



# Ichnological analysis of Pleistocene sediments from the IODP Site U1385 “Shackleton Site” on the Iberian margin: Approaching paleoenvironmental conditions



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## ABSTRACT

Ichnological analysis, focused on trace fossil assemblages and an ichnofabric approach, with special attention to cross-cutting relationships, tiering, relative abundances and bioturbation degrees, has been used to assess environmental parameters affecting the Pleistocene macrobenthic tracemaker community at the IODP Expedition 339, Site U1385 “Shackleton Site” on the Iberian margin. The trace fossil assemblage consists of abundant *Planolites*, frequent yet sparsely distributed *Palaeophycus*, *Thalassinoides* (and *Thalassinoides*-like structures), and *Taenidium*, and localized *Zoophycos* and *Chondrites*. Other ichnotaxa, such as *Phycosiphon* and *?Scolicia*, are rare. This assemblage is typical of the *Zoophycos* ichnofacies, though the distal expression of the *Cruziana* ichnofacies has a similar composition. Ichnofabrics reveal variable substrate colonization, with well defined cross-cutting relationships and tiering distribution. Differentiated ichnofabrics are: green mottled ichnofabric, *Planolites* ichnofabric, *Taenidium* and *Planolites* ichnofabric, *Thalassinoides*-like and *Palaeophycus* ichnofabric, *Planolites* and *Thalassinoides/Thalassinoides*-like ichnofabric, *Zoophycos* ichnofabric, and *Chondrites* ichnofabric, usually showing gradual transitions. A multi-tiered assemblage can be envisaged, with differentiation of the shallowest (biodeformational structures), shallow (*Planolites*, *Palaeophycus* and even *Taenidium*), middle (*Thalassinoides/Thalassinoides*-like structures), and lower (*Zoophycos* and *Chondrites*) tiers. According to the ichnological data, a general context of good bottom and pore-water oxygen conditions and organic matter availability can be interpreted, but localized dysaerobic intervals might be related with the record of *Zoophycos* and *Chondrites*. A constant rate of sedimentation shows only minor variations as revealed by ichnofabric succession. Soupy, soft, and stiffgrounds are interpreted as inducing changes in ichnological features. Salinity and temperature have a minor incidence on the macrobenthic tracemaker community, causing only small changes in the trace fossils.

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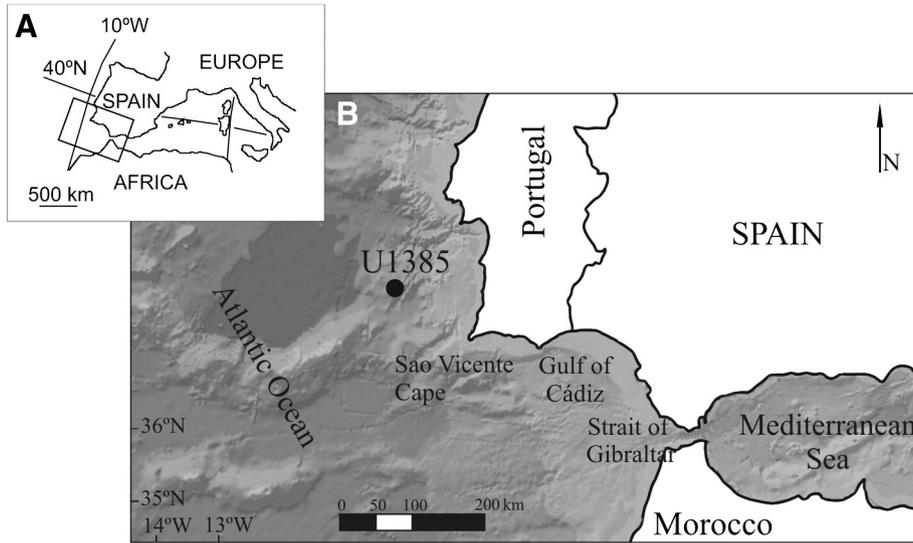
## 1. Introduction

IODP Expedition 339 drilled, from November 2011 to January 2012, a total of five sites in the Gulf of Cádiz (U1386–U1390) and two off the west Iberian margin (U1385 and U1391) (<http://iodp.tamu.edu>, Fig. 1) (Expedition 339 Scientists, 2012, 2013a). The drilled area is especially interesting for paleoceanographic aims; the Gulf of Cádiz is a key location to study the Mediterranean Outflow Water (MOW) through the Gibraltar Gateway and its influence on global circulation and climate, as well as to interpret the effects of tectonic activity on the evolution of the Gibraltar Gateway and on margin sedimentation (Expedition 339 Scientists, 2013a). In particular, the proposed drilling program in the studied area offers the opportunity to approach five broad scientific objectives (Expedition 339 Scientists, 2013a):

a) understand the opening of the Gibraltar Gateway and onset of MOW, b) determine MOW paleocirculation and global climate significance, c) establish a marine reference section of Pleistocene climate, d) identify external controls on sediment architecture of the Gulf of Cádiz contourite depositional system (CDS) and West Iberian margin, and e) ascertain synsedimentary neotectonic control on architecture and evolution of the CDS. From these general goals, especially interesting reveals objective (c), as the establishment of a marine reference section for paleoclimatic record during Pleistocene. With this general goal, Site U1385 was positioned at the “Shackleton Site” on the Portuguese margin (Expedition 339 Scientists, 2013b).

Site U1385 (37°34.285'N, 10°7.562'W) (Fig. 1) consists of a continuous record of pelagic–hemipelagic sediments from the Holocene to 1.45 Ma (Fig. 2), and became a marine–terrestrial–ice core point of reference for the study of orbital and sub-orbital (millennial-scale) variability (Hodell et al., 2013a). The research of Site U1385 is based on an integrative analysis involving different research specialties, including wireline logging, sedimentology, stratigraphic correlation,

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**Fig. 1.** (A) General geographical map showing the west Iberian margin. (B) Location of site U1385.

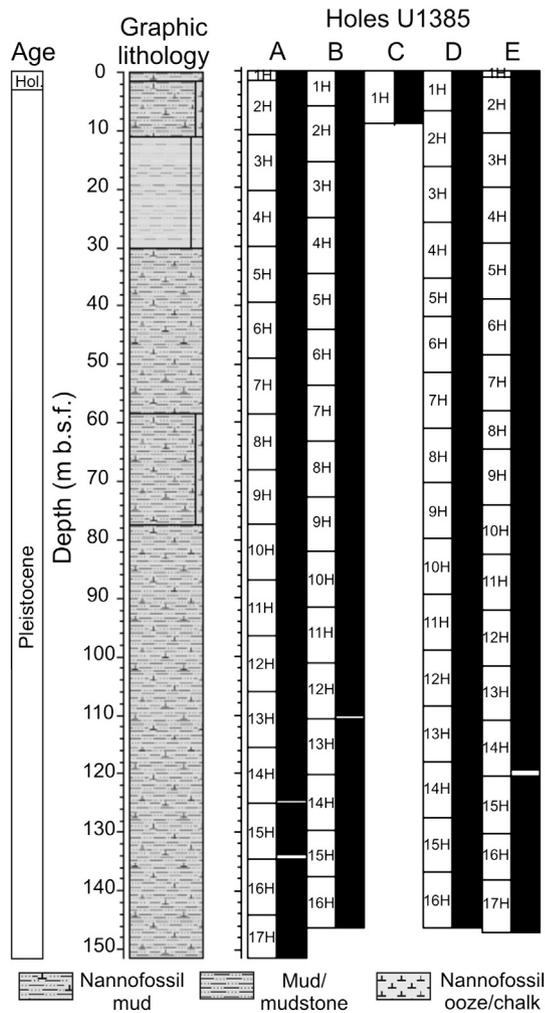
sediment physical properties, geochemistry, and micropaleontology. In this context, an often underestimated approach in core study now underway at Site U1385 consists of detailed ichnological analysis.

Ichnological research underwent rapid growth at the beginning of the twenty-first century, held to be of potential interest in a wide range of fields, from paleobiology, paleoecology, biostratigraphy and evolutionary aspects, to sedimentology and even reservoir characterization. Apart from trace fossil assemblages (i.e., their composition, abundance, ichnological features), the ichnofabric approach has recently been applied to evaluate paleoenvironmental changes due to variations in depositional and ecological parameters affecting tracemakers. Variations in paleoxygen conditions, nutrient availability, rate of sedimentation, or sub-environmental fluctuations, among others, have been interpreted based on ichnofabric analysis (see *Ekdale et al., 2012*). Its usefulness is particularly welcome in core samples, whether from shallow and continental environments or deep-sea deposits (*Knaust, 2009*).

The aim of the current research is the use of trace fossils as a proxy to interpret paleoenvironmental conditions affecting the macrobenthic environment at the Pleistocene in the western Iberian margin, based on the ichnological analysis of Site U1385; characterization of trace fossil assemblage and ichnofabric approach supported by a digital image treatment of the studied core.

**2. The “Shackleton Site” (IODP Site U1385)**

Site U1385, is located off the west Iberian margin on a spur, the Promontorio dos Principes de Avis, along the continental slope of the southwestern Iberian margin, at 2578 m b.s.l. (*Hodell et al., 2013a; Fig. 1*). The site was drilled near the position of Core MD01-2444 (*Skinner and Elderfield, 2007; Voelker and de Abreu, 2011; Channell et al., 2014*). The core MD01-2444 belongs to a series of cores retrieved from the SW Iberian margin by the *R/C Marion Dufresne* in 1995, 1999 and 2011, including Core MD95-2042 (the “Shackleton Site”), used as a key archive to approach millennial-scale climate variability over the last glacial cycle (*Shackleton et al., 2000, 2004*). The “Shackleton Site” on the Iberian margin (to honor Nick Shackleton’s seminal work in highlighting the global importance of these sections; *Shackleton et al., 2000*), has proven to be a fundamental site for assessing the atmospheric/oceanic dynamics of this region, providing detailed and high-fidelity records of different-scale changes in environmental parameters associated to climate variability (*Shackleton et al., 2000, 2004*). Correlation of the core MD95-2042 with other records worldwide underlines its significance for interpreting global environmental conditions, as well as for correlating climate events from the marine environment with polar ice cores and European terrestrial sequences (*Expedition 339 Scientists, 2013b*). Core MD01-2444, has



**Fig. 2.** Graphic lithology summary of Hole U1385A, and core recovery of Site 1385. A to E for holes cored at site U1385. Modified from *Expedition 339 Scientists (2013a,b)*.

been also extensively studied and provided an important record of millennial-scale variability of the last 190 ka (Vautravets and Shackleton, 2006; Martrat et al., 2007; Skinner et al., 2007; Margari et al., 2010; Hodell et al., 2013b; see Expedition 339 Scientists, 2013b for a detailed background).

Site U1385 on the Portuguese margin was drilled to create a marine reference section of sub-Milankovitch (millennial-scale) climate variability and changes in surface and deepwater circulation occurring during Pleistocene (Expedition 339 Scientists, 2013a,b). Five holes were cored at Site U1385 using the advanced piston core system, at 2578 m b.s.l., and a total of around 622 m of core were recovered (Hodell et al., 2013a; Fig. 2). This site shows a continuous record, consisting of a single lithologic unit composed of a Pleistocene–Holocene sequence (from 1.45 Ma, Marine Isotope Stage 47, to the Holocene) dominated by bioturbated calcareous muds and calcareous clays (Expedition 339 Scientists, 2013a, 2013b) (Fig. 2). No primary sedimentary structures were observed. Analysis of split cores from the five holes shows an accurate correlation among holes, making it possible to elaborate a complete spliced stratigraphic section, containing no notable gaps or disturbed intervals to 166.5 mcd (Expedition 339 Scientists, 2013b). Preliminary analysis allows estimation of a nearly uniform sedimentation rate around 10 cm/ky (Expedition 339 Scientists, 2013b; Hodell et al., 2013a,b). The completeness of Site U1385 favored a high-resolution analysis of changes associated with the atmosphere/oceanic dynamics, including climate variability. The site extends across the Middle Pleistocene Transition, the interval in which the change in orbital dominance takes place, from the 41 ky obliquity climate cycles to the 100 ky cycles of the late Pleistocene (Expedition 339 Scientists, 2013b).

Ichnological analyses of Quaternary sediments from areas close to Site U1385 in the southwestern Iberian margin have been previously conducted [cores PO200-10-(8-2, 6-2, 4-2) in Baas et al., 1997, 1998, and M39036 in Löwemark, 2003; Löwemark et al., 2004a], approaching environmental factors controlling trace fossil assemblages.

### 3. Ichnological analysis

#### 3.1. Material and methods

Ichnological analysis focused on trace fossil assemblages and an ichnofabric approach, with special attention to cross-cutting relationships, tiering, relative abundances and bioturbation degrees, the latter using the Bioturbation Index of Reineck (1963) as revised by Taylor and Goldring (1993). As usually occurs with core analysis, identification was limited, in most cases, to the ichnogenus level, except for some particular specimens displaying definitive features allowing ichnospecies characterization. Ichnological analysis was conducted on detailed observations of half-cut sections of the core in the IODP core repository at Bremen (Germany), together with high-resolution images. Several techniques of digital image treatment to improve the trace fossil visibility, allowing modifications of numerous parameters, were applied for ichnological characterization (Dorador et al., 2014a,b).

#### 3.2. Results

Bioturbational sedimentary structures were separated into biodeformational structures and trace fossils. Biodeformational structures are characterized by undifferentiated outlines and the absence of a defined geometry, impeding an ichnotaxonomical classification (see Uchman and Wetzel, 2011; Wetzel and Uchman, 2012), while revealing a more or less mottled ichnofabric (Virtasolo et al., 2011a). Biodeformational structures are related to the high bioturbation activity of organisms within soupy to soft sediments from the mixed layer, inducing a high disturbance of the sediment and then a more or less developed mottled background. Distinguishing of trace fossils from the host sediment is based on characteristic shape, and different

lithological features, such as composition and color, however this differentiation is, sometimes, difficult.

#### 3.2.1. Synopsis of trace fossils

A relatively diverse trace fossil assemblage was recognized, which includes *Chondrites*, *Palaeophycus*, *Planolites*, *Phycosiphon*, *?Scolicia*, *Taenidium*, *Thalassinoides*, *Thalassinoides*-like structures, and *Zoophycos* (Figs. 3, 4), typical of the *Zoophycos* ichnofacies, although the distal expression of the *Cruziana* ichnofacies has a similar composition. Small vertical structures were moreover observed. Relatively poor preservation precludes in most cases a conclusive differentiation at the ichnospecies level. *Planolites* is the dominant ichnotaxa, while *Palaeophycus*, *Taenidium*, and *Thalassinoides*, and *Thalassinoides*-like structures are frequent. *Chondrites* and *Zoophycos* are concentrated in located parts of the core. Traces such as *Phycosiphon* and *?Scolicia* are comparatively scarce.

*Chondrites* Stenberg, 1833 appears as clusters of circular to elliptical spots, and short tubes, showing occasional branching. Smaller forms are 0.5–1.5 mm wide and larger ones 2–3 mm wide. Specimens correspond

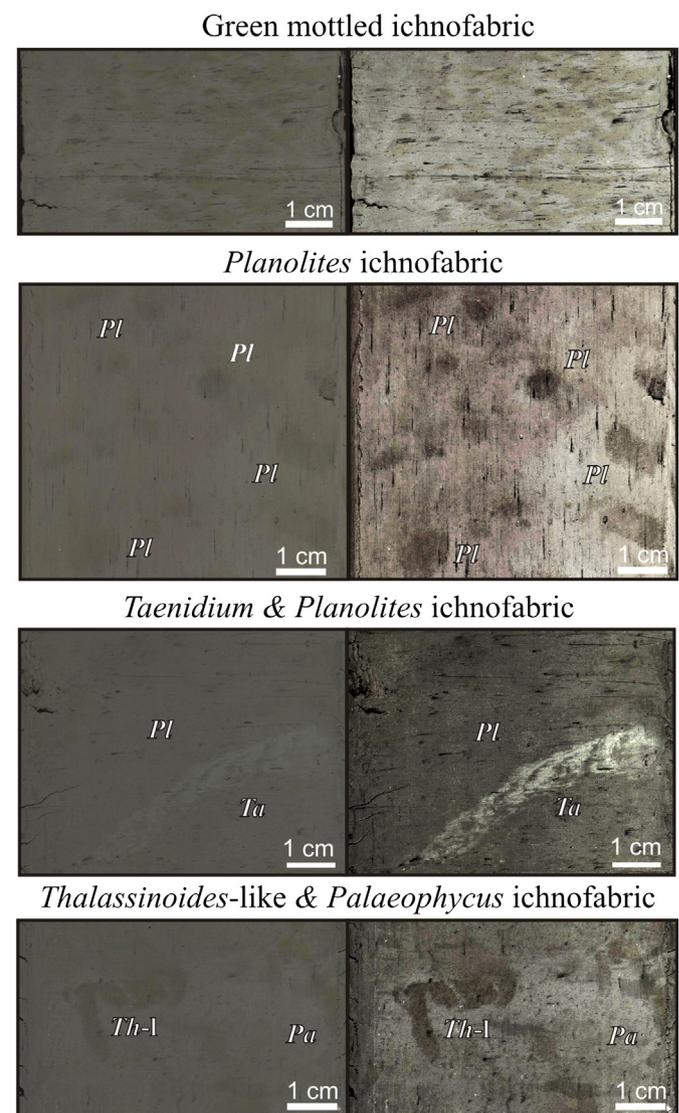
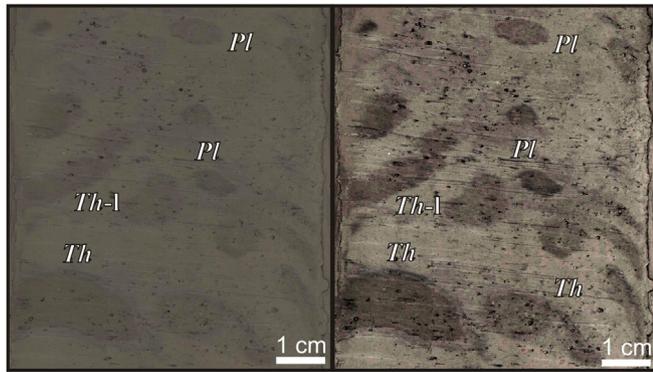
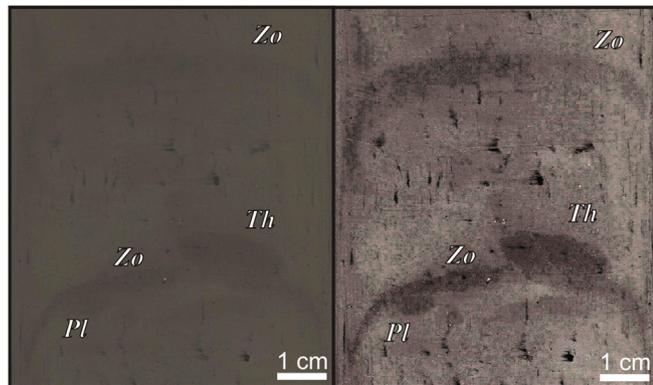
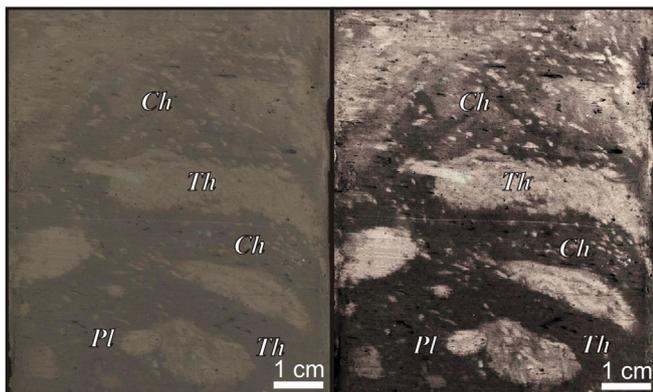


Fig. 3. Differentiated ichnofabrics. Left for not treated high resolution images, and right for same images with digital image treatment. Green mottled ichnofabric (1385D-13H-5-A; 11–16 cm), *Planolites* ichnofabric (1385A-6H-2-A; 10–17 cm), *Taenidium* and *Planolites* ichnofabric (1385A-4H-6-A; 14–19 cm), and *Thalassinoides*-like and *Palaeophycus* ichnofabric (1385E-13H-6-A; 128–133 cm). *Palaeophycus* (Pa), *Planolites* (Pl), *Taenidium* (Ta), and *Thalassinoides*-like (Th-1).

*Planolites* & *Thalassinoides*/*Thalassinoides*-like ichnofabric*Zoophycos* ichnofabric*Chondrites* ichnofabric

**Fig. 4.** Differentiated ichnofabrics: *Planolites* and *Thalassinoides*/*Thalassinoides*-like ichnofabric (1385B-3H-3-A; 46–54 cm), *Zoophycos* ichnofabric (1385A-6H-5-A; 20–28 cm), and *Chondrites* ichnofabric (1385B-5H-2-A; 113–122 cm). *Chondrites* (Ch), *Planolites* (Pl), *Thalassinoides* (Th), *Thalassinoides*-like (Th-1), and *Zoophycos* (Zo). Note: Left for not treated high resolution images, and right for same images with digital image treatment.

to variable cross-sections of branched tunnel systems filled with light/dark material (Fig. 4). Given the size (see Uchman, 1998), smaller forms could correspond to *Chondrites intricatus* (Brongniart, 1823) and larger forms to *Chondrites targioni* (Brongniart, 1828). *Chondrites* is considered as a feeding structure, usually registered in deep-tiers, produced by an unknown organism. Several interpretations have been traditionally proposed; as produced by a surface ingestor packing fecal pellets inside the structure (Kotake, 1991a); recently Izumi (2013) interprets these “pellet-filled *Chondrites*” as *Phymatoderma*, or as produced by a tracemaker able to live in dysaerobic conditions, at the aerobic–anoxic interface, as a chemosymbiotic organism (Seilacher, 1990; Fu, 1991).

*Palaeophycus* Hall, 1847 is represented by unbranched forms, mainly as circular to subcircular cylindrical burrows, smooth and lined. While usually observed as horizontal traces, occasionally it appears oblique, with a variable diameter (3–5 mm) and length (8–11 mm) (Fig. 3). Fill is structureless, having the same lithology as the host rock. *Palaeophycus* is a facies crossing form, interpreted as an open tube produced by carnivorous or omnivorous invertebrates, mostly polychaetes, and associated to pascichnia or domichnia (Pemberton and Frey, 1982; Keighley and Pickerill, 1995).

*Planolites* Nicholson, 1873 occurs in the studied core as unbranched, and mainly as circular to subcircular cylindrical tubular forms, clearly unlined. It is largely registered as horizontal, though there are occasional straight, smooth structures of variable size (diameter 2–7 mm, length 5–20 mm) (Figs. 3, 4). Fill is structureless, showing different lithology from the host rock. *Planolites* is a facies crossing form, featuring actively filled burrows, interpreted as a pascichnion, occurring in diverse environments, probably produced by different organisms, mainly soft bodied invertebrates (see Pemberton and Frey, 1982; Keighley and Pickerill, 1995 for discussion).

*Phycosiphon* Fischer-Oster, 1858 is registered in patches, oriented randomly, as horizontal, curved small lobes (less than 5 mm wide) and dark, fine grained cylindrical to circular cores (less than 1 mm in diameter). Dark filling of the core is encircled by lighter colored material. This trace is interpreted as produced by deposit feeders, fodinichnion, associated with high quantities of particulate organic matter in the sediment (Pervesler and Uchman, 2007). *Phycosiphon* is registered in fine grained, low energetic environments (Wetzel and Bromley, 1994; Pervesler et al., 2008, 2011), being common in poorly oxygenated sediments (e.g., Ekdale and Mason, 1988; Pervesler and Uchman, 2007).

*Scolicia* de Quatrefages, 1849 appears as horizontal cylindrical/subcylindrical forms, 40–50 mm long, with meniscate backfill, having an oval cross section, ~26 mm wide and ~20 mm high, with slightly concave top and bottom. *Scolicia* is produced by irregular echinoids, signaling full marine conditions, from shallow to deep sea environments, as locomotion and feeding structure (e.g., Bromley and Asgaard, 1975; Smith and Crimes, 1983). According to Fu and Werner (2000), *Scolicia* is associated with coarse silty to fine sandy sediments.

*Taenidium* Heer, 1877 is observed as horizontal to oblique tubular meniscate forms, 30–51 mm long, and 5–10 mm in diameter, simple, straight to sinuous, unlined (Fig. 3). Locally, differentiation between *Taenidium* and *Zoophycos* is difficult; presence of isolated tubular meniscate forms, with not repeated occurrence, allows designation to *Taenidium*. *Taenidium* is a common facies crossing trace fossil most likely produced by deposit feeders in shallow to mid-tiers, in some cases related to non-vagile worms that maintain a connection to the sediment surface or to shallowly burrowing worms keeping pace with sediment accumulation (Locklair and Savrda, 1998).

*Thalassinoides* Ehrenberg, 1944 is observed as oval spots, circular to subcircular (6–11 mm wide), together with straight or slightly winding, horizontal to oblique smooth cylinders (22–43 mm long), corresponding to variable cross sections of branching burrow systems (Figs. 3, 4). *Thalassinoides* is mainly interpreted as a dwelling and feeding structure (domichnial and fodinichnial) produced by crustaceans, mostly decapods (Frey et al., 1984). This facies crossing form is found in a great variety of marine environments, from intertidal to deep sea, usually associated with oxygenated, soft but cohesive sediments (see Fürsich, 1973; Ekdale et al., 1984; Ekdale, 1992; Schlirf, 2000, for a detailed discussion of this ichnogenus).

*Thalassinoides*-like structures occur as circular to subcircular sections, 6–12 mm wide, and more or less cylindrical structures, 15–20 mm long, showing a variably developed irregular wall, and diffuse shape (Figs. 3, 4). Shape similar to *Thalassinoides*, but without a well defined smooth wall, discards a conclusive assignation to *Thalassinoides*.

*Zoophycos* Massalongo, 1855, is registered as repeated, more or less horizontal, spreiten structures. At cross section, lamellae into the lamina

are obliquely distributed, consisting of alternating dark and light material. Observed spreiten structures (4–11 mm wide; Fig. 4) correspond to cross sections of a helical coiled system of protrusive oblique to horizontal lobes. The number of stacked lobes belonging to a unique structure is variable. In some cases cross sections of tubes were observed, corresponding to the marginal tube that constitutes the outer border of the spreiten structure. *Zoophycos* is generally considered to be produced by a yet undiscovered organism, which is referred to siphunculids (Wetzel and Werner, 1981), polychaete annelids, arthropods (Ekdale and Lewis, 1991), or echiuran worms (Kotake, 1992). Ethological interpretations are variable, including consideration as fodinichnia (Seilacher, 1967; Wetzel and Werner, 1981; Ekdale and Lewis, 1991; Olivero and Gaillard, 1996), or as produced by surface ingestors of organic detritus (Kotake, 1989, 1991b); more recently, lobes in its lowermost part were interpreted as sulfide wells for chemosymbiotic bacteria (Bromley and Hanken, 2003). Younger *Zoophycos* spreite fill than the host sediment suggests episodic surface feeding of the producers (Löwemark and Werner, 2001; Leuschner et al., 2002; Löwemark and Schäfer, 2003; Löwemark and Grootes, 2004). Thus, several ethological models have been proposed, as deposit feeder, detritus feeding, refuse dump, cache, gardening, or chemosymbiosis, among others (Bromley, 1991; see Bromley and

Hanken, 2003; Löwemark et al., 2004b, and Zhang, 2013 for a review). As occurs with the ethology, the paleoenvironmental significance and control environmental conditions of *Zoophycos* tracemakers are discussed, being associated to variations in energy, sedimentation rate, food content, or bottom water oxygenation. Highly lobed *Zoophycos* were linked to unstable environments and an opportunistic strategy, while simple unlobed *Zoophycos* could be associated to stable environments and a more specialized strategy (Olivero and Gaillard, 2007).

### 3.2.2. Ichnofabrics at the studied interval

Seven ichnofabric types and several subtypes were differentiated, showing a gradual/transitional change between successive ichnofabrics in most cases, thereby complicating the position of their corresponding boundaries. A detailed analysis to evaluate a possible recurrence of the differentiated ichnofabrics is actually under study. Differentiated ichnofabrics are the following: Green mottled ichnofabric, *Planolites* ichnofabric, *Taenidium* and *Planolites* ichnofabrics, *Thalassinoides*-like and *Palaeophycus* ichnofabrics, *Planolites* and *Thalassinoides*/*Thalassinoides*-like ichnofabrics, *Zoophycos* ichnofabric (with discrete *Zoophycos* subichnofabric, and diffuse *Zoophycos* subichnofabric), and *Chondrites* ichnofabric.

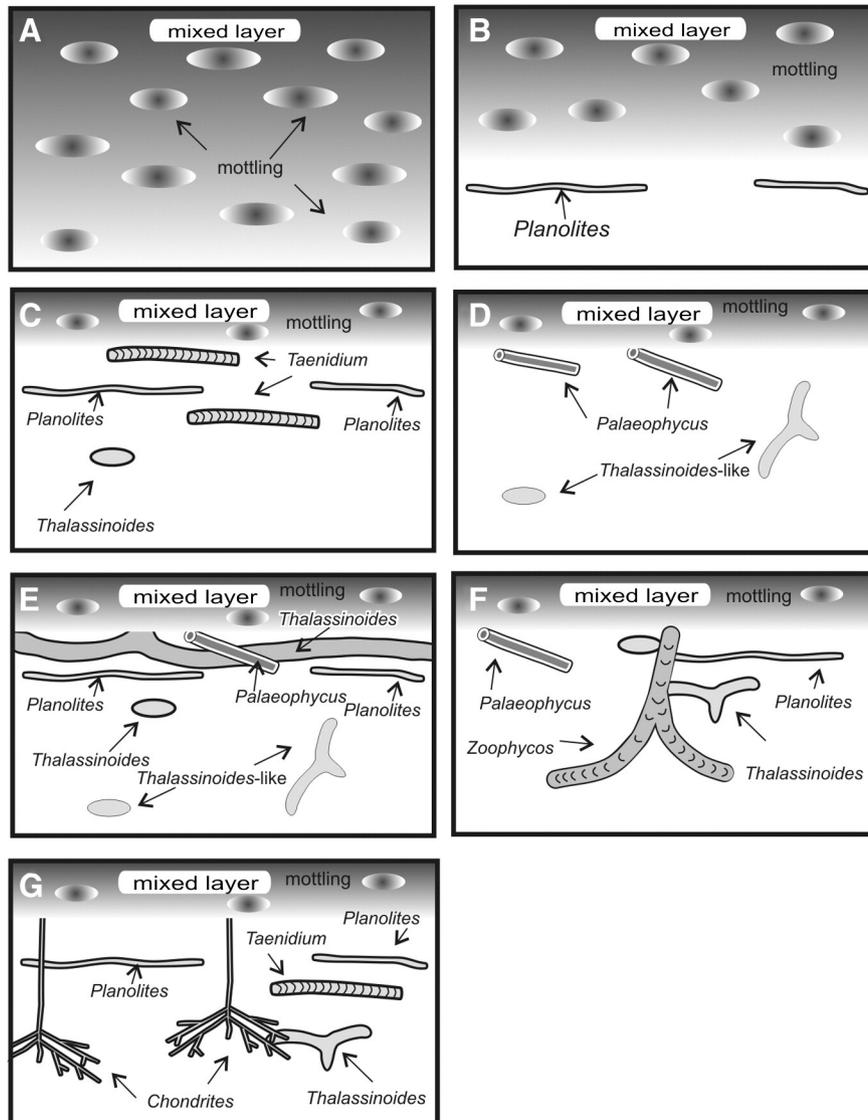


Fig. 5. Tiering patterns for the differentiated ichnofabrics. (A) Green mottled ichnofabric. (B) *Planolites* ichnofabric. (C) *Taenidium* and *Planolites* ichnofabric. (D) *Thalassinoides*-like and *Palaeophycus* ichnofabric. (E) *Planolites* and *Thalassinoides*/*Thalassinoides*-like ichnofabric. (F) *Zoophycos* ichnofabric. (G) *Chondrites* ichnofabric.

3.2.2.1. *Green mottled ichnofabric (abundant shallowest tier traces)*. The green mottled ichnofabric is characterized by the presence of a well developed structureless greenish, mottled, background (Figs. 3, 5), on which only diffuse trace fossils assigned to *Planolites* are locally observed. Biodeformational structures can be envisaged as determining this mottled appearance. This ichnofabric was originated by complete destruction of primary physical structures by shallowest burrowing organisms (BI = 6).

3.2.2.2. *Planolites ichnofabric (scarce shallow tier traces)*. The *Planolites* ichnofabric consists of scarce and diffuse *Planolites* on a greenish slightly/medium mottled lithology (Figs. 3, 5). Locally, carbon particles are abundant. The mottled background and biodeformational structures, as well as the scarce presence of *Planolites*, may be related to a colonization of soupy and softground by the shallower ichnofauna.

3.2.2.3. *Taenidium and Planolites ichnofabric (scarce shallow/middle tier traces)*. The *Taenidium* and *Planolites* ichnofabric (Figs. 3, 5) consists of dominant, but relatively sparse, *Taenidium* mainly occurring in a dark greenish/gray, local slightly mottled, background, together with sparse records of *Planolites*. Moreover, comparatively common *Thalassinoides*, and rare *Physicosiphon*, and ?*Scolicia*, were observed. Degree of bioturbation is variable, showing a gradual increase from low (1) when *Taenidium* is exclusive in the mudstone, to medium (2–3) when *Planolites* is registered on the slightly mottled fabric. Locally, *Taenidium* cross cuts *Planolites* (Figs. 3, 5).

3.2.2.4. *Thalassinoides-like and Palaeophycus ichnofabric (scarce shallow/middle tier traces)*. The *Thalassinoides*-like and *Palaeophycus* ichnofabric is characterized by scarce shallow and middle tier, low diversity of traces, mainly *Thalassinoides*-like, and locally occurring *Palaeophycus*, visible on a light gray mudstone, with slightly mottled fabric (Figs. 3, 5). Sparse *Planolites*, rare *Physicosiphon* and undeterminable vertical burrows are present. Bioturbation degree 1, locally BI = 2 can be present.

3.2.2.5. *Planolites and Thalassinoides/Thalassinoides-like ichnofabric (abundant shallow/middle tier traces)*. The *Planolites* and *Thalassinoides/Thalassinoides*-like ichnofabric is characterized by a relatively abundant and diverse shallow and middle tier assemblage in a mudstone showing slightly mottled gray fabric (Figs. 4, 5). *Planolites* and *Thalassinoides* are dominant, with *Thalassinoides*-like, *Palaeophycus*, and sparsely distributed ?*Scolicia*. Generally, *Thalassinoides* and *Thalassinoides*-like trace fossils are registered separately, with the latter substituting *Thalassinoides* and vice versa. Degree of bioturbation fluctuates from medium (2–3) to high (4). No cross cutting relationships were observed.

3.2.2.6. *Zoophycos ichnofabric (middle/deep tier traces)*. The *Zoophycos* ichnofabric is characterized by the presence of *Zoophycos* on a light, occasionally slightly mottled background (Figs. 4, 5). Together with *Zoophycos*, a relatively diverse trace fossil assemblage is recognized, consisting mainly of *Palaeophycus*, *Planolites*, and *Thalassinoides*. *Zoophycos* cross cuts *Planolites* and *Thalassinoides*. The degree of bioturbation varies from BI = 1 to 3. Occasionally, two subtypes can be differentiated based on the variations in the abundance of shallow/middle tier traces and outlines: a) discrete *Zoophycos* subichnofabric; comparatively scarce shallow/middle tier traces (*Planolites* and *Thalassinoides*) and conspicuous, well outlined *Zoophycos* cross cutting the other traces, on a light gray background, and b) diffuse *Zoophycos* subichnofabric; more diverse shallow/middle tier traces (*Palaeophycus*, *Planolites*, *Taenidium* and *Thalassinoides*) and the diffuse *Zoophycos*, showing unclear cross cutting relationships with the other traces, on a mudstone light gray/mottled background.

3.2.2.7. *Chondrites ichnofabric (middle/deep tier traces)*. The *Chondrites* ichnofabric is characterized by the presence of light *Chondrites* on a gray to greenish, occasionally slightly mottled background (Figs. 4, 5). Degree of bioturbation varies from 1 to 3, and ichnodiversity is high. Apart from *Chondrites*, *Planolites* and *Thalassinoides* are common, and *Taenidium* rare. *Chondrites* tunnels are slightly flattened. *Chondrites* cross cuts *Planolites* and *Thalassinoides*.

#### 4. Interpretation and discussion

Generally a multi-tiered ichnofaunal assemblage can be envisaged (Fig. 6). The mottled background, determined by biodeformational structures, reveals colonization of uppermost tiers, on or just below the seafloor, associated with relatively good life conditions. Maintenance of these favorable conditions facilitates the shallowest benthic activity and extension of the green mottled ichnofabric, with scarce presence of shallow, upper, tier traces (*Planolites*). *Planolites*, as dominant, and then *Palaeophycus* and even *Taenidium* are characteristic of trace fossil assemblages from the upper tier, mostly representing pascichnia. Dominance or exclusiveness of *Planolites* could be related to better conditions in shallower tiers. Deeper within the sediment, in an intermediate tier, *Taenidium*, *Thalassinoides*-like and *Thalassinoides* mainly represent the activity of dwelling or feeding structures (domichnial and fodichnial); a relative abundance of *Thalassinoides*-like/*Thalassinoides* could be associated with variation in environmental parameters (see below). Finally, the deep tier is represented by *Zoophycos* and *Chondrites*, showing a more complex and variable behavior, and associated with the final phases of colonization by the community, as revealed by the cross cutting relationships with *Planolites* and *Thalassinoides*. To date we have not observed any cross cutting relationship between *Chondrites* and *Zoophycos*, and thus cannot differentiate subtypes within the deep tier. The interpreted tiering pattern is similar to others from deep sea trace fossil communities (e.g., Ekdale and Bromley, 1984; Ekdale et al., 1984; Frey and Bromley, 1985; Bromley and Ekdale, 1986; Ekdale, 1988; Ekdale and Bromley, 1991; Bromley, 1996; Rodríguez-Tovar and Uchman, 2004).

##### 4.1. Paleoenvironmental conditions in the western Iberian margin

In deep sea environments, mainly characterized by pelagic-hemipelagic sediments, the principal environmental parameters—in most cases interrelated—determining bioturbation refer to organic matter availability, sedimentation rate and oxygenation (Uchman and Wetzel, 2011; Wetzel and Uchman, 2012). Further parameters, such as temperature or salinity, bear a comparatively minor incidence on the macrobenthic habitat in deep sea environments.

Previous ichnological analyses on Quaternary sediments from cores located close to the studied Site U1385, revealed the presence of different ichnocoenoses characterized by a variable trace fossil record of *Chondrites*, *Planolites*, *Thalassinoides* and *Zoophycos* (Baas et al., 1997, 1998; Löwemark et al., 2004a). Trace fossil assemblages were mainly related to bottom water oxygenation during the last 40 kyrs during Heinrich events H1 to H4 (Baas et al., 1998), and with bottom water environmental conditions (bottom water oxygenation and particulate organic matter content) linked to Mediterranean Outflow Water strength from back to around 34 kyrs (Löwemark et al., 2004a).

##### 4.1.1. Oxygenation level and organic matter content

In the case study, the absence of physical primary structures, the presence of mottled ichnofabrics, and the dominance of shallow tier trace fossils (e.g., *Planolites*, *Palaeophycus*) allow us to interpret generalized good paleoenvironmental conditions at the sediment water interface or just below the sea floor during the studied interval. Oxidic bottom and pore waters in the upper parts of the bioturbated zone, as well as available organic matter, can be envisaged. In this favorable generalized macrobenthic habitat at the Pleistocene, the localized

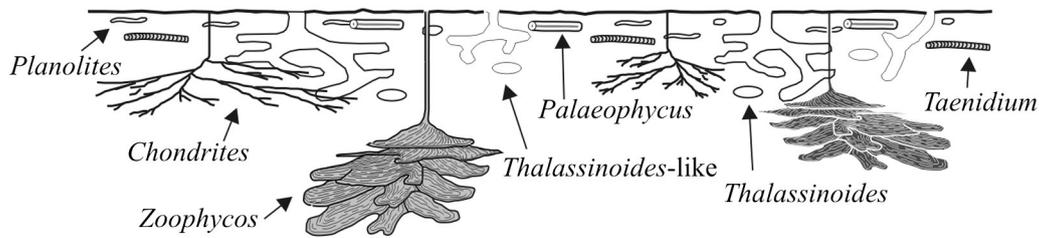


Fig. 6. Idealized cross cutting relationship and tiering pattern of trace fossil assemblage in Pleistocene sediments at IODP Site U1385, on the Iberian margin.

record of *Chondrites* and *Zoophycos*, and their corresponding ichnofabrics, may reveal occasional paleoenvironmental changes favoring the presence of *Zoophycos* and *Chondrites* tracemakers. Their producers have been considered as usually bioturbating organic rich, oxygen depleted (dysaerobic conditions) sediments, especially when they occur together. The relative independence of *Zoophycos* and *Chondrites* tracemakers from substrate features would allow for colonization of sediments with comparative low oxygenation and food content, because both maintain a connection to the sediment surface that makes it possible to obtain oxygen from the water pumped into the burrow system, or even in the case of *Zoophycos* to collect food particles from the sea floor (e.g., Bromley and Ekdale, 1984; Löwemark and Schäfer, 2003; Rodríguez-Tovar and Uchman, 2006, 2008). Therefore, the presence of *Chondrites* and *Zoophycos* could reflect changes in the ecological/depositional conditions favoring their colonization when environmental conditions are unfavorable for remaining macrobenthic tracemaker community. Low oxygen content, leading to dysaerobic conditions, and/or high organic matter could be envisaged. Yet there is no single relationship between the two parameters, even more when variations in the rate of sedimentation are considered (see Wetzel and Uchman, 2012, for a detailed review). Thus, although the incidence of oxygenation and/or organic matter content in the macrobenthic tracemaker community at the Pleistocene in the western Iberian margin is recognized, a conclusive evaluation on the relative significance of both parameters is, at the moment, difficult. It would moreover be necessary to consider, in some instances, the possibility of a vertical partitioning of a single multi-tiered community in a well oxygenated environment, the upper tiers (e.g., biodeformational structures, *Planolites*, *Palaeophycus*) being associated with good oxygen conditions, and the middle (e.g., *Taenidium*, *Thalassinoides*, *Thalassinoides*-like) and deep (e.g., *Zoophycos*, *Chondrites*) tiers reflecting the gradually decreasing oxygen in pore waters deeper in the sediment.

Benthic foraminiferal associations and trace fossil assemblages from cores located close to the studied Site U1385, allow interpretation of changes in the degree of bottom water oxygenation during the last 40 ka, with a major drawdown (to low oxic and dysoxic conditions) during the Heinrich events linked to reduction or even halting of deep water formation in the North Atlantic, and characterized by massive occurrences of *Chondrites* below the Heinrich layers (Baas et al., 1998). Variations of the ichnocoenoses (ichnofabrics dominated by *Thalassinoides*, by *Planolites* and indistinct bioturbation, and by *Chondrites*), from about 29 ka to the Holocene at the southwestern Portuguese continental slope, were related to changes in bottom and pore water oxygenation and in particulate organic matter content (Löwemark et al., 2004a). These changes were associated to variations in the current velocity of the MOW as well as in the North Atlantic thermohaline overturn. Massive occurrence of *Chondrites* probably was a response to low current velocities and enhanced deposition of particulate organic matter in the rough sediment surface, leading to low water oxygen level; in this context opportunistic *Chondrites* tracemakers took advantage against larger organisms (Löwemark et al., 2004a).

A possible recurrent record of *Chondrites* and *Zoophycos* ichnofabrics in the studied Site U1385 could be associated to variations in the global climate and in the Mediterranean paleocirculation, determining changes in bottom water conditions and organic matter content.

#### 4.1.2. Sedimentation rate and substrate consistency

The Site U1385 contains no notable gaps or disturbed intervals to 166.5 mcd (Expedition 339 Scientists, 2013b); an average, nearly uniform, sedimentation rate of 10 cm/ky has been proposed by the entire section cored at Site U1385, which is normal for a hemipelagic continental margin environment (Expedition 339 Scientists, 2013b). In a context of a generally constant sedimentation rate, minor changes could be interpreted based on the registered ichnofabrics. Accordingly, the presence of green mottled ichnofabric could indicate comparative diminution in the sedimentation rate, favoring bioturbation by the shallowest tracemakers at the water sediment interface or just below the seafloor; the occasional presence of carbon remains could confirm a decrease in sedimentation rate and availability of organic matter near the seafloor, allowing colonization by the shallowest tiers and hence the mottled appearance. The succession of ichnofabrics observed, from those mainly consisting of shallow tier ichnotaxa to those with dominant middle tiers, might reflect a slight increase in the rate of sedimentation, and probably more organic matter available in deeper levels (sedimentation rate controls the burial of organic matter in deep sea sediments; Uchman and Wetzel, 2011).

In the case of vertical partitioning of a single multi-tiered community existing in a well oxygenated environment, the registered tiering agrees with an increase in consistency from the shallowest to deep tiers, with traces as *Planolites* and *Palaeophycus* colonizing softgrounds and *Zoophycos* extending to stiffgrounds. Observed variations in the *Zoophycos* ichnofabric between discrete *Zoophycos* subichnofabric, with conspicuous, well outlined *Zoophycos*, and diffuse *Zoophycos* subichnofabric, could evidence minor variations in substrate consistency but not enough to impede colonization for *Zoophycos* tracemaker. The separate presence of *Thalassinoides* and *Thalassinoides*-like (with diffuse shape) within the *Planolites* and *Thalassinoides*/*Thalassinoides*-like ichnofabric, may be related to variations in substrate consistency, with softer grounds associated to *Thalassinoides*-like structures.

#### 4.1.3. Salinity and temperature

As previously indicated, parameters such as temperature or salinity have a comparatively minor incidence on the macrobenthic tracemaker habitat in deep sea environments, and they are also more difficult to recognize based exclusively on the ichnological record. The opposite is true of marginal marine, brackish, or hypersaline environments, which may display significant salinity changes reflected in ichnology record (e.g., Jaglarz and Uchman, 2010; Buatois and Mángano, 2011; Virtasolo et al., 2011b).

However, in a full marine environment, as in the studied Site 1385U with generally constant salinity and temperature, the oceanic dynamics associated with the Mediterranean Outflow Water, and significant climatic changes related to glacial–interglacial periods could induce fluctuations in salinity and temperature that can be referred to some ichnological features in the case study. Given the extreme sensitivity of echinoids to salinity changes (stenohaline organisms), *Scolicia* is usually related to full marine conditions, being very rare in environments stressed by lowered or fluctuating salinity (Demircan and Uchman, 2012); salinity changes could even be lethal for echinoids (Bernardi et al., 2010). Fu and Werner (2000) indicate that the

distribution pattern of *Scolicia* is influenced mainly by depositional factors, by bottom currents, grain size, sedimentation rate and the faunal association; preservation and record of *Scolicia* are facilitated during times of restricted competition by organisms of deeper burrowing tiers. In the study case, the sporadic occurrence of ?*Scolicia* through the studied interval may be related to fluctuations in salinity in the range of full marine conditions. Sporadic delivery of less saline water could cause a temporal change in salinity, unfavorable for echinoids. Replacement of *Scolicia*, associated with full marine conditions by *Thalassinoides*, a salinity tolerant crustacean burrow (Frey et al., 1984), could therefore be linked to changes in salinity (Pervesler and Uchman, 2007).

Application of ichnology in paleoclimatology is relatively scarce (Goldring et al., 2007; Ekdale et al., 2013 for recent researches). Based on modern examples applied to the fossil record, Goldring et al. (2004, 2007) proposed the recognition of three climatic zones: tropical and subtropical zones (latitudes 0–35°) with *Ophiomorpha* and echinoid trace fossils (*Bichordites* or *Scolicia*); a temperate zone (35°–66°) where echinoid burrows are also present, along with associated thalassinian burrow *Thalassinoides* but without *Ophiomorpha*; and an arctic zone (cold waters) with only a molluscan and annelid trace fossil association. In our case study, because the paleolatitude is close to the boundary between subtropic and temperate—the latitude of Site U1385 is around 37°N—agrees with the presence of echinoid burrows associated with trace of the thalassinian group (*Thalassinoides* and *Thalassinoides*-like structures).

## 5. Conclusions

The trace fossil assemblage at the Pleistocene in the “Shackleton Site” (IODP Expedition 339, Site U1385) on the Iberian margin consists of abundant *Planolites*, frequent and sparsely distributed *Palaeophycus*, *Taenidium*, *Thalassinoides*, and *Thalassinoides*-like, and localized *Zoophycos* and *Chondrites*. *Phycosiphon* and ?*Scolicia* are rare. This assemblage can be considered typical of the *Zoophycos* ichnofacies, even though distal expression of the *Cruziana* ichnofacies is of a similar composition.

Ichnofabrics largely show gradual transitions. They include green mottled ichnofabric, *Planolites* ichnofabric, *Taenidium* and *Planolites* ichnofabric, *Thalassinoides*-like and *Palaeophycus* ichnofabric, *Planolites* and *Thalassinoides*/*Thalassinoides*-like ichnofabric, *Zoophycos* ichnofabric, and the *Chondrites* ichnofabric.

A multi-tiered assemblage can be envisaged; biodeformational structures revealing colonization of uppermost tiers, above or just below the seafloor, with *Planolites*, *Palaeophycus* and even *Taenidium* as upper tier traces, *Thalassinoides*-like/*Thalassinoides* occupy a middle tier, and *Zoophycos* and *Chondrites* as deep tier forms associated with the final phases of colonization.

In a generalized context of good bottom and pore water oxygen conditions and organic matter availability, sporadic dysaerobic intervals and/or minor changes in primary productivity, could be interpreted as associated to the record of *Zoophycos* and *Chondrites*.

A constant sedimentation rate gives rise to a sequential colonization of soupy, soft, and even stiff conditions. Minor changes in sedimentation rate are envisaged based on ichnofabric succession, as well as on substrate consistency revealed by the diffusiveness of traces.

Salinity and temperature do not have a significant incidence on the macrobenthic tracemaker community, although local changes in particular ichnotaxa could point to variations in both parameters.

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