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Depositional palaeoenvironments in a tide-influenced delta plain with amphibian and Cycadophyta remains – the Triassic Zarzaitine Formation (Algerian eastern Sahara)

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Abstract

In the region of In Amenas (south-eastern Algeria) Triassic deposits crop out, on top of Palaeozoic rocks under an angular unconformity. A study of their sedimentological and palaeoenvironmental characteristics has revealed a sandy-clay unit with vertebrate remains, tree trunks and ichnofossils of Middle-Late Triassic age. This so-called Zarzaitine Formation, which reflects deposition in a deltaic environment, shows three facies associations. The first defines an upper and shallow intertidal mixed flat zone with in-situ temnospondyl capitosauroid remains, associated with Skolithos ichnofacies, while the second one defines a lower intertidal delta plain zone, composed of sandstone, distributary channels and muddy interdistributary areas,which record daily tidal rhythmites and monthly tidal bundles. The third, and last, facies association represents an upper delta plain of the supratidal zone, characterised by coarse sandstone deposits of braided rivers and a Cycadophyta palaeosol. Previous work, which led to considering these Triassic deposits as a series composed of four formations, deposited in a braided rivers environment, whose lower floodplains constituted ecological niche for a temnospondyl fauna, under hot and dry climatic conditions and plants belonging to this same formation, for mushrooms and algae, will also be considered.

Keywords: Delta, sedimentology, temnospondyls, tidalites, ichnotaxa, In Amenas, Illizi Basin

1. Introduction

The locality of Zarzaitine, situated in In Amenas (eastern Sahara, Algeria) is famous for its sandstone outcrops with stegocephalians of Middle Triassic age, which continue as far as the Chaamba Basin on the Algerian-Libyan border (Lefranc, 1964). These strata have gained attention for many years, because they constitute an important hydrocarbon reservoir (Ratcliffe et al., 2003). Indeed, the first research in the region dates back to the beginning of the twentieth century (de Lapparent & Lelubre, 1948), resulting in the distinction of Triassic sandstones with vertebrates at Zarzaitine from Jurassic sandy clays with tree trunks of Taouratine, but without solid palaeontological arguments.

The field campaigns that followed have uncovered remains of vertebrates belonging to rauisuchians (teratosaurid teeth), amphibians (capitosaurid stegocephalians) and selachians (Hybodus) (Lehman, 1957, 1971; de Lapparent, 1958; de Lapparent et al., 1958; Busson, 1968, 1972; Busson & Cornée,

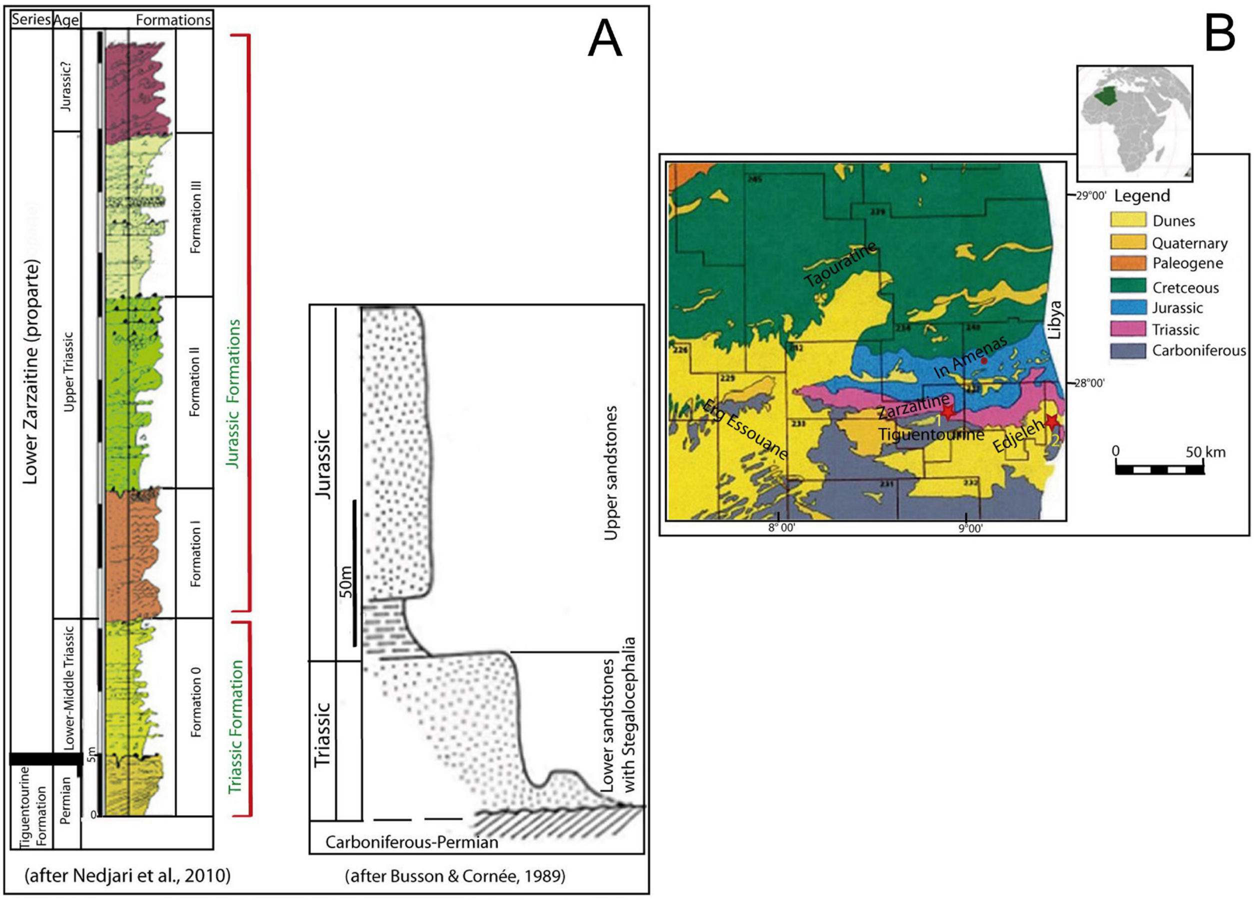

Fig. 1. A – Stratigraphical log of the Triassic series (Zarzaitine Formation) following previous studies. The red intervals refer to ages assigned by Ait Ouali et al. (2011); B – Location and geological map of the study area (Beicip-Sonatrach, 1975). Stars indicate study sites. 1: coordinates: 27°48′33.76′′ N - 9°21′10.13′′ E; 2: coordinates: 27°43′51.3′′ N - 9°52′2056′′ E.

1989). This fauna has been attributed to the Upper Triassic (Carpentier et al., 2016).

Busson (1970) distinguished a formation in which two levels could be differentiated: a lower level with sandstone, quartz pebbles and clay, alternating with green mud beds which contained mainly amphibians (stegocephalans) and reptiles (palaeosaurids) and teeth and spines of selachians towards the top. The upper sandstone level yielded hematised tree trunks and shark spines, stegocephalians and dinosaurs (teratosaurids).

Another geological campaign to the Triassic deposits of Zarzaitine (Nedjari et al., 2010) has revealed the existence of a series of four formations of terrestrial origin, represented by strata laid down by small braided rivers, intercalated with aeolian dunes (Fig. 1A). It was during this particular fieldwork that a new site of stegocephalic temnospondyls was discovered, the taphonomic study of which has revealed a palaeoenvironment of a shallow fluvial alluvial plain evolving towards a sabkha or salt pond, thus leading to the death of these aquatic vertebrates. The study of a well-preserved skull of these amphibians made it possible to define a new species, Stanocephalosaurus amenasensis (Dahoumane et al., 2016) and to confirm the age as ranging from Early to Middle Triassic, as indicated in previous work on this fauna (Jalil &Taquet, 1994).

In 2011, the work of Ait Ouali and co-workers concluded that there was a single formation of Triassic age (Formation F0) for this Zarzaitine series previously established by Nedjari et al. (2010). The three other formations (Formations F1, F2 and F3) were attributed to the Jurrassic.

During the same year, a study of plants from the top of the formation, undertaken by Arbey et al. (2011), led to their being considered as large-sized "Thallophyta" mushrooms and algae, by simple comparison with similar current species, with which they would have a „certain" resemblance.

Apart from the lithostratigraphical study and research into the vertebrate fauna, any sedimentological and palaeoenvironmental analyses of deposits of the Triassic Zarzaitine Formation were not carried out until now.

The aim of the present study is to provide a detailed lithostratigraphical description of the Triassic Zarzaitine Formation and highlight its palaeoenvironmental context. A delta plain with three sub-environments has been emphasised: 1) an upper intertidal delta plain with temnospondyl remains and ichnotaxa, 2) a channelised lower intertidal delta plain with clear tidal bedding and 3) an upper delta plain bearing tree trunks, among which Cycadophyta have been distinguished. The rediscovery of the temnospondyl pit, near the outcrops, has allowed the in-situ study of palaeoecological and palaeoclimatic contexts of these fossil vertebrates which concluded on an aquatic lifestyle in an intertidal delta environment, under a warm climatic context.

2. Location and stratigraphy of the study area

The In Amenas region is located in southeastern Algeria, close to the border with Libya (Fig. 1B) and belongs to the Illizi Basin, a Palaeozoic and early Mesozoic tectonic

depression situated within the Saharan Platform, to the south of the Atlas Orogenic Belt. It evolved during the Palaeozoic as intracratonic depocentres in which thick sedimentary series were laid down over a high-grade metamorphic and igneous Proterozoic basement. A major Late Palaeozoic Unconformity separates the Palaeozoic basins from a northwardly thickening Mesozoic wedge, which forms part of the northwest African passive margin of the Tethys basins (Boudjema, 1987; Burke et al., 2003). The complex Proterozoic basement was accreted during the Pan-African Orogeny, and the Gondwana, Tethys and Alpine 1st order tectono-sedimentary cycles formed the region's sedimentary and structural architecture. The sedimentary rocks, regional unconformities and varied structures register the geological evolution of the area throughout the Phanerozoic.

The clayey sandstones which crop out in the cliff to the south of In Amenas, and which dominate the Permo-Carboniferous plain of Tiguentourine, are referred to as the Zarzaitine Formation (Busson, 1970; Lehman, 1971). This region constitutes the only place in Algeria where the Triassic is known at outcrop. On the geological map (Fig. 1B), it appears in a strip of 10 to 30 km in width which extends eastwards to the Algerian-Libyan border before disappearing under the Erg Issaouane, towards the west.

Triassic outcrops were studied in two regions, Zarzaitine and Edjeleh, 47 km apart. Strata rest unconformably on the Tiguentourine Series dated as Carboniferous-Early Permian (Attar et al.,

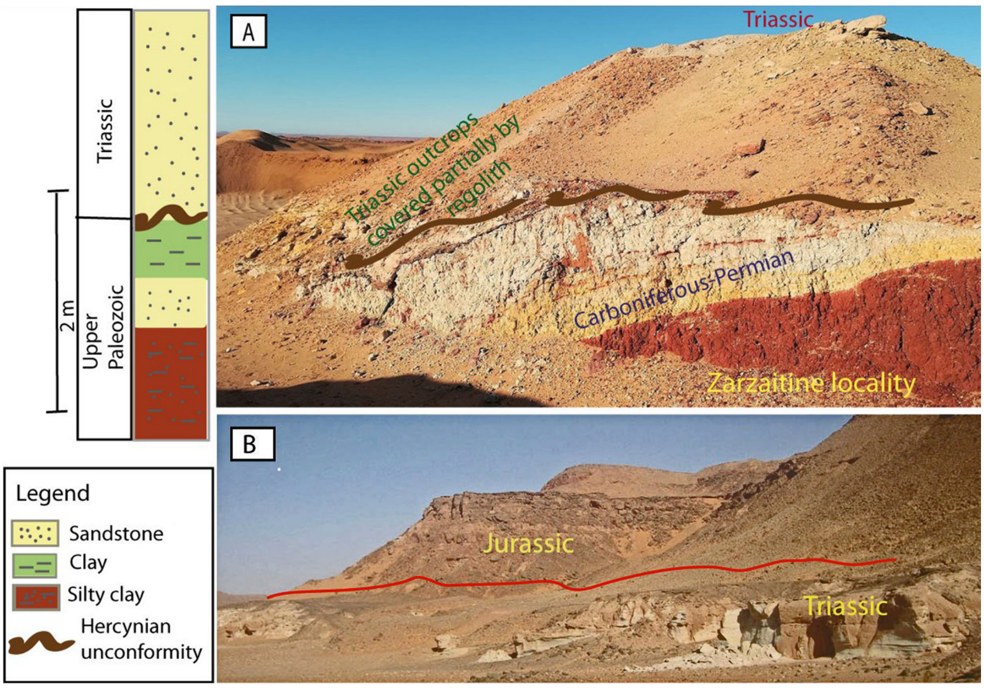

Fig. 2. A – Outcrop showing the lithological succession at the passage of the Hercynian unconformity Palaeozoic/Triassic (Zarzaitine, Algeria eastern Sahara); B – Cliff of Triassic-Jurassic strata.

1981) and are overlain, with a transitional contact, by the Taouratine reddish sandy clay series dated as Jurassic on the basis of a Weichselia palaeoflora (Busson & Cornée, 1989; Lefranc & Guiraud, 1990). This so-called Hercynian unconformity, which is a consequence of continental collision during the formation of Pangaea at the end of the Permian, is difficult to observe in outcrop (Bourquin et al., 2010). It was seen for the first time during our last campaign in the study area due to recent excavations and exploitation of Triassic sandstones (Fig. 2). This revealed the last reddish claystone and silty claystone layers, as well as the yellow and white sandstones of Permo-Carboniferous age, folded and eroded, on which horizontal layers of Triassic age followed, partially covered by waste. The yellowish and greenish colouration as well as ferruginisation at the top, are pedogenetic alterations induced by contact with the water table (Retallack, 2001). These alterations predate the Hercynian folding.

3. Methodology

Field data were amassed at two sites, 47 km apart, namely Zarzaitine and Edjeleh. The total length of the sections studied amounted to 500 m in a N-S and E-W direction at Zarzaitine and a N-S direction at Edjeleh. These data comprise detailed measured sections and descriptions of lithofacies (with symbols F), sedimentary structures (including tidal structures), ichnofacies and trees. Three facies associations (with symbols FA) have been identified and interpreted in terms of depositional setting.

Thirty-two trace fossils (in full relief) have been collected and examined in detail. Most of these are well preserved in fine- to coarse-grained sandstones. They were identified according to their standard characteristics and morphological criteria (Bertling et al., 2006), such as, branching or non-branching and type of burrow infill and wall characteristics. Trace fossils preserved in their entirety in beds are called complete relief structures (Seilacher, 1967). Those belonging to facies association 1 (FA1) of the Zarzaitine Formation appear in full relief in sandstone substrate, because part of this substrate is eroded. Around forty examples of burrows (ichnogenera Monocraterion and Skolithos) have been recorded at both sites, reflecting palaeocurrent orientations. Other burrow types represented include Thalassinoides (?), also showing orientation of apertures occurring on the surface of the sandstone channels. These traces were found in eight small channels juxtaposed on the same level belonging to FA1.

The bioturbation index (BI), as established by Reineck (1963), has been used to obtain an overview of the bioturbation intensity in these sedimentary successions. The index ranges between 0 (= no bioturbation) and 6 (= complete bioturbation) (see Taylor & Goldring, 1993).

Certain tree trunks from these Triassic deposits (top of the Zarzaitine Formation) were the subject of a preliminary identification: based on general morphological appearance, presence and shape of leaf scars and presence of seeds and their position on the trunks, cycads and Bennettitales have been distinguished (Wieland, 1906).

4. Sedimentological and palaeoenvironmental study

The sedimentological study and palaeoenvironmental analysis of outcrops in the study area led to the distinction of fourteen lithofacies (F) (Table 1) and three facies associations (FA) which follow one another vertically over a thickness of 15 m (Fig. 3). These facies associations are described in detail below.

4.1. Facies association FA1: Intertidal mixed flat with vertebrate remains, dominated by Skolithos ichnofacies (upper intertidal zone)

Description. FA1 includes the basal part of the formation. This is indicated by a slightly inclined palaeosurface, which may attain a lateral extension of approximately 40 m (the same palaeosurface also existing in the Edjeleh region). It shows small sandy accumulations with small tree trunks, as well as a Lagerstätte that contains significant remains of stegocephalians, as documented previously. Several additional specimens are currently under study (Fig. 4). These remains of temnospondyl amphibians were found in a depression of around thirty square metres and a depth of approximately 0.5 m (Figs. 3, 5B). In essence, these comprise skulls in excellent preservation, but also mandibles, vertebrae and dermal plates, all covered by structureless fine sand (F4) and a highly indurated greenish silty-clay facies (F11a).

The small sandstone outcrops, which across the palaeosurface occur either as small bodies with flat

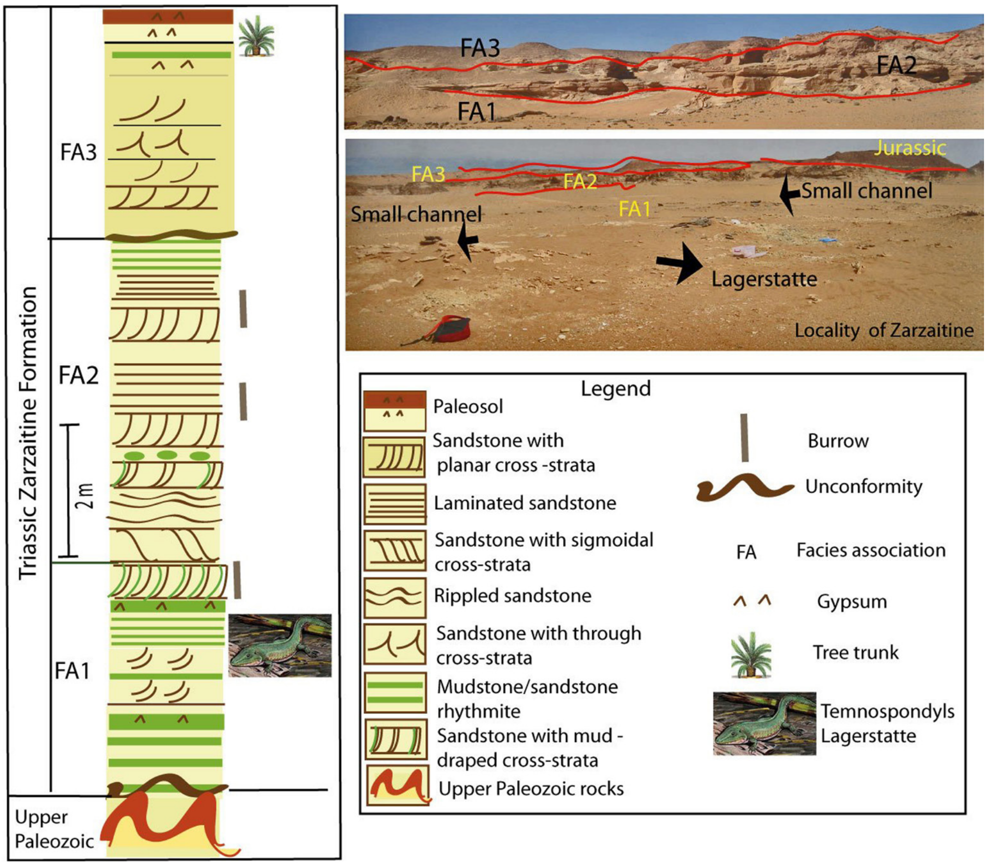

Fig. 3. Synthetic lithological log of the Zarzaitine Formation.

bases whose thickness is < 0.3 m (Fig. 5B) showing planar (F1a) and low-angle stratifications (F2a), or like elongated flat sandy sheets, oriented NNW (Fig.5A). Next to these mixed fine- and coarse-grained sandstones, peculiar burrows occur in full relief. They are of low diversity and moderate intensity (2<BI <3) (Figs. 5B, 6). Some tree trunks oriented NNW, whose length does not exceed 20 cm, and 8 cm in diameter, are present (Fig. 5A).

Burrows belong mainly to the Skolithos ichnofacies assemblage (Fig. 6) with the following ichnogenera recognised: Arenicolites, Monocraterion, Skolithos and Ophiomorpha, found both in the Zarzaitine and Ejeleh regions. Some Thalassi-

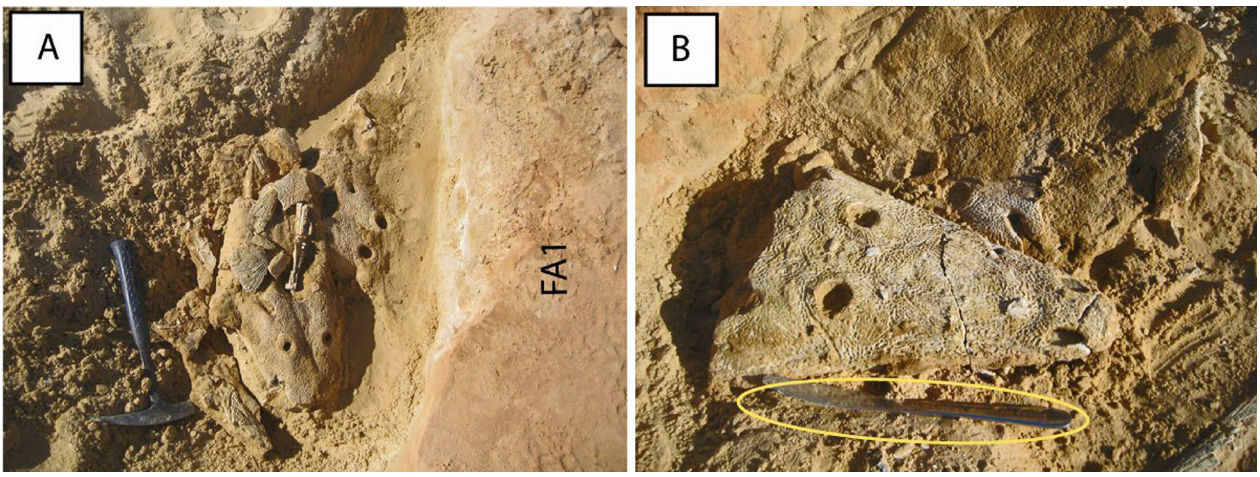

Fig. 4. Facies association FA1. A – Lagerstätte of skulls and other remains of temnospondyl bones; B – Closeup view of a mastodonsauroid temnospondyl Stanocephalosaurus amenasensis in dorsal view (hammer and knife for scale).

Table 1. Description of lithofacies identified within Triassic Zarzaitine Formation.

Facies	Description	Interpretation	Facies associations
Planar cross-stratified sandstones (F1a), with mud drapes (F1b)	Fine- to very coarse-grained sandstones with unidirectional planar or wedge-shaped cross-stratification. Sets up to 0.3 m thick. Mud drapes (1-3 mm thick) overlying sandstones. Skolithos burrows, tree-trunks and vertebrate bone remains.	2D-dunes of river and ebb channels or creeks. Upper intertidal environment. Mud drapes deposited from suspension settling during tidal phases of slack sea waters.	FA1, FA2, FA3
Low-angle cross-stratified sandstones (F2a), with mud drapes (F2b)	Fine- to medium-grained sandstones. Sets up to 40 cm thick. Laminae dip at 3-10°. Mud drapes often on the cross-stratified sets.	River and tidal channels and creeks. Flows of relatively low energy, or conditions of upper flow regime. Mud drapes were settled during tidal slack-waters.	FA1, FA2, FA3
Plane-parallel laminated sandstones (F3)	Very fine- to very coarse-grained sandstones with horizontal lamination. Bed thickness up to 50 cm.	In-channel deposition during slack water phases Conditions of upper flow regime.	FA1, FA2, FA3
Massive sandstones and siltstones (F4)	Massive, fine- to coarse-grained sandstones, siltstones. Bed thickness up to 30 cm.	Rapid deposition during ebb phases.	FA1, FA2,
Asymmetrical ripple cross-laminated sandstones (F5)	Fine- to medium-grained sandstones (and siltstones) with asymmetrical, unidirectional ripples.	Low-energy intertidal with weak currents.	FA1, FA2
Through cross-stratified sandstones (F6)	Cross-stratified medium- to very coarse-grained sandstones. Bed thickness up to 30 cm.	Sinuous and linguoid (3D) dunes.	FA3
Tidal bundles (F7)	Alternating horizontal intervals of tightly- and loosely-laminated sandstones. Clayey drapes atop.	Strong, dominant ebb current followed by weak current (flood). Neap-spring water cycles controlled different dune types.	FA2
Overturned ripple structures (F8)	Medium- to coarse-grained sandstones with overturned ripple cross-lamination.	Deposition from traction transport and deformation by shear stress of current and escaping pore water.	
Sigmoidal cross-stratified sandstones (F9)	S-shaped cross-stratified sandstone beds, dcm-thick beds.	Accelerating flow to full-vortex conditions, followed by deceleration phase during tide.	
Conglomerates (F10)	Clast-supported, moderately sorted subangular pebbly and gravelly clast debris with sandy-clayey matrix. Basal parts of sandstone channel infills. Muddy pebbles are present.	Scour-fill debris flows in braided channels. Muddy pebbles were torn up by the currents when they cross the more muddy interdistributary areas.	FA3, FA2
Mudstone deposits (F11): indurate greenish claystones (F11a), reddish mudstones (F11b)	Greenish claystones above stratified sandstones with vertebrate remains (FA1). Cm-thick reddish mudstones intercalated between sandstones (FA3).	Greenish claystones settled during slack-water tidal periods in the interdistributary channels, which formed the ponds for stegocephals. Reddish mudstones formed on inundated fluvial plains of FA3.	FA1, FA2, FA3
Desiccation polygons (F12)	Desiccation polygons on the sandstone beds at the top of the formation.	Palaeosol cracks formed when muddy sediment dried and contracted recurrently in hot climate	FA3
Laminated rhythmite (F13)	Vertical alternation of laminae: fine-grained sandstones, siltstones and mudstones.	Tidal flat and interdistributary channels influenced by intermittent currents, defined by ebb currents (sandstones and siltstones) and slack-water periods (mudstones).	FA2
Reactivation surfaces within foresets (F14)	High-angle (20-25°) erosion surfaces within multiple foresets. Clayey drapes.	Erosion of bedforms during reversal tidal flow.	FA2

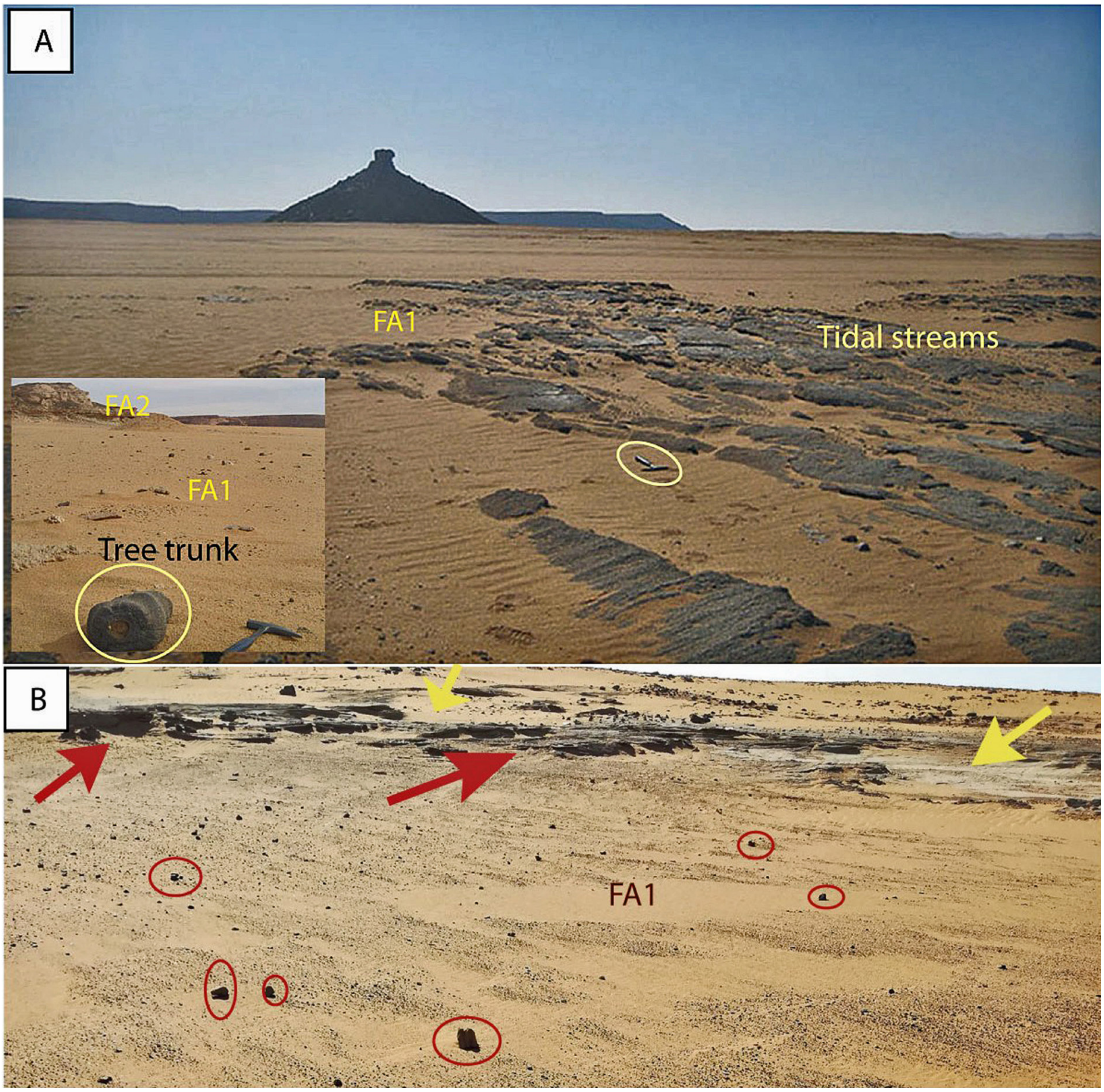

Fig. 5. General view of a tidal flat facies association (FA1). A – Palaeosurface fossilising sand sheets of oriented tidal streams or creeks (hammer for scale). The photograph on the left corner shows oriented tree trunk (circle); B – The same palaeosurface showing tidal channels (red arrows), depressions forming ancient ponds (yellow arrows) and burrows (circles).

noides(?) burrows (Fig. 5A, B) also occur just a few metres from the vertebrate-bearing bed. While awaiting further details on these burrows (in depth identifcations are under way), their different characteristics can be summarised as follows:

Thalassinoides (?) (Fig. 6A, B) is defined by interconnected burrows that extend vertically, horizontally and laterally. These traces occur in small coarse- to fine-grained sandstone channels exhibiting planar parallel laminations and current ripple laminations. They have no filling and their exterior wall is rather regular. The apertures are circular, 0.2 to 0.4 mm in diameter; those on the sandstone channel surface show an orientation parallel to the laminations recorded by current ripples.

Arenicolites (Fig. 6C) is defined by simple U-shaped tubes, the length of which varies between 1 and 5.5 cm, their width varying between 1 and 4.5 cm. The apertures are relatively small, circular and of different diameters, ranging from 0.4 to 1 cm. They occur in full relief on the eroded fine- to medium-grained sandstone channels.

Skolithos (Fig. 6D) (left small photograph) occurs as straight, vertical to slightly inclined cylindri-

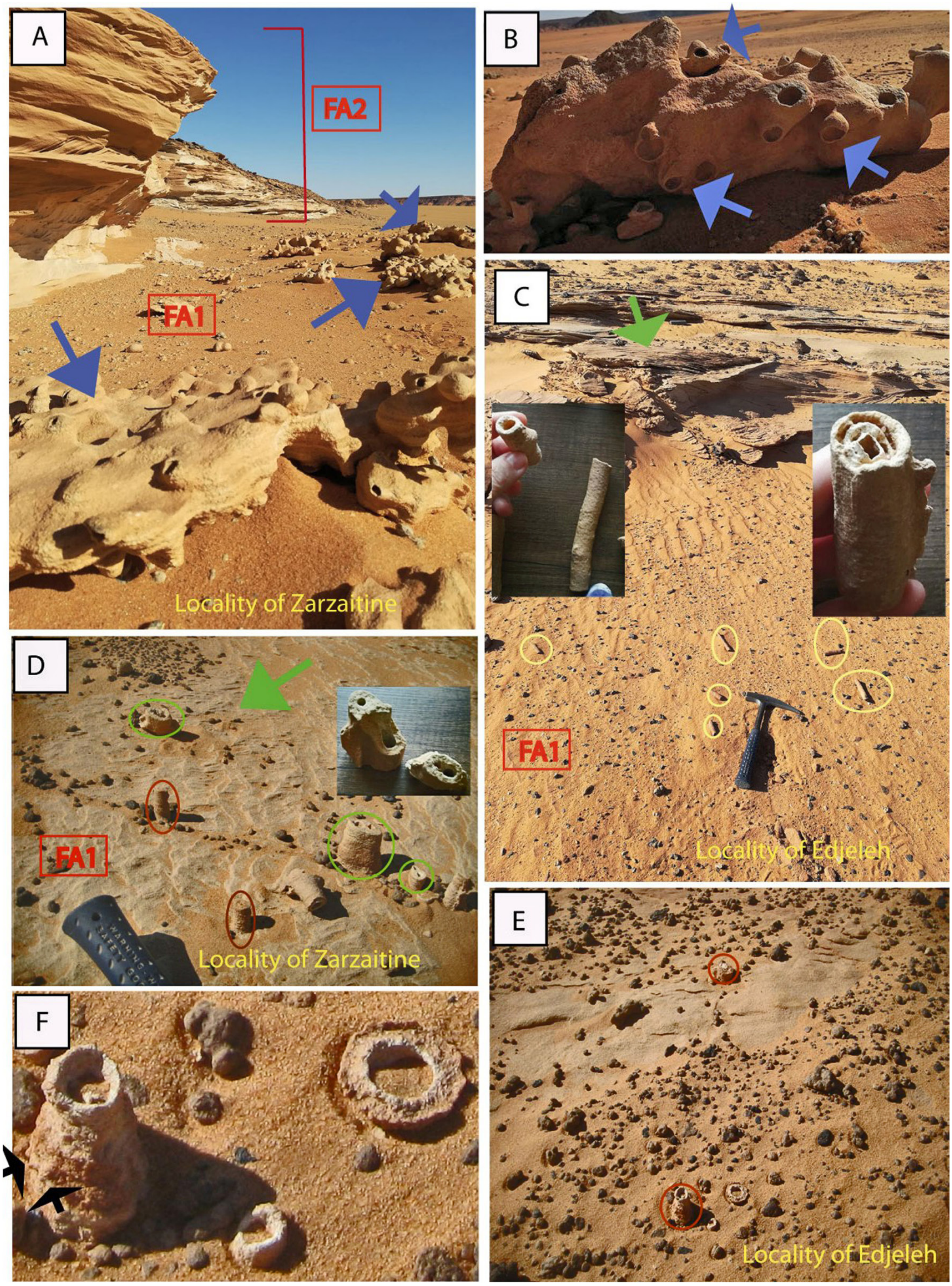

Fig. 6. Palaeosurface with full relief burrows of FA1. A – Thalassinoides (?) (blue arrows) occurring in small channels, overlain by FA2. See the oriented apertures on the sandstone channel surface; B – Details of Thalassinoides (?) showing circular apertures in different parts of the channel (blue arrows); C – Skolithos and Monocraterion (yellow circles) near the sandstone channel infill (green arrow). See closeup view of Skolithos (left-hand small photograph) and Monocraterion (right-hand small photograph); D – Arenicolites (green circles) and Ophiomorpha (red circles) on sandstones channel of FA1. See a closeup view of Arenicolites (small photograph); E, F – General and closeup views of Ophiomorpha (red circles). See the ovoid nodule pellets on the outer surface of Ophiomorpha (black arrows).

cal and unbranched burrows. The wall is smooth. These structures show more or less uniform diameters, varying between 3 to 25 mm, and lengths between 30 and 120 mm. Burrows are preserved in full relief and have no filling. They are either in vertical (living) position, or laid out horizontally and then roughly oriented parallel to the sandstone planar cross stratifications.

Monocraterion (Fig. 6D) (right small photograph) is a structure with vertically stacked funnels crossed by a straight empty central tube and with a thick wall composed of fine sand, thus giving the burrow a smooth outer surface. It is a straight, unbranched and full-relief burrow. The entire aperture is 1.5 to 2.5 mm and the main or innermost stem is 5 to 7 mm in diameter. Its length varies between 30 and 100 mm. These appear in full relief on the fine- to medium-grained sandstone channels (Fig. 6C). They are either in vertical (living) position or laid out horizontally and then roughly oriented parallel to the sandstone planar cross stratifications (Fig. 6D).

Ophiomorpha (Fig. 6E, F) is represented by vertical burrows, circular in cross section, 3–4 cm in diameter, 8–16 cm in length and with a roughly crenulated outline. The outer burrow surface displays a lining composed of robust, irregularly spaced, ovoid and dense nodules of faecal pellets (Fig. 6F). They are preserved in full relief.

Interpretation. FA1 is defined by the presence of minor sandy and low-energy tidal channels, as well as oriented flat sandstone bodies which represent tidal creeks. Between these tidal creek bodies, small depressions with fine sedimentation served as ponds and habitat for mastodonsauroid temnospondyl amphibians, represented by the Algerian species Stanocephalosaurus amenasensis, as described by Dahoumane et al. (2016).

The association of channels, interchannelised amphibian ponds, Skolithos ichnofacies, tree trunks and facies associations of the entire Triassic unit (FA2 and FA3, see below), indicate an upper and shallow intertidal mixed flat zone (e.g. Davis & Dalrymple, 2012; Desjardins et al., 2012).

The ichnogenus Skolithos is found in all types of environments, from deep-sea marine to continental. However, it has been widely recognised in shallow, high-energy marine environments (e.g., Alpert, 1974; Fillion & Pickerill, 1990; Droser, 1991; Knaust et al., 2018), especially in intertidal deposits (Seilacher, 1967). It is interpreted as a domichnion made by annelids or phoronids (Alpert, 1974) and suspension feeders.

Thalassinoides trace makers are burrowing shrimp, or closely related arthropods (Frey, 1975).

Monocraterion and Arenicolites are generally interpreted as vertical dwelling structures of suspension-feeding organisms typical of shallow and high-energy marine environments (e.g. Goodwin & Anderson, 1974; Pickerill et al., 1984; Bromley & Asgaard, 1991; Droser, 1991). Ophiomorpha has generally been attributed to the activity of crustaceans, mostly (but not only) decapods (Frey et al., 1978; Monaco et al., 2007). In modern environments it is produced by the mud shrimp Callichiurus (Frey et al., 1978; Uchman & Gaździcki, 2006; Dworschak et al., 2012). The ethology of this trace fossil maker is complex and may represent a variable combination of deposit- and suspension-feeding behaviours (Uchman & Gaździcki, 2006; Leaman et al., 2015). Ophiomorpha is considered a cross-facies trace fossil from shallow- to deep-water marine environments (Monaco et al., 2007). However, it is prolific in marine shorefaces and also found in brackish water and sandy substrates including estuaries and tidal shoals.

Although the majority of the above-mentioned trace fossils can be found in any depositional environment, and cannot in this case indicate a specific environment or physicochemical condition, their association or assembly in the same location provides more robust interpretations and is unique to specific palaeoenvironmental contexts (Ekdale et al., 1984; MacEachern et al., 2007a, b). Concerning the association or the suite of trace fossils attributed to the Skolithos ichnofacies, this is characteristic of the coastal zone with moderate to high-energy conditions, in general, and of the intertidal zone, in particular.

Low-density and depauperate trace fossil assemblages suggest a brackish-water environment (Pemberton & Wightman, 1992; Buatois & Mangáno, 2011). The occurrence of suspensivore domichnia (Skolithos, Arenicolites,Monocraterion and Thalassinoides(?)) and fodinichnia burrows (Ophiomorpha) indicate an intertidal zone where organisms have to be able to respond rapidly to stressful conditions (sedimentation and erosion variations).

The orientation of the apertures in Thalassinoides(?) indicates the direction of the palaeocurrent. Such a direction would be due to a protection of these ichnotaxa against their possible obliteration by sedimentation. As for Skolithos, which lie horizontal, their orientation indicates a rearrangement by the palaeocurrent, as shown by the channel infill cross stratifications.

4.2. FA2: Tidal distributary channels and interdistributary areas of lower delta plain (intertidal zone)

Description. FA2 is represented by an outcrop of approximately 10 m in thickness of alternating intervals composed mainly of sandy layer intervals containing few vertebrate remains and tree trunks, and intervals in which the major component is clayey. This facies association is topped by erosion and deposition of FA3 (Fig. 7).

The former interval is represented by a cyclical alternation of horizontal green claystones (F11a) and structureless siltstones or sandstone (F4) laminae, arranged in a succession of couplets or pairs of centimetre thickness (F13), succeeding one another vertically, followed by fine-grained, low-angle sandstones and siltstones with clayey drapes (F2b). The thickness of the interval which contains the couplets of claystones and sandstone laminations varies between 1 and 3 m (Fig. 8A, B) on average, and the thickness of laminae is 0.2 to 0.5 cm. A concave erosion surface separates these heterolithic facies from the overlying sandy deposits interval (Fig. 8A). Laterally, these couplets (F13) also overlie a concave erosion surface (Fig. 8B, C).

The succession of sandstone layers (Fig. 9A, B) that constitutes the second interval is 4 m in thickness. It shows erosional bases with mud clast rip-up, and is composed of mainly planar tabular cross stratifications (F1a), dipping under angles of 15 to 25°, low-angle bedding (F2a), parallel laminations (F3a), structureless sandstones (F4), sigmoidal cross-bedding (F9), reactivation surfaces (F14) and also tidal bundles (F7).

Reactivation surfaces are recognised by the discontinuities cutting across a foreset, whereas tidal bundles are characterised by the existence between two planar mud draped stratifications (F1b) of a horizontal alternation of spaced foreset laminae intervals the thickness of which ranges from a few to 10 cm, and tightly foreset laminae intervals reaching thicknesses of about a few millimetres (Fig. 9B). The grain size of the sands being very fine, these tightly or densely spaced cross stratifications are barely visible, or not at all.

The last levels of FA2 are defined by a bed bearing mud-draped planar- and low-angle, cross-stratified sandstone layers (F1b and F2b) and couplets of claystones and sandstones (F13).The same levels show laterally mud-draped overturned sandstone cross-stratifications (F8) (Fig. 10A) and tidal bundles (F7). They are overlain by well-sorted, coarse- to fine-grained sandstones which can be heavily bioturbated in places (2<BI<3), bearing planar stratifications, plane laminations and asymmetrical ripples (F1a, F3a, F5).

Burrows represented are mainly Skolithos and Arenicolites (Fig. 10B). Arenicolites are recognised by a pair of closely spaced circles whereas Skolithos has only a single circle occurring in sandstone beds. The diameter of each circle is less than 0.3 mm.

A significant erosion surface, 15 cm deep, typifies FA2 and separates it from the overlying FA3 (Fig. 10B).

Interpretation. The vertical succession of sandstone dunes with erosive bases, bearing amphibian remains as well as pieces of fossil wood, and finally, the existence of tidal structures, attest to a deltaic environment influenced by tides, composed of distributary channels and interdistributary areas (Coleman & Prior, 1981).

Sandstone deposits bearing stratifications indicating transport represent the channels. This was

Fig. 7. General view of FA2 and FA3 in outcrop.

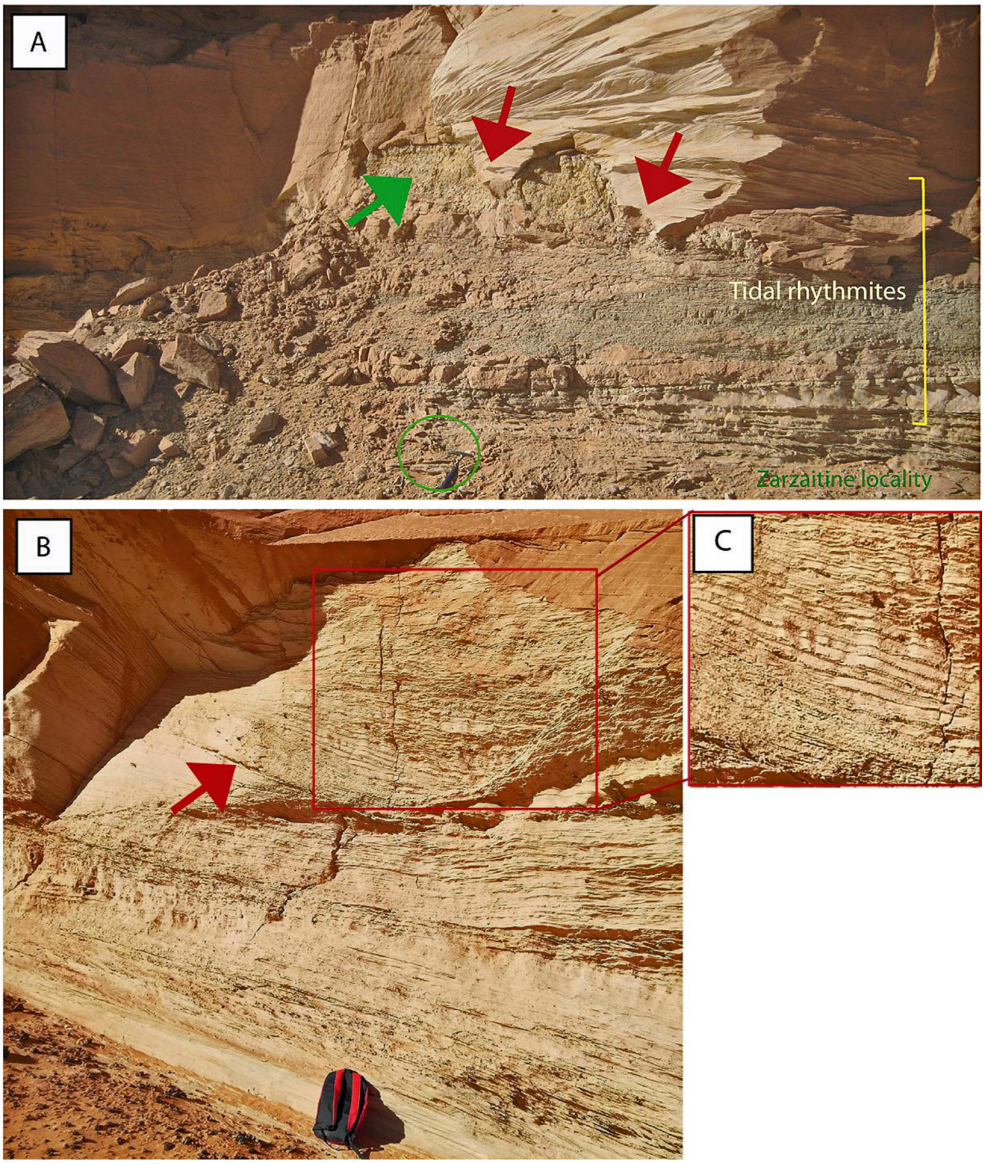

Fig. 8. A – Mud flat deposit (green arrow) and tidal rhythmites (yellow interval) eroded by channels. See basal erosional surface (red arrows). Hammer for scale; B – Tidal rhythmites.See the erosional surface of a channel (arrow); C – Closeup view of tidal rhythmites.

carried out during the ebb phases (in a deltaic environment, the sands are carried towards the open sea during the ebb phase).

The interdistributary areas are defined as a relatively calm sub-environment compared to that of the channels; they are characterised by sandstone deposits and a considerable amount of fine particles, mainly clayey or muddy, which are often eroded by the overlying sandstone channels (Coleman & Prior, 1981; Boggs, 2005).

FA2 reflects active sandstone channel deposits eroding muddy sediments. Sandstone dunes with erosional bases bearing amphibian remains and wood pieces and with tidal structures as well are tidally influenced deltaic channels. The interdistributary environment is characterised by high quantities of settling mud, which are often eroded by an overlying sandstone channels (Coleman & Prior, 1981; Boggs, 2005).

The occurrence of several types of tidalites, such as bundles, rhythmites, mud-draped cross stratifications and reactivation surfaces, reflects an intertidal environment (e.g., Boersma, 1969; Dalrymple & Choi, 2007; Davis & Dalrymple, 2012). Tidal signals originate either at daily tidal cycles (such as rhythmites and mud-draped stratifications) or monthly tidal cycles (such as tidal bundles).

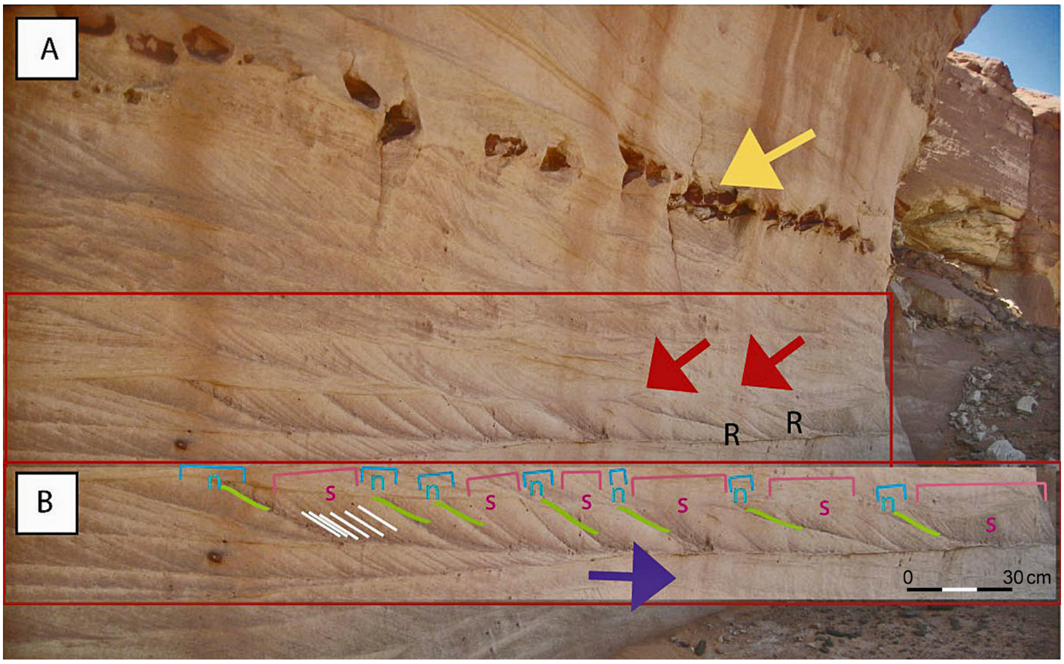

Fig. 9. A – Stacked sandstones strata of FA2. Interspersed mud clasts mark the base of a channel (yellow arrow); B– Closeup view: tidal bundle sequences of neap (n)-spring (s)-neap events (blue and pink intervals) and reactivation surfaces (R – red arrows). Thin white lines trace the internal bundles. Green bounding lines are mud drapes which reflect the cessation of the bedform migration during neap periods. The blue arrow indicates the dominant current direction.

Sandstone deposits with tidal structures are transported by ebb tractive current, whereas the mud drapes settled at maximum and minimum tidal height (when current velocity is almost zero) (Boersma, 1969; Davis & Dalrymple, 2012).

Rhythmites defined by the recurrent couplets or pairs of sand and mud laminae 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.

Reactivation surfaces generated by erosion during reversal tidal flow or changing flow strength before the resumption of the forward migration of the foreset. This reversible movement induces erosion of the underlying stratifications of reactivation surfaces.

Tidal bundles 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 the case of deltas), followed by a weak subordinate current, sand dunes with spaced stratifications are formed, followed by densely stratified dunes. The first dunes form during a spring tidal cycle (every 14 days, i.e., twice a month, when the Earth, Moon and Sun are aligned), while the second ones form during neap tidal cycle (when the Earth, Moon and Sun are perpendicular to each other) (e.g. Boersma, 1969; Terwindt, 1971; Boggs, 2005).

The intertidal milieu is also indicated by the presence of the low diversity of domichnia, represented by burrows of Arenicolites, Monocraterion and Skolithos type, where they are able to adapt to constant fluctuations in salinity and temperature, induced in particular by the arrival of fresh water through deltaic channels (Buatois & Mangáno, 2011; Desjardins et al., 2012).

4.3. FA3 braided river channels and palaeosol of upper delta plain (supratidal zone)

Description. The contact between the first sediments of FA3 and the last levels of FA2 is a concave erosion surface, 15 cm thick (Fig. 11) above which follow 5 m of poorly sorted, coarse- to medium-grained sandstones with cross-bedding. The first sandstone beds exhibit slightly concave eroded base surfaces with quartz gravels (F10), through cross-bedding (F6) and planar tabular stratifications (F1a). They are intercalated with centimetric layers of gypsiferous reddish silty clays (Fig. 11B). The last two metres are represented by very coarse sandstone bars with horizontal bedding (F3a), desiccation polygons (F12) and quartz pebbles at their tops

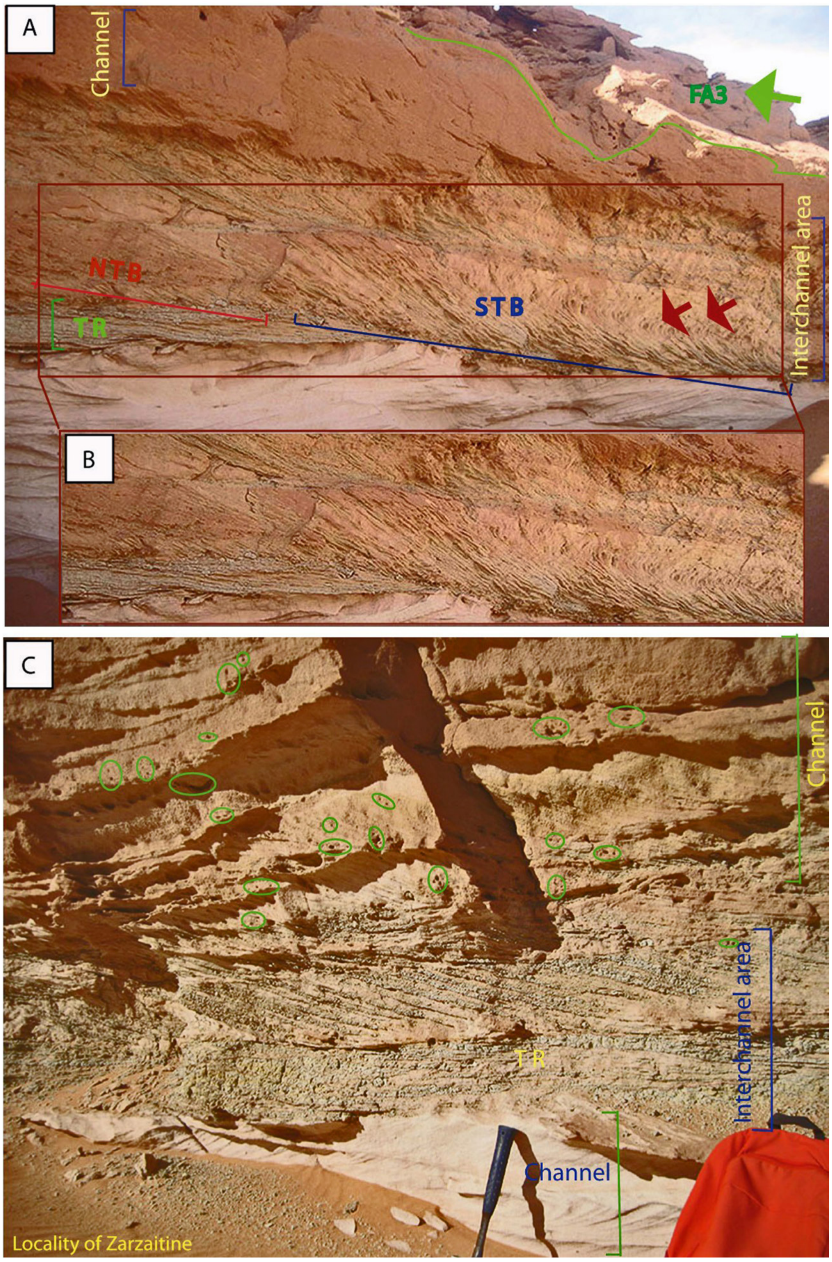

Fig. 10. The uppermost beds of FA2 showing: A – Interdistributary area defined by tidal rhythmite (TR), spring tidal bundles (STB), neap tidal bundles (NTB) and mud-draped overturned megaripple structures (red arrows), overlain by sandstone channel infill topped by erosional surface of FA3 (green arrow); B – Closeup view showing tidal bundles and overturned cross-stratifications; C – The same beds observed laterally showing interdistributary deposits defined by: tidal rhythmites (TR) and mud-draped planar cross-stratified sandstones, topped by a channel infill represented by planar cross-stratified sandstones rich in traces of burrows (circles).

(Fig.11A).These sandy deposits, which are characterised by a total absence of tidal structures, form coarsening upward successions (Fig. 11B, C) and are topped by remains of ferruginised small trunks of shrubs (Fig.12 A, B). These are in situ above or between some sandy bars, where they are often gathered in grooves scattered over more than 30 square kilometres. While awaiting the results of more in-depth studies of this Triassic flora, currently in progress, the first descriptions of some of these show tree trunks whose height varied between 15 and 23 cm, and a diameter between 13 and 20 cm. These mineralised trees are not branched and have short and spherical shape, with a very large or narrow opening. Their outer envelope (when unsilicified) presents barely visible scars due to mineralisation and/or covered by sand. These scars are subrounded or elongated or roughly diamond-shaped (Fig. 12C). Some of these trunks have in their apical part elongated slits of 1.5 cm, and other circular ones, arranged in a circle (Fig. 12E, F). Some bear circular cones on their outer envelope (Fig. 12E) surrounded by small pores of millimetre diameter, while others show two exceptionally well-preserved cones at their apical part (Fig. 1F).

Interpretation. The succession of sandy layers represents braided fluvial channels, with reduced thickness of floodplain silty-clay (Miall, 1996; Nich-

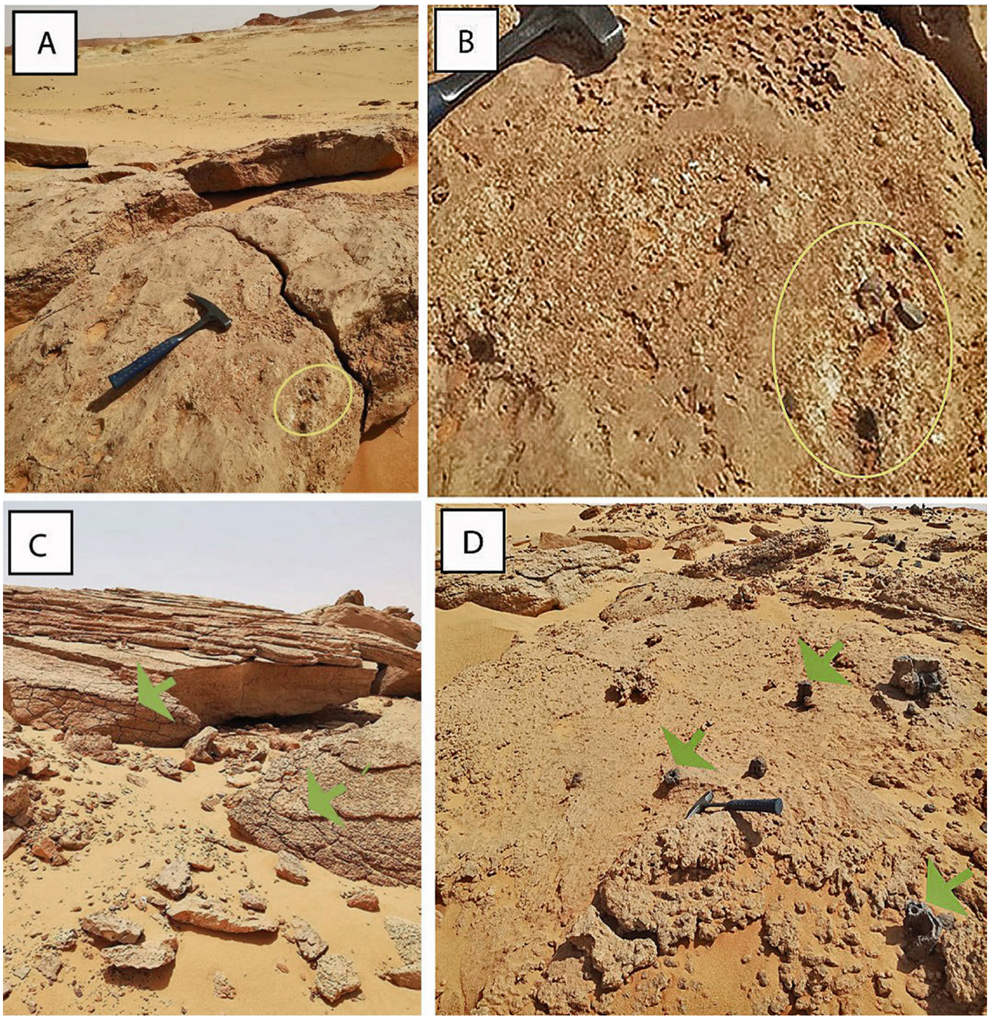

Fig. 11. A – Last level of coarse sandstone bars of FA3 with pebbles (circle). Hammer for scale; B – Closeup view of pebbles (circle); C – Desiccation polygons (arrowed); D – Tree trunks surmounting sandstone bars (arrows).

ols, 2009) whose red colour indicates an oxidised or subaerial environment (Retallack, 2001). Desiccation polygons attest to a hot and semi-arid climate.

The shape, size and diamond-shaped external scars of the stout cone-bearing trunks characterise Cycadophyta. Silicified trunks bearing circular cones above the trunks, correspond to the extinct group of Bennettitales, whereas those in which cones topped the trunk are cycads (e.g. Wieland, 1906; Cheng et al., 2016; Simpson, 2019; Liu et al., 2022). Elongated slits at the top would correspond to traces of inking of the crown of terminal leaves, specific to this type of trees.

Finally, the vertical succession of the three facies associations FA1, FA2 and FA3 highlights deltaic progradation.

5. Palaeoenvironmental, palaeoclimatic, palaeoecological and stratigraphical deductions

The Triassic Zarzaitine Formation, with temnospondyl fossils, typifies sedimentation in a shallow deltaic environment, influenced by tides, followed by braided river channels on which a palaeosol with numerous terrestrial palaeoflora developed. This succession of facies indicates deltaic progradation, from the SSE towards the NNW, in a hot and semi-arid climate, as evidenced by the gypsiferous crusts.

This sedimentation essentially occupies the lower deltaic plain which includes a tidal flat zone with temnospondyl amphibians (Fig. 13), and an area where distributary channels with numerous Skolithos, Arenicolites and Monocraterion burrows occur. These channels are separated by a relative-

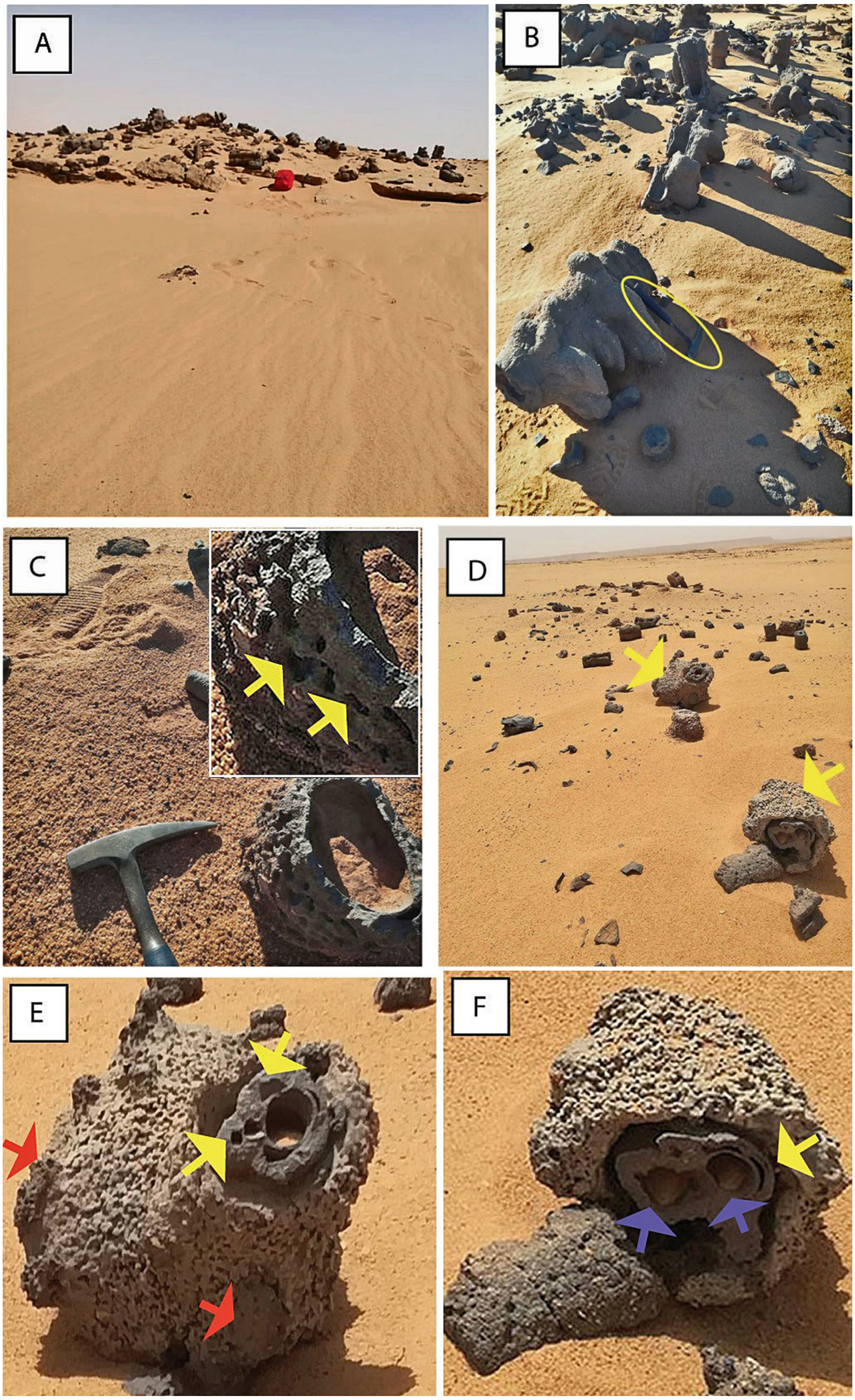

Fig. 12. A – Trees in situ within sandstone channel infill (bag for scale); B – Closeup view of indeterminate and ferruginous tree trunks (hammer for scale); C – Short and spherical shape tree with large apertures bearing scars of leaf bases on their external envelope (yellow arrows). Photograph in the right-hand corner shows a closeup view of subrounded or diamond-shaped scars; D – General view of two silicified Cycadophyta-bearing cones; E, F – closeup view of the Bennettitales bearing several cones above the trunk (red arrows) and cycad bearing two cones at the apex (blue arrows). See the elongated slits corresponding to frond scars (yellow arrows).

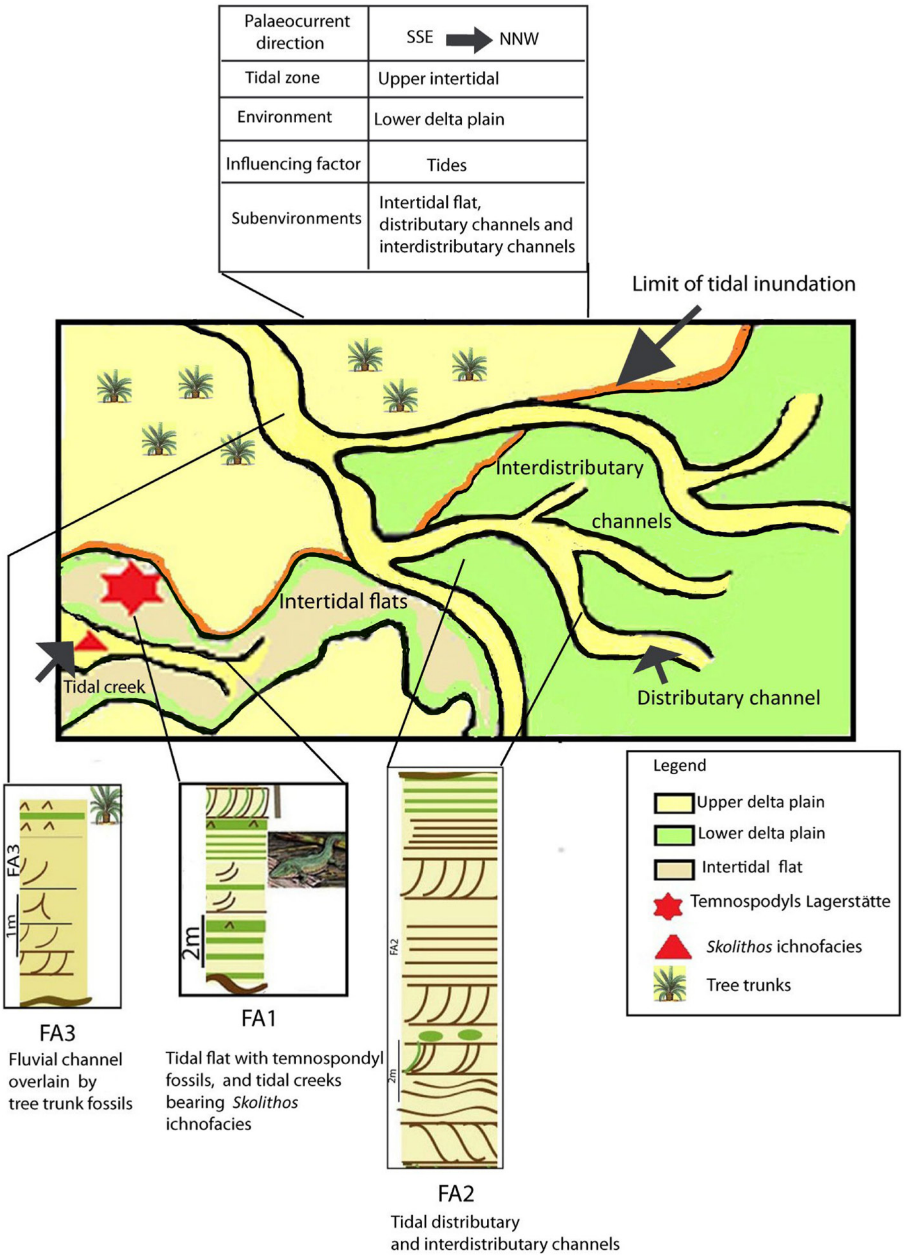

Fig. 13. Schematic diagram of tidally influenced Triassic delta of the Zarzaitine Formation (eastern Sahara of Algeria). Synthesis of facies associations and their palaeoenvironmental positions.

ly heterolithic facies of interdistributary bays, with numerous tidal signals.

The numerous temnospondyl fossils, whose age Early-Middle Triassic (Jalil & Taquet, 1994; Dahoumane et al., 2016) were found in situ, which attests to mass death. If the latter occurred at the end of the Middle Triassic, this is concomitant with the a sea level drop at the same time (Haq et al., 1987, 1988). This event led to the progradation of deltaic deposits of the Zarzaitine Formation, and the installation of a terrestrial area where a palaeosol developed. This marine regression would therefore be the probable direct cause of the mass death of these large Triassic amphibians.

6. Discussion

The sedimentological study of Triassic clayey sandstone deposits with remains of temnospondyls and plants at Zarzaitine showed a deltaic formation under tidal influence, followed by a palaeosol with Bennettitales and cycads. This diverges from the studies undertaken by previous authors (Nedjari et al., 2010; Dahoumane et al., 2016), for whom this formation was of a fluvial type and more precisely of a braided river type whose uppermost part was characterised by algal and fungal growth (Arbey, 2011). It is true that fluvial and deltaic environments are sometimes quite difficult to distinguish, because both contain terrestrial fossil remains (vertebrates and plants), and in ancient deltaic series organisms with shells are often rare, or even absent, because the waters which are often acidic inhibit the constitution of aragonitic or calcitic tests (Coleman & Prior, 1981; Mazrou & Mahboubi, 2021). However, the following arguments converge towards a deltaic environment, and a Cycadophyta palaeosol.

The stratigraphical succession of the Zarzaitine Formation shows a coarsening-upward arrangement, specific to regressive deltaic deposits (e.g. Coleman & Prior, 1981; Miall, 1996), and there is a relatively large quantity of claystones or mudstones compared to the quantity of sands and sandstones. These two features in fact contrast to characteristics of a braided fluvial formation, defined by a fining upward and the existence of a very reduced quantity of clays and silty clays settling on the flood plain (in the order of a few millimetres in thickness), or sometimes non-existent at all, because the flood plains are generally destroyed by the braided channels which succeed them (e.g. Miall, 1996; Nichols, 2009). In addition, this Zarzaitine deltaic formation clearly presents intertidal deposits characterised by a wide variety of tidal structures (rhythmites, tidal bundles, reactivation surfaces, sigmoidal and mud-draped cross-bedding), followed by supratidal deposits represented by fluvial sediments without any tidal structure and above which plants grow. Cyclic tidal structures are represented by daily tidal cycles (mud drapes and rhythmites) and monthly tidal cycles (tidal bundles). Bidirectional structures, also called herring bone structure, did not occur in the studied sedimentation, because they are rare or can be completely absent in a prograding deltaic system (e.g. Boggs, 2005; Dalrymple & Choi, 2007; Davis & Dalrymple, 2012), where there is only one dominant current (which is that of the ebb) responsible for transporting sands from the coast to the open sea, and not two opposed currents.

Trace fossils represented by the ichnogenera Skolithos, Monocraterion, Diplocraterion, Ophiomorpha and Thalassinoides, exhibit a strong similarity to the archetypal Skolithos ichnofacies which is characteristic of the littoral zone with moderate- to high-energy conditions (Ekdale et al., 1984; MacEachern et al., 2007a, b). The association of Skolithos ichnofacies with sediments bearing numerous tidal structures, indicate clearly an intertidal zone. The small number and low diversity of ichnofossils indicate a brackish milieu, which is specific to a deltaic environment.

The presence of hybodont sharks whose teeth and spines were found in the deposits of the study area (e.g. Busson & Cornée, 1989; Fabre, 2005) (see Introduction) cannot be ascribed to a freshwater environment, because shallow braided rivers which dried up frequently (see Nedjari et al., 2010; Dahoumane et al., 2016), could never have provided a suitable habitat for these large fish that lack lungs. Furthermore, hybodonts associated with other vertebrates have been described from paralic environments in the southwest of France (Vullo et al., 2005).

As to the occurrence of amphibian fossils, contrary to observations by Nedjari et al. (2010) and Dahoumane et al.(2016), Stanocephalosaurus amenasensis was not found in a layer of gypsum (correspondng to the infill of a salt lake or sabkha), but in fine-grained sandstones intercalated with claystones, which are covered by a probably recent layer of gypsum sands of centimetre thickness (Fig. 4). In fact, the authors noted above considered the gypsum to have protected the bones from degradation and thus allowed their exceptional preservation. However, if these amphibians had really died in a sabkha, they would have been completely epigenised in gypsum (which it is not the case), which would have completely weakened the bones and precluded their excellent preservation.

Previous sedimentological studies carried out on the Triassic deposits of Zarzaitine came to the conclusion that braided fluvial channels, respectively their adjacent flood plains, constituted habitats for temnospondyl amphibians (Nedjari et al., 2010; Dahoumane et al., 2016). However, the braided rivers which are typical of arid zones have flood plains of very reduced thickness or depth, which is of the order of centimetres, and which dry out very quickly because of a hot climate (e.g. Miall, 1996; Nichols, 2009). This type of environment could therefore never have constituted a habitat for these large-sized amphibians, accustomed to an aquatic lifestyle, as evidenced by the presence of sensory-line canals running on the skull roof (e.g., Warren, 2000; Damiani & Jeannot, 2002; Steyer, 2002, 2003; Dahoumane et al., 2016). Their presence in a deltaic environment is more in line with their amphibian nature and with other physiological characteristics.

Temnospondyls from deltaic environments are known, for example, from the Permo-Triassic Beaufort Group (Karoo Basin, South Africa), which hosted a significant number of taxa. Indeed, detailed studies on the sedimentology, undertaken by Rubidge et al. (2000), concluded that there was a tidal deltaic plain, which would have constituted the habitat of these amphibians, even if palaeontologists still continue to link these Karoo amphibians to a terrestrial or ‚non-marine' environment (e.g. Damiani & Rubidge, 2003; Steyer et al., 2021; Groenewald et al., 2023), probably due to a lack of sedimentological studies concerning the deposits which yielded these amphibian vertebrates in general. Coastal marine temnospondyls have also been described by a few authors (e.g. Laurin & Soler-Gijon, 2001; Scheyer et al., 2014; Slodownik et al., 2021).

Finally, plants that grew above sandy rivers and their alluvial plains in a hot and dry climate (FA3), and which bear seeds and leaf scars on their trunks belong to Cycadophyta. A similar Triassic flora that grew under similar palaeoenvironmental conditions has been described by many authors across the globe (e.g. Cúneo et al., 2010; Moisan et al., 2011; Simpson, 2019; Blomenkemper et al., 2021). Their simple comparison with mushrooms and algae (Arbey et al., 2011) is impossible, because first of all, these two types of plants show no morphological resemblance, in addition, mushrooms and algae which prefer humid and shady places, could never have lived in the channel rivers or on their banks, because these rivers were not only exposed to the sun, but they underwent frequent periods of drying out, as proved by traces of desiccation in the sandstone channels (Fig. 11C).

7. Conclusions

In the In Amenas region, a single Triassic unit of regional extent crops out; it is the clay-sandstone Zarzaitine Formation with temnospondyls and Cycadophyta. It shows a prograding deltaic sedimentation from SSE to NNW. From the base to the top, the following were distinguished:

- an upper and shallow intertidal mixed flat zone with Skolithos ichnofacies, in which mainly termospondyls proliferated was distinguished. These vertebrates, which had an aquatic lifestyle, lived in a deltaic environment in a warm climate. The skulls accumulated en masse in a clayey-sandy zone and do not show any gypsum epigenisation, which allowed their excellent preservation;
- a lower intertidal deltaic plain, composed of sandstone channels and muddy sands of interchannelised areas, and which recorded numerous daily and monthly tidal structures;
- an upper deltaic plain of a supratidal zone, represented by coarse sandstones deposited by braided rivers, which are topped by shrubby plants where cycads and Benettitales were documented.

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References

Aït Ouali R., Nedjari A., Taquet P., Bitam L. & Tayeb Cherif L., 2011. Le Zarzaïtine Inférieur: derniers développements dans une série du Trias pro-parte [The Lower Zarzaitine (In Amenas, Algerian Sahara). Last developments in the Triassic pro-part series]. *Mémoire du Service Géologique National – Algérie*, 17, p. 9–26.

Alpert S.P., 1974. Systematic review of the genus *Skolithos*. *Journal of Paleontology* 48, 661–669.

Arbey F., Aït Ouali R., Nedjari A., Bitam L. & Keddadra B., 2011. Découverte de peuplements diversifiés de "Thallophytes" champignons, algues, de grande taille, dans les séries continentales, triasiques et Jurassiques d'In Amenas [Discovery of diversified stocking of big-sized populations "Thallophyta" mushrooms and algae in the continental Triassic and Jurassic series of In Amenas]. *Mémoire du Service Géologique National – Algérie* 17, p. 27–65.

Attar A., Fabre J., Janvier P.H. & Lehman J.P., 1981. Les vertébrés de la formation de Tiguentourine (Permo-Carbonifère, bassin d'Illizi, Algérie) [Vertebrates from the Tiguentourine Formation (Permo-Carboniferous, Illizi Basin, Algeria)]. *Bulletin du Muséum national d'Histoire naturelle de Paris*, 4e Série, section C, 301–309.

Beicip-Sonatrach, 1975. *Etude structurale et cartographique du Bassin d'Illizi In Amenas. Rapport Interne, Sonatrach-Exploration* [*Structural and cartographic study of Illizi Basin., In Amenas, Sonatrach-Exploration*]. A 1812.

Bertling M., Braddy S., Bromley R.G. & Demathieu G.R., 2006. Names for trace fossils: A uniform approach. *Lethaia* 39, 265–286. DOI:10.1080/00241160600787890.

Blomenkemper P., Bäumer R., Backer M., Abdalla Abu Hamad A., Wang J., Kerp H. & Bomfleur B., 2021. Bennettitalean leaves from the Permian of Equatorial Pangea – The early radiation of an iconic Mesozoic Gymnosperm Group. *Frontiers in Earth Science* 9, article 652699. doi: 10.3389 /feart. 2021. 652699.

Boersma J.R., 1969. Internal structure of some tidal mega-ripples on a shoal in the Westerschelde estuary. *Sedimentology* 28, 151–170.

Boggs J.R., 2005. *Principles of sedimentology and stratigraphy*. 4th edition. Pearson & Prentice Hall, New Jersey, 657 pp.

Boudjema A., 1987. *Evolution structurale du bassin pétrolier triasique du Sahara nord oriental (Algérie)*[*Structural evolution of the Triassic oil basin of the north-eastern Sahara (Algeria)*]. Université de Paris XI, 289 pp.

Bourquin S., Bercvici A., Lopez-Gomez J. & Amour F., 2010. The Permian–Triassic transition and the onset of Mesozoic sedimentation at the northwestern peri-Tethyan domain scale: Palaeogeographic maps and geodynamic implications. *Palaeogeography Palaeoclimatology Palaeoecology* 299, 265–280. DOI: 10.1016/j.palaeo.2010.11.007.

Bromley R.G. & Asgaard U., 1991. Ichnofacies: a mixture of taphofacies and biofacies. *Lethaia* 24, 153–163.

Buatois L. & Mangano M.G., 2011. *Ichnology: Organism-substrate interactions in space and time*. Cambridge University Press, 358 pp.

Burke K., Macgregor D.S. & Cameron N.R., 2003. Africa's petroleum systems: four tectonic 'Aces' in the past 600 million years. [In:] Arthur T.J., Macgregor D.S. & Cameron N.R. (Eds): Petroleum geology of Africa: New themes and developing technologies. *Geological Society of London, Special Publication* 207, p. 21–60.

Busson G., 1968. Le Trias gréseux de du Nord-Est de la plate forme saharienne (à la lumière des données de sondages et de l'étude des affleurements [The Triassic sandstone of the North-East of the Saharan platform (in the light of survey data and the study of outcrops)]. *Comptes Rendus de l'Académie des Sciences* 267, 2095–2098.

Busson G., 1970. Le Mésozoique saharien.2ème partie: essai de synthèse des données des sondages algéro-tunisiens [The Saharan Mesozoic. Part 2: Attempt to synthesize data from Algerian–Tunisian surveys]. *Publications du Centre de Recherche des Zones arides, CNRS, Paris, série Géologique* 11, vol. I, II, 810 p.

Busson G., 1972. Principes, méthodes et résultats d'une étude stratigraphique du Mésozoïque saharien [Principles, methods and results of a stratigraphic study of the Saharan Mesozoic]. *Mémoires du Muséum National d'Histoire Naturelle*, *Série C* 26, Paris, 441 p.

Busson G. & Cornée A., 1989. *Données sur lespaléoclimats déduites de la sédimentation continentale du Mésozoïque saharien* [*Paleoclimate data inferred from Saharan Mesozoic continental sedimentation*]. Publication occasionnelle du Muséum national d'Histoire Naturelle de Paris, 95 p.

Carpentier C., Hadouth S., Bouaziz S., Lathuiliere B. & Rubino J.L., 2016. Basin geodynamics and sequence stratigraphy of Upper Triassic to Lower Jurassic deposits of Southern Tunisia. *Journal of African Earth Sciences* 117, 358–388.

Cheng Y.M., Wang X., Yang X.N., Tan K. & Jin Y.G., 2016. The first discovery of a Cretaceous big Cycadeoidaceae (Bennettitales) trunk from Inner Mongolia. *Geological Bulletin of China* 35, 1230–1233, ID. 1671-2552(2016) 08-1230-04.

Coleman J.M. & Prior D.B., 1981. Deltaic environments of deposition. [In:] P.A. Scholle & D. Spearing (Eds): Sandstone depositional environments: *AAPG Memoir* 31, 139–178.

Cúneo N.R., Escapa I. Villar de Seoane L., Artabe A. & Gnaedinger S., 2010. *Review of the Cycads and Bennettitaleans from the Mesozoic of Argentina.* [In:] Gee C. (Ed.): Plants in Mesozoic time: Morphological innovations, phylogeny, ecosystems. Indiana University Press, pp. 187–212.

Dahoumane A., Nedjari A., Aït-Ouali R., Taquet P., Vacant R. & Steyer J.S., 2016.A new mastodonsauroid temnospondyl from the Triassic of Algeria. Implications for the biostratigraphy and palaeoenvironments of the Zarzaïtine Series, northern Sahara. *Comptes Rendus Palevol* 15, 918–926. DOI: 10.1016/j.crpv.2015.09.005.

Dalrymple R.W. & Choi K., 2007. Morphologic and facies trends through the fluvial-marine transition in tide-dominated depositional system: a schematic for environmental and sequence stratigraphic interpretation. *Earth-Science Reviews* 81, 135–174.

Damiani R.J. & Jeannot A.M., 2002. A brachyopid temnospondyl from the Lower *Cynognathus* Assemblage Zone in the northern Karoo Basin, SouthAfrica. *Palaeontologia Africana* 38, 57–69.

Damiani R.J. & Rubidge B.S., 2003. A review of the South African temnospondyl amphibian record. *Palaeontologia Africana* 39, 21–36.

Davis R.A. & Dalrymple R.W., 2012. *Principles of tidal sedimentology*. Springer, 621 pp.

Desjardins P.R., Buatois L.A. & Mangano M.G., 2012. Tidal flats and subtidal sand bodies. *Developments in Sedimentology* 64, 529–561. DOI:10.1016/B978-0-444-53813-0.00018-6.

Droser M., 1991. Ichnofabric of the Paleozoic *Skolithos* ichnofacies and the nature and distribution of *Skolithos* piperock. *Palaios* 6, 316–325.

Dworschak P.C., Felder D.L. & Tudge C.C., 2012. *Infraorders Axiidea de Saint Laurent, 1979 and Gebiidea de Saint Laurent, 1979 (for merly known collectively as Thalassinidea)*. [In:] Schram F.R., Vaupel Klein J.C., von Forest J. & Charmantier-Daures M. (Eds): Treatise on zoology-anatomy, taxonomy, biology. The Crustacea. Interactive Factory, Leiden, 109–219.

Ekdale A.A., Bromley R.G. & Pemberton S.G., 1984. *Ichnology: the use of trace fossils in sedimentology and stratigraphy*. SEPM Short Course 15, 317 pp.

Fabre J., 2005. *Géologie du Sahara occidental et central*. Vol. 108. African geoscience collection, Musée royal de l'Afrique centrale, 572 pp.

Fillion D. & Pickerill R.K., 1990. Ichnology of the Upper Cambrian? to Lower Ordovician Bell Island and Wabana groups of eastern Newfoundland, Canada. *Palaeontographica Canadiana* 7, 1–119.

Frey R.W., 1975. *The realm of ichnology, its strengths and limitations*. [In:] R.W. Frey (Ed.): The study of trace fossils. Springer, New York, 13–38.

Frey R.W., Howard J.D., Fames D. & Pryor W.A., 1978. *Ophiomorpha*: Its morphologic, taxonomic, and environmental significance. *Palaeogeography, Palaeoclimatology, Palaeoecology* 14, 199–229. https://doi.org/10.1016/0031-0182(78)90094-9.

Goodwin P.W. & Anderson E.J., 1974. Associated physical and biogenic structures in environmental subdivision of a Cambrian tidal sand body. *Journal of Geology* 82, p. 779–794.

Groenewald D.P., Kruger A., Day M.O., Penn-Clarke C.R., Hancox P.J. & Rubidge, B.S., 2023. Unique trackway on Permian Karoo shoreline provides evidence of temnospondyl locomotory behaviour. *PLOS ONE* 18, doi.org/10.1371/journal.pone.0282354.

Haq B.U., Hardenbol J. & Vail P.R., 1987. Chronology of fluctuating sea-levels since the Triassic. *Science* 235, 1156–1167.

Haq B.U., Hardenbol J. & Vail P.R., 1988. *Mesozoic and Cenozoic chronostratigraphy and eustatic cycles*. [In:] Wilgus C.K. et al. (Eds): Sea-level changes. An integrated aproach. *SEPM Special Publication* 42, pp. 71–108.

Jalil N.E. & Taquet P.H., 1994. Les vertébrés triasiques de la série de Zarzaïtine (Algérie). Liste faunique et implications stratigraphiques. *Mémoire du Service Géologique d' Algérie* 6, p. 99–104.

Knaust D., Thomas R.D.K. & Curren A. H., 2018. *Skolithos linearis* Haldeman, 1840 at its early Cambrian type locality, Chickies Rock, Pennsylvania: Analysis and designation of a neotype. *Earth Science Reviews* 185, 15–31. 10.1016/j.earscirev.2018.05.009.

Lapparent A.F., 1958. Nouvelles reconnaissances géologiques entre Ohanet et Bourharet (Sahara central). Chronique des missions [New geological reconnaissances between Ohanet and Bourharet (Central Sahara). Chronicle of the missions]. *Travaux de l'Institut des Recherches Sahariennes* 18, 213–218.

Lapparent A.F de & Lelubre M., 1948. Interpretation stratigraphique des séries continenentales entre Ohanet and Bourahret (Sahara central*). Centre de Recherche de l' Académie des Sciences de Paris* 232, 1430–1432.

Lapparent A.F. de, Claracq P. & Nougared F., 1958. Nouvelles découvertes de Vertébrés dansles séries continentales au Nord d'Edjeleh (Sahara central) [New discoveries of vertebrates in the continental series north of Edjeleh (central Sahara)]. *Centre de Recherche de l' Académie des Sciences de Paris* 227, 1106–1108.

Laurin M. & Soler-Gijón R., 2001. The oldest stegocephalian from the Iberian Peninsula: evidence that temnospondyls were euryhaline. *Comptes Rendus de l'Académie des Sciences, Ser. III* 324, 495–501. doi.org/10.1016/S0764-4469(01)01318

Leaman M., McIlroy D., Herringshaw L.G., Boyd C. & Callow, R.H.T., 2015. What does *Ophiomorpha irregulaire* really look like? *Palaeogeography, Palaeoclimatology, Palaeoecology* 439, 38–49, https://doi.org/10.1016/j.palaeo.2015.01.022.

Lefranc J.P., 1964. Grandes lignes du Sahara central au nord des pays prétassiliens: le bassin des Chaambas à l'aurore des temps secondaires [Outline of the central Sahara north of the pre-Tassilian countries: the Chaambas basin at the dawn of secondary times]. *Comptes Rendus de l'Académie des Sciences, Série. D,* Paris, 0567-655X, 258, 971–973.

Lefranc J.P. & Guiraud R., 1990. The continental intercalaire of northwestern Sahara and its equivalents in the neighboring regions. *Journal of African Earth Sciences* 10, 27–77.

Lehman J.P., 1957. Les stégocéphales sahariens. *Annales de Paléontologie (Vertébrés)* 53, 139–146.

Lehman J.P., 1971. Nouveaux vertébrés du Trias de la série de Zarzaïtine. *Annales de Paléontologie (Vertébrés.)* 57, 71–93.

Liu F., Yang X. & Cheng Y., 2022. Anatomical study of Cretaceous, permineralized, bennettitalean fossils from Heilongjiang Province, NE China. *Acta Geologica Sinica*, DOI: 10.1111/1755-6724.14902.

MacEachern J.A., Pemberton S.G., Gingras M.K. & Bann K.L., 2007a. *The ichnofacies paradigm: A fifty-year retrospective*. [In:] Miller W. (Ed.): Trace fossils – concepts, problems, prospects. Elsevier, p. 52–77.

MacEachern J.A., Pemberton S.G., Gingras M.K., Bann K.L. & Dafoe L.T., 2007b. *Uses of trace fossils in genetic stratigraphy.* [In:] Miller W. (Ed.): Trace fossils – concepts, problems, prospects. Elsevier, p. 52–77.

Mazrou S. & Mahboubi M., 2021. Tidally dominated Miocene deltaic deposits and pipe rocks in the Tebessa Basin, eastern Algeria: sedimentological and ichnological characteristics *Geologos* 27, 15–34, DOI: 10.2478/logos-2021-0002.

Miall A.D., 1996. *The geology of fluvial deposits. Sedimentary facies, basin analysis, and petroleum geology*. Springer, 582 pp.

Moisan P., Voigt S., Pott C., Buchwitz M., Schneider J.W. & Kerp H., 2011. Cycadalean and bennettitalean foliage from the Triassic Madygen Lagerstätte. (SW Kyrgyzstan, Central Asia). *Review of Palaeobotany and Palynology* 164. 93–108.

Monaco P., Caracuel J.E., Giannetti A., Soria J.M. & Yébenes A., 2007. *Thalassinoides and Ophiomorphaas cross-facies trace fossils of crustaceans from shallow to deep-water environments: Mesozoic and Tertiary examples from Italy and Spain*. [In:] Garassino A., Feldmann R.M. & Teruzzi G. (Eds): 3rd Symposium on Mesozoic and Cenozoic Decapod Crustaceans, Milano, 79–82.

Nedjari A., Bitam L., Steyer J.S., Taquet Ph., Vacant R. & Kedadra B., 2010. Découverte d'un nouveau gisement de Stégocéphales d'une conservation exceptionnelle dans le Trias d'In Amenas (Bassin d'Illizi, Algérie) [Discovery of a new deposit of Stegocephali of exceptional preservation in the Triassic of In Amenas (Illizi Basin, Algeria)]. *Bulletin du Service Geologique National* 21, pp. 211 – 228.

Nichols G., 2009. *Sedimentology and stratigraphy*. 2nd ed. Wiley-Blackwell, 432 pp.

Pemberton S.G. & Wightman D.M., 1992. *Ichnological characteristics of brackish water deposits*. [In:] S.G. Pemberton (Ed.): Applications of ichnology to petroleum exploration, a core workshop. Society of Economic Paleontologists and Mineralogists, Core Workshop 17, 141–167.

Pickerill R.K., Romano M. & Melendez B., 1984. Arenig trace fossils from the Salamanca area, western Spain. *Geological Journal* 19, 249–269.

Ratcliffe K.T., Pearce T.J., Martin J. & Hughes A.D., 2003. *Enhanced reservoir characterisation of the Triassic Argilo Greseux-Inferieur, Algeria using high resolution che-*

mostratigraphy. AAPG Annual Meeting, Salt Lake City, Abstract Volume, Tulsa, A143.

Reineck H-E., 1963. Sediment Gefüge im Bereich der südlichen Nord-see. *Abhandlungen der Senckenbergischen Naturforschenden Gesellschaft* 505, 1–138.

Retallack G.J., 2001. *Soils of the past, an introduction to paleopedology*. 2nd ed., Blackwell Science, Oxford, 404 pp.

Rubidge B.S., Hancox J.P. & Octavian C., 2000. Sequence analysis of the Ecca-Beaufort contact in the southern Karoo of South Africa. *South African Journal of Geology* 103, 81 – 96. DOI: 10.2113/103.1.81.

Scheyer T.M., Romano C., Jenks J. & Bucher H., 2014. Early Triassic marine biotic recovery: The predators' perspective. *PLOS ONE* 9, e88987. https: //doi. org /10. 1371/ journal.pone.0088987

Seilacher A., 1967. Bathymetry of trace fossils. *Marine Geology* 5, 413–428.

Simpson M.G., 2019. *Evolution and diversity of woody and seed plants*. [In:] Plant systematics. Elsevier Academic Press, 3rd Edition, pp. 131–165, DOI:10.1016/B978-0-12-812628-8.50005-5

Slodownik M.A., Mörs T. & Kear B.P., 2021. Reassessment of the Early Triassic trematosaurid temnospondyl Tertrema acuta from the Arctic island of Spitsbergen. *Journal of Vertebrate Paleontology*, DOI: 10.1080/02724634.2021.1900209.

Steyer J.S., 2002. The first articulated trematosaur 'amphibian' from the lower Triassic of Madagascar: Implications for the phylogeny of the group. *Palaeontology* 45, Part 4, pp. 771–793.

Steyer J.S., 2003. A revision of the early Triassic "capitosaurs"(Stegocephali, Stereospondyli) from Madagascar, with remarks on their comparative ontogeny. *Journal of Vertebrate Paleontology* 23, 544–555.

Steyer J.S., Peecook B.R., Arbez T., Nesbitt S.J., Tolan S., Stocker M.R., Smith R.M.H., Angielczyk K.D. & Sidor C.A., 2021. New data on the Triassic temnospondyls from the Karoo rift basins of Tanzania and Zambia. [In:] Steyer J.S., Augé M.L. & Métais G. (Eds): Memorial Jean-Claude Rage: A life of paleo-herpetologist. *Geodiversitas* 43, 365–376. Doi.org/10.5252/geodiversitas2021v43a12. http://geodiversitas.com/43/12.

Taylor A.M. & Goldring R., 1993. Description and analysis of bioturbation and ichnofabric. *Journal of the Geological Society* 150, 141–148.

Terwindt J.H.J., 1971. Lithofacies of inshore estuarine and tidal inlet deposits. *Geologie en Mijnbouw* 2, 515–526.

Uchman A. & Gaździcki A., 2006. New trace fossils from the La Meseta Formation (Eocene) of Seymour Island, Antarctica. *Polish Polar Research* 27, 153–170.

Vullo R., Néraudeau D., Allain R. & Cappetta H., 2005. Un nouveau gisement à microrestes de vertébrés continentaux et littoraux dans le Cénomanien inférieur de Fouras (Charente-Maritime, Sud-Ouest de la France) [A new deposit of microremains of continental and coastal vertebrates in the Lower Cenomanian of Fouras (Charente-Maritime, South-West France)]. *Comptes Rendus Palevol* 4, 95–107. Doi.org/10.1016/j.crpv.2004.11.006.

Warren A.A., 2000. *Secondarily aquatic temnospondyls of the Upper Permian and Mesozoic*. [In:] Heatwole H. & Carroll R.L. (Eds): Amphibian biology, vol. 4. Paleontology, Surrey Beatty & Sons, p. 1121–1149.

Wieland G.R., 1906. *American fossil cycads – vol. I: Structure*. Washington, Carnegie Institution, 296 pp.

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