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Sedimentology and palaeoenvironmental reconstruction of the late Pleistocene deposits along the Bizerte Coast, N-E Tunisia

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The N–E Tunisian coast (Bizerte region) shows several Quaternary sedimentary archives of middle to late Pleistocene age. Sedimentological analyses carried out (grain size, morphoscopy, exoscopy, petrography, mineralogy, and fossil content) on 12 sections reveal a succession that begins with infratidal deposits attributed to the last Interglacial period, followed by intertidal, continental (palaeosol) and/or aeolian deposits (aeolianites). The arrangement of these deposits, their lithological characteristics and their faunal contents are the basis for a palaeoenvironment reconstruction and estimation of palaeoclimatic conditions. A warmer climate and a high sea level characterize the beginning of this interval, followed by a sea level fall accompanied by an alternation of humid and arid climate. This alternation is reflected by intercalations of the palaeosol levels between the aeolian deposits.

Key words: sedimentology, palaeoenvironmental reconstruction, palaeoclimate, Pleistocene, N–E Tunisia.

INTRODUCTION

Quaternary deposits outcrop widely along the Tunisian Coast, from the Tabarka region to the Tunisian-Libyan border (>1300 km). The late Pleistocene deposits of the Cap Bon, Sahel, and south-east regions are well-known (Paskoff and Sanlaville, 1976, 1983; Mahmoudi, 1986; Oueslati, 1994; Jedoui, 2000; Jedoui et al., 2002, 2003; Chakroun, 2006; Temani et al., 2008; Chakroun et al., 2009; Mauz et al., 2009, 2012; Elmejdoub and Jedoui, 2009; Mejri, 2012; Gzam et al., 2016) due to their lithological and stratigraphic diversity and fossil content.

The classification and chronology of these deposits have evolved. Issel (1914) attributed at Tyrrhenian age to Mediterranean Quaternary deposits with *Persististrombus latus* (a senior synonym of *Strombus bubonious*). Paskoff and Sanlaville (1976) were the first to use the term "formation" and proposed a complete Quaternary classification in Tunisia by distinguishing three formations (the Douira-Rejiche and Chebba formations). Mahmoudi (1986) disputed this classification and used the concept of "Regional Stratigraphic Unit" based on sedimentological criteria to describe the lithological changes of the Sahel Pleistocene deposits. He distinguished three units separated by erosion surfaces (Douira unit, Khniss unit, and Rejiche unit). Oueslati (1994) subdivided the Quaternary deposits of the Cap Bon region into four morphostratigraphic units (Oued Youssef unit, Diar Ben Salem unit, Douira unit, and Rejiche unit). The Rejiche and Douira units were correlated to the marine isotope stages (MIS) 5 and 7 based on geomorphological and biostratigraphic arguments. Later, Jedoui (2000) distinguished two lithostratigraphic units (a lower quartzose unit and an upper carbonate unit) separated by a discontinuity in the Tunisian south-east. Furthermore, Chackroun (2006), Temani et al. (2008) and Chakroun et al. (2009) extended this classification to the Cap Bon and identified the two units (quartzose and carbonate) based on their sedimentological and stratigraphic characteristics and faunal content. These two units are correlated to MIS 5e.

Based on OSL (optically stimulated luminescence) dating, several authors abandoned the classical classifications and adopted an isotopic stratigraphy. Elmejdoub and Jedoui (2009) subdivided the Pleistocene into "Pleistocene marine units" and numbered them from 1 to 5, and they assigned unit 4 (the Khniss unit equivalent) and unit 5 (the Rejiche unit equivalent) to MIS 5. Mauz et al. (2009, 2012) placed the interglacial period between 125–75 Ka. Recently, Mejri (2012) and Balescu (2015), based on the lithostratigraphy and IRSL (infra-red stimulated luminescence) dating, reused the term "formation" and correleted the Douira Formation with MIS 7-9.

Towards the north, Pleistocene deposits exposed along the Bizerte coast exhibit various lithological and sedimentological

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characterictics. Our present work comprises, a detailed sedimentological study (grain size, morphoscopy, exoscopy, petrography, mineralogy, and fauna content) of these deposits from the Ras el Korane region, in the west, to the Cap Zbib, in the east, allowing palaeoenvironmental reconstruction, determination of sea level variation, and palaeoclimate estimation during the late Pleistocene (MIS 5) along the NE Tunisia coast (Bizerte area).

GEOGRAPHICAL SETTING

The Bizerte area (N–E Tunisia; Fig. 1) is characterized by a marine Mesozoic structural succession of Cretaceous-Upper Eocene age (Rouvier, 1977; Paskoff and Sanlaville, 1983), overlapped by the Oligo-Miocene Numidian sheet.

The Pleistocene marine deposits are located a few metres above the modern sea level and rest unconformably on the earlier substrate (Triassic, Eocene, Numidian, and Pliocene). Twelve sections were studied from Ras el Korane, in the west, to Cap Zbib, in the east, grouped into four sectors, making easier the presentation and the interpretation, which are:

- Ras Angela sector: with the Ras el Korane 1 (RK1), Ras el Korane 2 (RK2) and Ras Angela (RA) sections;
- Corniche of Bizerte sector: contains the Ain Damous (AD), Grottes (Gr), Cap Bizerte (CB), Ras Blatt (RB) and El Khyem (KH) sections;
- R'Mel/Metline sector: includes the R'Mel (RM), Metline (Me) and Metline (MT) sections;
- Cap Zbib sector: with the Cap Zbib section (CZ).

MATERIAL AND METHODS

Along the NE Tunisian coast, from Ras el Korane to Cap Zbib, the Pleistocene successions exposed at the 12 sections were investigated by stratigraphic logging, and samples were collected for a series of analyses (grain size, morphoscopy, exoscopy, petrography, mineralogy and faunal content).

To interpret sediment transport mode, grain size distribution was anlysed using an "*AFNOR*" column composite by 9 sieves. The analysis was carried out on 200 grams of sediment dried in an oven at 105°C. Following sieving, weight percentage frequencies and cumulative weight percentage frequencies were computed. Grain size parameters such as graphic mean size (Mz), sorting (So), skewness (SK), and kurtosis (K) were calculated according to Folk and Ward's (1957) method.

The morphoscopic analysis was performed on the 0.25 and 0.5 mm fractions and observed under a binocular microscope (*Nikon, X40*). Based on their visual observation, quartz grains were classified in terms of roundness, sphericity and superficial appearance (Pettijohn et al., 1987). This analysis allowed palaeoenvironmental characterization and inference of transport mode.

For the exoscopic analysis, quartz grains were selected and prepared for analysis by scanning electron microscopy (SEM). Organic particles were eliminated by treatment with 15% HCL and 30% H_2O_2. The grains were then observed under a binocular microscope, picked out, and coated with gold. Photomicrographs were taken at different scales using an SEM instrument (*JEOL-JSM5400*, Tunisian Petroleum Business – ETAP, Tunisia). Microtextural features were identified on the quartz grains and classified based on previous studies (Mahaney, 2002; Costa et al., 2012; Vos et al., 2014). A semi-quantitive approach for each grain was used, based upon the proportion of the grain surface occupied by each feature. Linking these features observed on the grain surface to a defined sedimentary environment allows the reconstruction of past environments.

Petrographic studies (thin-section observations) provided information on palaeoenvironments and diagenetic transformations.

Mineralogical analysis was carried out by X-ray diffraction (XRD), used to recognize the mineralogical assemblage of the rock. This assemblage allowed a complete description of all the mineralogical phases (qualitative determination) and their rela-

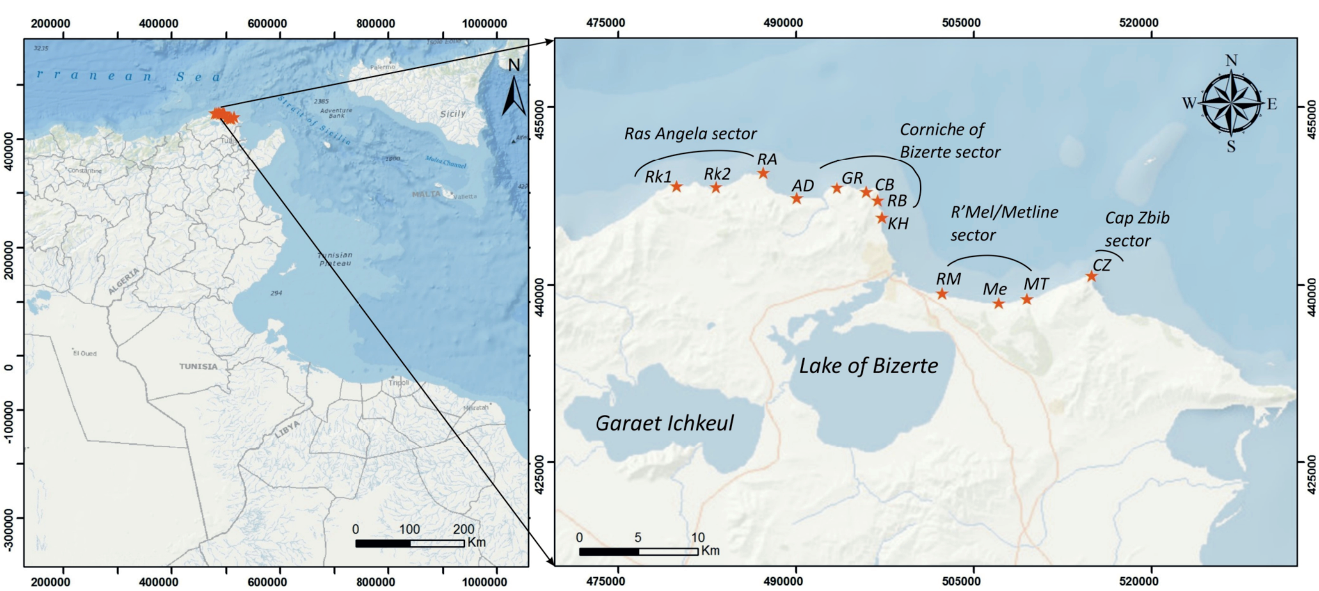

Fig. 1. Location of the region studied (Bizerte region marked by red on the left-hand map) and the sectors and sections studied (right-hand map) with RK 1 – Ras Korane 1, RK 2 – Ras Korane 2, RA – Ras Angela, AD – Ain Damous, GR – Grottes, CB – Cap Bizerte, RB – Ras Blatt, KH – El Khyem, RM – R'Mel, Me – Metline Me, MT – Metline MT, CZ – Cap Zbib

tive proportions (semi-quantitative determination). The results, in diffractogram form, show a series of peaks belonging to several minerals. The counting of the diffractograms was carried out by the "*X'pert Hight Score plus*" software.

These analyzes were completed by determination of the marine macrofauna and using their ecological characteristics to help characterize the palaeoenvironments. Taxonomic attributions were based on the World Register of Marine Species Database and the Paleobiology Database.

RESULTS – FIELD DESCRIPTION AND SEDIMENTOLOGY

RAS ANGELA SECTOR

The Pleistocene outcrops in the Ras Angela region (Fig. 2A) lie unconformably either on Numidian siliciclastic deposits (Ras Korane 1 and 2) or on the Trias (at Ras Angela). The succession begins with a thick conglomeratic level (especially in the Ras Korane 2 section, 20 cm thick) with centimetre-to decimetre-sized pebbles, of which some are lithophagous. This conglomeratic facies passes into finer facies represented by clays enriched in small pebbles arranged in oblique laminae and sandy marls. Locally, sandy limestone is observed (Ras korane 2 section) containing *Helix* shells and fossilized root traces (Fig. 3A). A second conglomerate appears either in direct contact (Ras Korane 1) or by channelling into the underlying layer (Ras Korane 2).

At the Ras Korane 2 section, the matrix hosts several species of marine gastropod [*Bolma rugosa* (Linnaeus, 1767), *Cerithium vulgatum* (Bruguière, 1792), *Conus ventricosus* (Gmelin, 1791), *Columbella rustica* (Linnaeus, 1758)], the bivalve [*Venus verrucosa* (Linnaeus, 1758)], echinoderms, sponges, and corals. Above there is a terrestrial sandstone rich in *Helix* shells and fossilized root traces. The succession ends in an aeolianite with large-scale cross-bedding.

In the Ras Korane 1 section, the succession starts with bioclastic clayey sands and *Helix* shells, and ends with a small aeolianite (0.5 m thick) with abundant *Helix* shells.

CORNICHE OF THE BIZERTE SECTOR

A basal conglomeratic bed is common to all sections (except the El Khyem section) of this sector with centimetre-to decimetre-sized pebbles of different shapes and lithologies. Locally (the Grottes section), this level hosts several marine gastropod species [*Cerithium vulgatum, Conus ventricosus, Columbella rustica, Gibbula ardens* (Von Salis, 1793), *Patella coerulea* (Linnaeus, 1758), *Phorcus richardi* (Payraudeau, 1826), *Trochus* sp. (Linnaeus, 1758), *Vermetus triquetrus* (Bivona-Bernardi, 1832)] and a bivalve species [*Glycymeris glycymeris* (Linnaeus, 1758)].

This conglomerate is followed either by sandy marls or lumachelles (at the Ain Damous and Grottes sections), or is directly overlain by fine sands with *Helix* shells (at the Cap Bizerte and Ras Blatt sections; Fig. 3B, C).

The aeolianite development marks this sector and can reach 15 m in thickness (at the Ain Damous) with abundant *Helix* shells; the large-scale cross-bedding has been commonly destroyed by intense fossil root traces.

At the Cap Bizerte and El Khyem sections, this aeolianite is intercalated by a thin sandy layer containing, at the El Khyem section, fossil wood. A calcareous encrustation appears which laterally changes into whitish sandstone rich in small gastropod shells (of an undetermined species); this is interpreted as a lagoon facies.

At the Grottes section, the Pleistocene succession is comparable to that of the previous sector, with the appearance of a second conglomerate. The following levels are represented by

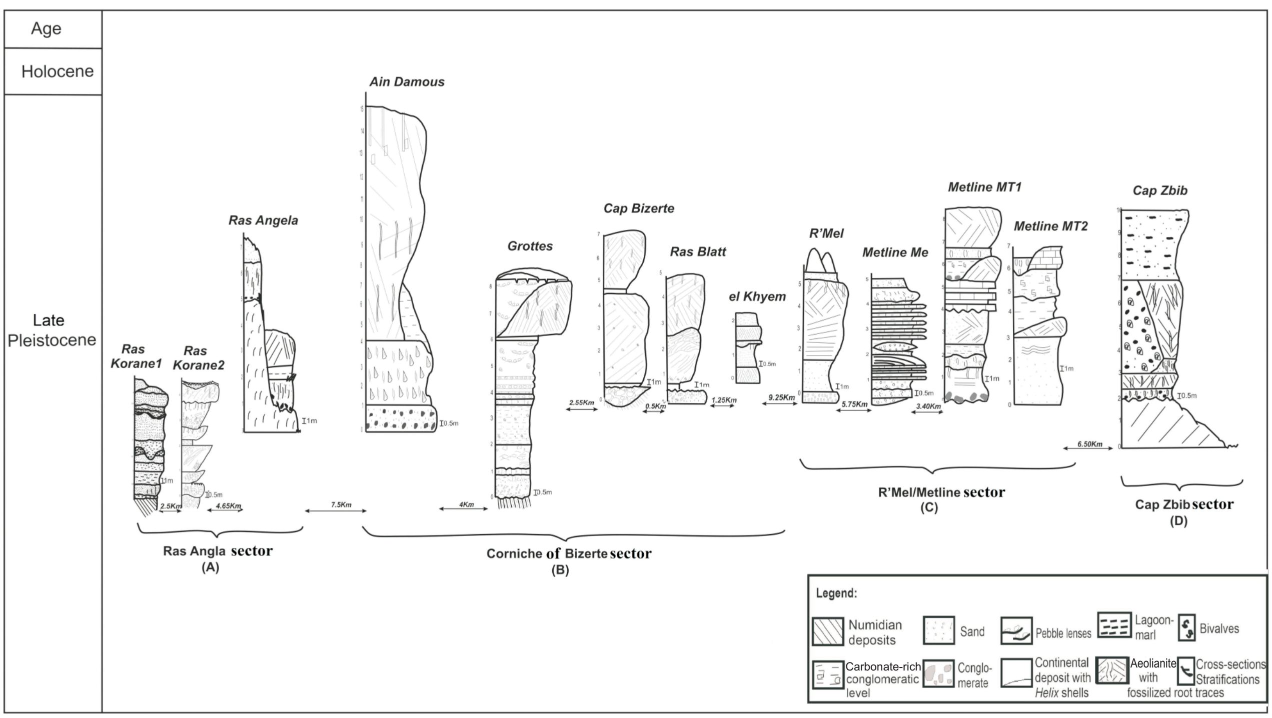

Fig. 2. Lithostratigraphic logs of the sections along the N–E Tunisia coast

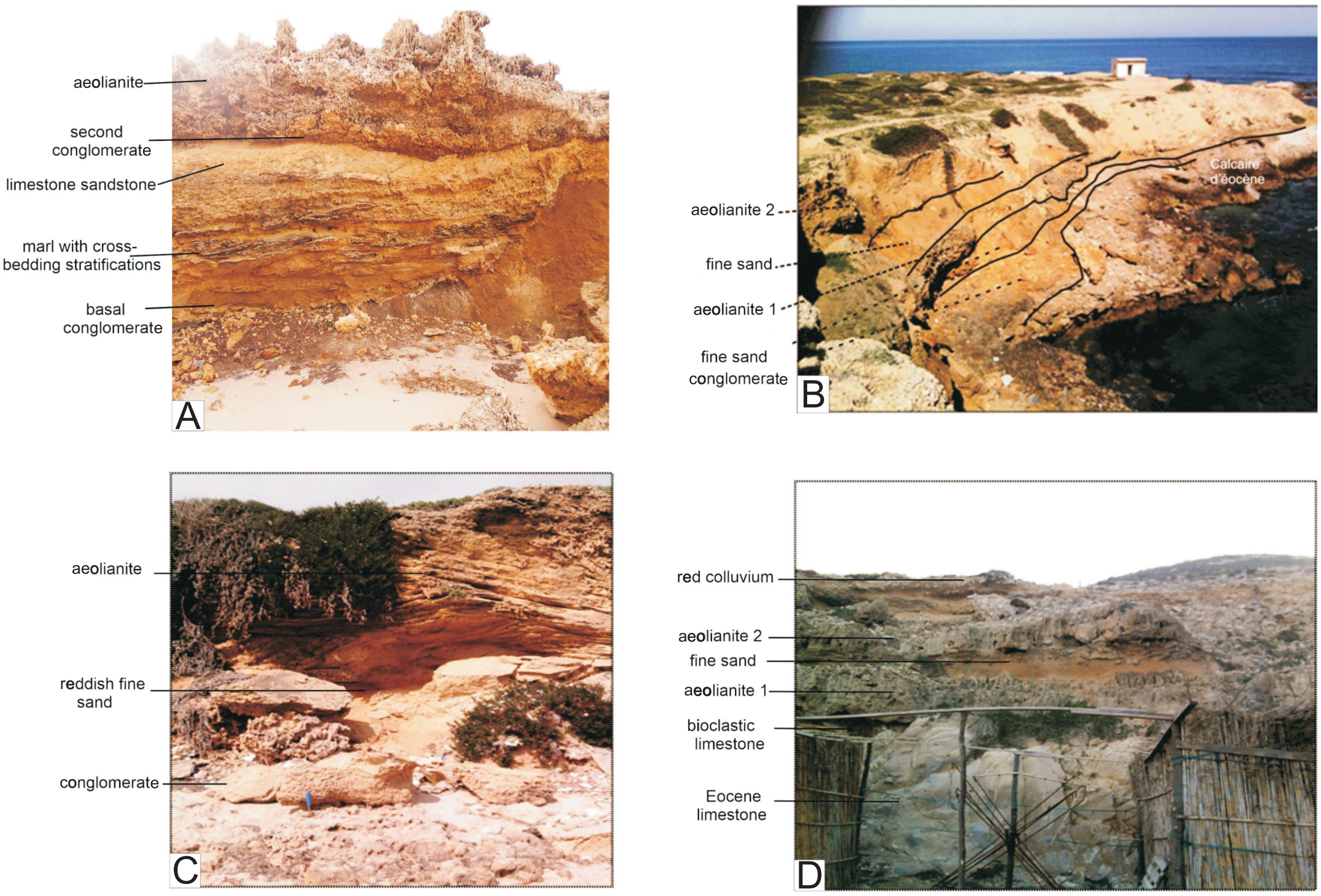

Fig. 3A – Ras Korane 2, B – Cap Bizerte, C – Ras Blatt, D – Cap Zbib outcrops with identified facies limits

clayey sands with centimetre-sized pebbles, an aeolianite which pinches out laterally and is overlain by colluvium, representing fine sand-filled channel with pebble lenses. The succession ends in an erosional surface with iron oxides and a limestone crust.

R'MEL/METLINE SECTOR

This sector represents different palaeolandscapes (Fig. 2C) following tectonic activity in the R'Mel region (Ben Ayed et al., 1979; Paskoff and Sanlaville, 1983; Martinez and Paskoff, 1984). The succession begins with intertidal facies represented either by sandstones with flat laminae or by fine sands with bivalves. Locally (at the Metline MT section) there is a 0.5 m thick conglomeratic level with different-sized pebbles.

In the Metline region, the succession continues with finer deposits. These thin sequences, of tempestite-origin, are overlain by a bioturbated level, then a thin sandy layer. The unit is overlapped by a lenticular bivalve-rich level. These members are better developed in the Metline Me section with a thicker succession and enrichment in bivalve shells. This level passes into a thin aeolianite with large-scale cross-bedding. This aeolianite can be subdivided into two members separated by a reddish fine sand layer (palaeosol).

These aeolianites are well developed in the R'Mel region with large-scale cross-bedding, fossilized root traces, and decarbonation chimney development in its uppermost part. These pockets are filled with reddish sands.

CAP ZBIB SECTOR

The Pleistocene at Cap Zbib outcrop is exposed in a steep shaped by the sea showing four notches. The section lies on white Eocene limestone (Fig. 2D). It begins with 20 cm thick bioclastic limestone rich in decimetre-to centimetre-sized pebbles and fossil shell debris. Above lies a 1 m thick aeolianite with cross-bedding and fossilized root traces. This aeolianite includes a fine reddish sand layer. 50 m to the east, this level thickens to 60 cm and is enriched in fossil shells (whole and fragmentary; Fig. 3D).

The aeolianite disappears (100 m to the west) to be replaced by a 3 m thick layer of whitish sand containing entire gastropod shells and pebbles (centimetre-sized, rounded). The succession is capped by a thick layer (~2 m) of red colluvium with angular decimetre-sized pebbles.

INTERPRETATION

RAS ANGELA SECTOR

Late Pleistocene sedimentation along the Ras Angela sector is represented by diverse facies (based on the nature, morphology and depositional features of the sediment): subtidal, intertidal, continental, lagoonal, and dune. It begins with a conglomeratic deposit with sub-angular to sub-rounded pebbles. This conglomerate underlines a first marine transgression which seems to be important, testified by the pebble size (decimetre-scale) and the faunal richness. The facies diversity is linked to the change in the depositional environment, resulting in progressive sea level retreat. This shift is represented by:

- an intertidal environment, with bioclastic sandstone limestone (carbonate content 38.4%). Laterally in the Ras el Korane 2 section, centimetre-sized carbonate nodules are developed in the uppermost part of a sandy marl layer. These nodules mark the end of the marine cycle and the transition to a hot, arid climate with contrasting seasons.
- in a lagoon environment open to the sea (only at Ras Korane 1), by greenish sandy marls enriched in *Helix* shells and marine gastropods.
- in a continental environment, by sandstone limestone or by marly sand.
- in a dune environment, by fine yellowish sand indicating a continental sedimentary regime.

A second marine pulse is represented by coarse facies with different-sized pebbles and a marine fauna. This faunal richness (Table 1) suggests a stable and favourable environmental conditions. The diverse assemblage (11 species) likely reflects a marine palaeoenvironment corresponding to the photosynthetic zone (shallow subtidal environment), in which Ca^{2+} and CO^{3-} ions were sufficiently available to allow formation of calcareous shells (Chakroun and Zaghbib-Turki, 2017). These shells are entire and well-preserved and the debris are rare. This good preservation suggests that they have not undergone long transport. Thus, they were indubitably fossilised in or close to their appropriate biotope. Moreover, the shells have never been encrusted by algae or bryozoans or perforated by lichens, showing that they were quickly buried where they lived (with the exception of *Conus ventricosus,* which includes perforated specimens with clione traces reflecting a sedimentation delay).

The faunal assemblage is dominated by *Conus* and *Bolma rugosa*. *Conus* lived at medio-to infralittoral levels under warm waters and a calm environment. *Conus ventricosus* can be considered as a biomarker reflecting a shallow subtidal environment with warm waters similar to current conditions in the tropical zone. Whereas, *Bolma rugosa* lived on rocky bottoms rich in vegetation as well as on muddy bottoms at 1–2 m depth.

The fauna within this level hosts marine and continental gastropods (*Helix* spp.). This assemblage suggests the proximity of land and the possible transport of continental sediment through a lagoon or along a river. This last hypothesis suggests an agitated environment with cold waters. However, the faunal association rather represents warm, shallow and calm waters. This biotope probably formed in a lagoon connected with the sea or in a sheltered bay.

Coral development characterizes this level. Stable climatic conditions allow the proliferation of large limestone structures, formed by corals (Laborel, 1980, 1987). However, the corals identified are poorly developed and scattered, indicating constant change in the climatic conditions.

The second marine pulse (described above) is smaller than the first, shown by the decrease in pebble size (not exceeding a few centimetres). The sea level retreat was faster, leading directly a to continental environment, and then a dune environment where large sand bodies and limestone (carbonate content 36%) were deposited.

A third sea level pulse was only detected in the Ras Korane 1 and Ras Korane 2 sections. It is shown by layer with marine fossils (rich in bivalves, gastropods, bryozoans, and corals). Above the Ras Korane 1 section, a second level of dune strata, less developed than the previous ones, appears with large-scale cross-bedding and *Helix* shells. This third transgression was of small extent and cannot be traced regionally. It may rather represent a major local event such as a tsunami or large storm (Sahli et al., 2019).

At the Ras Korane 2 section, the succession is capped by a limestone encrustation. This crust overlies carbonate-rich marine deposits (carbonate content 43%) which evolved in a subaerial environment exposed to the open air for a long period, during a regressive episode after their deposition (Mejri, 2012). The possible sea level retreat and the onset of a hot and arid climate led to induration of this limestone encrustation.

CORNICHE OF BIZERTE SECTOR

This sector is characterized by well-developed aeolian strata (Figs. 4A, B, F and 5E). The thickest dunes were recorded in the Ain Damous and Cap Bizerte/Ras Blatt sections, where they exceed 15 metres in height. Their lithology (fine to very fine sands), their petrographic criteria (packstone to grainstone texture, palisadic, stalactitic, and meniscus cement, various microfauna) and their carbonate content (36%) seem to be those of infra-intertidal environment deposits (Loope and Abegg, 2001; Le Guern, 2004; Le Guern and Davaud, 2005; Frébourg et al., 2008).

The large-scale cross-bedding reflect the prevailing palaeowind direction responsible for the particles' mobilization. The direction was determined by measuring the strike and dip of the steepest cross-beds. This shows that the generalized direction of the dominant palaeo-wind during the Late Pleistocene was to the N–W, a similar direction to the dominant wind direction today (according to the meteorological station of Bizerte, 2019).

At the El Khyem section, the development of these dunes has separated a restricted shallow environment represented by a whitish sandstone facies, carbonate-cemented and rich in *Cardium* and *Ceritium* shells.

Coastal sedimentation was more diverse in the Grottes section, showing typical facies and a unique landscape. The marine transgression was identified at two separete levels with, in each case, a conglomeratic facies with pebbles (dm- to cm-scale) and a marine fauna.

The first sea level rise brought with it gastropod shells and a single species of bivalve (Table 1). These shells range from complete to broken (worn and rolled). The poor preservation of shells reflects strong marine currents and that the biota was not fossilised in situ, but underwent substantial transport by waves and storms. The faunal assemblage reflects a marine palaeoenvironment in the photosynthetic zone, with herbivorous species (*Cerithium vulgatum, Columbella rustica, Patella coerulea*) indicating the development of algae and marine plants.

Some of the species collected (*Cerithium vulgatum, Conus ventricosus, Columbella rustica, Trochus* sp.) lived fixed or attached to plants suggesting an infralittoral, shallow, and calm environment. Other species are suspension feeders (*Vermetus triquetrus*). Their presence requires a constant renewal of the water column to ensure oxygenation and maintenance of nutrients in suspension. Therefore, such an assemblage suggests a calm, shallow marine environment, little affected by currents but with moderate agitation from tides and waves (Chakroun and Zaghbib-Turki, 2017).

The transgression in the Grottes region was gradual, passing through the intertidal (bioclastic limestone), beach (sandy marl with limestone concretions), and continental/dune (sand with *Helix* spp. shells) domain. Exoscopic analysis of various grains from these domains evokes a complex and polyphase evolution (Fig. 5C), including aeolian, subtidal, intertidal transit, fluvial evolution, and possible wind reworking. The aeolian phase seems to have been dominant and sometimes violent, as shown by the development of mechanical shock traces. Transi-

Table 1

Taxonomic composition and ecology of specimens identified in the Pleistocene deposits of Bizerte

Class	Species	Gr	RK2	Ecological characteristics (substrate, mobility, feeding)
Gastropoda	*Bolma rugosa* (Linnaeus, 1767)		■	rocky, muddy substrate, 3 to 100 m depth, mobile, epifaunal, phytophagous (feeds on algae)
	Cerithium vulgatum (Bruguière, 1792)	■	■	sandy or muddy bottoms covered with algae, shallow water, often near hard substrates, herbivorous, epifaunal
	Conus ventricosus (Gmelin, 1791)	■	■	Sandy or rocky substrate, epifaunal, creeping, mid to infralittoral; warm waters, predator, scavenger
	Columbella rustica (Linnaeus, 1758)	■	■	rochy, infralittoral (3–12 m), benthic, fixed, herbivorous
	Gibbula ardens (Von Salis, 1793)	■		warm and shallow waters, in sea grass beds, microphagal filter (bacteria and diatoms)
	Patella coerulea (Linnaeus, 1758)	■		rocky, shallow calm zone, fixed occasionally mobile, epifaunal, herbivorous
	Phorcus richardi (Payraudeau, 1826)	■		intertidal zone, rocky, herbivore (algal grazer)
	Trochus sp. (Linnaeus, 1758)	■		rocky, infratidal zone
	Vermetus triquetrus (Bivona-Bernardi, 1832)	■		rocky, infratidal zone, fixed, filter
Bivalvia	*Glycymeris glycymeris* (Linnaeus, 1758)	■		sandy or gravelly substrate, lower mediolittoral to 100 m depth, buried, suspension feeder, microphagal filter
	Venus verrucosa (Linnaeus, 1758)		■	sandy, gravelly or muddy substrate, the first metres of the infratidal (0 to 50 m), burrowing, suspension feeder
Echinoidea			■	sandy, slow-moving, deposit feeder-detritivore
Sponge			■	fixed on hard substrate, temperate marine waters, suspension feeder
Coral			■	shallow waters, biobuilders, fixed by the narrowest part

Gr – Grottes section, RK2 – Ras el Korane2 section; grey boxes – species occurrence; taxonomy and the ecological characteristics are determined from references: Abott (1960), Perrier (1975), Meco (1977), Gianolla et al. (2010), Sessa et al. (2013), Chakroun et al. (2016), Chakroun and Zaghbib-Turki (2017) and the database DORIS (Observational Data for the Recognition and Identification of Underwater flora and fauna); taxonomic attributions were up dated by using the database: the World Register of Marine Species

tion to a moderate-energy continental domain of some grains was seen in beach and continental samples. This phase is reflected by precipitation of the silica globules on the front faces and edges of the grains.

At the second conglomerate level, the pebble beds are interbedded with medium to coarse sands, with a high carbonate content (35%), and rich in entire *Helix* shells.

R'MEL/METLINE SECTOR

The absence of conglomeratic levels in this sector is a relevant difference (except in the Metline 1 section). The sedimentation environment was essentially intertidal, continental, and dune. In the Metline section, sea level changed constantly with the facies alternating between intertidal and continental. The formation of a calcareous concretion layer reveals a period of continental conditions in a warm semi-arid and seasonal climate. SEM examination of these intertidal quartz grains reveals a long and complex sedimentary history producing various micro-features (Fig. 5A). The grains observed show evidence of an earlier high-energy aeolian evolution. These grains were subsequently transported to a subtidal environment where dissolution processes dominated, then to a coastal environment with phases of emergence and submergence that characterize most of the grains. During the emergence periods, grains were easily transported by wind, as identified by conchoidal and V-shaped fractures with straight and arcuate steps.

Fining sequences allow the determination of positive sea level pulses generated by major local events (storms). These sedimentary patterns, developed on open platforms, show a vertical evolution that begins with a coarse deposit containing bivalve shells (lumachelle), sands with flat and graded laminations, and ends in fine bioturbated sands attributed to sedimentation in fair weather conditions following the storm, with a decrease in both sedimentation rate and grain size.

In the R'Mel region, sea level movement created flat oblique stratifications rich in animal bioturbations intercalated between the laminae. This bioturbation appears as straight tube burrows and reflect accommodation traces in soft, low-energy substrates. This fossil trace assemblage, or ichnofacies, belongs to the Skolithos type, which generally indicates an intertidal environment where these organisms must react quickly under stressful conditions. This ichnofacies type usually contains traces of Ophiomorpha, widely described from the Pleistocene deposits of the Tunisian Sahel (Mahmoudi, 1986).

The flat stratifications described evolve into large-scale cross-bedding, testifying to the development of dune regime sedimentation. This sedimentary regime shift was followed by a change in intrinsic properties, including a decrease in quartz grain percentage (from 50 to 30%), an increase in carbonate content (to 34%), and change in cement types (with fibrous followed by stalactitic cement).

The bedding structure of the aeolianites are mostly obscured by fossilized root traces and decarbonation chimneys (at the R'Mel section). Plant development participated in the stabiliza-

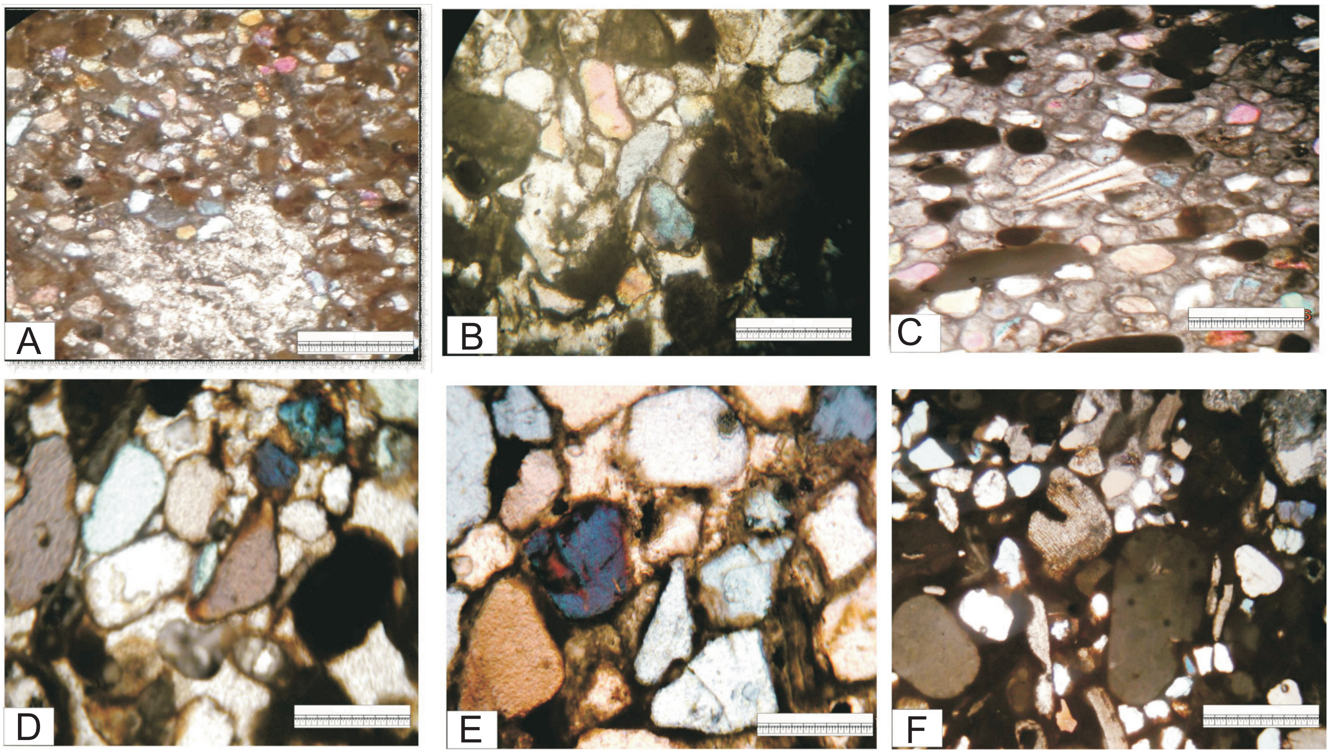

Fig. 4 – Aeolian deposit microfacies observed in the Cap Bizerte and El Khyem sections (Corniche of Bizerte sector), Metline MT section (R'Mel/Metline sector) and Cap Zbib sector

A – CB1 thin-section (Cap Bizerte section, aeolianite 1), packstone to grainstone texture, well-sorted quartz grains of sub-angular to subrounded shape and 25% abundance; **B** – CB3 thin-section (Cap Bizerte section, aeolianite 2), packstone to grainstone texture, well-sorted quartz grains of subrounded shape, meniscus cement; **C** – MT1 thin-section (Metline section), grainstone texture, abundant quartz grains different size and subangular to subrounded shape, red algae, echinoderm fragment; **D** – CZ2 thin-section (Cap Zbib section, aeolianite 1), packstone to grainstone texture, abundant quartz grains (40%) of subrounded shape, cement in meniscus; **E** – CZ4 thin-section (Cap Zbib section, aeolianite 2), packstone texture to grainstone, quartz grains 40% abundance, meniscus cement; **F** – KH1 thin-section (El Khyem section), packstone to grainstone texture, subangular to subrounded quartz grains shape; scale bar 100 μm

tion and fixation of sand particles during dune formation. The forest cover developed (to form chimneys in the deposits) contributed to the conservation of these dunes after their lithification. Therefore, the prevailing climate was characterized by abundant rainfall and cool temperatures, promoting the development of a varied and abundant flora (Paskoff, 1999). This climate characterizes Pleistocene pluvial periods in North Africa.

CAP ZBIB SECTOR

The Cap Zbib Pleistocene succession rests on conglomeratic sandstone and includes marine transgressive deposits overlain by aeolian dunes (Fig. 4D, E) with large-scale cross-bedding and fossilized root traces. These dunes are intercalated with a palaeosol, reflecting a brief period of humid, continental conditions.

SEM study of quartz grains from these sands (Fig. 5D) reveals a polyphase evolutionary history characterized by a prolonged evolution in a subtidal environment where previous wind action traces (V-shaped traces) were exploited by chemical dissolution and siliceous cupule precipitations.

Decimetre-sized sub-angular pebbles (observed in the upper red colluvium) reflect communication between the sea and at lagoon.

DISCUSSION

The late Pleistocene deposits along the Bizerte coast are represented by a large variety of facies: infratidal, intertidal, continental, aeolian, and lagoon. The succession commonly begins with conglomeratic facies associated with sea level rise. The palaeosea level was around 8 ±5m during MIS 5e (Sahli et al., 2019; Mauz et al., 2020). This rise in sea level brought in decimetre- to centimetre-sized pebbles and an abundant marine fauna. Fossil *Persististrombus latus* was absent from all the sections studied. Strombe shells (Senegalese fauna) are moderately represented on the Tunisian northern coast, such as the R'Mel and Ras Tarf regions and are abundant in Rafraf region (Paskoff and Sanlaville, 1983; Chakroun, 2006; Chakroun et al., 2016; Chakroun and Zaghbib-Turki, 2017). However, *Conus* and *Vermetus triquetorus*, part of the Senegalese fauna, are better represented and indicate shallow and warm marine

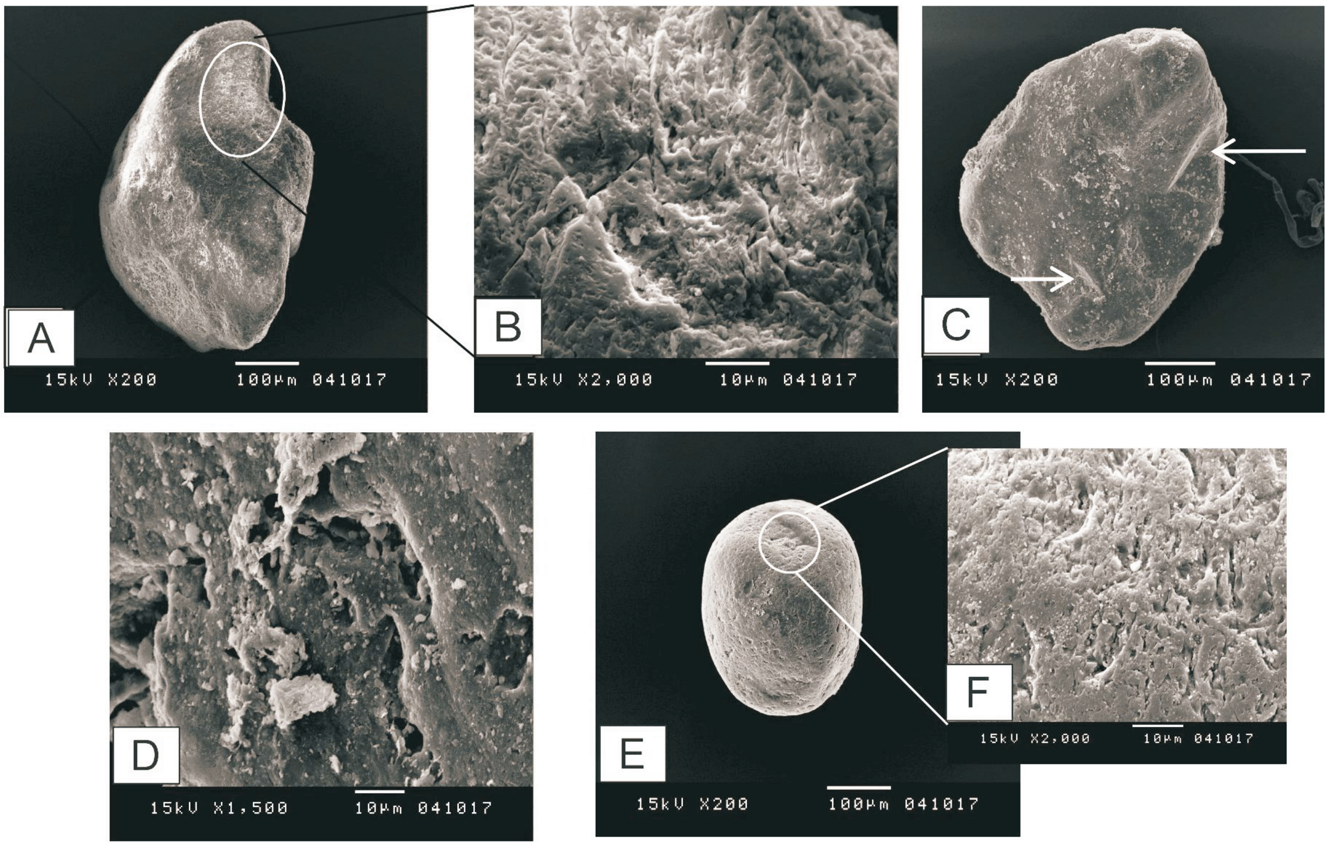

Fig. 5. Exoscopy of quartz grains from different deposits

A – general view of a quartz grain (Metline MT section, intertidal deposit, MT10 sample) elongated mat with rounded edges, a large break with a blunt outline, numerous traces of mechanical impact in nail form or large V-shaped with locally a preferential direction (image **B**, magnification); **C** – general view of a quartz grain (Grottes section, continental deposit, Gr9 sample) subrounded shiny with blunt edges and tops, two smooth crystal faces and conchoidal-fractures, precipitation of silica globules; **D** – quartz grains (Cap Zbib section, lagoon deposit, sample CZ3) showing successive V-shaped traces deeply exploited by chemical dissolution; **E** – general view of a well rounded quartz grain (Ain Damous section, eolian deposit, AD1 sample) with a surface marked by impact traces (**F**)

waters (Meco, 1977; Lozac'humeur and Mascarenhas, 1985; Muhs et al., 2014; Chakroun and Zaghbib-Turki, 2017).

The strong development of aeolianites reflects that the Bizerte coast was subject to marine currents and open sea winds, allowing carbonate particles to be transported towards the coastline on a well exposed, shallow and gently sloping platform (Le Guern, 2004; Frébourg et al., 2008). The Bizerte region is characterized by a platform extension of rasa type, which is interposed between the coastal relief and the shore (Solignac, 1927; Crampon, 1971; Miossec, 1977; Paskoff and Sanlaville, 1983). This platform is narrow at Oued Damous, then it widens at Ras Angela to reach 2 km before shrinking again. This morphology seems to be a preferential environment for dune accumulation.

The preservation of dunes dependent on climatic conditions that favor their stability (Loope and Abegg, 2001; Le Guern, 2004). This stabilization is governed by cementation (early and late) and plant cover. Rainfall must be sufficient with a moderate sedimentation rate so as to not bury the plants.

The palaeosol intercalation (fine sandy layers) between the aeolianites reflects a climate change from a humid to an arid climate (Paskoff and Sanlaville, 1983, 1986; de Menocal, 2004; Mejri, 2012). The aeolianites' development parallel to the shoreline delimits lagoons connected with the sea (at the Ras Korane 1, El Khyem, and Cap Zbib sections).

The record of major events (storms) indicates climatic deterioration during the Late Pleistocene. These events are identified either at the end of the Pleistocene succession (at the Ras Korane 1 section) or before the aeolianites' development (at the Metline section).

CONCLUSIONS

The Late Pleistocene deposits along the N–E Tunisian coast shows a sequence of subtidal to intertidal facies associated with palaeoshore and supratidal facies, and ends with dune (aeolianites) and/or continental facies (palaeosols), reflecting a high sea level followed by sea level retreat.

Field and laboratory analyses' of the faunal content and sedimentary structures indicates significant climatic changes. Maximum warming and major sea level rise mark the beginning of the Late Pleistocene, followed by a general sea level retreat and a humid climate. A relative sea level rise coincided with the aeolianites' development in an arid climate.

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