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Tidal signature recorded in burrow fill

ANDREAS WETZEL*, NOELIA CARMONA† and JUAN PONCE†
**Geologisch-Paläontologisches Institut, Universität Basel, Bernoullistrasse 32, CH-4056, Basel, Switzerland (E-mail: andreas.wetzel@unibas.ch)*
†Instituto de Investigación en Paleobiología y Geología, Universidad Nacional de Río Negro, Isidro Lobo y Belgrano, 8332, Roca, Río Negro, Argentina

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ABSTRACT

The arrangement of sediment couplets preserved in *Thalassinoides* shafts suggests that tides regulated the passive filling of these trace fossils and, thus, represent tubular tidalites. The thickness variation in individual layers and couplets implies a mixed diurnal, semi-diurnal tidal signature where packages of either thick-layered or thin-layered couplets alternate. Calcarenitic sediment accumulated when tidal current velocity was too high to allow deposition of mud, whereas a marly mud layer is interpreted to have formed during more tranquil times of a tidal cycle (in particular, low-tide slack water). The tidal record within the burrows covers a few weeks and the corresponding spring–neap cycles. The fill of the *Thalassinoides* shafts is the only known record to decipher the tidal signature from otherwise totally bioturbated sediments. These deposits accumulated in a lower-shoreface to upper-offshore setting during the late Miocene on a shallow shelf extending from the Atlantic Ocean to the west into northern Patagonia. The fill of all investigated burrows started around spring tide and, thus, the behaviour of the burrow producers – probably crustaceans – is speculated to have been affected by tides or the high water level because all studied burrows became abandoned around the same period of a tidal cycle.

Keywords Miocene, mixed tides, Patagonia, *Thalassinoides*, tidal bundles, tubular tidalites.

INTRODUCTION

Under normal marine conditions, burrowing organisms homogenize the originally layered stratigraphic record if sediment accumulation is not interrupted too severely by physical reworking or depositional events. In particular, in areas below (storm) wave base experiencing slow sedimentation, burrowing organisms normally mix the stratigraphic record completely (e.g. Reineck, 1977; Bentley *et al.*, 2006; Buatois & Mangáno, 2011). However, on shelves around (storm) wave base and above, waves and currents may reduce sediment accumulation locally for some time or even lead to erosion and, hence, favour a stiff to firm substrate to be exposed on the sea floor. In such a stable sediment, burrowers produce open tubes or tube systems. Because the sediment does not collapse for some time, abandoned open tubes or parts of them may act as sediment traps; these are effective in trapping particles, if they are vertical or steeply inclined or have a funnel-shaped opening at the sea floor. In addition, the burrows may contain sediment particles that otherwise are not preserved in the rock record of an area as a result of sediment bypass associated with an omission surface (e.g. Bromley *et al.*, 2009). Burrows penetrating down from omission surfaces may store, when passively filled, information about the sediment dynamics on the omission surface at this time.

The passive infill in open burrows regulated by tides, in particular large diameter tubes, has been termed ‘tubular tidalites’ (Gingras *et al.*, 2007, 2012; Gingras & MacEachern, 2012). The fill of such burrows has been recognized in some instances (e.g. Gingras *et al.*, 2002, 2007), but to date there has been no detailed investigation of the tidal signature. In the case reported here, the passive fill of burrows is arranged in couplets typical of tubular tidalites. This record provides information about the hydrographic conditions and, hence, is useful for environmental interpretation, especially because the sediments are otherwise bioturbated completely and the palaeogeographic situation is poorly constrained. The potential of such burrow fill for palaeoenvironmental interpretations appears to have been under-estimated because, in most cases, horizontal tubes having a diameter of a few centimetres are observed that document only a few tidal cycles. The vertical shafts, however, may store a comparatively long, well-preserved record of the tidal processes. It is the purpose of the present paper to provide an example for unravelling the tidal signature from burrow fill.

GEOLOGICAL SETTING

Along the Atlantic coast of northern Patagonia, Mio-Pliocene strata are exposed in a sea cliff near the village of Viedma (Fig. 1). These

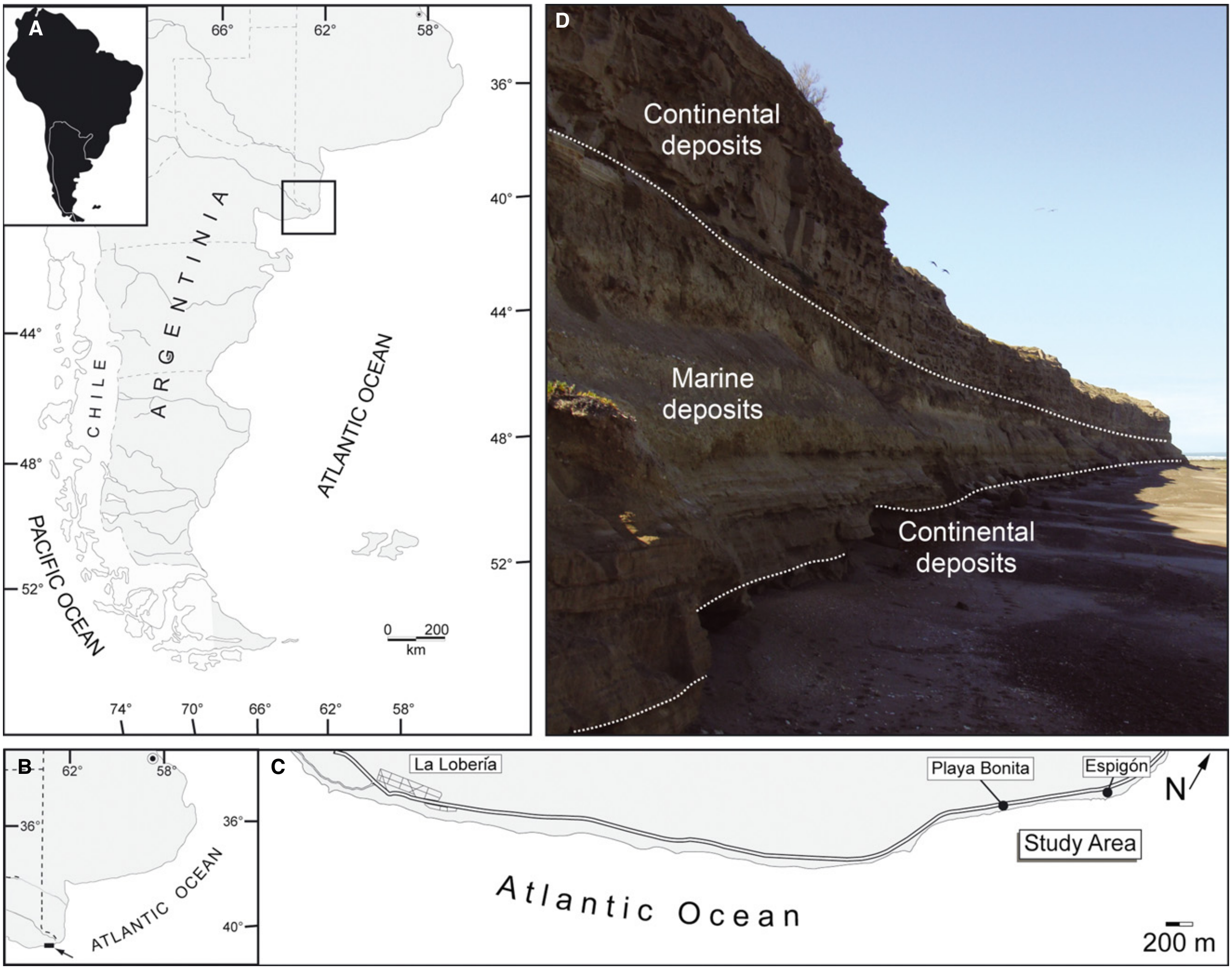


Fig. 1. Location of the study area. (A) South America (upper left), Argentina, boxed area is shown in detail in (B). (B) North-eastern part of Patagonia, small boxed area marked with an arrow is shown in detail in (C). (C) Study area, showing the analysed localities along the Atlantic coast of northern Patagonia. (D) Vertical cliff of the Río Negro Formation exposed along the Atlantic coast of Balneario El Cóndor locality, Río Negro Province, Argentina.

deposits form part of the Río Negro Formation that accumulated in an area between two Cenozoic basins; the Colorado Basin in the north and the San Jorge Basin in the south (e.g. Lohmann & Hoffmann-Rothe, 1995; Zavala & Freije, 2001). The Río Negro Formation comprises mainly continental deposits with an intercalated thin interval consisting of marginal marine and marine sediments (Figs 2 and 3). At the sea cliff near Viedma, at the localities of La Lobería and El Espigón, the middle part of the Río Negro Formation is exposed (e.g. Andreis, 1965; Zavala & Freije, 2001). The deposits studied in detail represent a *ca* 6 m thick marine interval that is underlain and overlain by aeolian deposits and record a complete transgressive–regressive cycle (Zavala & Freije, 2000; Farinati & Zavala, 2002; Carmona *et al.*, 2012; Fig. 2). The marine sediments consist of greenish-grey marly mud and brownish calcarenitic material (Zavala & Freije, 2000; Farinati & Zavaldata, 2002; Carmona *et al.*, 2012). According to its position in the succession and to K-Ar-dating of equivalent marine tuff levels (9·41 Ma; Zinsmeister *et al.*, 1981), the marine interval was assigned to the Tortonian stage (late Miocene).

The marine deposits accumulated while the area was flooded by the Atlantic Ocean from the east (e.g. Zavala & Freije, 2001). Because outcrops are restricted to the cliff along the coast and some river banks, the depositional setting of the Río Negro Formation is not fully known (e.g. Zavala & Freije, 2001). The marine sediments of

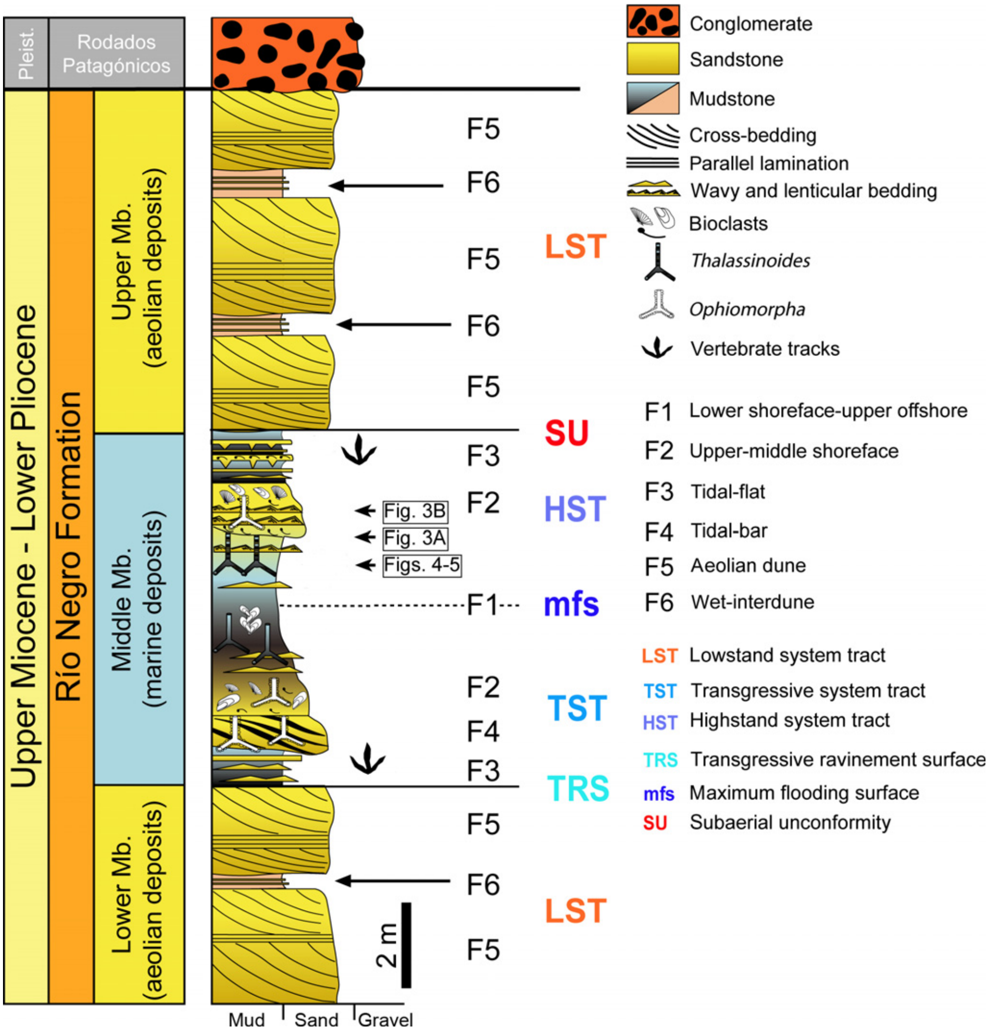


Fig. 2. Simplified lithological and stratigraphic log of the studied section showing dominant sedimentary facies and occurrence of *Ophiomorpha* and *Thalassinoides* trace fossils; sequence stratigraphic subdivision from Farinati & Zavala (2002) (modified from Zavala & Freije, 2000, and Carmona *et al.*, 2012).

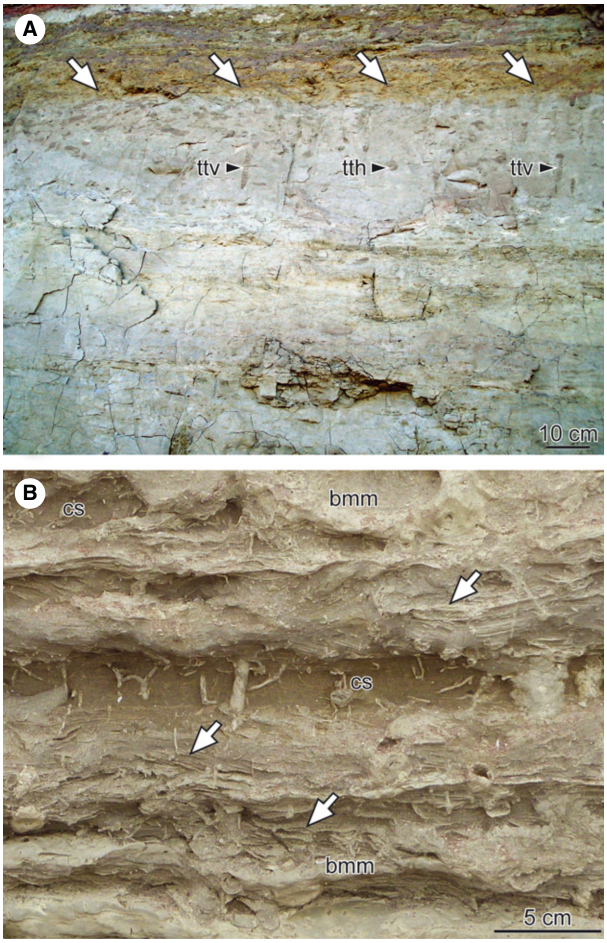


Fig. 3. Studied marine interval with the *Glossifungites* ichnofacies. (A) Most of the studied *Thalassinoides* burrows pipe down from the same colonization interval (marked by arrows); note the indistinct, while bioturbated and reworked transition between both lithologies; vertical tubular tidalites (ttv); horizontal tubular tidalites (tth). (B) Some relict primary sedimentary structures are preserved locally in otherwise totally bioturbated deposits. The light marly mud layers are bioturbated (bmm), but marly mud also constitutes the draping of primary sedimentary structures (arrows) at the transition to brownish, mainly calcarenitic intervals (cs).

the Río Negro Formation were affected by tides while deposited in an area connected to or extending from the Atlantic Ocean. Tidal flat deposits have been recognized recently and some relicts of supposed tidal sand waves have been encountered above transgressive lag deposits (Carmona *et al.*, 2012; table 1). Nonetheless, these sediments provide little information about the tidal character in this area during the late Miocene. Today, the modern coast experiences semi-diurnal tides (D'Onofrio *et al.*, 2010) but, towards the north, a mixed semi-diurnal tidal signature is increasingly developed (e.g. Dietrich *et al.*, 1975). The tidal signature within the Río Negro Formation has not yet been studied in detail.

OBSERVATIONS

At the studied locality, marly to calcareous sands accumulated around the interval covering the maximum flooding surface during peak transgression in Tortonian times (Fig. 2; Farinati & Zavala, 2002). The carbonate content of these marine sediments can be as high as 60 to 80% $CaCO_3$. The vertical facies transitions are rather continuous and marked unconformities have not been recognized (e.g. Carmona *et al.*, 2012, 2013). The sediments show fairly well horizontal bedding. Major erosional–depositional structures being typical of incised valley fill have not been observed along a several-kilometre long studied part of the sea cliff. The studied deposits were strongly affected by bioturbation that extinguished primary sedimentary structures to a very high degree (Figs 3 and 4). Besides biodeformational structures that have no distinct outlines and that only mix pre-existing sedimentary structures, a suite of marine trace fossils has been found; it comprises *Arenicolites*, *Asterosoma*, *Chondrites*, *Diplocraterion*, *Helicodromites*, *Maiakarichnus*, *Ophiomorpha*, *Scalichnus*, *Scolicia*, *Siphonichnus, Taenidium*-like traces and *Thalassinoides* (Carmona *et al.*, 2013). Some burrowers penetrated several tens of centimetres deep when producing *Asterosoma*, *Scalichnus, Siphonichnus*, *Thalassinoides* and *Ophiomorpha*. Furthermore, composite trace fossils occur as the fill of *Thalassinoides* was reworked by producers of *Chondrites* and *Taenidium*-like traces. In addition, large thick clusters of oyster shells occur that exhibit considerable evidence of boring (Farinati & Zavala, 2002; Farinati, 2007; Carmona *et al.*, 2013). Borings by producers of *Caulostrepsis*, *Entobia*, *Gastrochaenolites* and *Meandropolydora* and encrustation by balanids, bryozoa and serpulids occur together. Locally, small domains representing *ca* 5% of an outcrop area of several square metres were not completely bioturbated and exhibit alternating light and dark layers (Fig. 3B). Mainly calcarenitic intervals display primary sedimentary structures, such as mud drapes and herringbone cross-stratification, that document the influence of tides (Fig. 3B) but these structures are not sufficient to

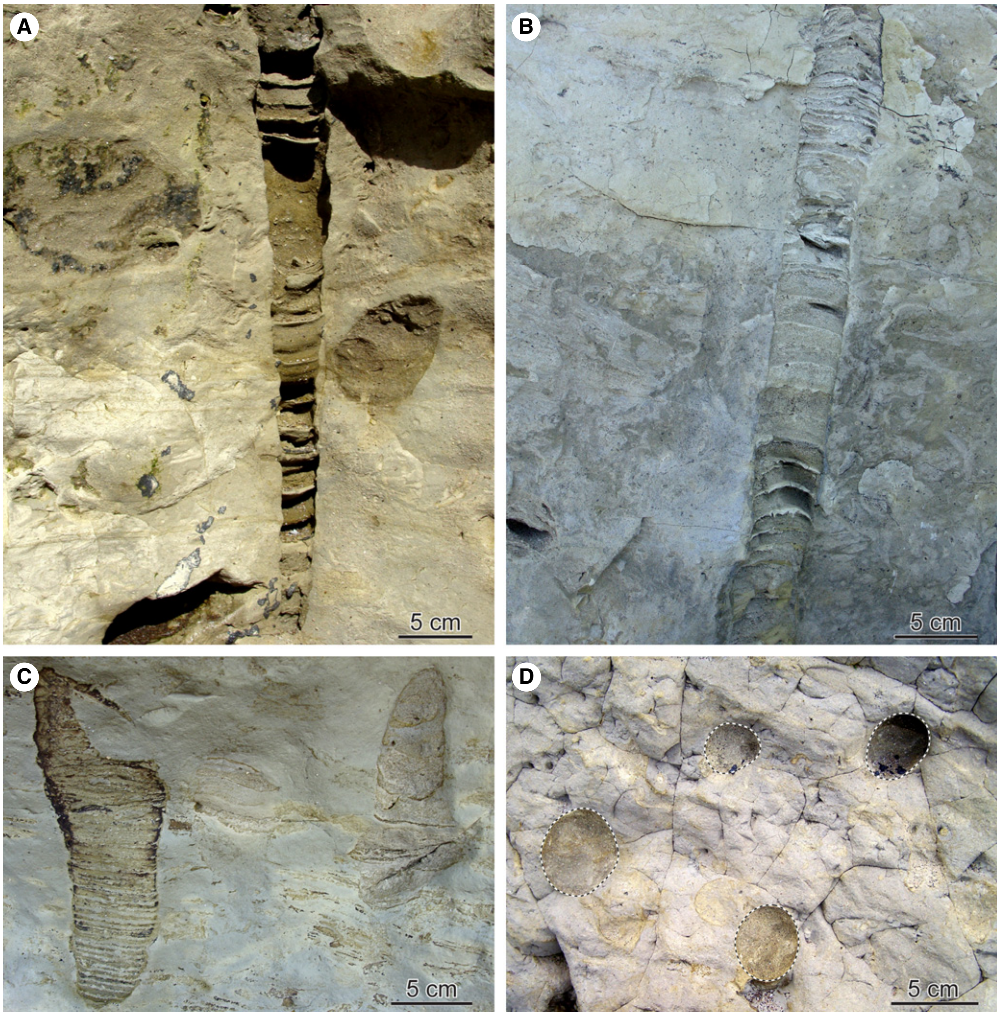


Fig. 4. Examples of tubular tidalites from Viedma; (A) to (C) vertical sections, note that the fill of the tubular tidalites has thick layers at the base. (A) and (B) Intercalated extraordinary thick or distorted layers that could result from storm or other high-energy events. (C) Quite regularly arranged tubular tidalite that was studied in detail. (D) Horizontal plane showing several tubular tidalites implying – at least locally – a high abundance.

decipher the tidal signature. Within the intervals exhibiting the primary sedimentary structures, no indication of temporary emergence was observed.

Within the studied bioturbated deposits, conspicuous trace fossils occur; they are cylindrical, *ca* 3 to 5 cm in diameter, and consist of up to a few tens of centimetres long vertical shafts and approximately horizontal tubes (Fig. 3A). These trace fossils pipe down from a somewhat erosive, slightly down-cutting surface that was later reworked to some degree (Fig. 3A); they exhibit a layered fill that is less resistant against erosion. Therefore, both shafts and tubes exhibit a sharp boundary with the host sediment and they cross-cut previous generations of burrows that bioturbated the host sediment (Fig. 4). The layered fill is composed of couplets that consist of alternating brownish calcarenitic sediment rich in sand-sized shell fragments and greenish-grey marly mud. The trace fossil fill varies from regularly laminated, to irregularly layered or even distorted (Fig. 4).

The mean thickness for each layer was defined as shown in Fig. 5. The layered fill exhibits two populations of couplets, thin ones and thick ones, being <2 mm and 2 to 4 mm thick, respectively. Apparently, there is no gradual transition between these two thickness classes (Fig. 6). Furthermore, the thick and thin couplets constitute alternating groups of about five to ten couplets, respectively.

Fig. 5. Tubular tidalite studied in detail, superimposed black and white bars mark the thickness of dark (= brownish calcarenitic material) and light (= greenish-grey marly mud) layers. Note the arrangement of couplets into thick-layered and thin-layered packages; for further details see text.

INTERPRETATION

The host sediment of the studied trace fossils was first bioturbated and mixed or even homogenized by soft-bottom burrowers within a fully marine environment as suggested by, for instance, Farinati & Zavala (2002). A full-marine subtidal setting is indicated by the high carbonate content, the absence of any indication of temporary emergence and the encountered suite of 12 co-occurring ichnogenera and the large clustered oyster shells that contain borings belonging to four ichnogenera, and a diverse group of encrusters (e.g. Buatois & Mangáno, 2011). Similar oyster clusters formed during the Oligo-Miocene in southern Patagonia in a full-marine subtidal environment (Parras & Casadío, 2006). It is not clear why the locally preserved primary sedimentary structures were not burrowed completely by organisms. Intense bioturbation and the few relict primary sedimentary structures imply a lower-shoreface to upper-offshore setting (e.g. Buatois & Mangáno, 2011; Carmona *et al.*, 2012).

The investigated trace fossils are ascribed to the ichnogenus *Thalassinoides* because of their morphology (e.g. Schlirf, 2000; Gerard & Bromley, 2008). *Thalassinoides* burrows are known to be produced today, most commonly by crustaceans (e.g. Bromley, 1996). The sharp boundary of the trace fossils furthermore implies that they were emplaced in a stiff to firm substrate (e.g. Goldring, 1995; Wetzel & Uchman, 1998). The sharp outline of the trace fossils, the cross-

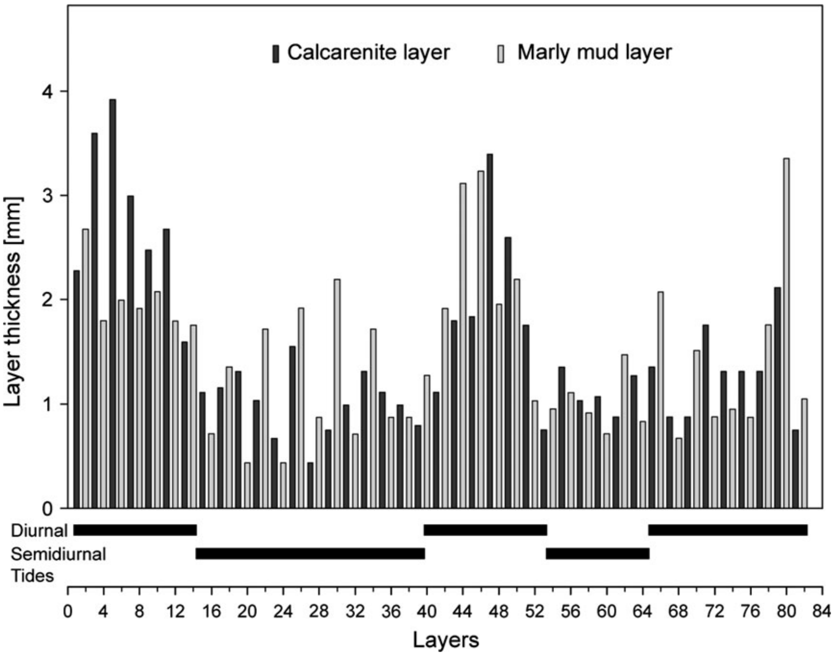


Fig. 6. Layer thickness of the tubular tidalite shown in Fig. 5; maximum layer thickness does not occur at multiples of 7 (or 14). Thick-layered packages consist of one couplet per diurnal period and formed around spring tide, thin-layered packages consist of two couplets per diurnal period and formed around neap tide when the semi-diurnal signature prevailed; for further details see text.

cutting of the palimpsest suite of burrows and the passive infill classify them as belonging to the *Glossifungites* suite of burrows that are substrate controlled and produced in semi-consolidated deposits that pipe down from sedimentary discontinuities (e.g. Seilacher, 1967, 2007). In the studied case, these burrows are very likely to have originated at the base of a distal subtidal channel, as suggested by the slightly down-cutting geometry of the *Glossifungites* surface.

Abandoned *Thalassinoides* burrows are known to represent temporary sediment traps (e.g. Goldring, 1996; Gingras *et al.*, 2007). The layered fill of the studied *Thalassinoides* trace fossils is arranged in couplets and, hence, it is strongly suggestive of tidal influence in that specific depositional setting. Therefore, the *Thalassinoides* fill represents a tubular tidalite (Fig. 4). The mode of deposition of these layers is interpreted based upon observations of modern depositional processes and the few relict primary sedimentary structures preserved.

The domains not mixed by bioturbation exhibit calcarenites with primary sedimentary structures. Therefore, the brownish calcarenitic sediment accumulated during a phase of the tidal cycle when high current velocities prevailed, whereas the marly mud layer is interpreted to have formed during more tranquil times of a tidal cycle (see below). However, the depositional processes leading to the accumulation of mud in tidal environments are still under investigation (e.g. Wang, 2012).

In modern tidal settings, mud is deposited mainly as aggregates (e.g. Flemming, 2012; Wang, 2012). Aggregates settle more rapidly than the single constituent mud particles; their settling velocity is in the range of sortable silt to fine sand (8 to 63 μm) when compared with hydraulically equivalent siliciclastic grains (Flemming, 2012). Sedimentation of aggregates consisting of fine-grained material occurs in subtidal settings mainly during (low-tide) slack water as observations in modern environments demonstrate (e.g. Baeye *et al.*, 2011).

Sedimentation of mud, however, is controlled by the size of the aggregates (e.g. Wang, 2012). The size of aggregates depends on current velocity because increasing shear stress and turbulence break them up into smaller particles (e.g. Wang, 2012). Nonetheless, McCave (1969) suggested that mud layers may form under the influence of tidal currents while deposited from the viscous sublayer (bottom boundary layer). In fact, the formation of mud layers from currents flowing at considerable velocity has been demonstrated recently in experiments (Schieber *et al.*, 2007). However, it remains unsolved which of these processes led to the formation of marly mud layers in the studied case.

Based on the observations and inferences, the brownish calcarenite layers of the studied tubular tidalites are interpreted to have been formed

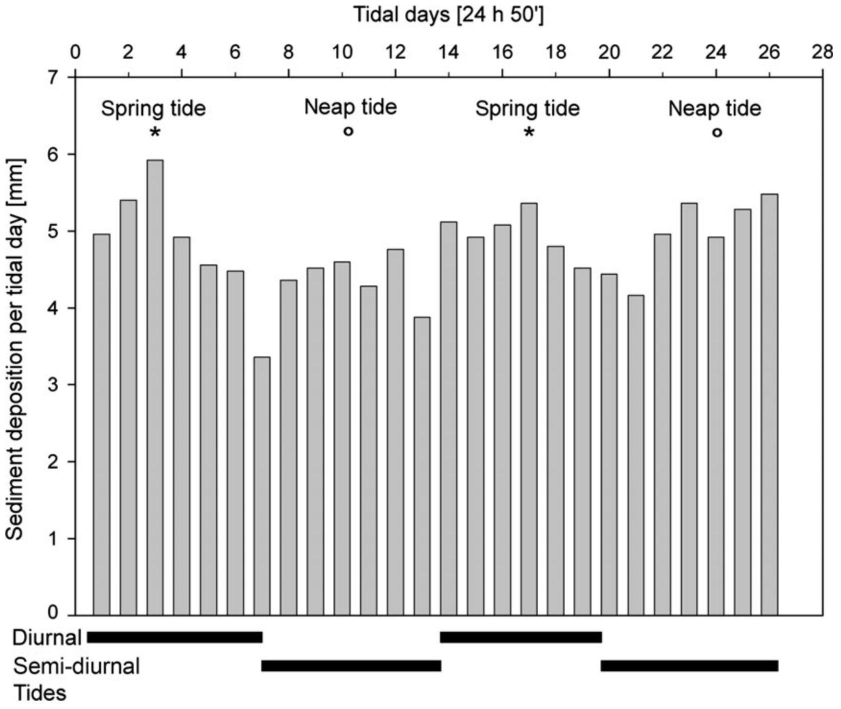


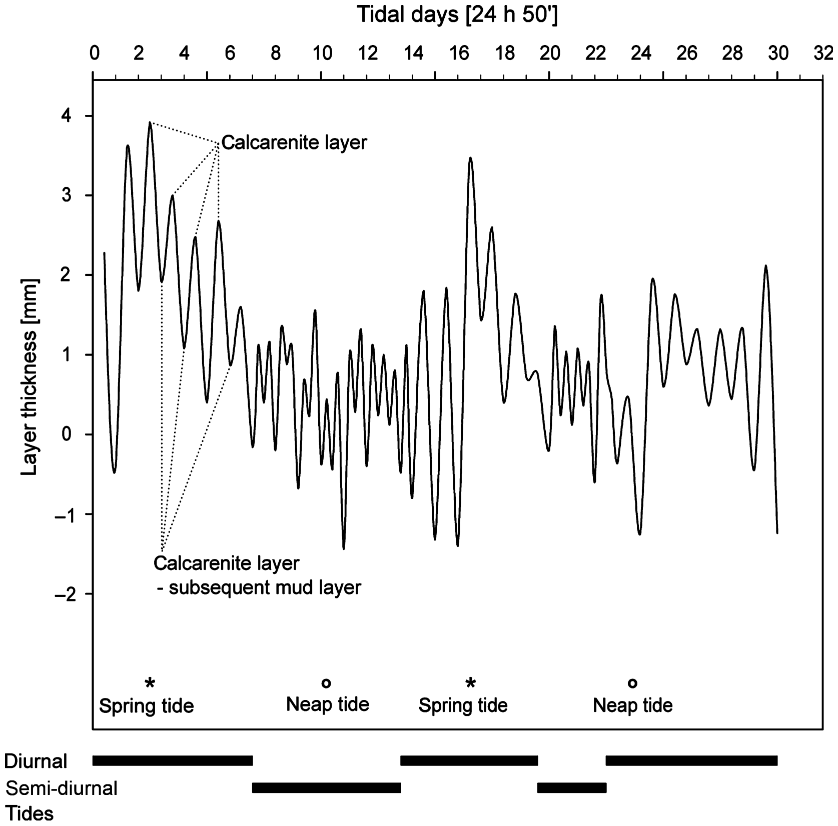
Fig. 7. Sedimentation rate within tubular tidalites determined for a day (in fact, a diurnal period lasting 24 h 50 min). A clear neap–spring cyclicity of sedimentation rate is not evident because around neap tide two couplets form and, hence, overcompensate for lowered sedimentation rate due to decreasing tidal amplitude. Only spring-tide sedimentation rate maxima are weakly seen at days 3 and 17.

during the phase of the tidal cycle when current velocities were sufficiently high to prevent the deposition of mud, whereas the greenish-grey mud layers represent more tranquil times, in particular low-tide slack water deposits.

To unravel the rhythmicity of the burrow fill, layer thickness was plotted versus layer number (Fig. 6). The overall thickness variation in the layers does not contain a signal of multiples of 7 or 14 that are expected for tidally influenced deposits (e.g. Kvale, 2012). However, the layers constitute two populations of couplets, thick ones and thin ones, that are arranged in groups (Fig. 6). The number of thin-layered couplets is nearly two times higher than that of the thick couplets. The shift from thick couplets to double the number of thin layers in tidal deposits is strongly suggestive of a setting experiencing mixed diurnal and semi-diurnal tides as evidenced by tidal gauge records (e.g. Dietrich *et al.*, 1975, fig. 9·06). The change in layer thickness is suggestive of ascribing a particular part of the couplet record to a specific phase of a neap–spring cycle. At the base of the studied tubular tidalite, a decrease in the mud-layer thickness and, after a short increase, also of the calcarenites layers is evident for the first 16 layers (Fig. 6). Thereafter, the thicknesses of both sand and mud layers show marked differences when subsequent couplets are compared. The difference in layer thickness of subsequent couplets becomes increasingly pronounced towards layer 32; thereafter it weakens and finally disappears (layer 40). The fluctuating layer thickness of subsequent couplets implies the interference of a subordinate tide (thin layers) and a dominant tide (thick layers) (e.g. Kvale, 2012). The observed pattern of changes in layer thickness not only suggests but also strongly supports the interpretation of a mixed diurnal semi-diurnal, predominantly diurnal tidal signature (e.g. Dietrich *et al.*, 1975, fig. 9·06). The semi-diurnal signal evolves after spring tide and becomes stronger until neap tide; thereafter it weakens and disappears prior to the next spring tide. Consequently, the thin-layered couplets of the studied tubular tidalites would have formed around neap tide, whereas the thick-layered couplets developed around spring tide.

When ascribing the thin couplets to semi-diurnal tides and the thick couplets to diurnal tides, the thickness variation versus tidal days shows multiples of seven (Fig. 7). Using a linear time scale, having tidal days as units, the variation in sedimentation rate during the fill of the burrow can be calculated based on the above interpretation. At the base of the tubular tidalites, couplet thickness normally exhibits a maximum that is interpreted to represent a diurnal tide associated with spring tide. Thereafter, sedimentation rate per day decreases and then rises again. The

Fig. 8. Tidal dynamics extracted from the tubular tidalites; the thickness of the greenish-grey marly mud layer (representing more tranquil times of a tidal cycle) was subtracted from that of the preceding brownish calcarenitic layer that formed during the dominant tide and that is expressed as a positive value. This procedure provides the best graphic representation of tidal cyclicity. For the time scale, semi-diurnal or diurnal formation of couplets was taken into account. Spring and neap tides and the change from diurnal to semi-diurnal couplet formation and vice versa are well-expressed; spring tide at days 3 and 17, neap tide around days 10 and 24.



renewed increase in sedimentation rate per day coincides with the onset of inferred semi-diurnal tides. Around neap tide, the semi-diurnal sedimentation rate per tidal day (= 24 h 50 min) is high while sediment is carried to the depositional site by two tidal cycles.

To decipher the obviously rhythmic nature and to differentiate clearly between both sediment fill types, the thickness of the brownish calcarenitic layers is expressed as a positive value, whereas the thickness of light mud layers is expressed as a negative value that was subtracted from the preceding value. If for the time axis tidal days (= 24 h 50 min) are applied, the resultant graph exhibits a clear dual rhythmicity being composed of partly superimposed long-term and short-term fluctuations that are typical of a mixed diurnal semi-diurnal, predominantly diurnal tidal system (Fig. 8). Furthermore, long-term fluctuations occur in the range of multiples of seven layers constituting relative minima or maxima (Fig. 8).

It is an intriguing observation that all of the studied tubular tidalites have thick couplets at the base of the burrows; this implies that the producers abandoned their burrows around spring tide. A behaviour affected by the neap–spring tidal cycle is known for some intertidal and subtidal crustaceans, mainly with respect to reproduction or moulting as outlined below.

The number of migrating female *Uca formosensis* is highest around spring tide. Then, four to five days before neap tide (i.e. two to three days after spring tide) males attract females into their burrows and provide optimal conditions for egg incubation (Shih *et al.*, 2005). Consequently, the females leave their burrows after spring tide.

After moulting, mantis shrimp protect against predation by hiding in burrows. The timing of moulting and reproduction appears to be regulated by lunar and tidal synchrony of moulting in the population to reduce mortality (Reaka, 1976). The moulting peak occurs in the week prior to new and full moon on rising spring tides. For intertidal species, spring tide excludes predators for a large percentage of the time while exposure time is restricted. Therefore, around spring tide intertidal mantis shrimp leave their burrows to moult (Reaka, 1976).

Many shrimps occupy their burrows permanently and rarely abandon them. Nonetheless, the studied tubular tidalites imply that at least a few *Thalassinoides* producers could respond to neap–spring tidal cycles, but this remains a matter of speculation.

DISCUSSION

The bioturbated deposits addressed in this study accumulated in a shallow marine setting, as suggested by: (i) a carbonate content up to 60 to 80% $CaCO_3$; (ii) a high ichnodiversity (12 full-relief ichnogenera, four ichnogenera of borings and several encrusters); (iii) a very high degree of bioturbation; (iv) lack of any indication of temporary emergence; and (v) the thinness of the marine deposits (*ca* 6 m) that are underlain and overlain by tidal flat and then aeolian deposits in the absence of marked unconformities (Carmona *et al.*, 2012). Complete bioturbation, with the exception of some relict layers implies that the bioturbation rate exceeded the sedimentation rate in the long term (e.g. Reineck, 1977). The general depositional environment of the interval comprising the tubular tidalites is interpreted, therefore, as a lower-shoreface to upper-offshore setting (Carmona *et al.*, 2012, 2013). In detail, however, the *Glossifungites* surface (*sensu* Seilacher, 1967) from which the tubular tidalites pipe down is slightly erosive and cuts somewhat into the underlying deposits and, hence, it is suggestive of representing the base of a low-relief channel setting evidently affected by tides. In such an environment, sedimentation is often discontinuous and consolidated mud may be exposed on the sediment surface (e.g. Reineck & Singh, 1980). In such substrates, endobenthic organisms (including burrowing crustaceans) may produce open tubes or tube systems having stable walls (e.g. Goldring, 1995; Gingras *et al.*, 2007; and references therein). However, the colonization surface from which the tubular tidalites originated was affected later by bioturbation and physical sediment reworking (Fig. 3A).

The sediment constituting the tubular tidalite couplets consists of calcarenitic material and marly mud. Based on the analysis of many tidal rhythmites, Kvale (2012) stated that the thickness of a lamina is related directly and positively to tidal current strength, which also provides an estimate of the tidal range. The studied tidalites, however, record only the signature. The calcarenitic sediment accumulated during the phase of a tidal cycle when current velocity was too high to allow for the deposition of mud, whereas the marly mud layer is interpreted to have formed during more tranquil times (in particular low-tide slack water; see above). This interpretation is consistent with modern tidal settings where the relatively coarse material is enriched around the low tide line, while the mud content increases seaward and landward in response to decreasing hydraulic energy (e.g. Flemming, 2012).

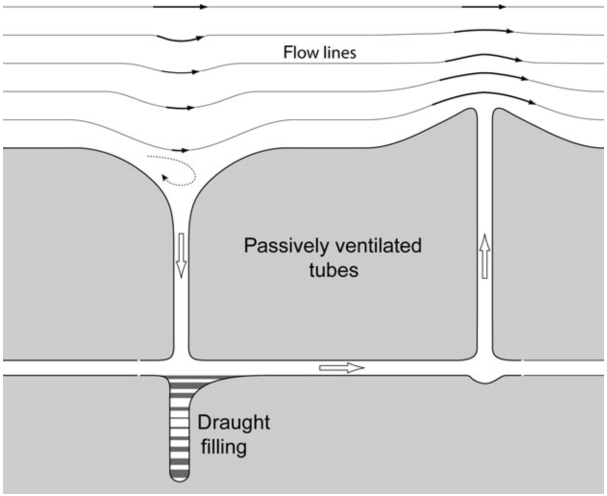


Fig. 9. Passive current-induced ventilation of a burrow having a funnel and cone. According to the Bernoulli principle, the flow cross-section indicated by the flow lines is enlarged over the funnel and leads to a decrease in flow velocity and an increase in pressure in the connected tube while, over the cone, the reduced flow cross-section leads to an increase in flow velocity and, hence, to a decrease in pressure in the tube. The resultant circulation in the tube system is shown by arrows. The circulation within the tube system is independent of its orientation to flow direction. Sediment carried by the circulating water may be deposited in the burrow as 'draught filling' (Goldring, 1996).

The openings of the *Thalassinoides* tubes to the surface acted as sediment traps because it is very likely that they were funnel-shaped, similar to modern equivalents (e.g. Frey & Mayou, 1971). In the tubes, hence, for a short while all sediment settling out of the water column and that moving on the surface could accumulate and provide an excellent record of short-term sedimentation. However, the thickness of the layers constituting the tube fill is affected by various processes, for instance, passive ventilation, hydraulic events such as storms, or funnel collapse. Passive ventilation of *Thalassinoides* burrows might have enhanced sedimentation because many of them have more than one opening at the sea floor, then often one is funnel-shaped and the other ones form cones (e.g.

Frey & Mayou, 1971). This configuration favours passive ventilation by currents due to the Bernoulli principle (e.g. Vogel, 1994); the resultant infill was termed draught filling by Goldring (1996; Fig. 9). In that case, couplet thickness may vary in response to the local current velocity that can be influenced by the changing morphology on the sea floor, for instance by a cone.

While hydraulic conditions fluctuate or even strong events occur, it is not surprising that regular tidal couplets are interrupted by extraordinarily thick or even distorted layers. In addition, grazing or bulldozing epifauna may cause the collapse of the funnels or near-surface tube segments.

Therefore, a long-lasting record covering more than five to 10 weeks is not often preserved by tubular tidalites. In the studied outcrops, only one of four analysed examples contains such a long record. Taking into account the examples from literature, it appears that the record of about two weeks predominates for the few tubular tidalites studied in detail (e.g. Gingras *et al.*, 2002; Gingras & MacEachern, 2012).

To recognize all possible irregularities preserved by tubular tidalites, a quantitative analysis of couplet thickness and its variation is necessary. If a long-lasting fairly undisturbed record has been recognized, it provides information about the tidal signature and the local sedimentation rate. Thus, the potential sedimentation rate in an area can be evaluated from the sediment thickness and the number of tidal cycles. The studied tubular tidalites formed at sedimentation rates of 100 to 300 cm yr^{-1} (Fig. 4A and C). These values are in agreement with those reported from literature. In the Miocene, Amazonian foreland basin tubular tidalites filled at a rate of *ca* 300 cm yr^{-1} (Gingras *et al.*, 2002). Sedimentation rates in Carboniferous tidal rhythmites from Kansas have been estimated at 380 cm yr^{-1} (Lanier *et al.*, 1993). In modern tidal settings, 250 to 270 cm yr^{-1} were reported from an experimental study extrapolating daily sedimentation rates (Fan, 2012). Somewhat lower values have been found within a large-scale filled-up excavation site (100 cm yr^{-1}; Unsöld, 1974). Compared to these modern values, the sediment mobility within the Miocene shelf sea covering northern Patagonia has to be classified as high (cf. Fan, 2012). When comparing sedimentation rates on tidal flats, it has to be taken into account that the newly generated accommodation space fills rapidly. Mean sedimentation rate then decreases with time while the sediment surface approaches base level and tidal currents and storm events remove previously accumulated deposits and lead to a lower long-term sediment net-aggradation (e.g. Reineck, 1960; Fan, 2012).

However, it is possible that records longer than two weeks could be found more frequently because *Thalassinoides* burrows normally have an extensive, up to 40 cm long or even longer, vertical shaft (e.g. Schlirf, 2000; Gerard & Bromley, 2008). Therefore, systematic excavation of *Thalassinoides*-hosted tubular tidalites could provide information about the tidal signature covering several weeks. As an example, a 40 cm long vertical shaft could act as a sediment trap for more than 10 weeks at a sedimentation rate of 200 cm yr^{-1}.

The Miocene tidal signature (mixed diurnal semi-diurnal, predominantly diurnal) is different from the present one (semi-diurnal). Today, however, the semi-diurnal signal increases towards the north (e.g. Dietrich *et al.*, 1975). Therefore, the Miocene palaeogeographic setting, accentuated by basins extending into the present-day continent and a shelf wider than today, might have led to an extension of the area affected by mixed tides to the south.

Furthermore, these observations may provide additional information about the lifestyle of the tube producers. For the studied *Thalassinoides*, the thick layers at the base of the tubular tidalites imply the onset of infill around spring tide. For intertidal and subtidal crustaceans, a tide-regulated behaviour has been reported. When water level is high and temperature is low, both favouring the migration of these animals, then the crustaceans abandon their burrows (e.g. Reaka, 1976; Shih *et al.*, 2005). However, further investigations are required to determine whether *Thalassinoides* producers exhibit such a behaviour.

CONCLUSIONS

The passive fill of *Thalassinoides* burrows stores the tidal record within a Miocene embayment extending from the Atlantic to the west into northern Patagonia. Therefore, the *Thalassinoides* burrow fill represents tubular tidalites; they occur in highly bioturbated sediments that accumulated in a lower-shoreface to upper-offshore setting. The tubular tidalites pipe down from a slightly erosive surface interpreted to have formed in a distal channel setting affected by tides. The tubular tidalites preserve the main record of previous tidal influence.

Tides led to the formation of couplets consisting of marly mud and somewhat coarser calcarenitic material. The coarser calcarenitic material is ascribed to be deposited during times of strong tidal currents, while the finer marly mud was deposited during more tranquil times of the tidal cycle (in particular, low-tide slack water). Two groups of couplets, thin-layered and thick-layered ones, are arranged in alternating packages suggesting a mixed semi-diurnal diurnal tidal setting. Around spring tide, thick-layered couplets dominate, suggesting a predominant diurnal tidal signature, whereas around neap tide the semi-diurnal signature leads to the formation of two thin-layered couplets per day. In contrast, today this coast experiences semi-diurnal tides.

The passive fill provides a record of four weeks documented within one example, whereas three other specimens contain intercalated unusual thick or even distorted layers and, hence, restrict the undisturbed record to about two weeks. For the undisturbed intervals, the sedimentation rate within the tubes ranges between 100 cm yr^{-1} and 300 cm yr^{-1}. These values are in agreement with short-term sedimentation rates in modern tidal settings. The upper value refers to modern high-sediment yield depositional sites. The potential sedimentation rates shed some light onto the sediment dynamics in this part of the Miocene Patagonian shelf sea.

The sediment fill of the *Thalassinoides* tubes normally starts with thick-layered couplets and, hence, suggests onset of fill around spring tide. This process indicates that the *Thalassinoides* producers were influenced by the tidal cycle and that they abandoned their burrows around spring tide, although this remains a matter of speculation.

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