

Contourite facies model: Improving contourite characterization based on the ichnological analysis



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ABSTRACT

The calcareous contourites from the Late Oligocene and Early Miocene in the Petra Tou Romiou type section (southern Cyprus) have been studied in detail, being regarded as outstanding examples of fossil bioclastic contourites and representative of the standard facies model of contourite bigradational sequence. These bigradational sequences of sand-dominated contourites consists of whitish calcarenite beds with wavy layering in the middle portion of the sequence. Gradual alternations of whitish and greenish calcilutites appear above and below these calcarenites. The internal wavy layering is composed by compacted interlayers and non-compacted interstratified layers. In the present study, an in-depth ichnological analysis of the bigradational sequence has been conducted, focusing on ichnological features such as length, shape, diameter, and orientation of individual burrow segments, the configuration of burrow systems, as well as external features, fill material, and finally taphonomy. Trace-fossil assemblages differ, containing *Planolites* isp., *Chondrites* isp., and *?Thalassinoides* isp. at the compacted interlayers, and non-compacted layers bearing only *Planolites* structures. The compacted interlayer structures are flattened and elliptical, containing similar fill material as the calcilutite host sediment, though lighter in color. In the non-compacted layers, *Planolites* are near un-deformed, being cylindrical and tubular, with circular to sub-circular cross-sections. These are located mainly at the base or occupy the entire layer, locally showing longitudinal striae (*Planolites reinecki* Książewicz), and filled with calcarenite material. The different trace-fossil assemblages in the compacted layers and non-compacted interlayers, varying in fill material, evidence an original primary differentiation, presumably indicative of fluctuating paleoenvironmental conditions. In consecutive non-compacted layers, the distribution of *Planolites* is separated by compacted interlayers. This indicates that the middle portion of the contourite type facies, with internal wavy layering, underwent a multi-phase deposition. In the non-compacted layers, the almost undeformed *Planolites*, marked by striae, is consistent with a higher substrate consistency, which is interpreted as being associated with sedimentary condensation or omission, immediately before the next compacted interlayers were deposited. This evidence clearly supports the contention that sedimentary processes governing contourite deposition were intermittent rather than continuous, as traditionally proposed. These findings raise basic questions regarding the bottom current processes, and consequent bedform development in these deep-marine environments.

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1. Introduction

Knowledge of contourites has progressed significantly since the first studies of the mid '60s. Progress has been due partly to the growing number of papers on modern and fossil examples, the analysis of cores

as well as outcrops, and the applied multidisciplinary methodology. This has generated debate –even controversy– within the scientific community, with special attention to diagnostic features and the role of bioturbation in characterizing and differentiating contourites. In most of the papers describing contourites, bioturbation is considered as diagnostic criteria, while some other studies consider that primary sedimentary structures are of higher importance (see Rodríguez-Tovar and Hernández-Molina, 2018 for a recent review). The study of contourites, as highlighted by Rebesco et al. (2014), is now considered

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crucial in several fields: paleoceanography and paleoclimatology, hydrocarbon exploration, and slope-stability/geological-hazard assessment.

Extensive research on contourites has differentiated various contourite facies, with six main groups of contourite deposits being recently classified. Some of these have several subtypes: clastic contourites, volcano-clastic contourites, shale-clast or shale-chip layers, calcareous contourites, siliceous bioclastic contourites, and chemogenic contourites (Stow and Faugères, 2008). The contourite types reflect certain environmental conditions, and a detailed analysis provides information on the sedimentological processes involved, as well as the factors controlling contourites.

Reflecting the behaviour of trace makers, trace fossils provide meaningful information on ecological and depositional parameters that affect the trace-maker community during contourite deposition (Rodríguez-Tovar and Hernández-Molina, 2018). The sedimentation rate, current energy, substrate consistency, bottom water oxygenation or food availability can be interpreted based on trace fossils (Rodríguez-Tovar et al., 2009a, 2009b, 2015a, 2015b; Rodríguez-Tovar and Uchman, 2010; Buatois and Mángano, 2011; Mángano and Buatois, 2012; Knaust and Bromley, 2012 for a review of using trace fossils as indicators of sedimentary environments; Rodríguez-Tovar and Dorador, 2015). These conditions can change during contourite deposition, and then its characterization provide greater information about the processes involved.

1.1. The contourite facies model

In the early '80s, researchers proposed a facies model for muddy contourite facies in the Gulf of Cadiz (S Spain) (Fig. 2). This “standard” contourite facies model roughly coincided with proposals in several papers (Faugères et al., 1984; Gonthier et al., 1984; Stow and Holbrook, 1984). The original descriptions indicate a vertical sequence containing three main facies: homogeneous mud, mottled silt and mud, and sand and silt. These were arrayed in coarsening-up/fining-up cycles (negatively/positively graded), giving rise to the typical bigradational sequence characterizing contourites (Fig. 2). This model has received wide acceptance, with only minor modifications, the main change probably being of the one proposed by Stow et al. (2002a), and later used in Stow (2005) and Stow and Faugères (2008). These authors introduced interval divisions (C1 to C5) as well as amendments concerning variations for partial contourite sequences (Rebesco et al., 2014; Shanmugam, 2017). Later an ideal contourite sequence, but without the five internal divisions, was presented by Faugères and Mulder (2011).

One significant development regarding ichnological features in the contourite facies model should be highlighted. In the earliest papers, the vertical facies “sequence” was characterized by bioturbational mottling (at a μm , mm and cm scale), together with iron sulphide mottles and filaments (Stow and Holbrook, 1984). Also, rather distinct, isolated pockets and streaks were described (Faugères et al., 1984), as well as clearly discerned trace fossils (burrows) including *Chondrites*, *Planolites*, *Scolicia*, *Teichichnus*, and *Zoophycos*. The vertical facies distribution bears mottled mud and silt in the upper and lower parts, with bioturbated silt-sand in the middle. Gonthier et al. (1984) presented a more extensive analysis, using data on biogenic structures and photographs. Accordingly, three main facies types were distinguished in the contourites (Fig. 2):

a) Silts and sand, with erosional contact being slightly more numerous at the base of the beds, possibly altered by secondary bioturbation. In such facies, bioturbation is the most usual structure; however, in much of the sand, this is visible only as faint mottling (cm-scale) in X-radiography. At the top and bottom contacts of beds, bioturbation injects sand pockets into the adjoining sediment with muddy wisps or streaks evident in the sand. Large burrows (up to 10 cm long) filled with mud or sand appear as straight, isolated protrusions (some of these appearing to be *Lophoctenium*), or as a tortuous

network of finer tubes.

b) Mottled muds and silts have contacts that can also be altered by bioturbation. Their predominant feature throughout is the mm- and cm-scale bioturbational mottling, with rather distinct isolated pockets and streaks. These structures are tentatively associated with *Chondrites*, *Planolites*, *Scolicia*, and *Teichichnus*. Also, certain horizons contain thin, elongated iron-sulfide filaments as well as larger burrows filled with pyrite. Furthermore, various episodes of superimposed bioturbation are often apparent.

c) Homogeneous mud that appears to have undergone thorough bioturbation where not laminated, although the pockets, mottles, and streaks in X-radiographs are mainly indistinct and of a very small size (mm scale). Some structures of small size could be *Chondrites*, but the larger burrow types found in other facies do not appear. Locally, pyrite-filled burrows and iron-sulfide traces are common.

Illustrations of the model in the early papers cited (Fig. 3 in Stow and Holbrook, 1984; Fig. 4 in Faugères et al., 1984; Fig. 12 in Gonthier et al., 1984), include a drawing of bioturbation, but with no accompanying ichnological information.

Stow et al. (1986) introduces a major change, which is illustrated later in Fig. 2 of Stow et al. (1998) (Fig. 2). In addition to the bioturbation drawing, these latter authors propose the composite contourite facies models, depicting the structure and lithology, as well as the bioturbation from bottom to top. Also, they characterize the negatively graded interval by bioturbated mud, followed by bioturbated mottled mud and silt, and finally the massive sandy silt containing irregular sandy pockets together with bioturbation. Finally, this is followed by a positive grading back (Stow et al., 1998). A comparable illustration, indicating bioturbation, and even with distinct facies divisions (C1–C5 in Fig. 2), appears in later papers by the same authors (Stow et al., 2002a; Stow, 2005; Stow and Faugères, 2008). In these later papers new information is included indicating the presence of “ \pm hiatuses” within the sandy silt part (C3 division) of the bigradational sequence (Fig. 2). The presence of hiatuses is emphasized by Shanmugam (2017) as indicative of different depositional events above and below hiatuses.

More recently, Faugères and Mulder (2011) present an illustration of the ideal contourite sequence, following the early version of Faugères et al. (1984), without indicating (lettering) the various bioturbated parts.

The present study offers a detailed, short-scale ichnological analysis of sand-dominated contourite sequences from the Late Oligocene and Early Miocene in the Petra Tou Romiou type section of southern Cyprus (Fig. 1). This is meant to refine the above-mentioned contourite facies model and to improve the characterization of contourites, with special emphasis on the continuity/discontinuity of the sedimentary processes involved.

2. Upper Oligocene contourites in Cyprus

Within the upper part of the Lefkara Formation (Late Cretaceous to Early Miocene) in Cyprus (Fig. 1), Oligocene contourites have been recognized and thoroughly studied (Robertson, 1976; Kähler, 1994; Kähler and Stow, 1998; Stow et al., 2002b; Turnbull, 2004; Hüneke and Stow, 2008). These have even been regarded as type examples of contourites in fossil series exposed on land (Stow et al., 2002b).

In the studied Petra Tou Romiou section, the Lefkara and the Pakhna formations are recognized (Fig. 1). The lower part of the Petra Tou Romiou section corresponds to the upper Lefkara Formation, the Upper Marls Unit, and the upper part of the Chalk Unit, consisting of chalky calcilutites and marls with individual calcarenite beds and chert layers, having regular calcilutite-calcarenite-calcilutite grain-size cyclicity, as well as traces of lamination with intense bioturbation throughout (Fig. 1). In the upper part of the Petra Tou Romiou section, the Lefkara Formation is overlying by the Pakhna Formation, made up

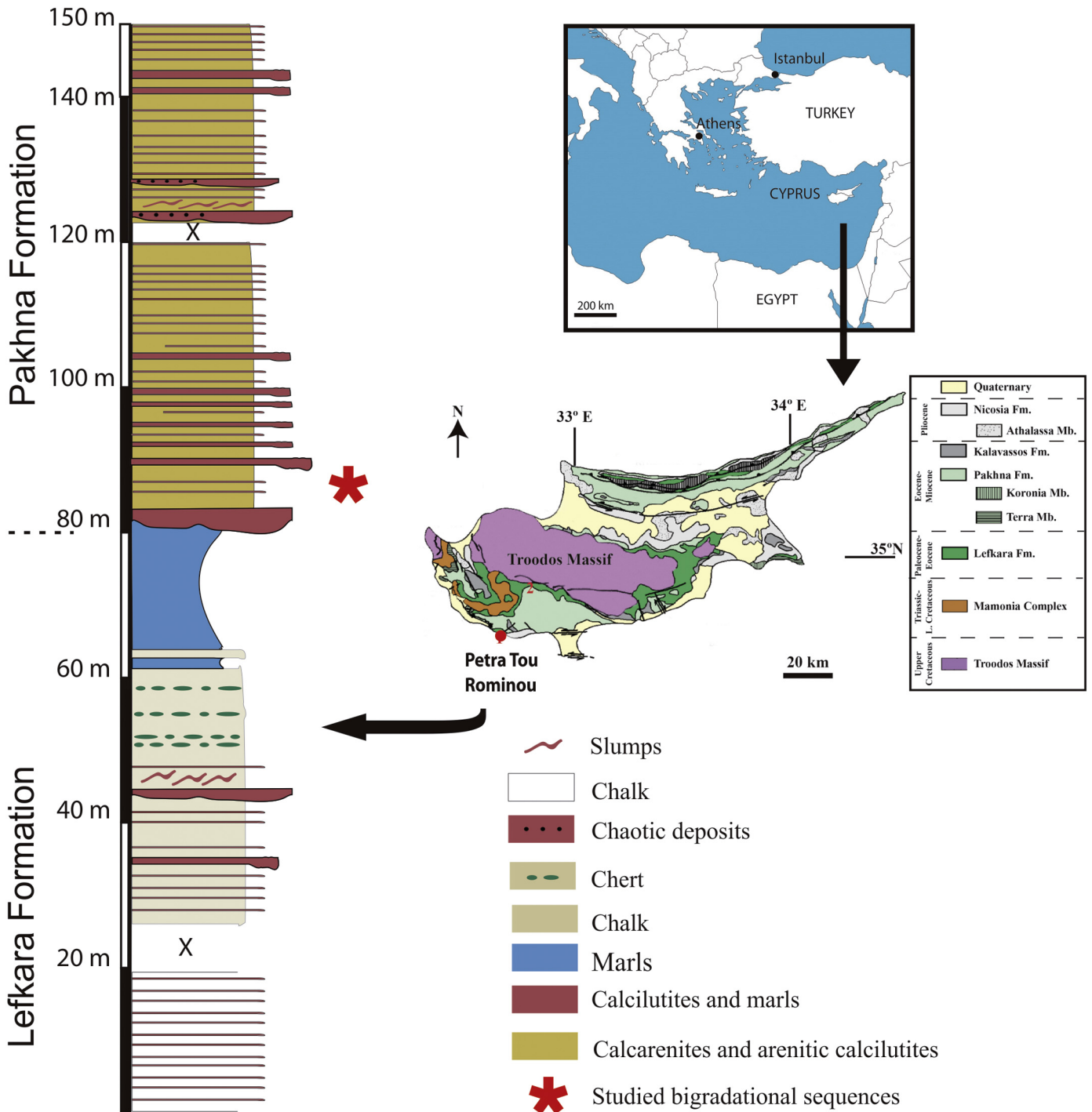


Fig. 1. Geographical and geological location of the Petra Tou Romiou section (Cyprus) and simplified lithological column with position of the studied bigradational sequences (modified from Hüneke et al., submitted).

of chalky calcilutites and thick calcarenite beds (Fig. 1). In this Pakhna Formation, sedimentation was controlled, in part, by bottom currents determining deposition of contourites. Initially, these muddy to sandy calcareous contourites, calcilutitic to calcarenitic contourites, were attributed to the Lefkara Formation (Kähler, 1994; Kähler and Stow, 1998; Stow et al., 2002b). In Stow et al. (2002b), Fig. 7D–F presents various outcrop photos of the fossil contourites from the Petra Tou Romiou type section. Part of the upper lenticular, thin-bedded contourite unit reveals examples of bigradational sequences that have some grain-size cyclicity as well as details of sandy, bioclastic contourites. Later, Hüneke and Stow (2008) characterize these calcicontourites in detail,

figuring the same example of the Petra Tou Romiou section (Fig. 17.1 in Hüneke and Stow, 2008) as that previously illustrated in Stow et al. (2002b); Fig. 7D). Previous works differentiated three main facies that characterize these bioclastic contourite facies (Stow et al., 2002b; Hüneke and Stow, 2008; Fig. 2): a) a fine calcilutite, mostly structureless but having lenses of calcisiltite and some indistinct discontinuous laminae; b) calcilutite (or marl) richer in clay, and c) a thin-bedded, distinctively lenticular calcarenite/calcilutite and rare lamination and cross-lamination. Hüneke and Stow (2008) report with the presence of clear burrows including small *Chondrites*, *?Helminthoides*, and less uniform micro-traces, together with larger forms such as *Thalassinoides*,

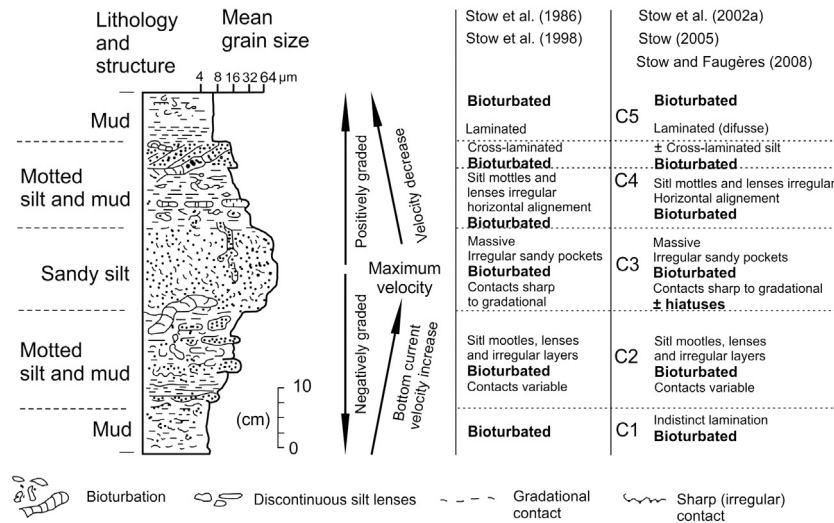


Fig. 2. Contourrite Facies Models with indication of ichnological information (bold) (modified from Rodríguez-Tovar and Hernández-Molina, 2018). Note proposed subdivisions (C1–C5) as well as presence of “± hiatuses” (Stow et al., 2002a; Stow, 2005; Stow and Faugères, 2008).

Planolites, and sub-vertical *Ophiomorpha*, the latter typically below a presumed omission surface. A recent detailed microfacies analysis provides better characterization of these sand-dominated contourrite sequences (Hüneke et al., submitted). Thus, whitish calcarenite beds having internal wavy layering with thicknesses of between 5 and 60 cm are visible in the middle portion of the sequence, with a gradual transition alternating between whitish or greenish calcilutites, above as well as below these calcarenites. The distinguishing feature is the

internal wavy layering, where individual layers measure 3–30 mm thick (Hüneke et al., submitted). Microscopically, the internal wavy layering is made up of non-compacted layers, some 10 mm thick with a homogeneous or a mottled bioturbated texture, formed by globigerinid packstones and grainstones, which are interstratified by thin compacted interlayers of 1–10 mm thick showing a slightly content of fine-grained materials such as micrite and clay mineral (Hüneke et al., submitted).

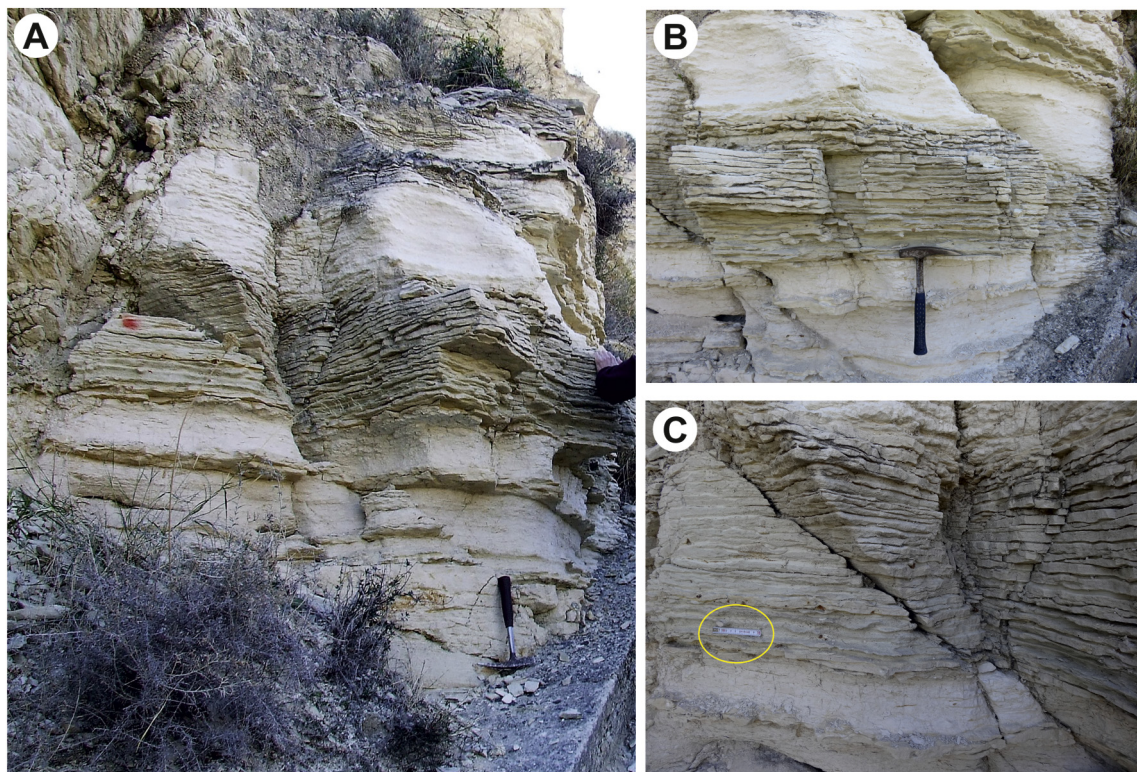


Fig. 3. Field photographs showing Oligocene contourrites in the Petra Tou Romiou section, indicating the main facies differentiated. A) Contourrites show alternating calcilutite (above and below) and calcarenite beds (middle). Note the wavy layering in calcarenite beds. B) Calcilutite-calcarenite sequence and internal wavy layering showing interstratified compacted layers of calcilutites/calcarenites between non-compacted calcarenite layers. C) Photograph details of a calcarenite beds showing cm-scale compacted (calcilutites/calcarenites) layers and interstratified non-compacted (calcarenites). Scale: Hammer (33 cm long) in A and B, and scale of 10 cm (yellow circle) in C. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

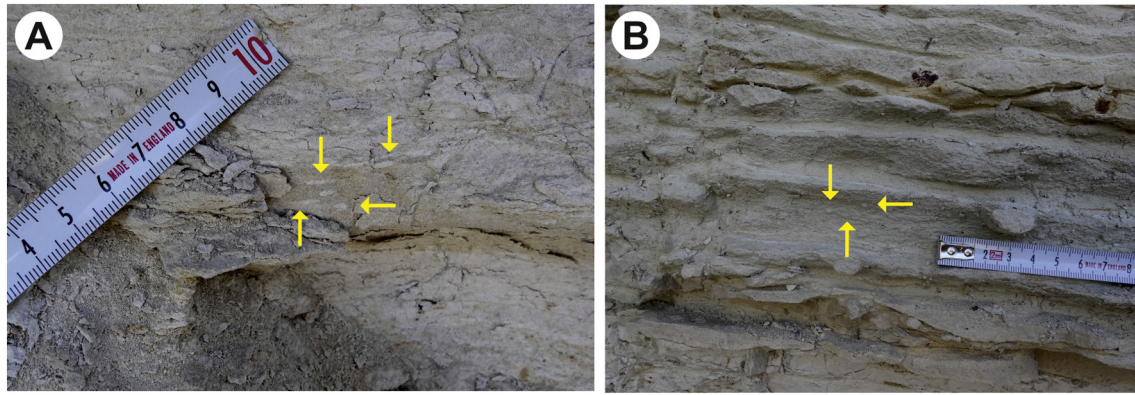


Fig. 4. *Chondrites* isp. and *Planolites* isp. (yellow arrows) in the calcilutite beds below the calcarenite beds (A) and in the interstratified compacted calcarenite layers into the internal wavy layering (B). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3. Methodology

Several bigradational sequences registered at the lower part of the Pakhna Formation at the Petra Tou Romiou section (Fig. 1) were studied focusing on the bigradational sequence of sand-dominated contourites previously studied by Stow et al. (2002b) and Hüneke and Stow (2008). These are composed of whitish calcarenite beds with internal wavy layering that makes a gradual transition of alternating whitish and greenish calcilutites above and below these calcarenites (Hüneke et al. submitted; Fig. 3). On the basis of the detailed microfacies analysis conducted previously by Hüneke et al. (submitted), the present study concentrates on ichnological aspects. This means a detailed analysis into both the calcarenite and the calcilutite beds, as well as on the boundaries between. With regard to calcarenite, a detailed ichnological examination has been made of the internal wavy layering, differentiating between compacted interlayers and non-compacted layers. Ichnological analysis is based on outcrop observations of macroscopic morphological features, centers on: shape, orientation, diameter and length of individual burrow segments, the arrangement of burrow systems, fill material, external features, and taphonomy. Photography recorded specimen position within the bed. Some of the specimens collected were studied in the laboratory focusing on the external features as longitudinal striae and on the infilling material (samples housed in the Stratigraphy and Palaeontology Department of the University of Granada), focusing mainly on the infill material.

4. Result: Ichnological analysis

In the bigradational sequence of sand-dominated contourites, two main ichnotaxa were clearly recognized: *Chondrites* and *Planolites*.

Chondrites Stenberg, 1833 has small circular or elliptical spots, less than 3 mm in diameter. This ichnotaxon is found in the whitish or greenish calcilutites appearing above and below the calcarenite beds as well as in the compacted interlayers of calcarenites. The composition of the fill material, consisting of fine-grained material as micrite and clay minerals (Hüneke et al., submitted), resembles that of the host sediment, though of a slightly lighter color (Fig. 4).

Planolites Nicholson, 1873 has straight, unbranched structures and is found in both the calcarenite and calcilutite beds (both in compacted interlayers and in non-compacted layers). Those recorded in the calcarenite and calcilutites beds differ notably in shape and composition. In the calcilutites, both above and below the calcarenite beds as well as in the compacted interlayers within the calcarenites, *Planolites* isp. shows elliptical sections of less than 1 cm wide, which have a composition similar to that of the host sediment, though lighter in color (Fig. 4). The non-compacted layers of the calcarenite beds contain cylindrical tubular forms that are circular to sub-circular (1–2 cm in diameter, minimum length of 5 cm; Figs. 5–7), primarily at the base of the calcarenite layers, or throughout the layer. Sometimes longitudinal striae were discerned, supporting a provisional assignment to *Planolites reinecki* Książewicz (Fig. 6).

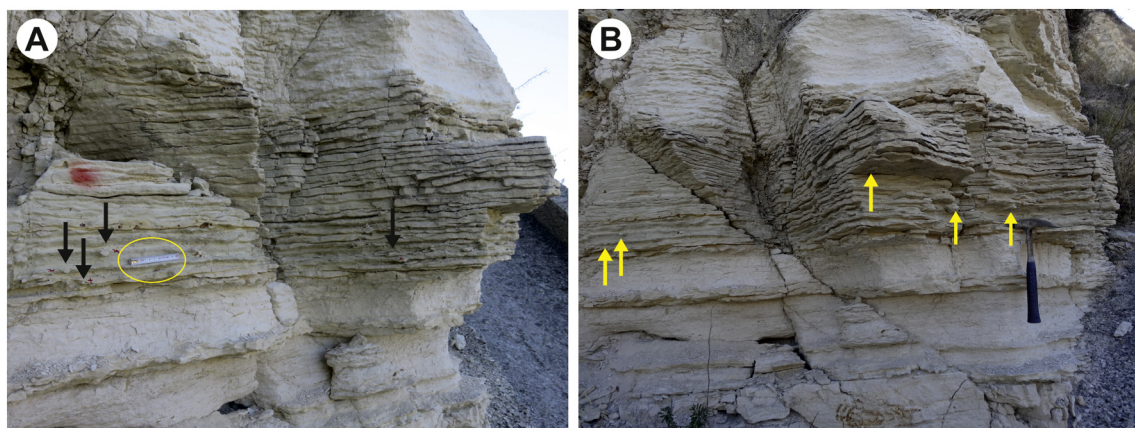


Fig. 5. Trace fossils in the calcarenite beds. A) *Planolites* in consecutive lenticular horizons, separated by mm-cm compacted layers. B) *Planolites* located mainly at the base of the amalgamated horizon or appearing throughout the horizon. Scale: Hammer (33 cm long) in B and scale of 10 cm (yellow circle) in A. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

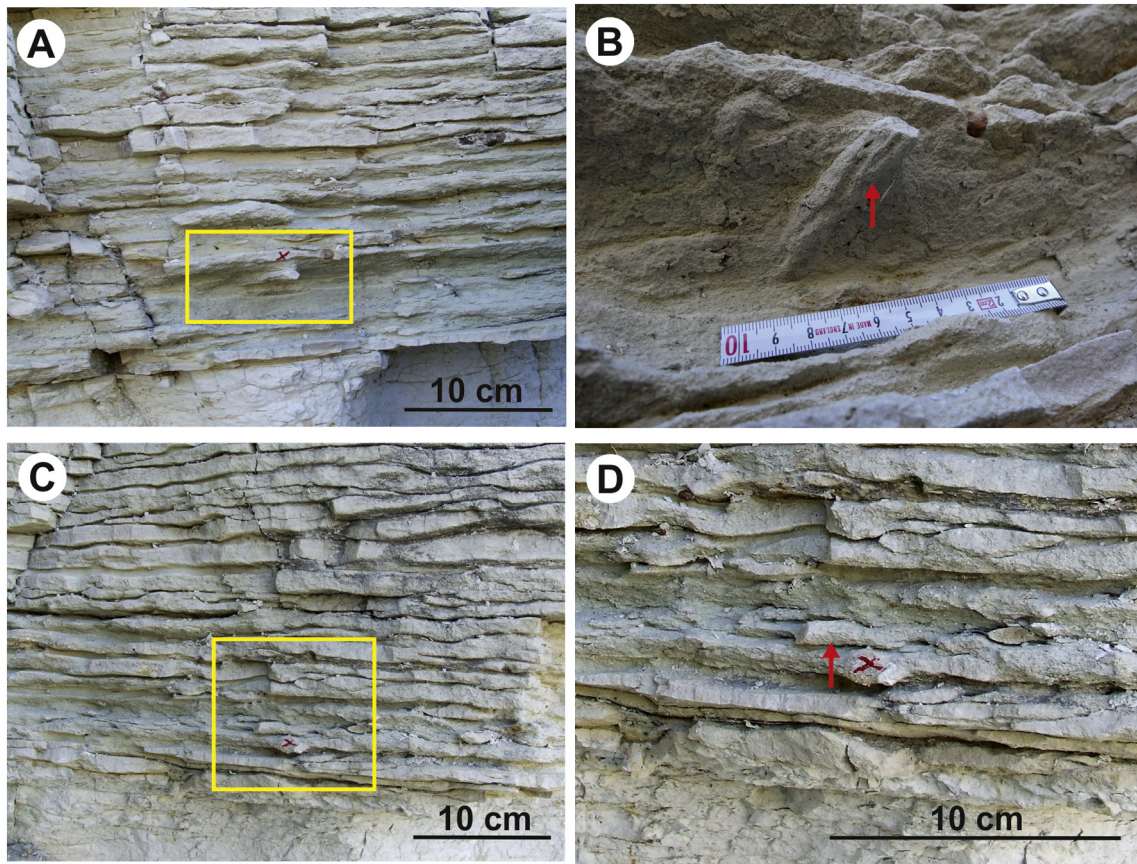


Fig. 6. Trace fossils of the calcarenite beds. A and C) Field photographs of *Planolites reinecki*, with longitudinal striae (red arrows) in detailed images B and D, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Planolites in this case are filled with the sediment from the corresponding calcarenite bed, formed by globigerinid packstones and grainstones (Hüneke et al., submitted), which differs in composition with respect to the sediment from the upper and lower calcilitite horizons.

In this sense, the ichnological assemblages can be clearly differentiated throughout the bigradational sequence of sand-dominated contourites:

- Both *Chondrites* isp. and *Planolites* isp. have been identified in the calcilitite below and above the calcarenite beds, although the presence of *Thalassinoides* isp. cannot be ruled out. Both ichnotaxa have flattened, elliptical sections, with fill material similar to that of the host calcilitite, though slightly lighter in color (Fig. 4).
- A clear differentiation was possible in the whitish calcarenite beds having internal wavy layering. A first trace-fossil assemblage similar to that of the calcilitites was found within the compacted interlayers. The specimens include flattened, elliptical *Chondrites* isp. and *Planolites* isp. Meanwhile, non-compacted layers present a second trace fossil assemblage consisting only of well-differentiated *Planolites* (*P. reinecki*), in full relief, near un-deformed structures (Fig. 7), locally with longitudinal striae (Fig. 6) and filled by sediment similar to that of the calcarenite beds. These structures are located primarily at the base of the non-compacted layers, where several specimens appear occasionally in the same layer (Fig. 5).

5. Discussion

In the first models of contourite facies, contourites were thought to have resulted from a continuous process, giving rise to a characteristic bigradational vertical facies array (e.g., Faugères et al., 1984; Gonther

et al., 1984; Stow and Holbrook, 1984) related to shifts in the energy of the bottom current (weak to strong, to weak again; Rebesco et al., 2014, and references therein). However, recent fluctuations in the supply of a coarser, terrigenous particles are currently also considered key in the vertical conformation of facies, this being only partly related to variations in the velocity of the bottom current (Mulder et al., 2013; Rebesco et al., 2014). In the first models, the illustrations indicated gradational contacts through a vertical succession of contourite facies, with only local sharp ones (irregular contacts). Later modifications of the models included illustrations offering some indication of lithology and structure and the bioturbation from bottom to top, in addition to the existence of “variable contacts” within the mottled silt and mud facies and “sharp to gradational contacts?” in and sandy-silt facies (Stow et al., 1986, 1998). However, the most notable change appeared in the contourite facies model presented in Shanmugam (2017; see red arrow in its Fig. 9.19) in reference to Stow and Faugères (2008). This was also indicated in earlier papers differentiating facies divisions (Stow et al., 2002a; Stow, 2005). The novelty concerns an indication of “± hiatuses” within the C3, this being the middle sandy contourite division. For the interpretation of contourites, internal hiatuses in the model of contourite facies are of paramount importance, as these could be associated with discontinuity, breaks or reduction in sediment deposition, a lack of deposition, changes in substrate consistency, or erosion. Moreover, Shanmugam (2017) proposed that in the C3 division the record of hiatuses could signify that intervals above and below the hiatuses point to two different depositional events.

Wetzel et al. (2008) stated that if deposition is prevented by bottom currents for a substantial time period, and/or erode sediments, then submarine hiatuses will develop. These may appear as variable records of either semi-consolidated firm- or hardground or partially dewatered

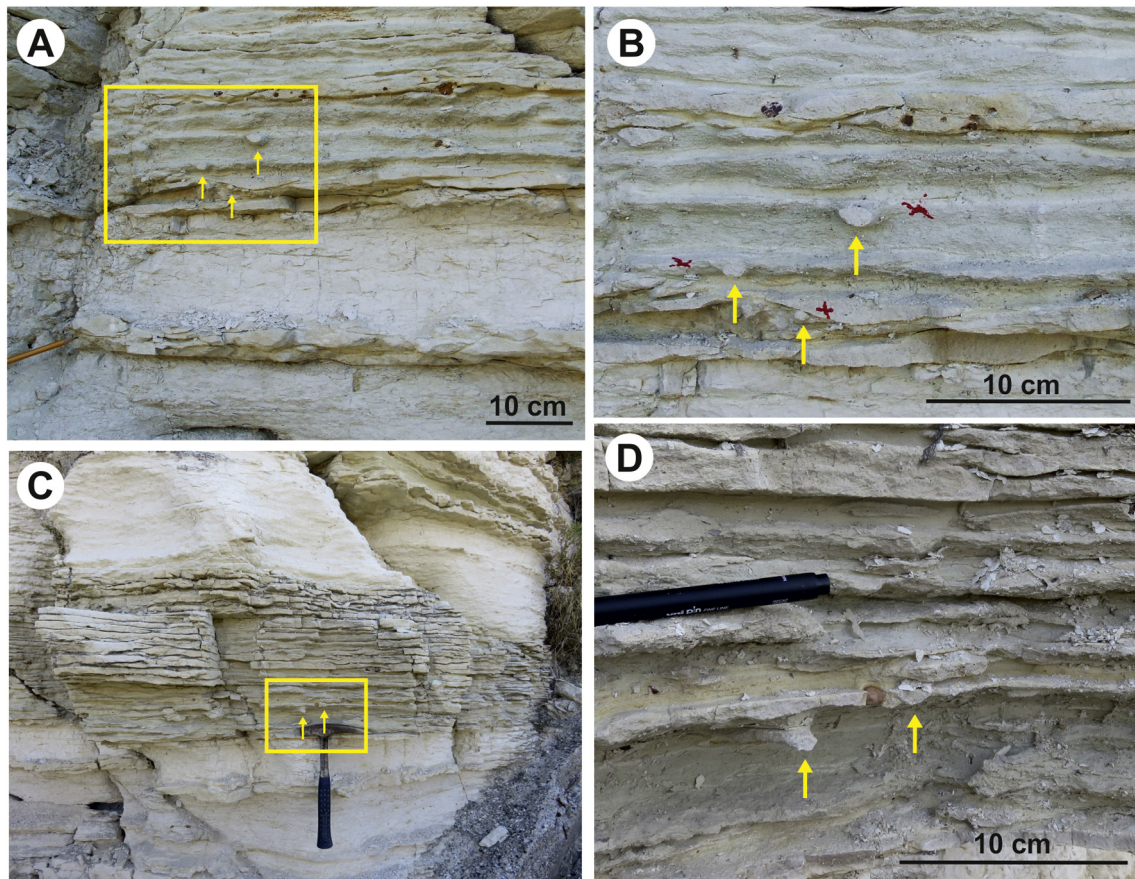


Fig. 7. Trace fossils of the calcarenite beds. A and C) Field photographs of *Planolites* showing nearly undeformed structures (yellow arrows) with fill material similar to that of the calcarenite beds (detailed in B and D, respectively). Scale: Hammer (33 cm long) in C. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

muddy substrates that are cohesively stable (Wetzel et al., 2008). They may also appear as lag deposits associated with strong bottom currents (Hüneke and Stow, 2008; Martín-Chivelet et al., 2008; Stow and Faugères, 2008; Wetzel et al., 2008; Shanmugam, 2017), or as phosphoritic hardgrounds and phosphorites (Hüneke, 2013). The presence of these omission surfaces is notable in separating micro-sequences measuring 2–10 cm thick, in calcareous bioclastic contourites (Hüneke, 2013). Moreover, hardgrounds, hiatus surfaces, and non-depositional surfaces have recently been found in various types of contourite facies (Rebesco et al., 2014), such as calcareous sandy contourites, chemogenic contourites, or manganiferous contourites. These hiatuses, whether omission surfaces or breaks in sedimentation, can be interpreted on the basis of ichnological features. Hüneke and Stow (2008) place emphasis on finding *Ophiomorpha* in finer grained calcilutites and coarser-grained calcarenites, which develop typically beneath a presumed omission surface. Wetzel et al. (2008), studying sandy mud and muddy-sand contourites from the Northwest Atlantic Margin, off New Jersey, noted the distinctness of the *Glossifungites* ichnofacies that typify the non-deposition horizons, based on a record of *Thalassinoides* infilled with coarser material that is associated with firm- or hardground. According to Hüneke (2013), slow accumulation or a lack of deposition, increasing erosional surfaces, and hardground cementation, can be detected by fluctuations in bioturbation intensity as well as other ichnological features, such as stenomorphic *Planolites*, boring in hardgrounds, or truncated burrows.

The archetypal *Glossifungites* ichnofacies record indicates substantial changes in depositional conditions, leading to the firm- or hardground conditions. However, the *Glossifungites* ichnofacies together with its related ichnological features (Buatois and Mángano,

2011; MacEachern et al., 2012) are: a) unlined, sharp-walled, passively filled burrows; 2) predominance of vertical to subvertical, robust, simple and spreite U-shaped burrows; 3) branched burrow systems; 4) burrows having ornamented walls (bioglyphs); and/or 5) pseudoborings, which do not occur under milder changes in depositional conditions. In these cases, the ichnological analysis should place special attention on any features that enable contourite characterization.

The ichnological features recorded in the contourite type facies studied in the Petra Tou Romiou section lend special significance to the interpretation of the origin of the stratigraphic pattern observed as well as to an assessment of paleoenvironmental conditions prevalent during contourite deposition, affecting mainly current velocity, sedimentation rate, and substrate consistency.

5.1. Trace-fossil assemblages and the origin of the internal wavy layering

The recent microfacies analysis indicated that the internal wavy layering can be interpreted as a primary sedimentary feature. Also diagenetic shift can be termed a secondary modifying process (Hüneke et al., submitted). This wavy layering represents a recurring change between bedload deposition and greater suspension fallout. However, currently, the mechanism controlling the short-term fluctuation in flow strength remains unknown.

Different trace-fossil assemblages in the calcarenite bed, with deformed *Chondrites* isp., *Planolites* isp., and ?*Thalassinoides* isp., in the compacted interlayers, and only nearly undeformed *Planolites* (*P. reinecki*) in the non-compacted layers evidences the primary origin of this differentiation, reflecting variable depositional conditions.

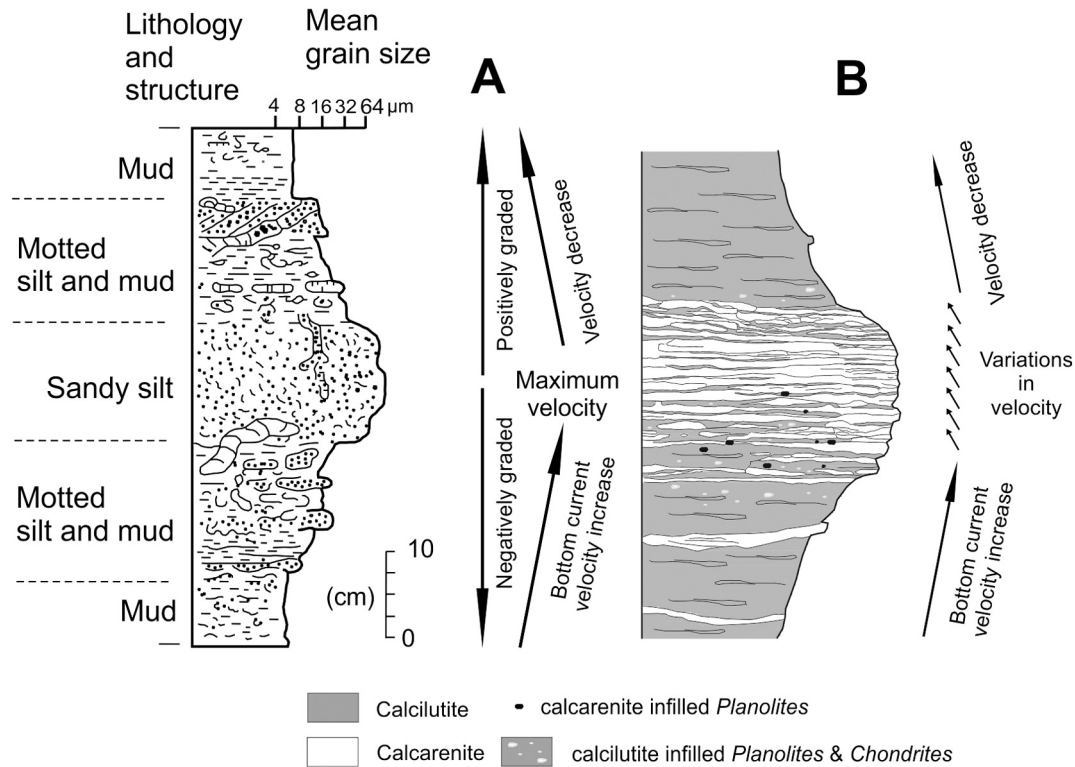


Fig. 8. A) Standard facies model of contourite sequence with deduced contour-current velocity (i.e. Rebesco et al., 2014). Note the bigradational sequence and the deduced continuous process with increased velocity from bottom to middle of the sequence, the maximum velocity being associated with the sandy-silt interval, followed by decreasing velocity towards the top. B) Proposed modification of the facies model based on ichnological information, with small discontinuities and variations in current velocity towards the middle part of the sequence.

This scenario gains support from the different fill material of the traces recorded, in any case similar to that of the corresponding host sediment, offering evidence of bioturbation during the deposition of calcilutite and calcarenite sediments. It cannot be ruled out that this alternation was diagenetically intensified, as suggested by the mild deformation of the *Chondrites* and *Planolites* structures within the compacted interlayers. The similarity between the trace-fossil assemblages found in the compacted interlayers and in the calcilutites above and below the calcarenite beds may reveal similar depositional processes under the dominance of pelagic deposition.

5.2. A multiphase deposition: the record of *Planolites*

In line with the above, the multiphase deposition of a calcarenite bed at the middle portion of bigradational sequences of the sand-dominated contourites is interpreted. This part was not continuously deposited as a single process, but rather intermittently over shifting depositional conditions. The finding of *Planolites* in consecutive non-compacted layers strengthens this interpretation, also. As a trace fossil typical of shallower tiers, *Planolites* is produced on or just beneath the seafloor (normally around 1 cm underneath the seafloor surface; Rodríguez-Tovar and Uchman, 2004a, 2004b). The presence of *Planolites* in various non-compacted layers containing similar calcarenite fill material, separated by compacted interlayers, rules out that bioturbation came from a single horizon marking colonization from the uppermost part of the calcarenite bed following continuous deposition. This observation in fact supports several bioturbation phases, each related to the corresponding compacted layer. Hence, each compacted bioturbated layer is separated due to a phase of greater calcilutite deposition.

5.3. *Planolites reinecki*: continuous vs. discontinuous depositional processes and changes in substrate consistency

The presence of only *Planolites* within the non-compacted layers, in some specimens with diameters equal to the thickness of the corresponding interlayer, might be related to a relatively swift deposition and/or reworking of this layer. The rapid deposition and thinness of the deposited material precludes colonization of deeper tiers by trace makers (i.e., *Chondrites* and *Thalassinoides* producers), allowing only shallow tier organisms (*Planolites* tracemaker) associated with favorable paleoenvironmental factors such as nutrient availability and aerobic conditions during deposition.

The relatively minor flattening of *Planolites*, while roughly maintaining the original shape, suggests a soft but somewhat cohesive substrate. This somewhat cohesive character is deduced also from the longitudinal striae in some specimens, tentatively assigned to *Planolites reinecki* Książewicz. Cohesiveness. Two alternatives may explain this somewhat cohesive sediment colonized by the *Planolites* trace maker: a) an omission period with either sedimentary condensation or interruption after the non-compacted layers were deposited, immediately before the next compacted interlayer was deposited; and b) minor erosion giving rise to the exhumation of concealed semi-consolidated substrates (i.e., buried sediment). The absence of stratigraphic features related to this hypothetical erosion lends strength to the first interpretation.

5.4. The ichnological signal: refining the contourite model

As indicated above, the contourite facies model that was proposed at the beginning of the '80s for muddy contourite facies in the Gulf of Cadiz, and presented almost simultaneously in a number of papers (Gonthier et al., 1984; Faugères et al., 1984; Stow and Holbrook,

1984), reflects the vertical sequence arrayed in coarsening-up/fining-up cycles (negatively/positively graded), and supports the idea of the typical bi-gradational sequence that characterizes contourites. This bi-gradational sequence was thought to have been caused by a continuous process, with an increase in velocity from bottom to middle of the sequence, reaching maximum velocity associated to the sandy-silt interval, and then a decreasing in velocity towards the top (Fig. 8A). The energy of the bottom current shifted from weaker to stronger, and then to weaker again (Rebesco et al., 2014, and references therein). Only occasionally, hiatuses, below, into and above the C3 division has been recognized and interpreted as revealing discontinuous deposition and different depositional events (Stow et al., 2002a; Stow, 2005; Stow and Faugères, 2008; Wetzel et al., 2008; Hüneke, 2013; Shanmugam, 2017).

In general, indistinct boundaries between the calcarenites and the whitish or greenish calcilutites indicate a gradual shift in the depositional regime that went from and to both facies (Hüneke et al., submitted). However, the data recorded do not support a continuous process during deposition throughout the calcarenite bed in the middle portion of the bigradational sequence, but rather suggest the presence of several small-scale hiatuses, leading to ichnological changes. The variable lower-order hiatuses point to depositional changes, and then shifts in the depositional conditions, such as bottom current velocity and rate of sedimentation. The data compiled indicate that the original proposal for the bigradational sequence, until now considered part of a continuous process that reflects greater to lesser bottom current velocity, should be reconsidered in favor of intermittent processes, which appear to be the most plausible origin. Thus, contourite sequence thus does not reflect an uninterrupted deposition process of the entire sequence, but rather numerous discontinuities related to lower- or higher-order sedimentary changes determining the sedimentation rate and the sedimentary facies, at least in the middle portion of the sequence (Fig. 8B). The interpretation proposed agrees with the explanation of the internal wavy layering as representing discontinuous accumulation resulting from short term fluctuations between phases of flow acceleration deposition of un-compacted layers and deceleration producing compacted interlayers (Hüneke et al., submitted). This fact reflects the complex contourite depositional processes of sediment winnowing, entrainment, and accumulation (McCave, 2008; Stow et al., 2008), notably differing from the traditional and previous interpretations, but supporting the presence of hiatuses as those sometimes recognized into the C3 division (Stow et al., 2002a; Stow, 2005; Stow and Faugères, 2008; Hüneke, 2013; Shanmugam, 2017). However, the ichnological analysis allows the characterization of minor-order hiatuses only recognized by ichnological features.

6. Conclusions

The detailed trace-fossil analysis of bigradational sequences of the sand-dominated contourites in Petra Tou Romiou section (Cyprus) indicates major ichnological features that improve the interpretation and identification of contourite deposits.

Below and above the calcarenite beds and in the compacted interlayers found within the calcarenite beds, calcilutites show a similar trace-fossil assemblage that consists of *Chondrites* isp. and *Planolites* isp., which have flattened elliptical sections and fill material resembling that of the host calcilutite, though slightly lighter in color. Non-compacted layers within the calcarenite beds reveal the presence only of nearly un-deformed *Planolites* (*P. reinecki*) structures bearing occasional longitudinal striae, and filled by sediment similar to that of the calcarenite beds.

Ichnological and sedimentary results indicate a gradual transition from and to the greenish and whitish calcilutites found above and below the calcarenite beds. However, a different trace-fossil assemblage present between the compacted interlayers and the non-compacted layers within the internal wavy calcarenite beds support the

contention of a primary differentiation. This presumably reflects variable paleoenvironmental or hydrodynamic conditions, with a strong impact on sedimentation rate and substrate consistency.

Planolites, recorded in consecutive non-compacted layers, separated by compacted interlayers, is associated with several bioturbation phases during a multiphase deposition in the middle part (i.e., the calcarenite bed) of the contourite-type facies sequence. Increased substrate consistency related to omission after the deposition of the non-compacted interlayer or to sedimentary condensation, been interpreted on the basis of the relatively mild flattening of *Planolites*, maintaining more or less the original shape, and the striae (*P. reinecki*). This indicates sedimentation processes that were discontinuous during contourite deposition, as opposed to the main idea, formerly accepted, that sediment accumulation induced by the bottom current is an uninterrupted process with a gradually changing flow velocity related to the bigradational sequence formation.

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