Arabian Journal of Geosciences (2019) 12: 636
https://doi.org/10.1007/s12517-019-4719-z

ORIGINAL PAPER

Sedimentology and high-frequency cycles of the late Pleistocene of the Bizerte area (N-E Tunisia)

Sahli Wided[1] · Saadi Jalila[1] · Regaya Kamel[1]

Received: 11 October 2018 / Accepted: 27 August 2019 / Published online: 16 October 2019

Abstract
Quaternary deposits are well known around the Mediterranean basin especially those exposed along the Tunisia Coast. This work focuses on the Pleistocene deposits outcropping along the Bizerte littoral (Northeastern Tunisia) with special attention to coastal deposits and their evolution during the late Pleistocene. The sedimentologic analysis carried on four cross-sections exhibits a complete Quaternary series that begin with basal erosive surface and marine deposits attributed to the last interglacial period. The Pleistocene deposits represent a 3rd-order sequence that is divided into 2 (4th–5th order) shallowing-upward sequences that are interpreted as a response to glacio-eustatic events. The lower sequence consists mainly of shoreface facies which evolve to foreshore and continental facies. The upper sequence shows a dune facies with cross-stratification and continental gastropods (eolian deposit interbedded with red to gray paleosoils). Those eolian deposits and paleosoils levels are related to the highstand system track of the 3rd-order sequence.

Keywords Bizerte · Pleistocene · Rejiche sequence · Chebba sequence · Eolianites

Introduction

Quaternary deposits exposed along the Coast of Tunisia have been studied since the beginning of the past century and their nomenclature has evolved over time with the advances in dating and analysis techniques. These deposits have been the subject of several studies (Issel 1914; Allemand-Martin, 1923, 1924; Solignac 1927; Gruet 1950; Castany 1952; Castany et al. 1954; Castany 1955; Bonifay and Mars 1959; Paskoff and Sanlaville 1976, 1977, 1978, 1980, 1983; Fournet 1982; Bonvallot and Miossec 1985; Mahmoudi 1986; Oueslati 1986*)* *enabling* researchers to assign the stratigraphic succession to the so-called "Tyrrhenian." Recently, several researchers have been interested in these deposits, especially those along the eastern shorelines (the Sahel and the Cap Bon peninsula, Djerba Island) and the northern shorelines (Rafraf) (Jedoui 2000; Jedoui et al. 2001, 2002, 2003; Davaud, 2003; Chakroun et al. 2005; Chakroun 2006; Chakroun et al. 2009a, b, 2016; Chakroun and Zaghbib-Turki, 2017; Elmejdoub and Jedoui 2009; Gzam et al. 2009; Mauz et al. 2009; Elmejdoub et al. 2011, Mejri 2012; Mejri et al. 2012; Balescu et al. 2015*)*. They have established a new frame on stratigraphy, sedimentology, paleoecology, and chronology of the Pleistocene based on correlation with glacio-eustatic changes and related them to the last interglacial period, especially to the Marine Isotopic Stage 5 (MIS 5).

Toward the north, the Bizerte Coast exhibits various Quaternary deposits with varied ages and lithologies providing spectacular landscapes. The Pleistocene deposits exposed along the northeastern Coast of Tunisia are given special attention to their various facies (littoral, continental, and eolian) and fauna content. By using classical sedimentology tools (field study and sample, a study of granulometry, morphoscopy, and petrography), this study shows new results about these deposits leading us to a better understanding of their sedimentary evolution and stacking in high-frequency cycles.

Responsible Editor: Beatriz Badenas

✉ Sahli Wided
sahliwidad@gmail.com

[1] Department of Earth Science, Faculty of Sciences in Bizerte, University of Carthage, Bizerte, Tunisia

Geographic setting and stratigraphy

The Bizerte area (northeastern of Tunisia) lies on the scale area (Rouvier 1977; Paskoff and Sanlaville 1983) and is characterized by a marine Cretaceous-upper Eocene succession that is overlaid by the Numidian thrust sheet (Oligo-Miocene) (Fig. 1). The studied Pleistocene succession and cross-section crops out in the rocky cliffs are around 5–6 m thick.

The "Tyrrhenian" term was designated to the *Persististrombus latus* (a senior synonym of *Strombus bubonious*) Mediterranean Quaternary deposits (Issel, 1914). Paskoff and Sanlaville (1977) provide geomorphological arguments and present a summarized description and subdivision of Tunisian Pleistocene deposits into different formations being genetically linked to climate events (Table 1). The three first formations were associated to the Tyrrhenian transgression. The oldest one corresponds to Douira formation and corresponds to mollusk shell–bearing beach deposits. The second formation was called Rejiche formation and includes two members; the first one is formed up by coarse-grained calcareous sandstone containing shallow marine fauna especially *P. latus*; the second member corresponds to eolian sediments rich in ooliths and pellets. The third formation was called Chebba formation and is represented by conglomerates rich in reworked and broken mollusks shells. The recent formations were linked instead to MIS 4 (eolianite of Cap Blanc formation) separated by a red sand layer indicating a regression (respectively Ain Oktor and Sidi Daoud formations). Toward the south, the Cap Blanc II formation equivalent is represented by the Tlêt formation.

Paskoff and Sanlaville's stratigraphy was subsequently confirmed by Oueslati (1986) based on the Aterian artifacts found in the dunes and terrestrial deposits outcropping in the northwestern coast of Tunisia.

However, Mahmoudi (1986, 1988) used the concept of "stratigraphic regional unit" to describe the Tyrrhenian sedimentary units of the Sahel (Table 1). Later, toward the south (Djerba Island), Jedoui (2000) suggested a new chronologic data and subdivided the series into two units: a lower quartzous unit and an upper carbonate unit, separated by a discontinuity. Likewise, Chakroun (2006) and Chakroun et al. (2009) detailed the Tyrrhenian of the Cap Bon peninsula and identified two transgressive cycles displaying a quartzous unit and a carbonate unit. Those units were respectively attributed to the MIS 5e by correlation to the identified units in the south by Jedoui (2000).

Recently, several authors adopted an isotopic stratigraphy (Elmejdoub and Jedoui 2009; Mauz et al. 2009, 2012; Mejri 2012; Balescu et al. 2015). In fact, Elmejdoub and Jedoui (2009) divided the entire Pleistocene deposits into five Pleistocene units (Table 1) and attributed unit 4 (Khniss formation equivalent) and unit 5 (Rejiche formation equivalent) to the MIS 5. Mauz et al. (2009, 2012) assumed that the interglacial period in Tunisia is between 125 and 75 ka. The same team established a new chronology based on the OSL *(optically stimulated luminescence)* dating technique. Besides, Mejri (2012) followed by Balescu et al. (2015)

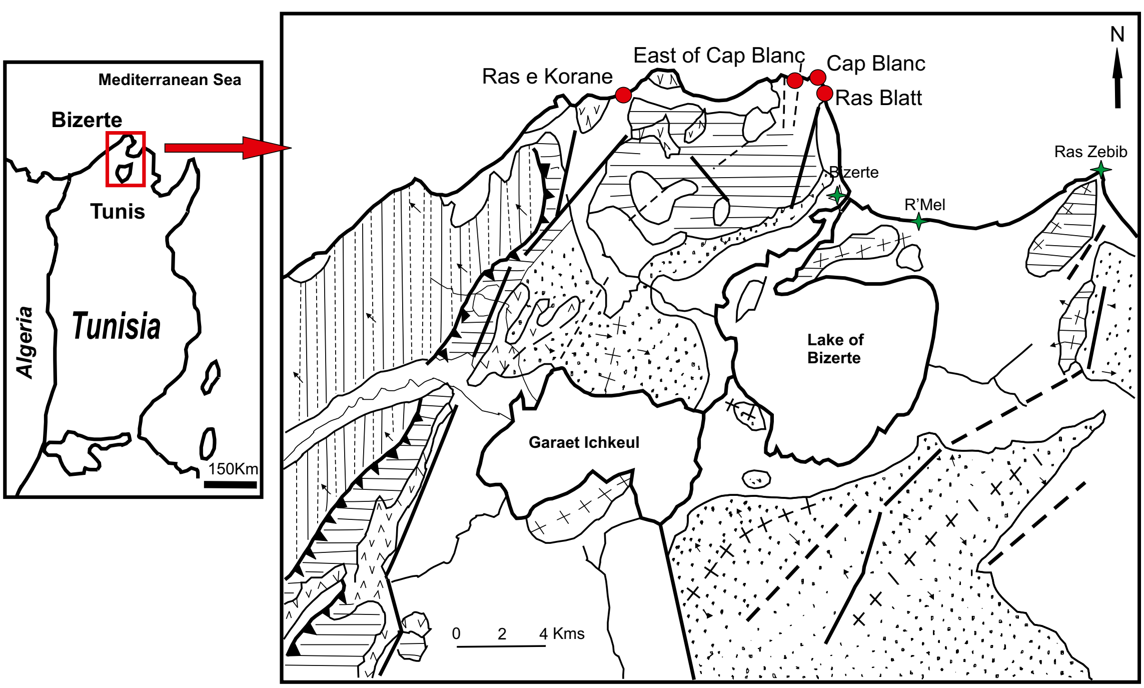

Fig. 1 Structural and tectonic map of the Bizerte area (from Rouvier 1977) and location of the studied cross-sections (Ras el Korane, East of Cap Blanc, Cap Bizerte, and Ras Blatt)

Table 1 Evolution of the Quaternary nomenclature of Tunisia. The brown squares indicate a sedimentary gap

<table>
<tr><th>Paskoff and Sanlaville (1976, 1983)</th><th>Mahmoudi (1986, 1988)</th><th>Oueslati (1994)</th><th>Jedoui (2000)</th><th>Chackroun et al. (2009)</th><th>Elmejdoub and Jedoui (2009)</th><th>Mejri (2012)</th></tr>
<tr><td></td><td rowspan="5"></td><td rowspan="5"></td><td></td><td rowspan="5"></td><td rowspan="5"></td><td rowspan="5"></td></tr>
<tr><td>Cap Blanc II formation
Tlêt formation (South)</td><td rowspan="3">Tlêt formation</td></tr>
<tr><td>Sidi Daoud formation</td></tr>
<tr><td>Cap Blanc I formation</td></tr>
<tr><td>Ain Oktor formation</td><td></td></tr>
<tr><td>Chebba formation</td><td rowspan="2">Rejiche local unit</td><td rowspan="2">Rejiche Equivalent stratigraphic unit</td><td rowspan="2">Carbonate unit</td><td rowspan="2">Carbonate unit</td><td>Pleistocene marine unit 5</td><td rowspan="4">Rejiche formation</td></tr>
<tr><td rowspan="2">Rejiche formation</td><td rowspan="3">Pleistocene marine unit 4</td></tr>
<tr><td rowspan="2">Khniss local unit</td><td rowspan="2">Khniss Equivalent stratigraphic unit</td><td rowspan="2">Quartzous unit</td><td rowspan="3">Quartzous unit</td></tr>
<tr><td>(gap)</td></tr>
<tr><td>Douira formation</td><td>Douira local unit</td><td>Douira Equivalent stratigraphic unit</td><td>(gap)</td><td>Pleistocene marine unit 3</td><td>Douira formation</td></tr>
</table>

attribute the Douira unit to the MIS 7–9 based on the IRSL (*infra-red stimulated luminescence)* dating technique.

Materials and methods

This study of the Pleistocene deposits exposed along the northeastern coast of Tunisia is based on classical sedimentological analysis, including granulometry, morphoscopy, petrography, and description of sedimentary structures and the fauna assemblage content.

The different outcrops detailed by Paskoff and Sanlaville (1983) were revisited and discussed. Four cross-sections were investigated with the most complete Pleistocene succession: Ras el Korane, East of Cap Blanc, Cap Bizerte, and Ras Blatt (Fig. 1). The stratigraphic sections were logged and coastal sediments were sampled. We have analyzed the sandy sediment (samples Gr5, Gr7, Gr8, Gr9, and Gr11 from East Cap Blanc section and RB3 from Ras Blatt section) by the granulometric method through an "AFNOR" column composite by 9 sieves for 20 mm. Weight percentage frequencies and cumulative weight percentage frequencies were computed. The grain size parameters like graphic mean size (Mz), sorting (So), skewness (SK), and kurtosis (K) were calculated according to Folk and Ward (1957) method, parameters widely used to reconstruct the depositional environment of sediments. Once decalcified with hydrochloric acid (0.1 N) and dried at 45 °C, a morphoscopic analysis was performed on the 0.25 mm and 0.5 mm refusals for all the samples, adequate size to provide quartz grains suitable for a record of both marine and eolian features. The petrographic studies of the Ras El Korane section (samples RK2, RK6, RK9, RK11, and RK13), East Cap Blanc section (samples Gr3, Gr6, Gr10, and Gr12), and Cap Bizerte section (CB2 and CB3) provide information on environmental deposits and diagenetic transformations. The sedimentary structures and the fossil content were also studied, providing valuable information about environments prevailing during the Pleistocene period. Taxonomic attributions of the fauna content were based on the World Register of Marine Species Database and the Paleobiology Database.

The correlation established in this paper is based on results from earlier-dating works (Table 2) on northern Bizerte (Paskoff and Sanlaville 1983; Richards 1986; Mathlouthi 1988; Mauz et al. 2009) and Cap Bon area (Miller et al. 1986; Elmejdoub et al. 2011), the Sahel and Southern Tunisia (Jedoui et al. 2003; Mejri 2012).

Description and sedimentology of the studied cross-sections

Ras el Korane section (GPS coordinates N37°20′0880″, E9°41′0583″)

The Ras el Korane section was detailed by Paskoff and Sanlaville (1983) where they distinguished 9 levels; however, in the present work, three main units have been differentiated

Table 2 Summary of dating results of Pleistocene littoral deposits from the Tunisian Coast

Site	Formation	Dating techniques	Dated material	Age (ka)	References
Ras el Korane	Sidi Daoud	Archeology	Upper Paleolithic industry	Aterian ≈ 40,000	Mathlouthi (1988)
R'Mel (top)	Cap Blanc	TH/U	*Glycymeris violascens*	116 ± 11	Richards (1986)
R'Mel (base)	Cap Blanc	TH/U	*Glycymeris violascens*	134 ± 12	Richards (1986)
R'Mel	Cap Blanc	OSL	Quartz	87 ± 8	Mauz et al. (2009)
Ras Zebib	Rejiche	OSL	Quartz	131 ± 7	Mauz et al. (2009)
Ras Zebib	Cap Blanc	OSL	Quartz	117 ± 7	Mauz et al. (2009)
Cap Bon	Rejiche	U/Th	*Cladocora caespitosa* (coral)	126 000 ± 700	Miller et al. (1986)
Cap Bon	Ain Oktor	OSL	Quartz	102–75	Elmejdoub et al. (2011)
Cap Bon	Sidi Daoud	OSL	Quartz	102–75	Elmejdoub et al. (2011)
Chebba	Chebba	Io-U	Lamellibranchia	61 000	Paskoff and Sanlaville (1983)
Khiss	Khniss unit	OSL	Quartz	123 ± 11	Mauz et al. (2009)
Sahel	Rejiche (marine unit)	IRSL	Alkaline Feldspars (K-Na)	101–82	Mejri (2012)
Sahel	Douira	IRSL	Alkaline Feldspars (K-Na)	213 ± 25	Mejri (2012)
Jerba	Carbonate unit	$^{230}Th/^{234}U$	*Ostrea*	120	Jedoui et al. (2003)
Jerba	Quartzous unit	$^{230}Th/^{234}U$	*Ostrea*	128	Jedoui et al. (2003)

(Fig. 2). This section brings up new data about the significant variation of facies, thickness, and coastal depositional prism. The described series disappears toward the west and exhibits only its lower part. However, its uppermost part appears toward the east. Those deposits outcrop in small cliffs notched by the sea and do not exceed 5 m in thickness.

Unit 1 has been attributed to Rejiche formation (Paskoff and Sanlaville 1983) and includes four levels ((a) to (d) in Fig. 2). The unit starts up with a shoreface bioclastic limestone (30 cm) rich in boulders and cobbles reworked from the Oligo-Miocene turbidites (level (a), Figs. 2 and 3). Size of these boulders (decimeter) and presence of lithophageal perforations indicate a river mouth where sediments are strongly removed by waves. Boulders and cobbles are embedded in a bioclastic packstone matrix rich in red algae, echinoids, miliolids, and bivalve shells (Table 4). This level is topped by hard-ground surface and is overlaid by a thin bed (20 cm) of brown clays and sandstone with mud balls (2–3 cm), which indicate a point bar estuarine deposit.

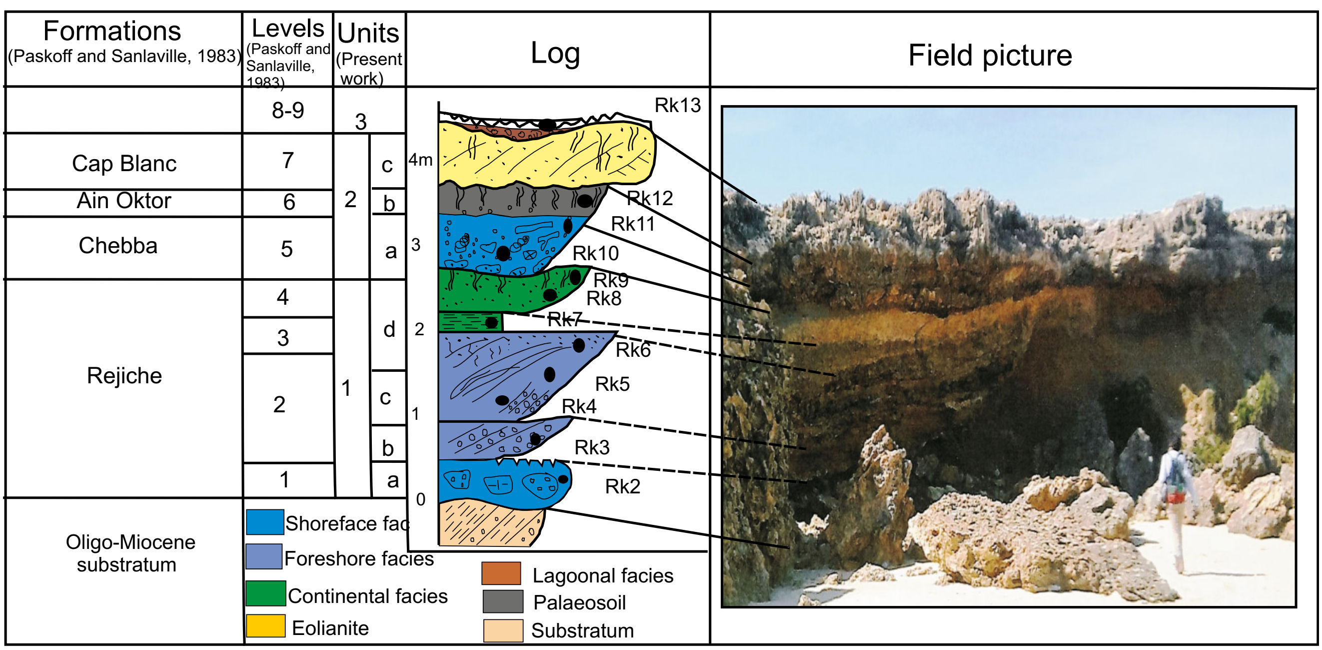

Fig. 2 Ras el Korane section with samples' location and field picture. Formations and levels from Paskoff and Sanlaville (1983) and detailed units recognized in the present work are also indicated

The following level (b) corresponds to foreshore deposits represented by bioclastic calcarenites with low-angle cross-stratification (Fig. 4). The series evolves to continental facies as yellow to brown silty marls (level (c), Fig. 4), to sandstone-limestone level (level (d)) with *Helix* shells and root structures on top. The level (d) matrix hosts several microfauna such as red algae and polypier (Fig. 5).

The lower boundary of unit 2 is an erosional surface which corresponds to a wave-ravinement transgressive surface (WRS) (Catuneanu et al. 2011), related to a second sea level rise. This unit includes three levels (a, b, and c in Fig. 2). Level (a) has been assigned to Chebba formation (Paskoff and Sanlaville 1983) based on its direct contact and clear reworking of the underlying formation (Rejiche formation). It consists of a lag deposit with reworked clasts (centimeter in size) from the underlying unit 1and Eocene limestones, and rich in entire shells of marine mollusks such as *Bolma rugosa*, *Cerithium vulgatum*, *Conus ventricosus*, *Columbella rustica*, *Glycymeris glycymeris*, and *Venus verrucosa*. The matrix hosts several marine fossils (gastropods, bivalves, red algae, echinoderms, calcareous sponges, bryozoans, and corals) (Fig. 5). Pebbles have features indicative of waves reworking (rounded to worn and flatted surfaces) and often include lithophageal perforations. Glossifungites ichnofacies appears on the upper part of this level and indicates starvation.

Level (b) is represented by continental sandstone rich in *Helix* shell and vertical root structures, attributed to the Ain Oktor paleosoil formation (Paskoff and Sanlaville 1983). The unit ends with level (c), an eolianite with root traces, attributed to the Cap Blanc formation (Paskoff and Sanlaville 1983).

Unit 3 is 20–30 cm thick corresponding to a lag deposit (Fig. 2) rich in centimeter-size pebbles and marine macrofauna (*Cerithium*, *Pecten*, oysters, sponges, corals) and a fine limestone crust with algal laminations on top. The observed matrix (Fig. 5) holds diversified microfauna (echinoids, red algae, green algae, benthic foraminifera, miliolids, and oysters). The series is topped by a sub-aerial unconformity marked by a ferruginous surface.

Unit 3 is thicker towards the west and clearly displays a shallowing-upward sequence beginning with marine deposits, lagoon deposits, and ending with eolian facies (Beseme 1981; Paskoff and Sanlaville 1983) allowing their interpretation as a distinct sedimentary sequence. In this work, we related this unit to a lenticular lagoonal deposit coeval backward of the Cap Blanc formation (level (c)).

East Cap Blanc section (GPS coordinates N37°19′5843″, E9°50′3398″)

The Cap Blanc area and its surroundings have attracted the attention since pioneer works of Aubert (1892) and Paskoff and Sanlaville (1983). The present section is logged in a cliff known locally as "les Grottes." Here, the Pleistocene deposits show a significant lateral continuity and are overlaying on the Paleocene strata with an angular unconformity.

Two units have been recognized in East Cap Blanc section (Fig. 6). Unit 1 belongs to Rejiche formation (Paskoff and Sanlaville 1983; Paskoff and Oueslati 1988) and includes four levels ((a) to (d)). Level (a) is a shoreface bioclastic marl (bivalves, gastropods) and sandy limestone. As in Ras el Korane outcrop, this first level contains pebbles from the underlying unit (Paleocene-Eocene). Pebble sizes range from

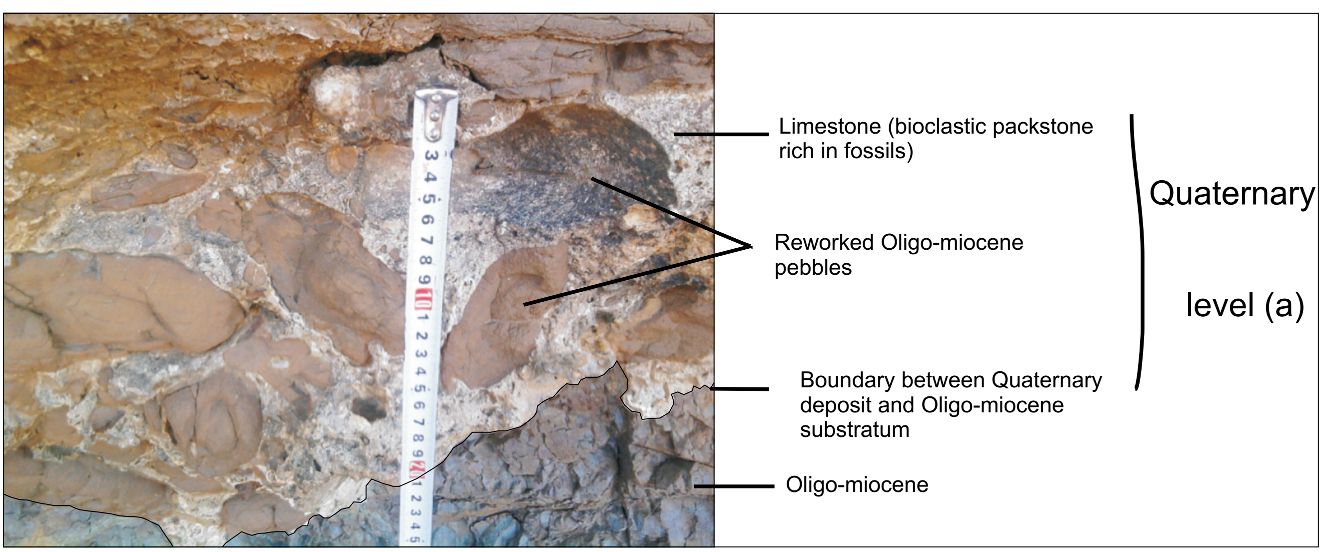

Fig. 3 Detail of the contact between Quaternary and Oligo-Miocene deposits

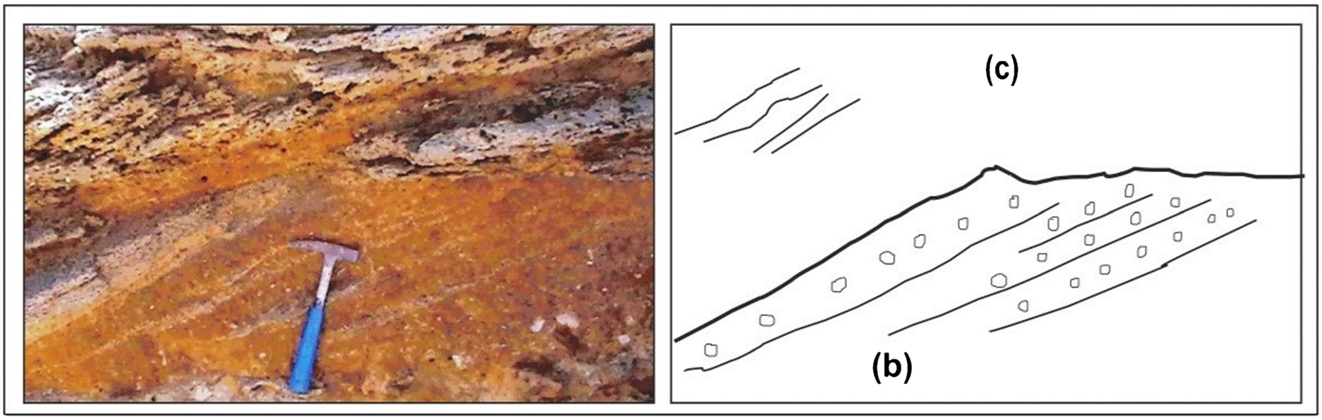

Fig. 4 Contact between level (b) and level (c); (b) foreshore deposit and (c) sandstone deposit with cross-stratification

centimeters to decimeters, and its blunted surfaces indicate wave reworking. The level hosts several marine shells such as *Cerithium vulgatum*, *Conus ventricosus*, *Conus ermineus* (synonym of *Conus testudinarius*), *Columbella rustica*, *Gibbula ardens*, *Patella caerulea*, *Phorcus richardi*, *Trochus* sp., and *Vermetus triquetrus*. However, it does not contain *P. latus* fossil. This fauna assemblage characterizes the so-called Senegalese fauna (especially *Conus ermineus* and *Vermetus triquetrus*) which refers to warm shallow sea water (Chakroun 2006; Chakroun et al. 2016; Chakroun and Zaghbib-Turki 2017). Level (a) is followed by a shoreface limestone layer (level (b)) with grainstone to packstone texture hosting several marine fossils (red algae, miliolids, bivalves, planktonic foraminifera and spicules of echinoderms) and reflecting an intertidal environment (Table 4), a foreshore sandy marl level (level (c), Fig. 5, sample Gr4), and a

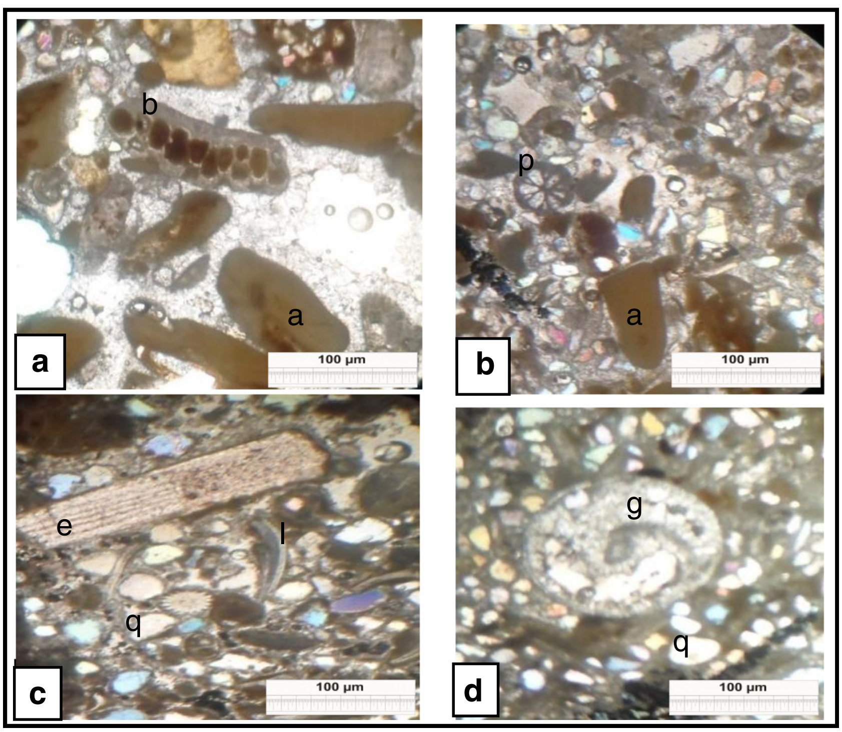

Fig. 5 Microfacies photographs of samples RK8, RK9, and RK13 from Ras el Korane section and sample Gr4 from East Cap Blanc section. (A) RK8 sample from Ras el Korane section, consolidated silty marl sediment and attributed to the eolien member of Rejiche formation, quartz grains showing angular forms. Diversified marine fauna fragments (red algae, bryoroans). (B) RK9 sample from Ras el Korane section formed by sandstone-limestone sediment, level (d) from unit 1 and attributed to Rejiche formation, quartz grains moderately classified showing sub-angular to sub-rounded forms rich in microfauna such as polypier and red algae. (C) RK13 sample from Ras el Korane section composed by consolidated sand (unit 3) with quartz grains (moderately classified and usually sub-rounded), echinoderm debris and bivalve fragments. (D) Gr4 sample from East Cap Blanc section attributed to the continental member of Rejiche formation, packstone to grainstone, misclassified quartz grains showing sub-angular to sub-rounded forms. In the middle is a large recrystallized gastropods

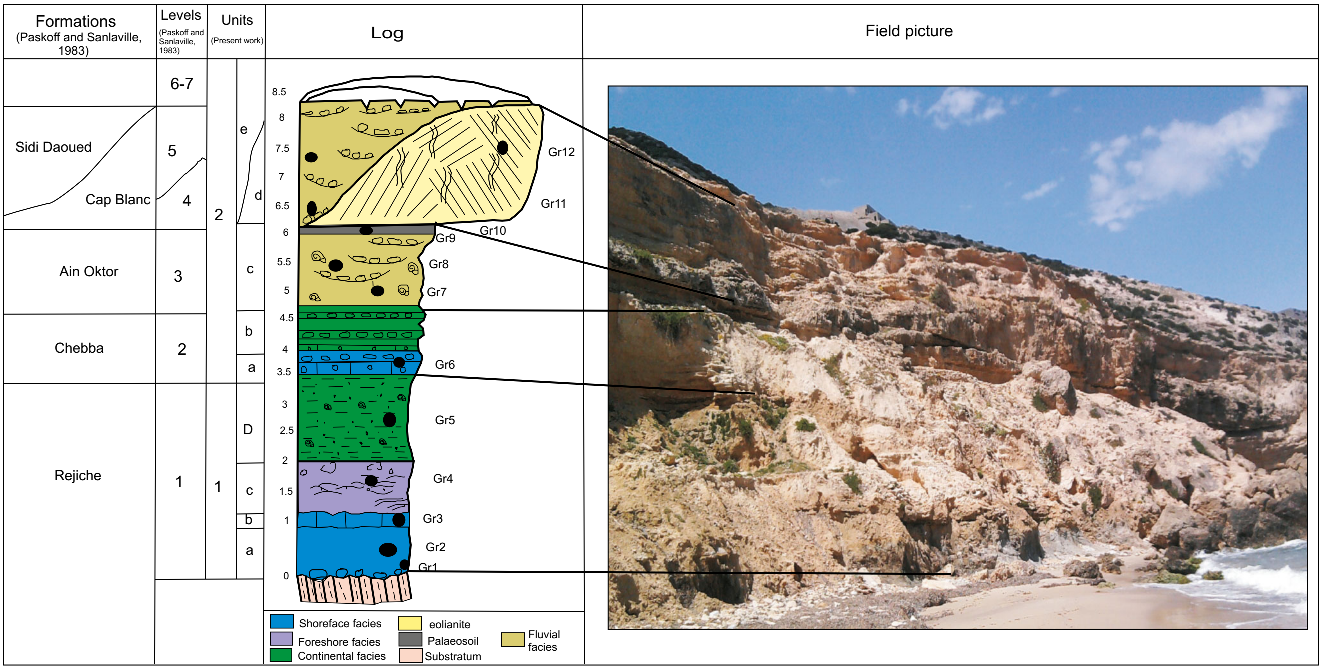

Fig. 6 East of Cap Blanc section with samples' location and field picture. Formations and levels from Paskoff and Sanlaville (1983); detailed units recognized in the present work are also indicated

continental well-sorted fine sandstone (level (d), Table 3, sample Gr5) with *Helix* shells, calcareous concretions, and a ferruginous surface on top.

Unit 2 includes 5 levels. The shoreface limestone of level (a) (Table 4) and the continental-sandstone of level (b) are attributed to the Chebba formation (Paskoff and Sanlaville 1983). This first level (level (a)) has a brecciated facies with a packstone texture, largely reworked intraclasts of clay and feldspar, and micritic cement. Its matrix hosts several marine shells (red algae, reworked miliolids, and bivalves). While, level (b) has a microbrecciated facies with a mudstone texture and few marine shells (red algae, echinoderm spicules, and bivalves). Following levels (c) and (e) are characterized by clay and sandstone (Table 3) with angular to sub-angular pebble lenses (Fig. 7), deposited by fluvial process. These levels are attributed to Ain Oktor and Sidi Daoud formations, respectively. The intercalated eolianite level (d) belongs to the Cap Blanc formation.

Sandstones of level (c) are medium-grained and well to moderately sorted and display a positive asymmetry relating to a better classification of the finest sediments (Gr7 and Gr8, Table 3). Indeed, according to Chamley (2000), positive asymmetries are mainly found in fluvial sediments enriched with fine particles decanted at the end of the flood. As a result, level (c) is a typical fluvial facies with high particle size heterogeneity (platykurtic distribution). Level (c) ends with red silty marl composed of moderately sorted, medium to coarse-grained sand grains (sample Gr9, Table 3), interpreted as a paleosoil. The eolianite of level (d) pinches out laterally as is overlaid by the fluvial sediments of level (e), representing fine sand channel with pebble lenses (sample Gr11, Table 3).

Table 3 Granulometric indices of the sandy fraction of East Cap Blanc section with mean size (Mz), sorting (SO), skewness (SK), and kurtosis (K)

Formation	Samples	Granulometric parameters				Description
		Mz	SO	SK	K	
Rejiche	Gr5	1.69	0.49	− 1.43	0.99	Fine sand, well-sorted, negative skewed, and mesokurtic distribution
Ain Oktor	Gr7	2.65	0.67	− 0.5	0.75	Coarse sand, well to moderately sorted, negative skewed, and platykurtic distribution
Ain Oktor	Gr8	0.2	0.65	0.033	0.5	Medium sand, well to moderately sorted, positive skewed, and platykurtic distribution
Ain Oktor	Gr9	0.11	0.84	− 0.43	1.58	Medium to coarse sand, moderately sorted, negative skewed, and mesokurtic distribution
Sidi Daoud	Gr11	1.91	0.38	− 0.46	1.92	Fine sand, well-sorted, negative skewed, and leptokurtic distribution

Table 4 Petrographic description of indurated levels of Ras el Korane and East of Cap Blanc sections

Formation	Sample	Site	Deposit thickness	Matrix/cement	Texture	Microfossils	Deposit environment
Rejiche unit 1, level (a)	RK2	Ras el Korane	0.5 m	Microsparitic to micritic with isopach cement	Packstone to grainstone	Red algae, echinoderm spicules, benthic forams, miliolids	Foreshore high energy facies
Rejiche unit 1, level (d)	RK6	Ras el Korane	1.5 m	Biomicritic to biomicrosparitic with an extended porosity	Packstone with angular to sub-angular quartz grains and extraclasts of clay and sandstone	Red algae, benthic forams, echinoderm spicules	Foreshore agitated
Rejiche unit 1, level (d)	RK9	Ras el Korane	2.5 m	Microsparitic to sparite	Grainstone with large debris and rounded quartz grains, acicular cement	Miliolids, red algae, spicules echinoderm, benthic forams. polypier, green algae	Beach rock high energy shore
Chebba, unit 2, level (a)	RK11	Ras el Korane	3 m	Microsparitic to sparite	Grainstone coarse quartz blunted	Red algae, green algae, benthic forams, miliolids, bryozoans, bivalves, gastropods, oysters	Foreshore
Unit 3	RK13	Ras el Korane	4.5 m	Microsparitic to sparite	Packstone to grainstone with high porosity and iron oxides	Miliolids, red algae, green algae, echinoderm spicules, polypier, bivalves, oyster	Foreshore
Rejiche, unit 1, level (b)	Gr3	East of Cap Blanc	1 m	Microsparite	Packstone to grainstone with many sub-rounded to rounded quartz grains	red algae, miliolids, bivalves, planktonic forams, spicules of echinoderms	Foreshore
Chebba, unit 2, level (a)	Gr6	East of Cap Blanc	2.5 ± 1 m	Brecciated facies with large reworked intraclasts (clay, feldspar)	Packstone, heterometric blunt rounded quartz grains	Reworked miliolids, planctonic forams, red algae	Foreshore
Ain Oktor unit 2, level (c)	Gr10	East of Cap Blanc	6 ± 1 m	Sandstone with limestone cement	Packstone with Eocene extraclacsts	Large debris of bivalves, echinoderm spicules	Continental high energy

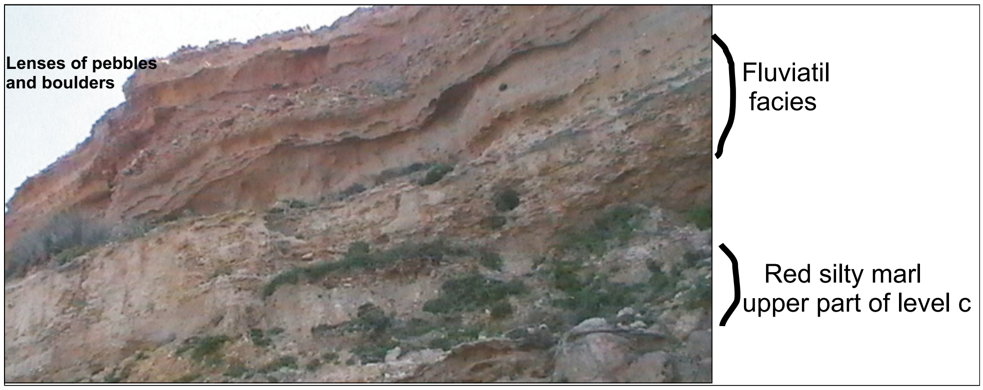

Fig. 7 Upper part of the eastern side of Cap Blanc section; detail of fluvial facies of level (e), unit 2

The eolianite and fluvial sediments of levels (d) and (e) are capped by an erosional surface with iron oxide and limestone crust, which separated them from the current sandy dunes.

Cap Bizerte section (GPS coordinates N37°20′0063″, E9°51′4303″)

The Cap Bizerte section was previously examined by Paskoff and Sanlaville (1983) then by Oueslati (1994) where they distinguish several levels (from (1) to (6)) (Fig. 8). Logged in a cliff near the current shoreline, the described Pleistocene series lies on Eocene limestones and laterally decreases in thickness before disappearing.

The Cap Bizerte section includes unit 2 of the present work (Fig. 8). It starts with a basal conglomerate (level (a)) attributed to the Chebba formation (Paskoff and Sanlaville 1983; Oueslati 1994). This attribution is based essentially on its facies, its geometry, and its stratigraphic position below the continental and eolian deposits of following levels. It is outcropping at 0 m unlike its higher altimetry observed at Ras el Korane section (3 m) and East Cap Bizerte section (3.5 m), due to recent tectonic action in the Bizerte area causing a collapse of about 100 m (Solignac 1927; Castany, 1954; Paskoff and Sanlaville 1983). This level is rich in marine fossils (red algae, bivalves, and gastropods) and animal bioturbations and includes Eocene pebbles that are centimeter to decimeter in size, dull-shaped, with frequent lithophageal perforations. This basal conglomerate ends with

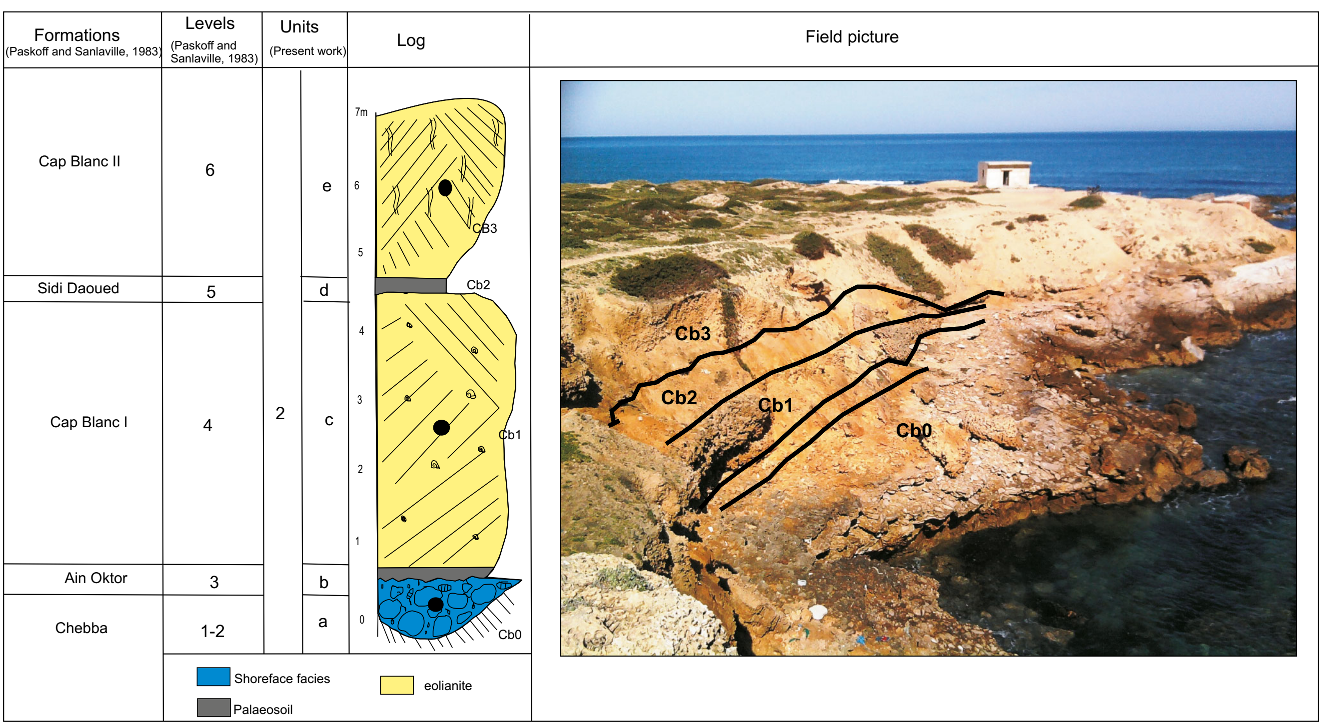

Fig. 8 Cap Bizerte section with sample location and field picture. Formations and levels from Paskoff and Sanlaville (1983); detailed units recognized in the present work are also indicated

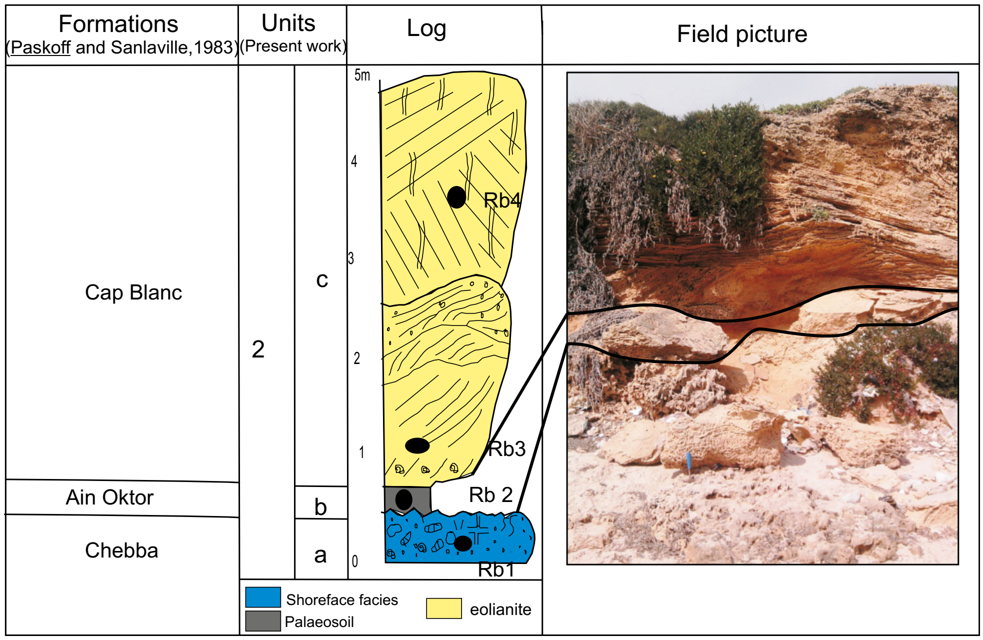

Fig. 9 Ras Blatt section with sample location and field picture. Formation and levels from Paskoff and Sanlaville (1983); detailed units recognized in the present work are also indicated

an unconformity marked by emersion surface and local iron concentrations.

Level (b) is a marl-sandy-red paleosoil corresponding to the Ain Oktor formation (Paskoff and Sanlaville 1983). Level (c) is a 3-m-thick eolianite (Cap Blanc I) and rich in *Helix* shells overcomes this paleosoil. Level (d) is the second darkest color (red to brown) paleosoil (Sidi Daoud formation; Paskoff and Sanlaville 1983). Its matrix is packstone, characterized by a high porosity percentage and the occurrence of iron oxide and phosphate grains. The meniscus cement indicates intertidal vadose environment. The series ends with a second eolianite (level (e), Cap Blanc II), less developed than the first one (2 m) and darker, showing large-scale cross-stratification and root structures (Fig. 8). The Cap Bizerte section is the only outcrop offering a superposition of the two members of the Cap Blanc formation separated by a continental level (Sidi Daoud formation). The weathered sand and silt of level (d) reflect a marine regression and a coastline too far away to supply sand-sized grains to the dune.

Ras Blatt section (GPS coordinates N37°19′4848″, E9°51′5448″)

The Ras Blatt section is located 500 m far from the Cap Bizerte section and exhibits an interesting lithostratigraphic succession compared with that of Cap Bizerte. This series starts on the border of the sea water with a marine erosional surface (wave cut platform) (Fig. 9). Formed by the present work unit 2, the first outcropping level is level (a) formed by a thin (1 m) layer of consolidated sandstone with glauconite, phosphates, strong bioturbations (vertical perforations), and desiccation cracks on top. This level holds centimeter- to decimeter-sized pebbles showing various forms depending on their nature. Sandstone pebbles are sub-angular pebbles and often are the largest ones; however, calcareous pebbles are blunt and smaller. This level is assigned to the Chebba formation (Paskoff and Sanlaville 1983; Oueslati 1994).

Level (b) is a fine layer (about 10 cm) of reddish sand (Fig. 9, Ain Oktor formation; Paskoff and Sanlaville 1983). The following level (c) consists of medium to coarse sub-angular sands, attributed to the Cap Blanc formation eolianite (Paskoff and Sanlaville 1983). The uppermost part of this eolianite exhibits preserved cross-stratification commonly destroyed by intense root traces.

Discussion

High-frequency sequences

Based on the recognition of sedimentary trends, thickness (less than 5 m), and time span, two high-frequency 4th–5th-order sequences (sensu Vail et al. 1977; Catuneanu et al. 2011) can be differentiated (Fig. 10). Each sequence includes marine to intertidal deposits, supratidal deposits, and eolian or/and continental deposits on top. The same approach was used by Le Févre and Raynal (2002) to describe the Plio-

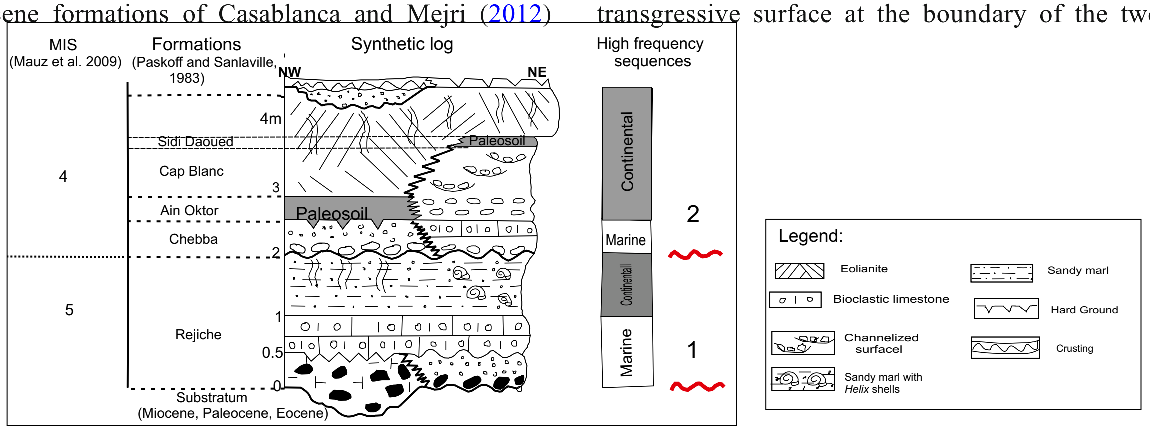

Fig. 10 Litho-stratigraphic charter and high-frequency sequences of Pleistocene of the Tunisia Northeastern Coast (Bizerte area)

Pleistocene formations of Casablanca and Mejri (2012) in the Pleistocene deposits of the Tunisian East Coast.

The two sequences are separated by an unconformity (an erosional surface) identified along the Tunisian Coast (Fig. 10) (Chakroun et al. 2005; Chakroun 2006; Chakroun et al. 2009; Temani et al. 2008).

1. The 1st sequence (Rejiche sequence) is represented by the Rejiche formation and is a shallowing- upward sequence, from shoreface deposits with a channelized bottom surface, with pebbles, foreshore deposits, and continental facies with fossilized root structures and *Helix* shells.
2. The 2nd (Chebba sequence) includes the rest of the lithostratigraphic units and begins with a conglomerate facies (lag deposit) that includes pebbles and marine macrofauna, attesting a relative sea level rise. The upper part is represented by an eolianite with fossilized root structures and *Helix* shells.

The basal discontinuity corresponds to an angular unconformity (depositional sequence boundary of a 3rd sequence order; Vail et al. 1977). Each high-frequency sequence corresponds to a regressive cycle and is separated by a transgressive surface. The origin of these sequences corresponds to the sea-level variations in relation to Quaternary climate changes (orbital cycles of Milankovitch 1930) with a 41,000-year period for each sequence.

A minor tectonic movement is noticed through these sequences which are in close relation with the general tectonic context. In fact, the northeastern part of Tunisia is one of the most tectonically active regions of North Africa (Melki et al. 2011; Bahrouni et al. 2014; Bejaoui et al. 2017). Those tectonic motions are well known along the Tunisian Coast (Kacem et al. 2001; Bouaziz et al. 2003; Mauz et al. 2009; Melki et al. 2010, 2011; Mejri 2012). Part of the northern coast is subsiding, so that the transgressive surface at the boundary of the two high-frequency cycles is below the current sea level (especially at R'Mel area; Ben Ayed et al. 1979); however, other parts are uplifted and the transgressive surface is 6 m above the modern sea level (at Ras Zebib area; Mauz et al. 2009). Moreover, Ras el Korane-Ras Angela region belongs to an anticline structure where Pleistocene marine deposits have been folded and faulted (Paskoff and Sanlaville 1983; Ben Ayed and Oueslati 1988). Thereby, significant differences in the present position of the two sequences are evident especially between Ras el Korane section and the other studied sections (East Cap Blanc, Cap Bizerte, and Ras Blatt).

Third-order sequence

Sequential analysis of the Late Pleistocene deposits exposed along the northeastern coast of Tunisia (Ras el Korane, East Cap Bizerte, Cap Bizerte, and Ras Blatt sections) and their correlation with the glacial-eustatic cycles are the basis of the definition of the sedimentary sequence (Le Févre and Raynal, 2002; Merzeraud 2009). In fact, after the rapid fall of the sea level during the Riss Glacial period (MIS 6, Emiliani 1955; Martinson et al. 1987), the platform was carved and an incised valley was formed (Fig. 11(A)). At the Riss-Würm interglacial transition (MIS 5), sea level rose and the platform was gradually flooded. During this elevation, gully bedrock is marked by the occurrence of multiple-sized pebbles at the base of the first high-frequency sequence (Rejiche sequence) originating from the underlying levels; it is indeed the initiation of the transgressive system tract (TST) of the 3rd-order sequence. The maximum flooding surface (MFS) of the 3rd-order sequence is characterized by the appearance of numerous fossils (*Cerithium vulgatum*, *Conus ventricosus*, *Conus ermineus*, *Columbella rustica*, *Gibbula ardens*, *Patella caerulea*, *Phorcus richardi*, *Trochus* sp., and *Vermetus triquetrus*) and minor channelized surfaces with flattened pebbles at the base of shoreface deposits of the high-

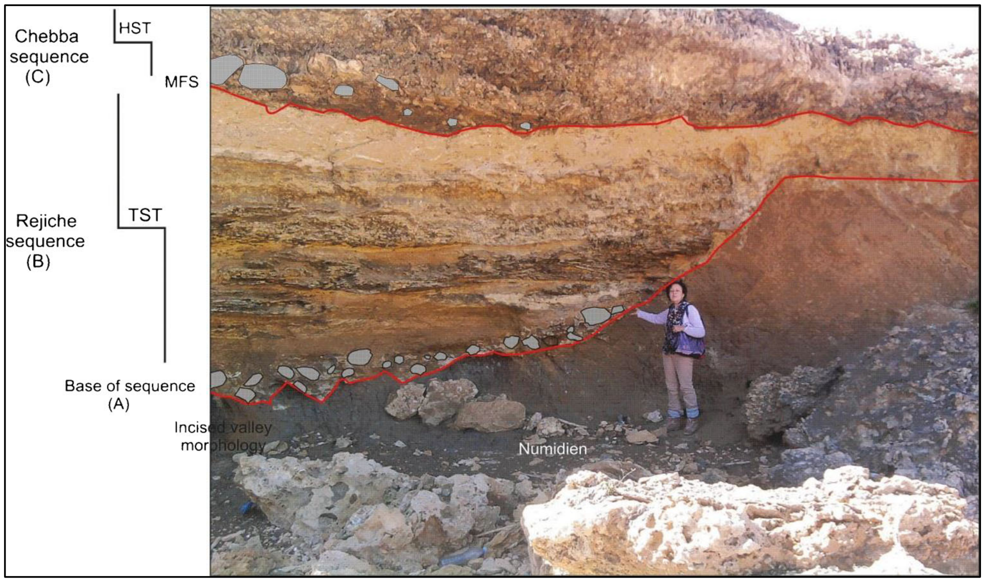

Fig. 11 Field picture of Ras el Korane section with indication of sequences limits. TST, transgressive system tract; HST, highstand system tract; MSF, maximum surface flooding

frequency Chebba sequence (Fig. 11(C)). This facies evolves to non-marine sediment (eolianite) alternating with paleosoils, representing the last sedimentary tract (highstand system tract, HST) (Fig. 11(C)).

These sedimentary successions are well-matched in the Pleistocene deposits exposed along the Tunisian Coast (Mauz et al. 2009) taking into account lithology and facies changes. Thereby, the transgressive succession is represented in the Central and Southern Tunisia by siliciclastic and carbonate shoreface deposits separated by a discontinuity. However, the highstand system tract (HST) deposits contain only coastal dunes. This significant variation in facies is the result of, on the one hand, the local tectonics and, on the other hand, the inherited paleomorphology and also the coastal dynamics prevailing during the Late Pleistocene.

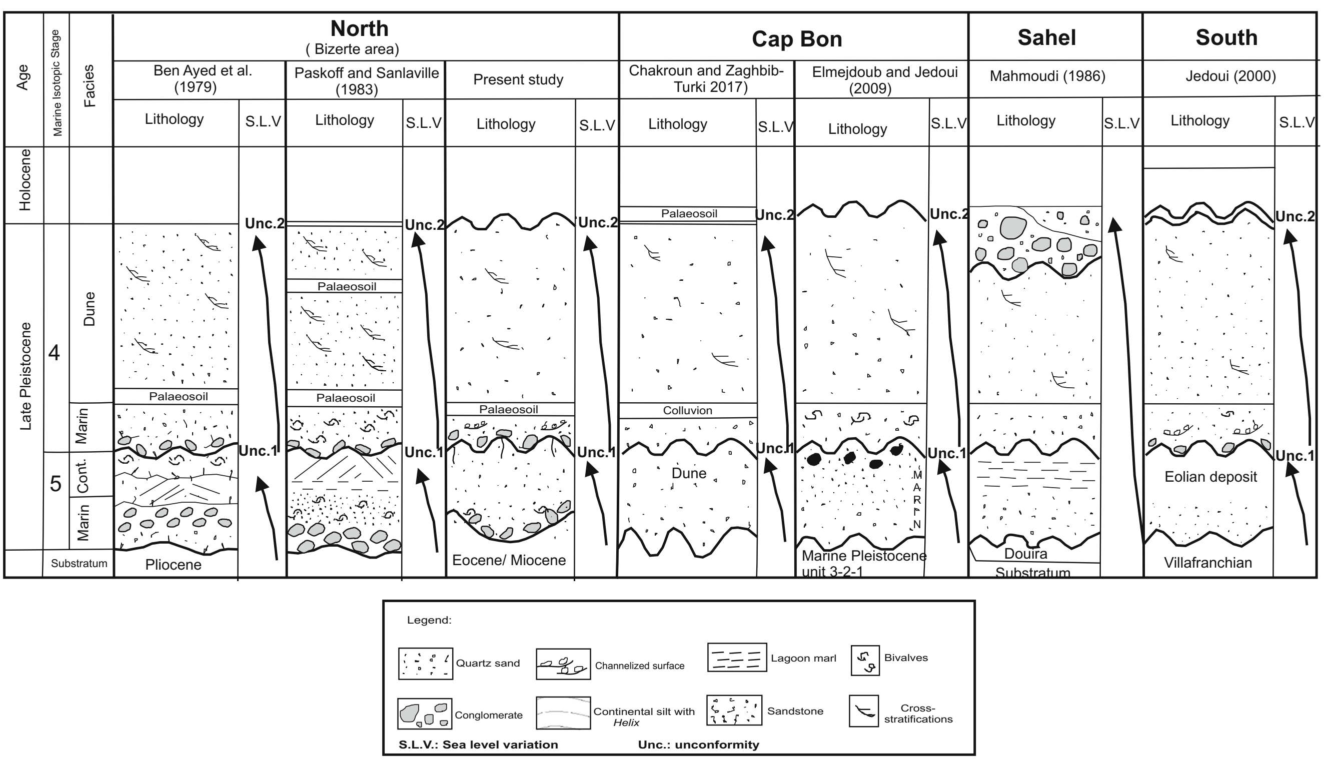

Fig. 12 Correlation of the Late Pleistocene deposits exposed along the Tunisian Coast (in the North, Cap Bon, Sahel, and the South)

Based on the works of several authors (Ben Ayed et al. 1979; Mahmoudi 1986; Jedoui 2000; Elmejdoub and Jedoui 2009; Paskoff and Sanlaville 1983; Chakroun and Zaghbib-Turki, 2017), a correlation has been established between the northeastern Pleistocene deposits and other areas (Cap Bon, Sahel, and Southern Tunisia) (Fig. 12). This correlation shows, in spite of a constant homogeneity, variation in the thickness and the facies.

Conclusion

A fine sedimentological analysis of the Pleistocene deposits exposed along the northeastern Coast of Tunisia (Bizerte Coast) provides valuable information regarding the depositional environments and sea level changes. The results obtained allowed us to recognize an alternate succession of lower marine facies and upper continental facies. These deposits are organized into 2 high-frequency sequences (Rejiche and Chebba sequences). These sequences are related to the sea-level variations in relation to orbital climate changes (glacio-eustatic) of the Milankovitch frequency band.

The originality of those Pleistocene deposits outcropping along the Bizerte Coast appears through their spatial distribution which is far from homogeneous and leads us to distinguish, over very short distances, significant differences in facies as well as in their stratigraphic position.

The chronology adopted for formations attribution and establishing correlation is based in several recent-dating works. Detailed geochronology is therefore needed to ascribe the sequences to the corresponding MIS and opens the way for further precision.

Acknowledgments We are grateful to the anonymous reviewers who kindly accept to examine our manuscript and helped to improve it through their constructive comments.

References

Allemand-Martin A (1923) Le Quaternaire de la peninsula du Cap Bon (Tunisie). C R Acad Sci 177:1446–1449

Allemand-Martin A (1924) Structure et stratigraphie générale de la peninsula du Cap-Bon. C R Acad Sci 178:778–790

Aubert F (1892) Explication de la carte géologique provisoire de la Tunisie, H. Barrière: 75–88

Bahrouni N, Bouaziz S, Soumaya A, Ben Ayed N, Attafi K, Houla Y, El Ghali A, Rebai N (2014) Neotectonic and seismotectonic investigation of seismically active regions in Tunisia: a multidisciplinary approach. J Seismol 18(2):235–256

Balescu S, Huot S, Mejri H, Barré M, Brisson LF, Lamothe M, Oueslati A (2015) Luminescence dating of Middle Pleistocene (MIS 7) marine shoreline deposits along the eastern coast of Tunisia: a comparison of K-feldspar and Na-feldspar IRSL ages. Quat Geochronol:1–6

Bejaoui H, Aifa T, Melki F, Zargouni F (2017) Structural evolution of Cenozoïc basins in northeastern Tunisia, in response to sinistral strike-slip movement on the El Alia-Teboursouk Fault. J Afr Earth Sci 134:174–197

Ben Ayed N, Oueslati A (1988) Déformations tectoniques dans le Quaternaire récent de Ras Engela (région de Bizerte Tunisie septentrionale). Géol Mediterr 23:17–21

Ben Ayed N, Bobier C, Paskoff R, Rebhi A, Viguier C (1979) Sur la tectonique récente de la plage du R'mel à l'Est de Bizerte (Tunisie nord-orientale). Géol Méditerr 6(4):423–425

Beseme P (1981) Contribution sédimentologique et micropaléontologique à la connaissance du Quaternaire récent de Ras el Korane (Tunisie septentrionale). Notes Service Géologique de Tunisie 46:119–127

Bonifay E, Mars P (1959) Le Tyrrhénien dans le cadre de la chrono. Bull Soc Géol 7:62–78

Bonvallot J, Miossec A (1985) Le Quaternaire moyen de la Tunisie: Un essai de synthèse. Physio-Géo 14(15):139–148

Bouaziz S, Jedoui Y, Barrier E, Angelier J (2003) Néotectonique affectant les dépôts marins tyrrhéniens du littoral sud-est tunisien : implication pour les variations du niveau marin. C R Géosciences 335:247–254

Castany G (1952) Paleogeographie, tectonique et orogenèse de la Tunisie. Monogr., Gégionales 2, 1, Geol. Congr., Alger: 63

Castany G (1954) Le niveau à Strombes de Tunisie. Sa place dans la chronologie préhistorique du Quaternaire. Compte-rendu Sommaire des Séances de la Société Géologique de France: 55–56

Castany G (1955) Données nouvelles sur la stratigraphie du Quaternaire de Djerba. Bull Soc Géol France 3:415–424

Catuneanu O, Galloway WE, Kendall CGSC, Miall AD, Posamentier HW, Strasser A, Tucker ME (2011) Sequence stratigraphy: methodology and nomenclature. Newsl Stratigr 44:173–245

Chakroun A (2006) Etude sédimentologique et paléontologique des affleurements du Quaternaire le long de la côte Nord Orientale de la Tunisie. PhD Thesis, University of Tunis and University of Perpignan

Chakroun A, Zaghbib-Turki D (2017) Facies and fauna proxies used to reconstruct the MIS 5 and MIS 7 coastal environments in eastern Tunisia. Geol Quart 61(2):000–000

Chakroun A, Zaghbib-Turki D, Moigne AM, De Lumley H (2005) Discovery of a Pleistocene mammalia fauna in El Geffel Cave (Cap Bon, Tunisia). C R Paleovol 4:317–325

Chakroun A, Zaghbib-Turki D, Miskovsky JC, Davaub E (2009a) Two Tyrrhenian transgressive cycles in coastal deposits of Cap Bon Peninsula, Tunisia. Quaternary 20:215–226

Chakroun A, Miskovsky JC, Zaghbib-Turki D (2009b) Quartz grain surface features in environmental determination of Aeolian Quaternary deposits in northern Tunisia. Mineral Mag 73:521–528

Chakroun A, Zaghbib-Turki D, Turki MM (2016) The Upper Pleistocene deposits in Rafraf (Northeastern Tunisia): new data on the *Persististrombus latus* level. Arab J Geosci 1–13

Chamley H (2000) Bases de sédimentologie. Dunod 2éme Ed: 178

Davaud E (2003) U-series evidence for two high Last Interglacial sea levels in southeastern Tunisia. Quat Sci Rev 22:343–335

Elmejdoub N, Jedoui Y (2009) Pleistocene raised marine deposits of the Cap Bon Peninsula (N-E Tunisia): records of sea-level high stands, climatic changes and coastal uplift. Geomorphology 112:179–189

Elmejdoub N, Mauz B, Jedoui Y (2011) Sea-level and climatic controls on Late Pleistocene coastal aeolianites in the Cap Bon Peninsula, northeastern Tunisia. Boreas 40:198–207

Emiliani C (1955) Pleistocene temperatures. J Geol 63(6):538–578

Folk RL, Ward MC (1957) Brazos River bars: a study in the significance of grain size parameters. J Sediment Petrol 27:3–27

Fournet A (1982) Relation stratigraphique entre les séquences sédimentaires quaternaires continentales et marines dans la coupe du canal d'El Haouaria (Cap Bon-Tunisie septentrional). Cah. O.R.S.T.O.M. 1:29–39

Gruet M (1950) Compte rendu de conférence. Un moins de recherches en Tunisie. Bulletin de la société d'études scientifiques de l'Anjou 1:3

Gzam M, Souissi R, Choura M, Jedoui Y (2009) Caractérisation morphologique et sédimentologique de la côte orientale de l'ile de Djerba (Sud-Est tunisien). Conférence Méditerranéenne Côtière et Maritime. Hammamet, Tunisie

Issel A (1914) Lembi fossiliferi quaternari e recenti osservati nel la Sardegna meridionale. Rendi conti Z R Accademi Nazionale di Lincei 5:759–770

Jedoui Y (2000) Sédimentologie et géomorphologie des dépôts littoraux quaternaire: reconstitution des variations des paléoclimats et du niveau marin dans le Sud-Est tunisien. PhD Thesis, University of Tunis

Jedoui Y, Kallel N, Labeyrie L, Reyss JL, Montacer M, Fontugne M (2001) Abrupt climatic variability of the Last Interglacial (marine isotopic 5e substage) recorded in the coastal sediments of southeastern Tunisia. Comptes Rendus Acad Sci Paris Earth Planet Sci 333: 733–740

Jedoui Y, Davaud E, Ben Ismail H, Reyss JL (2002) Sedimentological analysis of marine Pleistocene deposits of southeastern Tunisia: evidence of two positive eustatic pulsations during the marine isotopic substage 5e (Eemian, Tyrrhenian). Bull Soc Géol Fr 173:63–72

Jedoui Y, Reyss JL, Kallel N, Montacer M, Ben Ismail H, Davaud E (2003) U-series evidence for two high Last Interglacial sea levels in southeastern Tunisia. Quat Sci Rev 22:343–351

Kacem J, Dlala M, Hfaiedh M (2001) Etude sismique et tectonique du bassin de Kechabta-Messiftine. Implication sur l'évolution géodynamique au Nord-Est de la Tunisie. Notes du Servies Géologique de Tunis 68:5–15

Le Févre D, Raynal JP (2002) Les formations plioquaternaires du Casablanca et la chronostratigraphie du Quaternaire marin revisitées. Quaternaire 13:9–21

Mahmoudi M (1986) Stratigraphie, Sédimentologie et Diagenèse des dépôts tyrrhéniens du Sahel tunisien (Tunisie orientale). PhD Thesis, Université de Paris sud

Mahmoudi M (1988) Nouvelle proposition de subdivisions stratigraphiques des dépôts attribués au Tyrrhénien en Tunisie (région de Monastir). Bull Soc Géol Fr 3:431–434

Martinson DG, Pisias NG, Hays JD, Imbrice J, Moore TC, Shackleton NJ (1987) Age dating orbital theory of the Ice Ages: development of a high-resolution 0 to 300.000 years chronostratigraphy. Quat Res 27: 1–29

Mathlouthi S (1988) Les héritages continentaux et marins d'age quaternaire dans les environs du système lacustre de Bizerte (extreme nord-est tunisien). Méditerranée 64:42–51

Mauz B, ElMejdoub N, Nathan R, Jedoui Y (2009) Last interglacial coastal environments in the Mediterranean-Saharan transition zone. Paleogeogr Palaeoclimatol Paleoecol 279:137–146

Mauz B, Faneli F, ElMejdoub N, Barbieri R (2012) Coastal response to climate change: Mediterranean shorelines during the last interglacial (MIS5). Quat Sci Rev 02:1–10

Mejri H, Balescu S, Lamothe M, Barre M, Abichou H, Bouaziz S (2012) Mise en évidence par la luminescence des feldspaths de deux hauts niveaux marins interglaciaires du Pléistocène moyen (MIS 7 et MIS 9) le long de la côte orientale de la Tunisie (Sahel). Quaternaire 23(2):175–186

Melki F, Zouaghi T, Ben Chelbi M, Bedir M, Zargouni F (2010) Tectonosedimentary events and geodynamic evolution of the Mesozoic basins of the alpine margin, Gulf of Tunis, north-eastern Tunisia offshore. Compt Rendus Geosci 342:741–753

Melki F, Zouaghi T, Harrab S, Casas Sainz A, Bedir M, Zargouni F (2011) Structuring and evoluting of the Neogene transcurrent basins in the Tellian foreland domain, north-eastern Tunisia. J Geodyn 52: 57–69

Merzeraud G (2009) Stratigraphie séquentielle: Histoire, Principes et Applications. Société géologique de France

Milankovitch M (1930) Metematische Klimalehre und astronomische theorie der klimaschwankungen. Koppen, W. and Geiger, R., Hanbuch der klimatologie, GerbruderBorntraeger, pp 1–176

Miller GH, Paskoff R, Stearns CE (1986) Amino-acid geochronology of Pleistocene littoral deposits in Tunisia. Z Geomorphol 62:197–20.7

Oueslati A (1980) Jerba et Karkna (iles du Sud-est tunisien): Étude géomorphologique. PhD Thesis, Université de Tunis

Oueslati A (1986) Jerba et Kerkna, évolution géomorphologique au cours du Quaternaire. Publi Univ Tunis 21:210

Oueslati A (1994) Les côtes de la Tunisie. Recherches sur leur évolution au Quaternaire. La Faculté des Sciences humaines et sociales de Tunis 2:1–402

Paskoff R, Oueslati A (1988) Acquisitions récentes à propos du Quaternaire supérieur des côtes de la Tunisie. Méditerranée 64:79–84

Paskoff R, Sanlaville P (1976) Sur le Quaternaire marin de la région de Mahdia, Sahel de Sousse (Tunisie). Comptes Rendus Hebdomadaires des Séances de l'Académie des Sciences, D, Sciences Naturelles 283(16):1715–1718

Paskoff R, Sanlaville P (1977) Les Formations quaternaires de l'ile de Jerba (Tunisie), essai sur les lignes de rivages. Compte Rendu Sommaire des Séances de la Société Géologique de France 4:217–219

Paskoff R, Sanlaville P (1978) Sur l'origine de la Formation Tlêt et sa place dans la stratigraphie du Quaternaire récent de la région de Jerba-Zarzis (sud tunisien). Comptes Rendus de l'Académie des Sciences, Paris 287:1265–1268

Paskoff R, Sanlaville P (1980) Le Tyrrhénien de la Tunisie: essai de stratigraphie. Comptes Rendus de l'Académie des Sciences, Paris 290:393–396

Paskoff R, Sanlaville P (1983) Les côtes de la Tunisie: variation du niveau marin depuis le Tyrrhénien. Maison de l'Orient et de la Méditerranée:19–33

Paskoff R, Sanlaville P (1986) Oscillations climatiques en Tunisie littorale depuis le dernier interglaciaire jusqu'au début de l'holocène. Association française pour l'étude du Quaternaire 23: 78–83

Richards GW (1986) Late Quaternary deformed shorelines in Tunisia. Z. Geomorph. N. F.62: 183–195

Rouvier H (1977) Géologie de l'extrême nord tunisien, tectonique et paléogéographies superposées à l'extrémité orientale de la chaine nord maghrébine. PhD Thesis, Université de Paris

Solignac M (1927) Etude géologique de la Tunisie Septentrionale. PhD Thesis, University of Lyon

Temani R, Gaaloul N, Jedoui Y, Razgailah S (2008) Les dépôts du Pléistocène supérieur du Cap Bon (Tunisie Nord-Orientale) Caractérisation biosédimentologique et évolution spatio-temporelle. Géo-Eco-Trop:83–90

Vail PR, Mitchum RM Jr, Todd RG, Widmier JM, Thompson SIII (1977) Seismic stratigraphy and global changes of sea level. See. Payton, 49–212