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Tidally dominated Miocene deltaic deposits and pipe rocks in the Tebessa Basin, eastern Algeria: sedimentological and ichnological characteristics

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Abstract

Analyses of sedimentology, ichnology and depositional environments of Langhian–Tortonian siliciclastic deposits in the southern Tebessa Basin (eastern Algeria) have revealed a tidally dominated deltaic setting with a high concentration of vertical burrows. From south to north, two depositional environments are here distinguished in the Tebessa Basin: a subaerial lower delta plain in the Oum Ali region with the trace fossils *Ophiomorpha* and *Skolithos linearis*, and a proximal delta front with numerous *Skolithos*, situated in the Hjer Essefra area. The occurrence of *Skolithos* pipe rock in this Miocene subtidal domain is unusual. Pipe rocks have been commonly reported from shallow and well-oxygenated environments, especially from Cambrian strata; their number decreased significantly during the Ordovician, coupled with an increase in biodiversity. Here different deltaic subenvironments and tidal signals that are exceptionally well preserved in outcrops are analysed and interpreted. Different ichnotaxa are briefly described, and the uncommon density and size of *Skolithos* pipe-rock in these Miocene strata are discussed.

Key words: Delta, palaeoenvironments, *Skolithos*, Langhian–Tortonian, North Africa

1. Introduction

The siliciclastic Miocene formations of the eastern Saharan Atlas of Algeria are well known for their mammal remains, mainly in the southern part of the Tebessa Basin, Nementcha Mountains (Ducrocq et al., 2001; Mahboubi et al., 2003; Lihorau et al., 2014). Such fossils have also been recorded from Miocene strata in southwestern Tunisia (Robinson & Black, 1969; Biely et al., 1972) and have been dated as Langhian–Serravallian or Langhian–Tortonian. In spite of the importance of previous palaeontological discoveries, these formations are still relatively unexplored in terms of sedimentological and palaeoenvironmental aspects, in particular in the study area and in southwestern Tunisia, where the strata continue uninterruptedly (e.g., Durozoy, 1961; Kowalski et al., 1996).

The first studies of the Miocene series started with discoveries of teeth of *Deinotherium* and *Mastodon* in the El Kouif sandstones, approximately 2 km north of Tebessa, by Brives (1919). Later, Dubourdieu (1956), Durozoy (1961) and Vila (1977) conducted stratigraphical studies of Miocene formations to the west of Tebessa in the Khenchela area of eastern Algeria. Using planktonic foraminifera, an early Langhian–Tortonian age could be determined for these strata. Kowalski et al. (1995, 1996) conducted several tectonic studies in the study area, documenting extensive tectonic activity during the Miocene. Sedimentological studies in the study area are primarily based on petrographic analyses carried out by Hamimed & Kowalski (2001). Recent fieldwork by Mazrou & Mahboubi (2016, 2018, 2019) in the Nementcha area (south of Tebessa) and Tebessa has suggested that the Miocene tidally dominated deltaic system extends from the southeast to the northwest. These deltaic deposits have been reported as being rich in trace fossils which form pipe rocks in the Hjer Essefra area.

The highly bioturbated sandstones reveal a predominance of vertical burrows of *Skolithos* type and are commonly called 'pipe rocks' (Droser, 1991; Knaust et al., 2018). This term was initially used to describe the heavily bioturbated sandstones with vertical pipe-like burrows in the Lower Cambrian Eriboll Sandstone of Scotland (Peach & Horne, 1884). Cambro–Ordovician coastal marine sandstones have been reported to contain high densities of *Skolithos* (e.g., Beuf et al., 1971; Fabre, 1976, 2005; Droser, 1991), but *Skolithos* density diminished since then (Droser, 1991; Desjardins et al., 2010), on account of faunal diversification which led to spatial competition and possible radiation of predators.

The objectives of the present paper are to analyse Miocene palaeoenvironments of the southern Tebessa Basin and to identify the various ichnofossils. A comparison with other tidal deltas characterised by many *Skolithos*, together with a discussion of similarities and differences, is added.

Fig. 1. Location of the study area (red rectangle) and localities mentioned in the text.

2. Geographical and stratigraphical settings

2.1. Study area location

The Tebessa region is located in northeastern Algeria, along the border with Tunisia (Fig. 1). The study area extends from Btita to Hjer Essefra-Tebessa, covering nearly 634 km². It represents the southern part of the Tebessa Basin and is part of the eastern Saharian Atlas. The latter is limited by the highlands to the north, and the Saharan platform to the south (Fig. 1).

2.2. Stratigraphy

The sedimentary series outcropping in the study area, of Mesozoic–Cenozoic age (Fig. 2), is about 7,000 m thick (Dubourdieu, 1956). Miocene units overlie an angular unconformity with Cretaceous or Eocene rocks that were folded during the Middle Eocene (Lutetian). This compressive tectonic event is known as the Atlasic Phase, which led to significant northeast-northwest folding during these times.

Tectonic studies of the Tebessa area have highlighted the opening of grabens at Malabiod during the Miocene. This distension phase extended towards the Foussana and Kasserine regions in southwestern Tunisia. (e.g., Philip et al., 1986; Kowalski et al., 1996) (Fig. 2). During the same time, relatively thick detritic strata were deposited. Their thickness is about 150 m at outcrop and 250 m in the subsurface according to Durozoy (1956). In the study area, the barren deposits of Oum Ali-Malabiod have been dated as Langhian–Serravallian; those of the Bouremane and Tenoukla and Hjer Essefra zones, near Tebessa, as Tortonian (see Fig. 1 for location), by analogy with equivalent and well-dated deposits at Mechta Rmila, Koudiat Naga, located 50 km to the northwest of Tebessa (Fig. 2) (Durozoy, 1956; Kowalski et al., 1996; Hamimed et al., 2015). In contrast, the Langhian–Serravallian series of Mechta Rmila and Koudiat Naga are separated from the Tortonian sequence by an iron-crust that was dated as late Serravallian–early Tortonian (Vila, 1977; Kowalski et al., 1995). This iron-crust, which was described by several authors (Durozoy, 1961; Vila, 1977; Defaflia et al., 2015), has a regional extension and coincides with a Serravallian/Tortonian sea level fall (Haq et al., 1987).

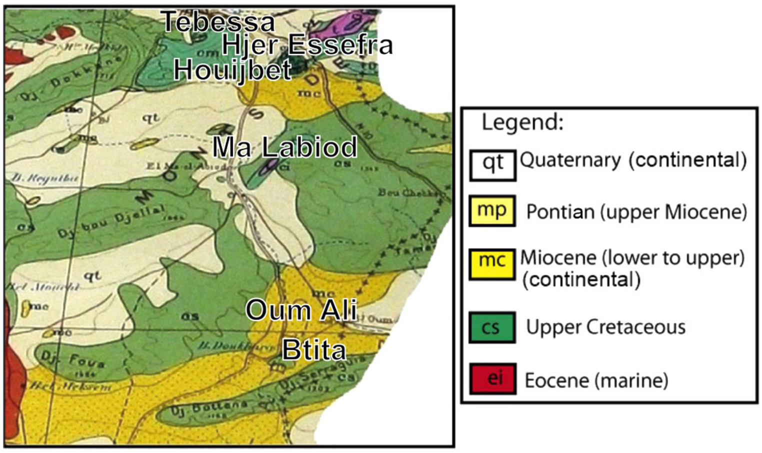

Fig. 2. Geological map of the study area.

3. Methodology

Field data were collected from a total of six quarries and seven outcrops, all situated between Btita and Tebessa, following a SSW–NNE oriented section. These data comprise detailed measured sections and descriptions of lithofacies (with symbols F), of sedimentary structures (including tidal structures) and of ichnofacies. Eight facies associations (with symbols FA) have been identified and interpreted in terms of depositional setting. Trace fossils have been studied in the field, documenting morphology, type of host rock and infill, size and orientation. The bioturbation index (BI), as established by Reineck (1963), has been used to obtain an overview of the bioturbation intensity in sedimentary successions. The index goes from 0 (= no bioturbation) to 6 (= complete bioturbation) (see Taylor & Goldring, 1993).

4. Sedimentological, ichnological and palaeoenvironmental study

The sedimentological study and palaeoenvironmental analysis of outcrops and quarries between Btita and Hjer Essefra, extending over 40 km (see Fig. 1 for location), have allowed fifteen facies (Ta-

Table 1. Description of lithofacies identified within Miocene deposits of the southern Tebessa Basin.

Facies	Description	(Ichno-)fossils	Interpretation	Facies associations
Mudstone and/or claystone (F1)	Laminated, green mudstone with rhizoliths (F1a), desiccation cracks (F1b) and gypsum (F1c). Ferrugenised sandstone with root traces (F1d). Brown mudstone with fossil trees and gypsum (F1e).	Rhizoliths, wood fragments, *Skolithos*	Aerial exposure of upper intertidal or supratidal zone (origin of palaeosoil). Hot and dry climate (gypsum, desiccation cracks, ferrugenisation).	FA1, FA2, FA8
	Laminated, green mudstones interbedded with yellow, massive and/or laminated yellow siltstones (F1f) and fine-grained sandstones, with oxidised leaf and stem imprints (F1g).	Oxidised plants	Subaerial, marshy upper intertidal flat and/or chenier. Alternating oxidation phases (colour variation of organic matter). Tidal cycles (sand-and-mud laminites). Temporary emersions (palaeosoil).	
	Mudstone with massive silt and mud (F1i) with organic matter (F1h), locally ochre-coloured horizon with syneresis cracks (F1j) and *Planolites* atop.	Planolites montanus	Anoxic conditions. Salinity changes (syneresis cracks). Prodelta distant (~40 km) from intertidal zone.	
Debris flows (F2)	Pebbly and gravelly conglomerate with sandy-clayey matrix, gypsum traces.	Tree trunks, vertebrate bones, *Palaeomastodon* or *Phiomia* tooth	Subaqueous channels with high-energy gravity flows. Proximity of exposed land (wood and bone fragments, tooth).	FA4

Facies	Description	(Ichno-)fossils	Interpretation	Facies associations
Planar cross-stratified sandstone (F3)	Sandstone (gravelly sandstone) with unidirectional planar or wedge-shaped cross-stratification. Sets up to 0.7 m thick.	*Skolithos linearis, S. annulatus, Ophiomorpha nodosa*, root traces	2D-dunes of ebb channels or ebb bars. Coastal marine environment (burrows). Temporary aerial exposure (root traces).	FA3, FA4, FA5, FA6, FA7
Low-angle cross-stratified sandstone (F4)	Fine- to coarse-grained sandstones. Sets up to 40 cm thick. Laminae dip at 4-10°.		Tidal channels. Flows of relatively low energy. Sometimes conditions of upper flow regime.	FA4, FA5, FA6, FA7
Plane-parallel laminated sandstone (F5)	Fine- to very coarse-grained sandstone with horizontal lamination. Bed thickness up to 60 cm. Sometimes clayey drapes and traces of roots.		In-channel deposition with slack water phases (F5a). Some high-energy channels (F5) on tidal bars. Conditions of upper flow regime.	FA1, FA4, FA5, FA6, FA7
Ripple cross-laminated sandstone (F6)	Fine- to medium-grained sandstones and siltstones with asymmetrical, unidirectional ripples (F6a). Medium- to coarse-grained sandstones with symmetrical ripples/dunes (F6b).	Skolithos	Low-energy tidal environment with weak currents. Oscillatory waves predominate over unidirectional currents in subtidal zone.	FA2, FA3, FA5, FA6
Structureless sandstone and siltstone (F7)	Massive, fine- to coarse-grained sandstones, siltstones. Bed thickness up to 35 cm.		Rapid deposition during ebb phases.	FA1, FA2, FA3
Heterolithic--stratified beds (F8)	Fine-grained sandstones with siltstones and mudstones. Alternation of flaser (F8a) and lenticular (F8b) lamination.	Rare *Skolithos linearis*	Tidal flat with intermittent currents. Alternating ebb currents (sandstones and siltstones) and slack-water periods (mudstones).	FA3
Sandstone with large-scale cross-stratification (F9)	Medium- to coarse-grained sandstones with trough and tabular cross-stratification. Set thickness up to 60 cm.	Numerous *Skolithos* (pipe rocks): *S. linearis, S. verticalis, S. annulatus, Diplocraterion*	3D-dunes and bars in coastal ebb channels.	FA7
Reactivation surface within foreset (F10)	High-angle (15-25°) erosion surfaces within multiple foresets. Ferruginous or ferruginous-clayey drapes.	Ophiomorpha, Skolithos linearis	Erosion of bedform during reversal flow.	FA5
Tidal bundles (F11)	Alternating intervals of tightly- and spaced-stratified sandstones. Clayey, ferruginous, marly drapes atop.	*Skolithos linearis, Ophiomorpha*	Strong, dominant ebb current followed by weak current (flood). Neap-spring water cycles controlled different dune types.	FA4, FA5
Mudstone drapes (F12)	Single and double mudstone drapes overlying sandstone beds. Drapes are 1-5 mm thick.	Rare *Skolithos linearis*	Suspension settling during tidal phases of 'slack sea'. Sand/silt layers between single and double drapes resulted from dominant tidal current and subordinate/flood current.	FA3, FA4a
Overturned ripple structures (F13)	Medium- to coarse-grained sandstone with overturned ripple cross-lamination.		Deposition from traction transport and deformation by shear stress of current and escaping pore water.	FA6
Bipolar stratified sandstone (F14)	Bipolar ('herringbone') beds up to 1 m thick.		Two (ebb and flood) currents of equal intensity.	FA4, FA5, FA7
Sandstone with sigmoidal cross-stratification (F15)	S-shaped cross-stratified beds of centimetric-to-decimetric thickness.		Accelerating flow to full-vortex conditions, followed by deceleration phase during single tide.	FA5, FA7

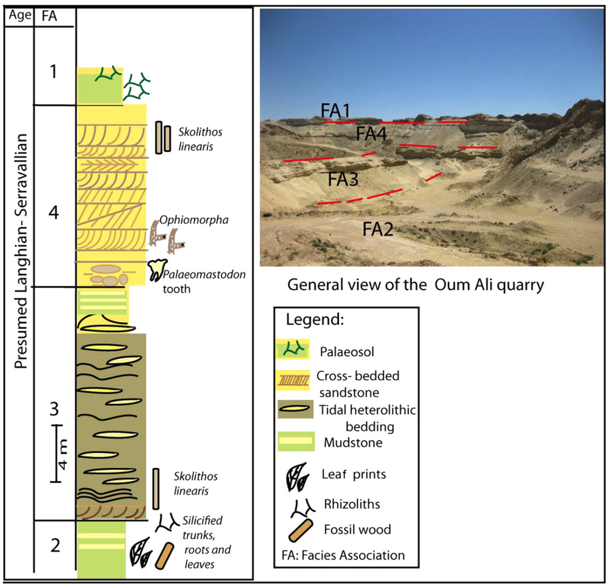

Fig. 3. Generalised synthetic log of and facies associations in the Oum Ali succession.

ble 1) and eight facies associations (FA) to be documented; these are described in detail below.

Facies associations FA1, FA2, FA3 and FA4 are well represented in the Oum Ali and Btita regions (Fig. 3), whereas FA5, FA6, FA7 and FA8 crop out between Malabiod and Hjer Essefra (Fig. 1).

4.1. Facies association FA1: palaeosoil of supratidal zone

Description. FA1 (Fig. 4) is well represented at the Oum Ali and Houijbet quarries (Fig. 1), where it overlies FA4. It is represented by green or/and brown, sandy or silty-clayey deposits, locally with tree trunks. Greenish silty-clayey deposits contain rhizoliths (F1a) (Fig. 4A), desiccation cracks (F1b) and gypsum (F1c). FA1a is also locally represented by ferrugenised sandstones bearing tubular root traces and a few *Skolithos* burrows (F1d) (Fig. 4B). Mudstone with a rhizolith level is overlain by brown clays, mudstones or sandy-clay with traces of organic matter, bearing tree trunks (F1e) and gypsum (Fig. 4C).

Interpretation. Fine deposits with tree fossils and rhizoliths, constituting a palaeosoil which formed under hot and semi-arid climatic conditions, as evidenced by gypsum and desiccation cracks (e.g., Vatan, 1967; Miall, 1996), which are often observed in mudstones. Such climatic conditions were also highlighted in prior studies by Laffite (1939) and Guiraud (1990), who studied Miocene deposits in neighbouring regions.

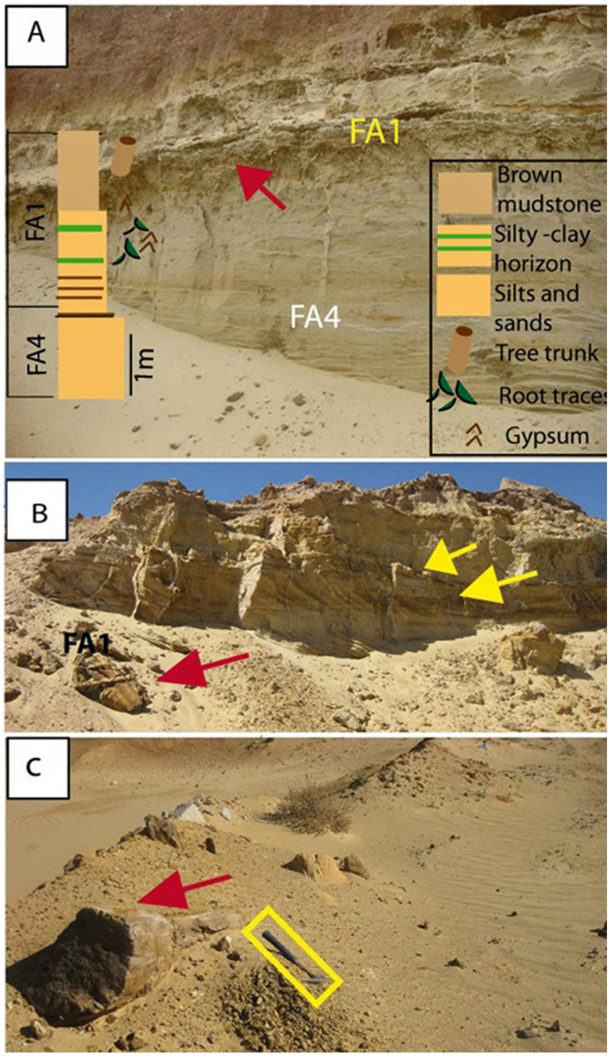

Fig. 4. FA1 at Oum Ali: palaeosoil. **A –** Green silty clays with rhizoliths (FA1, arrowed); **B –** Oxidised level at top of sandstone (FA4, yellow arrows). Ferruginised tubular root traces, not in place (red arrow); **C –** *In-situ* tree trunks within a brown mudstone (arrowed), hammer for scale.

Deposits of FA1 belong to the supratidal zone and/or upper intertidal zone (Desjardins et al., 2010; Daidu et al., 2013).

4.2. Facies association FA2: vegetated upper intertidal flat and/or interchannel zone of lower deltaic plain

Description. FA2 is a weakly laminated green mudstone (Fig. 5A) interbedded with yellow structureless and/or laminated siltstones and fine-grained sandstones (F1f), usually with black, red and yellow traces of plant leaf and stem imprints (F1g) (Fig.5B).

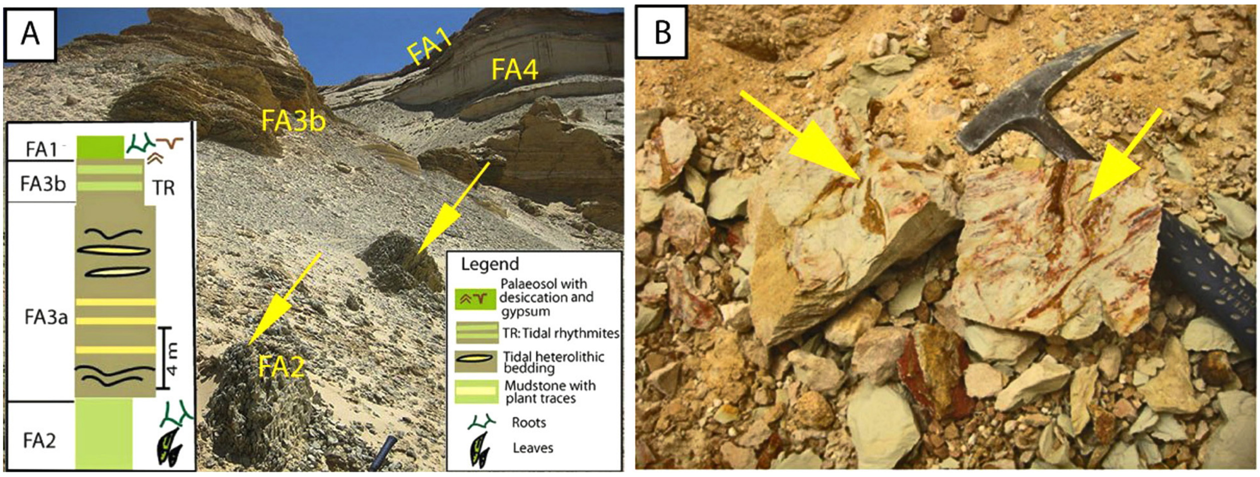

Fig. 5. A – FA2 exposed in the Oum Ali area; **B –** Traces of oxidised plants in mudflat deposits (yellow arrows).

Plants can attain over 1.2 metres in length and are less than 10 mm in width. This tabular lithofacies association extends laterally across the study area for several hundred metres and is overlain by FA4 and FA1 associations.

Interpretation. The tabular and laterally extended mudstone and/or sandy-clay unit, bearing a significant number of plants, can be interpreted as a subaerial vegetated upper intertidal flat area, or as an interchannel zone of a lower deltaic plain (Coleman & Prior, 1981; Dalrymple et al., 2003). Alternating sand and mud indicate a tidal cycle that is confirmed by numerous tidal structures present in the remainder of the deposits studied. Structureless sand and silt deposits indicate high-energy transport. Silts and sands transport occurred during ebb phases (the ebb phase being dominant over the flow phase in deltaic systems), whereas clays settled during periods of slack water (Davis & Dalrymple, 2012; Desjardins et al., 2010; Daidu et al., 2013). Imprints of stems and plant leaves suggest the presence of muddy marshes, whereas plant colour variations with low organic matter (black colour) reflect different oxidation states induced by subaerial exposure during low-tide phases in the intertidal zone (Varela et al., 2012).

However, the absence of wave currents and the presence of vegetated mudflats and tidal heterolithic facies, which extend over several tens of metres in a subaerial delta, suggest a sheltered area like chenier or chenier plain (Daidu et al., 2013). A chenier plain is a nearshore, intertidal sandy-clayey ridge, which rests on muddy and marshy sediments, and is entirely surrounded by mud flats and marshes (Otvos, 2000). All these characteristics are found in FA2.

4.3. Facies association FA3: heterolithic intertidal flat

FA3 is represented by two types of heterolithic tidal flat: the flaser and lenticular stratified deposits (FA3a) and tidal rhythmites (FA3b).

4.3.1. FA3a: flaser and lenticular stratified deposits

Description. FA3a is illustrated by a series of flat-based layers; about 20 m thick, reaching several hundred metres in lateral extension and showing a fining-upward trend (Fig. 6A). Generally, the basal part of the series exhibits a layer of 30 cm in thickness, which is composed of a successive regular arrangement of sandy foresets enclosed between two bounding mud drapes (F12) deposited on the lee sides of the dunes (Fig. 6B). Mud occurs in single (F12a) or double drapes (F12b) (Fig. 6C), is dark greenish in colour and rich in organic matter, and the thickness of the single mud drapes ranges from less than 1 mm to 3 mm. The double mud-drapes appear as two adjoining (paired), subparallel laminae of mud, and often coexist and alternate in the same cross section with single drapes and sands. These mud drapes are overlain by an alternation of very fine sands or silts and mudstone laminae of 1–3 mm in thickness. In detail, this is an alternation of flaser (F8a) and lenticular stratification (F8b) (Fig. 6B–E). The lenticular stratification is characterised by a higher clay content than sand and isolated sand lenses within mud laminae (Fig. 6B, E), whereas the flaser stratification contains more sand than mud. The latter exhibits thin streaks of mud between sets of sandy rippled laminae (Fig. 6B–D) and contains only a few *Skolithos* burrows (Fig. 6B).

Interpretation. The cyclic interbedding of sand and mud laminae, referred to as tidal bundling, is

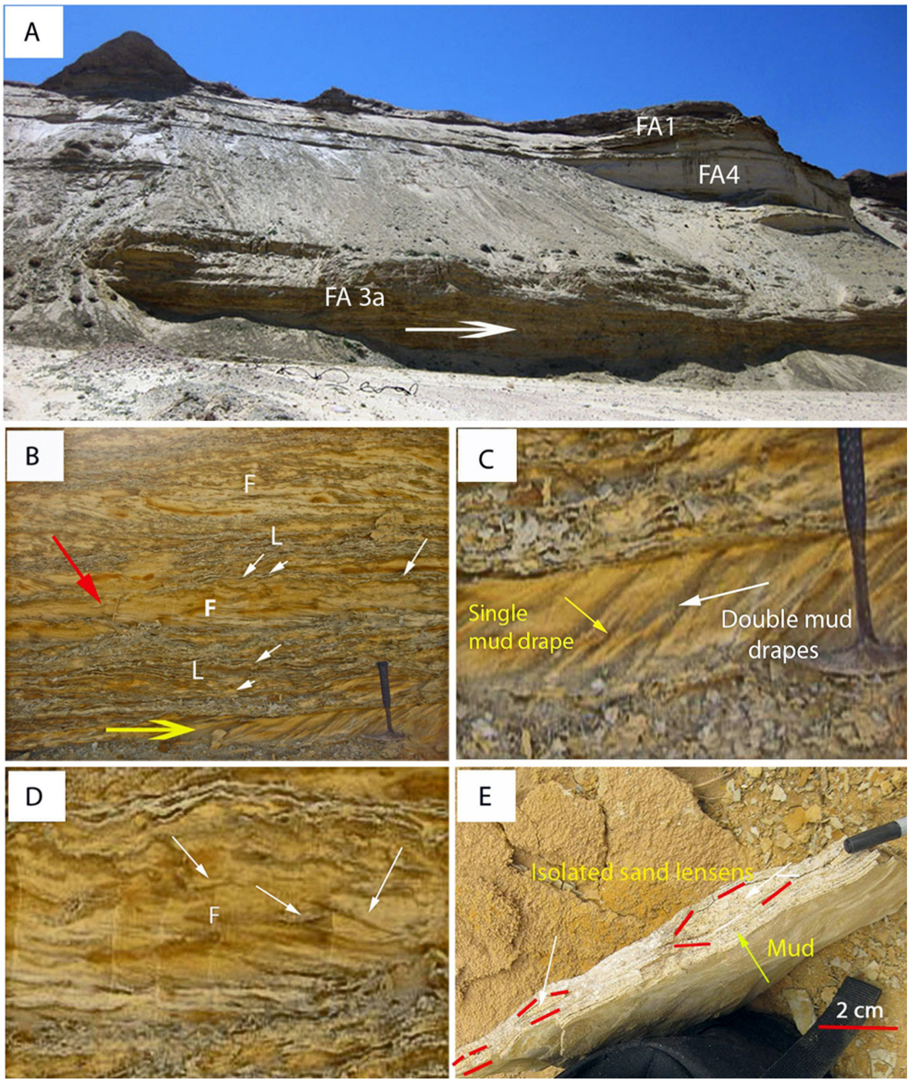

Fig. 6. FA3a exposed in the Oum Ali area. **A –** General view of FA3a (white arrow); **B –** Tidal bundles at base of FA3a (yellow arrow), overlain by intercalations of flaser (F) and lenticular (L) bedding. See also rare *Skolithos linearis* in the sandstone level (red arrow); **C –** Close-up view of tidal bundles. See the sandy cross-sets bounded by single mud drapes (yellow arrow) and double mud drapes (white arrow); **D –** Close-up view of flaser bedding; **E –** Lenticular bedding (not *in situ*) showing isolated sand lenses (white arrows) in mud matrix (yellow arrows).

considered to be definitive evidence of a tidal origin, being essentially known in the intertidal and subtidal environments (Dalrymple & Choi, 2007; Davis & Dalrymple, 2012). The sand and silts deposited between two successive single mud drapes result from the dominant tidal current (ebb current in this case), while the sands embedded between double-drapes are the product of a subsequent or subordinate current of the same tidal cycle (flood current) (e.g., Visser, 1980; Allen, 1982).

Flaser and lenticular stratifications are formed when sediments are exposed to intermittent flows or cyclic control of water velocity leading to an alternation of sand and mud laminae in a tidal flat environment (Martin, 2000; Boggs, 2005). The variability of current flow leads to different types of tidal structures. Flaser bedding exists where there is a strong tidal current resulting in an advantage of sand deposition over mud (high energy prevents mud settling), whereas lenticular bedding appears to form in low-energy environments that favour the settling of mud. Finally, the occurrence of FA3a in the same deposit zone as FA2, suggests an intertidal zone environment.

4.3.2. FA3b: daily and spring-neap tidal rhythmites

Description. Tidal rhythmites FA3b (Fig.7) exist both in the Oum Ali and Btita regions, near the Tunisian border (Fig. 1). They usually occur above the

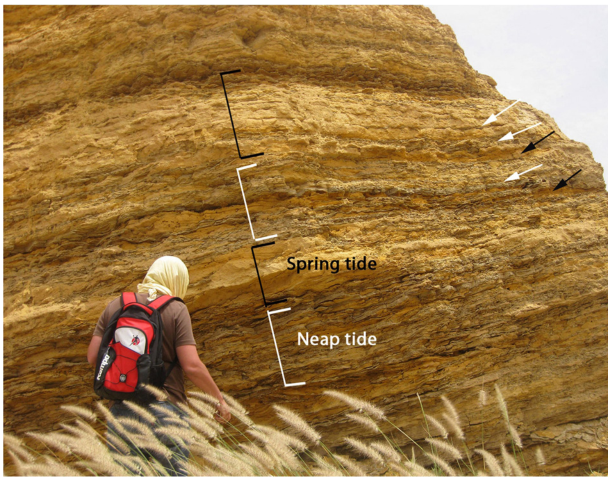

Fig. 7. FA3b at Btita: tidal rhythmites. Cyclic stacking of sandy (black arrows) and muddy (white arrows) laminae. Vertical alternation of mainly sandy interval (black line) with mainly muddy interval (white line), which define spring and neap tides, respectively.

ebb tidal channel of FA4. FA3b occurs as laminae or thin layers of alternating sand (very fine- to medium-grained) and mud (silt and clay) (F8c). It is 5 to 6 metres in thickness and extends over several dozens of metres laterally. Individual sandy and muddy layers or laminae are less than 1.5 mm in thickness and appear as yellow fine structureless or rippled sandy/silty laminae, vertically and cyclically stacked (F8c) and green muddy laminae with syneresis cracks (F8d). On a larger scale, these cyclic muddy and sandy beds show intervals with pairs composed mainly of sands or silts, alternating with pairs consisting mainly of clay or mud.

Sandy intervals show a few examples of *Skolithos arenicolites*. Their bioturbation index is low (2 < BI < 3). *Skolithos arenicolites* is distinguished by a pair of closely spaced circles in the sandstone beds. The diameter of each circle is less than 0.5 mm.

Interpretation. A cyclic stacking of sand and mud laminae whose thickness varies rhythmically is called a tidal rhythmite (Dreyer, 1992; Davis & Dalrymple, 2012; Longhitano et al., 2012). They reflect ebb-slack tidal cycle conditions. Structureless sandstone laminae reveal an upper flow regime and rapid deposition (Galloway & Hobday, 1996; Miall, 1996). The recurrent pairs of sand-mud laminae/layers suggest semi-diurnal tidal cycles (two high tides and two low tides per day), as evidenced by the equal thickness of the sand-mud pairs. Diurnal cycles, with unequal thickness of muddy and sandy layers, were not found within FA3b. It is assumed that the intervals containing the mud-sand pairs, in which the amount of sand is greater than mud, formed during cycles of 'springwaters' (every 14 days, i.e., twice a month, when the Earth, Moon and Sun are aligned). Intervals in which muds dominate reflect neap waters cycle (when the Earth, Moon and Sun are perpendicular to each other). The regular alternation of these two types of intervals represents spring-neap water cycles (Longhitano et al., 2012; Daidu et al., 2013). Syneresis cracks and depauperate ichnofaunal suites provide proof of salinity fluctuations and brackish water conditions.

4.4. Facies association FA4: tidal channels and tidal creeks

In the area of Oum Ali, FA4 is represented by stacked sandstone units with fining-and-thinning upward grading, with a palaeosoil (FA1a) at the top, and containing few burrows. Its total thickness is 5 metres, with a lateral extension of about 15 metres in the study area. FA4 presents two variants: FA4a is represented by an alternation of sandy-clayey beds, with BI = 0, whereas FA4b is characterised mainly by sandstone units that are relatively rich in ichnofossils (2 <BI< 3).

4.4.1. FA4a: sandy-clayey deposits of tidal creeks

Description. FA4a occurs as a succession of sand and clay layers, the thickness of which varies between 1 and 3 metres (Fig. 8). They are characterised mainly by tabular or wedge-shaped cross-stratified sandstone beds (F3). These fine sands include low-angle (F4), rippled (F6) and parallel lamina-

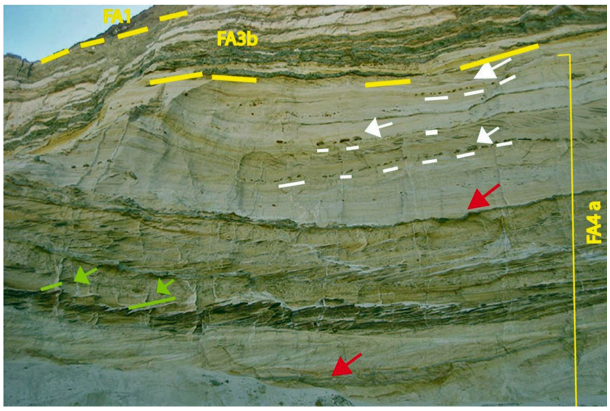

Fig. 8. Tidal creek deposits (FA4a). Alternate sandy-muddy channelised deposits. Note the undulated bases of each bed (red arrows), overlain by mud layer or mud clasts (white arrows and white dashed lines). Mud-draped sandstone (fossil dunes) with reactivation surfaces (green arrows and green lines) and rhythmites. FA3b (rhythmites) and FA1 (palaeosoil) separated from FA4a by yellow lines.

tions (F5), as well as few sigmoidal cross-bedding (F15) and reactivation surfaces (F10). Sandy layers show irregular bases, overlain by thin muddy deposits (between 1 and 3 cm thick), as well as mudstone rip-up clasts (Fig. 8). FA4 is topped by tidal rhythmites (FA3b) and palaeosoil (FA1).

Interpretation. Sand dunes with tidal structures and large quantities of suspended sediment are characteristic of tidal creeks (or gullies), which are small and shallow inlets dissecting tidal flats in the intertidal zone. They are characterised by low hydrodynamic energy, without significant wave action (Wells, 1995). Tidal currents rework fine-grained sediments in the creeks, which settle during quiescent periods. The power of tidal current causes scouring at the channel bases, leaving mud clasts. Tidal creeks typically occur in intertidal muddy settings, and act as conduits for flow during rising and falling tides (Nichols, 2009). Fining-upward trends with a palaeosoil developing at the top of FA4a attest to intertidal zone progradation (Daidu et al., 2013).

4.4.2. FA4b: ebb deltaic channels

Description. FA4b is composed mainly by 5-m-thick, planar tabular or wedge-shaped cross-bedded sandstones with unidirectional (to the northwest) lamination (F3) and with *Ophiomorpha* and *Skolithos* burrows (see details below) (Fig. 9).

FA4b consists of well-sorted coarse- and fine-grained sandstones which dip at 28–39° towards the north. These cross-strata also include low-angle bedding (F4), parallel laminae laminations (F5), tidal bundles (F11) and very rare and isolated herringbone (bipolar) stratifications (F14). Tidal bundles are formed by a horizontal alternation of tightly foreset laminae intervals and spaced foreset laminae intervals (Fig. 9). Towards the base, FA4 shows 0.25-m-thick lag deposits, with very coarse and poorly sorted wood pieces, fragments of indeterminate bones and a mammal tooth (F2) (Fig. 10). Towards the top of this facies association, fine-grained sandstones and muddy layers with rhizoliths and

Fig. 10. Overview of a Miocene mammalian tooth, belonging to either *Palaeomastodon* or *Phiomia*.

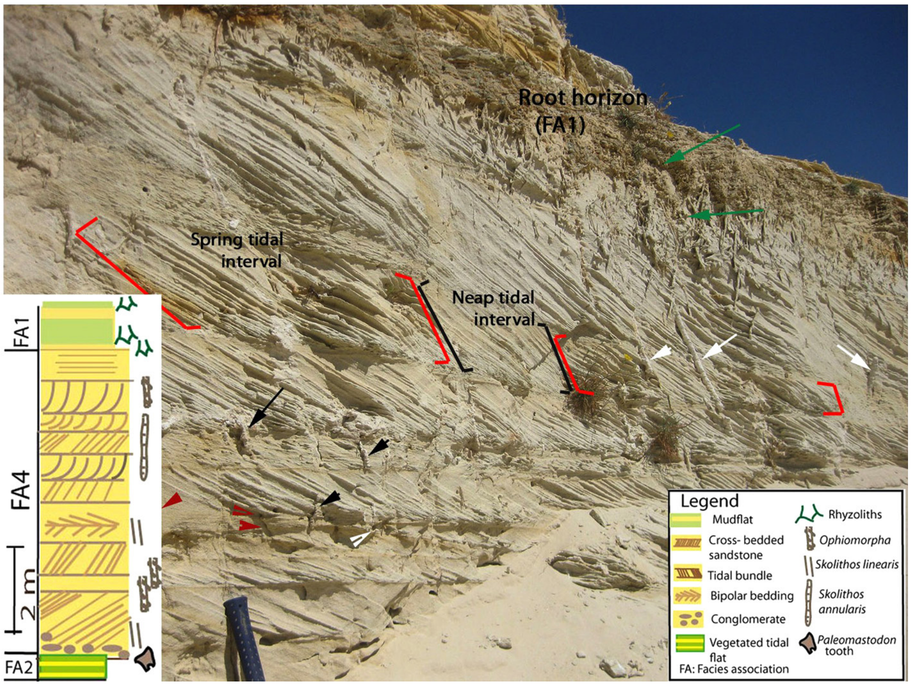

Fig. 9. Tidal channel (FA4b) in the Oum Ali area. **A –** Unidirectional tabular cross-bedded sandstones with tidal bundles. See the alternation of tight foreset intervals (black braces) and spaced foreset intervals (red braces). *Skolithos annularis* (white arrows), *Ophiomorpha* (black arrows), *Skolithos linearis* (red arrows) and rhizoliths (green arrows).

tree trunks (FA1) occur (Fig. 9), forming fining-upward and thinning-upward successions.

FA4b shows low diversity and moderate intensity of bioturbations (2 <BI < 3) (Fig. 9) and slightly destroyed sedimentary structures. Three ichnotaxa were recorded: *Skolithos linearis*, *Skolithos annulatus* and *Ophiomorpha nodosa* (Fig. 11).

Skolithos linearis Haldmann, 1840 is the most abundant ichnotaxon in the sandstone beds (Fig. 9) and occupies entire sandstone beds, occurring as vertical or slightly inclined, unbranched, cylindrical to subcylindrical, non-aligned and isolated burrows that are perpendicular to the bedding with a negative relief. The burrow diameter is 0.6–1.5 cm, its length 2–6.2 cm, and openings are circular or subcircular. They present morphological characteristics that are similar to those of material of this ichnospecies as described by Alpert (1974).

Skolithos annulatus Howell, 1957 is a simple, vertical or slightly tilted, unbranched sandy infill of a burrow, preserved as positive (cigar-shaped) epirelief (Fig. 11A). The burrow's average diameter is 1.2 cm, and length 5–35 cm. The burrow wall is characterised by tight circular and irregularly arranged rings. The ornamentation and filling characteristics resemble those of material assigned to *S. annulatus* by Alpert (1974), and are believed to have been produced as dwelling burrows (domichnia).

Ophiomorpha nodosa Lundgren, 1891 occurs as individual vertical sandy tubes, ramified or unramified, of 3–13 mm in diameter, with dense nodules on the outside of 2–10 mm-thick ovoid faecal pellets (Fig. 10). Possible trace makers are decapod crustaceans (Frey, 1975).

Interpretation. Planar sandstone beds with unidirectional, seaward-dipping stratification derived from 2D sand bars, deposited within tidal channels dominated by ebb tide (Dalrymple & Choi, 2007; Davis & Dalrymple, 2012), occasionally with near-equal occurrence of high and low tidal currents, leading to bidirectional cross-strata (Nichols, 2009; Davis & Dalrymple, 2012). Bundle sequences are formed by migration of small dunes during a full neap-spring-neap tide cycle. Under the influence of a strong dominant current (ebb current in this case), followed by a weak subordinate current, sand dunes with spaced stratification are formed, followed by densely stratified dunes. The first dunes form during a spring tidal cycle, while the second ones form during neap tidal cycle (e.g., Boersma, 1969; Terwindt, 1971; Boggs, 2005).

The tooth belongs to *Palaeomastodon* or *Phiomia*, the oldest representatives of elephantiform mammals (Gheerbrant & Tassy, 2009). These two genera have documented in Oligocene and Miocene strata. The presence of a lag deposit with terrestrial fossil remains at the base of FA4b indicates high-energy ebb-channels and the brackish proximal zone. This interpretation is supported by low-diversity (almost monospecific) trace fossils, represented by *Skolithos*. The taxa responsible, suspension or filter feeders, are indicative of relatively high current energy, and stressed setting induced by salinity reductions and/or fluctuations (McEachern et al., 2005). These, in turn, are evidenced by syneresis cracks (in tidal rhythmites of FA3b) and depauperate ichnofaunal suites.

4.5. Facies association FA5: sandy compound dunes or 3D bars of lowermost intertidal or uppermost subtidal zone

Description. FA5 (Fig. 12) was studied in the Malabiod area, located 20 km from Oum Ali (Fig. 1)

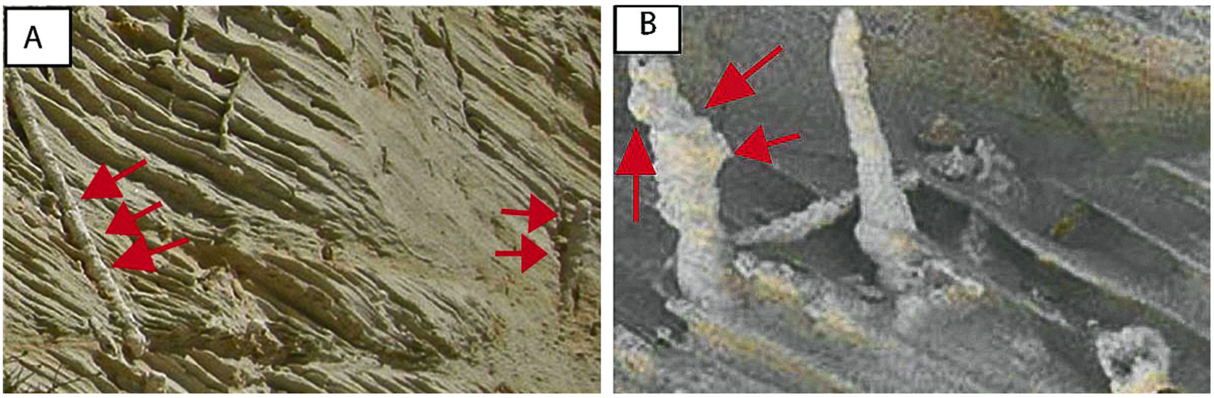

Fig. 11. Ichnotaxa of FA4b (Oum Ali area). **A –** *Skolithos annulatus* showing circular strangulations along burrow (red arrows); **B –** Unbranched *Ophiomorpha nodosa* with ovoid granular pellets covering burrow walls (red arrows). Specimen measures 30 mm in height.

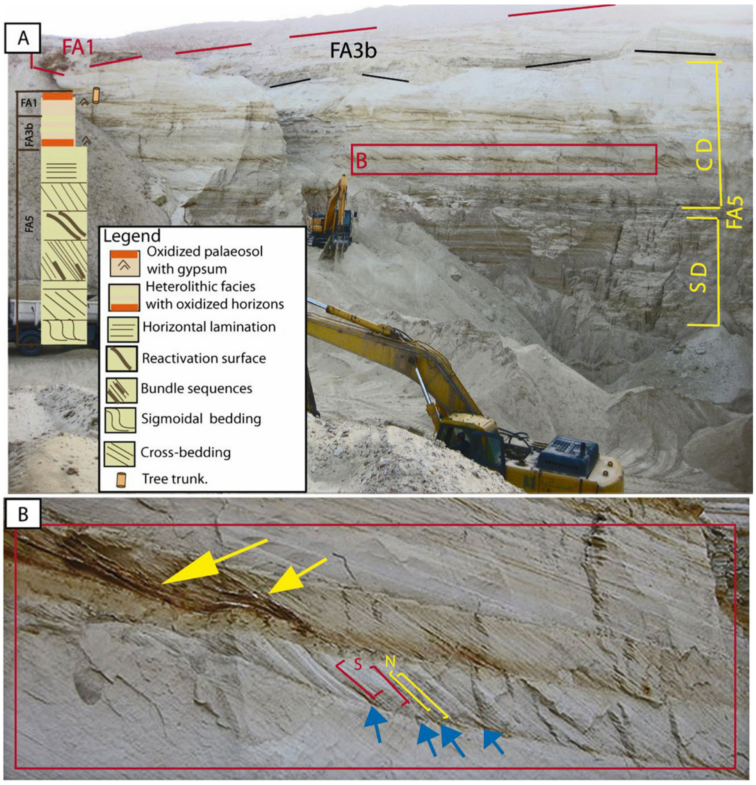

Fig. 12. A – Overview of stacked unidirectional simple (SD) and compound (CD) sandstone dunes, overlain by FA3b and FA1; **B –** Close-up view framed by rectangle in (A) showing: bundle sequences represented by yellow and red intervals, defining (neap) (N) and spring (S) cycles separated by mud drapes (blue arrows), as well as reactivation surfaces (yellow arrows).

and is composed principally of 8-m-thick sandstone beds (Fig. 12A). Predominating are tabular planar and wedge-shaped (F3) and stacked sandstone bodies with unidirectional internal stratification. Less common lithofacies are: low-angle cross-stratification (F4), current ripple cross-lamination (F6), plane parallel lamination (F5) and sigmoidal cross-stratification (F15), with some mud clasts at the base and in the middle of FA5. Some successions show thick-thin alternations of foreset laminae, separated by mud drapes, as well as reactivation surfaces (F10) (Fig. 12 B). FA5 is topped by tidal rhythmites (FA3b) and a palaeosoil (FA1). The ichnofacies of FA5 were obliterated during work at the quarry and could therefore not be studied.

Interpretation. Unidirectional sandy dunes, with tidal bundles, reactivation surfaces, sigmoidal and bipolar stratification, area compound dunes or 3D bars, deposited in the uppermost and high-energy subtidal zone, or in the lowermost intertidal zone (e.g., Davis & Dalrymple, 2012). These reflect the existence of a dominant and subordinate current, evidenced by herringbone and sigmoidal stratifications and tidal bundles. This environment was subject to progradation, as evidenced by the presence of FA3b and FA, which covers FA5.

4.6. Facies association FA6: terminal distributary channel

Description. FA6 occurs in the Hjer Essefra region, located 20 km from Malabiod. It is represented by 5-m-thick sandstone deposits, commonly forming fining-upward and thinning-upward successions. FA6 overlies the mudstones of FA8 and it is incised by channelised sandstones that define FA7 (see below) (Fig. 13). This is composed of cross-stratified sandstone beds with the laminae dipping in one direction (Fig. 14), symmetrical ripple cross-lamination (F6b), planar cross-stratification (F3), low-angle cross-stratification (F4), reactivation surfaces (F10) and rare bipolar (herringbone) structures (F14). Slump or overturned ripple structures (F13) are visible in the basal part of this facies association (Fig. 14A). The vertical succession reveals slightly wavy or concave-up basal erosion surfaces (Fig. 14B), commonly mantled by very coarse-grained and poorly sorted sandstones and gravelly sandstones with mudstone rip-up clasts. Plant remains, such as wood fragments, are also present. Heteroliths (FA3b), as well as greenish gypsiferous mud layers with desiccation cracks (FA1), exist at the base and top of FA6.

FA6 shows sparse bioturbations (1 <BI< 2), represented by *Skolithos linearis*.

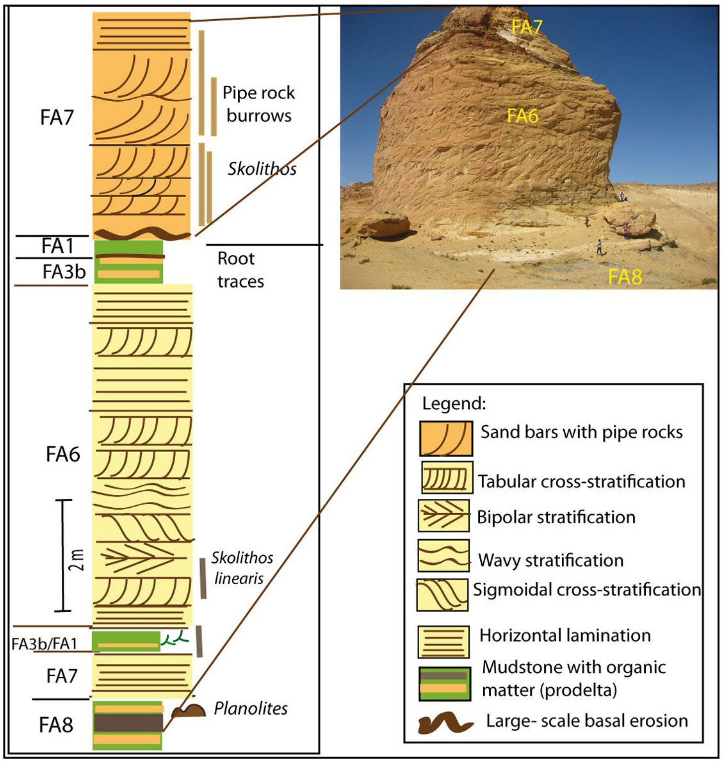

Fig. 13. The Hjer Essefra site. Synthetic log showing facies associations of proximal delta front (FA6 and FA7) and prodelta (FA8).

Interpretation. The stacked sandstone layers with several basal erosion surfaces and fining-upward trends indicate multi-storey channels (Miall, 1996). The existence of wave ripples, horizontal laminations, bipolar and sigmoidal structures indicate submarine transport, mostly under high energy, with concomitant wave and tidal influences. These channelised deposits (FA6) which are deposited directly above the mudstones of the prodelta (FA8), and under a tidal mouth bars (FA7), are interpreted as terminal distributary channels (Davis & Dalrymple, 2012). Both heterolithic deposits (FA3b) and mudflat (FA1) covering the sandy deposits, result from intertidal and supra-tidal zone progradation, respectively (e.g., Nichols, 2009), whereas the reddish oxidations at the top of FA6 indicate subaerial conditions. Salinity fluctuations and brackish-water conditions are supported by low intensity of bioturbations, commonly monospecific trace fossils.

4.7. Facies association FA7: tidal mouth bars

Description. FA7 occurs above FA6, with a deep erosion contact, bearing traces of ferrugenisation (Fig. 13). Further north, it is represented mainly

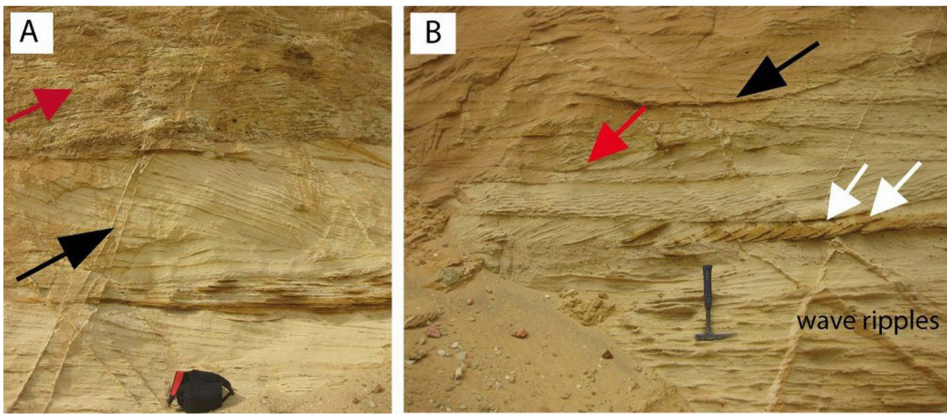

Fig. 14. Sandstones of FA6. **A –** Succession of sandstone strata. See overturned sandstone layer (black arrow) overlain by very coarse-grained sandstone (red arrow); **B –** Sand wave ripples and reactivation surfaces (white arrows) with lateral accretion surface (red arrow). Note erosive concave-up channel base (black arrow).

by discontinuous tabular, gently inclined sandstone bodies aligned towards the NNW (basinwards) (Fig. 15), with an extension of 500 metres and a downward decrease in thickness in the same direction. Sandstone bodies are 0.2 to 3 metres in thickness. They consist of poorly sorted, medium- to very coarse- or coarse-grained sandstones, with gravels and angular quartz pebbles (2.5 cm in length) at their top, forming coarsening-upward successions (Fig. 16A). They are characterised by small-scale (F3) and large-scale planar cross-stratification (F9a) with accretion surfaces (Fig. 16 B, C). Large trough cross-stratification (F9b), symmetric ripple cross-lamination (F6b) and parallel lamination (F5) are also common.

FA7 exhibits a large number of almost monospecific ichnotaxa. They are characterised by vertical tube shape, aligned next to each other. They are perpendicular or slightly tilted to the depositional surface. Only four ichnospecies occur in this facies association which are associated with dwelling behaviour: *Skolithos linearis*, *Skolithos verticalis*, *Skolithos annulatus* and *Diplocraterion*.

Skolithos linearis are straight vertical cylindrical tubes or pipes, with shafts parallel to each other, perpendicular to the bedding (Fig. 17). Their length varies from 20 to 620 mm, and their diameter from 1 to 18 mm. These vertical burrows are tightly packed on highly bioturbated sandstone bodies, forming a spectacular pipe rock (3 <BI <4 or 4< BI <5) (Figs. 17,

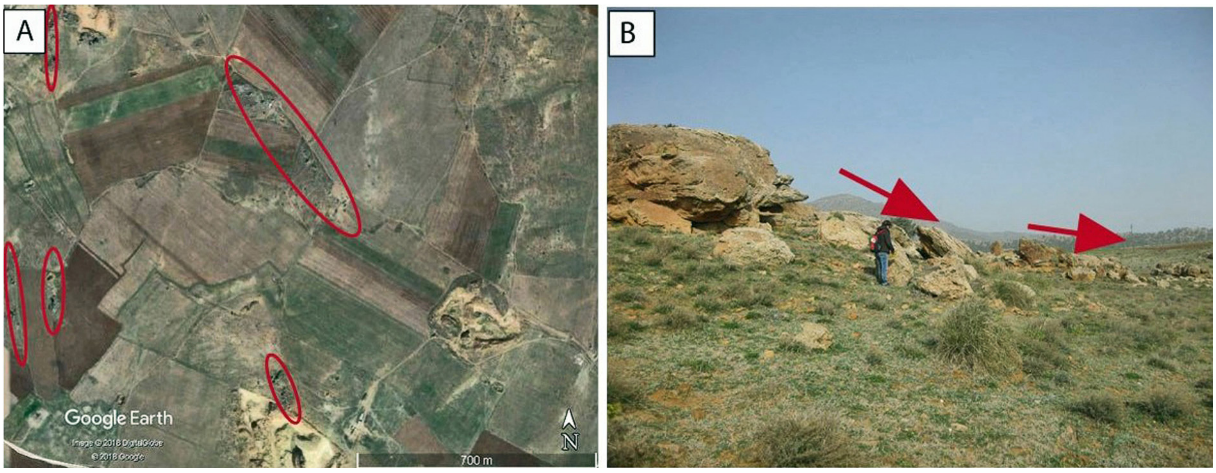

Fig. 15. A – Satellite image of the Hjer Essefra area showing aligned tidal sand bars FA7 (circles); **B –** Close up view of aligned sand bodies; their basinward progradation is arrowed.

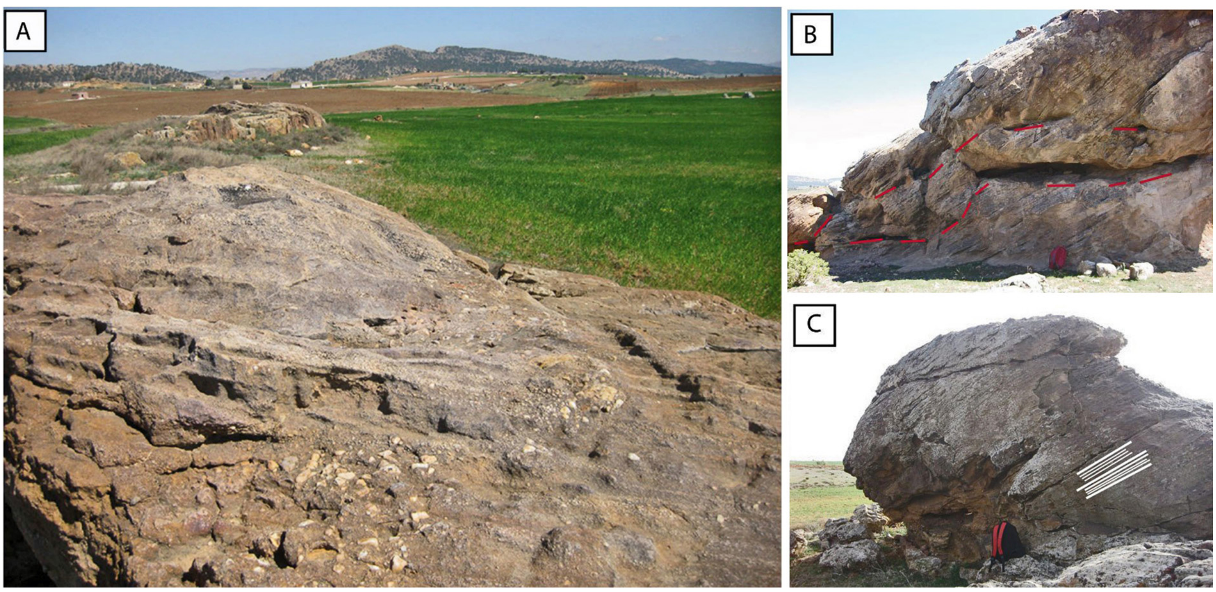

Fig. 16. A – Angular quartz pebbles in bar-top sandstone. **B, C –** Large planar cross-bedded sandstone (fossil bars) showing lateral accretion surfaces (red lines) and planar cross-stratification.

18). The longest examples (200–620 mm in length) and the most frequent ones occupy the middle parts of the thickest sandstone bodies (Fig. 17). *Skolithos linearis* completely invade the medium and small sandstone bodies (Fig. 18). Towards the top of the sandstone bodies the bioturbation intensity gradually decreases (0 <BI < 1).

Skolithos verticalis (Hall, 1843) (Fig. 19A) is cylindrical in transverse section, straight, vertical with a smooth wall, with a diameter of about 5 mm and

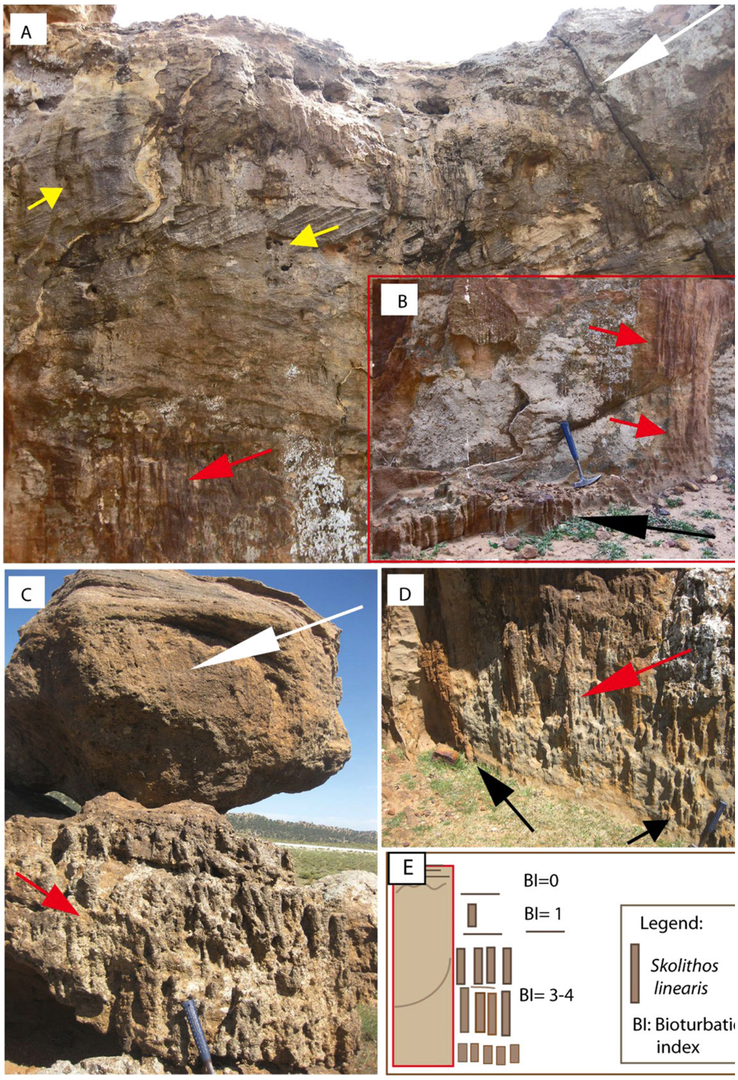

Fig. 17. Pipe rocks of Hjer Essefra. **A–D –** Largest number of *Skolithos linearis* occurring in lower half of fossil bars (3 < BI < 4). Note smallest *Skolithos* in basal parts of fossil bars (black arrows) overlain by largest ones (red arrows). Their frequency decreases upwards (BI=1) (yellow arrows), being absent at the top (BI=0) (white arrows); **E –** Variation of bioturbation index in the succession studied.

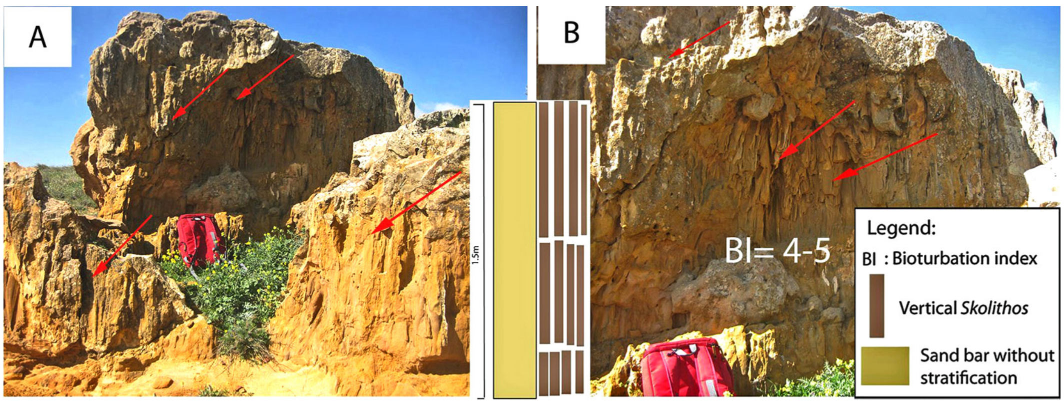

Fig. 18. Dense population of *Skolithos linearis* (4 < BI < 5) forming pipe rocks (mouth bars of Hjer Essefra).

length between 20 and 100 mm. These crowded burrows occur near the large sandstone bodies.

Skolithos annulatus (Howell, 1957) comprises cylindrical, vertical and crowded burrows (Fig. 19B–C), with diameters of 0.5–0.8 cm and a length that varies between 4 and 15 cm; rings are irregularly arranged and between 1 and 2 mm apart. Their BI varies from 4 to 5.

Diplocraterion (Fig. 20) is a U-shaped structure of inclined or horizontal burrows with a stacked, curved and layered structure within the paired, U-shaped tubes referred to as spreite. Lengths vary from 20 to 66 mm, average diameters between 2 and 10 mm and BI from 2 to 3.

Interpretation. FA7 defines deltaic-tidal mouth bars, deposited in subtidal environments near a river mouth. Typical are the arrangement and orientation of the sand bars, the presence of the coarsest sediments, their distance from the intertidal zone of Oum Ali, as well as their deposition on top of and/or parallel to the terminal distributary channels (FA6) and above the prodelta (FA8) (Coleman & Prior, 1982). The alignment and orientation of the bars in a specific direction (towards NNW, i.e., basinwards) result from reworking by tidal currents (Coleman & Prior, 1982; Davis & Dalrymple, 2012). Large, planar and trough cross-stratified sand bars resulted from 3D-dune migration, or lateral accretion of bar surfaces (Bridge & Demicco, 2008). The presence of symmetrical ripple laminations within the sand bars indicates wave-influenced deposition (Coleman & Prior, 1982). The coarsening-upward trends of mouth bars are consistent with the progradation mechanism in a deltaic environment.

The presence of *Skolithos* dwelling structures, which were produced by suspension-feeding organisms, is coupled with the low diversity of trace fossil suites. The high bioturbation intensity found in most mouth bars suggests that the tracemakers adapted to stressful conditions, such as brackish waters and a high-energy environment. The very limited rate or absence of suspended sediment (i.e., limited turbidity) allowed a proliferation of suspension feeders (e.g., MacEachern et al., 2005; Buatois & Mangáno, 2011). The presence of examples that are characterised by a small size (represented by *Skolithos linearis* and *Skolithos verticalis*) near the sea floor indicates that certain ecological conditions (for

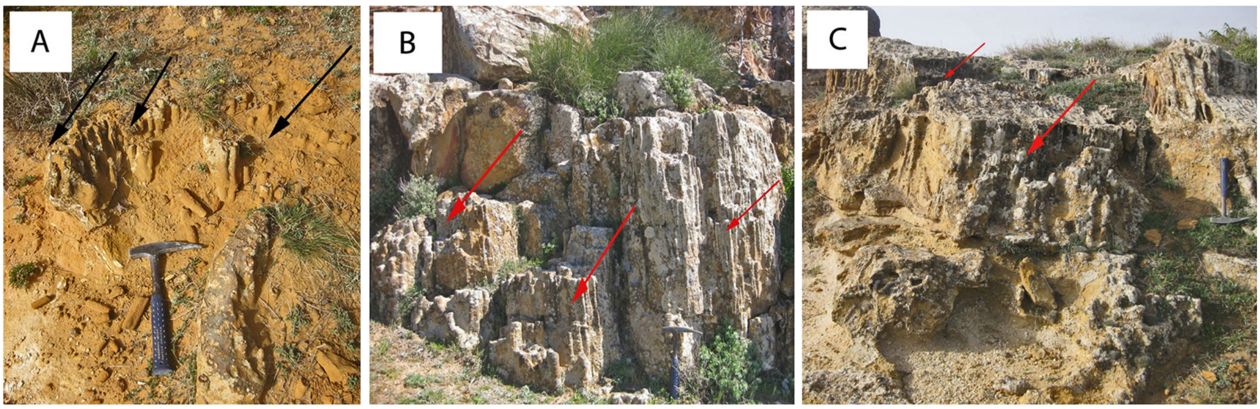

Fig. 19. A – Crowded population of Skolithos *verticalis*; **B, C –** Dense population of *Skolithos annulatus*.

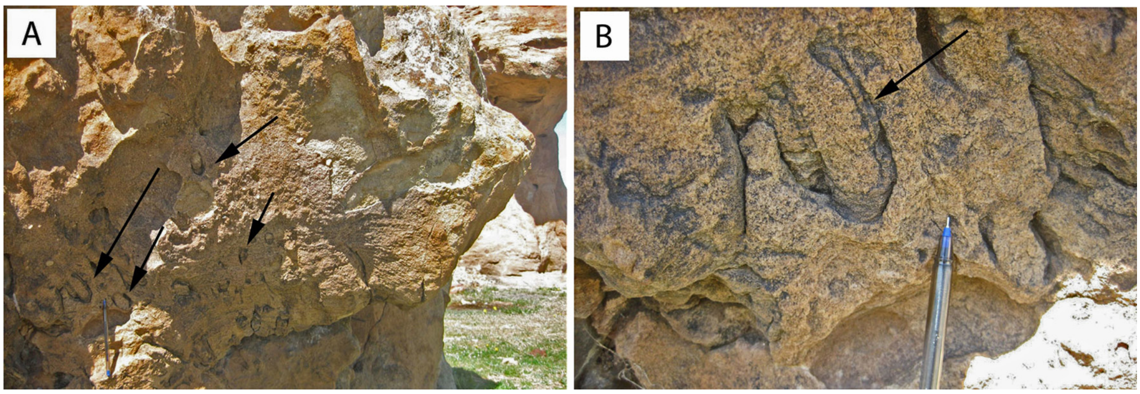

Fig. 20. A – U-shaped *Diplocraterion* burrows in tidal mouth bars; **B –** Close-up view of *Diplocraterion*. Note the spreite within the paired U tube (arrow).

example, oxygen level) were insufficient for the development of larger burrows at this location. Moreover, the absence of trace fossils in the upper parts of the bar-derived sandstone bodies can be linked to high hydrodynamic conditions that prevailed at the surface of the highest mouth bars.

4.8. Facies association FA8: prodelta

Description. FA8 is represented by a 3-m-thick series of mudstones (Fig. 21A, B). These are black clays (F1h), with ochre-coloured mudstones, laminated or unstructured atop (F1i). The uppermost deposits are represented by green clays and ochre-coloured silts covered by an ochre-coloured surface which bears traces of syneresis cracks (F1j), as well as *Planolites*.

Planolites montanus (Nicholson, 1876) comprises horizontal, cylindrical burrows, with smooth surfaces and tortuous and circular cross sections. They are preserved in positive epirelief; their filling consists of an ochre-coloured ferruginous siltstone, which is distinguished from the host rock (black or yellow mudstone). Their length ranges from 1 to 7 mm and their diameter from 1 to 3 mm. The bioturbation index (BI) is estimated between 2 and 3.

Interpretation. The thin mudstone deposits, locally rich in organic matter, formed in a calm environment under anoxic conditions. Syneresis cracks on mudstone surfaces formed by contraction of clay in response to changes in salinity. The position of FA8 at the base of the terminal distributary channels and mouth bars (FA6 and FA7), as well as their distance from the intertidal facies of Oum Ali (i.e., 46 km), suggest that this facies association represents a prodelta (Milkeviciene & Bjorklund, 2009).The impoverished trace fossil suite and the predominance by monospecific deposit feeders, represented by *Planolites montanus*, suggest salinity stress, inferred by syneresis cracks; fluctuation in salinity induces the proliferation of opportunistic trace makers (MacEachern et al., 2005).

5. Discussion

The tidally dominated delta of the Tebessa Basin is characterised by extensive tidal currents, evidenced

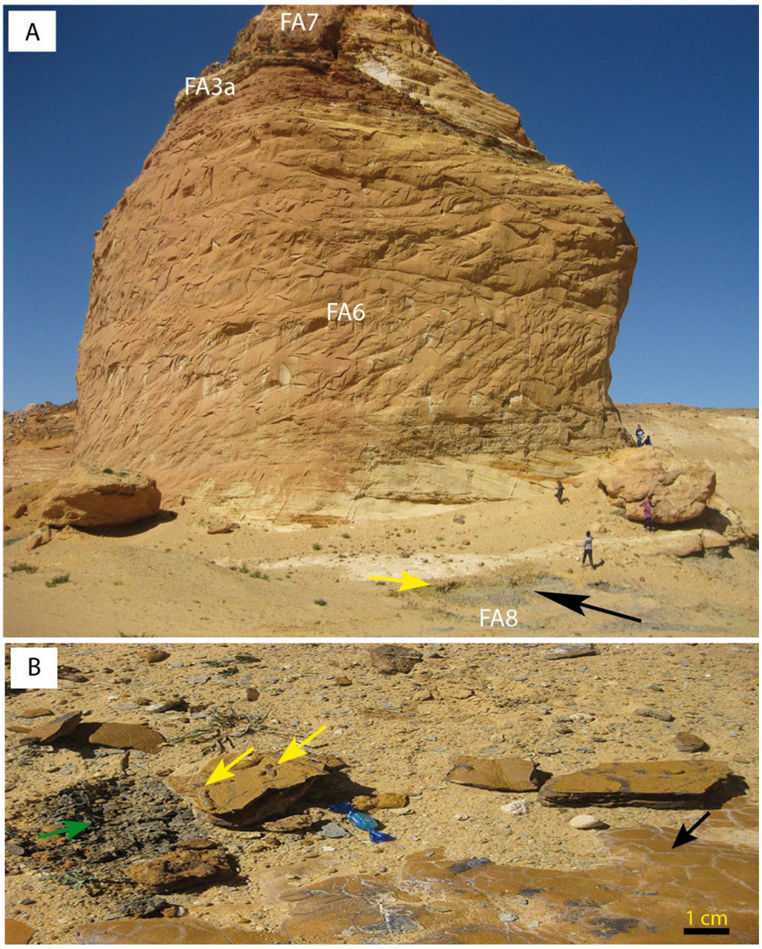

Fig. 21. Prodelta deposits (FA8). **A –** Ochre, black mudstone with *Planolites* (arrow) overlain by sandstones of terminal distributary channels (FA6) and mouth bars (FA7); **B –** Close-up view of *Planolites montanus* (two joined individuals, yellow arrows), syneresis cracks (black arrow) and black mudstone with organic matter (green arrow).

by rhythmites, bundles, double mud drapes and the typical alignment of the mouth bars (e.g., Nichols, 2009; Davis & Dalrymple, 2012). Field surveys and sedimentological analyses have revealed a tidally dominated and wave-influenced delta, prograding from the SSE to the NNW, and the existence of significant numbers of *Skolithos*, forming pipe rocks locally. The palaeoenvironmental analysis has shown, from the SSE to the NNW (Fig. 22):1) a lower-delta chenier-plain in the Oum Ali area, 2) a lower intertidal to upper subtidal compound sand bars at Malabiod, and 3) a proximal delta-front with pipe rocks at Hjer Essefra.

The lower-delta chenier-plain of Oum Ali is composed of four subenvironments which are: 1) a palaeosoil of the supratidal zone (FA1); 2) a marshy upper intertidal flat (FA2); 3) a shallow intertidal flat (FA3); and 4) ebb-tidal channels with *Ophiomorpha* and *Skolithos linearis* (FA4).

The Hjer Essefra proximal delta front, which is characterised by a coarsening-upward succession, is represented by three subenvironments; from base to top these are: 1) a muddy prodelta (FA8), 2) terminal distributary channels (FA6); 3) aligned sandstone mouth bars (FA7) with dense sets of *Skolithos.*

A comparison with analogous ancient and modern-day tidal deltas remains difficult because they are poorly known from the stratigraphical record to date (Mcllroy, 2004). Moreover, modern tide-influenced deltas occur in tropical settings and are fed by large rivers with very high suspended sediment loads (Coelman, 1969; Fisher, 1969; Coleman & Wright, 1975; Dalrymple et al., 2003). The Tebessa tidal delta analysed here was predominantly sandy, was fed by a relatively small river system and formed in a hot and semi-arid climate. Gypsum and desiccation cracks occurring in the tidal flat deposits prove such an interpretation of climate.

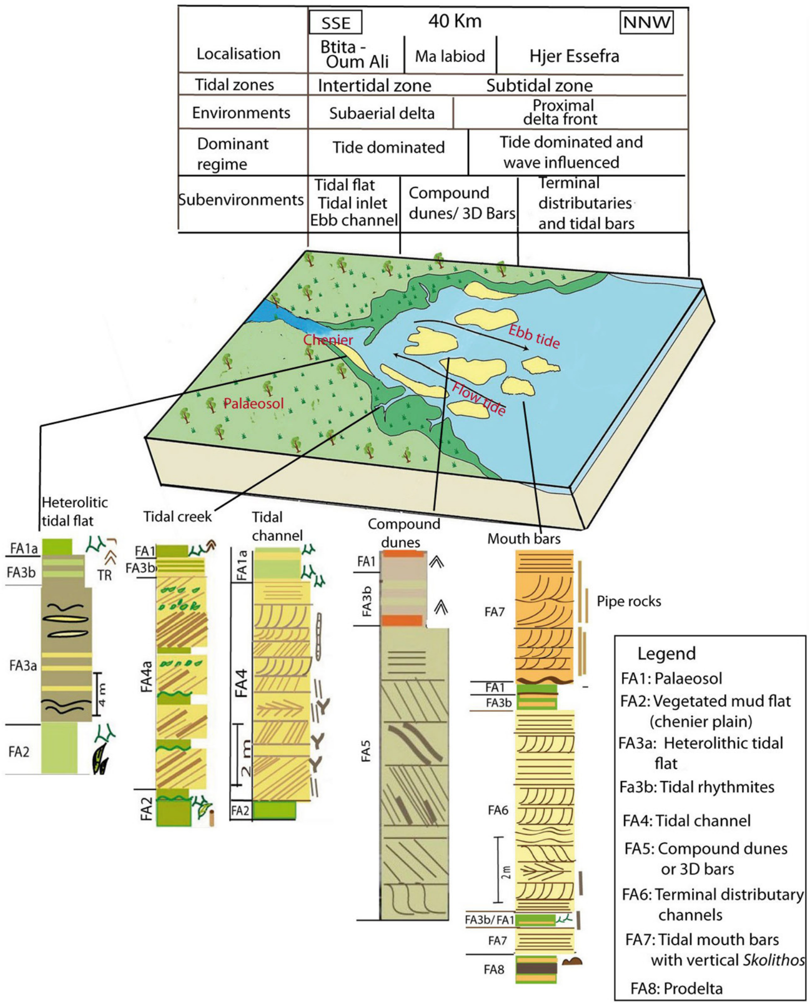

Fig. 22. Schematic diagram of tidally dominated delta of the southern Tebessa Basin. Synthesis of facies associations and their palaeoenvironmental positions.

Goodbred & Saito (2012) recognised that a muddy tidal flat was the most important component of a tidally dominated delta, with the typical sediment facies comprising sand and mud alternation in flasers, lenticular and wavy laminations, especially close to the river mouth, where sedimentation rates are high and bedding is well preserved. The muddy-sandy tidal flat deposits in the Oum Ali area show flaser, lenticular and wavy bedding, as well as tidal rhythmites, but they were deposited at a considerable distance (approximately 40 km) from the river mouth.

Concerning the ichnological suite of the study area, it can be noted that this is dominated mainly by the ichnogenus *Skolithos*, occurring in a stressed setting that was colonised by trophic generalists. A comparison with other ichnofacies specific to tidal delta is not easy, because there are few ichnological studies that encompass both tidal-deltaic plains and delta fronts. Mcilroy (2004) studied the ichnology of the Jurassic Ile Formation in Norway, which is interpreted as a tide-dominated delta. He observed a high ichnodiversity in the delta front, represented by *Skolithos*, *Ophiomorpha*, *Diplocraterion*, *Palaeophycus* and *Chondrites*. Such ichnodiversity is absent from the mouth-bar deposits of Hjer Essefra. This would be due to the fact that the mouth bars of the Ile Formation in Norway were situated in a low-energy, microtidal setting, which allowed such ichnodiversity to be established, while the ichnofacies of Hjer Essefra formed in a high-energy environment and macrotidal context, as is demonstrated by all of the above-mentioned tidal signals.

Neogene tidal-delta plain deposits in the eastern Venezuela Basin, studied by Buatois & Mangano (2011), showed a typical brackish-water trace fossil assemblage, represented by *Ophiomorpha nodosa*, *Skolithos linearis* and *Planolites*, although, interdistributary-bay and lagoon deposits proved more heavily bioturbated than sandy channel deposits. Conversely, the lower intertidal delta plain deposits of Oum Ali document sandy channels that were invaded by a nearly monospecific, but relatively frequent ($2 < BI < 3$), brackish-water trace fossil assemblage (*Ophiomorpha*, *Skolithos linearis* and *Skolithos annularis*), whereas, in the intertidal flat or interdistributary mud-flat deposits trace fossils are almost absent ($BI < 1$). This can be explained by the fact that the tidal plain deposits of Oum Ali formed in a semi-enclosed area (a chenier plain), and such low-energy environment, with brackish and poorly oxygenated waters, hindered the establishment and development of benthic fauna. Unlike the equivalent Neogene deposits of Venezuela, which open directly onto the Atlantic Ocean, they probably benefitted from an environment of much higher energy and better oxygenation.

6. Conclusions

Siliciclastic deposits in the southern part of the Tebessa Basin, dated as Langhian–Tortonian, are the result of a south-north progradation of a tidally dominated and wave-influenced delta in a semi-arid and hot climate. It is represented by a lower delta plain that covers the entire region of Oum Ali-Malabiod, where all tidal signals are recorded. The most characteristic ones are double mud drapes, tidal bundles and tidal rhythmites, reflecting daily tidal cycles (ebb and flood) and semi-monthly cycles (spring and neap).

Further north, in the Hjer Essefra region, the aligned tidal mouth bars form a proximal delta front in a subtidal environment. This shallow coastal setting was the site of extraordinary growth of vertical *Skolithos*, mainly in tidal sandbars, creating real pipe rocks.

The high degree of bioturbation, recording monogenic suites, reflects gregariouss colonisation by opportunistic euryhaline-tolerant communities in a stressed setting. Such ecological stress is induced by brackish-water conditions and salinity fluctuations, prevailing in the lower deltaic plain and mouth bar area. These conditions are corroborated by depauperate ichnofaunal suites and syneresis cracks. However, the presence of high numbers of such filter feeders, mainly in the proximal delta front, is indicative of high waves, a clean sandy substrate, an abundance of food (presence of organic matter), a lack of competition (deposits are devoid of shelly organisms) and a hot climate. These are all factors that may have contributed to the proliferation of *Skolithos*-producing biota in the deposits studied.

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