Crowded tubular tidalites in Miocene shelf sandstones of southern Iberia

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Abstract

The passive and active fill of burrows potentially stores information about sedimentary processes that are otherwise not preserved in the rock record. In recent years, abandoned passively-filled vertical burrows were introduced as “tubular tidalites” when their infilling displays rhythmic lamination reflecting a tidal signature. In the shallow-marine Miocene sandstones exposed at Oura (southern Portugal), 36 tubular tidalites occur in a 1.5 m-thick interval. Their high abundance is likely a consequence of both an environment favourable for the production of open burrows in a tidal setting, and post-depositional conditions facilitating the preservation of the tubular tidalites. Besides vertical tubes, 13 horizontal burrows preserve a tidal signature indicating draught-fill processes. All specimens belong to *Thalassinoides* and, for the first time, to *Gyrolithes*. The rhythmic infill of two well-preserved specimens shows two significant features: (1) The thickness pattern allows for differentiation into groups having 7 couplets (consisting of a dark and a light lamina) or multiples thereof, and (2) the thickness patterns of both, consecutive couplets as well as dark and light laminae match sine curves. Both patterns indicate a diurnal tidal cyclicity. The tidalites record up to four spring-tide and three neap-tide cycles. In addition to the neap-spring cycles, a long-period lunar fortnightly tide regime can be envisaged. The tubular tidalites imply diurnal tides during the Miocene in contrast to the Recent semidiurnal tides affecting southern Portugal.

1. Introduction

Over the last decades, ichnology has become a useful approach in Earth Sciences to obtain supplementary information about environmental processes and factors, since burrowing organisms sensitively respond to the ecologic conditions in their habitat (Buatois and Mángano, 2011, and references therein). The behavior of tracemakers is documented by the biogenic sedimentary structures produced, which provide valuable information about the depositional setting (Pemberton et al., 2001; Taylor et al., 2003; MacEachern et al., 2007; Knaust and Bromley, 2012). Ichnology is, however, not restricted to the environment-related ethological aspects of trace fossils; particular actively and passively filled burrows may store a sedimentary record that is otherwise not preserved (e.g., Wetzel, 2015). Of special interest are burrows infilled by material subsequently eroded from the sediment surface, but not from the burrows. Hence burrow fill can represent the only lasting record of a material.

Three terms have become established in recent years to denote different processes: "tubular tempestites", "tubular tidalites" and "tubular turbidites". The term "tubular tempestites" was introduced first and refers to "*forced fillings of subsurface burrows during storms*" (Wanless et al., 1988). The deep-encased tubular tempestites have a high preservation potential, whereas that of the tempestite layers on the surface is lower. Tubular tempestites form in a stable, stiff or firm substrate, while open, mostly abandoned tubes are subsequently filled with sediment transported by storm-generated currents. Observations on modern open *Callianassa* burrows form the basis for this concept, but it has also been successfully applied to ancient sediments wherein large, open *Callianassa*-like burrows such as *Ophiomorpha* and *Thalassinoides* occur (Wanless et al., 1988; Tedesco and Wanless, 1991). Tubular tempestites were described, for instance, from Lower Cambrian sandstones (Jensen, 1997), Cambrian-Ordovician deposits housing *Trichophycus*-related tubular tempestites (Droser et al., 2004), Permian siltstones of the *Skolithos*- *Cruziana* ichnofacies containing *Diplocraterion* and *Rhizocorallium* filled with tempestite material (Bann et al., 2004), and Lower and Middle Jurassic mud-firmgrounds exhibiting *Thalassinoides* and *Spongeliomorpha* filled with storm- current transported sediment (Leonowicz, 2016).

In the bathyal realm, for passively filled burrows belonging to the *Glossifungites* ichnofacies, which are also entrenched in firmgrounds, Hubbard et al. (2012) proposed the term "tubular turbidites" that indicate sediment bypass. They are "*...sand-filled burrows (in some instance)* [that] *record the passage of coarse-grained material through an erosional conduit such as a submarine canyon or channel, without deposition of a coarse lag*" and "*…the only evidence of coarse-grained sediment in the system may be recorded within the burrow fills*".

Among the three terms, tubular tidalites are increasingly recognized. This term was coined to refer to sedimentary couplets documenting tidal processes preserved in *Psilonichnus* and *Thalassinoides* burrows (Gingras et al., 2002). Yet the term was initially used beyond a strict sense, and in most cases the infill was not analyzed in detail with respect to a tidal signature (Gingras et al., 2007, 2012a, 2012b; Gingras and MacEachern, 2012; Pearson et al., 2012; Baniak et al., 2014). Tubular tidalites can provide a detailed record of the tidal pattern (e.g., Wetzel et al., 2014; Gingras and Zonneveld, 2015). In many instances, they are formed within *Thalassinoides* shafts. Ideally, a tidal record covering several weeks is preserved, and neap-spring cycles as well as the tidal pattern (semi-diurnal, mixed semi-diurnal-diurnal, diurnal) can be recognized (Wetzel et al., 2014).

The term "tubular tidalites" was formally defined by Gingras and Zonneveld (2015) as "*…trace fossils that are infilled by tidal currents and display a rhythmic, laminated passive infill*". These authors presented several examples of tubular tidalites from various marginal marine deposits, Mesozoic, Cenozoic, and Recent in age. The deposits were found to occur in a variety of open burrows, such as *Arenicolites*, *Ophiomorpha*, *Palaeophycus*, *Psilonichnus*, and *Thalassinoides* (Gingras and Zonneveld, 2015). To date, the number of tubular tidalites studied is low (Gingras and Zonneveld, 2015), perhaps owing to the difficulties in creating such a particular sediment trap, or to its preservation. The aim of this study is to present the record of tubular tidalites in Miocene sediments from the Oura seacliff section (southern Portugal). The exposed tubular tidalites are exceptional because of their high abundance, their preservation, and the associated ichnotaxa. Furthermore, a local tidal regime during the Miocene could be interpreted, differing from the modern one.

2. Geological setting

The studied Oura section is located on the seacliff of the Leixão dos Alhos peninsula, situated about 1.5–2 km east of the city of Albufeira (central Algarve, southern Portugal; coordinates 37° 05' 01.58" N, 08° 13' 49.92" W; Fig. 1). Cachão et al. (1998) discerned within the whole Neogene sequence three formations, from bottom to top: (i) the Lagos–Portimão Formation, (ii) the Cacela Formation, and (iii) the Ludo Formation; respectively, they are (i) Langhian–Serravallian, (ii) Late Tortonian to Messinian, and (iii) Late Miocene to Early Pliocene in age (Fig. 2).

In the studied section, the lowermost 5 m display highly cemented fossiliferous biocalcarenites and bioclastic limestones ("Biocalcarenito de Lagos" sensu Cachão et al., 1998; Fig. 2),

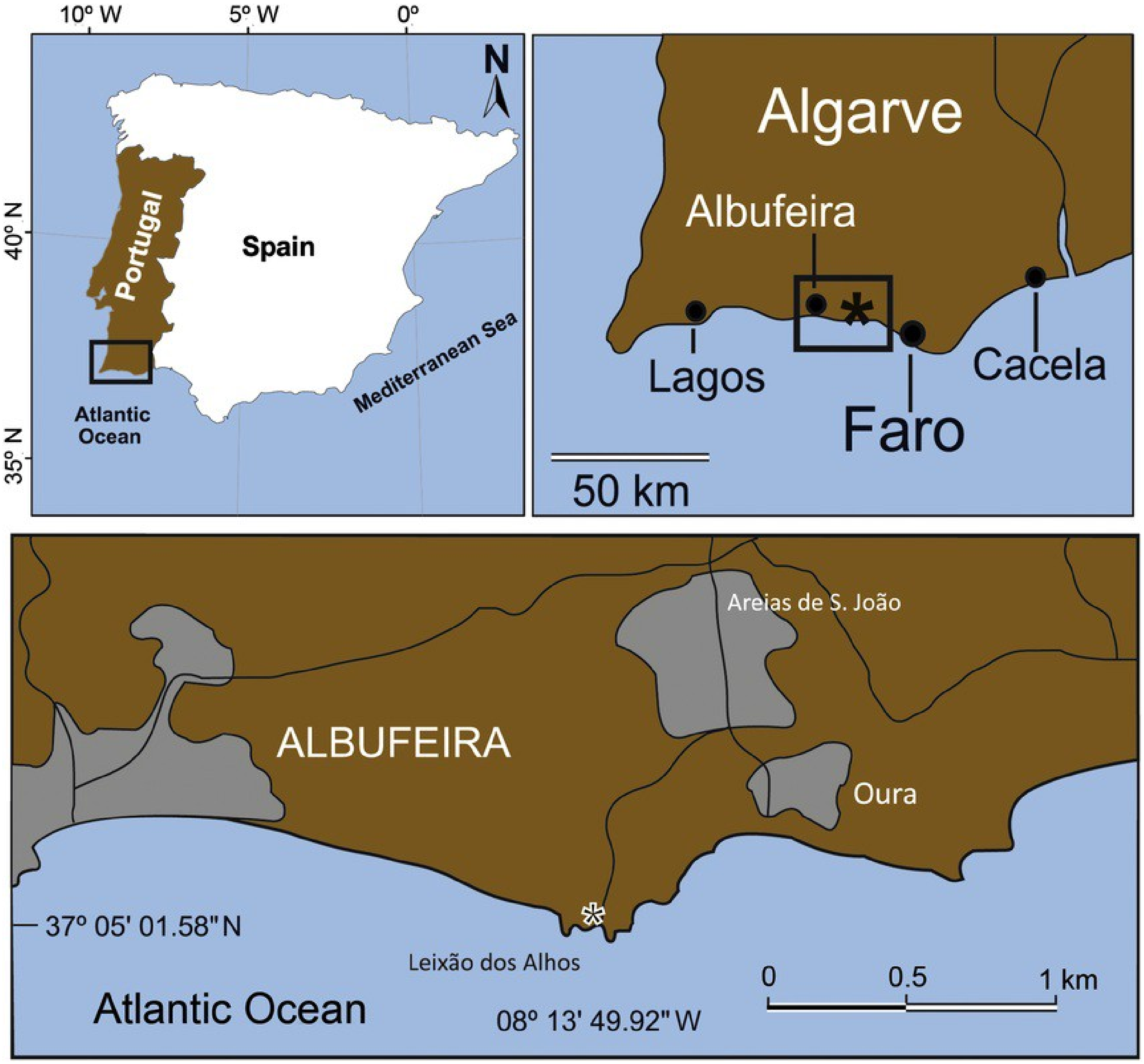

Fig. 1 Location of the study site, the Oura section, east of Albufeira (central Algarve, southern Portugal).

which constitute the lower member of the Lagos–Portimão Formation. These biocalcarenites have a high fossil content including, as most representative, bivalves (Pectinidae, Ostraeidae), gastropods (*Turritella*), tests of echinoids (*Clypeaster*, *Echinocardium*) and rhodoliths (Fig. 2). The uppermost part of these calcarenites is heavily bioturbated, displaying *Bichordites* and *Thalassinoides*. The top surface is affected by intense bioerosion evidenced by *Gastrochaenolites* (Cachão et al., 2009), which sculpts the surface and crosscuts *Thalassinoides* burrows. This surface marks the boundary to the overlying unit and can be traced several kilometres along the cliff. It constitutes an important regional intra-Miocene paraconformity representing a hiatus encompassing the uppermost Serravallian and the Lower to Middle Tortonian (Cachão and da Silva, 1992, 2000).

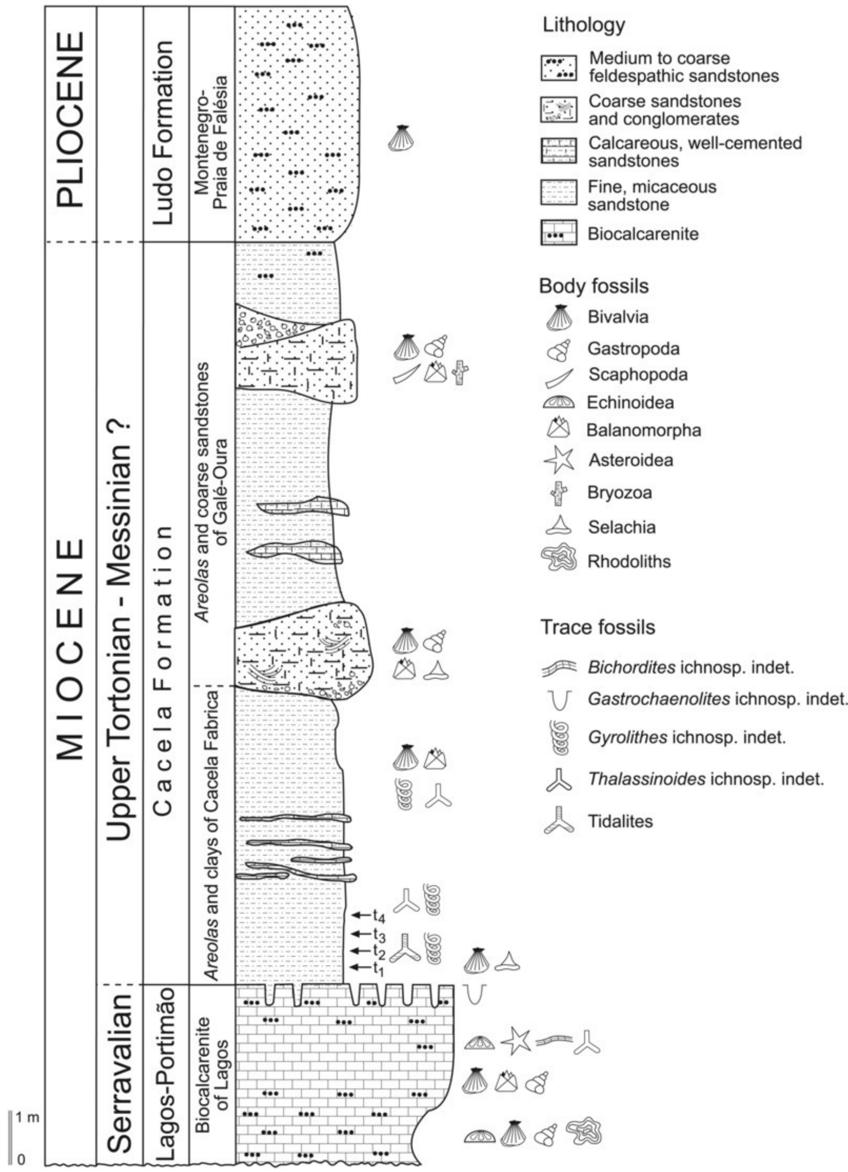

Fig. 2 Synthetic log of the Oura section, showing lithology and occurrence of body fossils and trace fossils (modified from Cachão et al., 2009). Note location of the intervals (arrows) containing tubular tidalites in the lower part of the section.

Above this surface, 13.1 m of fine to very fine, poorly cemented, yellow micaceous sandstone and clays occur. They are known as "areola" in the Portuguese literature (Cachão and Freitas, 1998). A few intercalations of calcareous medium-sized sandstone lenses, locally associated with conglomerates, are present. These sandstones represent the middle and upper member of the Cacela Formation, the so-called *Areolas* and clays of Cacela Fabrica and *Areolas* and coarse sandstones of Galé-Oura (Cachão et al., 2009; Fig. 2). Fossils are common and include pectinids and balanomorphs throughout the whole interval, selaceous teeth mainly in the lower-middle part, and moulds of gastropods and scaphopods, together with bryozoans, in the middle and upper parts. In the lower and upper parts of the interval trace fossils are present, in particular *Thalassinoides* and truncated vertical shafts up to 5 cm in diameter. The latter probably correspond to the upper parts of *Thalassinoides* or *Gyrolithes* burrow systems (Fig. 2).

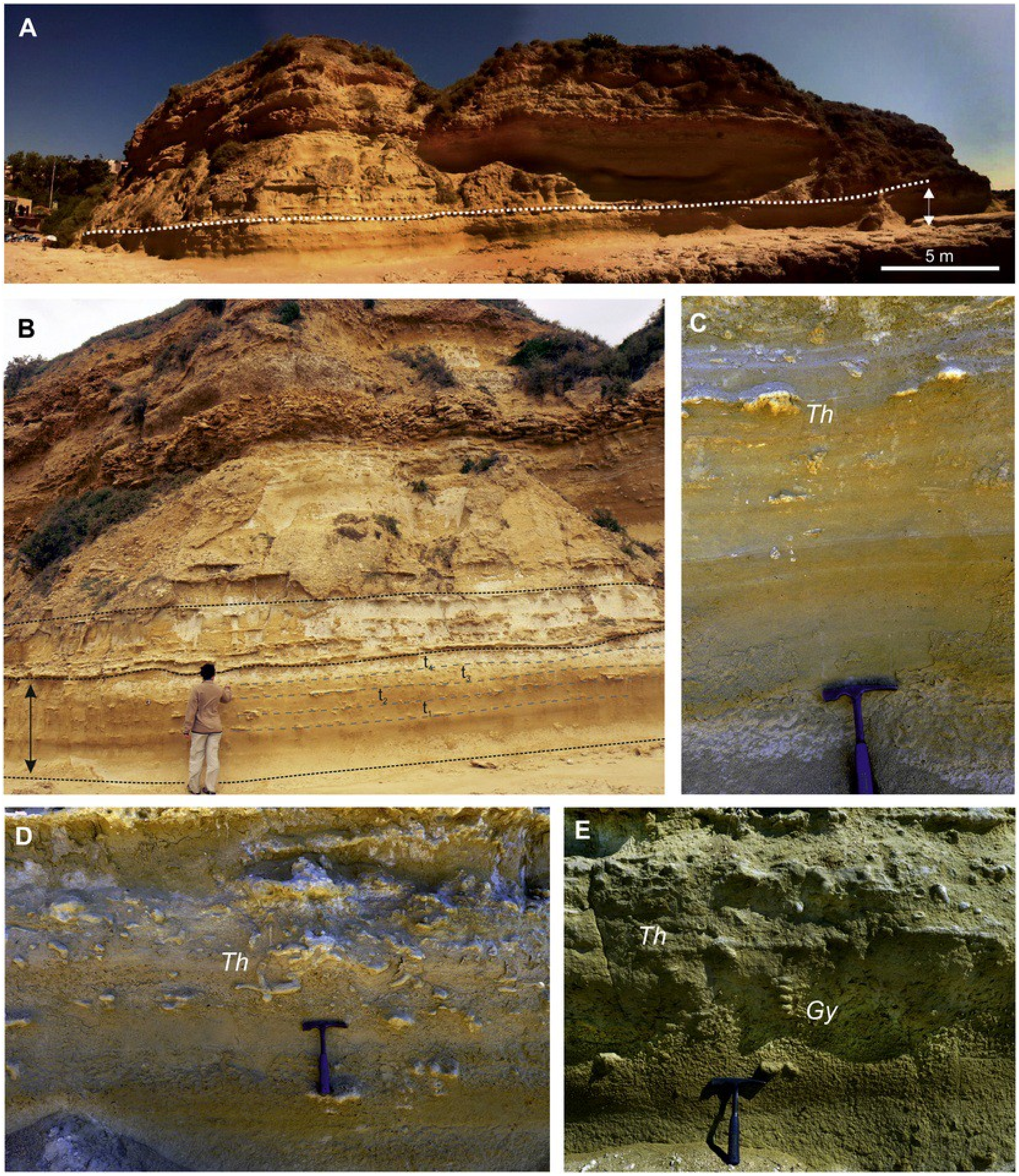

Fig. 3 Panoramic (A) and general (B) view of the studied outcrop (*Areolas* and clays of Cacela Fabrica Member, Cacela Formation); horizons containing tubular tidalites (t_1 to t_4; arrows) and the overlying calcareous sandstone. (C), (D) and (E) details of the lower interval, recognized The tubular tidalites and the trace fossils *Thalassinoides* (*Th*) and *Gyrolithes* (*Gy*); hammer (33 cm long) for scale.

Several horizons with tubular tidalites are located within the lower 1.5 m-thick interval of *Areolas* and clays of the Cacela Fabrica Member. They are addressed in this study (Figs. 2, 3).

The upper part of the studied section comprises 4.3 m of white and reddish medium to coarse feldspathic sandstones of the Montenegro-Praia de Falésia Member, which corresponds to the lower member of the "Ludo Formation" (sensu Cachão et al., 1998; Fig. 2).

Paleontological assemblages (benthic foraminifera, bivalves and trace fossils) allow interpret the Cacela Formation as corresponding a to low energy, shallow-marine environment, with a depth between 20 and 30 m, even shallower (Cachão et al., 1998, 2009; Santos, 2005; Pais et al., 2012; Santos et al., 2016).

3. Material and methods

Along the 87 m-long cliff studied, 36 tubular tidalites were encountered in two intervals having similar lithologies; but the lower one shows a slightly cemented appearance. Within the lower interval 15 tubular tidalites occur in three horizons (t_1, t_2, and t_3; Fig. 3), while 21 pertain to the upper interval (t_4; Fig. 3). Ichnological features such as preservation, orientation, shape, geometry, size, and relation to the host sediment were recorded. Some specimens were selected for high-resolution photography and detailed study in the laboratory.

Field and laboratory pictures were processed to enhance the contrast and visibility of the fill structures, in particular laminae, using a high-resolution image treatment successfully applied in previous ichnological studies (e.g., Dorador et al., 2014; Dorador and Rodríguez-Tovar, 2018). The method entails modification of certain image adjustments (level, brightness and vibrance). In the present study, an additional exposure correction was applied to correct for overexposed areas. Thereafter, the thickness of consecutive dark and light laminae constituting couplets was measured and their number was counted. All the measurements were obtained using scaled photographs with 0.01 mm resolution. Detailed analysis of the rhythmic infilling sediment, in particular the type (dark, light) and thickness of laminae and couplets, was conducted for two well preserved specimens containing a few tens of laminae (O-li-1 and O-li-11).

4. Results

The Areolas and clays of Cacela Fabrica Member at the Cacela Formation, including the lower 1.5 m-thick interval containing the four horizons with tubular tidalites (t_1 to t_4), shows an ichnoassemblage mainly composed by *Gyrolithes* and *Thalassinoides*/*Ophiomorpha* (Cachão et al., 2009; Santos et al., 2016).

Respect to the tubular tidalites, size (diameter and extent) and orientation of burrows, as well as the number of laminae of the infill material was measured for 35 specimens (Table 1; Fig. 4). Laminae show a contrast in colour between light and dark) with only small differences in grain size. Most the specimens (23) appear as vertical/sub-vertical tubes, and 12 are horizontally oriented; in 2 cases vertical and horizontal parts are observed for the same specimen. The horizontal specimens are restricted to the lower interval. The tubes are occasionally branched and show bulb-like enlargements at branchings. The vertical tubes are 1.5–4.2 cm in diameter, but mainly 2.4–3 cm, and have a vertical extent of 2.9 to 30.7 cm. The horizontal tubes have a similar diameter and show a horizontal extent of up to 20.8 cm. For the vertical specimens, the

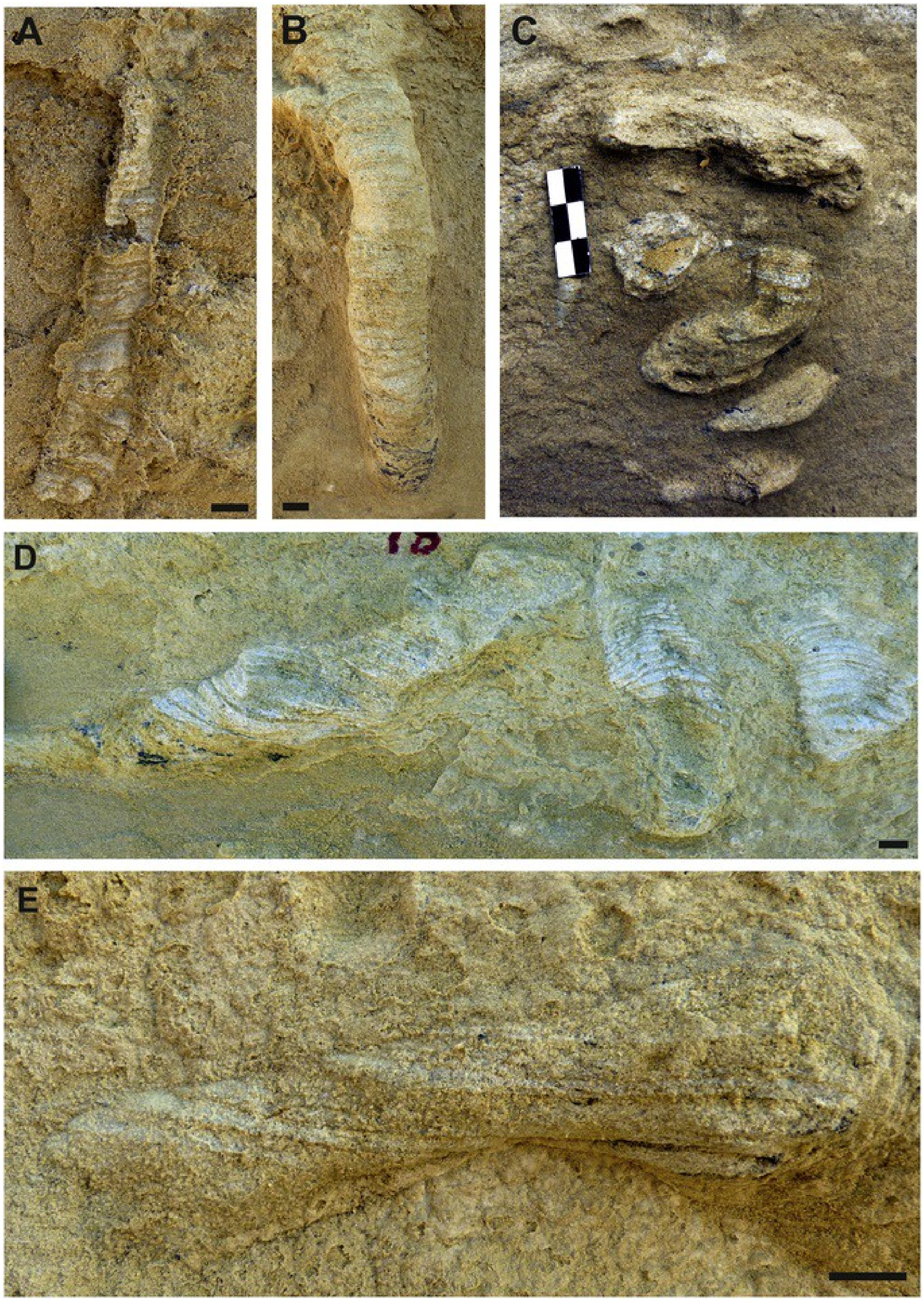

Fig. 4 Examples of the studied tubular tidalites. A, O-li-1 (vertical); B, O-li-2 (vertical); C, O-li-14 (helicoidal); D, O-ui-18 (vertical & oblique); E, O-ui-7 (horizontal). Scale bars 1 cm. All the specimens represent parts of *Thalassinoides* except C (*Gyrolithes*). Note li refer to lower interval and ui to upper interval.

vertical extent clearly decreases from the lower interval (from 6.0 cm up to 31 cm) to the upper interval (usually <5.0 cm). One burrow within the lower interval exhibits helicoidal morphology (O-li-14; Table 1; Fig, 4C); it has a 3.1 cm tube diameter, 7 cm coil diameter and shows 5 turns. There is no significant difference in terms of ichnological features among the horizons t_1 to t_4 or between the lower and upper intervals except for an increased abundance of distinct burrows upward, and the presence of horizontal structures exclusively in the upper interval.

Table 1 Ichnological data from the studied tubular tidalites

	Orientation	Diameter [cm]	Horizontal extent [cm]	Vertical extent [cm]	Laminae (Number)
Upper interval					
1	V	2.9		3.9	4
2	H	5.0	9.4		6
3	H	2.6	4.7		3
4					
5 a	H	2.2			5
5 b	V	1.7		2.9	3
6	V	2.5		3.6	7
7	H	3.2	11.0		7
8	H	5.1	5.1		4
9	V	2.4		3.4	4
10	V	2.8		5.7	6
11	H	2.3	16.3		5
12	H	2.1	9.8	4.2	10
13	H	2.3	19.2	4.3	6
14	V	1.9	2.4	6.4	13
15	H	5.1		6.5	9
16	H	4.1	11.4		12
17	H	3.4	10.6		7
18 a	H	3.6	20.8	3.9	12
18 b	V	3.8		8.9	11
18 c	V	4.2		6.3	12
Lower interval					
1	V	1.9		12.2	30
2	V	3.4		19.1	21
3	V	2.4	2.7	8.9	7
4	V	2.5		4.3	3
5	V	2.1		7.7	5
6	V	2.6		29.0	
7	V	1.5		4.3	5
8	V	2.7		30.7	9
9	V	2.7		9.8	
10 a	V	2.8		4.2	3
10 b	V	2.6		8.3	11
11	V	3.0		17.0	17
12	V	2.9		6.5	
13	V	2.7		6.3	3
14	V	3.1	7.8	11.4	6

Two specimens preserve a comparatively large number of distinctly consecutive laminae. Measured in specimen O-li-1 were a total of 30 couplets composed of dark and light laminae.

The thickness of the laminae varies between ~1 and 5 mm, and that of the couplets between ~2 and 8 mm. The dark laminae are thinner than 2 mm, whereas the light laminae are commonly thicker than 2 mm, especially in the lower half of the burrow. The thickest couplets tend to occur in the lower part of the tube (Fig. 5). For the whole fill succession, the thickness of the couplets matches a sine curve displaying four clear cycles, each consisting of 6–8 couplets. Furthermore, an enveloping sine curve is envisaged, showing a laminae-thickness with an upward decreasing trend. In specimen O-li-11, 17 couplets composed of consecutive dark and light laminae were measured. Their thickness ranges from 3 to 7 mm (Fig. 6). The thickness variation of the couplet succession matches a sine curve displaying two clear cycles, each one consisting of 6-–8 couplets. The individual dark and light laminae differ significantly in thickness; the dark laminae tend to be thinner than 2 mm, while the light laminae are usually from 2 mm to 6 mm thick. Once again, the thickness record of the laminae fits well with a sine curve; the dark laminae show three sine cycles, but the light laminae only two cycles.

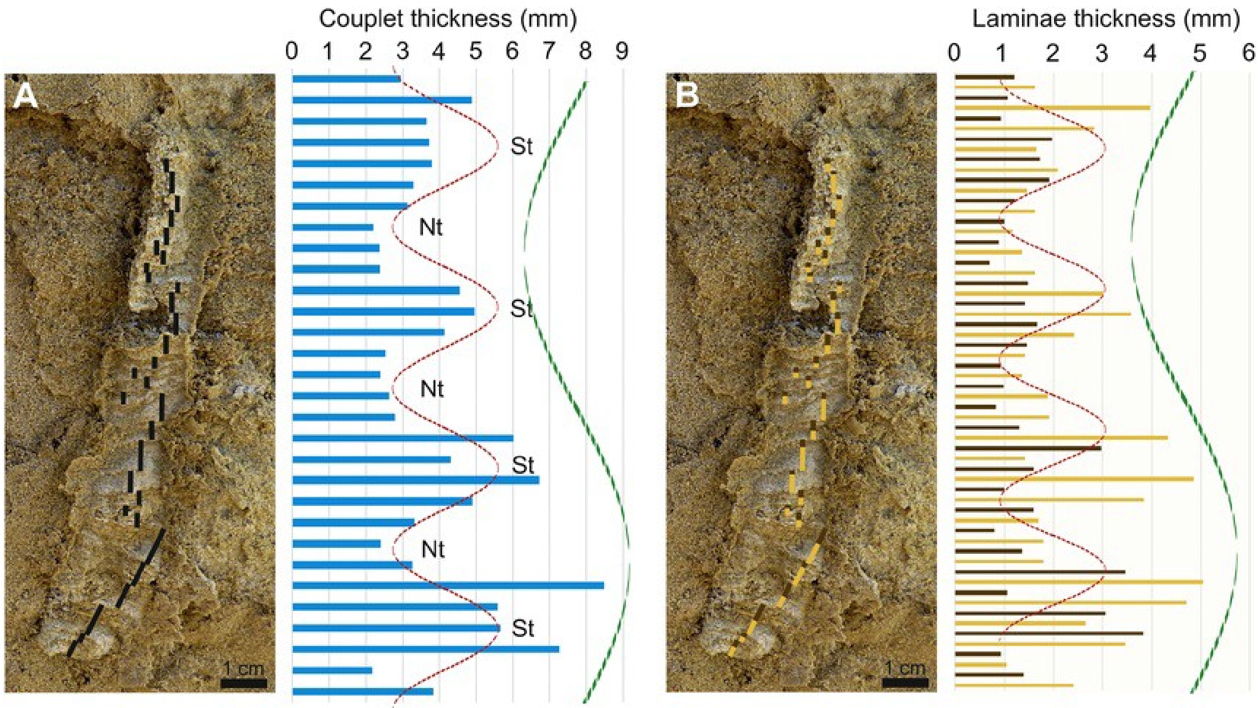

Fig. 5 Distribution of laminae and couplet thickness of specimen O-li-1; Nt – neap cycle, *St* – spring cycle, enveloping sine curve (red) and enveloping fortnightly curve (green), for dark laminae (brown) and light laminae (yellow).

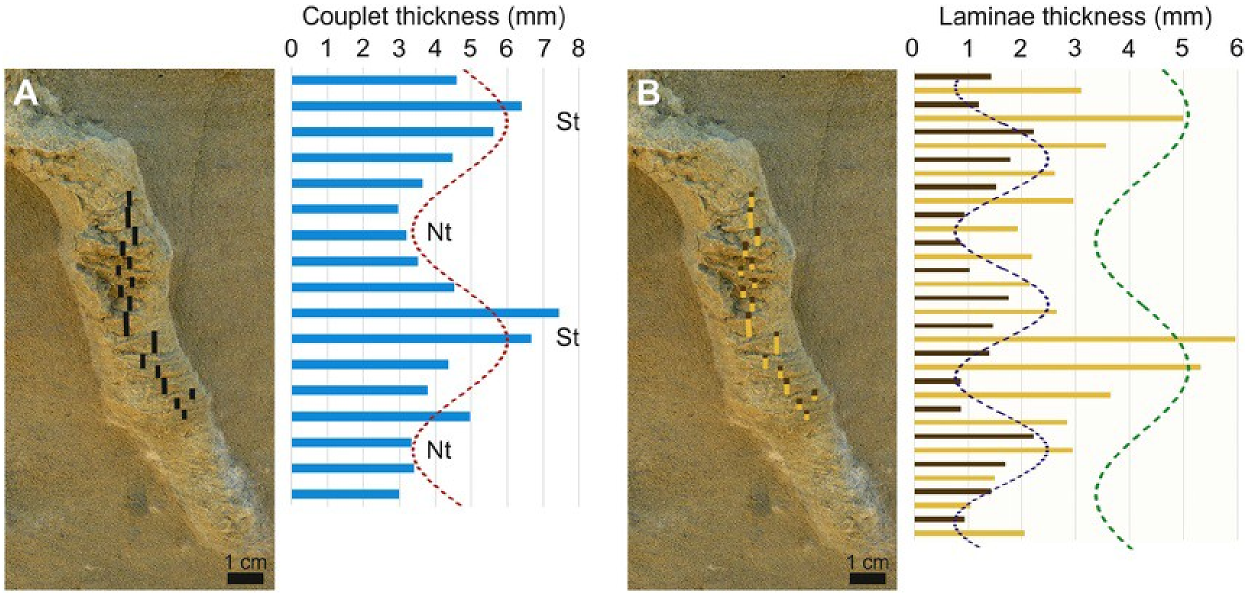

Fig. 6 Distribution of laminae and couplet thicknesses of specimen O-li-11; Nt – neap cycle, *St* – spring cycle, sine curve (red) and sine curves for dark laminae (brown) and light laminae (yellow).

5. Interpretation

The laminated fill of the tubes fulfills the criteria to be called tubular tidalites (see Gingras and Zonneveld, 2015). When infilled, the tubes were evidently still open, even the horizontal ones. The thickness variation of the laminae/couplets succession can be approximated by a sine curve; one sine cycle comprises 7 couplets, each comprising a light and a dark lamina. Such a pattern is typical of diurnal tides that modulate the deposition of these laminae (light and dark) regardless of individual thickness, in agreement with previous interpretations of tubular tidalites (Wetzel et al., 2014; Gingras and Zonneveld, 2015). Wetzel et al. (2014) interpreted couplets consisting of alternating dark and light layers as revealing diurnal tidal signature, and Gingras and Zonneveld (2015) observed lamina-thickness trends consisting of approximately seven laminae as corresponding to diurnal sedimentation. Consequently, specimen O-li-1 would document four spring-tide and three neap-tide periods (Fig. 5), whereas specimen O-li-11 stores the record of two spring-tide and two neap-tide cycles (Fig. 6).

The horizontal tubes exhibiting a laminated fill indicate that tidal currents induced water circulation within the open tube system fairly deep below the sediment surface; thus the laminate fill is passively introduced at the horizontal tubes and these can be assigned to tubular tidalites.

Concentrically laminated passive fill was termed draught-fill by Goldring (1996). Bromley (1996, fig. 8.9) illustrates slightly inclined laminae passive fill in *Thalassinoides* and *Ophiomorpha* deposited in the draught canal. Several crustaceans producing *Thalassinoides*-like burrows are known to follow variable nutrition modes, from suspension or filter to deposit feeding (e.g., Gingras et al., 2008; Pervesler and Uchman, 2009). The draught-fill and the sandy nature of fill of the tubular tidalites indicate that burrows were passively ventilated and hence, currents very likely introduced food particles into the burrows and adjacent sediment when inhabited. The fairly good water circulation within the burrows and considerable water flow at the sediment surface represent conditions favourable for benthic organisms. Besides oxygenation, the currents normally carry nutrients to fuel primary production along with suspended food particles to be utilized by benthic organisms (e.g., Thistle et al., 1985; Huettel et al., 1996; Shum and Sundby, 1996; Kędra et al., 2013). Furthermore, crustaceans are known to have the capability to burrow deep and therefore escape erosion (e.g., Dworschak and Rodrigues, 1997; Knaust, 2017). This is also very likely for the studied deposits, while the surfaces separating the intervals containing the tubular tidalites document considerable sediment reworking of up to a few tens of centimetres, documented by the truncated *Thalassinoides* shafts. The reason for the absence of other distinct bioturbational and primary sedimentary structures could be weathering, or perhaps intense bioturbation (e.g., cryptobioturbation) obscuring all but the deepest ichnofossils.

6. Discussion

The tubular tidalites observed at Leixcão dos Alhos formed mainly within *Thalassinoides* burrows match other examples (e.g., Wetzel et al., 2014; Gingras and Zonneveld, 2015). Unusual, however, is the tidally modulated fill of a *Gyrolithes* burrow, registered for the first time, and horizontal *Thalassinoides* tubes representing about one third of the specimens.

The studied record is abundant compared to other occurrences described in the literature (Wetzel et al., 2014; Gingras and Zonneveld, 2015). Thus, at the south Iberian margin the conditions would have been favourable for (1) the production of *Thalassinoides* burrows in a context of nutrient availability and substrate consistency conditions appropriate for tracemakers (Rodríguez-Tovar et al., 2008, 2017; Miguez-Salas et al., 2017, 2018), (2) the passive fill of these burrows by tidal currents developed in a shallow-marine environment (Cachão et al., 1998, 2009; Santos et al., 2016), and (3) the preservation of the tubular tidalites because tidal sediment was emplaced in the burrows deep within the surrounding sediment, thereby eluding mixing by bioturbation or later complete erosion. Over a considerable time, periods of sand deposition alternated with phases of omission and bypass during which crustaceans produced their burrows.

Unfortunately, the duration of deposition, omission and colonization, or erosion lies beyond stratigraphic resolution. The comparatively low abundance of distinct traces within the host sediment as compared to modern counterparts could, however, imply that the colonization and bioturbation episodes lasted from several months to a few years (e.g., Reineck, 1958, 1977). Episodic deposition in the range of intervals of several months, involving thick layers of sediment in comparatively high-energy conditions, can determine generalized scarce bioturbation, with traces present only in the uppermost centimetres (Reineck, 1977). Similarly, phases of active migration and quiescence of shallow-marine sand bodies affected by tidal currents could take place in the same, or even longer time spans (e.g., Reineck and Singh, 1980; Johnson and Baldwin, 1996).

The absence of significant differences in ichnological features in horizons t_1 to t_4, but the exclusive presence of horizontal structures produced deep within sediment found in the upper interval, can be interpreted as the result of substantial shaft truncation (Fig. 7). The preservation of different parts of the *Thalassinoides* burrow systems implies that the vertical shafts passed into the historical record when erosion was less pronounced than in case where only the horizontal tube is preserved (e.g., Wetzel and Aigner, 1986; Tedesco and Wanless, 1991).

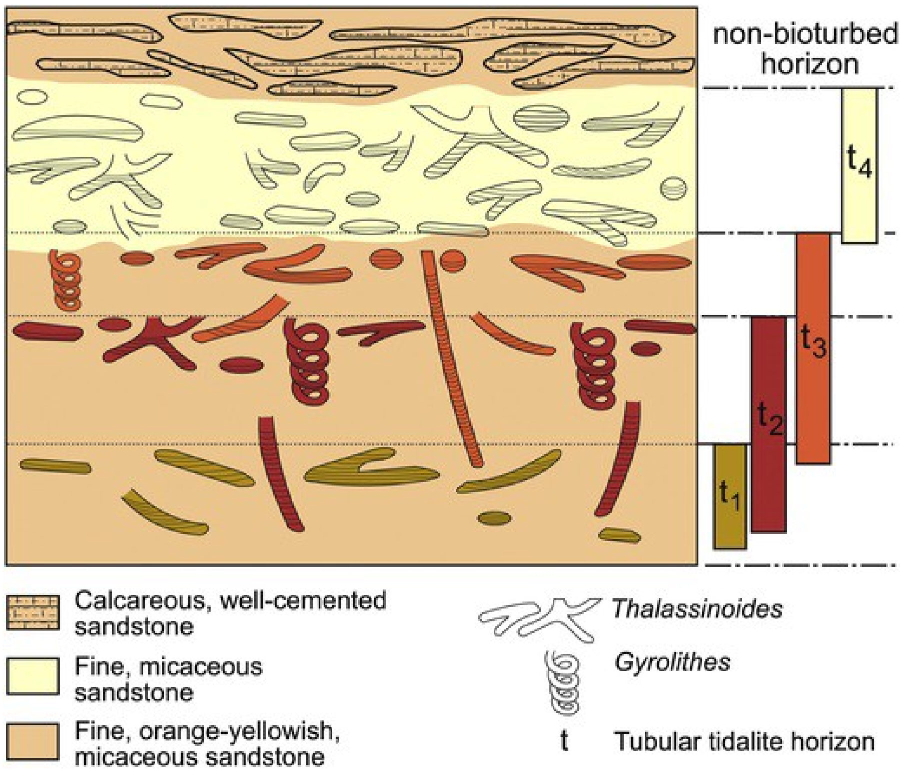

Fig. 7 Sketch of the vertical arrangement of burrows and the registered tidalites and their vertical extent within the intervals t_1 to t_4.

The fill of *Gyrolithes* by tidal-laminated sediment is in itself an interesting case, since a helicoidal tube attenuates flow because of increased friction and Reynolds number (e.g., Hon et al., 1999). Hence the laminated infill of *Gyrolithes* could point to currents on the sediment surface strong enough to transport sand within a deep helicoidal tube, located up to a few tens of centimetres below surface (e.g., Dworschak and Rodrigues, 1997; Wetzel et al., 2010). The two best-preserved specimens (O-li-1 and O-li-11) store important information about the tidal dynamics in the study area during the Miocene (Figs. 5, 6). Groups of 7 (6–8) laminae or couplets provide evidence of diurnal tides. Consequently, the tubular tidalites record around two weeks in specimen O-li-11 and four weeks in O-li-1.

Generally dark laminae are thinner (< 2 mm) than light laminae (> 2 mm); and for any particular couplet, once again, a dark lamina is thinner than an adjacent light lamina. This pattern documents a dominant tidal current, ebb or flood, forming the thick light laminae alternating with a subordinate tidal current, flood or ebb, leading to deposition of thin dark laminae (Davis Jr, 2012). An assignation of dominant and subordinate current to ebb or flood tide is not possible, because the differences in grain size between light and dark laminae are minor, and lamination resulted from currents rather than settling from suspension. In contrast, for tubular tidalites filled by suspended material as those studied by Wetzel et al. (2014), the thickness of the laminae might reflect water depth – during high-tide slackwater thick laminae form, and thin laminae during low-tide slackwater.

Today, the Albufeira area in southern Portugal is affected by semidiurnal tides (Cravo et al., 2013). This change in the tidal pattern from the Miocene to present-day can be explained by a modified topographic situation, likewise observed today in the eastern Gulf of Mexico and the NW coast of Alaska. There, local topographic features such as peninsulas and bights affect the tidal dynamics; semidiurnal tides locally become diurnal (e.g., He and Weisberg, 2002; Huang et al., 2012). The inferred change from diurnal to semidiurnal tides from Miocene to today could reflect the original variation in the tidal regime or the effect of the previous topographic context. This is one possible interpretation, yet other possibilities can be not discarded. For example, the location of the burrows in some areas of the tidal flat where may have been affected exclusively by stronger tides, or that the sediment was received from a diffuse tidal channel active only during flood or ebb tides.

Besides the sets comprising 7 couplets and the associated neap-spring cycles, some lower-frequency patterns can be observed. The trend of decreasing laminae thickness upward in O-li-1 points to a low-frequency envelope that can be represented by two sine cycles each comprising about 14 couplets. This low-frequency rhythmic change would match long-period lunar fortnightly tides (Kantha et al., 1998; Ray and Egbert, 2012). However, for the time being this hypothesis must be considered as preliminary, requiring more detailed studies for clarification.

7. Conclusions

The Oura section in southern Portugal houses an exceptional record of tubular tidalites: 36 specimens occur in a 1.5 m-thick interval. Their high abundance comes to document conditions favourable for the production of open burrows, their fill by tidal currents, and their preservation in a dynamic depositional setting. The latter is indicated by the sandy infill of numerous (13) deep, even horizontal parts of *Thalassinoides* and helicoidal *Gyrolithes* tubes. Furthermore, considerable parts of the *Thalsassinoides* shafts were later removed by erosion.

The rhythmically infilled material exhibits laminae and couplets (each composed of two consecutive, dark and light laminae) of varying thickness that allows their grouping into sets of 7 couplets. The couplet thickness within a fill succession follows a sine curve. Both are typical of a diurnal tidal pattern. Furthermore, up to four spring-tide and three neap-tide cycles are recorded. A long-period lunar fortnightly tide regime can be envisaged given the record of low-frequency sine cycles, each comprising about 14 couplets.

The Miocene diurnal pattern contrasts with the modern semidiurnal tides. Peninsulas and bights, however, are now known to change the tidal pattern over relatively short distances. During the Miocene such a topographic situation is not unlikely for the south Iberian margin, but this hypothesis clearly needs further proof.

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