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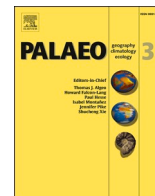
Ichnological characterization of deep-sea muddy deposits: Macrobenthic communities revealing palaeoenvironmental conditions within turbidite systems

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ABSTRACT

Traditionally, studies on turbiditic systems were mostly focused on sedimentological features, but later some other features as bioturbation have been included. Ichnological analysis is probed as a powerful tool for deep-sea sediments studies, revealing accurate information about palaeoenvironmental conditions during deposition. For the first time, a detailed ichnological and sedimentological integrative analysis focused on Miocene muddy turbiditic deposits from the westernmost Mediterranean at the Tabernas Basin (SE Spain) is here presented. The representative Rambla de Tabernas section has been selected to identify dominant palaeoenvironmental conditions before the deposition of the well-known Gordo megabed. The ichnological content reveals a trace fossil association comprising 26 ichnospecies, belonging to 14 ichnogenera ascribed to the *Nereites* ichnofacies in an overall stable and well oxygenated environment dominated by low-energy conditions. The distribution, and abundance of trace fossils, integrated with sedimentological information, allow to characterize variation in depositional conditions within the turbiditic system. Before deposition of the Gordo megabed, the turbiditic system in the lower part of the studied area had generalized low energy conditions. These conditions are probably linked to distal depositional areas, characterized by the record of the *Paleodictyon* ichnosubfacies in interbedded sandstones-mudstones, with a common occurrence of Tab/Tabc Bouma intervals. In contrast, higher energy conditions and deposition prevailed in proximal settings (e.g., channels and proximal lobes) in the upper part. They arecharacterized by the *Ophiomorpha rudis* ichnosubfacies in interbedded sandstones-mudstones with dominant Tab Bouma intervals. Additionally, the low ichnodiversity in comparison with similar deposits from other worldwide areas, is probably caused by the influence of local environmental conditions in the studied basin.

1. Introduction

Studies on turbiditic deposits at the beginning were mostly focused on sedimentological features, in reference to coarse-grained (Lowe, 1982), sandy (Bouma, 1962) or fine-grained turbidites (Stow and Shanmugam, 1980; Rotzien et al., 2022 for a recent review). In the last decades, some other features as bioturbation among others have also been considered. However, the ichnological content has frequently been underrated in defining depositional models and characterization of deep-sea fan systems. The study of trace fossils is widely recognized as a powerful tool in sedimentary basin analysis, which provides information about depositional and ecological conditions. When working with deep-sea deposits, this information is especially useful because this helps to

characterize and classify deep-marine facies (i.e., pelagites/hemipelagites, turbidites, contourites and hyperpycnites) (e.g., Dorador et al., 2019, 2021; de Castro et al., 2021; Rodríguez-Tovar, 2022; Rodríguez-Tovar et al., 2022). Focusing on turbidites, numerous ichnological studies have established a distinction between pre- and post-depositional trace fossils, revealing information about macrobenthic communities before and after the turbiditic event (e.g., Książkiewicz, 1954; Seilacher, 1962). A particular trace fossil association allowed Seilacher (1967) to define an ichnofacies related to deep-marine turbidites (i.e., *Nereites* ichnofacies), characterized by complex grazing and patterned feeding/dwelling structures. This ichnofacies was later subdivided into the *Ophiomorpha rudis*, *Paleodictyon* and *Nereites* ichnosubfacies, which could be roughly associated with an inner to outer fan

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distribution but also with a trend from channel axis to overbank deposits (Seilacher, 1974; Uchman, 2001, 2007, 2009; Heard and Pickering, 2008). Nowadays, ichnological studies on deep-sea turbidites can be used to analyze palaeoenvironmental conditions and to recognize different sub-environments within the deep-sea fan system (Uchman, 1995; Cummings and Hodgson, 2011; Uchman and Wetzel, 2011, 2012; Rodríguez-Tovar et al., 2016; Rodríguez-Tovar, 2022, for a recent review).

Turbidite deposits from the Tabernas Basin (SE Spain) are well known for their exceptional exposure, and frequently visited by students, researchers and people working in oil industry. These turbidite outcrops have been profusely studied from different perspectives, including stratigraphy, sedimentology, and geodynamics (Kleverlaan, 1989a, 1989b; Haughton, 2000; Pickering et al., 2001; Hodgson, 2002; Hodgson and Haughton, 2004; Baudouy et al., 2021). They serve as a reference to analyze flow and depositional features from turbidite deposits (Postma et al., 2009, 2014). However, their ichnological content has rarely been considered, and most studies only indicate the presence of bioturbation structures or report some ichnogenera. The first study to address bioturbation structures in the study area was conducted by Kleverlaan (1989a), but without characterization of particular trace fossils. Later recognition of bioturbation structures without ichnotaxa assignation was documented by Haughton (2000), Hodgson and Haughton (2004) and Baudouy et al. (2021). However, Doyle et al. (1996), published a study focused on the barnacle records in nearshore deposits, indicating the occurrence of the trace fossils *Thalassinoides* and *Zoophycos*. Hodgson (2002) reported other trace fossils, such as *Helminthoida*, *Ophiomorpha*, *Paleodictyon*, *Skolithos*, *Taphrhelminthopsis*, *Thalassinoides* and *Zoophycos*, in his Ph.D. thesis. More recently, De Matteis et al. (2016a, 2016b) recognized a trace fossil association composed of *Chondrites*, *Palaeophycus*, *Phycosiphon*, *Planolites*, *Scolicia*, *Skolithos*, *Teichichnus*, *Thalassinoides* and *Zoophycos* in drilled cores crossing the solitary channel complex (i.e., one of the three turbidite system recognized in the basin), differentiating three ichnofabric types (i.e., the *Ophiomorpha*, *Planolites-Palaeophycus-Nereites*, and *Phycosiphon-Nereites-Planolites* ichnofabrics), but without any interpretation. Thus, ichnological information from the Tabernas Basin is remarkably scarce, despite its interest.

Here, a detailed ichnological study is presented of one of the most representative sections of the Tabernas turbidite deposits. The main aim is to characterize the composition and distribution of the trace fossil association, distinguishing ichnofacies and ichnosubfacies, to arrive at a better understanding of the palaeoenvironmental conditions during deposition, and a more precise sub-environmental discernment within the deep-fan system.

2. Geological setting. The Rambla de Tabernas section

The Tabernas Basin (Fig.1) is a Neogene western Mediterranean basin pertaining to the Betic Cordillera (southeastern Iberian Peninsula),
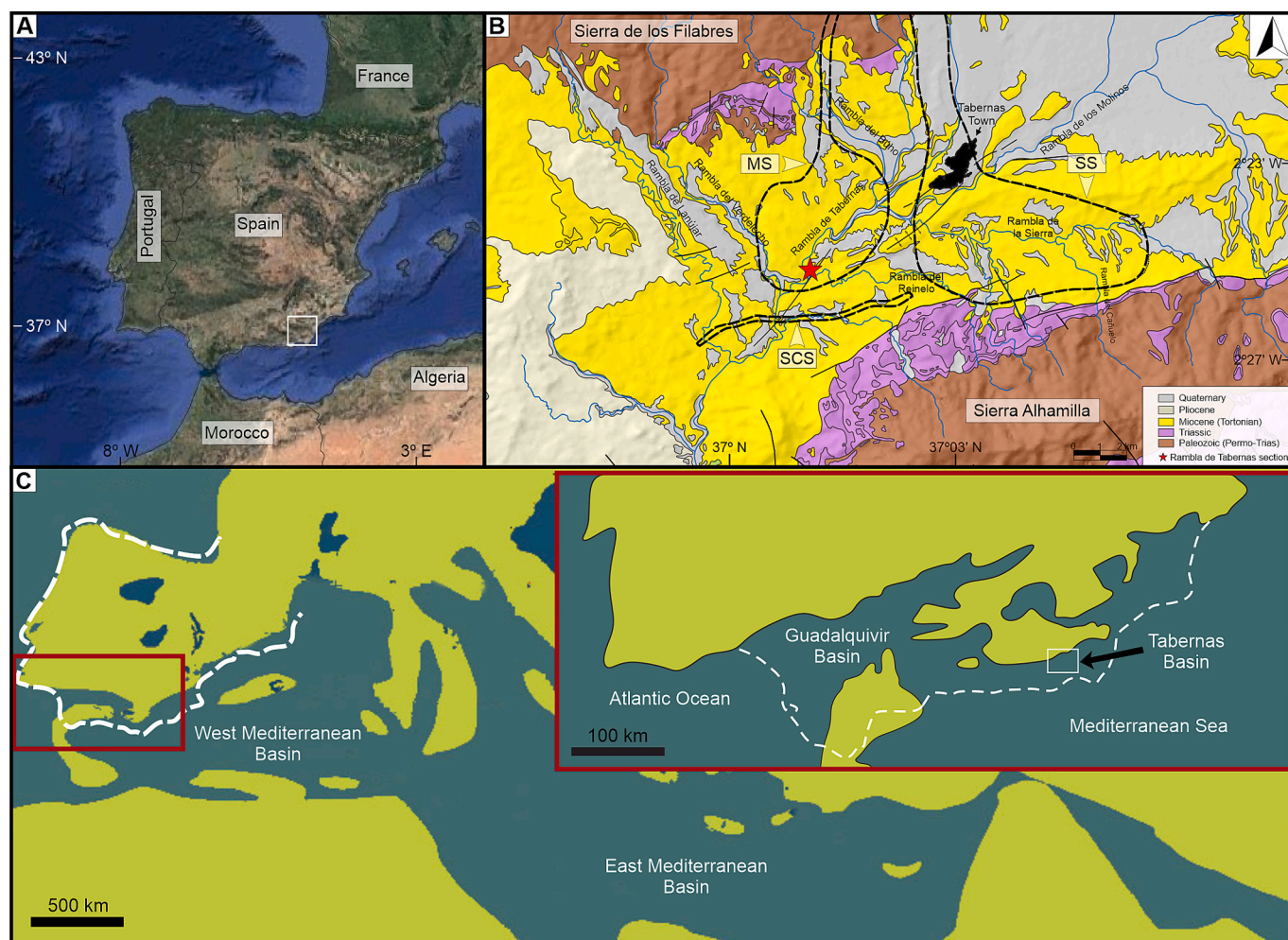

Fig. 1. Location of the study area. A, B) Localization map of the study area. Contours of turbidite systems defined by Kleverlaan (1989a) in broken lines. MS, Muddy system; SS, Sandy system; SCS, Solitary channel system. C) Palinspastic map of the western Mediterranean Sea for the Late Miocene (modified after Popov et al., 2004) and location of Tabernas Basin (modified from Braga et al., 2003); broken line shows the current coastal line in the area of interest.

filled by Serravallian to lower Messinian, marine to continental sediments (Kleverlaan, 1989b). During the Tortonian, submarine fan complexes grew in a subsiding basin, whereas during the Messinian, basement uplift and sediment accumulation caused a regressive trend. Kleverlaan (1989a) identified three feeder channels that were active simultaneously, or alternatively, allowing for an informal differentiation of three systems: i) a sandy system consisting of a straight valley finishing in sand-filled scours, ii) a muddy system defined by a straight channel terminating in fine-grained turbidite deposits, and iii) a sinuous solitary channel without lobe deposits (Fig. 1). These depositional systems are well exposed, and sections can be laterally correlated using the Gordo megabed as a marker across the basin (Kleverlaan, 1989b; Haughton, 2000). The megabed, up to 40 m thick, is intercalated within Tortonian submarine fan sediments and underlies deformed basinal sediments, being interpreted as a seismite (Kleverlaan, 1987). Haughton (2000) provided a reanalysis of the western end of the Tabernas Basin, tracing distinctive stacked systems to differentiate five informal stratigraphic units denoted from A to E. Unit A, the oldest one, contains heavily bioturbated marls, followed by erosional sand bodies determining Unit B, in which the solitary channel system defined by Kleverlaan (1989a) is included. Unit C comprises interbedded marls and sheet turbidites, overlain by Unit D, with sandier deposits, including numerous thin-bedded sandstones. Haughton (2000) characterized the Gordo megabed as the youngest and final Unit E. Hodgson and Haughton (2004) assigned formal lithostratigraphy and proposed a new nomenclature after studying the southern part of the basin (Alfaro subbasin), expanding the earlier classification of Haughton (2000). They identified the Molinos Formation at its base, made up of alluvial fanglomerates, overlain by the Sartenella Formation (related to previously defined Unit B), containing marls with interbedded thin turbidites and some sandstones and conglomerates bodies. They are covered by muddier deposits featuring sheet turbidites defined as the Loma de los Baños Formation, linked to the Unit C defined by Haughton (2000). Finally, they identified the Verdelecho Formation, made up of sandier deposits with thin-bedded turbidites, comprising Units D and E of Haughton (2000).

The depositional settings of these units have been discussed largely in terms of sedimentological features, but it is lacked deeper interpretations regarding these deposits. Ichnological analysis can provide new information about the predominant paleoenvironmental conditions during deposition, allowing for a more accurate interpretation of the studied deposits.

Accordingly, a detailed ichnological study of one of the most representative turbidite sections from Tabernas Basin, the Rambla de Tabernas section (Fig. 2) is presented, discussing palaeoenvironmental conditions and distinguishing sub-environments in the turbidite system.

This section has been selected within a number of sections into the muddy system, to be especially interesting for correlation within the basin, as it is the closest section exposed stratigraphically below the most representative outcrop for the Gordo megabed, used as a marker in the basin. In view of the systems, stratigraphic units and formations defined in the Tabernas Basin, this section belongs to the muddy system defined by Kleverlaan (1989b), and to the Verdelecho Formation according to Hodgson and Haughton (2004), comprising units D and E of Haughton (2000). The Rambla de Tabernas section is close to the section "I" studied by Hodgson and Haughton (2004) in the northeastern part of the Tabernas Basin. Study of this section will therefore allow us to analyze conditions before deposition of the Gordo megabed in the turbiditic muddy system.

3. Methods

Detailed bed-by-bed ichnological and sedimentological analysis was conducted across the 52 m long studied section (Fig. 2). Ichnological analysis is based on outcrop observations of trace fossil features (orientation, shape, size, diversity and abundance of specimens, and relationship between trace fossils and type of facies). The trace fossils were carefully measured and photographed, and some specimens were collected for a precise laboratory analysis of internal structures and some minor scale features. According to their abundance, ichnogenera were qualitatively classified as abundant (>10 specimens), common (5–10 specimens), scarce (2–4 specimens) and rare (1 specimen). Finally, the trace fossils were classified following the morphological groups introduced by Książkiewicz (1977), with further modifications by Uchman (1995). Sedimentological study entailed the analysis of lithology, color (Munsell chart), composition, grain size, bedding geometry and sedimentary structures (i.e., erosional signatures, boundaries, depositional and post-depositional structures) following conventional procedures.

4. Results

4.1. Sedimentological analysis

In view of the sedimentological features, four intervals could be differentiated throughout the Rambla de Tabernas section (Fig. 3).

Interval A (0–9.6 m) corresponds to the base of the section. It is dominated by mudstones with a few thick-bedded sandstones packages. Mudstones beds are 15–170 cm thick, light olive brown to light olive gray in color (5Y 5/6 - 5Y/ 5/2), and are highly compacted. As an exception, at the base of the interval there is a 20 cm thick mudstones bed with elongated reddish mud clasts (Fig. 3A). Sandstones are
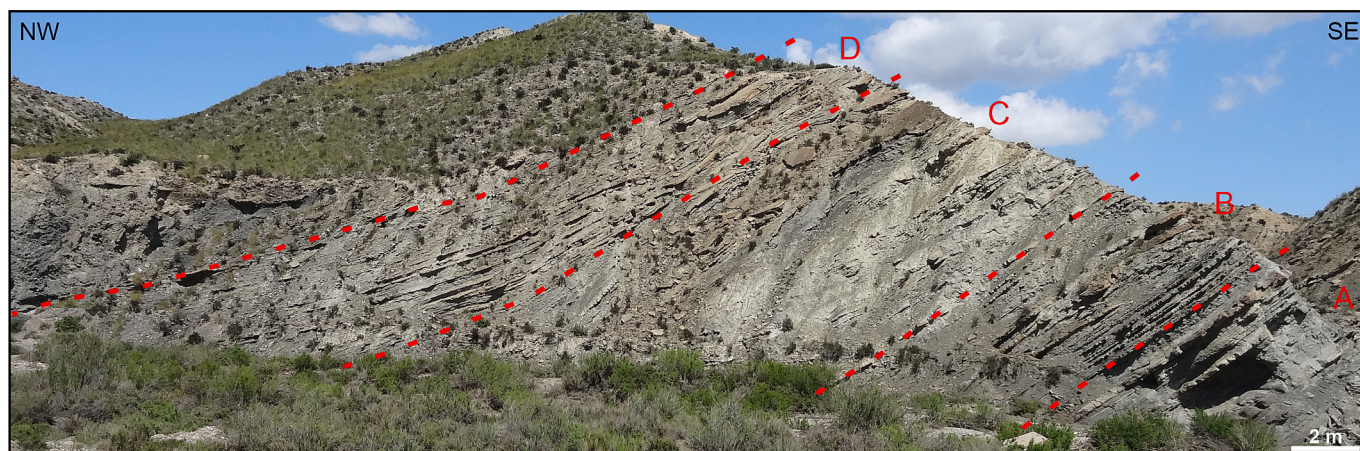

Fig. 2. Study outcrop. Field view of the Rambla de Tabernas Section differentiating intervals based on sedimentological analysis.
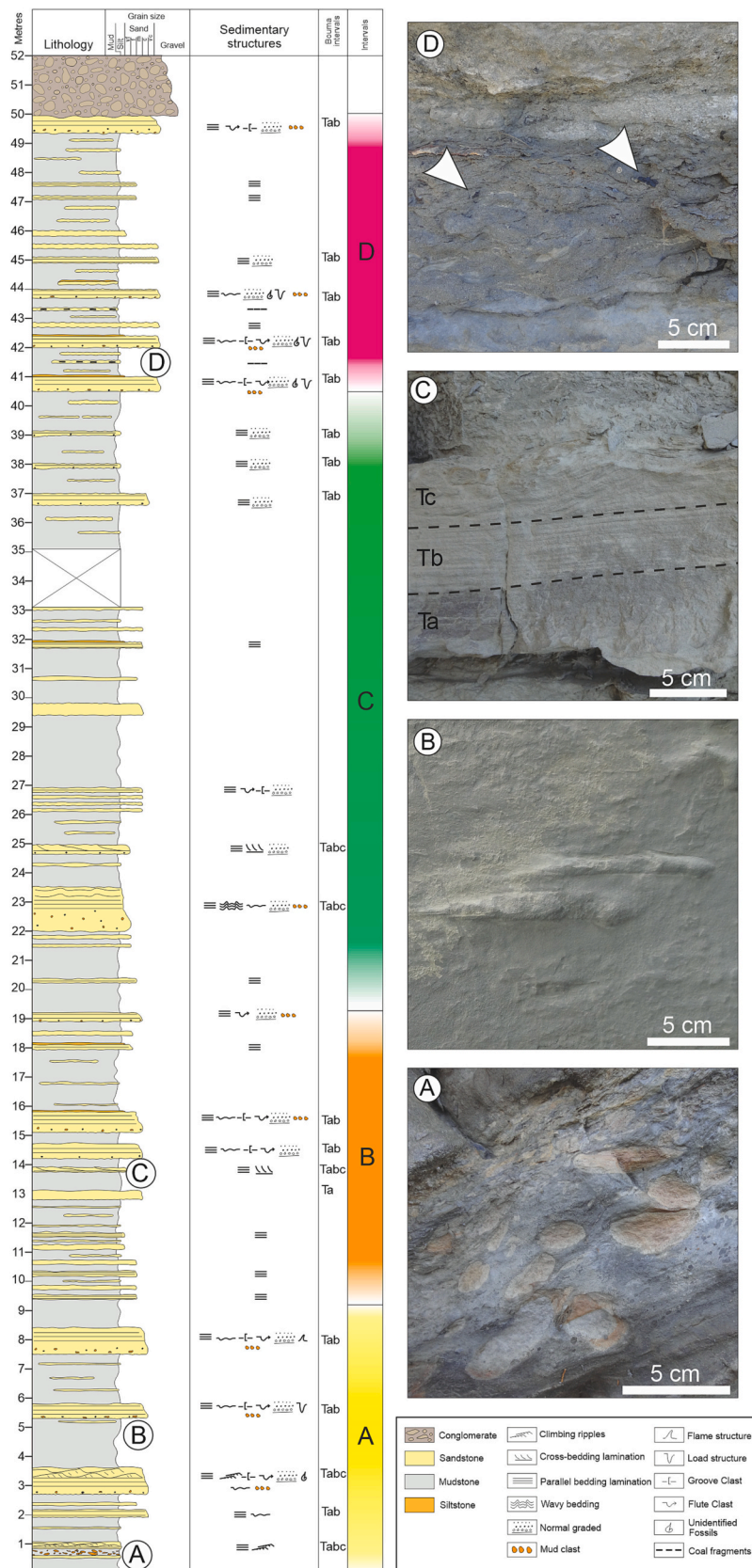
Fig. 3. Lithostratigraphic column. Sedimentary log of the Rambla de Tabernas Section differentiating intervals based on sedimentological data. In the right, some details of remarkable aspects. A, mud clasts; B, flute cast structures; C, example of a Tabc Bouma sequence from the section; and D, coal fragments.

interbedded in medium or —less frequently— thick packages (10 cm to 90 cm thickness). They are structureless at the base and some parallel and cross-bedded at the top, with local climbing ripples, wavy lamination and flute marks (Fig. 3B), groove casts and some load and flame structures in the thick beds. The Bouma intervals Tab are common and Tabc less frequent.

Interval B (9.6–19.1 m) mainly consists of sandstones-mudstones intercalations, and rarely thin siltstones layers (<10 cm thick). Sandstones beds are tabular and 5–70 cm thick. Overall, grain size is fine (commonly) to medium, while moderately to poorly sorted, and parallel- and cross-lamination are identified. The thickest sandstones beds show an erosive base, having some flute marks and groove casts, and parallel lamination structures towards the top. Tab interval is identified in the thickest beds, whereas Ta and (less frequent) Tabc sequences (Fig. 3C) are found in the thinner sandstones beds.

Interval C (19.1–40.5 m) is clearly dominated by mudstones with some interbedded sandstones, and rare very thin siltstones layers (<5 cm thick). Sandstones beds range from 10 cm to 150 cm in thickness, and medium to (less frequently) coarse-grained in size. The thickest sandstones bed (22–23.5 m in the column) is coarse grained at its base, then fining upward and showing parallel, cross and convolute laminations. Mudstones beds range from 20 cm to 250 cm thick, yet mostly thicker than 100 cm, being light olive gray in color (5Y 5/2) and massive. It is possible to recognize Tab and less frequent Tabc intervals in some sandstones beds.

Interval D (40.5–50 m) is largely represented by sandstones-mudstones interbedding, and very rare thin siltstones layers (<10 cm). Sandstones beds are 5–50 cm thick, generally thicker at the base and thinner towards the top. Grain size tends to be coarse at the base and medium to fine at the top. Sedimentary structures such as parallel, cross, and wavy laminations are commonly found in the sandstones beds, along with erosional structures such as flute marks, groove casts, and load structures. Some undetermined bivalves are registered, as well as coal and wood fragments in certain beds (40.5 to 44 m) (Fig. 3D). Mudstones beds vary from around 10 to 40 cm in thickness, showing tabular or lenticular sandstones interlayers. Regarding the Bouma sequences, Tab is mainly identified.

Finally, the top of the section (50–52 m) is capped by a Quaternary clast-supported pebbly and cobbly conglomerates.

4.2. Trace fossil association

The Rambla de Tabernas section shows a relatively diverse post-and pre-depositional trace fossil association consisting of 14 ichnogenera and 26 ichnospecies (Table 1). The term "post-depositional" refers to trace fossils produced within a turbidite bed after deposition (e.g., Seilacher, 1962; Kern, 1980; Leszczyński, 1993). In the case study, they are represented by *Chondrites* isp. (von Sternberg, 1833), *Ophiomorpha* isp. (Lundgren, 1891), ?*Palaeophycus* isp. (Hall, 1847), *Phycodes* isp. (Richter, 1850), *Planolites* isp. (Nicholson, 1873), *Scolicia* isp. (de Quatrefages, 1849) and *Thalassinoides* isp. (Ehrenberg, 1944). The term "pre-depositional", introduced by Książkiewicz (1954), is used for those biogenic structures that were produced prior to the deposition of a turbidite, including highly organised, often delicate burrows. This group includes many ichnotaxa commonly found as positive semi-reliefs at the base of turbidite layers, showing complex meandering patterns in most cases (Książkiewicz, 1970, 1977; Seilacher, 1977a, 1977b, 2007; Uchman and Wetzel, 2012). In the studied section, the pre-depositional association is composed of ?*Circulichnis* isp. (Vialov, 1971), *Scolicia strozzii* (Savi and Meneghini, 1850) and graphoglyptids such as *Cosmorhaphe* isp. (Fuchs, 1895), *Desmograpton* isp. (Fuchs, 1895), *Helminthorhaphe*: *H.* isp. (Seilacher, 1977a) and *H. japonica* (Tanaka, 1970), *Megagrapton* isp. (Książkiewicz, 1968), *Paleodictyon*: *P. arvense* (Barbier, 1956), *P. majus* (Meneghini in Peruzzi, 1880), *P. maximum* (Eichwald, 1868), *P. minimum* (Sacco, 1888), *P. miocenicum* (Sacco, 1886) and *P. strozzii* (Savi and Meneghini, 1850) and *Urohelminthoida* isp (Sacco, 1888).

Table 1

Trace fossils found in the studied section, differentiating post-depositional and pre-depositional structures. BWM – branched winding and meandering; C – Circular and elliptical; N – network; SB – simple and branched structures; WM – winding and meandering.

Ichnotaxa	Ethological category	Morphological group	Abundance
Post-depositional traces			
Chondrites intricatus	?Chemichnia/ Fodinichnia	SB	Common
Chondrites isp.	?Chemichnia/ Fodinichnia	SB	Abundant
Ophiomorpha annulata	Domichnia	SB	Scarce
Ophiomorpha isp.	Domichnia	SB	Abundant
Ophiomorpha nodosa	Domichnia	SB	Common
?*Palaeophycus* isp.	Pascichnia/ Domichnia	SB	Scarce
Phycodes isp.	Fodinichnia/ Domichnia	SB	Scarce
Planolites isp.	Pascichnia	SB	Abundant
Scolicia isp.	Pascichnia	WM	Abundant
Scolicia prisca	Pascichnia	WM	Common
Thalassinoides isp.	Fodinichnia/ Domichnia	SB	Abundant
Thalassinoides suevicus	Fodinichnia/ Domichnia	SB	Common
Pre-depositional traces			
?*Circulichnis* isp.	Fodinichnia/ Pascichnia	C	Rare
Cosmorhaphe isp.	Agrichnia/ Irretichnia	WM	Rare
Desmograpton isp.	Agrichnia	BWM	Rare
Helminthorhaphe isp.	Agrichnia	WM	Common
Helminthorhaphe japonica	Agrichnia	WM	Scarce
Megagrapton isp.	Agrichnia	N	Rare
Paleodictyon arvense	Agrichnia	N	Rare
Paleodictyon majus	Agrichnia	N	Common
Paleodictyon maximum	Agrichnia	N	Scarce
Paleodictyon minimum	Agrichnia	N	Abundant
Paleodictyon miocenicum	Agrichnia	N	Abundant
Paleodictyon strozzii	Agrichnia	N	Common
Scolicia strozzii	Repichnia/ Pascichnia	WM	Rare
Urohelminthoida isp.	Agrichnia	BWM	Scarce

4.2.1. Post-depositional traces

4.2.1.1. Simple and branched structures. Chondrites von Sternberg, 1833 are recognized as small and dendritic forms, straight or slightly curved bars or spots as part of a branched burrow system, the branches forming an acute angle, bars, 0.5–0.8 mm wide, and the filled sediment being lighter than the host rock (Fig. 4A). Some specimens recognized are assigned to *Chondrites intricatus* Brongniart, 1828 (Fig. 4B) given the downward radiating straight branches with angles under 45° (e.g., Uchman, 1998), but most are considered as *Chondrites* isp. *Chondrites* has been traditionally interpreted as produced by selective deposit feeding, but there are some other alternative hypotheses as chemosymbiotic or farming structures (Seilacher, 1990; Fu, 1991; Kotake, 1991; Baucon et al., 2020).

Ophiomorpha Lundgren, 1891 appears as horizontal, vertical and occasionally inclined cylindrical to sub-cylindrical burrows, with agglutinated pelletoidal walls, and in some cases only preserved as a mould. *Ophiomorpha annulata*, *Ophiomorpha nodosa* and *Ophiomorpha* isp. were differentiated in the studied section. *Ophiomorpha annulata* (Książkiewicz, 1977) appears as vertical, endichnia, semi-relief, straight forms up to 95 mm long and 5 mm wide (Fig. 4C), being scarce in the
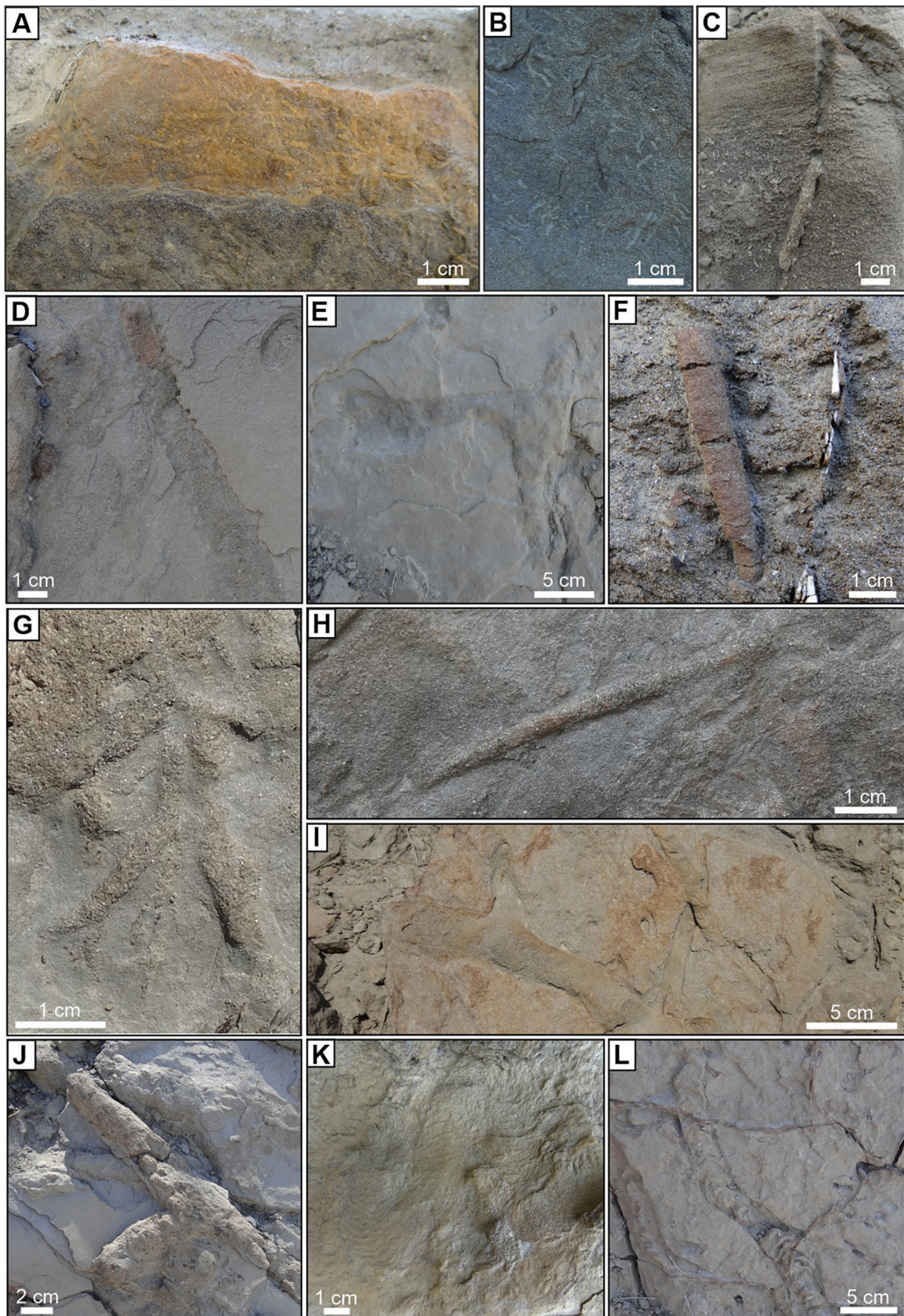
Fig. 4. Post-depositional association. Post-depositional traces fossils characterized in the studied section. A, *Chondrites* isp.; B, *Chondrites intricatus*; C, *Ophiomorpha annulata*; D, *Ophiomorpha nodosa*; E, *Ophiomorpha* isp.; F,?*Palaeophycus*; G, *Phycodes*; H, *Planolites*; I, *Thalassinoides suevicus*; J, *Thalassinoides isp.*;. K, *Scolicia* isp.; L, *Scolicia prisca*.

section. *O. annulata* is a common trace fossil in deep-water turbidites (Uchman, 2001). *O. nodosa* Lundgren, 1891 (Fig. 4D) is commonly found in the study section as horizontal, epichnial, and cylindrical, with pellet lining. Pellets are well distributed along the burrow, up to 155 mm long and 18 to 20 mm wide. *Ophiomorpha* isp. is abundant across the section, as horizontal, vertical or slightly oblique burrows, smooth or punctually covered with a poorly developed pelletoidal wall, the diameter ranging from 5 to 15 mm (Fig. 4E). *Ophiomorpha* is interpreted as a dwelling structure (domichnia) commonly attributed to suspension and/or deposit feeding decapod crustaceans, which constructed linings to limit the collapse of burrows in relative unstable substrates (Frey et al., 1978; Pemberton et al., 1992; Uchman, 2009).

?*Palaeophycus* Hall, 1847 occurs as horizontal, epichnial burrow, cylindrical and unbranched, smooth walled, straight to curved, at least 45 mm long and up to 7 mm wide (Fig. 4F). It is scarce in the section. *Palaeophycus* is a facies-crossing pascichnion or domichnion, interpreted as an open tube produced by carnivorous or omnivorous invertebrates, mostly polychaetes (Pemberton and Frey, 1982; Keighley and Pickerill, 1995).

Phycodes Richter, 1850 is scarce in the section and can be identified as a horizontal, epichnial burrow with a main stem divided into three tunnels with acute angles in between, and in some cases a flabellate pattern, showing a spreite-like structure (Fig. 4G) (Muñiz et al., 2002; Singh et al., 2008). *Phycodes* has been interpreted as a deposit-feeding trace of annelid worms (Fillion and Pickerill, 1990; Han and Pickerill, 1994; Mayoral et al., 2013).

Planolites Nicholson, 1873 is a horizontal to subhorizontal, hypichnial cylindrical burrow, straight to slightly sinuous, unbranched, at least up to 53 mm long, up to 5.6 mm wide, with active fill (Fig. 4H), and is abundant throughout the section. *Planolites* is a facies-crossing form and can be found in most settings, from freshwater to deep marine (Rodríguez-Tovar and Uchman, 2004, 2017; Rodríguez-Tovar et al., 2009). It is interpreted as a pascichnion, probably produced by numerous different organisms (Pemberton and Frey, 1982; Keighley and Pickerill, 1995).

Thalassinoides Ehrenberg, 1944 is an abundant structure in the section. It appears as a system of horizontally branched, Y to T shaped smooth cylinders. Horizontal, epichnial structures having Y-shaped bifurcation with unlined smooth walls, up to 138 mm long and 23 mm wide, were assigned to *T. suevicus* Ehrenberg, 1944 (Fig. 4I). *Thalassinoides* isp. occurs as poorly preserved straight, horizontal, branched, smooth cylindrical burrows (Fig. 4J). *Thalassinoides* is a facies-crossing ichnogenus commonly found in oxygenated marine environments and soft and firm sediments (Ekdale et al., 1984; Rodríguez-Tovar et al., 2008, 2017; Miguez-Salas et al., 2017).

4.2.1.2. Winding and meandering structures. *Scolicia* de Quatrefages, 1849 occurs as horizontal, winding to meandering backfilled burrows (Fig. 4K). *S. prisca* de Quatrefages, 1849 is commonly identified in the studied section and recognized as horizontal, epichnial, slightly meandering, and presenting a ribs-like structure, which is 2.7 cm wide (Fig. 4L). Other abundant specimens in the section were classified as *Scolicia* isp. due to poor preservation. *Scolicia* is a grazing trace produced by irregular echinoids commonly in sand-rich deposits (Uchman, 1995; Wetzel and Uchman, 2001).

4.2.2. Pre-depositional traces

4.2.2.1. Circular and elliptical structures. ?*Circulichnis* Vialov, 1971 is rare, observed as horizontal, hypichnial, circular, smooth tunnels, 16 mm in diameter (Fig. 5A). This is interpreted as a feeding exploration burrow produced by polychaetes in marine sediments (see Uchman and Rattazzi, 2019 for a recent review).

4.2.2.2. Winding and meandering structures. *Cosmorhaphe* Fuchs, 1895 is rare, recognized as a horizontal, meandering hypichnial, unbranched graphoglyptid, with first and second order meanders, being 5 mm width, and 5 mm amplitude (Fig. 5B). *Cosmorhaphe* has been interpreted as a shallow infauna burrow system constructed as an agrichnial activity produced by polychaetes (Ekdale, 1980; Uchman, 1998); Although it may also be interpreted as irretichnia (a praedichnia subcatergy) (Vallon et al., 2016).

Helminthorhaphe Seilacher, 1977a is a common graphoglyptid throughout the section, occurring as a horizontal, hypichnial, non-branched structure, with one order of meanders (Fig. 5C). According to the diagnostic features, the ichnospecies *H. japonica* Tanaka, 1970 (Fig. 5D) was identified as horizontal, hypichnial, regularly high amplitude meanders, smooth, string diameter 1.1 mm and meander width 3.1 mm; *H. japonica* is a scarce trace in the section. The remaining specimens were considered as *Helminthorhaphe* isp. *Helminthorhaphe* is interpreted as an agrichnion structure produced by polychaetes (Książkiewicz, 1977; Nielsen et al., 2012; Fan et al., 2017).

Scolicia strozzii Savi and Meneghini, 1850 is rare, identified as horizontal, epichnial, bilobate ridge, with a medium groove separating the ridge, apparently meandering. The ridge is straight smooth, 6 mm wide (Fig. 5E). *Scolicia strozzii* is interpreted as a shallow-tier pre-depositional irregular echinoid trace (Uchman, 1995).

4.2.2.3. Branched winding and meandering structures. *Desmograpton* Fuchs, 1895 occurs rarely in the section, as horizontal curved segments semi-parallel and inwardly oriented, non-branched burrows, preserved as hypichnial, the string being 0.7–1.5 mm wide (Fig. 5F). *Desmograpton* is interpreted as an agrichnion considered as a three-dimensional graphoglyptid burrow with some preservational variants (Seilacher, 1977a; Uchman, 1995, 1998).

Urohelminthoida Sacco, 1888 is scarce within the section and it is identified as horizontal, hypichnial meanders, the string, 2.8–4.3 mm in diameter, with some poorly preserved lateral appendages (Fig. 5G). It is considered a typical graphoglyptid agrichnion from deep-sea turbiditic deposits (Seilacher, 1977a; Uchman, 1995; Rodríguez-Tovar et al., 2016).

4.2.2.4. Networks. *Megagrapton* Książkiewicz, 1968 is a rare trace fossil in the section, occurring as poorly preserved horizontal curved burrows forming an irregular net up to 8 mm (Fig. 5H). It is considered a typical graphoglyptid from turbidite deposits (e.g., Uchman, 1998; Uchman et al., 2022).

Paleodictyon Meneghini in Savi and Meneghini, 1850 is observed as a horizontal burrow system comprising a regular net of hexagonal meshes, inferred as produced for the farming of microbes (Ekdale, 1985; Seilacher, 2007). Six ichnospecies were identified according to morphometric changes in maximum mesh size and string diameter (Uchman, 1995): *Paleodictyon arvense*, *P. majus*, *P. maximum*, *P. minimum*, *P. miocenicum*, and *P. strozzii*.

Paleodictyon arvense Barbier, 1956 (Fig. 5I) is rare, being characterized by meshes 14–17 mm wide and string 2–2.8 mm wide. *Paleodictyon majus* Meneghini in Peruzzi (1880) (Fig. 5J) is common, showing well-preserved specimens with meshes that are 5 to 7 mm wide and string 1 to 1.5 mm wide. *Paleodictyon maximum* (Eichwald, 1868) (Fig. 5K) is scarce, characterized by well-preserved hexagonal nets with 6 to 10 mm wide meshes and strings between 1.8 and 2.5 mm wide. *Paleodictyon minimum* Sacco (1888) (Fig. 5L) is the most abundant *Paleodictyon*, consisting of hexagonal nets having 1 to 1.3 mm meshes and 0.5 mm wide strings. *Paleodictyon miocenicum* Sacco (1886) (Fig. 5M) is abundant, occurring as hexagonal nets, whose meshes are 4–5 mm wide and strings are 1.3–1.5 mm wide. *Paleodictyon strozzii* Meneghini in Savi and Meneghini, 1850 (Fig. 5N) is common, with mesh size 2.5–3 mm and string diameter 0.8 mm.
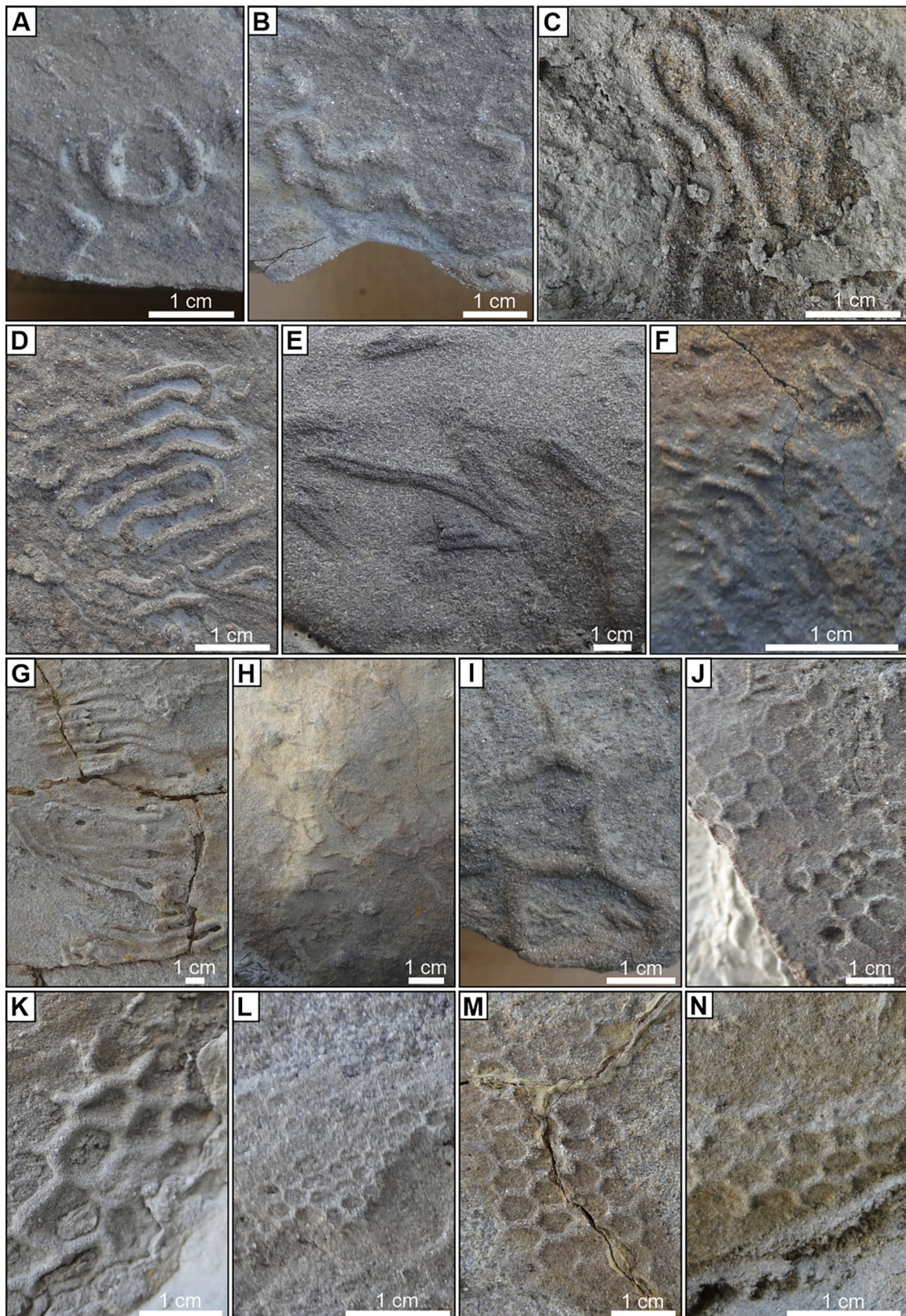
Fig. 5. Pre-depositional association. Pre-depositional traces fossils characterized in the studied section. A,?*Circulichnis*; B, *Cosmorhaphe*; C, *Helminthorhaphe*; D, *Helminthorhaphe japonica*; E, *Scolicia strozzii*; F, *Desmograpton*; G, *Urohelminthoida*; H, *Megagrapton*; I, *Paleodictyon arvense*; J, *Paleodictyon majus*; K, *Paleodictyon maximum*; L, *Paleodictyon minimum*; M, *Paleodictyon miocenicum*; N, *Paleodictyon strozzii*.

4.3. Ichnological content of the section

As indicated above, *Chondrites* isp., *Ophiomorpha* isp., *Paleodictyon minimum*, *P. miocenicum*, *Planolites* isp., *Scolicia* isp. and *Thalassinoides* isp., are abundant, *Chondrites intricatus*, *Helminthorhaphe* isp., *Ophiomorpha nodosa*, *Paleodictyon majus*, *P. strozzii*, *Scolicia prisca* and *Thalassinoides suevicus* are common, *Helminthorhaphe japonica*, *Ophiomorpha annulata*,?*Palaeophycus* isp., *Paleodictyon maximum*, *Phycodes* isp., and *Urohelminthoida* isp. are scarce, and?*Circulichnis*, *Cosmorhaphe* isp., *Desmograpton* isp., *Megagrapton* isp., *Paleodictyon arvense* and *Scolicia strozzii* appear as rare traces in the section. The trace fossil distribution and abundance vary throughout the studied section, allowing five intervals to be discerned in view of ichnological content (Fig. 6).

Interval I in the lower part of the section (0–9 m) is represented by a low diverse association, almost exclusively composed of low-abundant post-depositional trace fossils. *Chondrites* isp., *Planolites* isp. and *Thalassinoides* isp are common, while *Chondrites intricatus*, *Ophiomorpha* isp., *O. nodosa* and *Thalassinoides suevicus* are rarely identified. In general, these trace fossils are found in the sandstones beds and less bioturbated mudstones remains.

Interval II (9–19.5 m) is defined by a more diverse association composed of post- and pre-depositional trace fossils, the latter prevailing. The post-depositional association is mainly dominated by *Ophiomorpha* isp., *O. nodosa*, but *Chondrites intricatus*, *Chondrites* isp., *Planolites* isp. and *Thalassinoides* isp. are also found. The pre-depositional association is characterized by common *Helminthorhaphe* isp, *Paleodictyon minimum, P. miocenicum* and *P. strozzi* and less frequent?*Circulichnis*, *Cosmorhaphe* isp., *Helminthorhaphe japonica*, *Paleodictyon majus*, *P. maximum* and *Urohelminthoida*. In general, abundance is relatively low, but locally may increase substantially.

Interval III (19.5–31.5 m) is characterized by a very lowly diverse and scarce association of exclusively post-depositional trace fossils: common *Thalassinoides* isp. and rare *Ophiomorpha* isp., *O. annulata* and *O. nodosa*), *Planolites* isp and *Thalassinoides suevicus*.

Interval IV (31.5–46.5 m), representing most of the upper half of the studied section, is the most diverse and bioturbated interval, It almost exclusively contains of post-depositional trace fossils, which are dominated by *Chondrites* isp., *Ophiomorpha* isp., *Planolites* isp., *Scolicia* isp., *Thalassinoides* isp., *Chondrites intricatus*, *Ophiomorpha nodosa*, *Scolicia prisca* and *Thalassinoides suevicus* are common. *Ophiomorpha annulata*, ? *Palaeophycus* isp. and *Phycodes* isp. are rare. Pre-depositional trace fossils are nearly absent, except for more *Scolicia strozzi*.

Interval V (46.5–50 m) is defined by the reappearance and dominance of pre-depositional trace fossils. Some post-depositional trace fossils —e.g. *Chondrites* isp., *Scolicia* isp. and *Thalassinoides* isp.— are identified, being less abundant than pre-depositional structures. The pre-depositional association is more abundant and diverse, being represented by *Cosmorhaphe* isp., *Desmograpton* isp., *Megagrapton* isp., *Paleodictyon arvense*, *P. minimum*, *P. miocenicum*, and *Urohelminthoida* isp.

5. Discussion

5.1. Palaeoenvironmental conditions during the Tortonian muddy fan system deposition in the western Mediterranean Tabernas Basin

Integrative analysis of the sedimentological and ichnological features of the studied section sheds new light on the palaeoenvironmental conditions in the western Mediterranean Tabernas Basin during development of the Tortonian fan system. A dominance of mudstones with intercalated sandstones agrees with the context of deposition in a muddy turbidite system, as previously proposed (e.g., Kleverlaan, 1989a). The registered trace fossil association in the Rambla de Tabernas section can be assigned to the deep-sea *Nereites* ichnofacies, characterized by the abundant presence of graphoglyptids, complex grazing trails and feeding traces, dominant shallow tier trace fossils, and high ichnodiversity (Seilacher, 1964, 1967; Frey and Seilacher, 1980; MacEachern et al., 2007, 2010, 2012; Buatois and Mángano, 2011; Uchman and Wetzel, 2012). The *Nereites* ichnofacies is typically linked to flysch deposits (Rodríguez-Tovar et al., 2010, 2016, 2020; Rodríguez-Tovar, 2022 for a recent review), associated with a continuous and very slow pelagic and hemipelagic background sedimentation, interrupted by episodic turbiditic deposition. In general, the *Nereites* ichnofacies tends to develop under stable, low-energy environmental conditions in quiet, well-oxygenated settings (MacEachern et al., 2007, 2010, 2012; Buatois and Mángano, 2011; Uchman and Wetzel, 2012). The presence of pre-depositional structures throughout the studied section agrees with this favourable developmental habitat for the macrobenthic tracemaker community. Abundant post-depositional trace fossils atop the turbiditic sandstones beds would support oxygenated conditions during and after deposition of the upper part of the turbidite.

5.2. Temporal and lateral variations within the muddy fan system

There is a noteworthy absence of any trend in the sedimentological and ichnological features from bottom to top of the studied section. However, the recognition of both sedimentological and ichnological intervals —in some cases showing recurrent features— would point to temporal and lateral variations within the muddy fan system. Particularly, the *Nereites* ichnofacies can be divided into three ichnosubfacies related to different parts of a turbidite system (Seilacher, 1974; Uchman, 2009). The *Ophiomorpha rudis* ichnosubfacies, mainly consisting of *Ophiomorpha rudis*, *O. annulata* and *Scolicia*, with less common *Nereites* and *Chondrites*, is commonly found in channels and/or proximal lobes of turbidite systems; the *Paleodictyon* ichnosubfacies, characterized by the presence of abundant graphoglyptids, is often found in lower energy environments, such as channel margins, distal lobes or fan fringe sub-environments (Uchman, 2001, 2007, 2009; Heard and Pickering, 2008; Pickering and Hiscott, 2016), and the *Nereites* ichnosubfacies, showing the presence of trace fossils such as *Nereites*, *Phycosiphon* or *Zoophycos*, is common in the most distal parts of turbidite systems, associated with muddy flysch sediments (Seilacher, 1974; Heard and Pickering, 2008; Knaust, 2009; Uchman, 2009; Buatois and Mángano, 2011; Uchman and Wetzel, 2012; Pickering and Hiscott, 2016).

On this basis, some of the differentiated ichnological intervals can be assigned to particular ichnosubfacies in the *Nereites* ichnofacies, associated with temporal and lateral variations in depositional settings in the muddy fan system. An integration of sedimentological data helps support the interpretation (Fig. 7).

Ophiomorpha rudis ichnosubfacies can be tentatively linked to that interval mainly dominated by abundant post-depositional trace fossils mostly found in sandstones beds (i.e., Interval IV), although the eponymous trace fossil (*O. rudis*) was not clearly observed. The abundant presence of *Ophiomorpha*, including *O. annulata*, and *Scolicia* would support the assignation in the study section. This interval correlates mostly with the upper part of sedimentological interval C and the lower part of interval D, mainly characterized by sandstones-mudstones interbedding, and very rare thin siltstones layers, and dominant Tab Bouma intervals. As mentioned, the characterization of *O. rudis* ichnosubfacies has been traditionally linked to proximal areas, e.g. channels and proximal lobes, within a turbiditic system (Uchman, 2001, 2009; Cummings and Hodgson, 2011; Uchman and Wetzel, 2012; Rodríguez-Tovar, 2022). Proximal and axial areas show a low diversity association, mainly post-depositional trace fossils dominated by fodinichnia and domichnia structures (Heard and Pickering, 2008). Turbiditic flows are more erosive in these areas, removing the uppermost part of the sea floor, which contains most of the pre-depositional structures, thereby causing a low preservation of these traces. Only certain deeper ichnotaxa are preserved from the pre-depositional macrobenthic association. These areas also feature a higher presence of post-depositional trace fossils, partly because some tracemakers can survive burial by incoming sediment (Uchman, 1995; Wetzel and Uchman, 2001; Heard and
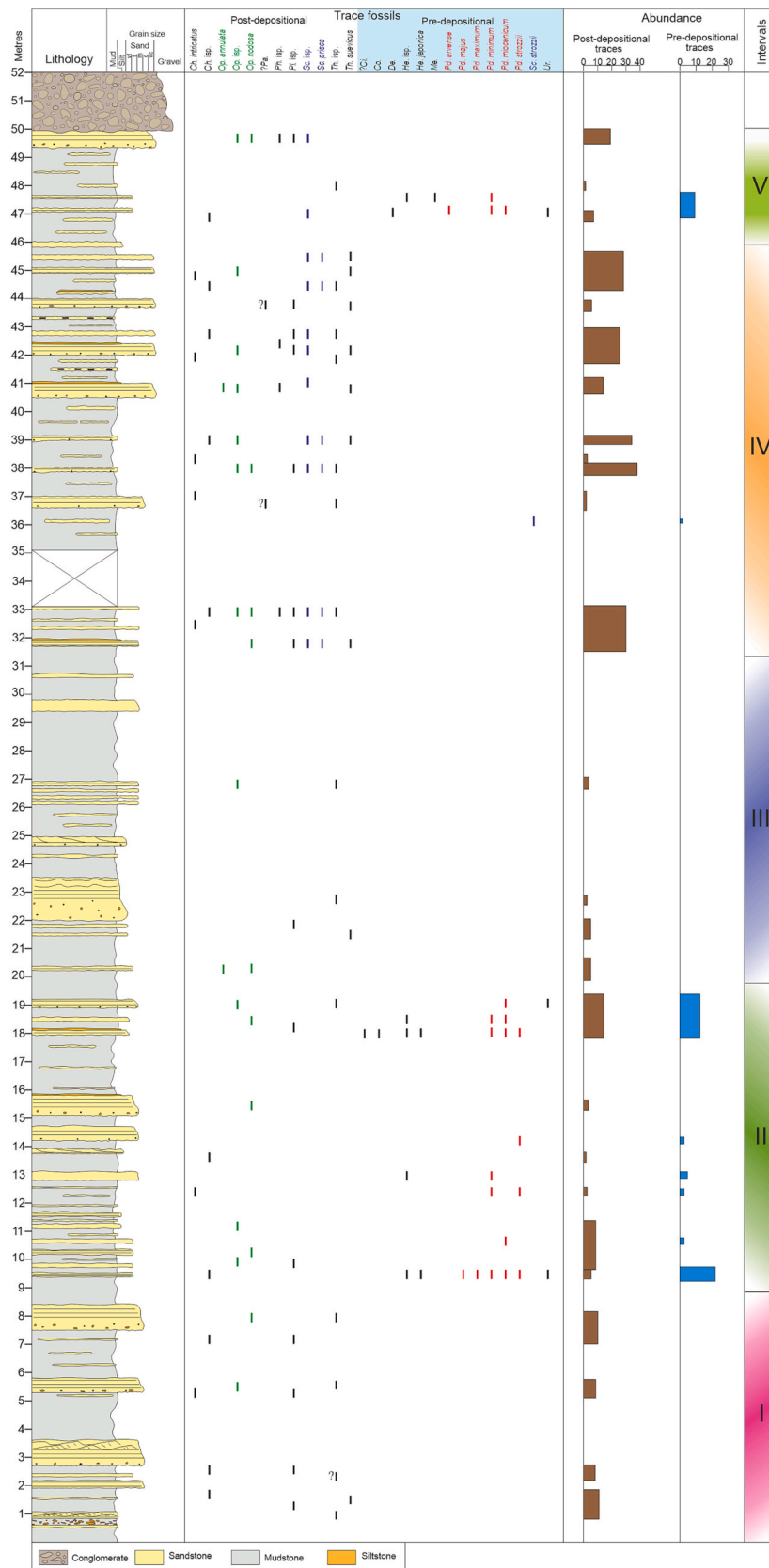
Fig. 6. Ichnological content of the studied section. Sedimentary log of the Rambla de Tabernas Section with the ichnological data, differentiating intervals (i.e., I to V) based on ichnological content. *Ch, Chondrites*; *Ci, Circulichnis*; *Co, Cosmorhaphe*; *De, Desmograpton*; *He, Helminthorhaphe*; *Me, Megagrapton*; *Op, Ophiomorpha*; *?Pa, ? Palaeophycus*; *Pd, Paleodictyon*; *Ph, Phycodes*; *Pl, Planolites*; *Sc, Scolicia*; *Th, Thalassinoides*; *Ur, Urohelminthoida*.
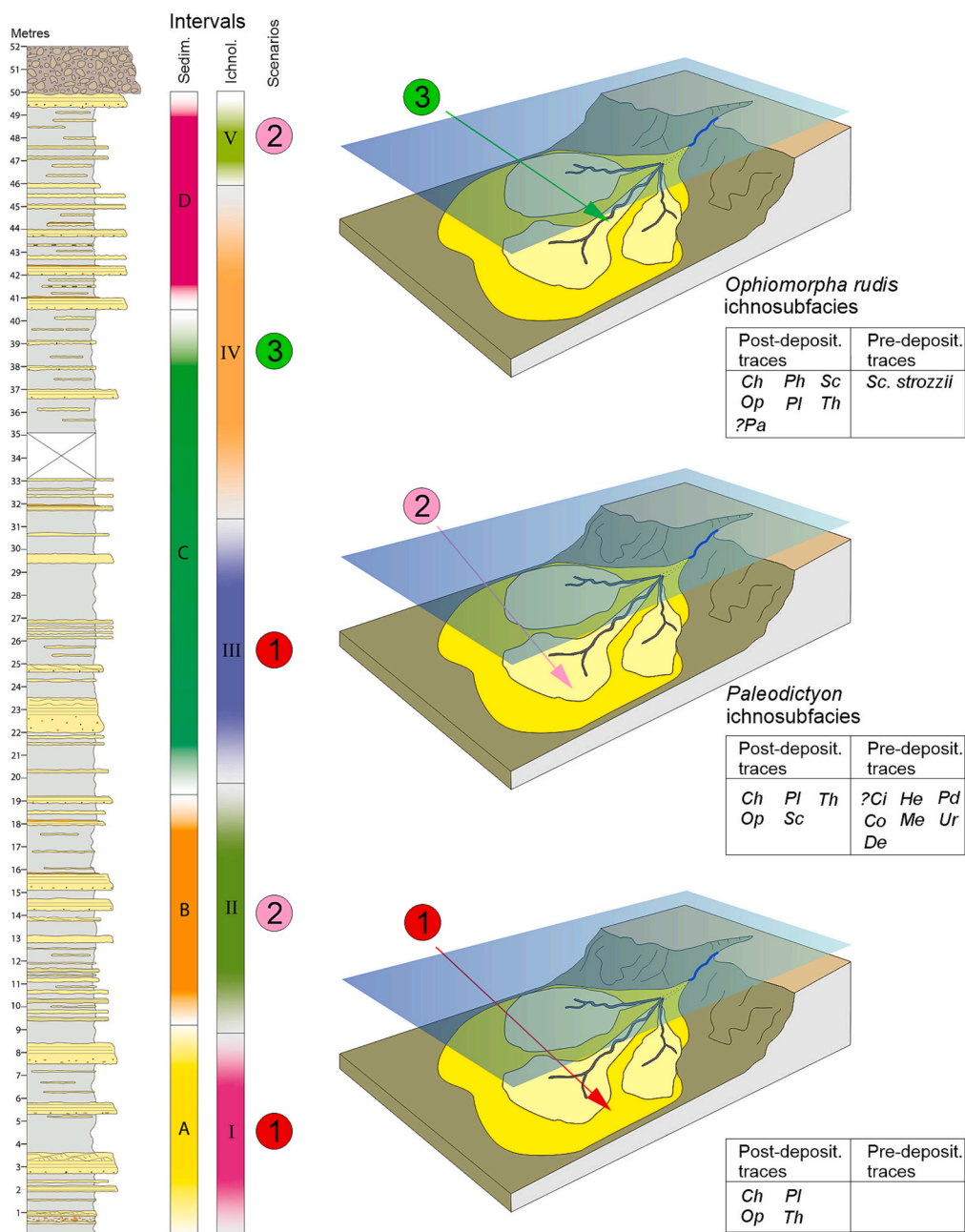
Fig. 7. Interpreted depositional settings. Summarizing sketch showing the different sub-environments within a deep-sea muddy system characterized in the Rambla de Tabernas Section. *Ch, Chondrites*; ?*Ci, ?Circulichnis*; *Co, Cosmorhaphe*; *De, Desmograpton*; *He, Helminthorhaphe*; *Me, Megagrapton*; *Op, Ophiomorpha*; ?*Pa, ?Palaeophycus*; *Pd, Paleodictyon*; *Ph, Phycodes*; *Pl, Planolites*; *Sc, Scolicia*; *Th, Thalassinoides*; *Ur, Urohelminthoida*.

Pickering, 2008). Interpretation of proximal, higher energy settings within the studied turbiditic system is supported by the increased proportion of sandstones and Tab Bouma intervals.

The *Paleodictyon* ichnosubfacies has been assigned to intervals II and V, which are characterized by the abundance of pre-depositional traces. These intervals correlated mostly with the sedimentological interval B and upper part of interval D, showing sandstones-mudstones interbedding, very rare thin siltstones layers, and the presence of Tab/Tabc Bouma intervals. As indicated, this ichnosubfacies is usually related to sandy, medium- to thin-bedded flysch deposits, with a characteristic presence of graphoglyptids (Uchman, 2001, 2007, 2009; Heard and Pickering, 2008; Buatois and Mángano, 2011; Pickering and Hiscott, 2016). Preservation of graphoglyptids is linked to turbidity currents that remove the unconsolidated mud without notable erosion (Seilacher, 2007), hence commonly linked to lower energy environments of the

turbidite system, or outer fan areas (e.g., Wetzel, 1984; Uchman, 2001; Cummings and Hodgson, 2011; Uchman and Wetzel, 2012). Such areas are characterized by a lower presence of domichnia and a substantial increase in agrichnia (Heard and Pickering, 2008). The presence of Tabc Bouma intervals could support depositional settings affected by weaker gravity flows, but the scarcity of data impedes a conclusive correlation.

Finally, the other two intervals (I and III) are characterized by less abundant post-depositional trace fossils and an absence of pre-depositional ones. These intervals have dominant mudstones with some interbedded sandstones, and only Tabc Bouma intervals. Considering the general muddy fan system context, one might envisage a depositional setting located in the lowest energetic part of the system, for instance the most distal parts, usually associated with the *Nereites* ichnosubfacies. Yet the absence of trace fossils such as *Nereites*, *Phycosiphon* or *Zoophycos*, common to such distal parts, precludes assignation

to this ichnosubfacies. Low energy depositional settings as those related with distal levees, overbanks, or interdistributary channels could be interpreted.

In short, the temporal distribution of ichnosubfacies and sedimentological features throughout the studied section reveals marked changes in the turbiditic system before deposition of the Gordo megabed, with a lower half reflecting generalized low energy conditions, probably related to distal areas, and the recurrence of depositional settings; and an upper half revealing increased high energy conditions and deposition in proximal settings (i.e. channels and proximal lobes).

5.3. Paleogeographic context influencing ichnodiversity at the western Mediterranean Tabernas muddy fan systems; a particular case worldwide?

Detailed ichnological analysis of the Miocene Rambla de Tabernas section revealed a trace fossil association comprising 26 ichnospecies belonging to 14 ichnogenera (eight of them pre-depositional). These numbers are relatively low for deep-sea fan systems, considering previous studies. For example, Crimes and Crossley (1991) studied a Silurian flysch from the Aberystwyth Grits Fm. in Wales, describing 36 ichnospecies pertaining to 25 ichnogenera. Wetzel et al. (2007) recognized 32 ichnogenera (18 pre-depositional trace fossils) in turbiditic deposits from the Upper Triassic Al Ayn Fm. in Oman. Bayet-Goll et al. (2014) identified 36 ichnogenera in the deep-marine turbiditic succession of the Amiran Formation (upper Maastrichtian–Paleocene), Iran. Further examples in the Cenozoic show assemblages of higher diversity, such as the studies of Uchman (2001) and Heard and Pickering (2008) on Eocene turbiditic sections from the Ainsa-Jaca basin (northern Spain), respectively, identifying 63 ichnotaxa (40 ichnogenera), and 95 ichnotaxa (from 49 ichnogenera). Rodríguez-Tovar et al. (2010) identified 41 ichnospecies belonging to 28 ichnogenera in the coeval Eocene turbiditic section of Gorrondatxe in the northern Iberian Peninsula; and later among mostly Paleocene turbidites from the Campo de Gibraltar (SE Spain), Rodríguez-Tovar et al. (2016) found 32 ichnogenera (12 of them from graphoglyptids). Other examples are the Eocene siliciclastic Kusuri Fm. in Turkey, with 38 ichnospecies (23 pre-depositional trace fossils) belonging to 27 ichnogenera (Uchman et al., 2004), or the 42 ichnogenera characterized in some outcrops from the Lower Eocene Gurnigel Flysch in Switzerland (Crimes et al., 1981). It should be considered that the diversity of deep-sea ichnogenera varies though time, reaching the maximum in the Eocene (see Uchman and Wetzel, 2012), but anyway the diversity of the study area is relatively low. The lower ichnodiversity and abundance in the studied section, especially of pre-depositional structures, suggest the particularity of the Tabernas muddy fan system.

A highly diverse association of pre-depositional trace fossils is usually associated with stable conditions, good oxygen levels and low food availability (Uchman, 1992). The development of pre-depositional trace fossils, especially graphoglyptids, requires a long time interval and low sedimentation rate between turbidite deposition. In the case study, a relatively high sedimentation rate of hemipelagic material between turbidites, along with a short recurrence time between turbidites, may impede a diverse pre-depositional tracemaker community and therefore explain the recorded low ichnodiversity.

6. Conclusions

This integrative sedimentological and ichnological analysis of the Rambla de Tabernas section revealed new information about the deepsea muddy system of the Tabernas Basin (southeastern Spain). The relative abundance of mudstones-sandstones, in addition to the thicknesses, sedimentary structures and identified Bouma intervals, allowed us to distinguish four intervals that fit with previous interpretations of a turbiditic muddy system.

The trace fossil association is characterized by 26 ichnospecies, belonging to 14 ichnogenera, that are grouped in post-depositional

(*Chondrites* ips., *Ophiomorpha* isp., ?*Palaeophycus* isp., *Phycodes* isp., *Planolites* isp., *Scolicia* isp. and *Thalassinoides* isp.) and pre-depositional (?*Circulichnis* isp., *Scolicia strozzii* and graphoglyptids as *Cosmorhaphe* isp.*, Desmograpton* isp., *Helminthorhaphe* isp.*, H. japonica, Megagrapton* isp., *Paleodictyon arvense, P. majus, P. maximum, P. minimum, P. miocenicum, P. strozzii* and *Urohelminthoida* isp.,) structures which are associated to the *Nereites* ichnofacies. Based on their distribution along the section, five intervals were differentiated. Intervals I and III are dominated by low abundant post-depositional trace fossils in mudstones dominated beds, being linked to the lowest energy conditions in the most distal parts of the system. In turn, Intervals II and V were defined by dominant and abundant pre-depositional structures, assigned to the *Paleodictyon* ichnosubfacies, in a sandstones-mudstones interbedding, related to outer fan areas. Finally, Interval IV is characterized by abundant post-depositional trace fossils, related to the *Ophiomorpha rudis* ichnosubfacies, in sandstones dominated beds, being linked to proximal areas such as channels or proximal lobe settings.

Before deposition of the Gordo megabed, the turbiditic system in the studied area shows generalized low energy conditions in the lower part, probably related to distal areas, and then high energy conditions and deposition in proximal settings (i.e., channels and proximal lobes) in the upper part.

The ichnological analysis reveals a relatively low diversity trace fossil association when compared with previous studies in similar settings. This anomalous ichnodiversity can be caused by relatively high sedimentation rates between turbiditic events in addition to a short recurrence time between turbidites, thus impeding a diverse predepositional tracemaker community.

This novel detailed ichnological study evidences the usefulness of trace fossils to improve our understanding of palaeoenvironmental conditions during turbiditic deposition in the Tabernas Basin, with significant scientific and potential economic implications.

Declaration of Competing Interest

All the authors approve the manuscript and confirm that all the results and interpretations therein are original and have not been previously published. Moreover, we declare there is not any conflict of interest associated with the present contribution.

Data availability

Data will be made available on request.

References

Barbier, R., 1956. Découverte d'un Palaeodictyon dans le Dogger ultradauphinois de la région des Aiguilles d'Arves. Trav. Lab. Fac. Sci. Univ. Grenoble 33, 125–133.
Baucon, A., Bednarz, M., Dufour, S., Felletti, F., Malgesini, G., Neto de Carvalho, C., Niklas, K.J., Wehrmann, A., Batstone, R., Bernardini, F., Briguglio, A., Cabella, R., Cavalazzi, B., Ferretti, A., Zanzerl, H., McIlroy, D., 2020. Ethology of the trace fossil

Chondrites: form, function and environment. Earth-Sci. Rev. 202 https://doi.org/10.1016/j.earscirev.2019.102989.

Baudouy, L., Haughton, P.D.W., Walsh, J.J., 2021. Evolution of a fault-controlled, deep-water Sub-Basin, Tabernas, SE Spain. Front. Earth Sci. 9 https://doi.org/10.3389/feart.2021.767286.

Bayet-Goll, A., Neto De Carvalho, C., Moussavi-Harami, R., Mahboubi, A., Nasiri, Y., 2014. Depositional environments and ichnology of the deep-marine succession of the Amiran Formation (upper Maastrichtian–Paleocene), Lurestan Province, Zagros Fold–Thrust Belt, Iran. Palaeogeogr. Palaeoclimatol. Palaeoecol. 401, 13–42. https://doi.org/10.1016/j.palaeo.2014.02.019.

Bouma, A.H., 1962. Sedimentology of Some Flysch Deposits: A Graphic Approach to Facies Interpretation. Elsevier, Amsterdam, 168 pp.

Braga, J.C., Martín, J.M., Quesada, C., 2003. Patterns and average rates of late Neogene-recent uplift of the Betic Cordillera, SE Spain. Geomorphology 50, 3–26.

Brongniart, A., 1828. Histoire des végétaux fossiles ou recherches botaniques et géologiques sur les végétaux renfermés dans les diverses couches du globe. Paris.

Buatois, L.A., Mángano, M.G., 2011. Ichnology: Organism-Substrate Interactions in Space and Time. In: Cambridge University Press, Cambridge, p. 358.

Crimes, T.P., Crossley, J.D., 1991. A diverse ichnofauna from Silurian flysch of the Aberystwyth Grits Formation, Wales. Geol. J. 26, 27–64.

Crimes, T.P., Goldring, R., Homewood, P.Van, Stuijvenberg, J., Winkler, W., 1981. Trace fossil assemblages of deep-sea fan deposits, Gurnigel and Schlieren flysch (Cretaceous-Eocene), Switzerland. Eclogae Geol. Helv. 74, 953–995.

Cummings, J.P., Hodgson, D.M., 2011. Assessing controls on the distribution of ichnotaxa in submarine fan environments, the Basque Basin, Northern Spain. Sediment. Geol. 239, 162–187. https://doi.org/10.1016/j.sedgeo.2011.06.009.

de Castro, D., Miramontes, E., Dorador, J., Jouet, G., Cattaneo, A., Rodríguez-Tovar, F.J., Hernández-Molina, F.J., 2021. Siliciclastic and bioclastic contouritic sands: textural and geochemical characterisation. Mar. Pet. Geol. 128, 105002 https://doi.org/10.1016/j.marpetgeo.2021.105002.

de Quatrefages, M.A., 1849. Note sur le Scolicia prisca (A. de Q.) Annélide fossile de la Craie. Ann. Sci. Nat. 3 series Zoologie 12, 265–266.

De Matteis, M., Belaústegui, Z., Arbués, P., Granado, P., Cabello, P., Demko, T., Abreu, V., 2016. In: Ichnological analysis of the turbidite Solitary Channel Complex from drillcore data (Miocene, Tabernas Basin, SE, Spain). Ichnia 4th. Portugal, pp. 78–79.

De Matteis, M., Arbués, P., Belaústegui, Z., Cabello, P., Granado, P., Demko, T., Abreu, V., 2016. Flow characteristics as inferred from core and outcrop data of turbidite channel-fill: The Solitary Channel (Miocene, Tabernas Basin, SE Spain), 32nd International meeting of sedimentology. Marrakesh, Morocco. http://programme.exordo.com/ims2016/delegates/presentation/421/, 32nd International meeting of sedimentology. Marrakesh, Morocco.

Dorador, J., Rodríguez-Tovar, F.J., Mena, A., Francés, G., 2019. Lateral variability of ichnological content in muddy contourites: weak bottom currents affecting organisms' behavior. Sci. Rep. 9, 17713.

Dorador, J., Rodríguez-Tovar, F.J., Mena, A., Francés, G., 2021. Deep-sea bottom currents influencing tracemaker community: an ichnological study from the NW Iberian margin. Mar. Geol. 437, 106503 https://doi.org/10.1016/j.margeo.2021.106503.

Doyle, P., Mather, A.E., Bennett, M.R., Bussell, M.A., 1996. Miocene barnacle assemblages from southern Spain and their palaeoenvironmental significance. Lethaia 29, 267–274. https://doi.org/10.1111/j.1502-3931.1996.tb01659.x.

Ehrenberg, K., 1944. Ergänzende Bemerkungen zu den seinerzeit aus dem Miozän von Burgschleinitz beschriebenen Gangkernen und Bauten dekapoder Krebse. Paläontol. Z. 23, 345–359.

Eichwald, E., 1868. Lethaea Rossica ou Paléontologie de la Russie. Atlas 1657.

Ekdale, A.A., 1980. Graphoglyptid burrows in modern deep-sea sediment. Science 207, 304–306. https://doi.org/10.1126/science.207.4428.304.

Ekdale, A.A., 1985. Paleoecology of the marine endobenthos. Palaeogeogr. Palaeoclimatol. Palaeoecol. 50, 63–81. https://doi.org/10.1016/S0031-0182(85)80006-7.

Ekdale, A.A., Bromley, R.G., Pemberton, S.G., 1984. Ichnology: the use of trace fossils in sedimentology and stratigraphy. Soc.Econ.Paleontol.Mineral. https://doi.org/10.2110/scn.84.15.

Fan, R.Y., Uchman, A., Gong, Y.M., 2017. From morphology to behavior: quantitative morphological study of the trace fossil Helminthorhaphe. Palaeogeogr. Palaeoclimatol. Palaeoecol. 485, 946–955.

Fillion, D., Pickerill, R.K., 1990. Ichnology of the Upper Cambrian? to Lower Ordovician Bell Island and Wabana groups of eastern Newfoundland, Canada, Palaeontographica Canadiana. Canadian Society of Petroleum Geologists; Geological Association of Canada, Calgary.

Frey, R.Q., Seilacher, A., 1980. Uniformity in marine invertebrate ichnology. Lethaia 13, 183–207.

Frey, R.W., Howard, J.D., Pryor, W.A., 1978. Ophiomorpha: its morphologic, taxonomic, and environmental significance. Palaeogeogr. Palaeoclimatol. Palaeoecol. 23, 199–229. https://doi.org/10.1016/0031-0182(78)90094-9.

Fu, S., 1991. Funktion, Verhalten und Einteilung fucoider und lophoctenoider Lebensspuren. Cour. Forschungsinstitut Senckenberg 135, 1–79.

Fuchs, T., 1895. Studien über Fucoiden und Hieroglyphen. Denkschr. Kais. Akad. Wiss. Zu Wien, Mathematisch-naturwissenschaftliche Klasse 62, 369–448.

Hall, J., 1847. Palaeontology of New York. Volume 1. C. Van Benthuysen, Albany. https://doi.org/10.5962/bhl.title.66970, 338 pp.

Han, Y., Pickerill, R.K., 1994. Phycodes templus isp. Nov. From the Lower Devonian of northwestern New Brunswick, eastern Canada. Atl. Geol. 30 https://doi.org/10.4138/2118.

Haughton, P.D.W., 2000. Evolving turbidite systems on a deforming basin floor, Tabernas, SE Spain. Sedimentology 47, 497–518. https://doi.org/10.1046/j.1365-3091.2000.00293.x.

Heard, T.G., Pickering, K.T., 2008. Trace fossils as diagnostic indicators of deep-marine environments, Middle Eocene Ainsa-Jaca basin, Spanish Pyrenees. Sedimentology 55, 809–844. https://doi.org/10.1111/j.1365-3091.2007.00922.x.

Hodgson, D.M., 2002. Tectono-stratigraphic evolution of a Neogene oblique extensional orogenic basin, southeast Spain (Ph.D. thesis). University of London, United Kingdom, 478 pp.

Hodgson, D.M., Haughton, P.D.W., 2004. Impact of syndepositional faulting on gravity current behaviour and deep-water stratigraphy: Tabernas-Sorbas Basin, SE Spain. Geol. Soc. Lond. Spec. Publ. 222, 135–158. https://doi.org/10.1144/GSL.SP.2004.222.01.08.

Keighley, D.G., Pickerill, R.K., 1995. The ichnotaxa Palaeophycus and Planolites: historical perspectives and recommendations. Ichnos 3, 301–309. https://doi.org/10.1080/10420949509386400.

Kern, J.P., 1980. Origin of trace fossils on Polish Carpathian flysch. Lethaia 13, 347–372.

Kleverlaan, K., 1987. Gordo Megabed: a possible seismite in a Tortonian submarine fan, Tabernas basin, province Almería, Southeast Spain. Sediment. Geol. 51, 165–180.

Kleverlaan, K., 1989. Three distinctive feeder-lobe systems within one time slice of the Tortonian Tabernas fan, SE Spain. Sedimentology 36 (1), 25–45.

Kleverlaan, K., 1989b. Neogene history of the Tabernas basin (SE Spain) and its Tortonian submarine fan development. Geol. Mijnb. 68 (4), 421–432.

Knaust, D., 2009. Characterisation of a Campanian deep-sea fan system in the Norwegian Sea by means of ichnofabrics. Mar. Pet. Geol. 26, 1199–1211. https://doi.org/10.1016/j.marpetgeo.2008.09.009.

Kotake, N., 1991. Packing process for the filling material in Chondrites. Ichnos 1, 277–285. https://doi.org/10.1080/10420949109386362.

Książkiewicz, M., 1954. Uziarnienie frakcjonalne i laminowane we fliszu karpackim (Graded and laminated bedding in the Carpathian Flysch). Ann. Soc. Geol. Pol. 22, 399–471.

Książkiewicz, M., 1968. O nietórych probleatykach z flisz Karpat polskich, Część III. [On the problematic organic traces from the flysch of the Polish Carpathians. Part 3]. Rocz. Pol. Tow. Geol. 38, 3–17.

Książkiewicz, M., 1970. Observations on the ichnofauna of the Polish Carpathians. In: Crimes, T.P., Harper, J.C. (Eds.), Geological Journal, Special, Issues 3. Seel House Press, Liverpool, pp. 283–322.

Książkiewicz, M., 1977. Trace fossils in the Flysch of the Polish Carpathians. Palaeontolologica Pol. 36, 1–208.

Leszczyński, S., 1993. A generalized model for the development of ichnocoenoses in flysch deposits. Ichnos 2, 137–146. https://doi.org/10.1080/10420949309380083.

Lowe, D.R., 1982. Sediment gravity flows: II. Depositional models with special reference to the deposits of high-density turbidity currents. J. Sediment. Petrol. 52, 279–297.

Lundgren, B., 1891. Studier öfver fossilförande lösa block. Geol. Fören. Stockh. Förh. 13, 111–121. https://doi.org/10.1080/11035899109446863.

MacEachern, J.A., Bann, K.L., Pemberton, S.G., Gingras, M.K., 2007. The ichnofacies paradigm: high-resolution paleoenvironmental interpretation of the rock record. In: MacEachern, J.A., Bann, K.L., Gingras, M.K., Pemberton, S.G. (Eds.), Applied Ichnology. Society for Sedimentary Geology Short Course Notes 52, pp. 27–64.

MacEachern, J.A., Pemberton, S.G., Gingras, M.K., Bann, K.L., 2010. Ichnology and facies models. In: James, N.O., Dalrymple, R.W. (Eds.), Facies Models 4. Geological Association of Canada, pp. 19–58.

MacEachern, J.A., Bann, K.L., Gingras, M.K., Zonneveld, J.-P., Dashtgard, S.E., Pemberton, S.G., 2012. The ichnofacies paradigm. In: Knaust, D., Bromley, R.G. (Eds.), Trace Fossils as Indicators of Sedimentary Environments. Developments in Sedimentology, vol. 64. Elsevier, pp. 103–138.

Mayoral, E., Ledesma-Vazquez, J., Baarli, B.G., Santos, A., Ramalho, R., Cachão, M., da Silva, C.M., Johnson, M.E., 2013. Ichnology in oceanic islands; case studies from the Cape Verde Archipelago. Palaeogeogr. Palaeoclimatol. Palaeoecol. 381–382, 47–66. https://doi.org/10.1016/j.palaeo.2013.04.014.

Miguez-Salas, O., Rodríguez-Tovar, F.J., Duarte, L.V., 2017. Selective incidence of the Toarcian oceanic anoxic event on macroinvertebrate marine communities: a case from the Lusitanian basin, Portugal. Lethaia 50, 548–560. https://doi.org/10.1111/let.12212.

Muñiz, F., Mayoral, E., Santos, A., 2002. Consideraciones taxonómicas sobre el icnogénero Phycodes. In: Civis, J., González Delgado, J.A. (Eds.), Libro de Resúmenes de las XVIII Jornadas de la Sociedad Española de Paleontología/II Congreso Ibérico de Paleontología, Salamanca (España), pp. 94–95.

Nicholson, H.A., 1873. Contributions to the study of the errant Annelides of the older Palaeozoic rocks. Proc. R. Soc. Lond. 21, 288–290. https://doi.org/10.1098/rspl.1872.0061.

Nielsen, J.K., Görmüş, M., Uysal, K., Kanbur, S., 2012. Ichnology of the Miocene Güneyce Formation (Southwest Turkey): oxygenation and sedimentation dynamics. Turk. J. Earth Sci. 21, 391–405. https://doi.org/10.3906/yer-1011-40.

Pemberton, S.G., Frey, R.W., 1982. Trace fossil nomenclature and the Planolites-Palaeophycus dilemma. J. Paleontol. 56, 843–881.

Pemberton, S.G., MacEachern, J.A., Frey, R., 1992. Trace fossil facies models: environmental and allostratigraphic significance. In: Walker, R.G., James, N.P. (Eds.), Facies Models. Response to Sea Level Change, Geological Association of Canada, St Jones, pp. 47–72.

Peruzzi, D., 1880. Osservazioni sui generi Paleodictyon e Paleomeandron dei terreni cretacei ed eocenici dell'Appennino sett. e centrale. Atti Della Soc. Toscana Sci. Nat. Resid. Pisa Memorie 5, 3–8.

Pickering, K.T., Hodgson, D.M., Platzman, E., Clark, J.D., Stephens, C., 2001. A new type of bedform produced by backfilling processes in a submarine channel, late Miocene,

Tabernas-Sorbas Basin, SE Spain. J. Sediment. Res. 71, 692–704. https://doi.org/10.1306/2DC40960-0E47-11D7-8643000102C1865D.

Pickering, K.T., Hiscott, R.N., 2016. Deep Marine Systems: Processes, Deposits, Environments, Tectonics and Sedimentation. John Wiley & Sons.

Popov, S.V., Rögl, F., Rozanov, A.Y., Steininger, F.F., Shcherba, I.G., Kovac, M., 2004. Lithological-Paleogeographic maps of Parathetys. 10 Maps. Late Eocene to Pliocene. Cour. Forsch. Senckenberg 250, 1–46.

Postma, G., Cartigny, M., Kleverlaan, K., 2009. Structureless, coarse-tail graded Bouma Ta formed by internal hydraulic jump of the turbidity current? Sediment. Geol. 219, 1–6. https://doi.org/10.1016/j.sedgeo.2009.05.018.

Postma, G., Kleverlaan, K., Cartigny, M.J.B., 2014. Recognition of cyclic steps in sandy and gravelly turbidite sequences, and consequences for the Bouma facies model. Sedimentology 61, 2268–2290. https://doi.org/10.1111/sed.12135.

Richter, R., 1850. As der Thüringischen Grauwacke. Z. Dtsch. Geol. Gesselschaft 2, 198–206.

Rodríguez-Tovar, F.J., 2022. Ichnological analysis: a tool to characterize deep-marine processes and sediments. Earth-Sci. Rev. 228, 104014 https://doi.org/10.1016/j.earscirev.2022.104014.

Rodríguez-Tovar, F.J., Uchman, A., 2004. Ichnotaxonomic analysis of the Cretaceous/Palaeogene boundary interval in the Agost section, south-East Spain. Cretac. Res. 25, 635–647. https://doi.org/10.1016/j.cretres.2004.06.003.

Rodríguez-Tovar, F.J., Uchman, A., 2017. The Faraoni event (latest Hauterivian) in ichnological record: the Río Argos section of southern Spain. Cretac. Res. 79, 109–121. https://doi.org/10.1016/j.cretres.2017.07.018.

Rodríguez-Tovar, F.J., Puga-Bernabéu, Á., Buatois, L.A., 2008. Large burrow systems in marine Miocene deposits of the Betic Cordillera (Southeast Spain). Palaeogeogr. Palaeoclimatol. Palaeoecol. 268, 19–25. https://doi.org/10.1016/j.palaeo.2008.07.022.

Rodríguez-Tovar, F.J., Uchman, A., Martín-Algarra, A., 2009. Oceanic Anoxic Event at the Cenomanian-Turonian boundary interval (OAE-2): ichnological approach from the Betic Cordillera, southern Spain. Lethaia 42, 407–417. https://doi.org/10.1111/j.1502-3931.2009.00159.x.

Rodríguez-Tovar, F.J., Piñuela, L., García-Ramos, J.C., 2016. Trace fossils assemblages from the Cenozoic "Flysch units" of the Campo de Gibraltar complex (Southern Spain). Ichnos an Int. J. Plant Anim. 23, 53–70. https://doi.org/10.1080/10420940.2015.1130708.

Rodríguez-Tovar, F.J., Pujalte, V., Payros, A., 2020. Danian-lower Selandian Microcodium-rich calcarenites of the Subbetic Zone (SE Spain): record of Nereites ichnofacies in a deep-sea, base-of-slope system. Sediment. Geol. 406, 105723 https://doi.org/10.1016/j.sedgeo.2020.105723.

Rodríguez-Tovar, F.J., Miguez-Salas, O., Duarte, L.V., 2017. Toarcian Oceanic Anoxic Event induced unusual behaviour and palaeobiological changes in Thalassinoides tracemakers. Palaeogeogr. Palaeoclimatol. Palaeoecol. 485, 46–56. https://doi.org/10.1016/j.palaeo.2017.06.002.

Rodríguez-Tovar, F.J., Miguez-Salas, O., Dorador, J., 2022. Deepwater ichnology: new observations on contourites. In: Rotzien, F.R., Yeilding, C.A., Sears, R.A., Hernández-Molina, F.J., Catuneanu, O. (Eds.), Deepwater Sedimentary Systems. Elsevier, pp. 533–554.

Rodríguez-Tovar, F.J., Uchman, A., Payros, A., Orue-Etxebarria, X., Apellaniz, E., Molina, E., 2010. Sea-level dynamics and palaeoecological factors affecting trace fossil distribution in Eocene turbiditic deposits (Gorrondatxe section, N Spain). Palaeogeogr. Palaeoclimatol. Palaeoecol. 285, 50–65. https://doi.org/10.1016/j.palaeo.2009.10.022.

Rotzien, J.R., Hernández-Molina, F.J., Fonnnesu, M., Thieblemont, A., 2022. Deepwater sedimentation units. In: Rotzien, F.R., Yeilding, C.A., Sears, R.A., Hernández-Molina, F.J., Catuneanu, O. (Eds.), Deepwater Sedimentary Systems. Elsevier, pp. 203–249.

Sacco, F., 1886. Impronte organiche Dei terreni terziari del Piemonte. Atti Della R. Accad. Della Sci. Torino 21, 297–348.

Sacco, F., 1888. Note di paleoicnologia Italiana. Atti Della Soc. Ital. Sci. Nat. 31, 151–192.

Savi, P., Meneghini, G., 1850. Osservazioni stratigrafiche e paleontologischeconcernati la geologia della Toscana e dei paesi limitrofi, Apendix Memoria sulla struttura geologica delle Alpi, degli Apennini e dei Carpazi. Firenze.

Seilacher, A., 1962. Paleontological studies on turbidite sedimentation and erosion. J. Geol. 70, 227–234.

Seilacher, A., 1964. Sedimentological classification and nomenclature of trace fossils. Sedimentology 3, 253–256.

Seilacher, A., 1967. In: Bathymetry of trace fossils. Mar. Geol., Depth indicators in marine sedimentary environments 5, pp. 413–428. https://doi.org/10.1016/0025-3227(67)90051-5.

Seilacher, A., 1974. In: Flysch trace fossils: evolution of behavioural diversity in the deep-sea. Neues Jahrbuch für Geologie und Palaontologie, Monatshefte, pp. 233–245.

Seilacher, A., 1977a. Pattern analysis of Paleodictyon and related trace fossils. In: Crimes, T.P., Harper, J.C. (Eds.), Trace Fossils 2Geol. J. Spec, Issues 9. Seel House Press, Liverpool, pp. 289–334.

Seilacher, A., 1977. Evolution of trace fossil communities. In: Hallam, A. (Ed.), Developments in Palaeontology and Stratigraphy, Patterns of Evolution as Illustrated by the Fossil Record. Elsevier, pp. 359–376. https://doi.org/10.1016/S0920-5446(08)70331-5.

Seilacher, A., 1990. Aberrations in bivalve evolution related to photo- and chemosymbiosis. Hist. Biol. 3, 289–311. https://doi.org/10.1080/08912969009386528.

Seilacher, A., 2007. Trace Fossil Analysis. In: Springer—Verlag, Berlin, p. 226 pp.. https://doi.org/10.1007/978-3-540-47226-1.

Singh, R.H., Rodríguez-Tovar, F.J., Ibotombi, S., 2008. Trace fossils of the upper Eocene-lower Oligocene transition of the Manipur, Indo-Myanmar Ranges (Northeast India). Turk. J. Earth Sci. 17, 821–834.

Stow, D.A.V., Shanmugam, G., 1980. Sequence of structures in fine-grained turbidites: comparison of recent deep-sea and ancient flysch sediments. Sed. Geol. 25, 23–42.

Tanaka, K., 1970. Sedimentation of the cretaceous flysch sequence in the Ikushumbetsu area Hokkaido, Japan. Geol. Surv. Jpn. 1–102.

Uchman, A., 1992. An opportunistic trace-fossil assemblage from the flysch of the Inoceramian beds (Campanian-Paleocene), Bystrica zone of the Magura Nappe, Carpathians, Poland. Cretac. Res. 13, 539–547.

Uchman, A., 1995. Taxonomy and palaeoecology of flysch trace fossils: the Marnoso-arenacea Formation and associated facies (Miocene, Northern Apennines, Italy), Beringeria Heft. Freunde der Würzburger Geowissenschaften, Würzburg.

Uchman, A., 1998. Taxonomy and ethology of flysch trace fossils: revision of the Marian Książkiewicz collection and studies of complementary material. Ann. Soc. Geol. Pol. 68, 105–218.

Uchman, A., 2001. Eocene flysch trace fossils from the Hecho Group of the Pyrenees, northern Spain. Beringeria 28, 3–41.

Uchman, A., 2007. Deep-sea ichnology: development a major concepts. In: Miller III, W. (Ed.), Trace Fossils. Concepts, Problems, Prospects. Elsevier, Amsterdam, pp. 248–267.

Uchman, A., 2009. The Ophiomorpha rudis ichnosubfacies of the Nereites ichnofacies: characteristics and constraints. Palaeogeogr. Palaeoclimatol. Palaeoecol. 276, 107–119. https://doi.org/10.1016/j.palaeo.2009.03.003.

Uchman, A., Wetzel, A., 2011. Deep-sea ichnology: the relationships between depositional environment and endobenthic organisms. In: Hüneke, H., Mulder, T. (Eds.), Developments in Sedimentology, vol. 63. Elsevier, pp. 517–556. https://doi.org/10.1016/B978-0-444-53000-4.00008-1.

Uchman, A., Wetzel, A., 2012. Deep-sea fans. In: Knaust, D., Bromley, R.G. (Eds.), Trace Fossils as Indicators of Sedimentary Environments. Developments in Sedimentology, vol. 64. Elsevier, pp. 643–671.

Uchman, A., Rattazzi, B., 2019. The trace fossil Circulichnis as a record of feeding exploration: new data from deep-sea Oligocene-Miocene deposits of northern Italy. Comptes Rendus - Palevol 18, 1–12.

Uchman, A., Janbu, N.E., Nemec, W., 2004. Trace fossils in the Cretaceous-Eocene flysch of the Sinop-Boyabat basin, central Pontides, Turkey. Annales Societatis Geologorum Poloniae 74, 197–235.

Uchman, A., Lebanidze, Z., Beridze, T., Kobakhidze, N., Lobzhanidze, K., Khutsishvili, S., Chagelishvili, R., Makadze, D., Koiava, K., Khundadze, N., 2022. Revision of the trace fossil Megagrapton Książkiewicz, 1968 with focus on Megagrapton aequale Seilacher, 1977 from the lower Eocene of the Lesser Caucasus in Georgia. Geol. Quart. 66, 66–68. https://doi.org/10.7306/gq.1640.

Vallon, L.H., Rindsberg, A.K., Bromley, R.G., 2016. An updated classification of animal behaviour preserved in substrates. Geodin. Acta 28, 1–16. https://doi.org/10.1080/09853111.2015.1065306.

Vialov, O.S., 1971. The rare Mesozoic problematica from Pamir and Caucasus. Paleontol. Sb. 7, 85–93.

von Sternberg, G.K., 1833. Versuch einer geognostisch – botanischen Darstellung der Flora der Vorwelt. 48..

Wetzel, A., 1984. Bioturbation in deep-sea fine-grained sediments, influence of sediment texture, turbidite frequency and rates of environmental change. In: Stow, D.A.V., Piper, D.J.W. (Eds.), Fine-Grained Sediments: Deep Water Processes and Facies. Geological Society Special Publication 15, pp. 595–608. https://doi.org/10.1144/GSL.SP.1984.015.01.37.

Wetzel, A., Uchman, A., 2001. Sequential colonization of muddy turbidites in the Eocene Beloveža Formation, Carpathians, Poland. Palaeogeogr. Palaeoclimatol. Palaeoecol. 168, 171–186. https://doi.org/10.1016/S0031-0182(00)00254-6.

Wetzel, A., Blechschmidt, I., Uchman, A., Matter, A., 2007. A highly diverse ichnofauna in Late Triassic deep-sea fan deposits of Oman. Palaios 22, 567–576.