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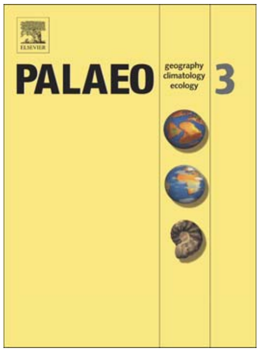

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Deep-sea trace fossils of the Oligocene–Miocene Numidian Formation, northern Tunisia

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Abstract

Twenty-two ichnogenera and thirty-one ichnospecies have been recorded in the Oligocene–Miocene Numidian Formation of northern Tunisia. Heterolithic successions of thin-bedded turbidite sandstones and interchannel mudstones contain the most diverse trace fossil assemblages. Thick- to very thick-bedded structureless sandstones and conglomerates representing the fill of channel complexes contain a low-diversity trace fossil assemblage. The ichnoassemblage in the lower part of the formation (Oligocene), which includes *Paleodictyon* isp., *Scolicia strozzii*, *Spirorhaphe* isp., ?*Cosmorhaphe* isp. and *Halopoa* isp., can be ascribed to the *Paleodictyon* ichnosubfacies of the *Nereites* ichnofacies. The ichnoassemblage in the upper part of the formation (Miocene: Aquitanian), including *Diplocraterion* cf. *habichi*, *Scolicia vertebralis* and *Ophiomorpha* isp., is interpreted as the shallower part of the *Ophiomorpha rudis* ichnosubfacies of the *Nereites* ichnofacies. The notable switch in ichnofauna between the Oligocene and lower Miocene reflects variation in environmental and depositional conditions. The common occurrence of trace fossils of the *Ophiomorpha rudis* ichnosubfacies, and *Diplocraterion* cf. *habichi* in the early Miocene, indicates an increase in energy level, greater environmental disturbance and probable shallowing. This is also confirmed by a corresponding decrease in the abundance and diversity of benthic foraminifera. The integration of ichnological, sedimentological and microfossil content has allowed the distinction of two quite distinct geographical depositional settings within the Numidian Formation. The first domain includes the Numidian succession of the Tabarka, Cap-Negro, Cap-Serrat and Bouhertma areas, which are characterized by «distal» turbidites, showing the *Paleodictyon* ichnosubfacies that is compatible with a lower bathyal depth in the Oligocene and an upper slope depositional environment during the early Miocene.

The second domain includes the NE part of Mogod Mountain (e.g. the Ras El Korane, Jebel Gattous-Zoukar), which exhibit more proximal characteristics compatible with a probable slope canyon interpretation. The southern margin of the Kroumirie (Balta and Zouza areas) and Sejnene area shows a distal setting compared with the Ras El Korane and Jebel Gattous-Zoukar areas. It is ascribed to a mid-to upper slope depositional environment during the Oligocene to early Miocene.

Keywords: Ichnofacies, Numidian Flysch, deep-water turbidites, Oligocene-Miocene, Tunisia.

1. Introduction

Analysis of ichnofacies, especially when integrated with sedimentological and palaeoecological studies, is recognized as a powerful tool in a better recognition of sedimentary environments (e.g., Buatois and Mángano, 2011). Further improvement of the current ichnofacies models includes subdivision of ichnofacies with respect to different Palaeoenvironmental parameters; e.g., the *Cruziana* ichnofacies has been subdivided into proximal, archetypal and distal parts (e.g., Pemberton et al., 2001). Similarly, the *Nereites* ichnofacies has been subdivided into the *Nereites, Paleodictyon* and *Ophiomorpha rudis* ichnosubfacies (e.g., Wetzel and Uchman, 2009; Uchman and Wetzel, 2012). These classifications should be tested by further studies on the distribution of trace fossils in depositional environments of different ages and locations.

In this paper, we focus on trace fossils of the deep-sea, turbidite and hemipelagite sediments of the Oligocene–Miocene Numidian Formation in the northern Tunisia and their potential as tools for reconstructing depositional conditions of these deposits. Such a detailed ichnological study has not been undertaken before, although several previous studies have noted the presence of trace fossils (Gottis, 1953; Vass, 1971; Rouvier, 1977; Beaudoin et al., 1986; Yaïch, 1997). In these works the Numidian Formation depositional environment has been interpreted as shallow-water in some cases (Gottis, 1953, 1954a, b) but deep-water by others (Wezel, 1968; Parize, 1988; El Maherssi, 1992; Yaïch, 1997). Recently, Belayouni et al. (2012) stated that the Numidian Formation of the southern margin of the Kroumirie Mountain can be considered as the shallowest deposits within the deep sea.

In addition, we have paid special attention to the relationship between the distribution of trace fossils and architectural elements (e.g. sheet sands, channel-fill, and channel-lobe transition) as determined by a separate sedimentological study (Riahi, 2011). Detailed age determination is on the basis of planktonic foraminiferal studies (Riahi et al., 2010; Riahi, 2011, 2004). Careful analysis is also made of foraminiferal ratios, benthic/planktonic (B/P) and deep-water agglutinated foraminifera/calcareous foraminifera (DWAF /C). This work has broader implications: (1) as the basis for interpretation of the Numidian Formation elsewhere in the western Mediterranean area (e.g., Algeria, Morocco, Italy and Spain); and (2) as a case study that informs our understanding of slope-system, turbidite ichnology in general.

2. Geological background

The Numidian Formation of northern Tunisia is mainly latest Oligocene to early Miocene in age and contains a series of deep-marine turbiditic sandstones and mudstones. It is closely linked with the much more extensive Numidian succession that outcrops discontinuously along the southern Mediterranean coast from the Gibraltar Arc in the west to Sicily and southern Italy in the east. This orogenic belt is approximately 2500 km long and up to 100 km wide (Fig. 1A). It represents an extensive mud-rich, slope-apron system characterised by a mature to ultramature, quartz-rich petrofacies (Johansson, 1998; Stow et al., 2009; Fildes et al., 2010; Riahi, 2011). The uses of the term “flysch” for this Formation has been widely discussed in the literature; Patacca et al. (1992) and Guerrera et al. (1993, 2012) considered it to be ambiguous and therefore proposed abandonment of the term. Furthermore the vast regional extent of this formation (~2500 km) has led some authors to promote it as a ‘facies’ rather than a single formation (Magné and Raymond, 1972; Giunta, 1985; Moretti et al., 1991). Whereas much of the past literature and recent papers still refers to «Numidian Flysch», we prefer to use the term ‘Numidian Formation’.

The Numidian Formation and its correlative deposits (e.g. Oligocene–Miocene of Kabyle and La Galite Flysch) were formed in a compressional tectonic setting during the Alpine tectogenesis (Durant Delga, 1980; Guerrera et al., 2005; Frizon de Lamotte et al., 2006), which produced a foreland basin in the late Eocene, to Miocene (Fig. 1B). The basin was bounded on the north by an active margin composed of a southward-verging accretionary prism underlain by the European crustal blocks, while to the south it is bounded by the African margin represented by the passive margin of the Maghrebian Flysch Basin (Fig. 1B).

By the Oligocene to early Burdigalian, a significant change in facies was caused by diversification of the tectonic regime in response to Mediterranean deformation events. This change is signalled by the relatively abrupt termination of carbonate sedimentation, and the equally sudden influx of quartz-rich clastic sediments throughout the Numidian basins offshore as well as the correlative continental deposits onshore in Northern Africa. During this period the geodynamic history of the region is dominated by: (1) Kabylides migration towards the south and the counter clockwise rifting of Corsica and Sardinia from Europe, and the opening to their north of the Algerian back-arc basin (Frizon de Lamotte et al., 2009); (2) formation of the foreland basin accommodated by various early Oligocene to mid-Miocene flysch (Oligocene–Miocene of Kabyle, La Galite Flysch and the Numidian Formation) dominated by turbidites. This also shows progressive migration southeastward.

The sedimentation of the Numidian Formation ceased by the end of the Burdigalian (16–15 Ma) except for the Numidian succession of Sicily and the Apennines, which are thought to extend into the Langhian (Guerrera et al., 2005; Thomas et al., 2010). At about 15 Ma (Langhian), the docking of the Kabylides against the continental African margin achieved the flexural stage (Frizon de Lamotte et al., 2006). This accretion of a continental terrane along the margin was accompanied by the propagation of thrust faults within the African domain forming the external Tell system with general uplift of the coastal range, which started during the late Miocene (post-11 Ma) and is interpreted by Benouali et al. (2006) and Frizon de Lamotte (2009) as the result of a rebound following detachment of the subducting slab. Evidence for this process is given by the type of the post-collisional magmatic activity and by seismic tomography imaging (Frizon de Lamotte et al., 2000). Since the beginning of the Pleistocene, the whole orogenic domain has been affected by diffuse compressive activity, mainly concentrated in the coastal areas, both onshore and offshore.

3. Study area and outcrops

The Numidian succession of northern Tunisia represents a complex allochthonous unit (Rouvier, 1977; El Euchi et al., 2004; Riahi et al., 2010) occupying the highest structural position in Kroumirie and Mogod mountains (Fig. 1C) and consists of approximately 2000–2500 m of alternating sandstones, quartz pebble conglomerates and mudstones of turbiditic affinity. Nappes of the Numidian Formation are stacked above the deformed upper Cretaceous limestones, Paleocene marls and Ypresian limestones of the Boudabbous Formation. The Numidian Formation overlies the Oligocene–Miocene Bejaoua Group (e.g. Nefza Window, Ain Jantoura) and is intruded by Triassic salt diapiric structures (e.g. in the Jebel Zouza and Jebel Ouled El Mejri in the Sejnene area) and, in some cases, by felsic plugs and mafic dikes, sills and basaltic flows (e.g. in Galeb Saad Moun in the Sejnene area) of late Miocene and Pliocene age (Laridhi Ouazaa, 1994; Jallouli et al., 2003; Talbi et al., 2008).

On la Galite Island (60 km north of Cap-Serrat), the Numidian Formation crops out along with contemporaneous deposits of the La Galite Flysch, which is dated as early Miocene in age (Yaïch, 1992; Rekhiss, 2007; Belayouni et al., 2010). These deposits are formed by immature, micaceous turbidites that may be interbedded with mature, to ultramature quartz-rich Numidian Formation sandstones.

For this study we have investigated a series of coastal outcrops, at Tabarka, Cap-Serrat and Ras El Korane, and inland sections at Bouhertma, Gassa-Msid, Sidi Shaieb, Ben Metir and Sejnene (Fig. 1C). In each case we have followed an integrated approach including: (1) bed-by-bed logging; (2) detailed survey of trace fossils; (3) carbonate content ($CaCO_3$); and (4) foraminiferal analysis with special emphasis on P/B and DWAF /C ratio variation. This work builds on previous detailed sedimentological and biostratigraphic work by the authors, and careful regional correlation between sections.

4. Stratigraphy and major lithofacies of the Numidian Formation

Based on biostratigraphic dating and detailed sedimentary logging of several sections located in the southern margins of Kroumirie and Mogod mountains and fringing the coastline, the Numidian Formation can be subdivided into: (1) the lower part or Zouza

Member (Oligocene succession), which is mainly mud-rich, with subsidiary sandstones and (2) the upper part or Kroumirie Member (lower Miocene succession) that is Aquitanian to early Burdigalian in age (N4–N5 zones) and more sand-rich (Fig. 2). The top of the Numidian Formation is marked locally by distinctive pelitic/siliceous horizons of Burdigalian age (N6 Zone) well exposed in Babouch and Oued Ziatine near Cap-Serrat and called the Babouch silexites. This stratigraphic scheme is comparable with the stratigraphic subdivision already recognised in the Aljibe Flysch of southern Spain (Didon et al., 1984; Martin Algarra, 1987; Esteras et al., 1995) as well as Morocco (Chalouan et al., 2008), Algeria (Caire and Mattaeur, 1960), Sicily (Broquet, 1968; Guerrera et al., 1992; Patacca et al., 1992) and the Apennines (La Manna et al., 1995) (Fig. 3).

Sedimentological study undertaken on the Numidian Formation allows the recognition of 21 lithofacies on the basis of grain size, sedimentary structures, bed thickness and deformational features following and adapting the classification schemes for deep-water siliciclastic sediments introduced by Stow et al. (1985) and Pickering et al. (1989). These are grouped into six major facies classes, including conglomerate (FC1), structureless massive sandstones (FC2), structured sandstones (FC3), mudstone & sandstone/siltstone couplets (FC4), mudstones (FC5) and chaotic lithofacies associations (FC6), including slump-slide deposits, shale clast units, debrites and slurry sands.

The first three facies classes can be grouped into the massive sandstones facies association *sensu* Stow and Johansson (2000) and interpreted as the product of high density turbidity currents (Lowe, 1982; Postma et al., 1988; Stow and Johansson, 2000) and/or sandy debris flows (Shanmugam, 1996, 2000; Stow and Johansson, 2000). The very thick-bedded, structureless sandstones are thought to be the product of gradual aggradation of sediment beneath steady or near-steady flows (Kneller and Branney, 1995). By contrast, the mudstone and sandstone/siltstone couplets and mudstone facies groups are interpreted as the result of low to medium concentrated turbidity currents, together with some hemipelagic input (Stow et al., 1996; Stow and Tabrez, 1998). Field mapping undertaken in the Tabarka, Cap-Serrat and Balta areas indicates that sinuous lower to upper slope channel complexes are entrenched within mud-rich slope deposits. They are filled mainly with conglomerates and thick to very thick, structureless massive sandstones interbedded with normally graded turbidites and chaotic deposits of lithofacies group FC6.

5. Trace fossils description

The present ichnological study was based only on outcrop observations carried out on several exposures of different scale, mainly along roads and streams. Trace fossils were analysed on well-exposed planes and have been arranged in morphological groups according to Książkiewicz (1977), with further modifications by Uchman (1995). Twenty-two ichnogenera and thirty-one ichnospecies were recorded in the Oligocene–Miocene Numidian Formation of northern Tunisia, most of them recognised for the first time in this formation. They include various post-depositional and pre-depositional forms reflecting colonization of the mudstone and sandstone/siltstone couplets, mudstone facies, and to lesser extent the very thick-bedded sandstones which form the channel complex fill. Neither trace fossils nor other bioturbation structures have been recorded in the conglomerates and coarser facies. The position of the recorded specimens is shown in Table 1 and Figure 4.

5.1. Circular and elliptical structures

Asteriacites aberensis Crimes and Crossley, 1991 (Fig. 5A) is a hypichnial star-shaped flat-top mound, which is 20 mm in maximum diameter. Five triangular rays, 3–4 mm long, are regularly distributed on the periphery of the mound. *Asteriacites* is produced by sea stars (asteroids) and brittle stars (ophiuroids) resting or hunting in the sediment (Seilacher, 1953). It is typical of well-oxygenated marine conditions, mostly in shallow waters (Müller, 1980; Twitchett and Wignall, 1996), but is also noted in the deep-sea Palaeozoic (Mikuláš, 1992 for review), including *A. stelliformis* Miller and Dyer from the Paleogene Flysch deposits of Romania (Brustur, 1992) and *A. aberensis*, known so far from the Ordovician and Silurian Flysch (Crimes and Crossley, 1991). The wide triangular rays in the described specimen suggest asteroids as the producers.

Cardioichnus isp. (Fig. 5B, C) is a hypichnial mound, usually higher on one side, which is subquadrately heart-shaped in outline, with rounded angles and a shallow, narrow longitudinal median depression running at least through a part of the mound. The mound is 32–55 mm long and 25–45 mm wide. Forms more oval to circular in outline are also present; they are 35–60 mm long and 30–53 mm wide, with an elongated depression located apically in the higher part, or with no distinct depression. The latter might be ascribed to *Bergaueria* Prantl, but transitional forms to the former one, allow their interpretation as a preservational variant of the same trace fossil. *Cardioichnus* is a resting burrow of irregular echinoids (Smith and Crimes, 1983).

Selenichnites isp. (Fig. 5D) is an epichnial, horse shoe-like depression with at least locally elevated margins, 70–90 mm wide, open from one side from which a flat, wedge-shaped ridge extends behind the depression. The depressions occur in a row, composed of two complete and two incomplete (crescent depression) structures that are located 10–40 mm apart. Moreover, isolated structures occur, which are subdivided by a median flat ridge through the whole depressions and appear as two symmetric crescent depressions (Fig. 5D). *Selenichnites* is interpreted as a resting trace of limulids (horse shoe crab) (Romano and Whyte, 1990), other xiphosurans or aglaspids (Gibb et al., 2011 for review). Or these, only limulids are present in the Cainozoic and can be considered as the tracemakers of the described forms. Limulids live mostly in shallow waters to 60 m depth, but they occur also on the shelf edge to upper slope at a depth of 290 m, where the shelf edge is close to the coast, and exceptionally at the depth of 1097 m (Botton and Ropes, 1987).

The plug-shaped form (Fig. 5E) is a hypichnial, elliptical, smooth mound, 130 mm long, 70 mm wide, elevated from one side. On the prolongation of the mound, a shallow, crescentic flat-bottomed depression is present on the more elevated side. This is considered to be a resting trace of unknown trace-maker.

5.2. Simple and branched structures

Archaeonassa isp. (Fig. 5F) is an epichnial, smooth, straight to gently curved furrow, 10–16 mm wide, with elevated margins. The furrow undulates slightly over longer distances, so it disappears in some segments. The longest observed length is 60 cm. *Archaeonassa fossulata* Fenton and Fenton, 1937 is shallower, and has been interpreted as a crawling trail produced mostly by gastropods (Fenton and Fenton 1937; Buckman, 1994; Stanley and Feldmann, 1998) or crustaceans (Yochelson and Fedonkin 1997; Mángano and Buatois, 2003). The furrows described herein, being deep and smooth, are ascribed to gastropods.

?*Chondrites* isp. (Fig. 5G) appears as a group of circular or oval spots on polished surfaces in mudstones. The spots are 0.5–1 mm wide. They are interpreted as cross sections of a three-dimensional burrow system composed of dendritically branched cylinders, typical of *Chondrites*. *Chondrites* is a deep-tier feeding system produced by an unknown organism that may be able to live at the oxic-anoxic interface as a chemosymbiotic organism (Seilacher, 1990; Fu, 1991) or even within the anoxic zone as found in modern sediments (Wetzel, 2008).

Chondrorhaphe bifida Seilacher, 1977 (Fig. 6A) occurs as hypichnial, dendritically branched semicylindrical ridges, that are 2 mm wide. The ridges run radially from a centre that does not display any particular morphological elements. The whole structure is up to 190 mm wide. This trace fossil is only recorded in the Meloula-Tabarka section in thin-bedded (FC4) fine-grained upper Oligocene turbidites. *Chondrorhaphe bifida* is a rare graphoglyptid trace fossil in deep-sea Campanian to Miocene turbiditic deposits (Uchman, 1999). Its overall morphology is similar to *Chondrites* but its branching pattern and tiering position are different.

Halimedides isp. (Fig. 6B) is a smooth, gently winding cylinder, 4–6 mm in diameter, with distinct chambers of different shape that are irregularly distributed along the cylinder. The chambers are 11–17 mm wide. Some of the chambers are heart-shaped but others are subquadrate. This trace fossil was discussed by Uchman (1999). Gaillard and Olivero (2009) regard it a deep-sea agrichnion whose chambers were used for food capture and storage, produced in stiff to firm substrates most probably by a small crustacean (see also Lukeneder et al., 2012).

Halopoa isp. (Fig. 6C–E) occurs as a hypichnial, horizontal bundle of straight to gently curved, dendritically branched ridges covered with longitudinal irregular ridges or wrinkles. The bundle converges from one side and diverges from other side forming a twig- or fan-like structure up to 400 mm long. The ridges, 4–12 mm wide, display gentle widening and constrictions. The fan-like structures resemble *Phycodes* Richter, but the wrinkles on the ridges are typical of *Halopoa*. As in other *Halopoa,* the sculptured surface of the ridges is an effect of the pushing of sand just above the base of the bed by an unknown deposit feeder (Uchman, 1998). *Halopoa* isp. occurs only in the Tabarka area.

Ophiomorpha rudis (Książkiewicz, 1977) (Figs. 6F, 7A–B) is represented by oblique to vertical shafts or oblique to horizontal, sand-filled, straight to slightly curved or winding, occasionally branched cylinders that are 5–25 mm wide. Some cylinders display a wall composed of muddy pellets. *Ophiomorpha rudis* is thought to be produced by shrimp-like decapod crustaceans (Uchman, 2009). It is characteristic of deep-sea sandy deposits (Uchman, 1991, 2009; Tchoumatchenco and Uchman, 2001; Phillips et al., 2011). In the studied sections, *Ophiomorpha rudis* co-occurs with graphoglyptids and abundant *Scolicia vertebralis* in the Ras El Korane section.

Ophiomorpha annulata (Książkiewicz, 1977) (Fig. 7C) consists mostly of horizontal, hypichnial, or rarely vertical to oblique endichnial or exichnial, rarely branched cylinders, 2–5.5 mm wide. The cylinders are straight to slightly winding, smooth or covered, commonly only partially, with delicate scratches or small, perpendicularly arranged muddy granules.

«*Ophiomorpha*» *recta* (Fischer-Ooster, 1858) (Fig. 7D, E) is an endichnial, simple, locally pinching or swelling, flattened cylinders 6–25 mm wide, filled with elongate pellets that are 1–1.5 mm long and 0.7–1 mm wide. The fill is commonly ferruginized. This trace fossil, known so far from Cretaceous–Palaeogene deep-sea sediments, was described under different ichnogenera (see synonymy list Uchman, 1998). It was termed as «*Tubotomaculum*» by Glaçon and Rouvier (1967) and used as a mapping criterion for the base of the Numidian Formation in the northern Tunisia, or as a marker of the “varicoloured clays” in the basal part of this formation fringing the western part of the Mediterranean Sea (Wezel, 1968; Broquet, 1968; Moretti et al., 1988). In the study area, it was recorded in mudstones and thin-bedded turbidites cropping out in the Meloula corridor and within the mudstone succession and thin-bedded turbidites separating the Mgad Rai sandy unit and the Needles.

Planolites montanus Richter, 1937 (Figs. 5B, 7F) is represented by hypichnial, straight or curved, smooth, short tubular ridges, 1–4 mm in diameter. They plunge into the bed at least from one side. *Planolites* is a widespread trace fossil in different marine and non marine environments; it is produced by organisms of various taxonomic affinities, which are attributed mostly to deposit feeders (Pemberton and Frey, 1982; Keighley and Pickerill, 1995).

Planolites isp. (Fig. 5G) is a straight, curved endichnial cylinder without wall, filled by sediment that is slightly different (darker) than the host rock. The cylinders are 3 mm in diameter. Also endichnial straight to curved or winding, cylindrical burrows, about 1 mm in diameter are considered as ?*Planolites* isp. (Fig. 8C).

Trichichnus isp. (Fig. 7G) is preserved as mostly vertical or subvertical, thin, ferruginous, slightly winding, rarely branched tubular burrows, which are up to 1 mm in diameter. The ferruginization is most likely derived from weathered pyrite. *Trichichnus* occurs mostly in fine-grained, shallow-water and deep-sea deposits (e.g., Frey, 1970; Kennedy, 1975; Wetzel, 1981). A strong tendency to pyritization is typical of this form. It is a deep-tier trace fossil produced by opportunistic organisms in poorly oxygenated sediments (McBride and Picard, 1991), which may be meio-infauna feeding on chemosymbiotic microbes (Uchman, 1995).

5.3. Winding and meandering structures

cf. *Cochlichnus* isp. (Fig. 8A) is a hypichnial, slightly sinuous and undulating semicylindrical ridge, 1–2 mm wide. Its sinuosity is irregular and much weaker than in typical *Cochlichnus*, which is a trace fossil known from marine and non-marine sediments and produced by different organisms, including nematodes (e.g., Fillion and Pickerill, 1990; Głuszek, 1995; Uchman et al., 2009).

?*Cosmorhaphe* isp. (Fig. 8B) is a hypichnial, meandering string, 1.7 mm wide, preserved in semi relief. The meander is 8 mm wide and 7 mm deep. Most probably, this is an incompletely preserved *Cosmorhaphe*, which is a typical graphoglyptid, characteristic of deep-sea turbiditic sediments (e.g., Seilacher, 1977; Uchman, 1998).

?*Gyrochorte* isp. (Fig. 8C, D) is an epichnial, slightly curved, smooth, bilobate ridge that is 3–5 mm wide. It is subdivided into two lobes by a narrow, discontinuous median furrow. Single occurrence and poor preservation prevent more detailed determination, but the overall morphology resembles *G. comosa* Heer, the type ichnospecies of *Gyrochorte,* which displays oblique ribs on the lobes and vertical repetitions in the bed: it occurs commonly in Jurassic shelf siliciclastics (Weiss, 1940; Schlirf, 2000). It was regarded as a trace of a polychaete-like worm (Heinberg, 1973; Seilacher, 2007) or aplacophoran mollusc (Heinberg & Birkelund, 1984), but Schlirf (2000) criticised this view and regarded it as the feeding trace of an arthropod. Similar *Gyrochorte* isp. occurs in Lower Cretaceous deposits of Bulgaria, interpreted as outer shelf–slope transition (Uchman and Tchoumatchenco, 2003).

Helminthopsis isp. (Fig. 8E) is a hypichnial, smooth, irregularly meandering, semicircular ridge, 1–3 mm wide, preserved in semi relief. It was encountered in Tabarka and the Cap-Serrat area. *Helminthopsis* is a repichnion common in many environments (Wetzel and Bromley, 1996).

Scolicia vertebralis Książkiewicz, 1970 (Fig. 8F, G) occurs as an epichnial, straight to curved, wide V-shaped furrow with elevated margins that is 15–50 mm wide. The outer side of the margin is slightly lobate. The furrow displays a single central string at the bottom. The string is 1–2 mm wide. The furrow displays oblique, arcuate ribs, which extends to the margins. *Scolicia* is a locomotion and feeding burrow (pascichnion) of a spatangoid echinoid (e.g., Smith and Crimes, 1983; Uchman, 1995; Bromley et al., 1997). *Scolicia* was recorded in the Oligocene and the early Miocene succession of the Numidian Formation exposed at Cap-Serrat, Ras El Korane, Zouza, Tabarka, Sidi Shaieb and Bouhertma.

Scolicia strozzii (Savi and Meneghini, 1850) (Figs. 8H, 9H) is a hypichnial bilobate ridge that displays two continuous, parallel semicircular lobes of more or less constant width that are separated by a smooth median furrow. The ridge is 13–30–40 mm wide, winding, tightly meandering or forming a single spiral coil. It was traced for up 90 cm on the bedding plane. This trace fossil is interpreted as a cast of washed- out *Scolicia* (Uchman, 1995; Donovan et al., 2005).

5.4. Branched winding and meandering structures

Urohelminthoida dertonensis Sacco, 1888 (Fig. 9A) is represented by incompletely preserved hypichnial, semi-cylindrical meanders composed of a winding ridge that is 1 mm wide. The limbs of the meanders are 3-5 mm apart and their amplitude exceeds 50 mm. Kinks of the meanders display a short protrusion in accordance with the course of one of the meander limbs. For discussion of this graphoglyptid see Uchman (1995).

Helicolithus ramosus (Vialov, 1971) (Fig. 9B) is a hypichnial semirelief composed of tightly spaced first-order meanders and a second-order, helicoidally undulating string. The first-order meanders are parallel and arcuate, 1–3 mm apart. They are at least 30 mm in height. The second-order meanders look like a stretched cork screw when more completely preserved. Mostly they are manifested as a row of small knobs. The string is 1.0–1.2 mm wide. This graphoglyptid, typical of flysch deposits, was described for stet as *Tuapseichnium ramosum* Vialov, 1971 or *Punctorhaphe parallela* Seilacher, 1977 (Tunis and Uchman, 1996).

5.5. Spirals and networks

Spirorhaphe involuta (De Stefani, 1895) (Fig. 9C) is a hypichnial semicylindrical ridge about 1 mm wide, forming a spiral that is about 70 mm in diameter. The ridge is winding and forms a loop in the centre of the spiral, in which the spiral coils in reverse direction. Coils of the spiral are 1–3 mm apart. *Spirorhaphe* is a typical graphoglyptid (Fuchs, 1895). In the Meloula-Tabarka section it is preserved on a sole of a 15 mm-thick, fine- to medium-grained sandstone bed (FC4), in which it co-occurs with *Paleodictyon.*

Paleodictyon latum Vialov and Golev, 1965 (Fig. 9D) is a regular net composed of polygonal to hexagonal meshes that are 1.8–2.2 mm wide. The meshes are formed by semicircular ridges (strings) 0.5–0.8 mm wide. *Paleodictyon* is a typical graphoglyptid

(Fuchs, 1895; Seilacher, 1977) that is common in thin- to medium-bedded turbiditic sediments (e.g., Uchman, 2007b, c).

Paleodictyon strozzii Meneghini in Savi and Meneghini, 1850 (Fig. 9C, E) is a regular net composed of polygonal to hexagonal meshes 3–4 mm wide. The meshes are formed by semicircular ridges (strings) that are 0.8–1 mm wide. Meshes on the edges of the network are not always closed This trace fossil was recorded in the Meloula-Tabarka and Cap-Serrat sections, where it occurs as casts on the soles of fine- to medium-grained turbidites (FC4).

Paleodictyon majus Meneghini in Peruzzi, 1880 (Fig. 9C, F–H) is a hypichnial, horizontal hexagonal net composed of semicircular ridges (strings), whose meshes are 8–9 mm wide and the string is about 1–1.5 mm in diameter.

Paleodictyon italicum Vialow and Golev, 1965 (Fig.9I) is a hypichnial, horizontal hexagonal net composed of semicircular ridges (strings), whose meshes are 31–35 mm wide and the string is about 2.4–3 mm in diameter. This specimens was recognized in the Numidian Formation located WNW of the Boussalem area, just south of the Oued Bouhertma ridge (Kroumirie Mountain) and was named "*Palaeodictyon maius"* by Vass (1971)

5. 6. Spreite structures

Diplocraterion cf. *habichi* (Lisson, 1904) (Fig. 10A–G) is a long, vertical to subvertical and occasionally distally horizontal U-shaped spreite structure that displays foremost a marginal, straight to gently winding, cylindrical tube, which is 5–30 mm in diameter. The limbs of the U-shaped tube are parallel and 2–15 mm apart, but their plane is commonly twisted and locally inclined. The vertical extent reaches at least 180 cm at Tabarka. The occasionally visible distal terminations resemble *Rhizocorallium*. The spreite is visible mostly only in cross section as a "bridge" between circular outlines of the limbs. This trace fossil is abundant, e.g. in the Sidi Shaieb, Ben Metir and Gassa-Msid areas. The best outcrops for its observation are in Meloula-Tabarka, Citadel, Cap-Negro, Jebel Ajout and Cap-Serrat. In some places it co-occurs with *Scolicia vertebralis*. The winding course of the burrow may have been affected by compaction or folding that has affected the Numidian Formation.

Diplocraterion cf. *habichi* was called *Tisoa* by Gottis (1954a, b). *Tisoa,* typified by *Tisoa siphonalis* Serres, 1840 from the Lower Jurassic of France, has recently been considered as an inorganic structure (Schootbrugge et al., 2010); however, it displays a U-shaped burrow and a concretionary structure surrounding as recognized by Dumortier (1869), Frey and Cowles (1969) and Häntzschel (1975). The problem needs separate studies that are beyond the scope of this paper.

In some localities (e.g., Tebaba), *D.* cf. *habichi* has been confused with *"Tubotomaculum*" leading to miscorrelation of outcrops in the Numidian thrust front (Zouza section) with those fringing the coastline in the Tabarka area (Glaçon and Rouvier, 1967; Rouvier, 1977). Beaudoin et al. (1986) called the broken fragments of *D.* cf. *habichi* "bourellets de cartouche". Generally, in the study area, *D.* cf. *habichi* occurs in two settings: commonly at the base of sand filled channels, and rarely at the top of the channel fills on overbank deposits.

Diplocraterion cf. *habichi,* sometimes described also as *D. habichi*, is a rare and poorly understood trace fossil. Gérard and Bromley (2008) referred it to transgressive and bypass surfaces in shallow-water settings down up to lower offshore. However, Gibert et al. (2001a, b) reported it from the bottom of an Eocene channel in the Ainsa Basin, Spain, and Hubbard and Shultz (2008) presented it from a basal firm ground of an Upper Cretaceous deep-sea channel fill in Chile. Also, Uchman and Cieszkowski (2008) reported this trace fossil from Oligocene thick marly turbidites, which are referred probably to a bypass surface. *Diplocraterion morgani* Fleming, 1973 from lower Miocene outer shelf mudstones in New Zealand displays the same features but is smaller (longest specimen 12 cm).

Phycosiphon hamatum (Fisher-Ooster, 1858) (Fig. 9J) is represented by (large, planar, and winding, narrow) spreite lobes, 18–60 mm wide, surrounded by a marginal tunnel that is about 4–5 mm wide. Some of the lobes are distally wider. Spreite laminae are arcuate, densely packed and filled with small oval pellets about 1 mm long. Some lobes are at least 80-300 mm long. The whole trace fossil extends for a distance of up to 450 mm. *P. hamatum* is a feeding structure that occurs in deep-sea Upper Cretaceous–Paleogene turbiditic deposits (e.g., Uchman, 1999, 2007a). It was found in the Miocene part of the Numidian Formation in Cap-Serrat at the top of thin-bedded turbidites, which most likely are levee deposits.

?*Phycosiphon* isp. (Fig. 8D) is observed as small, curved burrows, which are very thin (less than 0.5 mm in diameter), forming small, open loops penetrating sandstone beds in different directions. They resemble very small *Phycosiphon incertum* Fisher-Ooster, 1858, but poor preservation prevents a more reliable determination. *P. incertum* is produced by deposit-feeders and is common in fine-grained deep-sea and deeper shelf deposits (e.g., Wetzel and Bromley, 1994).

6. Trace fossil distribution and depositional environment

The distribution and diversity of trace fossils and composition of ichnoassemblages in the Numidian Formation vary throughout the vertical succession and laterally between areas. The most easily discernible difference exists between the lower, i.e., Oligocene (upper Rupelian–lower Chattian: P21 Zone), and the upper, i.e., lower Miocene (Aquitanian: N4 Zone of Blow, (1969)) parts of the formation.

The lower part (Zouza Member), only exposed in the Meloula-Tabarka, Bouhertma, Zouza, Sejnene and Ben Metir areas, is mostly dominated by green, grey to dark grey hemipelagic mudstones interbedded with thick- to very thick-bedded structureless sandstones and conglomerates that mostly represent the fill of channel complexes, channel-lobe transition and sheet sands (sheet sands and channel-lobe transition respectively being observed in the Meloula-Tabarka, Zouza and Sejnene sections). In this part the hemipelagic mudstones (FC5) and the heterolithic successions of thin-bedded turbidites are far the most dominant and are therefore ascribed to a mud-rich slope system (>70% mudstone and <30% sandstone).

The upper part (Kroumirie Member) is relatively sandier and commonly shows erosive sand-rich channel complexes within an overall mud-rich system. In some cases the succession can be considered a mixed mud/sand-rich system (e.g., the Needles section within the Meloula-Tabarka section).

Some trace fossils are continuously recorded in both members, including relatively abundant *Planolites montanus*, *Ophiomorpha rudis* and to a lesser extent *Scolicia vertebralis*. These, which can be considered as the permanent background components of the trace fossil assemblage. The main characteristics of the Zouza and Kroumirie members are summarized in Table 2. The hemipelagic mudstones and subsidiary glauconitic sandstones with silexites of the Babouch Member have not been investigated ichnologically in this study.

6.1. Zouza Member: Upper Rupelian─Lower Chattian

The Oligocene deposits of the Zouza Member are mainly represented by hemipelagic mudstones (FC5), heterolithic thin-bedded turbidites (FC4), subsidiary thick to very thick, structured or structureless massive sandstone units (FC2 and FC3) and conglomerates (FC1), which show a combination of different architectural elements including sheet sands, channel-lobe transition and channel complexes. These are characterised by a moderate diversity and abundance of pre- and post-depositional trace fossils. The most common include: *Paleodictyon strozzii*, *Paleodictyon majus*, *Paleodictyon latum*, *Paleodictyon italicum*, *Scolicia strozzii*, *Planolites montanus*, *Trichichnus* isp., *Urohelminthoida dertonensis*, and *Spirorhaphe involuta*, while *«Ophiomorpha» recta*, *Helminthopsis*, *Asteriacites aberensis*, *Chondrorhaphe bifida*, and *Halopoa* are rare and exclusively recognized in the Tabarka area. This trace fossil suite can be ascribed to the *Paleodictyon* ichnosubfacies of the *Nereites* ichnofacies, which is typical of «distal» turbidites, mostly in distal depositional lobes, fan fringe, or inter-channel settings in quiet oxygenated waters that are episodically interrupted by turbiditic flows (Uchman, 2007c), typically in bathyal to abyssal depths as confirmed by observation of recent traces (Chamberlain, 1975; Ekdale and Berger, 1978; Gaillard 1991; Wetzel, 2002).

The above interpretation is confirmed by an analysis of benthic foraminifera characterized by an abundance of the deep-water agglutinated foraminifera assemblages (Table 1). The species composition is virtually identical to the Mediterranean Tethyan and Carpathian flysch assemblages, corresponding to the flysch-type assemblage of Gradstein & Berggren (1981), which are characteristic of lower bathyal depths (~1000–2000 m). The assemblage shows a high content of *Rhabdammina* spp., *Paratrochamminoides* spp., *Paratrochamminoides draco*, *Glomospira charoides, Glomospira serpens*, *Ammodiscus tenuissimus*, *Haplophragmoides walteri*, *Karrerulina* spp., *Recurvoides* spp., *Saccammina placenta*, S*piroplectammina spectabilis*, *Reophax pilufier*, *Rhizammina* spp., *Hormosinella distarus*, and *Reticulophragmium amplectens*. This assemblage shows a high affinity to those of the Numidian Formation of Morocco (Kaminski et al., 1996) and the Carpathian Flysch (Kender et al., 2005). Furthermore, in the Meloula-Tabarka section, this interval is completely devoid of calcareous benthic foraminifera. This suggests that the seafloor was near or below the carbonate compensation depth (CCD), which was located at the lower bathyal to abyssal depths in comparison to the Mediterranean Tethyan and Carpathian Flysch assemblages (Kuhnt and Urquhar, 2001) (Table 2). However, the Numidian Formation of the southern margin of the Kroumirie and Mogod mountains (e.g. the Zouza (Gassa-Msid section), Sidi Shaieb, Balta and Sejnene areas) shows dominantly deep-water agglutinated foraminifera associated with calcareous benthic foraminifera and a high content of planktonic foraminifera, suggesting middle to lower bathyal depths (Table 2). This reveals N-S variation in the depositional environment during the Oligocene (i.e. between the deeper-water succession of Meloula-Tabarka and the relatively shallower-water succession of the Zouza, Sejnene and Balta areas). This distinction is also confirmed by variation in grain size between the two domains. Hence, some sand units of the Zouza Member (e.g. Oued Tassef sand unit) and Sejnene (La Krête sand unit) show a conglomeratic facies that is missing in the Meloula-Tabarka area. Nevertheless, the Oligocene deposits are not preserved in the northeastern parts of the Mogod Mountain. Their absence is probably related to tectonic ablation or major seafloor erosion in an area of slope canyons.

6.2. Kroumirie Member: Early Miocene (Aquitanian: N4 –N5 zones)

The Kroumirie Member is characterized by an increase in the contribution of turbiditic sandstones and a markedly different ichnofaunal and foraminiferal content. The trace fossil assemblage includes common *Ophiomorpha rudis*, *Diplocraterion* cf. *habichi*, *Scolicia vertebralis*, together with rare *Paleodictyon* and other graphoglyptids, noted especially in the Cap-Serrat area. This ichnoassemblage can be ascribed to the *Ophiomorpha rudis* ichnosubfacies of the *Nereites* ichnofacies, which is typical of channel fills and proximal depositional lobes (Uchman, 2007c, 2009; Wetzel and Uchman, 2010). The most intriguing is the presence of *Diplocraterion* cf. *habichi*, which is normally ascribed to transgressive and bypass surfaces in shallow-water settings (Gerard and Bromley, 2008), but occurs also at the base of deep-sea channel fills (Hubbard & Shultz, 2008) or in thick marly turbidites (Uchman and Cieszkowski, 2008). Probably, *D.* cf. *habichi* represents the shallower part of the *Ophiomorpha rudis* ichnosubfacies. Co-occurrence of *Selenichnites* and ?*Gyrochorte* also suggests a shallower environment.

The shallower environment is confirmed by analysis of foraminifers. The P/B and DWAF /C ratios indicate that foraminifera abundance and diversity both decrease concurrently with increased sand content. The faunal content can be considered a "Flysch-type Fauna" sensu Gradstein and Berggren (1981) and Kaminski et al. (1989) and therefore attests an upper bathyal depth (~200–600 m). This is well recognised in the Sidi Shaieb, Zouza and Tabarka areas, while in the Cap-Serrat section, horizons with exclusively deep-water agglutinated foraminifers alternate with horizons rich in calcareous and planktonic horizons.

As for the Oligocene time, the early Miocene Numidian succession is also marked by variation in depositional environment between areas [this is evidenced by facies variation between the early Miocene], e.g., the Numidian successions of Ras El Korane and Jebel Gattous-Zoukar (NW of Bizerte area) as compared to those of Tabarka, Cap-Negro and Cap-Serrat.

The grain size variation and distribution among the Numidian Formation outcrops indicates that the early Miocene Numidian succession of the northeastern Mogod Mountain (Ras El Korane, Jebel Gattous-Zoukar and Ras El Ali) have more proximal characteristics than those seen in Cap-Serrat and Meloula-Tabarka sections. The sandstone bodies of the Ras El Korane area are dominated by matrix-supported conglomeratic facies containing a high proportion of pebbles and common outsized blocks of glauconitic sandstone as well as reworked rock fragments of Tellian affinity (Ypresian limestones and glauconitic sandstones of the autochthonous Oligocene). Also, prominent cut- and -fill events are very evident in channel complexes of the Ras El Korane and Jebel Gattous-Zoukar sections, suggesting channel areas with common sediment bypassing compatible with a probable slope canyon interpretation. Nevertheless, in the Cap-Serrat and Tabarka sections, the sediments are generally medium-grained within migrating channel complexes. Additionally, unlike the Cap-Serrat and Tabarka sections, the trace fossils of Ras El Korane are of lower diversity represented only by *Scolicia vertebralis* and *Ophiomorpha rudis*.

7. Discussion

7.1. Vertical variation within the Numidian Formation

The notable switch in trace fossils and foraminifers recorded between the Oligocene and the lower Miocene parts of the Numidian Formation suggests a shallowing-upward trend. Hence the evolution from the *Paleodictyon* ichnosubfacies to the *Ophiomorpha* ichnosubfacies within the *Nereites* ichnofacies expresses a bathymetric trend from deeper (lower bathyal) to shallower (upper bathyal) parts of slope to deep-sea fan systems. This shallowing trend is a general characteristic of foreland basins as recognised worldwide. We propose the Meloula-Tabarka section can be used as a type-section illustrating the variation in depositional environment between the Oligocene and the early Miocene epochs. The shallowing trend during the early Miocene is progressive, tending to be well expressed at the top of sections which is generally sandier. Although we have not studied in detail the uppermost Babouch Member, it appears that this may represent subsequent transgression and a return to deeper-water conditions, at least locally.

The low diversity and density of trace fossils and foraminifera in the channelized sandstones of the early Miocene appear to be related to several factors including sand content and gravity flow. The increase in sand content implies greater energy levels and environmental disturbance unsuitable for organisms to survive and proliferate. These conditions are more suitable for the trace maker of *Diplocraterion* cf. *habichi*, which is associated with bypassing surfaces, not only in the shallow sea but also in the deeper sea. Also, in these environments, sediment gravity flows are generally more erosive and, therefore tend to remove the fertile top layer of the sea floor, which is a habitat for most of the ichnofauna forming predepositional trace fossils (e.g. Kern, 1980). Due to heavier erosion only the deepest burrowing trace fossils, e.g., *Halopoa*, *Scolicia* and *Ophiomorpha*, which were formed by large, robust, deeply burrowing organisms that could exploit organic-rich layers within the sands and were well-adapted to surviving burial by newly deposited thick sand beds (Wetzel and Uchman, 2001). Moreover, *Scolicia*, which is responsible for commonly intensive bioturbation of finer-grained intervals, overprinted an older ichnofabric (e.g., at Sidi Shaieb, Cap-Serrat and Ras El Korane) formed by smaller and diverse traces.

7.2. Relationship between trace fossils and architectural elements

The trace fossil assemblage throughout the Numidian Formation is typical of the deep-sea *Nereites* ichnofacies, with the general vertical distinction between the *Paleodictyon* ichnosubfacies in the Oligocene part (Zouza Member) and the *Ophiomorpha rudis* ichnosubfacies in the Miocene part (Kroumirie Member). Some of this distinctive distribution of trace fossils can be referred to the interpreted facies and architectural elements of the depositional system (Fig. 11).

7.2.1. Submarine channels

Sand-rich intervals (FC1, FC2 facies)

The topmost part of the Kroumirie Member of the Numidian Formation represents sand-rich and high-energy deposition. It is dominated by channel fill facies that include the

Ophiomorpha rudis ichnosubfacies. The ability to penetrate great thicknesses of sediment is considered to be an adaptation of the animal to exploit deeply-buried organic carbon-rich inter-turbidite mudstones. In some ways, this study sheds light on the water depth of the structureless massive sandstones, whose depositional environment is a matter of debate (Stow & Johansson, 2000). In the case of the Numidian Formation, the deep-water massive sandstones including the structureless massive sandstones and the structured sandstone facies classes were deposited in the variable depositional environment, oscillating between upper to lower bathyal settings.

Mudstones (FC4 facies) at the base of submarine channels

Deep-tiers of *Diplocraterion* cf. *habichi* are common within mudstone facies just below the channel fill (Fig. 11A–D). They are especially abundant at bypass surfaces within the channel axis and proximal margin (e.g., at Cap-Serrat, Tabarka and Jebel Ajout in Sejnene area). This is related to variations in hydrodynamic energy, seawater oxygenation and nutrient supply in that setting (Fig. 11D). The fine-grained sediments colonized by *Diplocraterion* cf. *habichi* are overlain by medium to coarse-grained sandstones and conglomerates. The vertical to oblique burrows are filled with medium grained sandstone comparable to the lithology of the overlying beds. As stated by Callow et al. (2014) the depth of the burrows (>1.80 m deep), their sharp margins and sandstone fill indicates that they were kept as open burrows during the lifetime of the organism and demonstrates the rigid and cohesive nature of the mudstone during colonization.

7.2.2. Levee and interchannel

Levee deposits and interchannel deposition are represented by interbedded millimeter-to centimeter-thick alternations of very fine sandstone, siltstone and mudstone forming heterolithic units (Fig. 11G) and showing common to pervasive bioturbation. The background ichnofauna is represented by *Scolicia vertebralis*, *Phycosiphon hamatum* and *Planolites montanus. Diplocraterion* cf. habichi has been also observed colonizing overbank deposits in Sidi Shaieb section (Fig. 4).

7.2.3. **Channel lobe-transition and lobes**

Sheet-like graded sandstones, medium to thick-bedded sandstones representing the lobe deposits have been noted in Cap-Serrat and Tabarka (Fig.11E, F). They are marked by a wide variety of trace fossils including feeding structures (e.g., *Halopoa* isp.), grazing trace fossils (*Scolicia strozzii*), and graphoglyptids, including *Spirorhaphe* isp., ?*Cosmorhaphe* isp. and *Paleodictyon strozzii.*

7.3. Variation of the depositional setting between areas

The integration of ichnological, sedimentological and microfossil evidence can be used to observe trends between the different study areas along N-S and NE-SW transects. This allows distinction of two quite different depositional settings of the Numidian succession, both of which show a shallowing-upward tendency.

The first domain includes the Numidian succession of the Tabarka, Cap-Negro, Cap-Serrat and Bouhertma sections showing the *Paleodictyon* ichnosubfacies corresponding to lower bathyal depths (slope or base of the slope) during Oligocene and to upper bathyal depths (upper slope) during the early Miocene.

The second domain includes northeastern part of the Mogod Mountain (e.g., Ras El Korane, Jebel Gattous-Zoukar and Jebel Sebaâ) which exhibit the more proximal characteristics compatible with a probable slope canyon interpretation. The southern margin of the Kroumirie and Mogod mountains (e.g., Zouza, Balta and Sejnene) shows a distal setting comparatively to the Ras El Korane, Jebel Gattous-Zoukar, but relatively less deep than the Cap-Serrat and Tabarka areas. Deposition was the middle to upper slope during the Oligocene and the upper slope during the early Miocene. The occurrence of *Paleodictyon* ichnosubfacies in the Bouhertma area reinforces this interpretation.

This differentiation is also correlated with facies occurrence and channel types between the two domains. The domain extending from Ras El Korane, Jebel Gattous-Zoukar, Jebel Sebaâ eastward to Ras El Ali, and Jebel Oum Tabel southwestward (Fig. 1) is dominated by erosional channel complex types showing wide erosional surfaces that truncate bedding (best known in the Ras El Korane and Jebel Gattous-Zoukar areas). Such surfaces bound a generally repeatable progression of facies with very coarse-grained sandstones and conglomerates (FC1) overlain by thickly stacked massive sandstones (FC2 and FC3). They are separated vertically by variably thick mudstone units (20–200 m) with isolated thin turbidite deposits (FC4). The conglomeratic facies (FC1) recorded in the Ras El Korane, Jebel Gattous-Zoukar, Jebel Sebaâ and Ras El Ali areas are similar to the bypass facies of Lowe (1982), and hence probably represent proximal deposition of very coarse-grained bedload from hyperconcentrated bipartite turbidity currents. The repetition of a fining-upwards facies trend separated by incised surfaces (e.g. stacked channel elements), signifies the repeated switching from bypass to fill within each channel-complex. Overall facies characteristics and the erosional channel complexes with the *Ophiomorpha rudis* ichnosubfacies of the *Nereites* ichnofacies are typical of proximal upper slope locations or a tectonically uplifting slope environment (e.g., Mayall et al., 2010).

The domain, including the Cap-Serrat, Cap-Negro and Tabarka areas, shows sheet sandstones and more depositional, aggradationally stacked channel complexes, which are characteristic of a low-grade, lower slope environment where the facies are dominated by fine to medium structureless massive sandstones (FC2) and structured sandstones (FC3). The conglomerate facies rarely occurs, as clearly noted by quantitative facies analysis for all areas and sections (Fig.12). This domain contains the *Paleodictyon* ichnosubfacies with a trace fossil suite that includes *Paleodictyon strozzii*, *P. majus*, *P. latum*, *Scolicia strozzii*, *Planolites montanus*, *Trichichnus* isp., *Urohelminthoida dertonensis*, and *Spirorhaphe involuta*, with *"Ophiomorpha" recta*, *Helminthopsis*, *Asteriacites aberensis*, *Chondrorhaphe bifida* and *Halopoa* only in Oligocene strata, and the *Ophiomorpha* ichnosubfacies within the *Nereites* ichnofacies only in the Miocene. The occurrence of *Paleodictyon* in Cap-Serrat among other types in the early Miocene indicates also the more distal position of this succession comparatively to Sejnene, Ras el Korane and Jebel Gattous. These results accord in partly with Wezel, (1968) who stated that the Numidian Formation outcrops of Tabarka and Cap-Negro correspond to basin facies. Nevertheless, the occurrence of *Paleodictyon* ichnosubfacies in Bouhertma area doesn't fit with a proximal position of the Numidian Formation outcrops of the southern margin of the Kroumirie Mountain as already stated by Wezel, (1968) and recently by Belayouni et al., (2012).

8. Impact of ichnofacies analysis on the Numidian Formation provenance debate

In the light of the present study, some comments on the Numidian Basin configuration can be made and consideration given to the ongoing debate on the provenance of the Numidian Formation sediments.

In the present work, the integration of ichnological and sedimentological data has led to the distinction of two domains, with the deeper one being confined to Tabarka, Cap-Negro Cap-Serrat and Bouhertma outcrops and the shallower to the NE of Mogod Mountain (i.e. Ras El Korane, Jebel Zoukar-Jebel Gattous sections). However, this scenario does' not accord with the palaeocurrent directions advanced in our earlier papers (Fildes et al., 2010; Riahi et al., 2010, 2011), in which we advocate a north to south dispersal pattern.

Additional paleocurrent measurements at Cap-Serrat, Ras El Korane and Jebel Zoukar-Jebel Gattous (NE part of Mogod Mountain) indicate prominent NE and E-W directed paleocurrent and confirm the detailed work of Hoyez, (1989). Facies and quantitative facies analyses also show a marked difference between the two domains. Hence the Numidian succession of the NE Mogod Mountain (e.g. Ras El Korane, El Garn, Jebel Zoukar-Jebel Gattous, Jebel Sebaâ and Ras El Ali) is marked by erosive channel facies types and widespread occurrence of conglomeratic facies including clasts of Tellian affinity (Ypresian limestones, outsized iron clasts and glauconitic sandstones of the autochthonous Oligocene). This is more compatible with bypass of the slope canyon. This conglomeratic facies or bypass zone has an E-W trend through the Mogod Mountain and extends from Ras El Korane to the Nefza Window (Fig. 12). Moreover, it tends to disappear in the Cap-Serrat and Sejnene sections. This fact explains the proximal position of the Ras El Korane, Jebel Gattous - Jebel Zoukar sections in comparison to the Cap-Serrat and Tabarka sections and also to Sejnene, Zouza and Bouhertma areas.

In the present work, the Numidian Formation was compared to a slope-apron system. In these systems the more proximal parts are generally more sand-prone, whereas the distal parts become more mud-prone. Nevertheless, the quantitative facies analysis undertaken between the Numidian succession fringing the coast (Cap-Serrat) and that on the Numidian front (e.g. Sejnene and Zouza areas) demonstrates no clear differentiation in terms of sand/shale content; all are mud-prone and can be ascribed to mud-rich slope systems. Both successions contain small amounts of conglomeratic facies in comparison with the NE of the Mogod Mountain. In other words, there appears to be a clear E-W differentiation (confirmed by the occurece of *Paleodictyon* ichnosubfacies in Numidian Formation outcrops fringing the costiine and those of the nappe front (Bouhertma)) rather than N-S differentiation as previously advanced (El Maherssi,1992; Riahi, 2011).

This facies distinction does not fit with the recorded paleocurrent directions in the Tabarka section, which are commonly from the north (Parize, 1986; El Maherssi, 1992; Yaïch, 1997; Riahi, 2011). The Numidian succession extending from Meloula to Needles (Tabarka town) shows a high angle dip to overturned strata. The N-S orientation of these structures is somewhat anomalous compared to the larger NE-SW structures that resulted from NW-SE compression during the Serravalian–Tortonian phase. Therefore, it would appear that this area has undergone a left-rotation, either during nappe emplacement or at a later stage.

Taking into account the possibility of rotation of the Numidian Formation blocks, a palaeomagnetic study is highly recommended to test this assumption and help resolve the debate on the provenance of the Numidian Formation.

9. Conclusions

Twenty-two ichnogenera and thirty-one ichnospecies were recorded in the Oligocene-early Miocene Numidian Formation of northern Tunisia. Integration of ichnological, sedimentological and microfossil studies have permitted characterisation of depositional and palaeoenvironmental conditions, and their variation both regionally and temporally.

The Zouza Member (e.g., the Oligocene in the Tabarka area) is characterised by the *Paleodictyon* ichnosubfacies of the *Nereites* ichnofacies (*Paleodictyon*, *Halopoa* and *Scolicia*) and was deposited in a slope or base-of-slope setting. The Kroumirie Member (e.g., lower Miocene at Tabarka [Needles], Citadel, Zouza, Ben Metir, and Cap-Serrat) displays the *Ophiomorpha rudis* ichnosubfacies of the *Nereites* ichnofacies (e.g., *Diplocraterion* cf.

habichi, *Ophiomorpha rudis*, *Scolicia vertebralis*), which corresponds to an upper slope depositional setting. This notable switch in ichnofauna between the Oligocene and Miocene implies shallowing-upward trend through the Numidian Formation, as also attested by a general decrease in abundance and diversity of foraminifera, coincident with increased sand content implying greater energy levels and environmental disturbance.

The distinction of two quite different geographical depositional settings of the Numidian Formation is also noted. The first domain includes the Numidian succession of Tabarka, Cap-Negro and Cap-Serrat showing the *Paleodictyon* ichnosubfacies corresponding to a lower bathyal depths (slope or base of the slope) during Oligocene and to the upper bathyal depths (upper slope) during the early Miocene. The second domain includes the NE part of Mogod Mountain (e.g. the Ras El Korane, Jebel Gattous-Zoukar) which exhibit more proximal characteristics compatible with a probable slope canyon interpretation. The southern margin of the Kroumirie (Balta, Zouza areas) and Sejnene area shows a more distal setting than that of Ras El Korane and Jebel Gattous-Zoukar, and is referred to a mid-to upper slope depositional setting during the Oligocene to early Miocene. The ichnological method used here has the potential to improve palaeoenvironmental analysis of other parts of both the Numidian Formation in Algeria, Morocco, Spain and Italy, as well as of deep-marine turbidite systems in general.

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Figure captions

Fig. 1. Geographic distribution and geodynamic context of the Numidian Formation. A. Location map showing the distribution of the Numidian Formation across the Western Mediterranean region (Hoyez, 1989). B. Oligocene (Rupelian) palaeogeographic map of the western Mediterranean highlighting the Numidian Formation at time of deposition and its time equivalent deposits .Map redrawn from Meulenkamp and Sissingh (2003).The AlKaPeCa block is redrawn from Thomas et al. (2012). Abbreviations: B=Betic, R,=Riff, Cs – Corsica, Sa – Sardinia, Ca/P – Calabria and Peloritan, G – Galite Block, Pka – Petit Kabylie, Gka – Grand Kabylie. C. Distribution of the Numidian Formation in northern Tunisia (Rouvier, 1977). The zones with light grey stars correspond to the main areas in which were recorded the trace fossils.

Fig. 2. Stratigraphy of the Numidian Formation in the northern Tunisia. In this scheme the lower part or Zouza Member of the Numidian Formation (Oligocene) is a shale-dominated while its upper part or Kroumirie Member (lower Miocene) is sandstone-dominated. This subdivision is easily recognised in outcrops of the Numidian Formation in northern Tunisia.

Fig. 3. Stratigraphic subdivision of the Numidian Formation in the northern Tunisia and along the Western Mediterranean area. **1:** Shales with subsidiary sandstones (lower member); **2:** Sand-dominated and channelized deposits (middle member), **3:** Silexites.

Fig. 4. The stratigraphic position and abundance of trace fossils through the Numidian Formation in the Tabarka, Cap-Serrat, Zouza and Sidi Shaieb areas. One open circle indicates that ichnospecies is present but not abundant, while double circles indicate high abundance.

Fig. 5. Circular and elliptical and some simple and branched structures. Field photographs. A. *Asteriacites aberensis,* hypichnion in a sandstone bed. Meloula-Tabarka section. B. *Cardioichnus* isp. and *Planolites montanus* (*Pl*), hypichnia in a sandstone bed. Sidi Shaieb section. C. *Cardioichnus* isp., hypichnia in a sandstone bed. Sidi Shaieb section. D. *Selenichnites* isp., epichnia in a sandstone bed. Sidi Shaieb section. E. *Paleodictyon majus* and plug-shaped form (pl). Meloula-Tabarka section. F. *Archaeonassa* isp., epichnia in a sandstone bed. Sidi Shaieb section. G. ?*Chondrites* isp. (*Ch*) and *Planolites* isp. (*Pl*), including *Planolites* isp. reworked by ?*Chondrites* isp. (*Pl+Ch*), endichnia on smoothed surface of a mudstone bed, Meloula-Tabarka section.

Fig. 6. Simple and branched structures. All are hypichnia in sandstones. A. *Chondrorhaphe bifida,* Meloula-Tabarka section. B. *Halimedides* isp., Cap-Serrat section. C–E. *Halopoa* isp., Meloula-Tabarka section. F. *Ophiomorpha rudis,* Cap-Serrat section.

Fig. 7. Other simple and branched structures. A. *Ophiomorpha rudis* crossing vertically a few muddy turbidite beds, Cap-Serrat section. B. *Ophiomorpha rudis*- hypichnial dense burrow system in a sandstone bed, Ras El Korane section. C. *Ophiomorpha annulata,* endichnion in loose sandstone block. Cap-Serrat section. D. Fragments of “*Ophiomorpha*” *recta*, endichnia from mudstones, Meloula-Tabarka section. E. "*Ophiomorpha*" *recta,* endichnion in a sandstone bed, Meloula-Tabarka section. F. *Planolites montanus*, hypichnia in a sandstone

bed. Sidi Shaieb section. G. *Trichichnus* isp., endichnion in mudstone. Meloula-Tabarka section.

Fig. 8. Winding and meandering ichnofacies types in sandstone beds. A. ?*Cochlichnus* isp., hypichnia. Sidi Shaieb section. B. ?*Cosmorhaphe* isp., hypichnion. Cap-Serrat section. C. ?*Gyrochorte* isp. (*Gy*) and ?*Planolites* isp. (*Pl*), epichnia. Sidi Shaieb section. D. ?*Gyrochorte* isp. (*Gy*) and ?*Phycosiphon* isp. (*Ph*), epichnia. Sidi Shaieb section. E. *Helminthopsis* isp., hypichnion. Sidi Shaieb section. F, G. *Scolicia vertebralis,* epichnia. Sidi Shaieb section. H. *Scolicia strozzii,* hypichnion. Meloula-Tabarka section.

Fig. 9. Branched winding and meandering structures, spirals, networks and some spreite structures in sandstones, preserved as hypichnia (A–I) or epichnia (J). A. *Urohelminthoida dertonensis*, Meloula-Tabarka section. B. *Helicolithus ramosus*. Cap-Serrat section. C. *Spirorhaphe involuta*, *Paleodictyon strozzii* (*Ps*) and *Paleodictyon majus* (*Pm*). Meloula-Tabarka section. D. *Paleodictyon latum*. Meloula-Tabarka section. E. *Paleodictyon strozzii*. Meloula-Tabarka section. F. *Paleodictyon majus*. Meloula-Tabarka section. G. *Paleodictyon majus* and plug-shaped form (pl). Meloula-Tabarka section. H. *Paleodictyon majus* and *Scolicia strozzii* (*Ss*). Meloula-Tabarka section. I. *Paleodictyon italicum*. Bouhertma section. J. *Phycosiphon hamatum* (*Ph*). Cap-Serrat section.

Fig. 10. *Diplocraterion* cf. *habichi*. All endichnia. A. Vertical form in mudstone. Cap-Serrat section. B. Twisted oblique form penetrating below a sandstone bed. Tabarka-Needles. C. Horizontal section on surface of sandstone bed. Tabarka-Needles. D. Twisted form along upper surface of sandstone bed. Sidi Shaieb section. E. Horizontal section on surface of sandstone bed. Sidi Shaieb section. F. Subhorizontally inclined form below a massive

sandstone bed, Jebel Saouania, east of Jebel Zouza. G. Cracked sand-filled marginal tunnel in mudstone. Tabarka.

Fig. 11. A. Base of channel fill sequence eroding the underlying mudstones, which are burrowed with *Diplocraterion* cf. *habichi*. Cap-Serrat section. B. Channel fill deposits overlying mudstones and thin-bedded turbidites, which are burrowed with *Diplocraterion* cf. *habichi*. Cap-Serrat section. C. Channel fill deposits showing *Diplocraterion* cf. *habichi*, reworked within shale clasts. Ras El Korane section. D. A 3D schematic model of the three channel complexes forming the base of Cap-Serrat section. The relationship between architectural elements and the occurrence of *Diplocraterion* cf. *habichi* is highlighted. Note that *Diplocraterion* cf. *habichi* are common within mudstone facies just below the channel fill. Their especial abundance is at bypass surfaces within the channel axis and proximal margin. In some cases *Diplocraterion* cf. *habichi* occur in position between storeys. E. Thickening upward package of sandstone-mudstone beds interpreted as depositional lobe. *Paleodictyon* occurs in some beds. Cap-Serrat section. F. Large bedding surfaces containing *Paleodictyon* and *Halopoa*. Meloula-Tabarka section. G. Thin-bedded turbidites (Levee and or isolated turbidity flow) with the upper surfaces intensively bioturbated with *Scolicia vertebralis*. Cap-Serrat section.

Fig. 12. Quantitative facies analysis showing the dominance of conglomeratic facies in the NE part of the Mogod Mountain (i.e. from Ras El Korane, Jebel Gattous-Zoukar to Ras El Ali and Jebel Oum Tabel). The paleocurrent direction is in major cases from the NE and E (some data redrawn from Hoyez, 1989).

Table captions

Table 1. Geographic location of recorded trace fossils and information on the outcrops hosting specimens.

Table. 2. Trace fossils, Benthic and planktonic foraminifera ratios (planktonic (P)/benthic (B) and deep-water agglutinated benthic foraminifera (DWAF)/Calcareous foraminifera (C) ratios) of each epoch of the Numidian Formation sedimentation. Facies and architectural elements are also indicated.

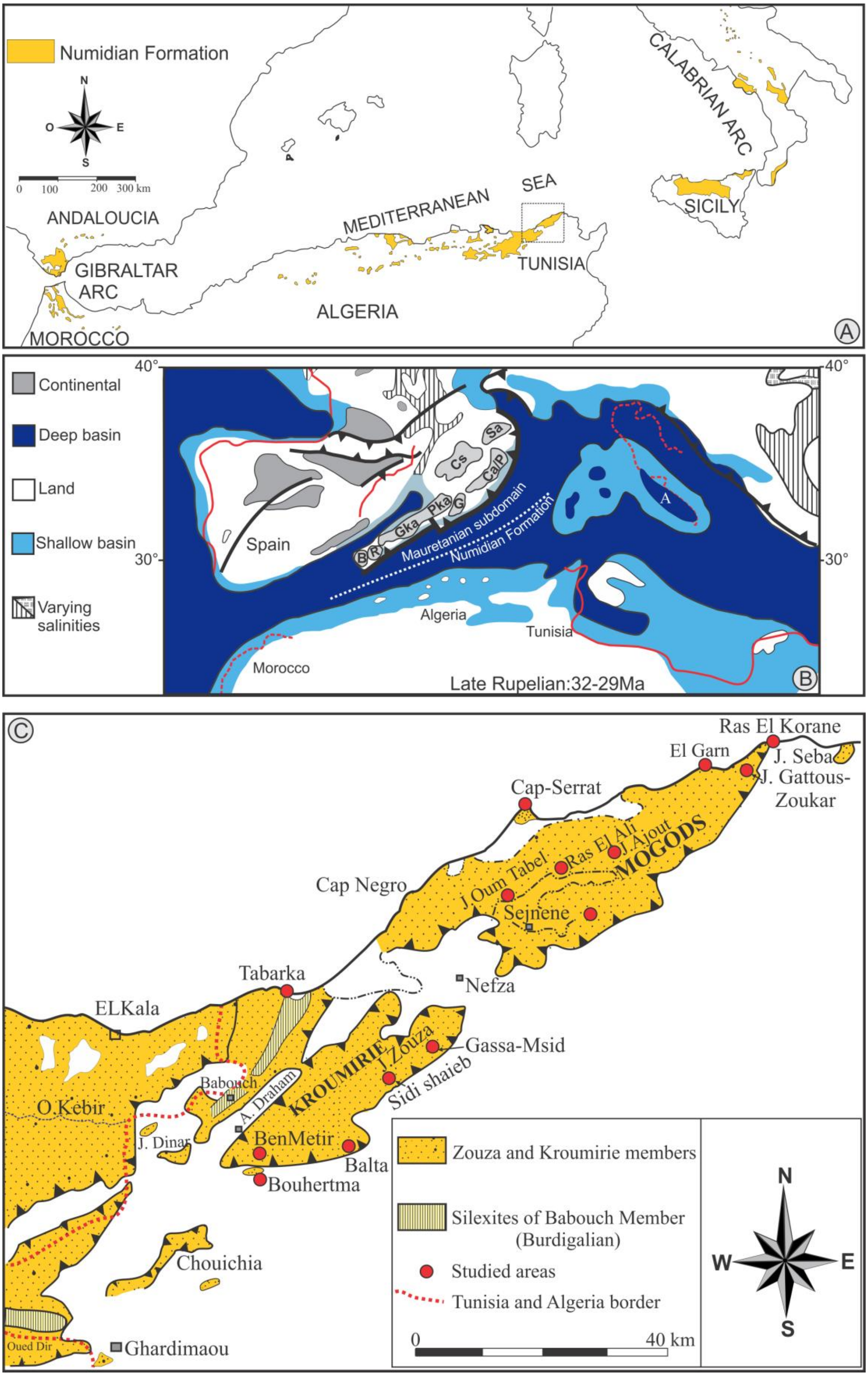
Numidian Formation
N
O
E
S
0 100 200 300 km
ANDALOUCIA
GIBRALTAR ARC
MOROCCO
ALGERIA
MEDITERRANEAN SEA
TUNISIA
CALABRIAN ARC
SICILY
A
Continental
Deep basin
Land
Shallow basin
Varying salinities
40°
30°
Spain
Sa
Cs
CalP
Pka
G
Gka
B
R
Mauretanian subdomain
Numidian Formation
Algeria
Tunisia
Morocco
A
Late Rupelian:32-29Ma
B
C
Ras El Korane
El Garn
J. Seba
J. Gattous-Zoukar
Cap-Serrat
Ras El Ali
J.Ajout
MOGODS
J.Oum Tabel
Sejnene
Cap Negro
Nefza
Tabarka
ELKala
Gassa-Msid
J. Zouza
KROUMIRIE
Sidi shaieb
Babouch
A. Draham
O.Kebir
J. Dinar
BenMetir
Balta
Bouhertma
Chouichia
Oued Dir
Ghardimaou
Zouza and Kroumirie members
Silexites of Babouch Member (Burdigalian)
Studied areas
Tunisia and Algeria border
0
40 km
N
W
E
S

Figure 1

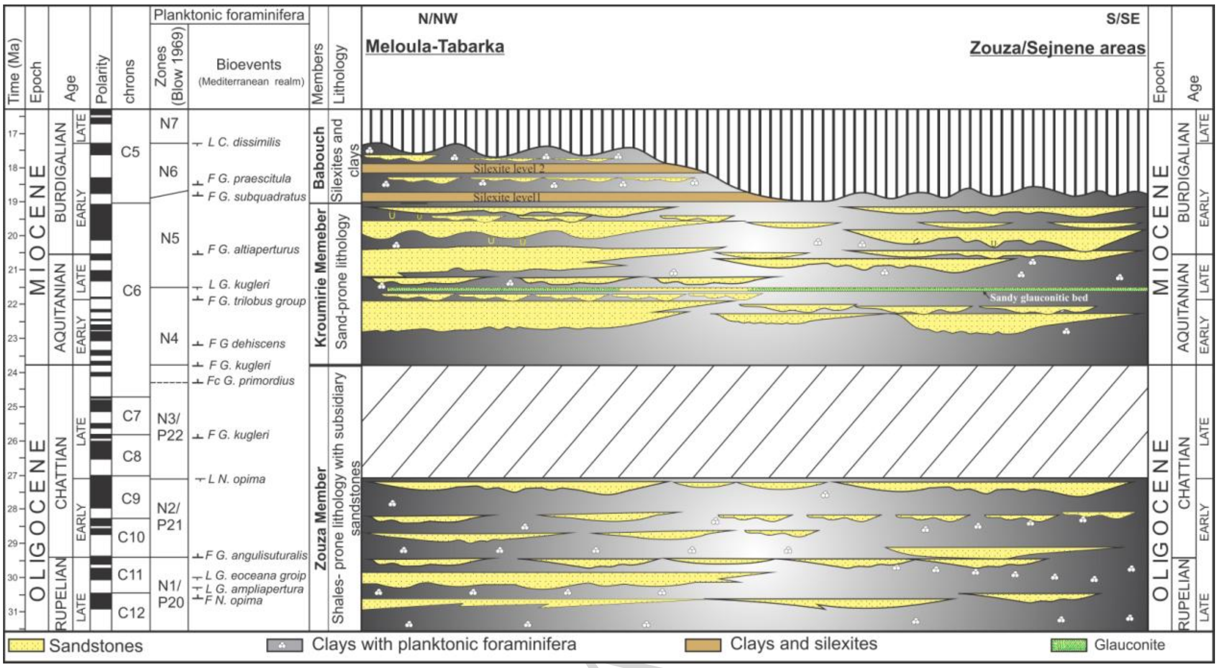
Time (Ma)
Epoch
Age
Polarity
chrons
Planktonic foraminifera
Zones (Blow 1969)
Bioevents (Mediterranean realm)
Members
Lithology
N/NW
S/SE
Meloula-Tabarka
Zouza/Sejnene areas
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
MIOCENE
OLIGOCENE
BURDIGALIAN
AQUITANIAN
CHATTIAN
RUPELIAN
LATE
EARLY
C5
C6
C7
C8
C9
C10
C11
C12
N7
N6
N5
N4
N3/ P22
N2/ P21
N1/ P20
L C. dissimilis
F G. praescitula
F G. subquadratus
F G. altiaperturus
L G. kugleri
F G. trilobus group
F G dehiscens
F G. kugleri
Fc G. primordius
F G. kugleri
L N. opima
F G. angulisuturalis
L G. eoceana groip
L G. ampliapertura
F N. opima
Babouch
Silexites and clays
Kroumirie Memeber
Sand-prone lithology
Zouza Member
Shales- prone lithology with subsidiary sandstones
Silexite level 2
Silexite level1
Sandy glauconitic bed
Sandstones
Clays with planktonic foraminifera
Clays and silexites
Glauconite

Figure 2

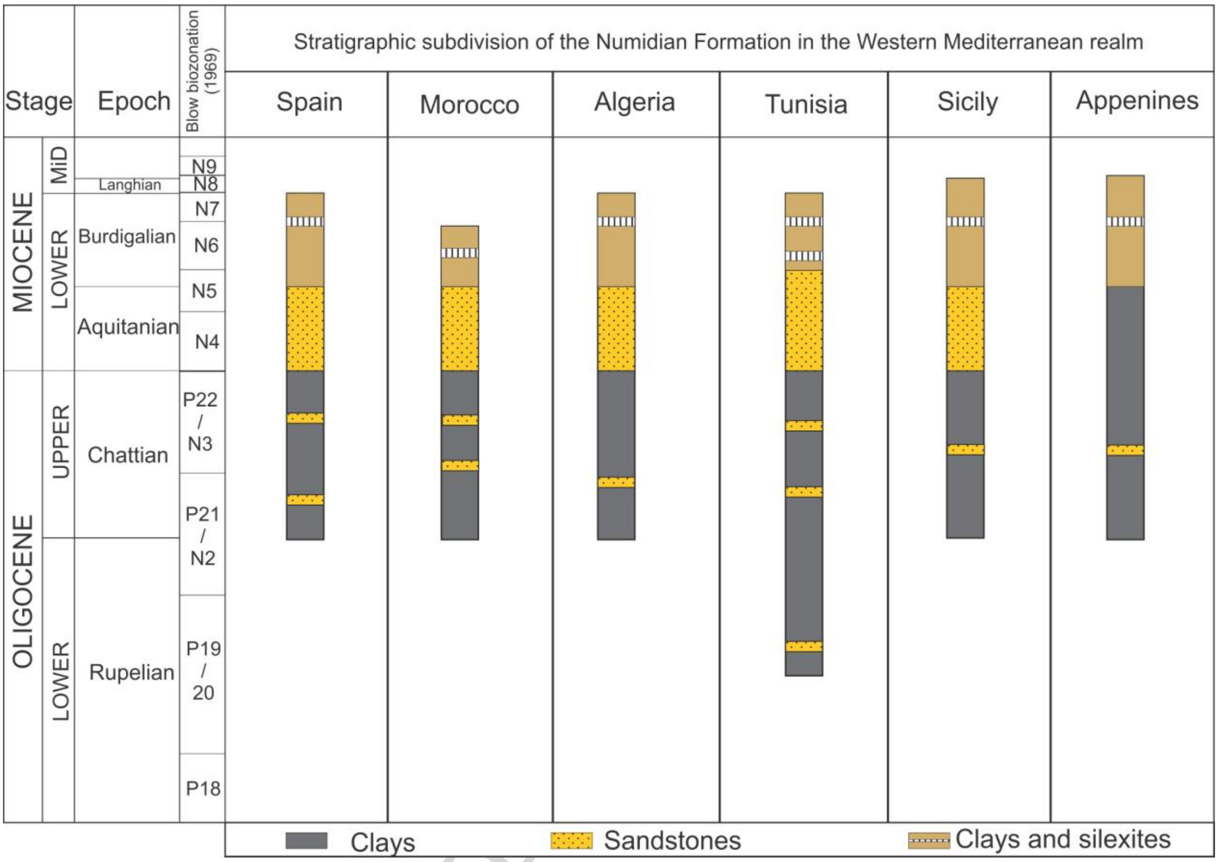
Stage
Epoch
Blow biozonation (1969)
Stratigraphic subdivision of the Numidian Formation in the Western Mediterranean realm
Spain
Morocco
Algeria
Tunisia
Sicily
Appenines
MIOCENE
MiD
LOWER
Langhian
Burdigalian
Aquitanian
N9
N8
N7
N6
N5
N4
OLIGOCENE
UPPER
LOWER
Chattian
Rupelian
P22 / N3
P21 / N2
P19 / 20
P18
Clays
Sandstones
Clays and silexites

Figure 3

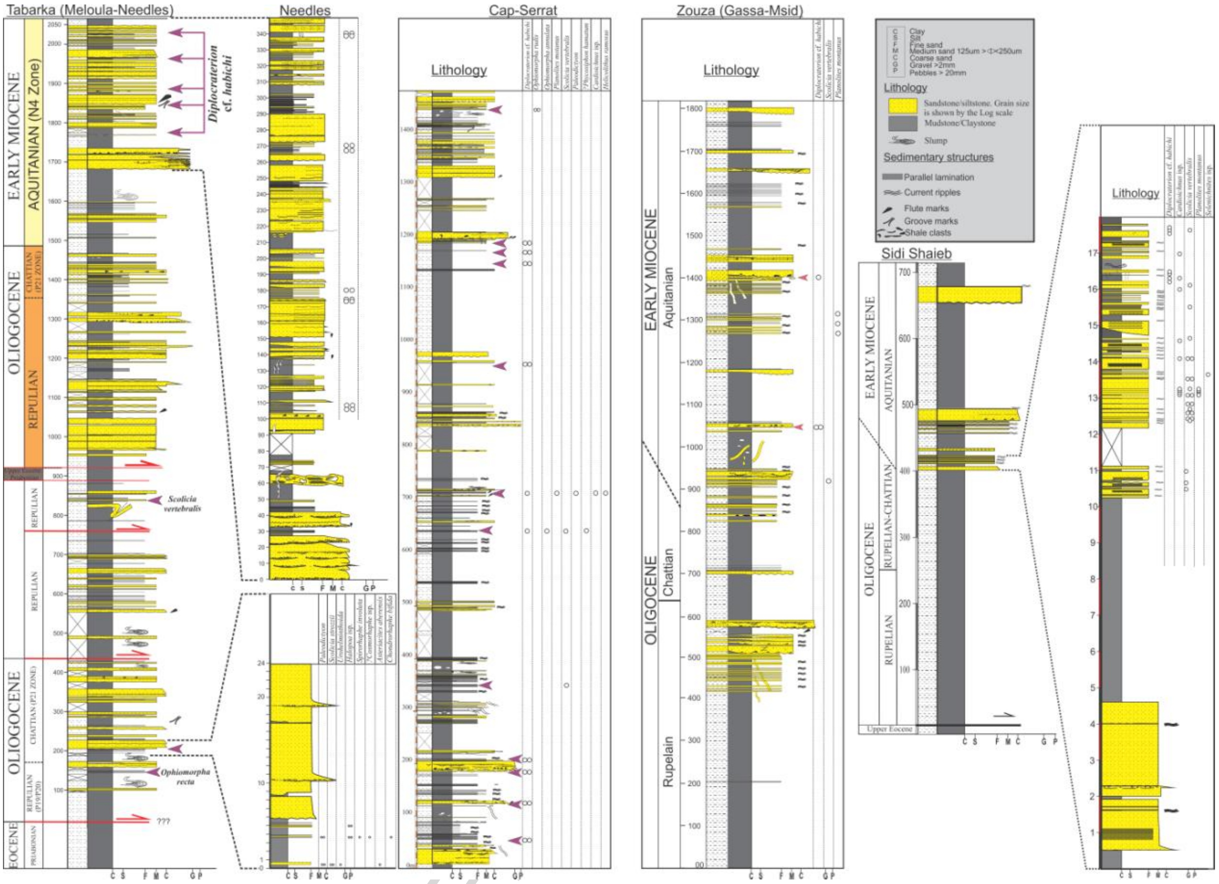
Tabarka (Meloula-Needles)
EARLY MIOCENE
AQUITANIAN (N4 Zone)
OLIGOCENE
CHATTIAN (P21 ZONE)
REPULIAN
CHATTIAN (P22 ZONE)
REPULIAN (P19/P20)
EOCENE
PRIABONIAN
Diplocraterion cf. habichi
Scolicia vertebralis
Ophiomorpha recta
???
C S F M C G P
Needles
C S F M C G P
Paleodictyon
Scolicia strozzii
Urohelminthoida
Halopoa isp.
Spirorhaphe involuta
?Cosmorhaphe isp.
Asterosoma oberentis
Chondrorhaphe bifida
Cap-Serrat
Lithology
Diplocraterion cf. habichi
Ophiomorpha rudis
Ophiomorpha annulata
Planolites montanus
Scolicia vertebralis
Paleodictyon
?Phycosiphon hamatum
Cardioichnus isp.
Helicolithus ramosus
C S F M C G P
Zouza (Gassa-Msid)
Lithology
EARLY MIOCENE
Aquitanian
OLIGOCENE
Chattian
Rupelain
Diplocraterion cf. habichi
Scolicia vertebralis
Planolites montanus
C S F M C G P
C
S
F
M
C
G
P
Clay
Silt
Fine sand
Medium sand 125um >Φ<250um
Coarse sand
Gravel >2mm
Pebbles > 20mm
Lithology
Sandstone/siltstone. Grain size is shown by the Log scale
Mudstone/Claystone
Slump
Sedimentary structures
Parallel lamination
Current ripples
Flute marks
Groove marks
Shale clasts
Sidi Shaieb
EARLY MIOCENE
AQUITANIAN
OLIGOCENE
RUPELIAN-CHATTIAN
RUPELIAN
Upper Eocene
C S F M C G P
Lithology
Diplocraterion cf. habichi
Cardioichnus isp.
Scolicia vertebralis
Planolites montanus
Selenichnites isp.
C S F M C G P

Figure 4

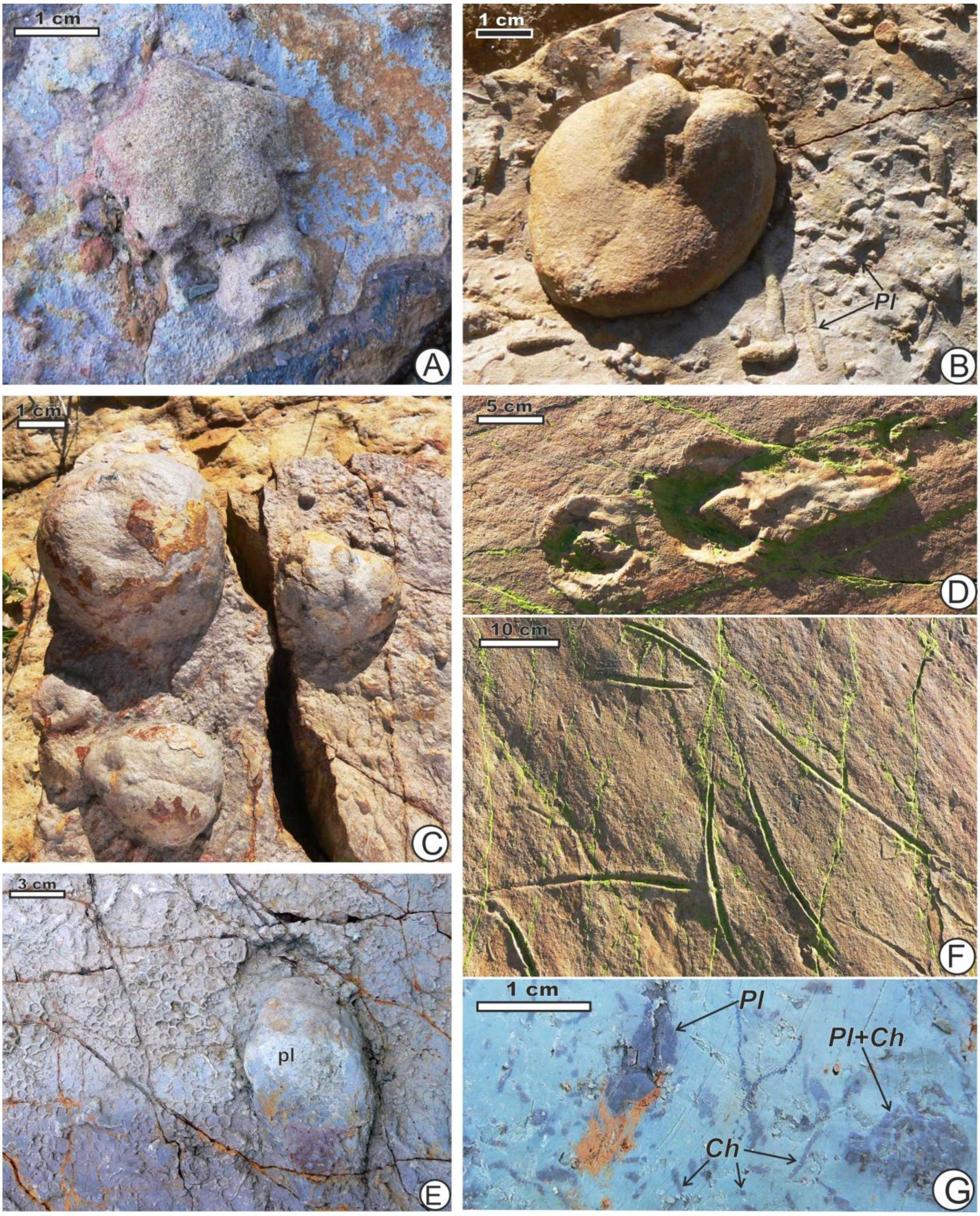

Figure 5

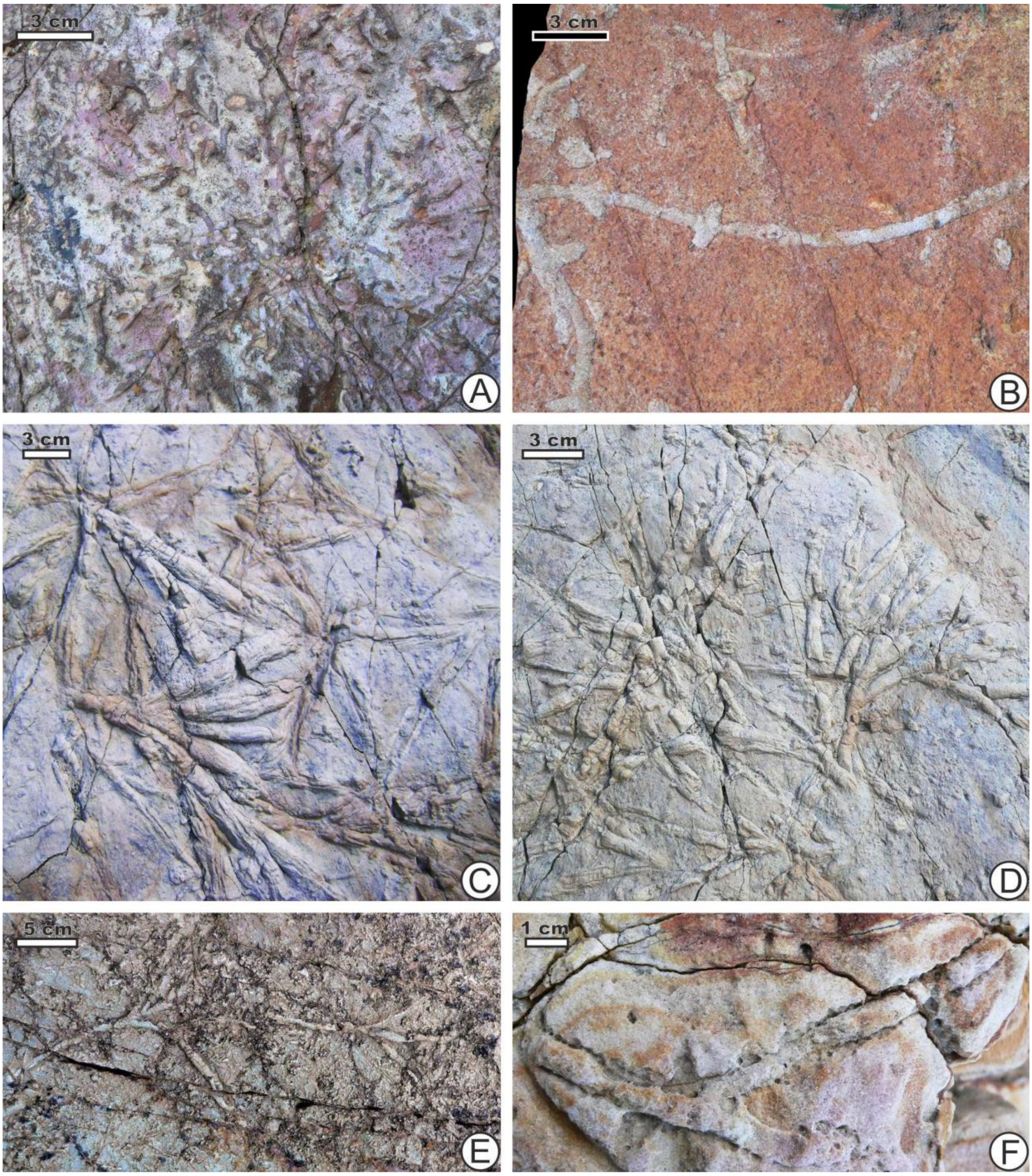

Figure 6

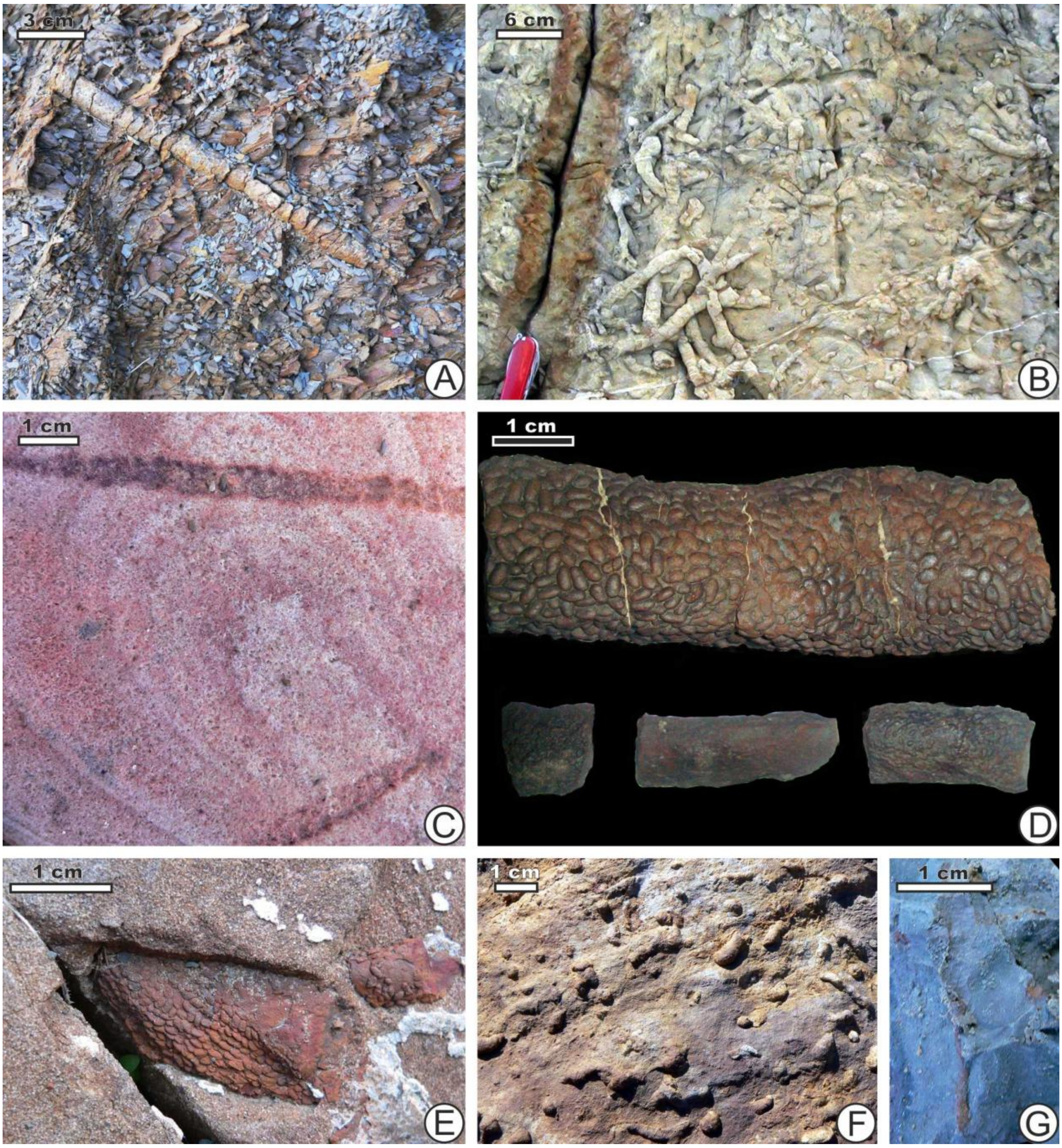

Figure 7

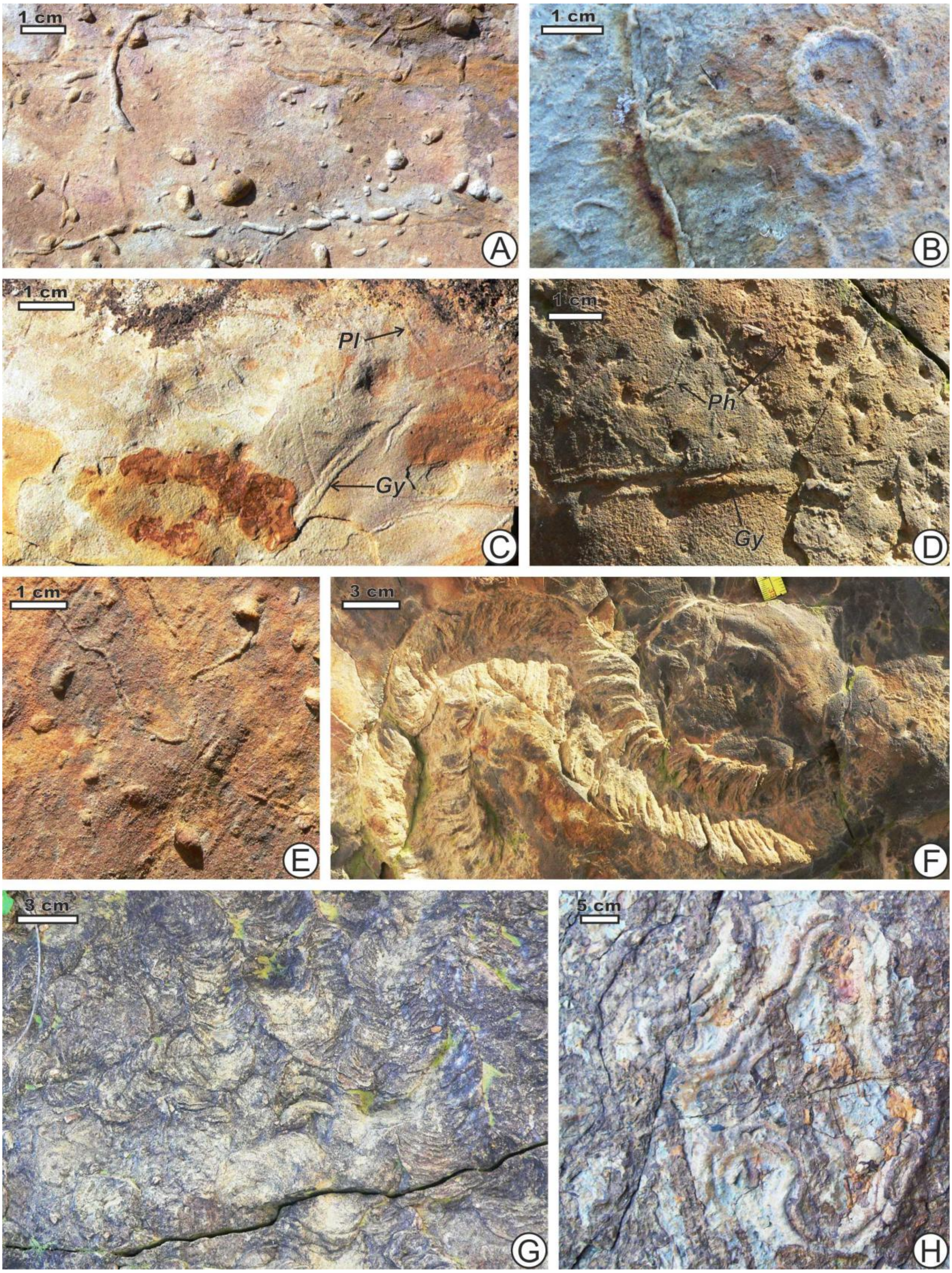

Figure 8

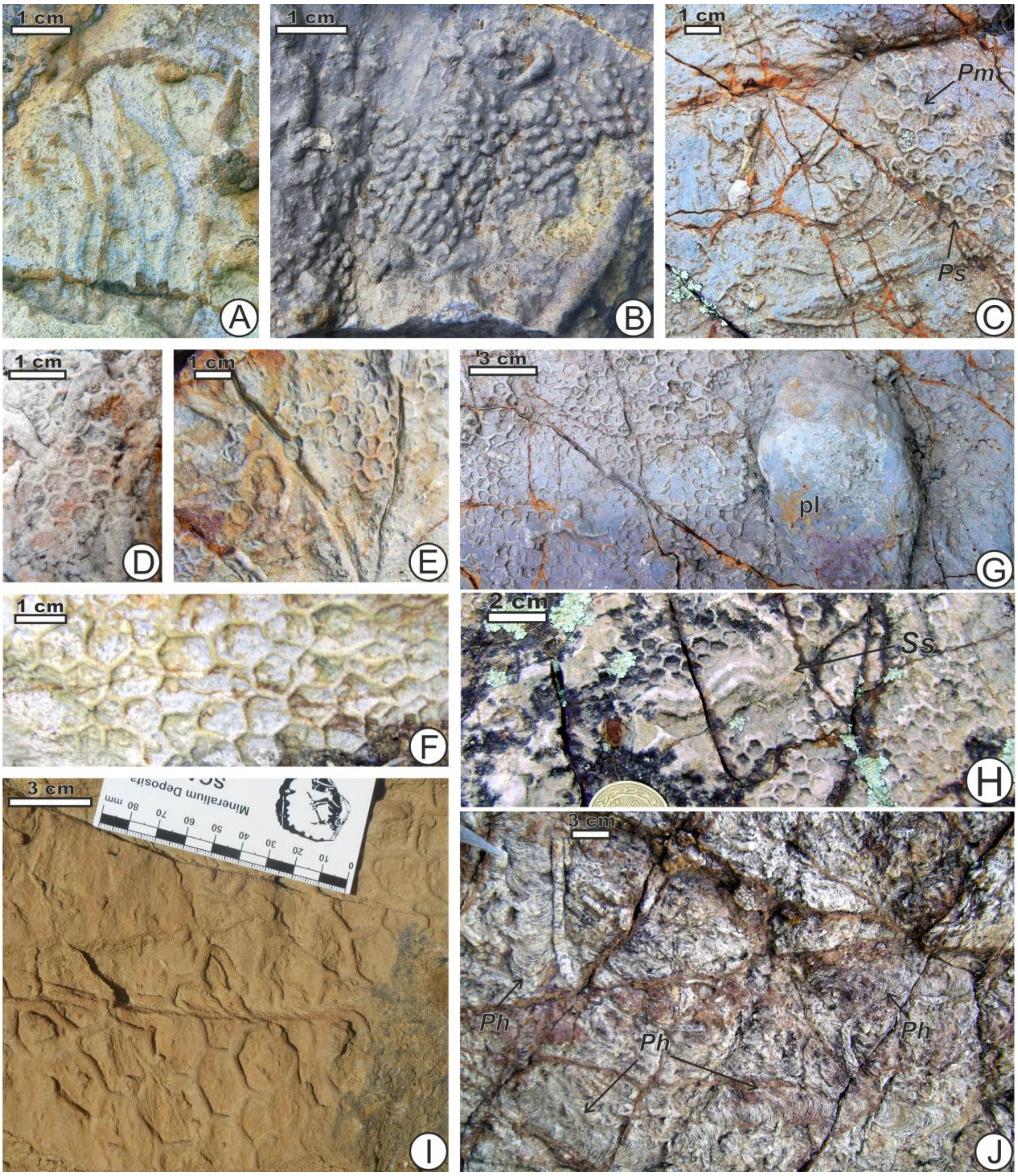
1 cm
A
1 cm
B
1 cm
Pm
Ps
C
1 cm
D
1 cm
E
3 cm
pl
G
1 cm
F
2 cm
Ss
H
3 cm
Mineralium Deposita
mm 80 70 60 50 40 30 20 10 0
I
3 cm
Ph
Ph
Ph
J

Figure 9

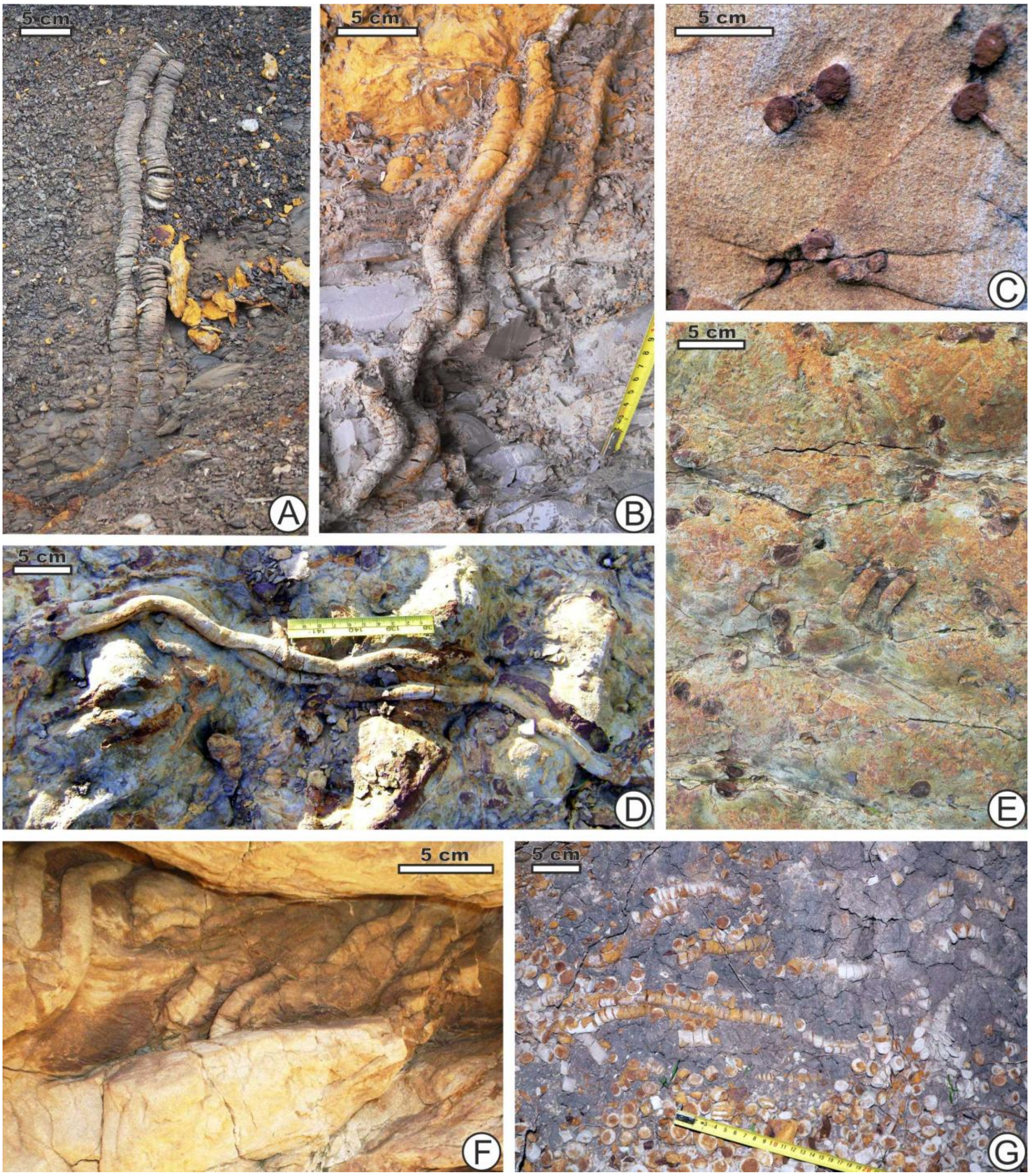

Figure 10

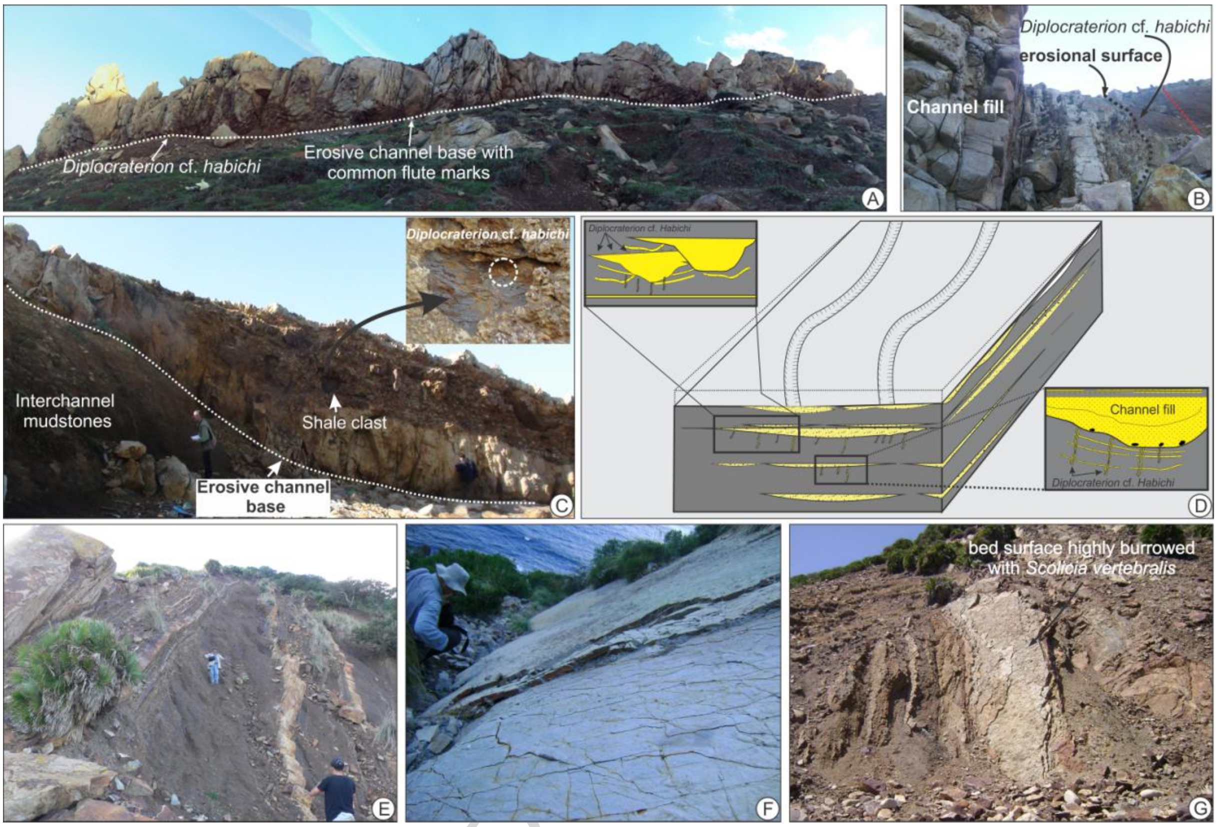
Diplocraterion cf. habichi
Erosive channel base with common flute marks
A
Diplocraterion cf. habichi
erosional surface
Channel fill
B
Diplocraterion cf. habichi
Interchannel mudstones
Shale clast
Erosive channel base
C
Diplocraterion cf. Habichi
Channel fill
Diplocraterion cf. Habichi
D
E
F
bed surface highly burrowed with Scolicia vertebralis
G

Figure 11

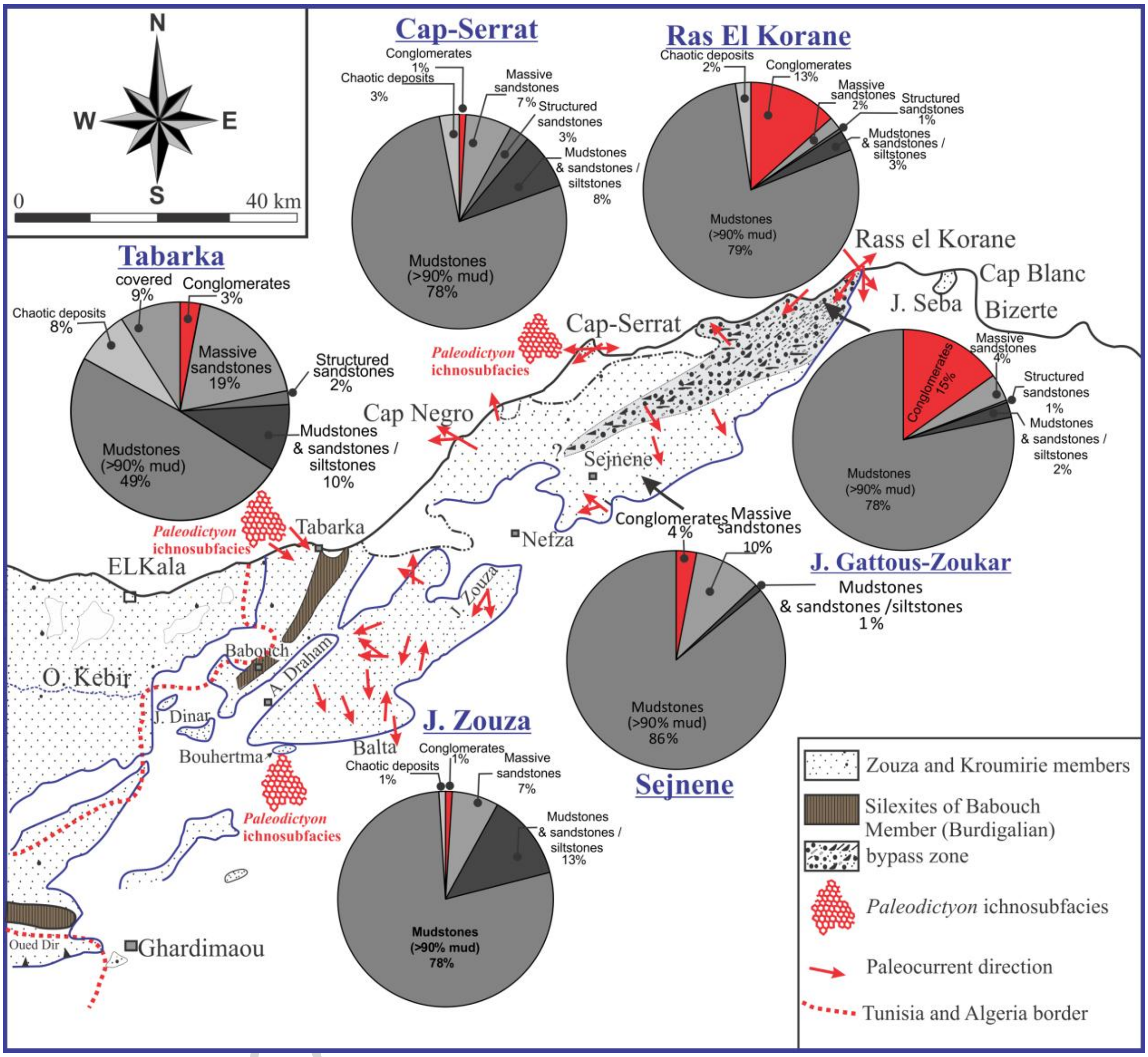
N
W
E
S
0
40 km
Cap-Serrat
Conglomerates 1%
Chaotic deposits 3%
Massive sandstones 7%
Structured sandstones 3%
Mudstones & sandstones / siltstones 8%
Mudstones (>90% mud) 78%
Ras El Korane
Chaotic deposits 2%
Conglomerates 13%
Massive sandstones 2%
Structured sandstones 1%
Mudstones & sandstones / siltstones 3%
Mudstones (>90% mud) 79%
Tabarka
covered 9%
Conglomerates 3%
Chaotic deposits 8%
Massive sandstones 19%
Structured sandstones 2%
Mudstones & sandstones / siltstones 10%
Mudstones (>90% mud) 49%
Rass el Korane
Cap Blanc
J. Seba
Bizerte
Cap-Serrat
Paleodictyon ichnosubfacies
Cap Negro
Conglomerates 15%
Massive sandstones 4%
Structured sandstones 1%
Mudstones & sandstones / siltstones 2%
Mudstones (>90% mud) 78%
?
Sejnene
Paleodictyon ichnosubfacies
Tabarka
Nefza
Conglomerates 4%
Massive sandstones 10%
ELKala
J. Zouza
J. Gattous-Zoukar
Mudstones & sandstones /siltstones 1%
Babouch
A. Draham
O. Kebir
J. Dinar
J. Zouza
Balta
Bouhertma
Paleodictyon ichnosubfacies
Conglomerates 1%
Chaotic deposits 1%
Massive sandstones 7%
Mudstones & sandstones / siltstones 13%
Mudstones (>90% mud) 78%
Mudstones (>90% mud) 86%
Sejnene
Oued Dir
Ghardimaou
Zouza and Kroumirie members
Silexites of Babouch Member (Burdigalian)
bypass zone
Paleodictyon ichnosubfacies
Paleocurrent direction
Tunisia and Algeria border

Figure 12

N°	**locality**	**GPS-coordinates**	**specimens**	**Information on the outcrop hosting specimens**
1	**Bouhertma**	*36°39'52.41"N 8°49'5.35"E	*Paleodictyon italicum*, *Scolicia vertebralis*, *Paleodictyon strozzi*	Thin bedded turbidites grading upward to very thick structurless massive sandstones
2	**Meloula-Tabarka**	*36°.57’.818 N 008.53.171 E *36°58'2.35"N 8°44'35.37"E	"*Ophiomorpha*" *recta* *Chondrites* isp., *Planolites montanus* (in mudstones)	Thin-bedded turbidites interbedded with light green mudstones
		*36.57.799 N 008.93.252 E	*Asteriacites aberensis*, *Chondrorhaphe bifida*, *Halopoa* isp., *Trichichnus* isp., *Scolicia strozzii*, *Urohelminthoida dertonensis*, *Spirorhaphe involuta*, *Paleodictyon strozzii*, *Paleodictyon majus*, *Paleodictyon latum*	Thin bedded turbidites grading upward to very thick structurless massive sandstones
		*36°57'35.41"N 8°45'7.00"E *36°57'33.92"N 8°45'15.69"E	*Diplocraterion* cf. *habichi* "*Ophiomorpha*" *recta*	Upper part of mudstone units just below the massive sandstone facies representing channel fill deposits
3	**Jebel Zouza**	*36.53.097 N 009.02.686 E *36°52'58.97"N 9° 3'9.08"E	*Diplocraterion* cf. *habichi*	Base of thick to very thick massive structurless sandstones
			Scolica prisca	Thin-bedded turbidites passing upward to thick structurless sandstones
4	**Cap-Serrat**	*37.13.966 N 009.13.220 E	*Paleodictyon strozzii*, *Cardioichnus* isp., *Diplocraterion* cf. *habichi*, *Helicolithus ramosus*, *Halimedides* isp.	Thin to medium turbidites sequence
		*37.13.994 N 009.13.114 E	*Phycosiphon hamatum*, *Ophiomorpha annulata*, *Diplocraterion* cf. *habichi*, *Scolicia vertebralis*	Thin to medium turbidites interbedded with mudstones
		*37.14.251 N 009.13.101 E	*Scolicia vertebralis*, rare *Diplocraterion* cf. *habichi*	Thin bedded turbidites
		*37.14.317 N 009.13.076 E	*Diplocraterion* cf. *habichi*	Interchannel mudstones, base of massive sandstones units

		*37°14'22.44"N 9°13'6.51"E *37°14'24.47"N 9°13'4.03"E *37°13'38.77"N 9°13'25.64"E		and top of massive sandstone units representing the fill of channel complexes
		*37°13'22.98"N 9°13'28.30"E	*Ophiomorpha rudis*	Base of thick massive sandstones unit representing the channel fill
5	**Ras–El Korane**	*37°20'3.07"N 9°39'38.01"E	*Ophiomorpha rudis*, *Scolicia vertabilis*	Upper surface of isolated thin bedded turbidites
6	**Sidi Shaieb**	*36.49.311 N 008.58.253 E	*Planolites montanus* and *Chondrites* isp. (in mudstones)	Light green to hemipelagic mudstones
		*36.49.398 N 008.58.266 E	*Cardioichnus* isp., *Planolites montanus*, *Selenichnites* isp., *Archaeonassa* isp., cf. *Cochlichnus* isp., ?*Cosmorhaphe* isp., *Gyrochorte* isp., *Planolites* isp., *?Phycosiphon* isp., *Helminthopsis* isp., *Scolicia vertebralis*	Thin-bedded turbidites showing thickening upward cycles
7	**Jebel Ajout (Sejnene)**		*Diplocraterion* cf. *habichi*	Base of thick to very thick bedded massive structurless sandstones
8	**Ben Metir**		*Diplocraterion* cf. *habichi*	Thin to medium turbidites

Table 1

Table 2

locality	epoch		P/B	DWAF	Calcareous benthic foraminifera (C)	DWAF/C	Trace fossils	Facies	Architectural elements	Depositional environment
Zouza area	Early Miocene	Aquitanian	P>B	Present (1/3)	Abundant (2/3)	<1	*Diplocraterion* cf. *habichi*, *Planolites* isp.	Thin to thick bedded	Base of channel fill	Upper slope
	Oligocene (Upper Rupelian-Lower Chattian)	Early Chattian		Abundant (90%)	Present (20%)	>1	*Scolicia vertebralis*	Thin bedded turbidites	Channel-lobe transition	Bathyal
		Rupelian	P>B	Present	Abundant	<1	*Planolites* isp., ?*Chondrites* isp.	Mudstones	Interchannel mudstones	Mid to upper slope
Tabarka area	Early Miocene	Aquitanian	P>B	Present 1/3	Abundant (2/3)	<1	*Diplocraterion* cf. *habichi*, *"Ophiomorpha" recta*	Interchannel mudstones and base of channel fill	Channel complexes	Upper slope
	Oligocene	Chattian	-	Abundant (100%)		>1	*Asteriacites aberensis*, ?*Chondrites* isp., *Chondrorhaphe bifida*, *Halopoa* isp.,*"Ophiomorpha" recta*, *Trichichnus* isp., *Scolicia strozzii*, *Urohelminthoida dertonensis*, *Spirorhaphe involuta*, *Paleodictyon strozzii*, *Paleodictyon majus*, *Paleodictyon latum*, *Scolicia*, *Spirorhaphe*, *Cosmorhaphe* isp., *Halopoa* isp.	Thin-bedded	Mostly sheet sands	Lower bathyal to base of slope
		Rupelian	P>B	Present	Abundant	<1		*********	Interchannel mudstones	Mid to upper slope
Sidi Shaieb	Miocene	Aquitanian	P>B	Present 1/3	Abundant (2/3)	<1	*Cardioichnus* isp., *Planolites montanus*, *Selenichnites* isp., *Archaeonassa* isp., ?*Cochlichnus* isp., ?*Cosmorhaphe* isp., ?*Gyrochorte* isp., ?*Planolites* isp., ?*Phycosiphon* isp., *Helminthopsis* isp., *Scolicia vertebralis*	Thin-bedded turbidites	Probable lobe	Upper slope
	Oligocene	Chattian	-	Abundant (80%)	Present (20%)	>1	*Planolites montanus* or *Chondrites* isp.	Mudstones	Interchannel mudstones	Mid to upper slope
Cap-Serrat	Early Miocene	Aquitanian	P>B	Present 1/3	Abundant (2/3)	<1	*Ophiomorpha rudis*	Thick bedded turbidites	-Channel complexes -Isolated turbidites	Varying between lower bathyal to upper slope
			variable	Present 1/3/variable	Abundant (2/3) /variable	variable	*Halimedides* isp., *Ophiomorpha rudis*, *Ophiomorpha annulata*, *Helicolithus ramosus*, *Phycosiphon hamatum*, *Diplocraterion* cf. *habichi*, *Paleodictyon* strozzii., *Planolites montanus*	Thin-bedded turbidites		

Highlights

- We focus on trace fossils of the Numidian Formation (NF) in northern Tunisia.
- The Oligocene (Zouza Member) of the NF contains the Paleodictyon ichnosubfacies.
- The early Miocene (Kroumirie Member) contains the Ophiomorpha rudis ichnosubfacies.
- Trace fossils suggest a shallowing-upward and E-W depositional environment variation.
- Distribution of trace fossils is related to the interpreted architectural elements