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ORIGINAL PAPER

Middle Miocene trace fossils from the Tenes area (NW Algeria) and their palaeoenvironmental implications

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Abstract

The Miocene succession (Allala River Sandstones and Tenes Blue Marls Formation) that crops out in the Tenes area, situated in the northeast of the Lower Chelif Basin in NW-Algeria, contains a low-diversity assemblage of trace fossils. Fifteen (15) ichnogenera were identified: *Arenicolites, Beaconites, Cylindrichnus, Diplocraterion, Macaronichnus, Ophiomorpha, Palaeophycus, Parahaentzschelinia, Planolites, Rosselia, Skolithos, Taenidium, Teichichnus, Thalassinoides* and *Zoophycos*. Ethologically, these ichnogenera chiefly display dwelling and feeding activities. The presence of thick, deep-tier, scattered, mainly vertical dwelling burrows attributed to the *Skolithos* ichnofacies indicates high energy conditions, normal oxygenation and soft substrate. Moreover, elements of the *Cruziana* ichnofacies show more varied behavioural strategies and higher inchnodiversity with the dominance of horizontal burrows of deposit-feeders. This ichnological study supports the palaeoenvironmental interpretation based on sedimentological analysis of a wave-dominated siliciclastic platform (backshore to offshore), allowing a more precise zonation of the shoreface zone (middle/upper and lower shoreface). In addition, this study allows evaluation of variable degrees of storm influence in response to the contrasting palaeogeomorphology of the coastline.

Keywords Ichnology · Tenes · Lower Chelif Basin · Shallow-marine · Storm influence

Introduction

The Tenes area offers outstanding Miocene outcrops, with variable degrees of accessibility, in general attributed to a period of time ranging from the terminal Burdigalian?/Langhian to the Tortonian (Cassan 1968; Lepvrier and Magné 1975; Neurdin-Trescartes 1992; Nemra 2020). These Miocene outcrops belong to the northeastern border of the Lower Chelif Basin, between Dahra mountains in the west and Beni Menacer mountains (also called Bou Maad) in the east (Fig. 1a and c).

Ichnological studies of the Neogene succession of the Lower Chelif Basin are scarce. In the study area, the trace fossils of the Miocene formations have not been investigated in detail. Neurdin-Trescartes (1992) mentioned the presence of burrows in the Allala River Sandstones Formation but without any further taxonomic assignment. Therefore, the systematic description of these trace fossils is one of the aims of this article.

The study of trace fossils is not only restricted to the determination of different ichnotaxa, but also includes the analysis of other related parameters as a valuable tool in sedimentological studies. The most important parameters used in this study are burrow diameter, bioturbation index, relative dominance between vertical in respect to horizontal burrows, ichnodiversity and the inferred behaviour of the producing organism. The studied Miocene succession was attributed to a wave-dominated siliciclastic platform (Nemra 2020); however, a detailed ichnological study allows us to refine the sedimentological interpretation and to assess degrees of storm influence.

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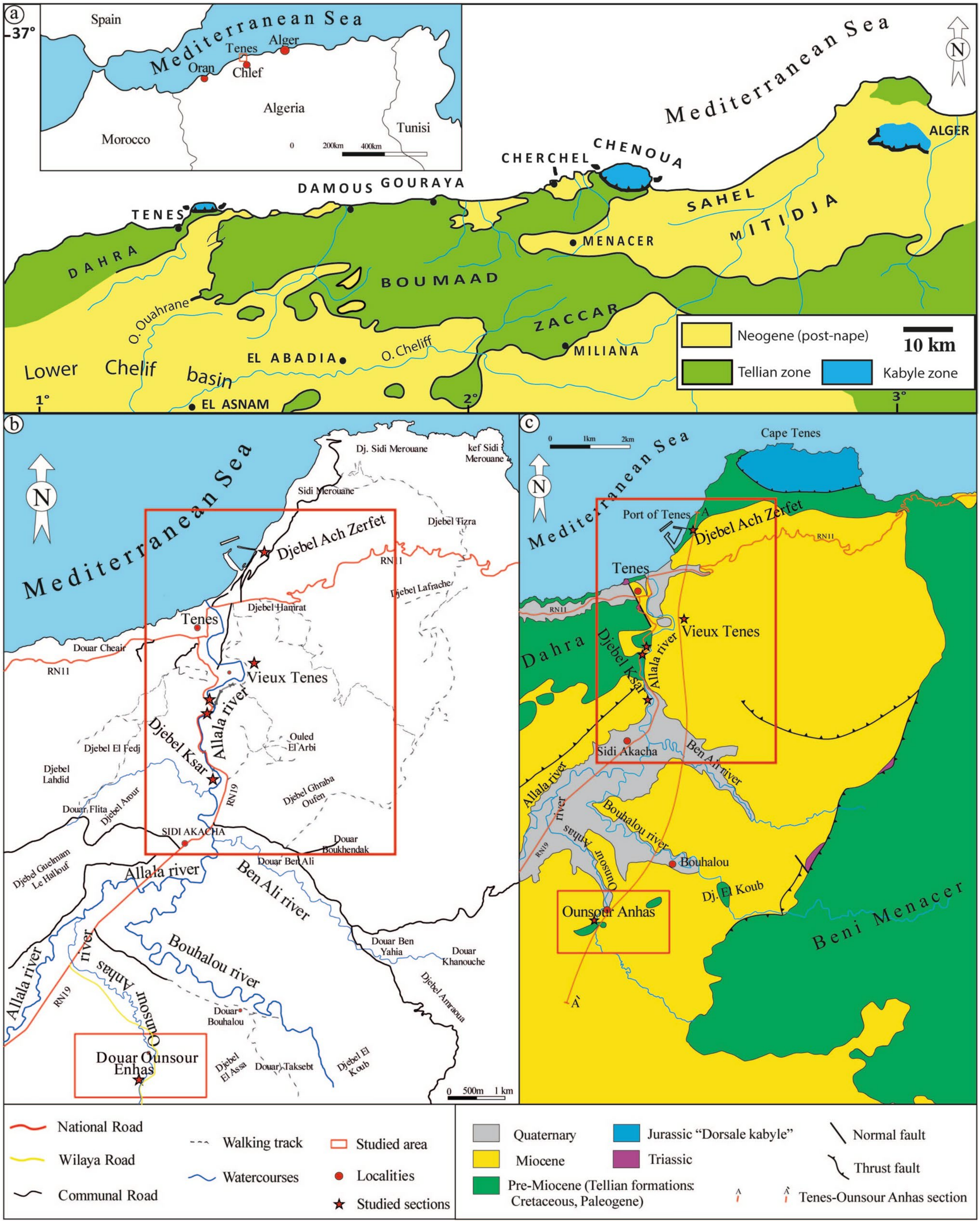

Fig. 1 Geographical context and geological map of the Tenes area. **a** large-scale map showing the location of Algeria and a simplified geological map of the central Tellian domain. The red square marks the position of the Tenes area; **b** geographical location of the studied areas; **c** geological map of Tenes area (modified from Brives 1913)

Geological setting

The Lower Chelif Basin, located in the external zone of the Tellian Atlas, developed during the Alpine orogeny and constitutes a part of the sublittoral basin of western Algeria (Perrodon 1957; Delteil 1974; Fenet 1975; Belkebir et al. 1996). Geomorphologically, it is a long depression, extending for 350 km in an ENE/WSW trend (Bessedik et al. 2002). In its axial zone, the Miocene formations, stacked essentially above the Cretaceous allochthonous basement, consist of approximately 4000 m of mostly marly deposits (SN Repal 1952; Perrodon 1957). The basement is formed of three distinct geological groups: (1) Triassic formations composed essentially of gypsum, dolomite and iridescent clay; (2) Jurassic limestone of Cape Tenes that forms an integral part of the "Dorsale kabyle" unit (= "chaîne calcaire" of Glangeaud 1932), and (3) Cretaceous-Paleogene sedimentary formations that constitute a major part of the succession (Fig. 1c). At the edges of the basin, an often angular unconformity subdivides the Miocene into two transgressive sedimentary cycles (Perrodon 1957). In the centre of the basin, the lateral equivalent of this discontinuity is a "concordance surface" (Perrodon 1957). These two Miocene cycles are designated by Neurdin-Trescartes (1992) as two transgressive megasequences (MSI and MSII). In the studied area, Miocene rocks are represented by deposits of the first cycle and the lowermost part of the second cycle sensu Perrodon (1957). The first cycle begins with continental deposits evolving to marine deposits. The continental deposits are mainly represented by conglomerates, often reddish in colour. Marine deposits are made up of conglomerates and sandstones containing the remains of marine organisms, bioclastic limestones, sandy marls and generally grey or blue marls (Perrodon 1957; Neurdin-Trescartes 1992; Nemra 2020). The deposits of the lowermost part of the second cycle rest in angular unconformity on first-cycle deposits and they are represented by yellow marls (Neurdin-Trescartes 1992; Nemra 2020).

The Miocene rocks in the Tenes area reach 500 m in thickness (Cassan 1968). The lithostratigraphic study of this Miocene succession has permitted definition of the superposition of two geological formations (Nemra 2020; Fig. 2), the Allala River Sandstones and the Tenes Blue Marls.

The Allala River Sandstones Formation is separated from the basement by an angular unconformity and its top coincides with a lithological change from sandstone to marls. It is essentially constituted by a well-developed succession of light-grey to brown, medium- to very thick-bedded, coarse- to fine-grained sandstone beds that contain sedimentary structures and traces fossils in some levels. These beds are partly separated by sandy marl and gravelly marl interbeds. Locally, in the basal part of this succession, the sandstones pass laterally into conglomerates and biodetritic limestones. Dark-grey, generally metric, sandy marls interrupt these coarse detrital facies locally. The thickness of this formation varies widely, reaching its maximum at Kaïsar outcrop (ca. 250 m) and its minimum at Ounsour Anhas outcrop (31 m).

The Tenes Blue Marls Formation extends from the top of the underlying Allala River Sandstones Formation to a flat discontinuity separating it from the overlying yellow marl unit. It consists essentially of thick, dark grey to blue marls, sometimes crossed by calcite veins. Marls are mostly intercalated by either thin sandstone beds or centimetre levels of indurated silty marls. Synsedimentary slump structures and normal faults have also been observed. It is difficult to

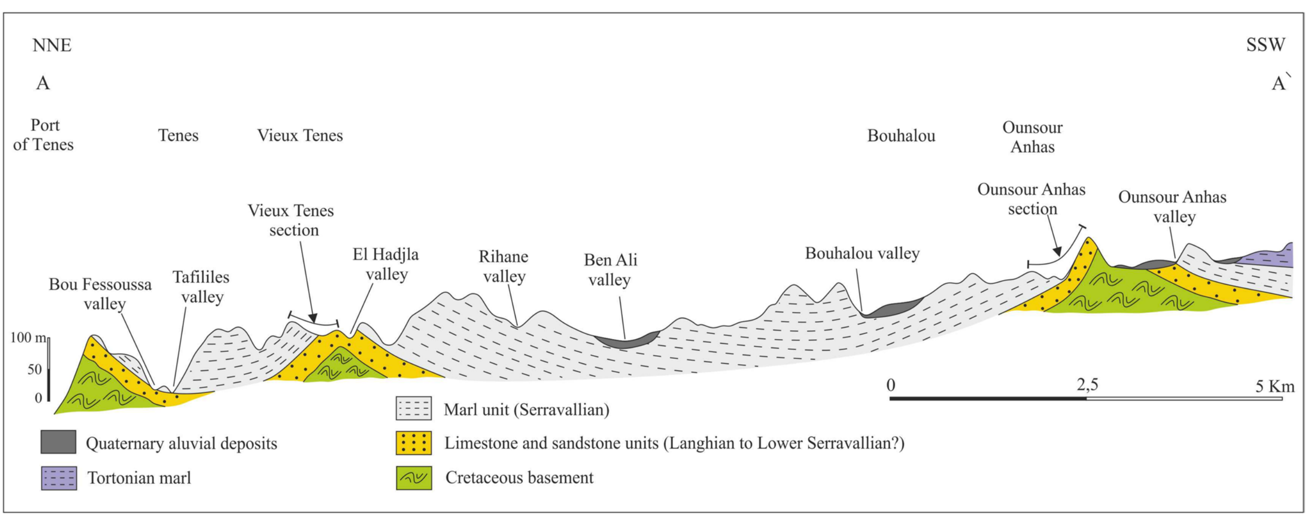

Fig. 2 The Tenes-Ounsour Anhas section (for position see Fig. 1c) showing superposition of different formations; based on field investigation, the geological map of Tenes/Cape Tenes (Nemra et al. 2019)

estimate the real thickness of this formation. Cassan (1968) reported a total thickness of 250 m, although this thickness is clearly less at the Ounsour Anhas outcrop (ca. 90 m). The upper limit of this formation is only observed at this locality (Neurdin-Trescartes 1992; Nemra 2020). These two formations are attributed to a time interval ranging from the terminal Burdigalian? or early Langhian to the middle Serravallian whereas the yellow marl unit is assigned to the early Tortonian (Cassan 1968; Nemra 2020).

In terms of sequence stratigraphy, the angular unconformity, separating the Miocene succession and the ante-Neogene basement, corresponds to a sequence boundary sensu Vail (1987). This discontinuity is overlain by continental deposits represented by conglomerates and clays, often reddish, belonging mainly to alluvial fan environments (Nemra 2020). These conglomerate-dominated continental deposits correspond to a low system tract (LST sensu Vail 1987). Marine sediments overlie these continental deposits and are represented at Vieux Tenes by stacking of three high-frequency sequences (Nemra 2020), displaying vertical evolution from coarse-grained deposits (conglomerate, sandstone or mixed siliciclatic-carbonate facies) to fine-grained deposits (marls dominated facies). These sequences correspond to a T-cycle sensu Zecchin (2007) and Catuneanu and Zecchin (2013), showing evolution from beachface/shoreface facies to upper/lower offshore facies and they are bounded by ravinement surfaces (Nemra 2020). The stacking sequences show a transgressive trend and represent the transgressive systeme tract (TST sensu Vail 1987).

Material and analytical methods

This study was based on field observations of the Miocene succession in the Tenes area carried out at five different outcrops (Djebel Ksar, Vieux Tenes, Ounsour Anhas, Djebel Ach Zerfet and Kaïsar; Fig. 1b). The upper part of the section at Djebel Ach Zerfet is partially covered; therefore, the description of this part was logged based on cores. The purpose of fieldwork was to collect detailed lithostratigraphic, facies and ichnological data. Lithology, grain size, bed thickness, sedimentary structures (including ichnofabrics), geological contacts and fossil content were logged bed-by-bed at each outcrop. The ichnological features examined at the bed scale were shape, orientation, position within the beds, length, diameter, degree of bioturbation and ichnodiversity. The description of the position of trace fossils within the beds follows the taphonomic classification scheme of Martinsson (1970). The Reineck (1963) and Taylor and Goldring (1993) classifications has been used to evaluate the bioturbation index. Ichnological data gathered from each outcrop are compared to better evaluate the hydrodynamic conditions, degrees of storm influence, oxygenation rate, etc.

Summary of palaeoenvironments

The major lithofacies of the Miocene outcrops in the Tenes area are represented by sandstones, conglomerates, limestones and marls. The detailed analysis of these lithofacies indicates that sedimentation took place on a wave-dominated siliciclastic platform, evolving from a gravel-dominated beachface-shoreface complex to an offshore complex (Fig. 3; Nemra 2020). The detailed sedimentary features of the facies associations are reported in Table 1.

The **beachface-upper shoreface** zone is characterised by conglomerate and sandstone facies with abundant bivalve clasts (Fig. 4f). The conglomerates are either open framework (Fig. 4c, d) or have a sandy matrix (Fig. 4a, b) and may show low-angle cross-stratification. The presence and abundance of coarse cobbles and boulders at Kaïsar outrop indicates close proximity of this site to the sediment source. Furthermore, the lithologic nature of these gravels suggests that they are mainly derived from the erosion of palaeo-cliffs (Cretaceous basement). Sandstone facies (coarse to medium) is represented by massive sandstones and massive pebbly sandstones (Fig. 4b), locally containing scour and fill structures. Episodically, pebbly beds and centimetre- to decimetre-thick conglomerate layers (less than 30 cm) are also intercalated within the sandstones (Fig. 4b).

The **upper to middle shoreface zone** includes sandstones, bioclastic limestones (mixed facies; Fig. 4e and g-h), bioclastic sandstones (mixed facies), conglomerates and scarce layers of sandy marl. The dominant facies consists of light-grey to light-brown, very thick to medium bedded, medium- to coarse-grained sandstones with an overall massive appearance and occasional normal grading. Sedimentary structures include current and oscillatory ripples (Fig. 5a and f), planar laminations (Fig. 5a and d), low-angle and high-angle cross-lamination (Fig. 5b). Hummocky cross-stratification sandstones (HCS) are rare, while erosive basal surfaces and amalgamated beds are frequent. Locally, tabular pebbly conglomerates are intercalated within the sandstones (Fig. 5i). The mixed facies (bioclastic limestones, sandy limestones and sandstones with bioclasts) occur at Djebel Ksar, Vieux Tenes and Djebel Ach Zerfet outcrops. They contained a benthic macrofauna characterised by bivalve clasts (often *Ostrea*), balanids, bryozoans, echinoderm plates, echinoid spines, benthic foraminifera and remnants of red algae. The sedimentary structures (oscillation ripples, planar lamination, low-angle parallel lamination and cross-lamination) preserved in this zone are dominantly wave-generated under both fair-weather and storm conditions. The sediments in this zone were constantly reworked by breaking waves, surf and swash-zone processes. Storm-wave influence is recorded as HCS, erosion surfaces, scour and fill structures (Fig. 5e), normally graded beds and tabular conglomerate beds. In general, the benthic fauna recorded in the mixed facies confirms

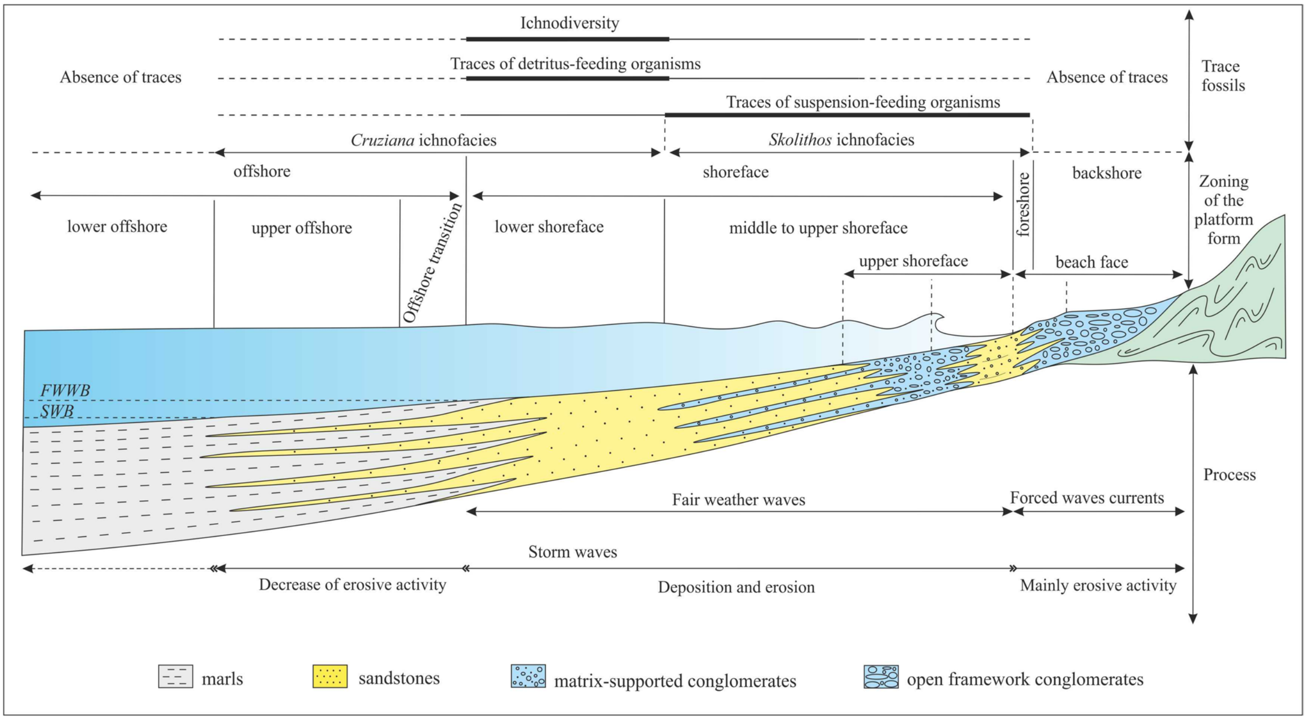

Fig. 3 Sedimentological model of the studied deposits (Nemra 2020). The sedimentological interpretations are based on the combination of a gravel beach with microtidal regime model (Bluck 1967; 1999; Massari and Parea 1988; Sanders 2000) and a standard siliciclastic platform model (Reading and Collinson 1996; Buatois and Mángano 2011). Ichnological interpretations are based on field data and the work of MacEachern et al. (2007), Buatois and Mángano (2011), and Pemberton et al. (2012)

an agitated shallow-marine environment. The fauna (*Ostrea*, balanids, bryozoans and echinoderms) suggests hard substrates such as gravels, shell clasts, etc.

The **lower shoreface zone** consists essentially of thin- to medium-bedded, fine- to medium-grained sandstones interbeded with thin layers of silty/sandy marls. Sandstone facies includes massive and rarely graded sandstones; planar, undulated and rarely oblique-laminated sandstones; as well as HCS (Fig. 5c). Current and oscillatory ripples occur at the top of some massive sandstone beds. The rare amalgamated beds and the presence of thin marl layers indicate a relatively deeper environment of deposition. The marly interbeds are a record of fair-weather conditions above the storm wave base (Pemberton et al. 1992).

The **offshore transition to upper offshore zone** is dominated by very thick, dark grey to blue marls with intercalations of sandstones (Fig. 5g, h). These sandstones are light grey, erosively based, often very thin to medium bedded (1 to 25 cm), rarely very thick (up to 2 m at Ounsour Anhas outcrop), very fine-grained, containing parallel laminations, low-angle cross-laminations (Fig. 5g), HCS and normal graded beds. Very thin (up to 5 cm), very fine-grained sandy to silty marl lenses occur locally. These facies record environmental changes related to an episodic sedimentation. The marl intervals essentially represent suspended sediment fall-out in a low-energy setting. The sandstone intercalations indicate alternation of lower-energy storm events between fair-weather wave base and storm wave base.

The **lower offshore to distal shelf zone** is represented by very thick, dark grey to blue marls intercalated locally by sandy to silty marl lenses. Marls of this zone mostly involve suspension fall-out in low-energy setting. The very rare sandy to silty marl lenses are interpreted as distal tempestites.

Systematic description of trace fossils

This part is devoted to the ichnological study of the Miocene of the Tenes region. The inventory shows fifteen (15) ichnogenera. These trace fossils have been analysed on well-exposed bedding planes and vertical sections at the different investigated outcrops (Vieux Tenes, Djebel Ksar, Kaïsar, Djebel Ach Zerfet and Ounsour Anhas). Figures 6, 7, 8, 9, 10a, b, and 11 show the distribution and trace fossils-bearing facies. No trace fossils have been observed in the conglomeratic facies. The preservation of trace fossils is, locally, very poor due to diagenetic factors and weathering/erosion obliteration, thus, their determination in some beds remains tentative.

Table 1 Facies associations and palaeoenvironmental interpretations

Associations	Lithological description	facies (abreviation)	ichnotaxa	Interpretation
association 1 : *beach face* to Upper *shoreface*	Decimetric to metric conglomerates sometimes containing bivalve shell fragments, decimetric to metric intercalations of coarse sandstones and coarse pebbly sandstones.	Low-angle cross-stratified pebbly conglomerate, Tabular pebbly conglomerate, Grain supported sandy matrix conglomerate (sometimes imbricated), Graded conglomerate, Open framework pebble to cobble conglomerate (mostly imbricated), Massive sandstone and Massive pebbly sandstones, Scour and pebbly fill structures.	*Thalassinoides*, *Skolithos*, *Ophiomorpha*	Segregation of elements, frequency of erosive events indicates high wave energy and storm-induced currents. The emerged part of the beach up to the wave breaking zone. Kaïsar, Ounsour Anhas.
association 2 : Upper to middle *shoreface*	Coarse- to medium-grained sandstones, bioclastic limestones and bioclastic sandstones, decimetric conglomeratic intercalations.	Massive sandstone, Cross-stratified sandstone, Planar-laminated sandstones, Low-angle parallel-laminated sandstones, Undulate laminated Sandstone, Normally graded sandstone, Hummocky cross-stratified sandstones, Tabular pebbly conglomerate, Massive bioclastic sandstone, Massive bioclastic sandy limestone.	*Ophiomorpha nodosa* (vertical), *Skolithos, Diplocraterion, Arenicolites, Rosselia erecta, Taenidium,*	Frequency of erosive events, sediment mobilization and episodic influence of storms. high oscillatory wave energy, normal oxygenation and soft substrate. Between zone of shoaling and low-tide limit. Vieux Tenes, Djebel Ksar,
association 3 : Lower *shoreface*	Fine- to medium-grained sandstone, sandy marl intercalations.	Massive sandstone, Planar-laminated sandstones, Low-angle parallel-laminated sandstones, Normally graded sandstone, Hummocky cross-stratified sandstones, Scour and sandy fill structures, Cross-stratified sandstone, undulated laminated Sandstone, Sandy marl intercalations.	*Thalassinoides* (horizontal), *Taenidium, Planolites, Ophiomorpha* (horizontal), *Ancorichnus, Arenicolites* (small size), *Rosselia erecta, Zoophycos.*	Variable energy (low, moderate to high). Episodic storm influence (oscillatory and combined flows). Deposition above the limit of fair-weather wave action. Vieux Tenes, Djebel Ksar,
association 4 : Upper to lower *shoreface*	Coarse- to medium-grained sandstone, limestone and calcareous sandstone, conglomeratic interlayers.	Massive sandstone, Massive pebbly sandstones, Bioclastic sandy limestones, Tabular pebbly conglomerate, Grain supported sandy matrix conglomerate (sometimes imbricated).	*Thalassinoides, Ophiomorpha, Skolithos.*	High to moderate energy, episodic storm influence. Deposits between basal tidal limit and fair-weather wave action limit. Kaïsar, Djebel Ach Zerfet, Ounsour Anhas.

Table 1 (continued)

Associations	Lithological description	facies (abreviation)	ichnotaxa	Interpretation
association 5 : Transition to upper *offshore*	Gravelly-sandy marls, monotonous metric to decametric marls intercalated by fine-grained sandstones and indurated sandy-silty marls, more rarely by sandy-silty limestone.	Massive marls, Planar-laminated sandstones, Low-angle cross-stratified sandstones, undulate laminated Sandstone, Normally graded sandstone, gravelly-sandy marls, silty-sandy marls intercalation, silty limestones.	*Planolites, Palaeophycus, Skolithos, Zoophycos* (mainly in sandstone intercalations).	Low energy, fine suspended particles fallout, episodic influence of storms (oscillatory and combined flows). Low-oxygen condition above storm action limit Vieux Tenes, Ounsour Anhas, Djebel Ach Zerfet
association 6 : Lower *offshore*	Monotonous decametric marls interrupted by centimetric levels of indurated sandy-silty marls.	Massive marls, silty-sandy marls intercalation,	unbioturbated	Low energy, fine suspended particles fallout, rarely affected by occasionally storm events. Low-oxygen environments immediately below the storm action limit. Vieux Tenes, Djebel Ksar, Djebel Ach Zerfet

Arenicolites Salter, 1857
Arenicolites isp.
(Fig. 12a and e)

Paired circular openings corresponding to U-shaped burrows without a spreite occur on upper sandstone bedding planes. In the Allala River Sandstone Formation, they are preserved as endichnia. Based on the size of the burrows, two types can be distinguished: (1) large *Arenicolites* (Djebel Ksar and Djebel Ach Zerfet; Fig. 12a) with a distance of 10 cm between the two circular openings and a tube diameter of 1.5 cm; and (2) small *Arenicolites*, with a few millimetres wide burrow apertures and a distance of less than 2 mm between the two tubes (Vieux Tenes and Ounsour Anhas; Fig. 12b and e; respectively).

Most *Arenicolites* correspond to a dwelling trace of suspension-feeding organisms, such as polychaete worms or amphipod crustaceans (Bradshaw 2010; Buatois and Mángano 2011; Hofmann et al. 2012; Knaust 2017). They are common in shallow-marine (Fillion and Pickerill 1984; Gingras et al. 1999; Gerard and Bromley 2008; Bradshaw 2010; Knaust 2017), continental (Ekdale et al. 1984; Ekdale and Bromley 2012; Scott et al. 2012), and deep–marine environments (Crimes et al. 1981; Uchman and Wetzel 2012). *Arenicolites* is typically associated with high-energy deposits (e.g. storm deposits) or migrating sand bodies (e.g. sand dunes) in an upper to middle shoreface environment (Bradshaw 2010; Pemberton et al. 2012; Knaust 2017).

Beaconites (Vialov, 1962)
Beaconites capronus (Howard and Frey, 1984)
(Fig. 13a)

This ichnospecies corresponds to straight to meandering, thinly lined, cylindrical to sub-cylindrical burrows, parallel to the bedding planes, with a chevron-shaped meniscus fill. It occurs as epichnia within the Allala River Sandstone Formation at Djebel Ksar and Vieux Tenes. The arcuate menisci are heterogeneous, regularly arranged and represented by an alternation of fine- and coarse-grained sediment segments. The diameter of the burrow ranges from 0.6 to 1 cm, and the preserved length can reach 40 cm.

Beaconites differs from other meniscate burrows (*Taenidium* and *Ancorichnus*) by a lining (Keighley and Pickerill 1995; Boyd and McIlroy 2017). *Beaconites capronus* is characterised by chevron-shaped meniscae and a thin lining (Howard and Frey, 1984; Boyd and McIlroy 2017). It is interpreted as a deposit-feeding vermiform organism that processed large amounts of sediment (Boyd and McIlroy 2017) and is common in shallow-marine environments (Howard and Frey, 1984; Boyd and McIlroy 2017). The tracemakers of meniscate burrows, such as *Beaconites,* progress horizontally through the sediments and deposit backfill sediments behind them as they advance (Frey et al. 1984;


a
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◂**Fig. 4** Photographic illustration of beachface-shoreface facies; Allala River Sandstone at Ounsour Anhas (**a, b, d** and **f**), Kaïsar (**c**), Vieux Tenes (**e**) and Djebel Ach Zerfet (**g-h**). **a** Clast-supported, sandy-matrix conglomerates (Gcs, Gps). Note the imbrication in the Gbs levels and the ravinement basal surface of the Gcs level; **b** Clast-supported, sandy-matrix conglomerates (Gps) intercalated by massive pebbly sandstones (Sp); **c-d** Clast-supported, open framework conglomerate (Gco, Gpo) levels with more-or-less imbricated clasts; **e** bioclastic limestone with Pectinidae fragments; f grain-supported, sandy-matrix conglomerates with *Ostrea* fragments (yallow arrow); **g** bioclastic sandy limestone evolving to a calcareous sandstone (positive grading); **h** detail of sandy bioclastic limestone

Boyd and McIlroy 2017). The direction of movement is indicated by the concave side of the menisci (Frey et al. 1984).

Cylindrichnus Toots in Howard, 1966
Cylindrichnus concentricus
(Fig. 13b-d)

This ichnospecies comprises a cylindrical, arcuate to J-shaped burrow with a funnel-like aperture, concentric lining and a passive fill. The diameter of the burrow decreases from top to bottom (from 1 cm to a few millimetres), the length of the burrow varies between 10 and 20 cm. The massive sandstone fill is identical to the host rock. These burrows are preserved as endichnia within decimetre-thick sandstone beds of the Allala River Sandstone Formation at Djebel Ksar (Fig. 13b) and Vieux Tenes (Fig. 13c, d).

Cylindrichnus is a dwelling trace of detritus-feeding organisms, probably produced by terebellid polychaetes (Goldring 1996; MacEachern and Gingras 2007; Buatois and Mángano 2011; Gingras and MacEachern 2012; Belaústegui and de Gibert 2013; Tonkin 2012; Knaust 2021). It is documented mainly from marine settings (lower shoreface to shelf), as well as marginal-marine, estuarine, delta-front to prodelta environments (Fürsich 1974; Pemberton and Frey 1984; Frey and Howard 1985). In general, *Cylindrichnus* is recorded in moderate to low-energy facies (Fürsich 1974), although it has also been assigned to high-energy regimes (Pemberton and Frey 1984; Frey and Howard 1985).

Diplocraterion Torell, 1870
Diplocraterion parallelum Torell, 1870
(Fig. 12c, d and g, h)

This trace was recorded as endichnia and in association with frequent *Ophiomorpha* within the Allala River Sandstone Formation at Ounsour Anhas. On the upper surface of sandstone beds, it appears as paired circular openings connected by a lamellar structure (spreite). The diameter of the apertures is variable (0.4 to 1 cm) and the distance between them ranges from 2 to 12 cm. Vertical U-shaped burrows are composed of two straight and parallel cylindrical tubes connected by a lamellar structure (spreiten). Only one specimen was observed at Djebel Ach Zerfet within Allala River Sandstone Formation. The tube diameter reaches 2 cm, and the burrow depth is about 12 cm.

Diplocraterion differs from *Arenicolites* by the presence of a spreite and from *Rhizocorallium* by its vertical orientation (Fleming 1973; Cornish 1986). It is a dwelling burrow of suspension-feeding organisms (Cornish 1986; Hofmann et al. 2012; Zhang et al. 2017). The laminae (spreite) correspond to remnants of the burrow wall reflecting the movement of the tracemaker through the sediment (Cornish 1986). This trace is characteristic of unstable substrates (moving sands) generally reported in high-energy environments from intertidal to proximal subtidal (foreshore to shoreface) (Fürsich 1975; Cornish 1986; Zhang et al. 2017).

Macaronichnus Clifton and Thompson, 1978
Macaronichnus segregatis Clifton and Thompson, 1978
(Fig. 14c-e)

Dense, thin, horizontal to subhorizontal, cylindrical burrows with a circular cross-section, characterised by a distinct dark lining and a relatively clear massive fill. They are slightly sinuous, unbranched, although interpenetrations are common. The size of the burrows is variable and ranges from 0.2 to 0.5 cm in diameter and up to 6 cm in length. They occur as endichnia within the Allala River Sandstone Formation at Djebel Ksar (Fig. 14c and e) and Vieux Tenes (Fig. 14d).

These burrows are common in foreshore and shoreface deposits (Głuszek 1998; Knaust 2004; Seike et al. 2011). They are produced by polychaete worms that feed on bacteria and organic matter on the sand-grain surfaces (Clifton and Thompson 1978; Knaust 2004; Seike et al. 2011).

Ophiomorpha Lundgren, 1891
Ophiomorpha irregulare Frey et al., 1978
(Figs. 13d and f, g and 15a-d and f-j)

Ophiomorpha was observed in the sandstones of the Allala River Sandstone Formation as endichnia at Djebel Ksar (Fig. 15a-d), Ounsour Anhas (Figs. 13d and f, g and 15h, i), Kaïsar (Fig. 15g), Djebel Ach Zerfet (Fig. 15f) and Vieux Tenes (Fig. 15j). It is vertical to subvertical, cylindrical, occasionally horizontal, with sandstone filling identical to the host rock. This ichnospecies is characterised by walls lined with sparse, irregularly distributed, flame-like, mastoid, conical or ovoid pellets. The diameter of the burrow varies between 0.8 and 2.5 cm and its length is between 15 and 30 cm.

Ophiomorpha irregulare is interpreted to be produced by decapod crustaceans (e.g. shrimps, Callianassidae; Bromley and Ekdale 1998; Buatois and Mángano 2011). It is regarded as a dwelling trace of suspensivorous organisms (Frey et al. 1978), or a feeding trace of a detritivorous tracemaker (Frey


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h
i

◂**Fig. 5** Photographic illustration of shoreface/offshore facies; Allala River Sandstone (**a**-**f**, **i**) and Tenes Blue Marls (**g**-**h**); **a** wave-ripple cross-laminated sandstones overlain by horizontal laminated sandstones (Djebel Ksar); **b** cross-stratified sandstones (Vieux Tenes); **c** hummocky cross-stratified sandstones "HCS" (Vieux Tenes); **d** ripple cross-laminations (black arrows) and horizontal laminated sandstones (Vieux Tenes); **e** scour structure filled with coarse lithic sands and mud chips (Djebel Ksar); **f** sandstone surface with wave-ripples (Djebel Ksar); **g** and **h** sandstone intercalated within marls showing low angle cross laminations (**g**) and ravinement surface (**h**) interpreted as tempestites (Vieux Tenes); **i** conglomerates with a ravinement surface and positive grading intercalated within sandstones (Ounsour Anhas)

and Howard 1990; Bromley and Ekdale 1998). *Ophiomorpha* is commonly reported from pure, homogeneous, or laminated sandstone deposits (Pollard et al. 1993; Nagy et al. 2016; Knaust 2017), where it has been considered as an important component of high-energy, shallow marine facies (Frey et al. 1978; Pollard et al. 1993; Uchman and Demircan 1999; Bendella et al. 2011; Uchman and Wetzel 2012; Nagy et al. 2016). The pellets of *Ophiomorpha* originated as a mixture of mucus (matrix) and sand grains (Frey et al. 1978) and were used to support the burrow wall to protect it from collapse (Buatois and Mángano 2011).

Palaeophycus Hall, 1847
Palaeophycus tubularis Hall, 1852
(Fig. 14c and f)

A horizontal, straight to slightly curved, cylindrical to subcylindrical, thinly lined and unornamented burrow. Its length is up to 30 cm and the diameter ranges from 0.8 to 1 cm. It is preserved as endichnia and exichnia within the Allala River Sandstone Formation at Djebel Ksar and as epichnia in silty limestone beds of the Tenes Blue Marls Formation at Vieux Tenes.

Palaeophycus is characterised by a lined wall and a burrow fill similar to the host rock (Pemberton and Frey 1982; Keighley and Pickerill 1995). It is classified as a feeding and dwelling trace (Pemberton and Frey 1982; Lucas and Lerner 2006; Virtasalo et al. 2006). Multiple marine suspension/detritus feeders or predacious organisms can generate this trace, such as annelids, arthropods and polychaetes (Pemberton and Frey 1982; Buatois and Mángano 1993; Knaust 2017), whereas in continental environments, it is probably produced by insects and other arthropods (Ekdale et al. 1984; Buatois and Mángano 1993). In marine environments, *P. tubularis* is considered as eurybathic (McCann 1988; Uchman 1995, 1998; Frey and Howard 1990; Lucas and Lerner 2006; Gani et al. 2007; Tiwari et al. 2011). In shallow-marine environments, the occurrence of *Palaeophycus* implies a well-oxygenated environment and abundant nutrients (Tiwari et al. 2011).

Parahaentzschelinia Chamberlain, 1971
Parahaentzschelinia surlyki Dam, 1990
(Fig. 14g, h)

This trace is rare and was oserved only at Ounsour Anhas as endichnia within parallel-laminated sandstone of the Allala River Sandstone. It consists of an overall funnel-shaped, vertical to inclined burrow, with a principal central tube. The upper funnel shaped part is irregularly disturbed by incorporated mud and may show a mud-lined, passively sand-filled tube. The lower part of the main tube appears as ovoid. The trace length is about 10 cm, the diameter of the cylindrical tube can reach 1.5 cm, while the diameter of the preserved funnel-shaped upper part is about 40 cm.

Parahaentzschelinia is mainly regarded as feeding activity of a tellinid bivalve (Fürsich et al. 2006; Knaust 2015). It is recorded in deep-marine deposits (Uchman 1995; Wetzel 2008), however, this trace is common in high-energy shallow- to marginal-marine settings such as foreshore, shoreface, tidal flat and tide-dominated delta (Dam 1990; Bann and Fielding 2004; Mángano and Buatois 2004; Fürsich et al. 2006; McIlroy 2007).

Planolites Nicholson, 1873
?*Planolites beverleyensis* Billings, 1862
(Fig. 14a)

This trace is rare, observed only at Vieux Tenes, where it is preserved as epichnia as well as exichnia within the Allala River Sandstone Formation. It is a cylindrical, horizontal to subhorizontal, cylindrical burrow. In cross-section, it appears circular to subcircular with a diameter of 0.5 cm and a length up to 30 cm.

Planolites isp.
(Fig. 14b)

This form is rare and was observed only in a core sample of the lowermost part of the Tenes Blue Marls Formation at Djebel Ach Zerfet. The burrows are small, unbranched, horizontal to slightly inclined, cylindrical to subcylindrical, straight, curved, or contorted. It is preserved as endichnia within centimetre- to decimetre-thick, light-grey sandy to gravely marl intercalations with grading. The burrow fill consists of dark-grey marl without any observed internal structures. The appearent length of the burrow is up to 5 cm and the diameter is about 4 mm.

Planolites differs from *Palaeophycus* by its infill, which is different from the host rock (colour, nature of the sediment) and the lack of lining (Pemberton and Frey 1982; Keighley and Pickerill 1995). It is regarded as a feeding trace of invertebrate deposit-feeders such as worms, insects, crustaceans and molluscs (e.g. bivalves) (Pemberton and Frey 1982; Frey and Howard 1985; Buatois and Mángano 1993; Uchman 1995; Knaust 2017). *Planolites* is considered as 'facies-crossing', occurring in a variety of depositional environments (Pieńkowski 1985; Buatois et al. 2001; Bendella and Ouali Mehadji 2014). It has been reported in continental environments, where it can

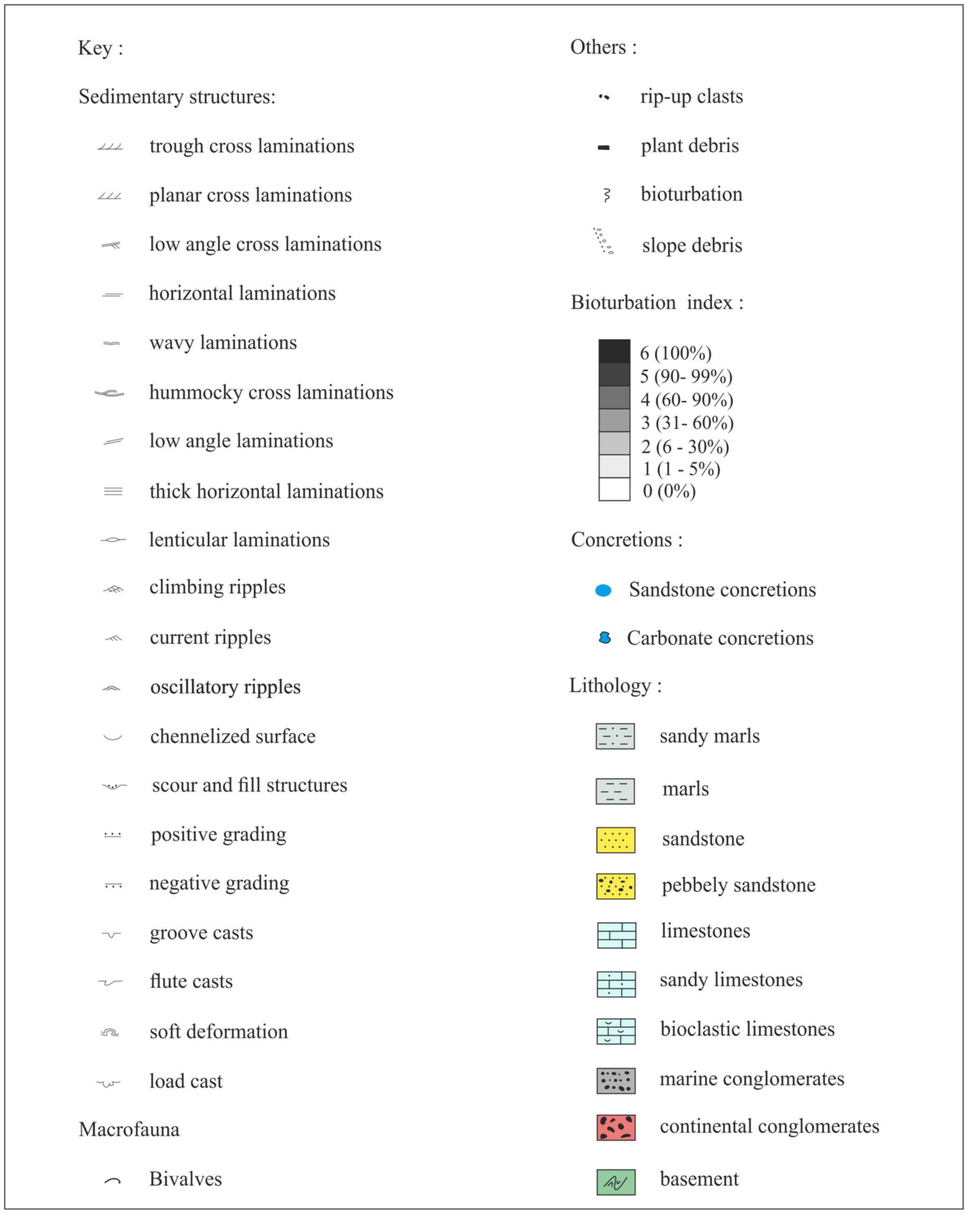


Fig. 6 Legend of symbols used for lithology, sedimentological structures, fauna and other features in Figs. 7, 8, 9, 10 and 11

be produced by insects (Buatois and Mángano 1993; Uchman et al. 2004; Ekdale et al. 2007), and in marine environments of varying depth (McCann 1988; Uchman 1995; 1998; Riahi 2014; Bendella and Ouali Mehadji 2014).

Rosselia Dahmer, 1937
Rosselia erecta (Torell, 1870)
(Figs. 15b and e and 16a, b)

Rosselia erecta was observed as endichnia within the Allala River Sandstone Formation at Djebel Ksar (Fig. 15b and e) and Vieux Tenes (Fig. 16a, b). It consists of a vertical to subvertical, fusiform (bulbous or spindle-like shape), unbranched burrow with a circular to ovoid, funnel-shaped aperture. The cylindrical tube occupies a major part of the funnel. Below the bulbous part, the burrow gradually narrows downward. The overall length of the burrow does not exceed 20 cm, the diameter varies between 1.5 and 3 cm for the bulbous part, whereas the diameter of the internal tube ranges from 0.3 to 1 cm.

Rosselia erecta corresponds to a dwelling trace produced by suspension-feeding organisms attributed to polychaetes and probably Cerianthidae (Anthozoa) (Knaust 2021), inhabiting long tubes within marine substrate (Uchman and Krenmayr 1995). It is often reported from marginal- to shallow-marine environments (e.g. shoreface; Knaust 2021).

Skolithos Haldeman, 1840
?*Skolithos annulatus* (Howell, 1957)
(Fig. 17c-g)

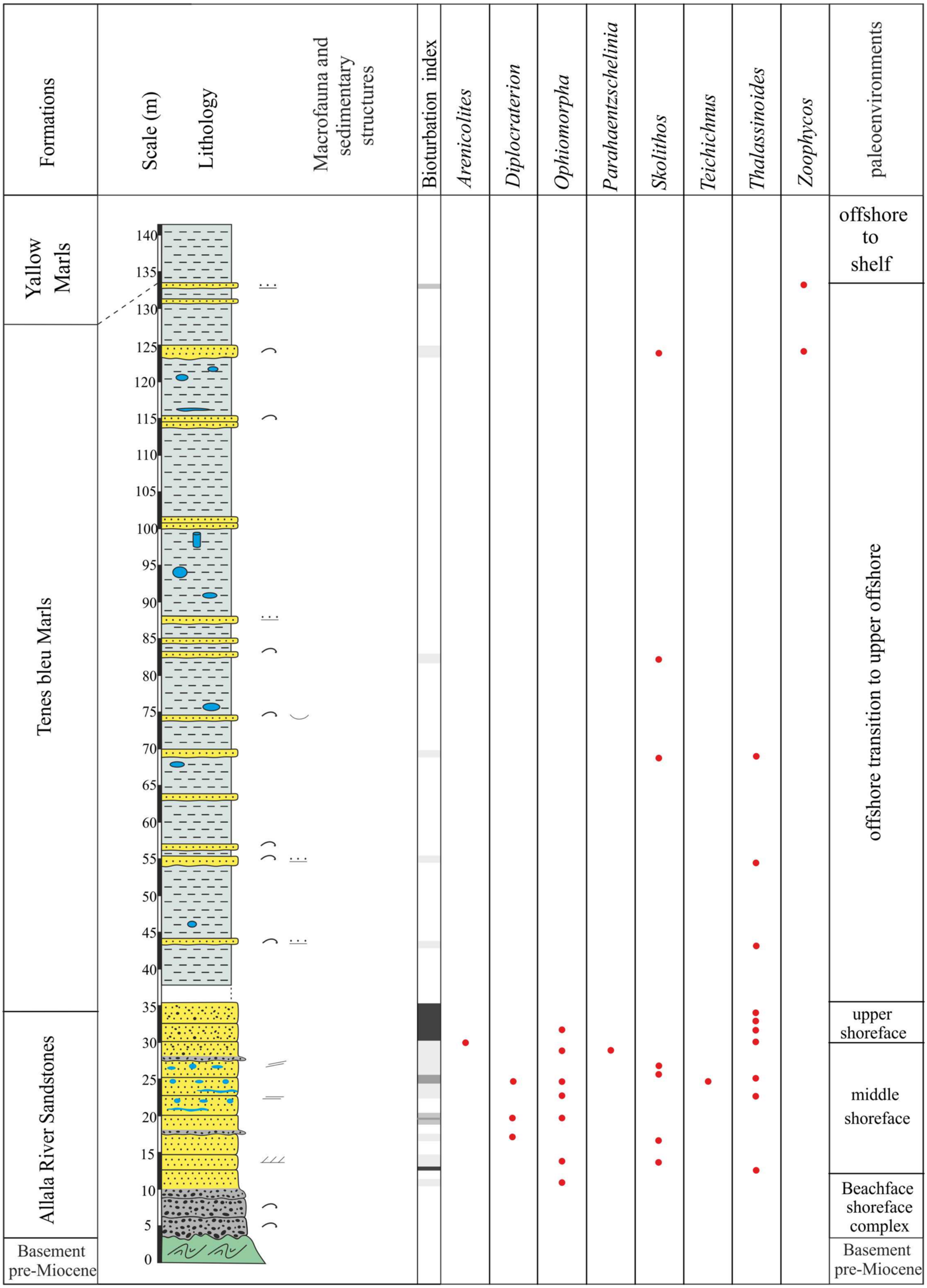


Fig. 7 Lithological log and trace fossils distribution at Ounsour Anhas outcrops

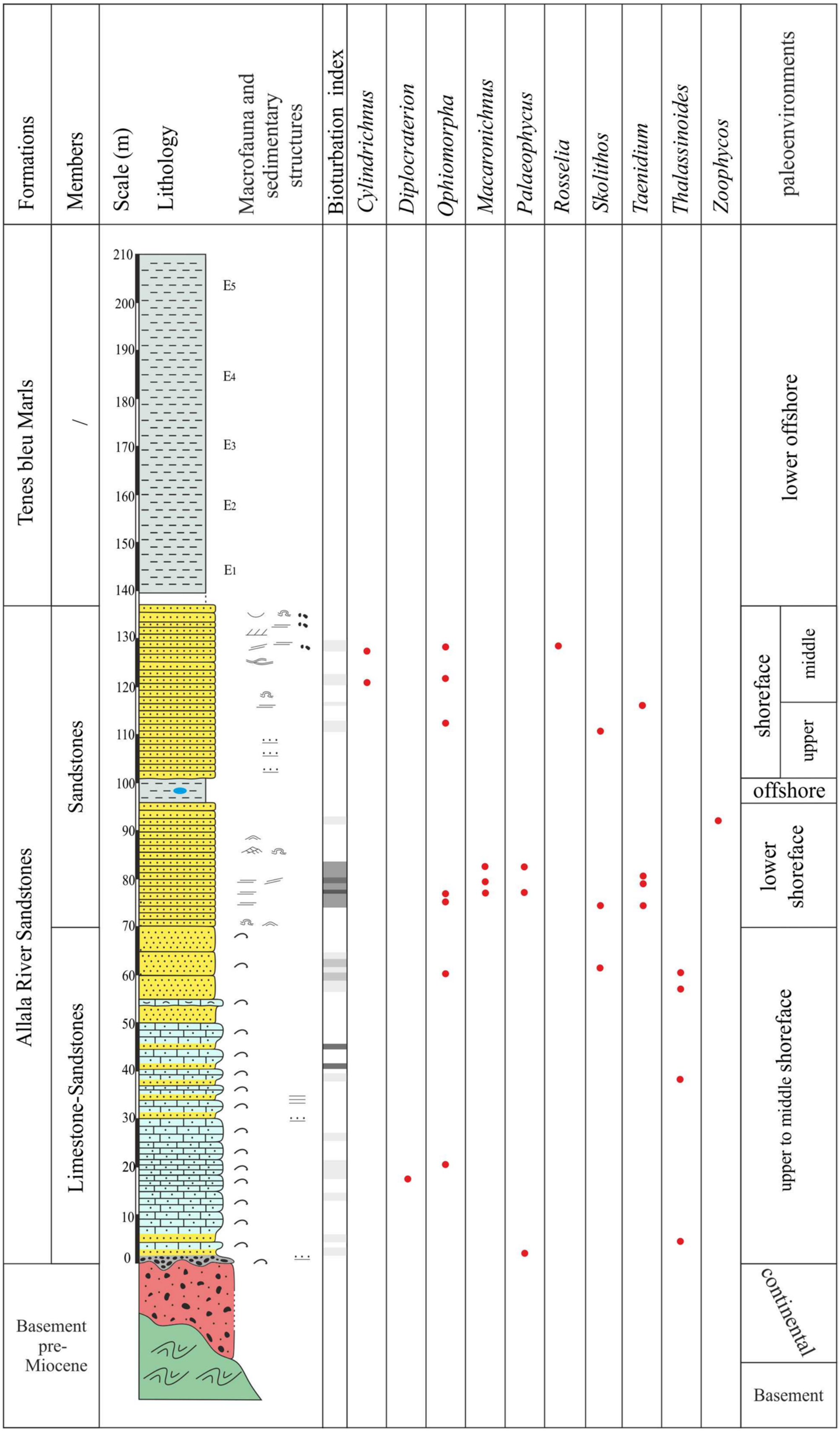


Fig. 8 Lithological log and trace fossils distribution at Djebel Ksar outcrops

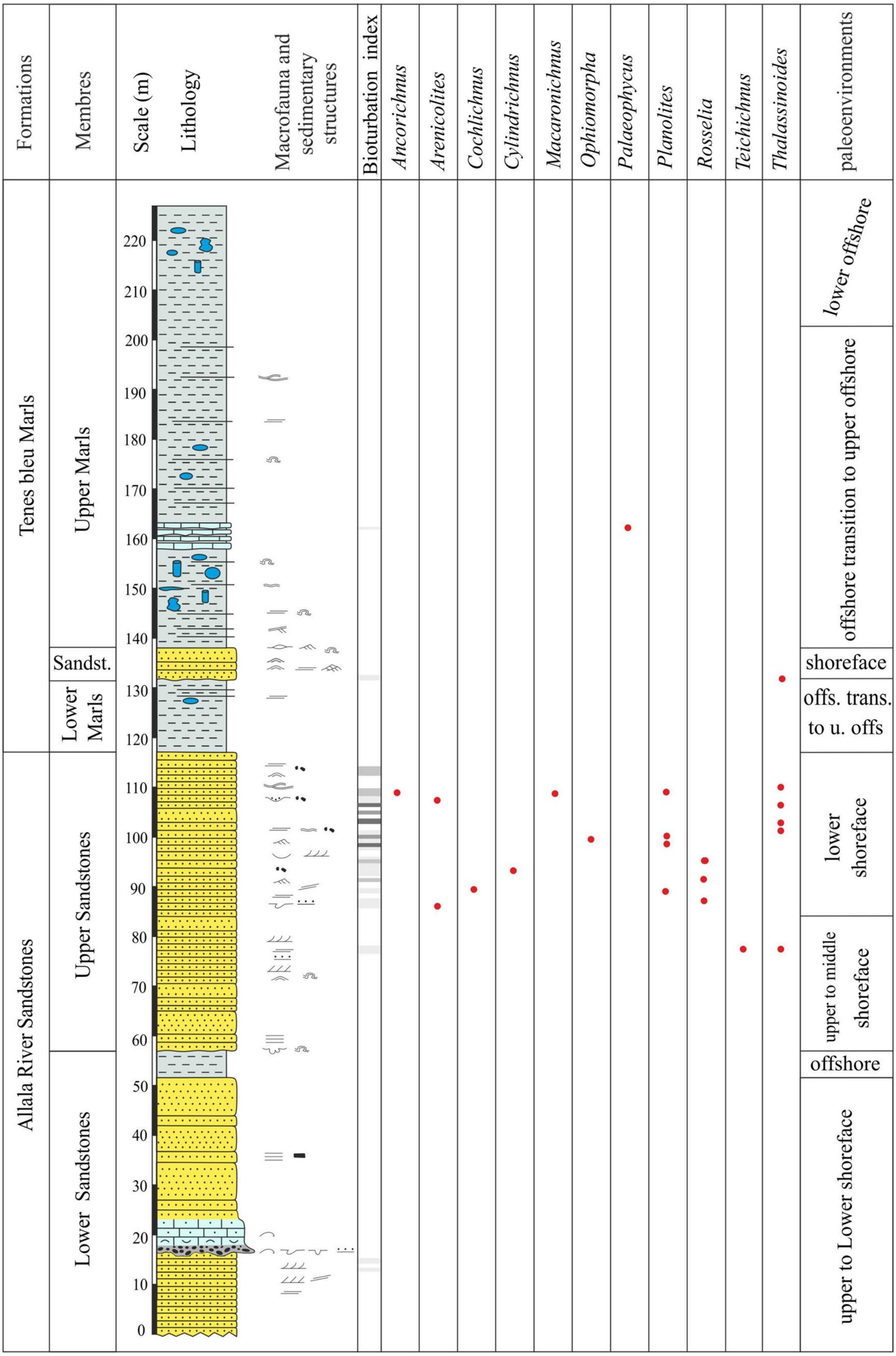


Fig. 9 Lithological log and trace fossils distribution at Vieux Tenes outcrops

Fig. 10 Lithological logs and trace fossils distribution at Kaïsar outcrops. **a** Kaïsar 1 section; **b** Kaïsar 2 section

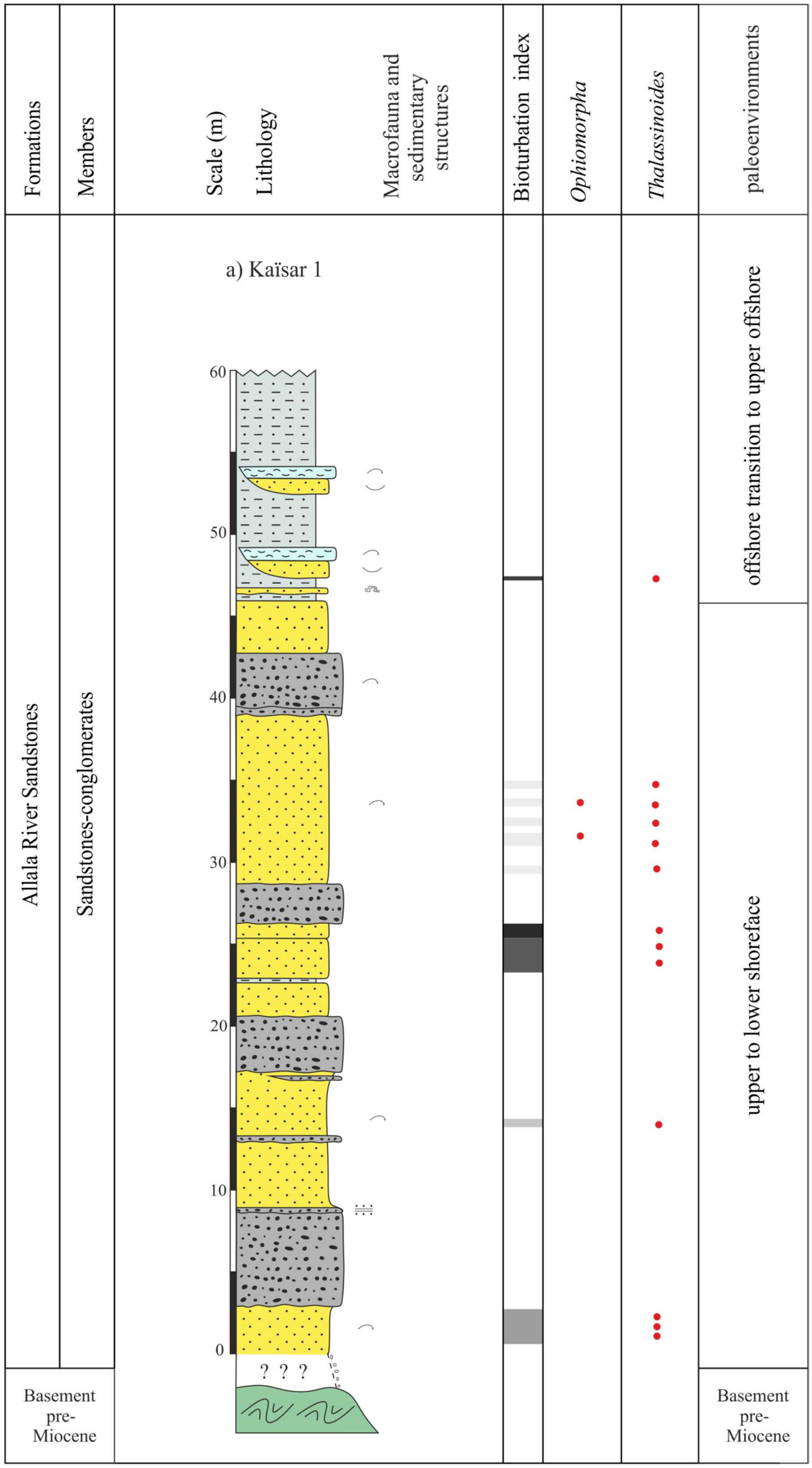
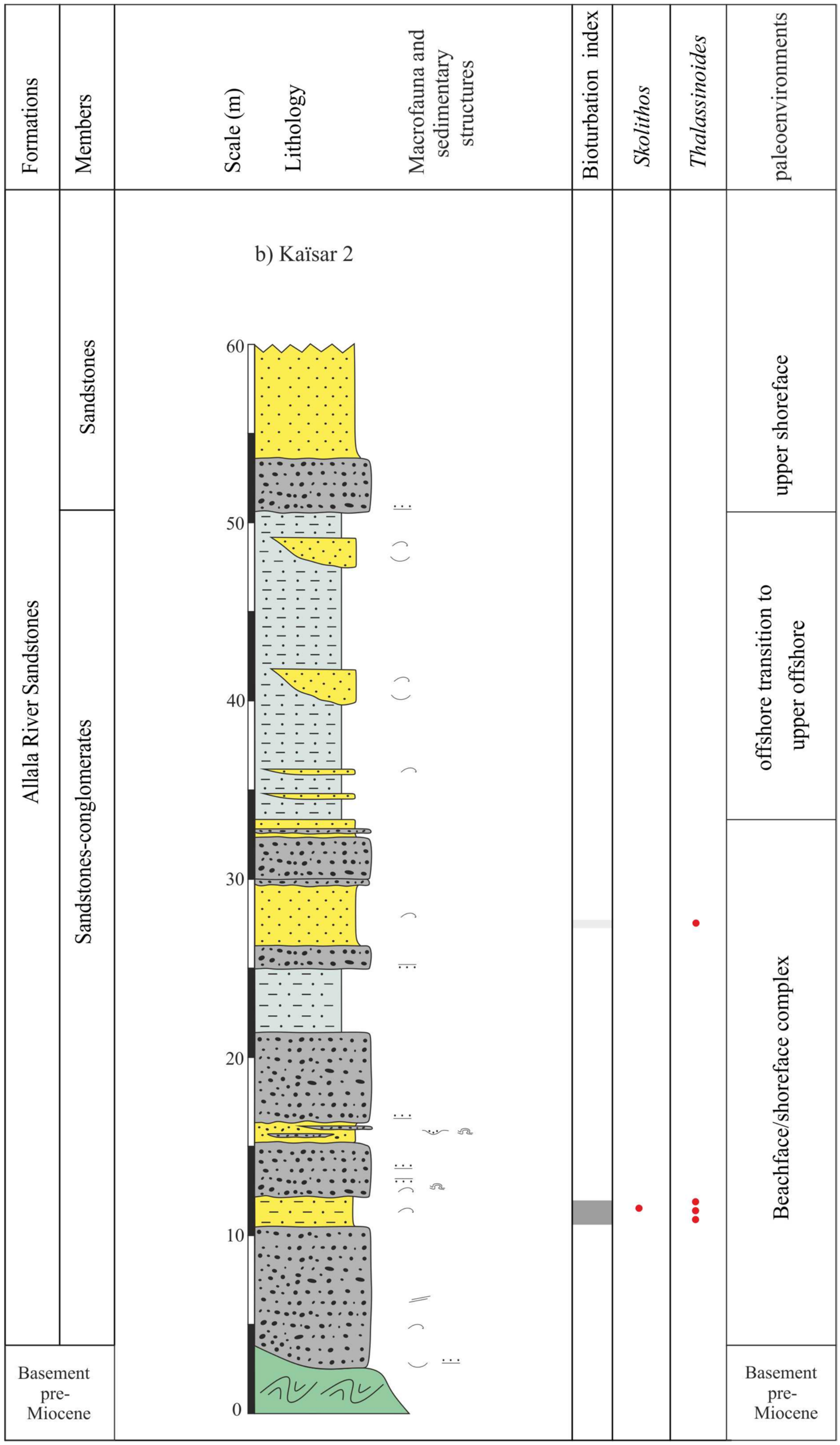


Fig. 10 (continued)



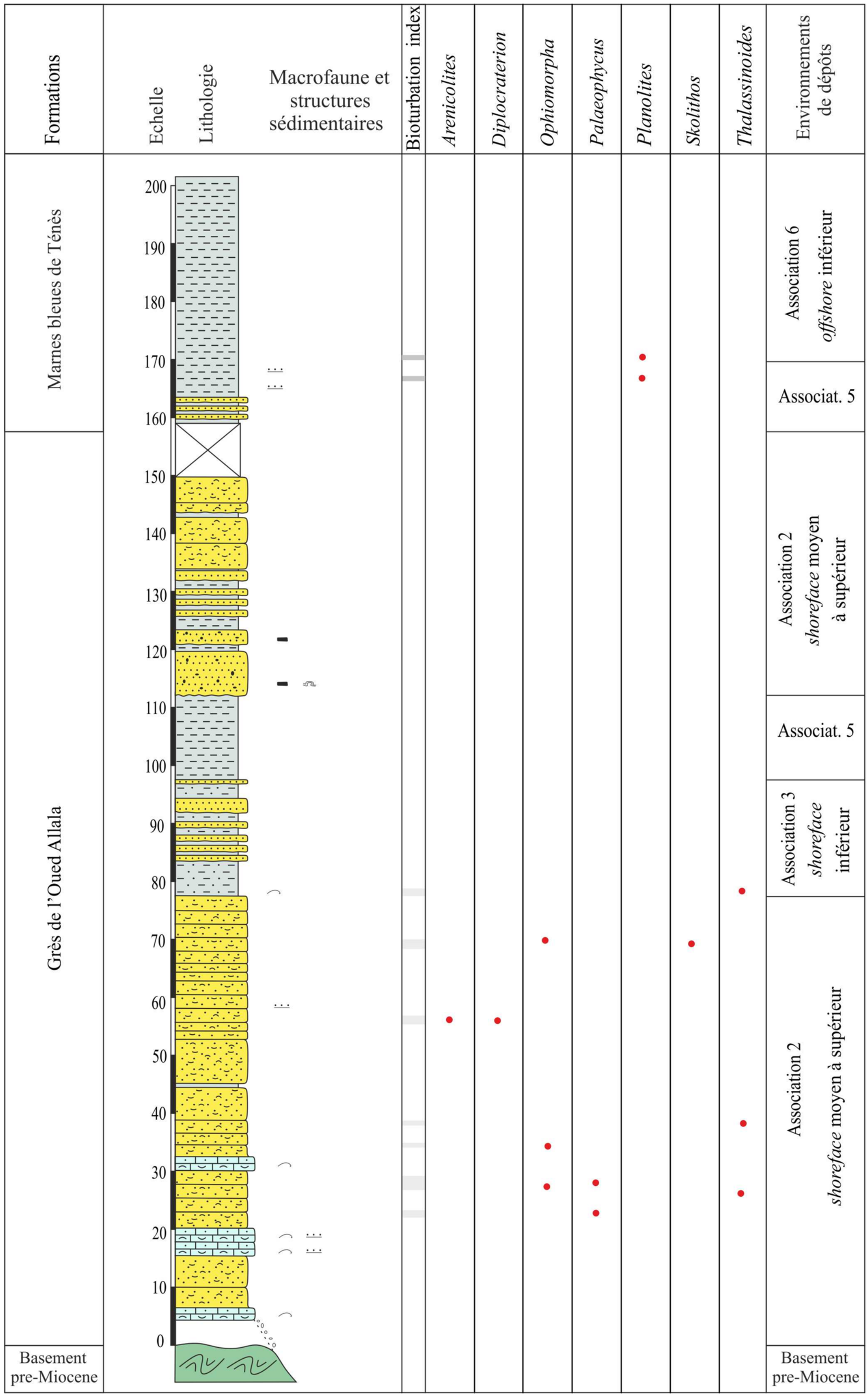


Fig. 11 Lithological log and trace fossils distribution at Djebel Ach Zerfet outcrops

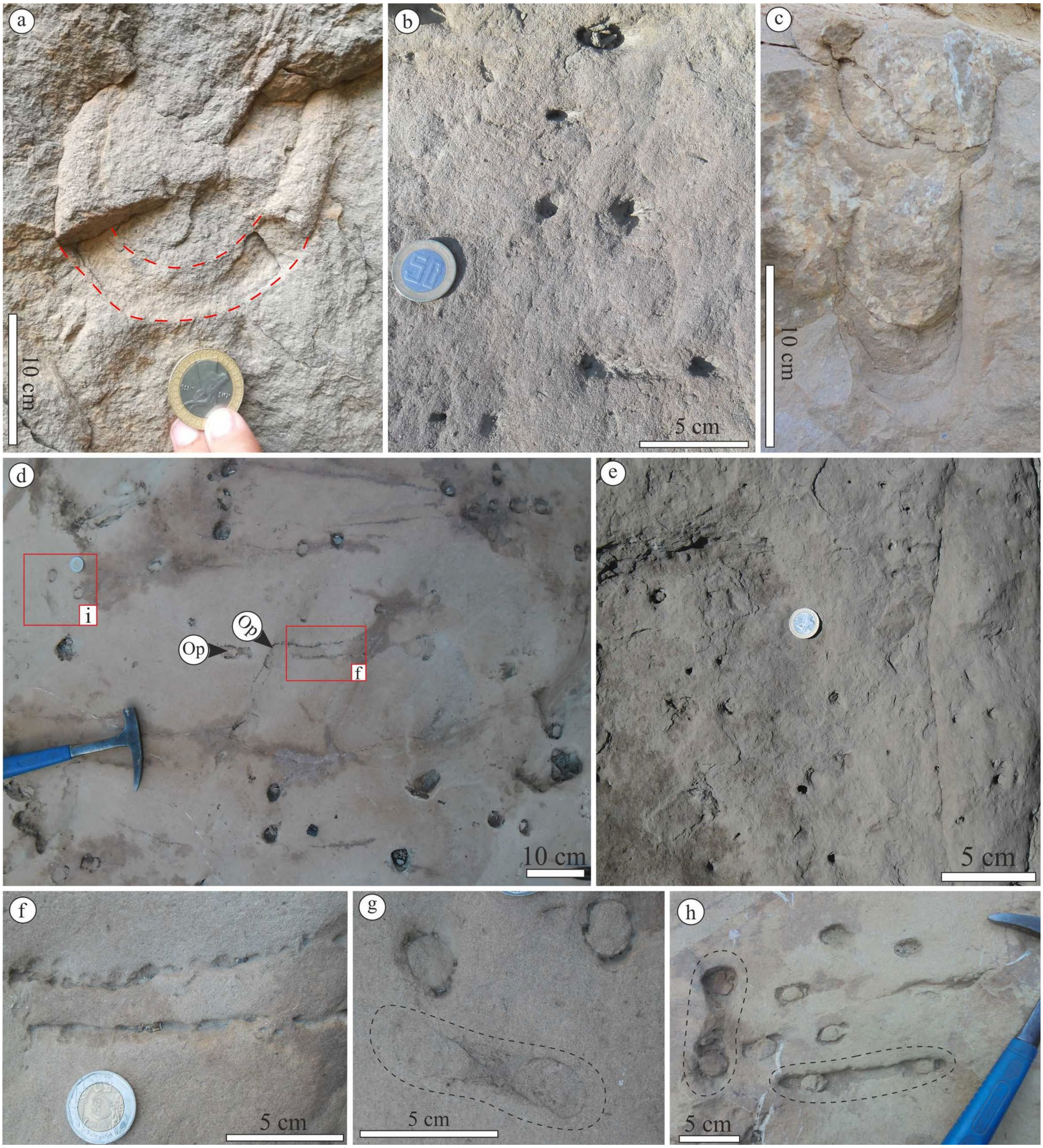


Fig. 12 Photographic illustration of *Arenicolites*, *Diplocraterion, Ophiomorpha* (Op)*;* endichnia within Allala River sandstone. **a** *Arenicolites* (cross-section; Djebel Ksar); **b** small *Arenicolites* or *Diplocraterion*? (bedding plane; Vieux Tenes); **c** *Diplocraterion parallelum* (cross section; Djebel Ach Zerfet); **d** *Ophiomorpha* and *Diplocraterion* (bedding plane; Ounsour Anhas); **e** small *Arenicolites* (bedding plane; Ounsour Anhas); **f** detail of (**d**) showing *Ophiomorpha* burrows; **g** detail of (**d**) showing *Diplocraterion* and *Ophiomorpha* with weakly developed pellets; **h** *Diplocraterion* (bedding plane; Ounsour Anhas)

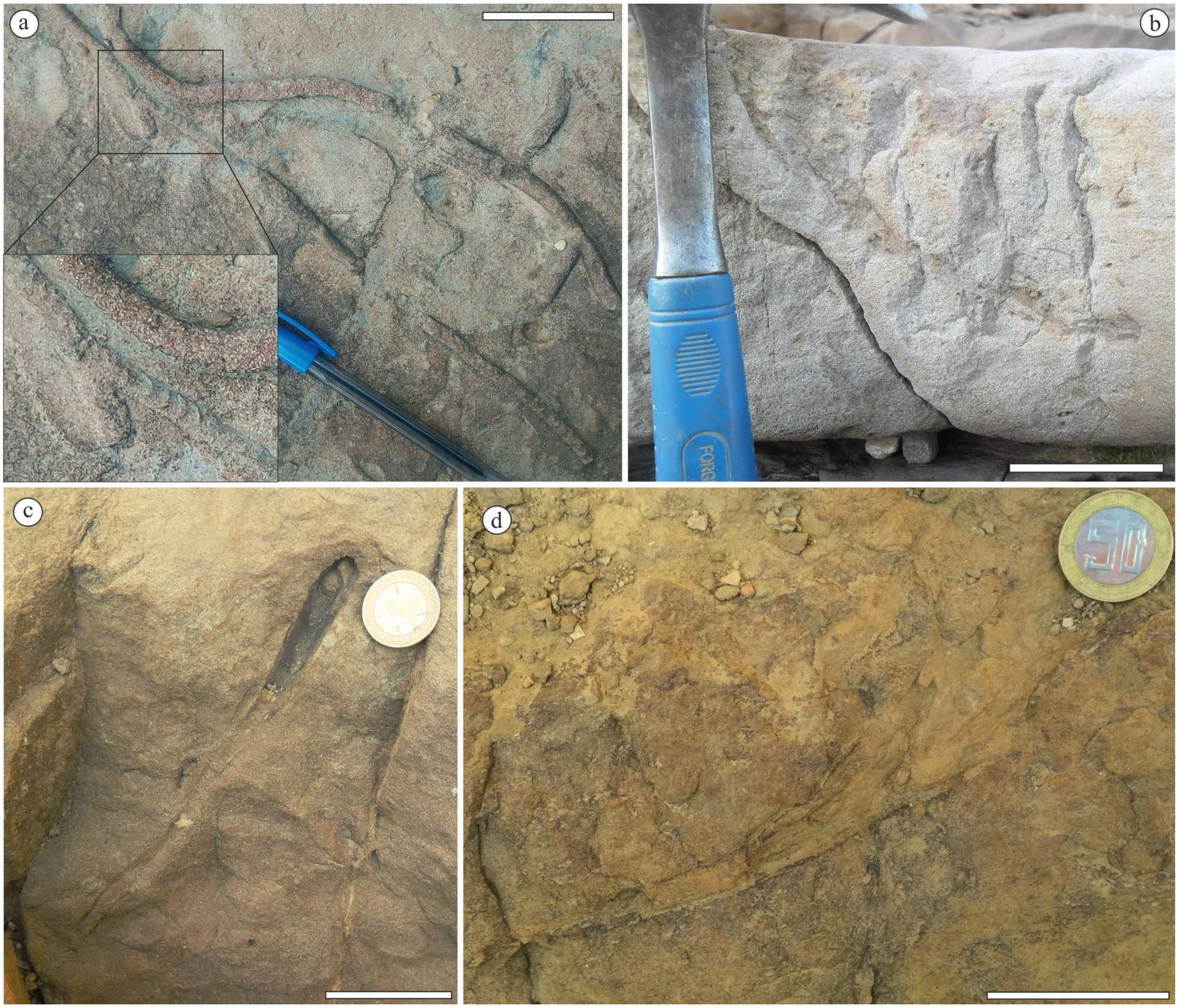


Fig. 13 Photographic illustration of *Beaconites* and *Cylindrichnus* (Allala River Sandstone). The scale bar = 5 cm. **a** *Beaconites capronus* (Vieux Tenes; bedding plane); the close-up photograph illustrates the meniscus filling; **b**-**d** *Cylindrichnus concentricus* in cross section at Djebel Ksar (**b**) and Vieux Tenes (**c** and **d**)

?*Skolithos annulatus* is characterised by a vertical to inclined, straight, annular burrow. The length of the burrow varies between 10 and 30 cm and the diameter can reach 2 cm. The rings are 0.8 to 2.5 cm in thickness. This ichnospecies was identified as (1) endichnia at Kaïsar (Fig. 17e, f) within the Allala River Sandstones and at Ounsour Anhas (Fig. 17d) within sandstone intercalation of the Tenes Blue Marls Formation; (2) exichnia at Ounsour Anhas (Fig. 17c and g) within the Tenes Blue Marls Formation**.**

Skolithos linearis Haldeman, 1840
(Fig. 17a, b and i)

This ichnospecies was identified as endichnia at Djebel Ach Zerfet, Djebel Ksar (Allala River Sandstones) and Ounsour Anhas (Tenes Blue Marls Formation). It is distinguished from other *Skolithos* ichnospecies by a straight to slightly curved burrow with homogeneous fill, and a very high length/diameter ratio (Knaust et al. 2018). The length of the burrow can reach 40 cm and the diameter is generally between 0.2 and 0.6 cm.

In marine sediments, *Skolithos* corresponds to dwelling traces produced by suspension- or deposit-feeders or organisms that exhibit passive predation strategies (e.g. annelids, phoronids and crustaceans) (Schlirf and Uchman 2005; Buatois and Mángano 2011; Adserà 2018). *Skolithos* indicates relatively high-energy, shallow-water conditions and occurs generally in various shallow-marine environments (Pieńkowski 1985; Alpert 1974; Fillion and Pickerill 1984; Schlirf and Uchman 2005). However, this trace has also been reported from continental environments where it is probably produced by insects and spiders (Schlirf and Uchman 2005), and in deep-marine environments (Uchman 1995), where it can be produced by aplacophores (mollusks) and holothurians (Dashtgard and Gingras 2012).

Taenidium Heer, 1877
Taenidium barretti (Bradshaw, 1981)
(Fig. 16c, d)

This ichnospecies is composed of straight to meandering, cylindrical to sub-cylindrical burrows, parallel to the bedding planes, with a meniscate fill. It occurs as epichnia within the Allala River Sandstone Formation at Djebel Ksar. The menisci are represented by heterogeneous, short and arcuate segments. The diameter of the burrow is less than 1 cm, and the apparent length can reach 40 cm.

Taenidium corresponds to deposit-feeding trace (Hammersburg et al. 2018). In marine environments, *Taenidium* may be produced by arthropods or worm-like organisms (Knaust 2017). It is a eurybathic trace that has been reported in both shallow-marine (middle to lower shoreface; Frey and Howard 1990; Sarkar et al. 2009) and deep-marine environments (MacDonald 1982; Crimes 1992), as well as in aeolian (Ekdale et al. 2007) and fluvial environments (Uchman et al. 2004). It is commonly found in marine environments in the *Cruziana* ichnofacies (Gerard and Bromley 2008; Sarkar et al. 2009; Bendella et al. 2011; Knaust 2017). *Taenidium* is considered to be produced by an animal which moves horizontally through the sediment and progressively deposits alternating backfill sediments (Bromley et al. 1999; Sarkar et al. 2009).

Teichichnus Seilacher, 1955
Teichichnus ?*zigzag* Frey and Bromley, 1985
(Fig. 16e)

One specimen was observed as endichnia within the Allala River Sandstone at Vieux Tenes that is associated with *Thalassinoides*. In cross-section, it appears as patches of concave-up spreiten vertical to the bedding plan. The width of the burrow is about 5 cm and and spreiten become wider downward to reach 2.5 cm in diameter.

Teichichnus isp.
(Fig. 16f)

This ichnospecies is rare and was recorded in association with *Ophiomorpha* as endichnia within the Allala River Sandstone at Ounsour Anhas. In cross-section, the observed specimen shows patches of vertical concave downwards spreiten. The basal part is the widest (3 cm) and shows a circular cross-section of the passively filled burrow that contrasts with the actively filled spreite. The depth of the observed burrow reaches 12 cm.

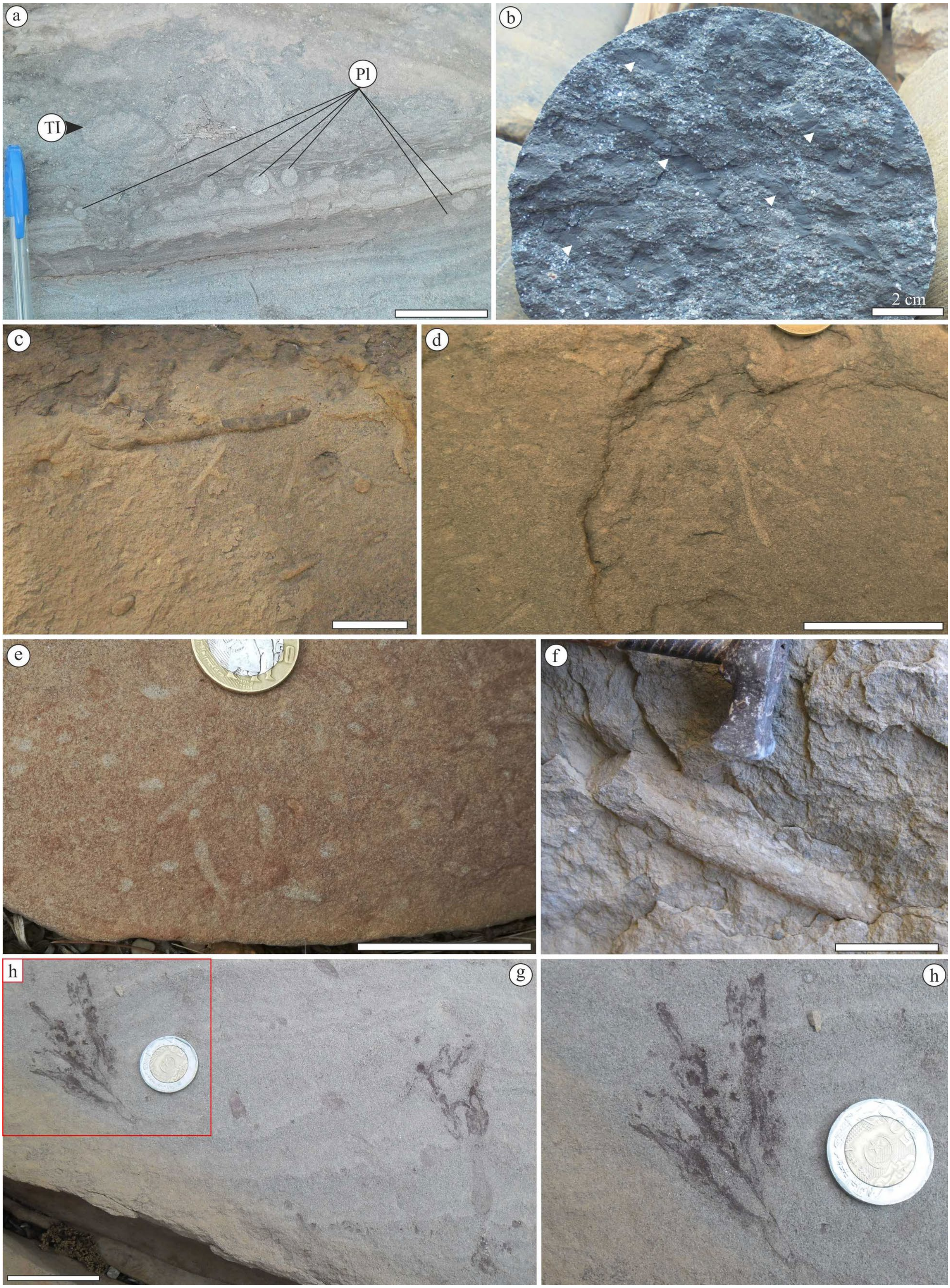
Teichichnus is interpreted as produced by worm-like animals (e.g. annelids) and arthropods (e.g. trilobites, crustaceans) (Knaust 2018a, 2018b; Vinn and Toom 2018). Since this trace fossil was found in association with *Thalassinoides* and *Ophiomorpha*, its tracemaker is assumed to be a crustacean. Different behaviours of the producing organims can be inferred, including dwelling, deposit- and suspension-feeding, as well as gardening (Knaust 2018a). *Teichichnus* is commonly reported from marginal-marine to shallow-marine environments (shoreface to offshore, tidal flat) with stressed conditions (i.e. salinity and oxygen fluctuations, sedimentation rate, erosional events). However, it is also mentioned in other environments such as deep-marine settings (Uchman and Wetzel 2012) and outer shelf or distal epeiric basin (Frey and Bromley 1985; Locklair and Savrda 1998). It is considered as equilibrium trace as indicated by stacked laminae that result from the movement of the producing organism in response to different sedimentation and colonization events (Knaust 2017, 2018a).

Thalassinoides Ehrenberg, 1944
Thalassinoides paradoxicus Kennedy, 1967
(Fig. 18b)

This inchnospecies shows a dense and irregular three-dimensional boxwork. The burrows are preserved as endichnia within the Allala River Sandstone Formation at Ounsour Anhas. They illustrate both "T" and "Y" shaped junctions. The tunnels are curved to straight and oriented at various angles. The diameter of the burrow ranges from 0.5 to 1.5 cm.

Thalassinoides suevicus (Rieth, 1932)
(Fig. 18a and c-i)

These burrows are cylindrical to subcylindrical, horizontally and/or vertically branched with a sandy fill and a smooth surface wall. They often bifurcate into "Y" or "T" shapes with an increase in diameter at the branching points to form irregular bulges and swellings. They are conserved within some sandstone beds of both Allala River Sandstone and Tenes Blue Marls Formations. Three configurations have been observed: (1) isolated burrows conserved as hypichnia at Kaïsar (Fig. 18c and i); (2) two-dimensional networks observed as epichnia, hypichnia or endichnia at Vieux Tenes (Fig. 18f), Kaïsar (Fig. 18e) and Ounsour Anhas (Fig. 18d); (3) three-dimensional boxworks observed as endichnia at Kaïsar (Fig. 18a). The diameter of the burrows is widely variable and ranges from 1 to 2 cm, whereas the length of the burrows varies from 10 to ca. 50 cm. The lowermost part of the Allala River Sandstone Formation contains vertical shafts that can reach 1.5 cm in diameter and 50 cm in length at Kaïsar (Fig. 18h) and Djebel Ksar (Fig. 18g). In the lower part of the Allala River Sandstones Formation (Kaïsar),


a
b
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2 cm

◂**Fig. 14** Photographic illustration of *Planolites*; *Macaronichnus*; *Palaeophycus* and *Parahaentzschelinia*; Allala River Sandstone (**a**, **c**-**h**) and Tenes Blue Marls (**b**). The scale bar = 5 cm. **a** *Planolites beverleyensis* (endichnia and exichnia; cross-section at Vieux Tenes); **b** *Planolites* isp. (Plan view in core; endichnia; Djebel Ach Zerfet); **c** *Palaeophycus tubularis and Macaronichnus segregatis* (endichnia and exichnia; cross-section at Djebel Ksar); **d**-**e** *Macaronichnus segregatis* in cross-section (**d**) and bedding plane (**e**) at Vieux Tenes and Djebel Ksar, respectively; **f** *Palaeophycus tubularis* (cross-section; Djebel Ksar); **g**-**h** *Parahaentzschelinia surlyki* (endichnia; vertical section at Ounsour Anhas)

thick *Thalassinoides* burrows (Fig. 18a) are preserved as endichnia, which diameter can reach 8 cm at swelling junctions. They are white coloured, calcite cemented with nodular aspect (individual burrows are visible) or completely nodular (individual burrows are hardly visible).

Thalassinoides is commonly recorded in shallow-marine environments (Frey and Howard 1990; El-Sabbagh et al. 2017), although it also occurs in deep-marine environments (Uchman 1995). Many of these dwelling and feeding burrows can be attributed to the activity of decapod crustaceans (Bromley and Frey 1974). However, these trace fossils have been reported in lower Palaeozoic rocks prior to the appearance of thalassinids and callianasids, where other arthropods likely produced similar patterns (Buatois and Mángano 2011). *Thalassinoides* tends to display a higher proportion of vertical components under high energy conditions (Buatois and Mángano 2011), as it is the case in the sandstones of the Kaïsar or Ounsour Anhas (Allala River Sandstone Formation). *Thalassinoides* is often considered as an indicator of oxic conditions (El-Sabbagh et al. 2017).

Zoophycos Massalongo, 1855
Two different morphotypes of *Zoophycos* have been observed.
Zoophycos isp. A
(Fig. 19a-f)

This morphotype consists of an unbranched spiral of a variable width between 30 and 100 cm and appears in form of a flattened cone (conical skirt-like zone; Bromley and Hanken 2003). It is composed of radiating lobe beams displaying small minor sigmoid lamellae (spreiten) bounded on both sides by major radial lamellae. The beams of minor lamellae emanate from a central cone (or an axial point in the middle of the trace, called "apex") and gradually widen towards the marginal edges of the trace, until reaching 4 cm in width. This trace is found at certain sandstone horizons, parallel to the bedding planes, as endichnia (just a few centimetres below the upper surface) within the Allala River Sandstone (Djebel Ksar; Fig. 19e, f and the Tenes Blue Marls Formations (Ounsour Anhas; Fig. 19a-d). *Zoophycos* isp. A shows some similarities with *Zoophycos rhodensis,* but the conical shape is more flattened and the J-shaped marginal tube is absent. Moreover, this trace fossil is also similar to *Echinospira pauciradiata,* but lacks a U-shaped burrow.

Zoophycos isp. B
(Fig. 19g, h)

This morphotype is distinguished from the previous one by a lack of minor lamellae. It is incompletely preserved as endichnia in a sandstone bed of the Tenes Blue Marls Formation at Ounsour Anhas. The central part of the trace (apex) is not preserved, and the remaining part is about 35 cm wide and shows a lobe composed of parallel to subparallel arching ridges (or lamellae) forming a broad "U" shape. The ridges (or lamellae) are tightly spaced, about 1 to 4 mm apart.

Zoophycos are feeding traces of worm-like animals, they are indicative of the ultimate stage of organic matter exploitation in seafloor sediments (Olivero and Gaillard 1996, 2007; Zhang et al. 2015). However, several behavioural strategies have been proposed, such as: feeding, gardening, resting, excreting, cache and refuse dump (Bromley 1991; Zhang et al. 2015). Ekdale and Lewis (1991) and Uchman and Demircan (1999) suggest for the formation of *Echinospira* (belonging to the *Zoophycos* group) a burrow system resulting from the successive lateral movement of a causative "U" shaped burrow. Bromley and Hanken (2003) proposedan active fill and a causative J-shaped burrow, based on the marginal continuous tube around the lobate perimeter of Pliocene *Zoophycos rhodensis* from Rhodes (Greece). Both forms (J-shaped and U-shaped) were collected in sediment cores sampled in the north-western African continental slope (Wetzel and Werner 1981). *Zoophycos* is probably produced by sipunculid worms, while exploiting nutrients deeply stored in the sediment (Olivero and Gaillard 1996, 2007; Gaillard et al. 1999; Olivero 2003). The representative palaeoenvironment of *Zoophycos* has shifted from shelf to deep sea over geological time (Bottjer et al. 1988; Olivero and Gaillard 1996; Zhang et al. 2015; Uchman et al. 2016).

Discussion

Ethology and depositional conditions

The nature of the substrate and environmental conditions (agitation, oxygenation, salinity, etc.) control the distribution, density, diversity and behaviours of trace fossil-producing organisms. This makes trace fossils very useful in sedimentological and palaeoenvironmental analyses (Pemberton et al. 2001, 2012; MacEachern and Bann 2008). Based on the sedimentologic analyses

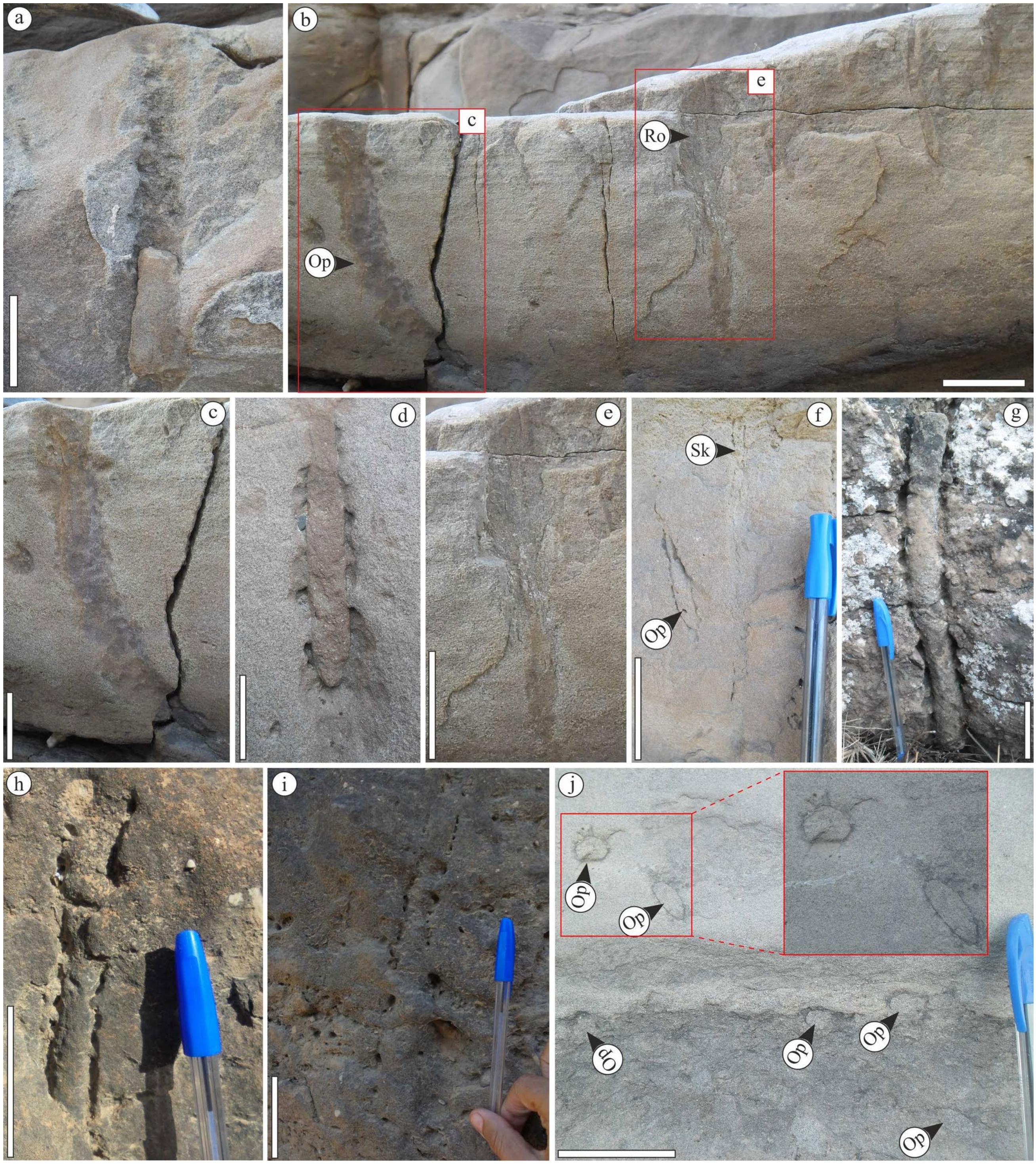


Fig. 15 Photographic illustration of *Ophiomorpha (*Op) and *Rosselia* (Ro) within Allala River Sandstone (vertical section). The scale bar = 5 cm. **a** *Ophiomorpha irregulare* (endichnia; Djebel Ksar); **b** horizontally laminated sandstone bed (Djebel Ksar) with a basal ravinement surface containing endichnial vertical burrows of *Ophiomorpha irregular* and *Rosselia erecta*; **c** detail of (**b**) showing the walls of *Ophiomorpha irregulare* with pellets (preserved as a cast); **d** *Ophiomorpha irregulare* (endichnia; Djebel Ksar); **e** detail of (**b**) showing *Rosselia erecta*; **f** *Ophiomorpha irregulare* with a poorly developed pellets (endichnia; Djebel Ach Zerfet); **g** *Ophiomorpha irregulare* (endichnia; Kaïsar); **h-i** *Ophiomorpha irregulare* (endichnia; Ounsour Anhas); **j** horizontal burrows of *Ophiomorpha irregulaire* (endichnia and exichnia; Vieux Tenes)

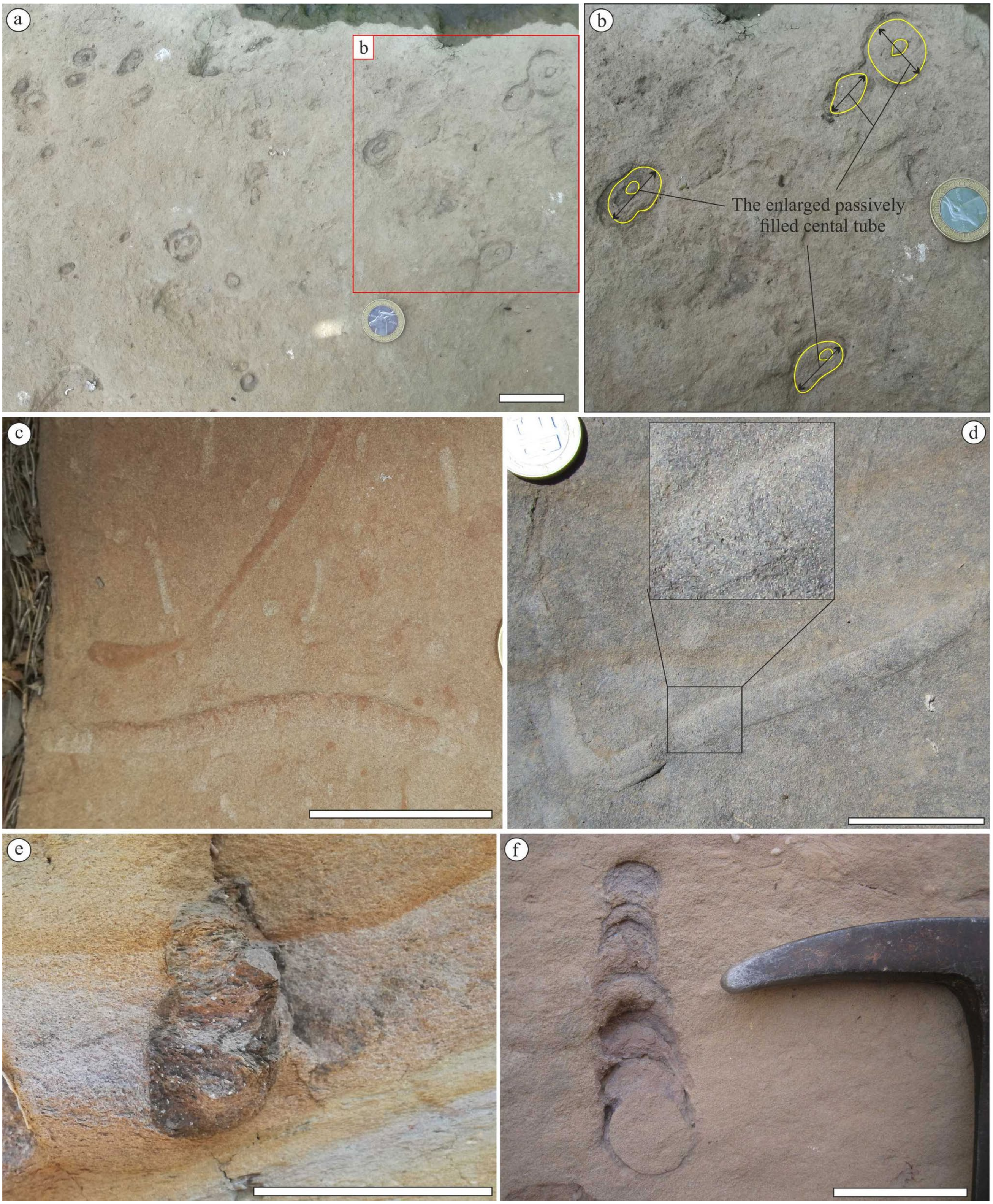
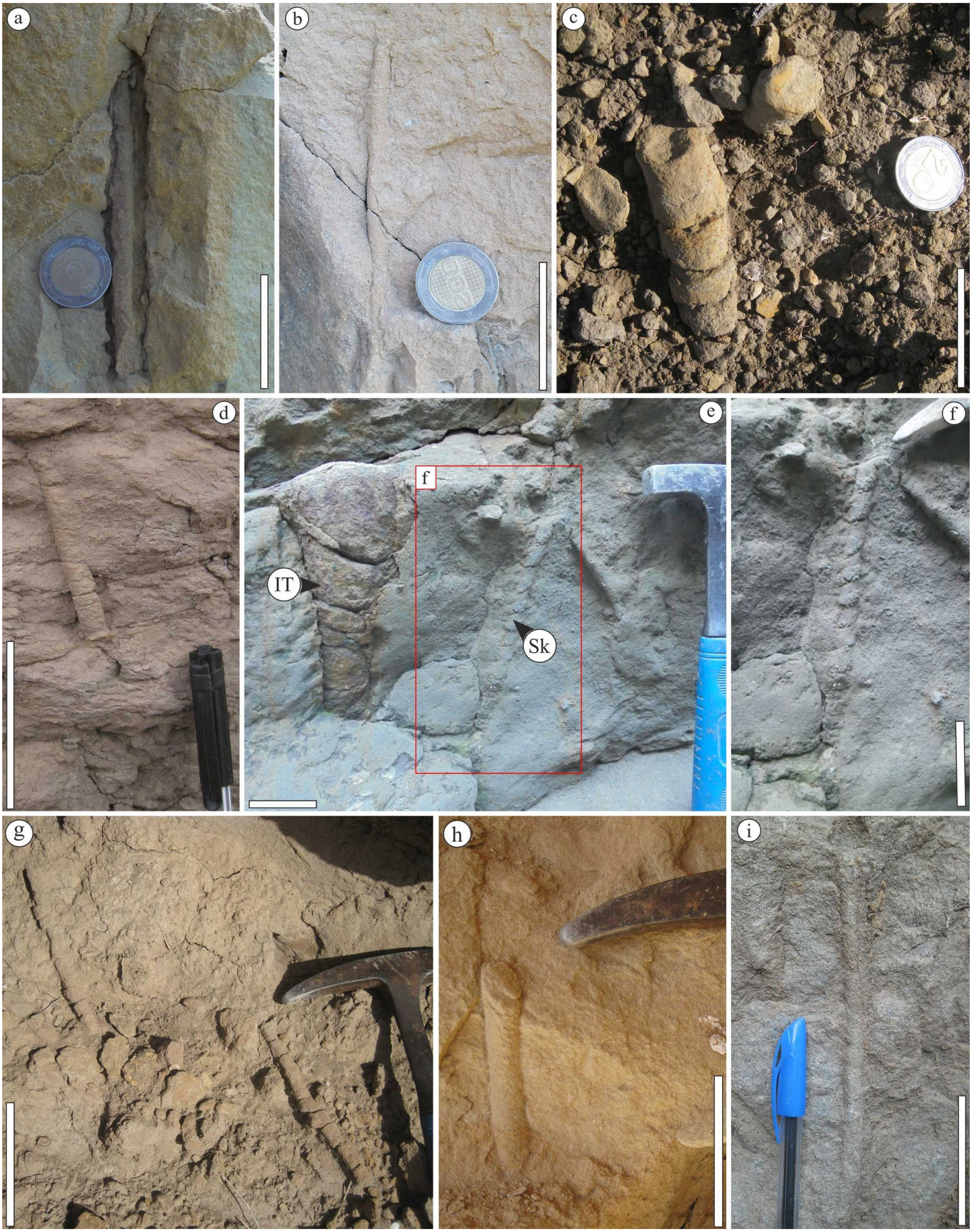


Fig. 16 Photographic illustration of *Rosselia, Taenidium and Teichichnus* within Allala River sandstone. **a**-**b** *Rosselia erecta* (endichnia; transversal section at Vieux Tenes); **c**-**d** *Taenidium barretti* (epichnia; bedding plane at Djebel Ksar); **e**-**f** *Teichichnus*; endichnia; cross-section at Vieux Tenes (**e**) and Ounsour Anhas (**f**)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◂**Fig. 17** Photographic illustration of *Skolithos*; vertical sections at Allala River Sandstone (**a**, **b**, **e**, **f**, h, **i**) and Tenes Blue Marls (**c**, **d**, **g**). The scale bar = 5 cm. **a**, **b** *Skolithos linearis* (endichnia; Djebel Ach Zerfet). Note in (**a**) the abnormally thick lining (mantle); **c** ?*Skolithos annulatus* (endichnia; Ounsour Anhas); **d** ?*Skolithos annulatus* (exichnia; Ounsour Anhas); **e** ?*Skolithos annulatus* (endichnia; Kaïsar). Note the vertical, thick, annulated, indeterminate burrow (IT) showing decrease in diameter downward; **f** detail of (**e**) showing an annulated fill of ?*Skolithos annulatus*; **g** ?*Skolithos annulatus* (endichnia; Ounsour Anhas); **h** *Skolithos* isp. (endichnia; Ounsour Anhas); **i** *Skolithos linearis* (endichnia; Djebel Ksar)

(Table 1), the palaeoenvironment of the Miocene succession at Tenes area has been interpreted as a wave-dominated siliciclastic platform that shows evolution from the gravel-dominated beachface-shoreface complex to offshore complex (Nemra 2020). The different ichnotaxa described above are consistent with this interpretation and can be grouped into two different ichnofacies: the *Skolithos* ichnofacies and the *Cruziana* ichnofacies. In addition, the comparison between the trace fossils of the five considered outcrops provides information on the depositional environment and the degree of influence of storm waves.

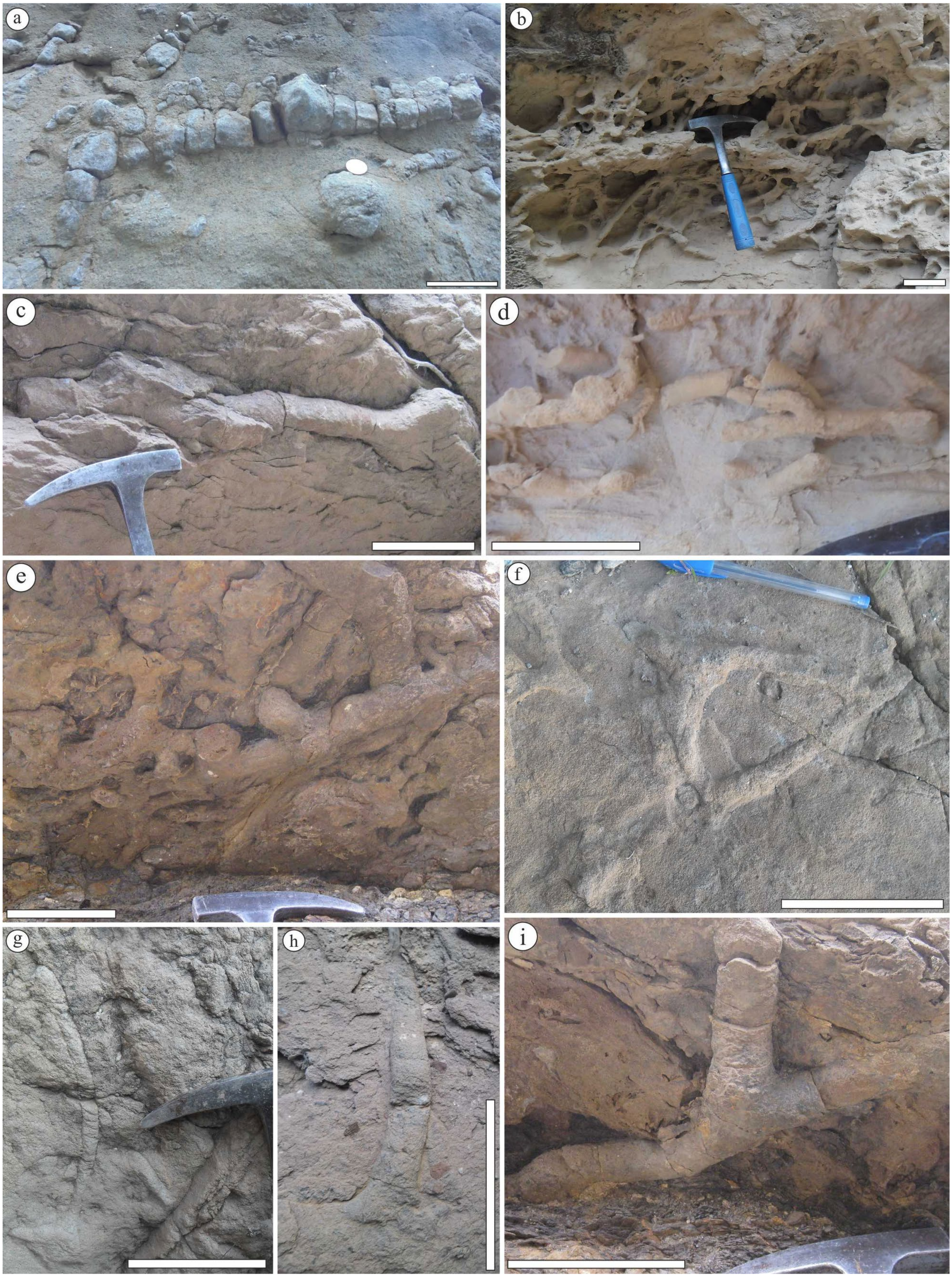
The facies related to the shoreface zone (Table 1) are characterised by the dominance of vertical burrows, the scarcity of trace fossils and a bioturbation index generally between 0 and 1. However, bioturbation index can reach 2 to 3 at (1) the base of Kaïsar sections in some sandstone intervalsbearing robust three-dimensional networks of *Thalassinoides* burrows; (2) Ounsour Anhas in some sandstone levels with *Diplocraterion* (Fig. 12d and g, h), *Ophiomorpha* (Fig. 12d) and other indeterminate traces. Occasionally, at Ounsour Anhas, some sandstone intervals show a strong bioturbation (BI: 5 to 6) with dense three-dimensional *Thalassinoides* boxwork (Fig. 18b). The ichnodiversity is also very low throughout the entire section.

In the Kaïsar area, three ichnogenera are identified: *Thalassinoides* (Fig. 18a and h, i) and, more rarely, *Skolithos* (Fig. 17e, f) and *Ophiomorpha* (Fig. 15g). *Thalassinoides* burrows are characterised by a large diameter and often occur in three-dimensional systems with vertical shafts, except for those (two-dimensional networks) observed at the base of the channelized beds intercalated within the sandy marls at the top of the section (offshore-related facies). In the Ounsour Anhas area, *Ophiomorpha* (Fig. 15h, i), *Diplocraterion* (Fig. 12g-h), *Teichichnus* (Fig. 16f) *Skolithos, Parahaentzschelinia* (Fig. 14g, h) and *Arenicolites* (Fig. 12e) have been observed. *Diplocraterion* and *Teichichnus* are produced by organisms that tolerate a decrease in salinity (Knaust 2017, 2018b). At Djebel Ach Zerfet, the bioturbation is represented by deep vertical burrows of *Skolithos* (Fig. 17a, b) and more rarely *Ophiomorpha* (Fig. 15f) and *Diplocraterion* (Fig. 12c). Horizontal burrows are rarely found and are represented by *Thalassinoides* and *Palaeophycus*. The upper to middle shoreface sandstones at Djebel Ksar contain *Thalassinoides* (including shafts; Fig. 18g), *Skolithos* (Fig. 17i), *Ophiomorpha* (Fig. 15a-d), *Diplocraterion* and *Arenicolites* (Fig. 12a).

The scarcity of traces and the dominance of vertical dwelling burrows of suspension-feeding organisms in these areas (Kaïsar, Ounsour Anhas and Djebel Ach Zerfet), as well as the low ichnodiversity there are characteristics of an agitated environment with frequent high-energy storm events, where oscillating and unidirectional currents maintain nutrient particles in suspension, and thus promote a strategy of suspension feeding behaviour (Pollard et al. 1993; Bendella et al. 2011; Bendella 2012; Rajkonwar et al. 2014; Zhang et al. 2017). Furthermore, the occurrence of equilibrium traces (*Diplocraterion* and *Teichichnus*) in sandstones of the Ounsour Anhas area, that might be produced by organisms that tolerate a decrease in salinity (Knaust 2017, 2018b), indicates the recurrence of erosive events and periods of sedimentation (Goldring 1964). Moreover, the large diameters of *Thalassinoides* burrows (up to 4 cm in diameter at Kaïsar) and the high proportion of vertical components (*Thalassinoides* shafts) also provide more evidence of an oxygenated environment and high-energy currents (Buatois and Mángano 2011; El-Sabbagh et al. 2017).

In the upper part of the upper sandstone member at Djebel Ksar, the bioturbation remains quite rare, with a moderate ichnodiversity containing *Ophiomorpha* (Fig. 15a-d), *Cylindrichnus* (Fig. 13b), *Rosselia* (Fig. 15b and e), *Skolithos* and *Taenidium*. The occurrence of rare elements of the *Cruziana* ichnofacies (*Rosselia* and *Taenidium*; Knaust 2017), in association with elements of the *Skolithos* ichnofacies (*Ophiomorpha*, *Cylindrichnus*, *Skolithos*), is indicative of the distal *Skolithos* ichnofacies, corresponding to the middle shoreface zone (Buatois and Mángano 2011).

The lower shoreface facies in the Djebel Ksar and Vieux Tenes outcrops show an inconsistency in the degree of bioturbation. The surfaces of some sandstone beds and some sandy marl interbeds are moderately to strongly bioturbated (BI: 3 to 6), while the interfaces of the sandstone beds are, in general, weakly bioturbated (BI: 0 to 1). The ichnodiversity is relatively high (eleven identified ichnogenera) compared to the upper to middle shoreface sandstones. The trace fossils are characterised by (1) the abundance of horizontal burrows such as *Beaconites* (Fig. 13a), *Thalassinoides* (two-dimensional networks; Fig. 18f), *Taenidium* (Fig. 16c, d), *Planolites* (Fig. 14a) and *Ophiomorpha* (horizontal components only; Fig. 15j); (2) the infrequent presence of vertical and inclined burrows such as *Cylindrichnus* (Fig. 13b-d), small-sized *Arenicolites* (Fig. 12b), *Rosselia* (Fig. 16a, b), *Ophiomorpha* that always occur in sandstone beds; (3) the dominance of traces generated by detritus-feeding organisms (*Beaconites, Taenidium*, *Planolites, Thalassinoides*); (4) a variety in the behaviour of organisms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◂**Fig. 18** Photographic illustration of *Thalassinoides*; Allala River sandstone. The scale bar = 10 cm. **a** thick nodular *Thalassinoides suevicus* (endichnia; vertical section at Kaïsar); **b** dense three-dimensional *Thalassinoides paradoxicus* boxworks (endichnia; vertical section at Ounsour Anhas); **c**-**d** *Thalassinoides suevicus* at Kaïsar (**c**) and Ounsour Anhas (**d**) (hypichnia; bedding plane); **e** dense bidimensional boxwork of *Thalassinoides suevicus* (hypichnia; bedding plane at Kaïsar); **f** bidimensional boxwork of *Thalassinoides suevicus* (epichnia; bedding plane at Vieux Tenes); **g**-**h** *Thalassinoides* shaft (endichnia) at Djebel Ksar (**g**) and Kaïsar (**h**); **i** isolated Y-shaped borrow of *Thalassinoides suevicus* (hypichnia; bedding plane at Kaïsar)

(feeding: *Thalassinoides*, *Taenidium*, *Planolites*, *Zoophycos* and dwelling: *Ophiomorpha*, *Arenicolites*). These combined features allow us to attribute this trace association to a relatively deeper and quieter environment of the *Cruziana* ichnofacies (Pemberton et al. 1992; MacEachern et al. 1999; Carmona et al. 2008; Frey and Dashtgard 2011). The vertical burrows mentioned above are related to opportunistic organisms that exploit nutrients during post-storm quiescent periods (Mángano et al. 2005; Buatois and Mángano 2011). Also, the presence of *Zoophycos* (Fig. 19e, f) in the last sandstone levels confirms a relatively deep environment and fair-weather conditions.

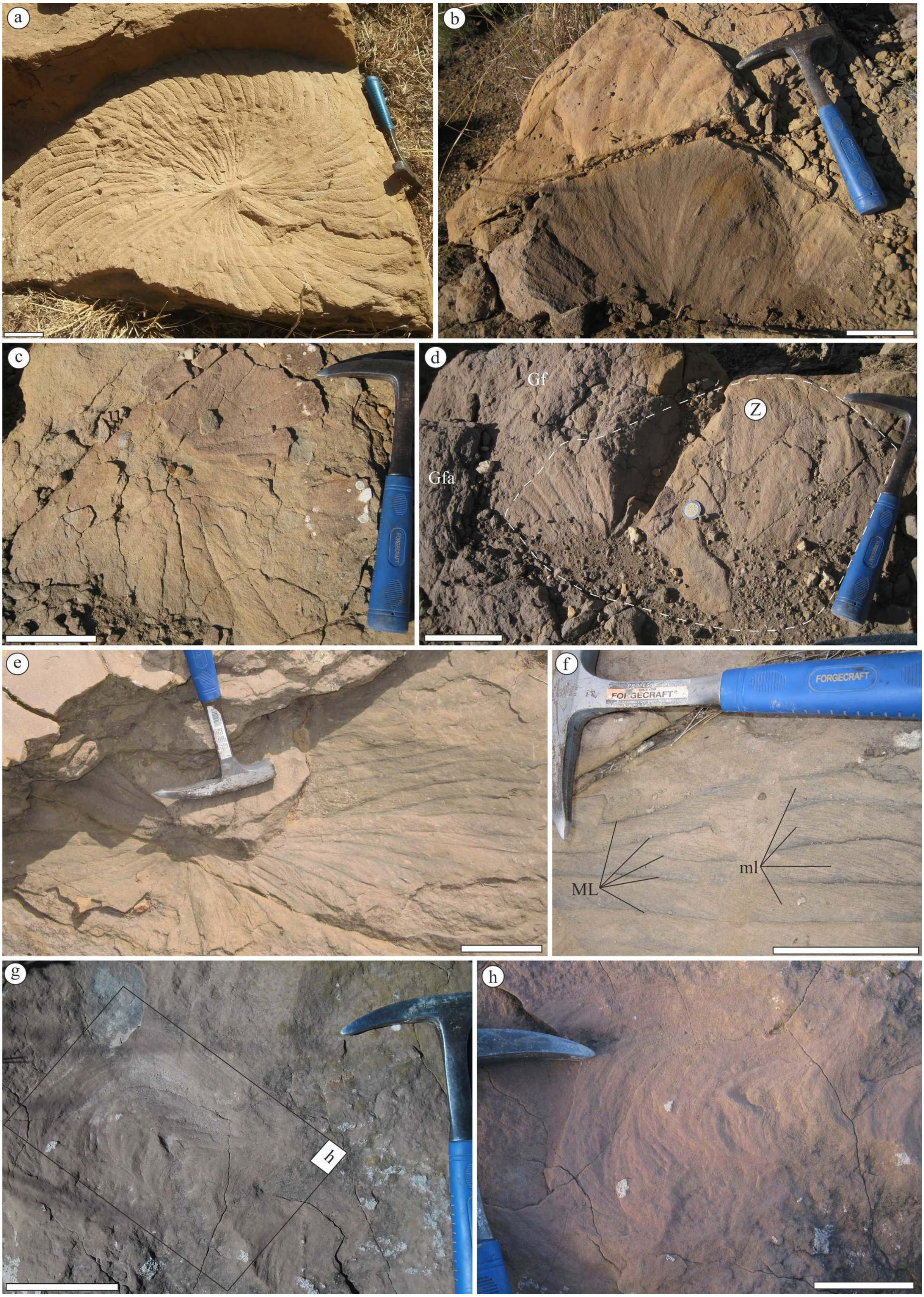
The highest sandstone levels (Allala River Sandstone Formation) at Ounsour Anhas, are also assigned to the lower shoreface. These deposits are heavely bioturbated (BI: 5 to 6), they yielded mainly three-dimensional *Thalassinoides* boxwork and rare *Ophiomorpha* burrows. These caracteristics suggest conditions of high oxygenation and abundance of nutrient matter (probably by fluvial supply).

In general, the offshore mudstone facies are characterised by pervasive burrowing (BI: 4–5) of high diversity. Distribution of ichnogenera is consistent with fully marine, unstressed settings (Pemberton et al. 2012; Dashtgard et al. 2012). In contrast to these data, the outcrops of the offshore dark, silty marls deposits of the Djebel Ksar, Vieux Tenes, Kaïsar, Ounsour Anhas and Djebel Ach Zerfet are weakly or unbioturbated. The scarcity or absence of trace fossils in the lower and upper offshore facies is probably related to oxygen-depleted conditions (Głuszek 1998; Mángano et al. 2005). The anaerobic conditions have been inferred by (1) the dark colour; (2) the presence of microbially induced carbonate concretions; (3) the occurrence of framboidal pyrite, clotted microfabric and the faint undulating lamination inside carbonate concretions; (4) pyritized and small foraminifera; (5) the preservation of plant debris (Nemra et al. 2019; Nemra 2020). These oxygen-depleted conditions were probably caused by sea-water column stratification.

Assessment of storm signature on sedimentation

Wave-dominated, generally non-tidal shorefaces may be weakly, moderately to intensely influenced by storms (MacEachern and Pemberton 1992; MacEachern and Bann 2008; Dashtgard et al. 2021). Based on this, three types of wave-dominated shorefaces have been distinguished: storm-affected, storm-influenced, and storm-dominated (Dashtgard et al. 2012). The storm-affected shoreface is characterised by intensely bioturbated muddy to silty sandstone beds of lower to middle shoreface related to fair-weather conditions. These deposits may be intercalated by thin storm beds that are commonly bioturbated with limited preservation of primary sedimentary structures (Buatois and Mángano 2011; Dashtgard et al. 2012). The storm-influenced shoreface is recognised by intensely bioturbated fair-weather muddy sandstone beds, alternating with unbioturbated to slightly bioturbated sandstone beds that reflect storm events. These latter might be bioturbated by vertical dwelling structures representing initial opportunistic colonisation (storm-related suite) and, at the top, by deposit-feeders, which in turn is followed by the re-establishment of fair-weather conditions (Mángano et al. 2005; Buatois and Mángano 2011; Dashtgard et al. 2012). The high energy conditions, causing repeated erosion in the storm-dominated shoreface, commonly preclude the preservation of biogenic structures (Mángano et al. 2005; Buatois and Mángano 2011). Only the remnant of deepest components of the storm-related suite might be preserved. In fact, the successions of the storm-dominated shoreface are represented by slightly to unbioturbated, low-angle undulatory and parallel-laminated sandstone beds (Buatois and Mángano 2011; Dashtgard et al. 2012). In the storm-dominated offshore, the bioturbation may be less and characterised by a small and dispersed vertical storm-related suite, most commonly *Skolithos*, *Arenicolites*, and *Ophiomorpha* (Mángano et al. 2005; Buatois and Mángano 2011).

In the Kaïsar, Ounsour Anhas and Djebel Ach Zerfet areas, the distinction between the lower and middle shoreface is difficult to determine due to the scarcity of sedimentary structures and the lack of trace fossils characteristic of fair-weather conditions. In these areas, the dominance of thick vertical dwelling burrows of suspension feeders, the rarity of traces and the low ichnodiversity in the shoreface facies confirm stressful conditions related the dominance of storm-wave activity. Furthermore, the offshore transition/upper offshore facies in Ounsour Anhas provide additional evidence of storm domination and high-energy conditions. The fining-upward sandstone intercalations with erosive or channelized basal surfaces within the sandy-silty marl are more frequent, thicker and host low-density *Skolithos* burrows (fig. 17d) and *Thalassinoides* shafts. At the top of the section, the presence of *Zoophycos* (Fig. 19a-d) in the uppermost sandstone intercalations is worth noting. The occurrence of these *Zoophycos* in offshore as well as in shoreface facies (Djebel Ksar) will be discussed later. The disseminated *Skolithos* burrows (elements of the *Skolithos* ichnofacies, storm–related *Skolithos*) are produced by post-depositional opportunistic organisms that exploit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◂**Fig. 19** Photographic illustration of *Zoophycos* (bedding planes; endichnia). The scale bar = 10 cm. **a**-**f** *Zoophycos* isp. A within sandstone intercalations of the Tenes Blue Marls at Ounsour Anhas (**a**-**d**) and Allala River sandstone at Djebel Ksar (**e**-**f**). Note the bundles of minor laminae (ml) bounded by major laminae (ML); Gf: fine sandstone; Gfa: very fine clayey sandstone; **g**-**h**) *Zoophycos* isp. B (sandstone intercalation of the Tenes Blue marls at Ounsour Anhas)

suspended nutrient matter in the water column after storm events (Pemberton et al. 1992; Mángano et al. 2005; Buatois and Mángano 2011).

At Vieux Tenes and Djebel Ksar, it is easier to distinguish the facies of the middle shoreface from those of the lower shoreface, according to the appearance of traces that indicate fair-weather conditions (horizontal burrows of the *Cruziana* ichnofacies). The trace-fossil association at these areas shows an alternation of fair-weather and agitated periods (storm-wave activity). The agitated periods are represented by non-bioturbed or weakly bioturbed sandstone beds with vertical dwelling burrows of suspension feeders (*Cylindrichnus*, *Arenicolites*, *Rosselia*, *Ophiomorpha*). In contrast, the facies related to fair-weather periods (sandstone and sandy marl) are characterised by a moderately to heavily bioturbated facies with horizontal burrows of detritus-feeding organisms (*Beaconites, Taenidium*, *Planolites*, *Thalassinoides*). This implies alternating agitated and calmer periods, thus, the shoreface in these localities was rather under the influence of storm-wave activity.

The lateral distance between the different outcrops is approximately one kilometre (Fig. 1b, c). In other words, the deposits of this same siliciclastic platform seem to be dependent on the localities that are either dominated or influenced by the storm-wave activity. This lateral variation in the intensity of storm waves might be controlled by a contrasting palaeogeomorphology of the coastline (narrow coastal reliefs and gravel beach adjacent to wider sandy bays). Therefore, the gravel beach is more exposed to wave activity, whearas the sandy bays are relatively less affected by wave action. This configuration, which results from differential erosion of the coast, can also be observed in present-day environments (Hemdane et al. 2016). Indeed, the facies at the base of Kaïsar (open framework conglomerates, sandstone, cemented conglomerates with *Ostrea* clasts, pebbly sandstones) have been assigned to a gravel-beach environment (beachface/shoreface complex) located at the base of the cliffs (Nemra 2020). In addition, the rapid lateral variations in thickness and facies have been documented (Nemra 2020); for example, at Vieux Tenes and Djebel Ksar, the conglomerates appear as a single bed (in each section) with a thickness of less than 1 m, whereas they occur as a set of decimetric to metric levels at Kaïsar.

Zoophycos of Tenes Miocene succession: palaeoenvironment and ethology

The different data regarding *Zoophycos* show that the palaeoenvironment shifted over geologic time (Bottjer et al. 1988; Olivero and Gaillard 1996). Indeed, the presence of *Zoophycos* in Palaeozoic successions has been reported from shallow-marine to deep-sea palaeoenvironments (Bottjer et al. 1988). Consequently, their occurence is not considered evidence of a palaeoenvironment deeper than shelf (Uchman et al. 2016). During the Jurassic, the *Zoophycos*-producing organism had migrated to the deep-sea environment (Olivero 2003) such as slopes, deep-sea fans and basin floors (Wetzel and Werner 1981; Uchman and Demircan 1999; Löwemark et al. 2006). Contrary to these observations, *Zoophycos* (Fig. 19) of the Tenes region (Middle Miocene) have been assigned to the *Cruziana* ichnofacies. They occur in sandstone facies of shallow-marine environments ranging from the lower shoreface (*Zoophycos* of Djebel Ksar area; Fig. 19e, f) to the upper offshore (*Zoophycos* of Ounsour Anhas area; Fig. 19a-d). Similarly, some Jurassic (Pemberton et al. 2001) and other Miocene (Pervesler and Uchman 2004) *Zoophycos* have also been reported in similar marine settings (lower shoreface to upper offshore). In conclusion, we support the idea of Pervesler and Uchman (2004) that though Mesozoic and Cenozoic *Zoophycos* have often been reported from deep-marine environments (slope edge to basin), it still occurs in the offshore to shoreface zone.

The studied *Zoophycos* (Fig. 19a-d, g, h) were observed as endichnia in the upper part of fining-upward sandstone beds, interpreted as the result of storm-wave action. Opportunistic organisms producing *Zoophycos* exploited the uppermost part of the nutrient-rich sandy-clay sediment. *Zoophycos* are often associated with low-oxygen environments (Ekdale 1992) and the large trace size (30-100 cm) is not necessarily related to the oxygenation of the environment (Wetzel and Werner 1981; Giannetti 2010), but rather to the search for and storage of nutrients, beneath the redox level, out of reach of other bioturbating organisms (Bromley, 1991). Their abundance and large size indicate that the sediment was nutrient-rich and the sedimentation rate was low, at least during the period of exploitation (Löwemark et al. 2006; Nasiri et al. 2018). The *Zoophycos* tracemaker colonised the surface that separates the Tenes Blue Marls Formation (Middle Miocene) from the overlying formation, represented by yellowish marls of Tortonian age (upper Miocene). This surface is regarded as a discontinuity surface (sedimentation breakup surface or omission surface *sensu* Ekdale and Lewis 1991) and may correspond to the maximum flooding surface of the first Miocene transgressive cycle *sensu* Perrodon (1957).

Zoophycos of the last sandstone beds of the Tenes Blue Marls were developed in the upper offshore zone (Nemra 2020) on a relatively narrow and steep sea floor. This is documented by (1) the occurrence of synsedimentary deformation structures like slumps and faults (Perrodon

1957; Nemra et al. 2019); (2) the co-existence of proximal material (plant debris and benthic foraminifera) and pelagic material (high abundance of planktic foraminifera), which can be explained by the narrow shelves common in tectonically active basins such as the Mediterranean basin (Nemra et al. 2019).

Conclusions

The trace fossils of the Middle Miocene outcrops in the Tenes area have been studied for the first time in five localities (Vieux Tenes, Kaïsar, Djebel Ksar, Djebel Ach Zerfet and Ounsour Anhas). Fifteen ichnogenera have been identified in the Allala River sandstone and Tenes Blue Marl formations, reflecting multiple responses of the benthic fauna to environmental factors and, thus, they provide valuable information on the depositional environments.

The trace-fossil assemblages show two ichnofacies: (1) *Skolithos* ichnofacies related to an upper/middle shoreface environment, and (2) *Cruziana* ichnofacies that reflects lower shoreface to transition offshore environment. *Skolithos* ichnofacies is characterised by low ichnodiversity and the presence of scattered vertical burrows (*Skolithos*, *Diplocraterion*, *Arenicolites, Ophiomorpha*) of suspension-feeding organisms, which suggests stressful conditions associated with frequent high-energy events (storms) and continuous sedimentation and remobilization of detrital deposits. Locally, *Thalassinoides* burrows are well developed (the lower part of Allala River sandstone at Kaïsar, Ounsour Anhas and Djebel Ksar) and show a higher proportion of vertical components, thick burrows and generally dense networks and boxworks (Ounsour Anhas and Kaïsar). All these characteristics suggest an oxygenated environment and high energy conditions. In some cases, distal expression of *Skolithos* ichnofacies might be distinguished by the occurrence of rare elements from the *Cruziana* ichnofacies (*Rosselia* and *Taenidium*) and allow us to assign the facies related to the middle shoreface zone.

The *Cruziana* ichnofacies is characterised by a relatively high bioturbation and dominance of horizontal burrows of deposit-feeding organisms, such as *Thalassinoides* (horizontal components)*, Taenidium, Planolites, Beaconites* and *Ophiomorpha* (horizontal components). These trace fossils represent a wide variety in behaviours (feeding, locomotion, gardening, resting and dwelling). In this ichnofacies, rare vertical burrows might occur, such as *Arenicolites* (small size)*, Rosselia and Skolithos,* which could be related to storm facies and suggest an opportunistic behaviour.

The comparison of trace fossils between the studied localities allows us to estimate different degrees of storm-wave influence. Kaïsar, Ounsour Anhas and Djebel Ach Zerfet outcrops are dominated by thick, deep, vertical dwelling burrows of suspension feeders and show low ichnodiversity that confirm storm-wave dominated conditions. In these localities the distinction between the zonations of shoreface is difficult because of the lack of trace fossils related to fair-weather conditions. On the other hand, at Vieux Tenes and Djebel Ksar localities, the alternation of fair-weather-related trace fossils (*Thalassinoides* networks, *Taenidium*, *Beaconites, Planolites*) and the storm-related trace fossils (*Cylindrichnus, Arenicolites, Rosselia, Skolithos*) in the lower shoreface zone indicate storm-wave influence. In these areas, the occurrence of fair-weather-related trace fossils allows as to easily identify the lower shoreface zone.

Contrary to what is globally documented in siliciclastic platforms, the offshore related facies in the Tenes area are weakly bioturbated to unbioturbated. This is interpreted as being the result of oxygen-depleted conditions, which suggests sea-water column stratification.

Finally, the *Zoophycos* recorded at Ounsour Anhas and Djebel Ksar outcrops are related to offshore transition and lower shoreface facies, respectively. Although Cenozoic *Zoophycos* are common in deep-marine deposits, these observations confirm that the occurrence of Cenozoic *Zoophycos* extends to the shoreface. In addition, the presence of these *Zoophycos* at the top of the storm-related sandstones beds attests to an opportunistic behaviour. The large size of these traces at Ounsour Anhas is probably related to oxygen-depleted conditions and low sedimentation rate or omission.

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Data availability Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

Declarations

Conflict of Interest The authors declare that they have no conflict of interest.

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