artificial aging test showing: A, B) Oligocene sandstone after the 3<sup>rd</sup> and 12<sup>th</sup> cycle of the test, respectively; C, D) Quaternary sandstone after the 3<sup>rd</sup> and 12<sup>th</sup> cycle of the test, respectively.

sandstone and iii) Quaternary conglomerate. The analysis of the geology surrounding Lixus supported by stratigraphic logging and sampling allows locating the sites from which the lithotypes were quarried. The Oligocene sandstone, which is largely the most used building rock, was directly mined from Tchemmis hill at the top of which Lixus was built. The Quaternary sandstone and conglomerate, which represent recent coastal deposits, were most probably mined from the Atlantic coast of Larache where equivalent rocks facies have been observed.

The performance of petrographic and petrophysics standard tests allows establishing some important characteristics as building rock of the three lithotypes studied here:

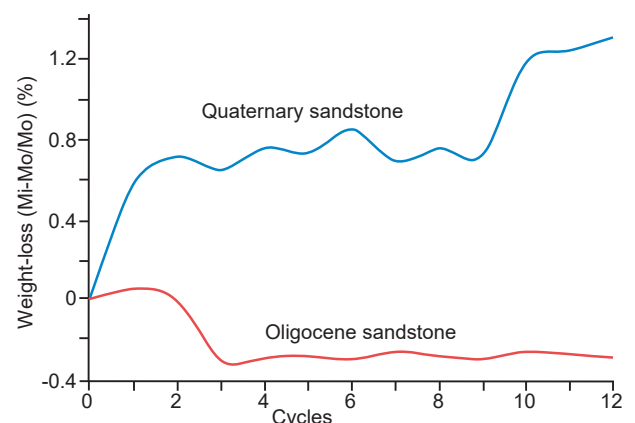
i) The Oligocene sandstone shows the best mechanical and hydric properties as a building stone due to the relatively high degree of cementation associated with the lowest porosity values. These properties make this lithotype resistant to both compression and salt crystallization, and presumably to ice too, resulting in a low level of weathering and high level of preservation.

ii) The Quaternary sandstone shows intermediate mechanical properties, resulting from a high porosity and cohesive structure. It shows a good hydric behaviour (high rate of water absorption by capillarity and an almost zero capacity of water retention) because of the high porosity values. These properties make this lithotype to be resistant to weathering by ice and salts due to the easy circulation of fluids in its pore network.

iii) The Quaternary conglomerate shows the worst mechanical properties, which result from the highest porosity (45.2%) value of all lithotypes. Its hydric

behaviour is good due to the high porosity, which facilitates the entrance and exit of the fluids through the pore system. Despite the artificial accelerated aging test not having been performed for this lithotype, this hydric behaviour indicates that the Quaternary conglomerate would probably have a low degree of deterioration due to salt crystallization.

The results of this study indicate that the generally good state of conservation of the building rocks in the city of Lixus is linked to intrinsic factors such as the petrophysical characteristics together with the gentle climatic conditions of the study area. Finally, the reported results constitute a basis for any potential work aiming to restore and preserve the historic city of Lixus for the benefit of future generations.



**FIGURE 10.** Weight-loss curves of the Oligocene sandstone (red) and Quaternary sandstone (blue) showing the behaviour of both lithotypes during salt weathering test. Mi (final weight) and Mo (initial weight). Values represent an average of six measures for each lithotype.

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