

## ICHOLOGY AND SALINITY FLUCTUATIONS: A CASE STUDY FROM THE EARLY MIOCENE (LOWER BARREIRAS FORMATION) OF SÃO LUÍS BASIN, MARANHÃO, BRAZIL

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**ABSTRACT** – The ichnofauna from the Early Miocene Lower Barreiras Formation (Unit 1) exposed in the Alcântara area (São Luís Basin, north of Maranhão State, Brazil) typically represents the general traits of brackish-water recurrent assemblages, developed in a wave-dominated incised valley estuarine setting, involving a variety of tidally influenced subenvironments. Nine distinct ichnofabrics were recognized, recording salinity fluctuations throughout the lower shoaling shoreline (SH) and the upper tidal channel (CH) facies associations formed in the estuary mouth complex. From base to top, *Ophiomorpha-Diplocraterion* ichnofabric occurs at the base of fining upward subtidal cycles developed along shoaling coastline environments (SH), representative of a depauperated Skolithos ichnocoenosis. Overlying fine-grained deposits bearing *Thalassinoides-Ophiomorpha* ichnofabric, representing an impoverished Cruziana assemblage, typical of brackish water conditions. Coarsening-upward cycles are present in the SH deposits, and show a composite ichnofabric dominated by *Teichichnus*, with associated *Ophiomorpha*, *Cylindrichnus*, *Arenicolites*, *Thalassinoides*, *Palaeophycus*, *Planolites*, *Rhizocorallium*, *Taenidium*, *Chondrites* and *Phycosiphon*, superimposed by monospecific ichnofabrics of *Gyrolithes* and *Taenidium*. While the *Teichichnus*-dominated ichnofabric reflects brackish-water conditions in a stable and predictable substrate, as the mixed Skolithos-Cruziana ichnocoenosis, the presence of *Gyrolithes* and *Taenidium* ichnofabrics reinforces periods with extreme salinity fluctuation through the prograding cycles of the SH deposits. A *Glossifungites* suite occurs locally, demarcating the beginning of rhythmic cycles alternating the *Teichichnus*-dominated and both *Gyrolithes* and *Taenidium*. The *Taenidium* ichnofabric dominates in the upper part of the SH deposits, representing the Scoyenia ichnocoenosis, which records phases with the lowest salt wedge. Discrete *Cylindrichnus-Skolithos* ichnofabric can be observed at the top of the SH succession. Reddish sandstones of the CH deposits present monospecific *Ophiomorpha nodosa* ichnofabric, suggesting reactivation of estuarine/tidal channels in back barrier environments. Upward, it is replaced by *Thalassinoides-Teichichnus* ichnofabric, developed in fine-grained sediments of lagoon settings. The monospecific *Taenidium* ichnofabric occurs again in muddy deposits probably in the attributed to inner mangrove areas.

**Key words:** Salinity fluctuation, ichnofabrics, Lower Miocene, Lower Barreiras Formation.

**RESUMO** – A icnofauna da Formação Barreiras Inferior (Unidade 1, Mioceno Inferior, Bacia de São Luís, norte do Brasil) exposta no litoral de Alcântara (MA) representa uma típica sucessão de assembléias recorrentes mixohalinas, geradas em um sistema estuarino dominado por ondas e envolvendo uma série de subambientes influenciados por marés. Nove icnofábricas distintas foram reconhecidas, demarcando flutuações de salinidade ao longo da deposição de associações de fácies litorâneas progradantes (SH) e de canais de maré (CH) formadas próximas à região de desembocadura do estuário. A icnofábrica de *Ophiomorpha-Diplocraterion* ocorre em arenitos dos ciclos granodecrescentes, produzidos em ambiente de inframaré e caracterizados por uma icnocenose de Skolithos empobrecida. Na porção superior mais pelítica destes ciclos, ocorre a icnofábrica de *Thalassinoides-Ophiomorpha*, caracterizando a associação de Cruziana empobrecida, típica de condições de água salobra. Ciclos granocrescentes mostram icnofábrica composta predominantemente *Teichichnus* nas porções pelíticas, com *Ophiomorpha*, *Cylindrichnus*, *Arenicolites*, *Palaeophycus*, *Thalassinoides*, *Rhizocorallium*, *Planolites*, *Taenidium*, *Chondrites* e *Phycosiphon*, superposta por icnofábricas monoespecíficas de *Gyrolithes* e de *Taenidium*. Enquanto a icnofábrica dominada por *Teichichnus* caracteriza substratos de ambientes mixohalinos mais estáveis, típicos da icnocenose mista Skolithos-Cruziana, a presença de *Gyrolithes* e *Taenidium* reforça a ocorrência de períodos com flutuações extremas de salinidade, ao longo dos ciclos progradacionais dos depósitos SH. Uma suíte de *Glossifungites*

ocorre localmente, demarcando o início de ciclos com alternância entre as icnofábricas dominadas por *Teichichnus* e as de *Gyrolithes* e *Taenidium*. A icnofábrica de *Taenidium* é dominante na porção superior da sucessão granocrescente, representando a icnocenose de Scoyenia e refletindo a menor cunha salina durante essa fase deposicional. No topo dos depósitos SH, observa-se uma discreta icnofábrica de *Cylindrichnus-Skolithos*. A icnofábrica monoespecífica de *Ophiomorpha nodosa* ocorre nos arenitos avermelhados dos depósitos CH, sugerindo reativação de canais estuarinos/marés em ambientes atrás de barreira. Em direção ao topo, a icnofábrica de *Thalassinoides-Teichichnus* substitui a anterior, desenvolvendo-se em sedimentos finos de zonas lagunares. No topo, a icnofábrica monoespecífica de *Taenidium* ocorre mais uma vez, em pelitos atribuídos a zonas marginais de mangues.

**Palavras-chaves:** Flutuações de salinidade, icnofábricas, Mioceno Inferior, Formação Barreiras Inferior.

## INTRODUCTION

Incised valleys represent probably some of the most significant concepts of sequence stratigraphy (Van Wagoner *et al.*, 1990; Zaitlin *et al.*, 1994). The distinction between fully marine and brackish water environments is useful for recognizing these features (Pemberton *et al.* 1992a, 2002; MacEachern & Pemberton, 1994). Several studies have demonstrated that trace fossils are useful to identify brackish water deposits (Pemberton & Wightman, 1992; Pemberton *et al.*, 2002), and to reconstruct ancient estuarine environments, which are a main component of incised valley systems. Ichnofaunal distribution is an excellent means of assessing the response of infaunal organisms to salinity flux (Howard & Frey, 1973, 1975, 1985; Ekdale *et al.*, 1984; Frey & Pemberton, 1985; Pemberton & Whigtman, 1992; Beynon & Pemberton, 1992; Pemberton *et al.*, 1992a, 1992b, 2002; Pattison, 1992; Buatois *et al.*, 1998b; Gingras *et al.*, 1999, 2002). In brackish water environments deep infaunal organisms are more abundant than epifaunal ones (Knox, 1986; Horward & Frey, 1975; Howard *et al.*, 1975; Dörjes & Howard, 1975; Pemberton & Wightman, 1992), recording frequent and distinctive biogenic reworking of the substrate.

The Miocene Barreiras Formation exposed in the Alcântara region (São Luís Basin, Maranhão State, north Brazil), records deposition in a wave-dominated incised valley estuarine setting involving a variety of tidally influenced subenvironments. These deposits were interpreted as estuarine by Rossetti (2000), based on: (i) the presence of a depauperate ichnofauna and the occurrence of *Gyrolithes*, both indicative of stressed brackish-water conditions; (ii) the dominance of sedimentary structures diagnostic of tidal processes; and (iii) the presence of widespread channel deposits. The aim of this paper is to recognize distinct, recurring brackish water trace fossil associations in Lower Barreiras Formation (Lower Miocene) and to evaluate salinity fluctuations towards the seaward-side of the estuarine system by ichnofabric analysis. Nine distinct ichnofabrics were recognized in the lowermost sedimentary succession (Unit 1), which records deposition behind barriers, in the in the estuary mouth complex (*sensu* Dalrymple *et al.*, 1992). These ichnofabrics reflect the salinity content of the water, recording colonization by fully saline marine water communities, brackish water communities, and freshwater communities that inhabited the substrate in different times.

## REGIONAL AND STRATIGRAPHICAL SETTING

The São Luís Basin is a small (18,000 km<sup>2</sup>), northwest/southeast-elongated half-graben formed by reactivations of normal and strike-slip faults during the last stages of the Gondwana break up in the Early Cretaceous (Figure 1). A thick (nearly 4,000 m) Cretaceous succession filled the bulk of the basin. These strata are unconformably overlain by a thin (i.e., maximum of 60 m thick) Miocene unit, represented by the Pirabas and Barreiras formations (Figure 1). Detailed sedimentological studies of deposits exposed along several coastal cliffs between the towns of Alcântara and Guimarães indicate deposition in a wave-dominated tidally-influenced estuarine paleovalley including tidal channels/inlets, fluvial-influenced channels, tidal flats, tidal deltas/washovers, lagoons and bays subenvironments (Rossetti, 2000). The estuary fill is complex, as revealed by the recognition of three stratigraphic units bounded by regional discontinuity surfaces, named Unit 1, 2 and 3 by Rossetti (2000) and representative of lower, middle/upper and post-Barreiras successions, respectively (Figure 2). The lowermost unit bears a variety of trace fossils that can particularly useful to interpret salinity fluctuations. These deposits unconformably overlie Cretaceous deposits of the Cuijue Formation (Rossetti, 1998), and are composed by two facies associations attributed to shoaling shoreline (SH) and tidal channel (CH) depositional settings (Figure 3). The SH facies association averages 6-8 m in thickness and is mostly composed by intergrading fining and coarsening upward cycles 0.5 to 2.0 m thick. These deposits are attributed to shoreline progradation near a wave-dominated estuary mouth with tidal influence. The fining- and coarsening-upward cycles recording several shoaling upward episodes, the former attributed to prograding tidal flats, and the latter reflecting shoaling of sandier areas at the estuary mouth (Rossetti, 2000). The shoaling shoreline facies association is cut by facies association CH, which provides a complete record of a large tidal channel at least 10 m deep and with an accretionary bank formed by lateral migration.

## ICHNOFABRIC ANALYSIS

Rossetti (2000) recognized 13 ichnogenera in deposits of Unit 1. The recorded ichnofauna is composed by *Arenicolites*,

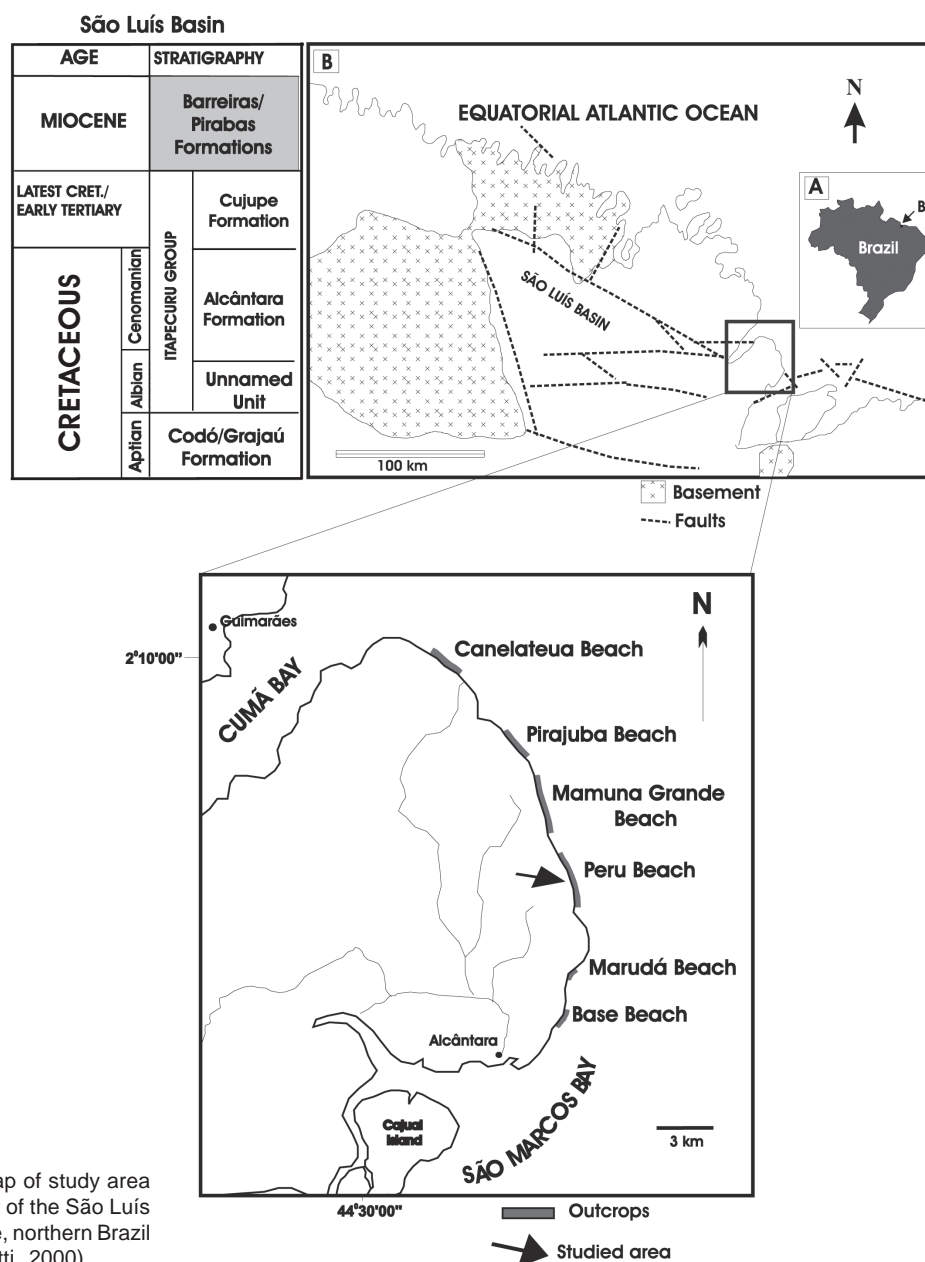
*Cylindrichnus*, *Gyrolithes*, *Macaronichnus*?, “*Macaronichnus anchonichnus*”, *Ophiomorpha*, *Palaeophycus*, *Planolites*, *Rusophycus*, *Skolithos linearis*, *Taenidium*, *Teichichnus*, and *Thalassinoides*, occurring chiefly as ichnofabrics. The references to *Rusophycus* and “*Macaronichnus anchonichnus*” are clerical errors, the former corresponding to *Rhizocorallium* and the latter to *Anchorichnus anchorichnus*. The occurrence of *Macaronichnus*? is not confirmed herein. Subsequently, Netto & Rossetti (2000, 2001, 2003a, 2003b) developed preliminary models based on ichnofabrics and utilized them to evaluate salinity fluctuations.

Ichnofabric analysis of Unit 1 at Peru Beach (Figure 1) led to the recognition of nine distinct ichnofabrics, each reflecting distinct salinity conditions consistent with the estuarine interpretation proposed (Figure 3).

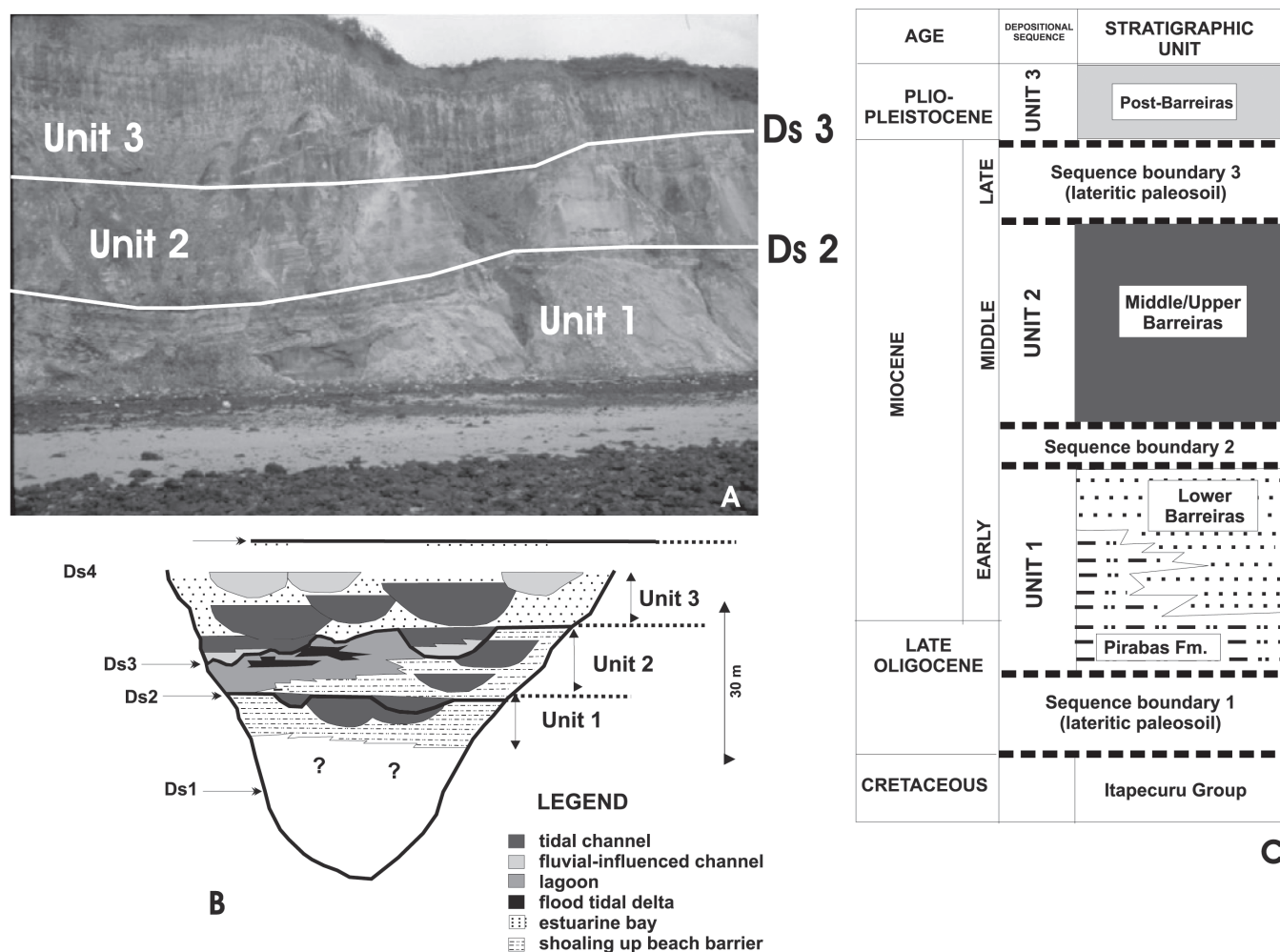
### *Ophiomorpha-Diplocraterion* ichnofabric

This ichnofabric occurs in the lowermost 30 cm of the exposed sedimentary succession in the study area (Figure 3C) and represents the activity of the first burrowing community established in the coarser-grained deposits of the fining-upward cycles of facies association SH (Figure 4). *Ophiomorpha* are the dominant biogenic structure, but *Diplocraterion* also occurs (Figure 5A and C). Escape structures are common (Figure 5B). The degree of bioturbation is moderate, disrupting between 30 and 60% of the primary fabric (BI3, Taylor & Goldring, 1993). The dominance of well-developed *Ophiomorpha nodosa*, and the presence of *Diplocraterion* and escape structures reveal a high-rate of deposition, and possibly high energy.

The trace fossil assemblage has characteristic components



**Figure 1.** Location map of study area and stratigraphic chart of the São Luís Basin, Maranhão State, northern Brazil (modified from Rossetti, 2000).



**Figure 2.** A. General view of Barreiras succession in the study area. B. Schematic diagram proposed by Rossetti (2000) to illustrate a summary of facies relationship and stratigraphic framework of the Miocene incised valley fill. C. Detailed stratigraphic chart of the Tertiary in northern Brazil.

of the *Skolithos* ichnocoenosis, suggesting deposition in subtidal environments (Frey & Pemberton, 1985; Buatois *et al.*, 1998b). Otherwise, truly marine trace fossils commonly reported in high-energy shallow marine sandy deposits, such as *Rosselia* (Nara, 2002) and *Macaronichnus* (Pemberton *et al.*, 2002), are absent. Ichnodiversity is very low, reflecting a depauperate *Skolithos* ichnocoenosis, probably due to discrete salinity fluctuations.

#### ***Thalassinoides-Ophiomorpha* ichnofabric**

This ichnofabric occurs from 0.30 to 0.53 m in the exposed sedimentary succession (Figure 3C), being typical of finer-grained sediments from the upper part of the fining-upward cycles in the facies association SH (Figure 4). Abundant *Thalassinoides*, common *Ophiomorpha nodosa* galleries, small *Palaeophycus*, and rare *Teichichnus* and *Planolites* are part of this assemblage (Figure 5C, D). Feeding and dwelling structures of trophic generalists are dominant. Ichnodiversity is very low. *Thalassinoides* shows normally flattened, and medium to small size galleries. The deposits are strongly bioturbated, showing disruption of almost 90%

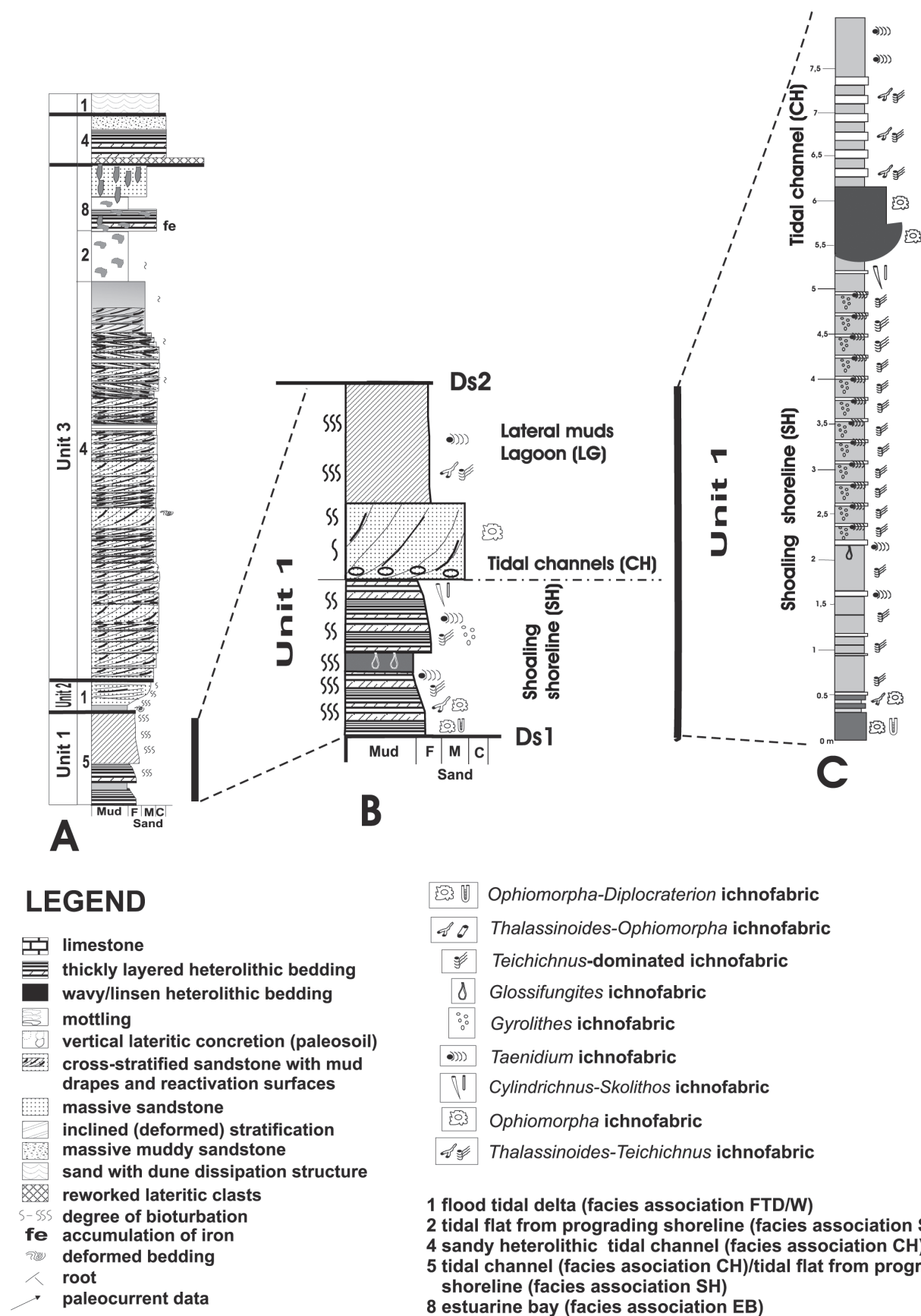
of the primary fabric (BI4-5, Taylor & Goldring, 1993).

This assemblage is an example of the depauperate Cruziana ichnocoenosis (Frey & Pemberton, 1985), typical of stressed environments from restricted basins such as lagoons and bays that occur behind barriers associated with outer estuarine areas (Pemberton *et al.*, 1992b; Pattison, 1992). Although salinity is low, a marine influence persists in those settings.

#### ***Teichichnus*-dominated composite ichnofabric**

This ichnofabric is complex and preserved in lower silty to muddy deposits of coarsening-upward cycles present in the SH facies association, occurring from 0.53 to 4.97 m of the studied profiles (Figures 3C and 4). It corresponds to the *Rhizocorallium-Teichichnus* ichnofabric reported by Netto & Rossetti (2000, 2001, 2003a, b) and contains abundant *Teichichnus*, common *Palaeophycus*, *Planolites*, *Chondrites*, *Phycosiphon*, and flattened, diminutive *Thalassinoides*, rare *Rhizocorallium*, *Arenicolites*, *Cylindrichnus* and *Ophiomorpha*, and rare small *Skolithos linearis* (Figure 6). The degree of bioturbation is extremely high (almost 100%





**Figure 3.** Strip log of the Barreiras succession at Peru Beach (A), detaching the Lower Miocene Unit 1 sedimentary sequence (B) and showing detailed ichnofabric distribution (C)

primary fabric disruption; BI5-6, Taylor & Goldring, 1993). *Cylindrichnus* (Figure 6A), *Arenicolites* and *Skolithos linearis* occupy the first, shallowest tier (Figure 7). They are crosscut by *Palaeophycus* and *Thalassinoides* (Figure 6B, E), which occupy the second, deeper tier (Figure 7), whereas *Teichichnus* and *Planolites* occupy the third one, crosscutting the previous suites (Figures 6B, C, F, and 7). The deepest tiers are occupied respectively by large *Chondrites* (mostly reworking *Thalassinoides* burrows) and *Phycosiphon* (Figure 6D, E, and 7), which crosscut the whole complex ichnofabric. Frequency of bioturbated beds is high (almost 100% of beds bioturbated) and diversity increases with respect to the *Ophiomorpha-Diplocraterion* and *Thalassinoides-Ophiomorpha* ichnofabrics. Feeding structures are dominant, and dwelling structures are

subordinate. The majority of traces represent structures generated by trophic generalists (i.e. *Palaeophycus*, *Planolites*, *Rhizocorallium*, *Teichichnus* and *Thalassinoides*).

Presence of both vertical and horizontal burrows, the dominance of feeding and dwelling structures of trophic generalists and the high degree of bioturbation are the main characteristics of the assemblage, allowing to interpret it as a mixed *Skolithos-Cruziana* ichnocoenosis (Pemberton *et al.*, 1992a, 2002). The abundance of biogenic structures (BI 5-6, Taylor & Goldring, 1993), the increasing in ichnodiversity and the tiering structure suggest stable mesohaline depositional settings. *Rhizocorallium* and *Cylindrichnus* are truly marine components (Pemberton *et al.*, 1992b), common both in fully marine and brackish-water settings (Pemberton

*et al.*, 2002). *Arenicolites* and *Skolithos* are common in marine settings, but have also been recorded in brackish and freshwater environments (Bromley & Asgaard, 1979; Pemberton *et al.*, 1992a; Buatois *et al.*, 1998a; Gibert & Martinell, 1998). In fact, most of the trace fossils observed are facies-crossing, ranging from shelfal to marginal-marine environments and several may reach freshwater settings. The abundance of vertical structures suggests periods of relatively high energy, consistent with deposition in a wave-dominated, tidally influenced estuarine setting (Rossetti, 2000). The characteristics of trace fossil assemblage suggest deposition at the seaward lower estuary environments (Ranger & Pemberton, 1992). Sparse galleries of *Ophiomorpha* also occur and, together with *Rhizocorallium*, are attributed to construction during a following stage of colonization (Figure 6F).

Glossifungites ichnofabric

This ichnofabric occurs locally, descending from the interface between an upper 50 cm-thick bed of muddy deposits bearing the *Teichichnus*-dominated ichnofabric and a lower 5 cm-thick bed of bright yellow fine- to medium sandstone located at 2.18 m in the study sections (Figure 3C). It is dominantly composed by sharp-walled, long and narrow, U-burrows of *Diplocraterion* and tear drop-shaped burrows, which penetrate deeply into the substrate, cross-cutting the previous *Teichichnus*-dominated composite ichnofabric (Figure 8). The deposits are weakly bioturbated, with

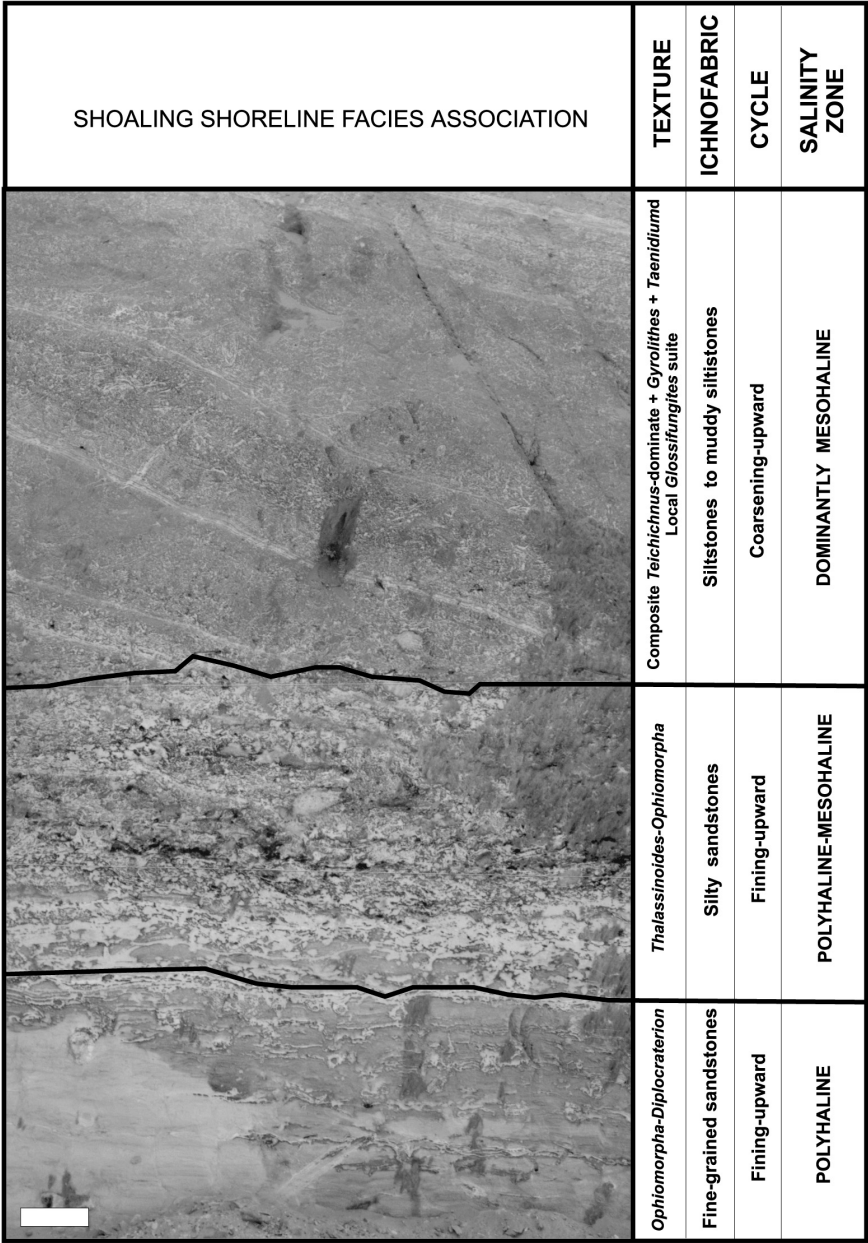


Figure 4. Lower to middle deposits of SH facies succession showing the upward distribution of the ichnofabrics, which reveals changes in the water salinity. Scale bar = 10 cm.



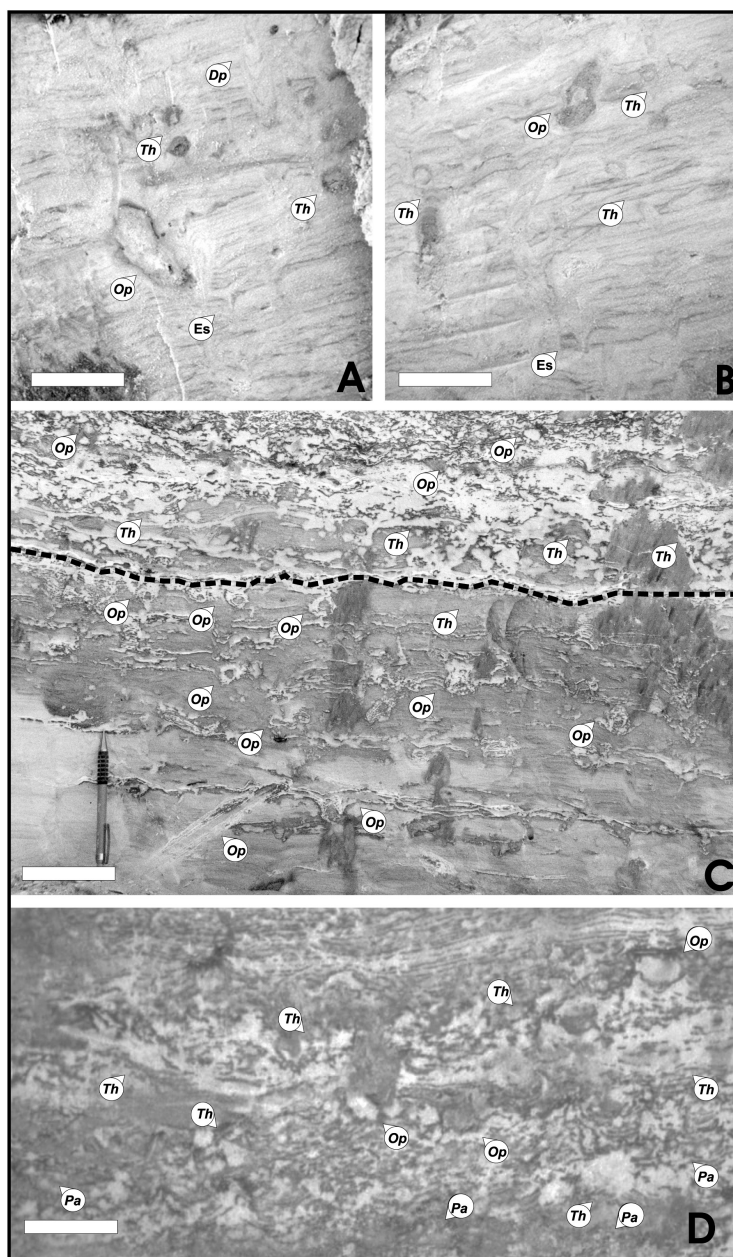
at least 70% of the previous fabric intact (BI2, Taylor & Goldring, 1993). The *Glossifungites* ichnofabric represents colonization of firmgrounds (resulting from exhumation of compacted mud). It is most common in marginal marine settings by marine organisms, and usually demarcates omission surfaces (Pemberton *et al.*, 1992a, 1992b, 1997, 2002; Bromley, 1996; Buatois & Mángano, 2000; Netto, 2001; Buatois *et al.*, 2002). A millimeter-scale laminae of black, oxidized material characterizes the omission surface in the study area (Figure 8). This surface is characterized by erosional exhumation of a mud surface, subsequent colonization by marine organisms during an interval of non-deposition, and finally burial of the surface by sand-dominated sediment.

### *Gyrolithes* ichnofabric

This ichnofabric is preserved in upper silty to muddy deposits of the coarsening-upward cycles from facies association SH, locating between 2.18 to 4.97 m in the study sections up to the surface bearing the *Glossifungites* ichnofabric (Figures 3C and 4). It consists solely of *Gyrolithes*, and is always superimposed over the *Teichichnus*-dominated composite ichnofabric (Figure 9). The corkscrew galleries of *Gyrolithes* are common in these deposits, but the degree of bioturbation is moderate to weak, disrupting approximately 30% of the previous fabric (BI2-3, Taylor & Goldring, 1993). Netto & Rossetti (2000, 2001, 2003a, 2003b) had been preliminarily interpreted a close relationship between *Gyrolithes* and *Taenidium*, proposing a *Gyrolithes*-*Taenidium* ichnofabric. However, more accurate analysis revealed that both ichnogenera occur in monospecific assemblages, representing distinct colonizations.

*Gyrolithes* is interpreted as a typical representative of brackish water conditions (Gernant, 1972; Powell, 1977; Beynon & Pemberton, 1992; Dworschak & Rodrigues, 1997; Pemberton *et al.*, 1992b, 2002), chiefly in Cretaceous and Tertiary rocks. The corkscrew morphology of *Gyrolithes* is usually considered an escape strategy to avoid extreme salinity fluctuations (Ranger & Pemberton, 1992). Monospecific assemblages of *Gyrolithes* have been interpreted as substrate reworking at the most landward reaches of the salt wedge inside the estuary (Pemberton *et al.*, 2002).

Spiral burrows were observed attached to galleries made by modern axianassid shrimps in mangrove settings by Dworschak & Rodrigues (1997). They usually are related to organic-rich layers in the substrate and are interpreted as a strategy to obtain maximum available food. Therefore, its presence in poorly-oxygenated mud of mangrove areas more likely represents a feeding strategy to efficiently exploit the organic-rich layers of the substrate rather than an escape strategy itself (Netto *et al.*,



**Figure 5.** Fining-upward cycles of SH facies association of Lower Barreiras succession (Unit 1) bearing the *Ophiomorpha*-*Diplocraterion* (A, B, lower half of C) and *Thalassinoides*-*Ophiomorpha* ichnofabrics (upper half of C, D). Deposits having dominance of *Ophiomorpha* show local occurrence of *Diplocraterion* (A) and frequent escape structures (B). *Palaeophycus* is a common trace fossil in the *Thalassinoides*-*Ophiomorpha* ichnofabric (D). **Dp** = *Diplocraterion*; **Pl** = *Planolites*; **Op** = *Ophiomorpha*; **Th** = *Thalassinoides*. Scale bar = 10 cm.

2001). Alternatively, it may well be a salinity-related behavior since mangrove swamps occur in supratidal settings.

### *Taenidium* ichnofabric

This ichnofabric is monospecific and well preserved in two 5 cm-thick bright yellow fine- to medium-grained sandstone beds located between 1.63 to 1.68 m and from 2.18 to 2.23 m, and in silty deposits occurring from 7.35 to the end of the study sections (Figures 3C and 4). These beds appear below and above the 50 cm-thick silty to muddy bed with the



Glossifungites ichnofabric. *Taenidium* is the unique component and large specimens occur (Figure 9). The *Taenidium* ichnofabric is also commonly observed descending from sandstone beds that intercalate with silty to muddy deposits along the entire succession of facies association SH, always superimposed to the previous *Thalassinoides-Ophiomorpha* and *Teichichnus*-dominated ichnofabrics. However, it is more common from 2.23 m to the top of the section. Density of *Taenidium* is considerable in some intervals, reworking between 30 and 60% of the previous fabric (BI3, Taylor & Goldring, 1993). As such *Taenidium* dominant- to monospecific assemblages tend to become more frequent towards freshwater to continental substrates (Scoyenia Ichnofacies, Pemberton & Frey, 1985; Buatois *et al.*, 1998b, 2002), salinity conditions in this part of study interval are interpreted to be equivalent to landward portions of estuarine deposits (oligohaline zones).

#### *Cylindrichnus-Skolithos* ichnofabric

This ichnofabric occurs from 4.97 to 5.15 m of the exposed sedimentary succession (Figure 3C). It contains dominant *Cylindrichnus* and *Skolithos*, and common *Arenicolites*. Diversity is low and bioturbation disrupts 30 to

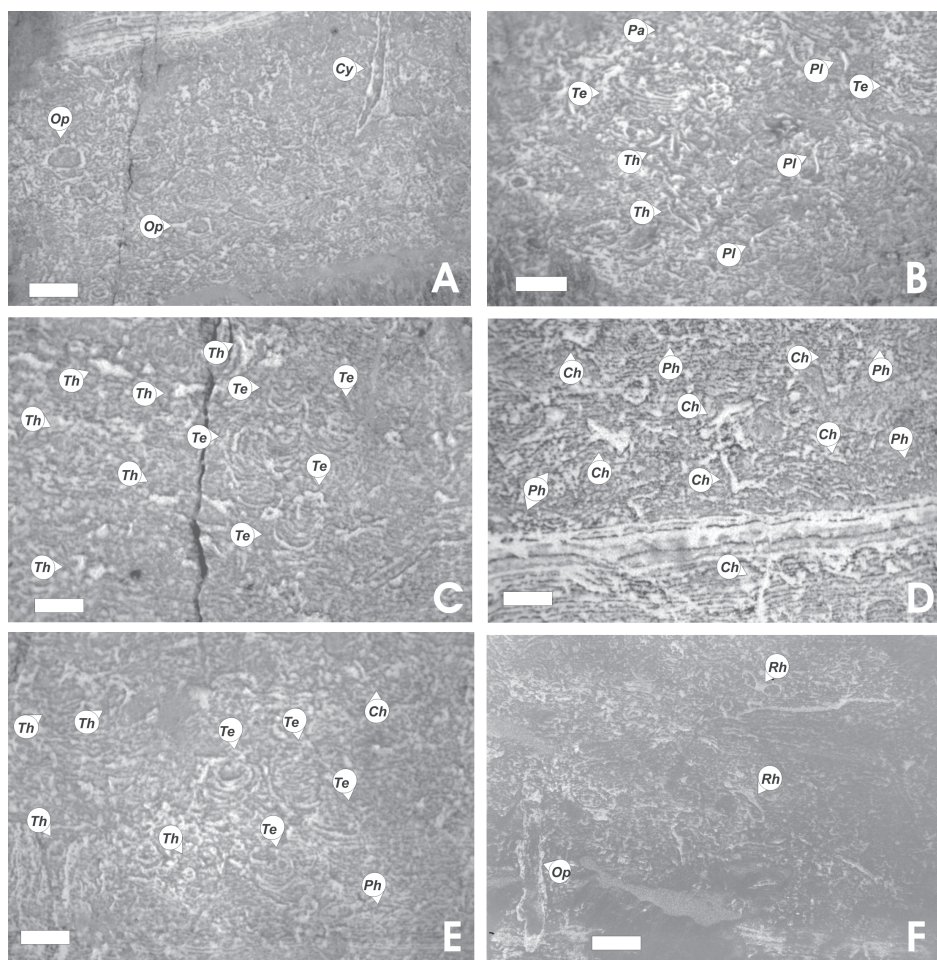
50% of the primary fabric (BI3, Taylor & Goldring, 1993). This ichnofabric represents a common association in brackish water ichnofacies (Pemberton *et al.* 2002), usually related to moderate to high energy settings, such as estuarine point bars under polyhaline to mesohaline conditions.

#### *Ophiomorpha* ichnofabric

This is a monospecific ichnofabric of *Ophiomorpha nodosa* that occurs in the coarser-grained deposits that characterize the lower half of facies association CH from 5.32 to 6.18 m of the exposed sedimentary succession (Figures 3C and 9). Huge, well-developed galleries, with diameters between 4 and 7 cm occur, disrupting at least 60% of the primary fabric (BI4, Taylor & Goldring, 1993). It represents an opportunistic behavior of marine organisms, commonly recorded in sand bars and which penetrate into the estuary during flood tides. The huge size of the *Ophiomorpha* tunnels, the well-sorted fine-grained quartz sand pellets in the burrow walls, and the well-developed system gallery suggest deposition in marine-influenced environments and probably polyhaline to mesohaline conditions.

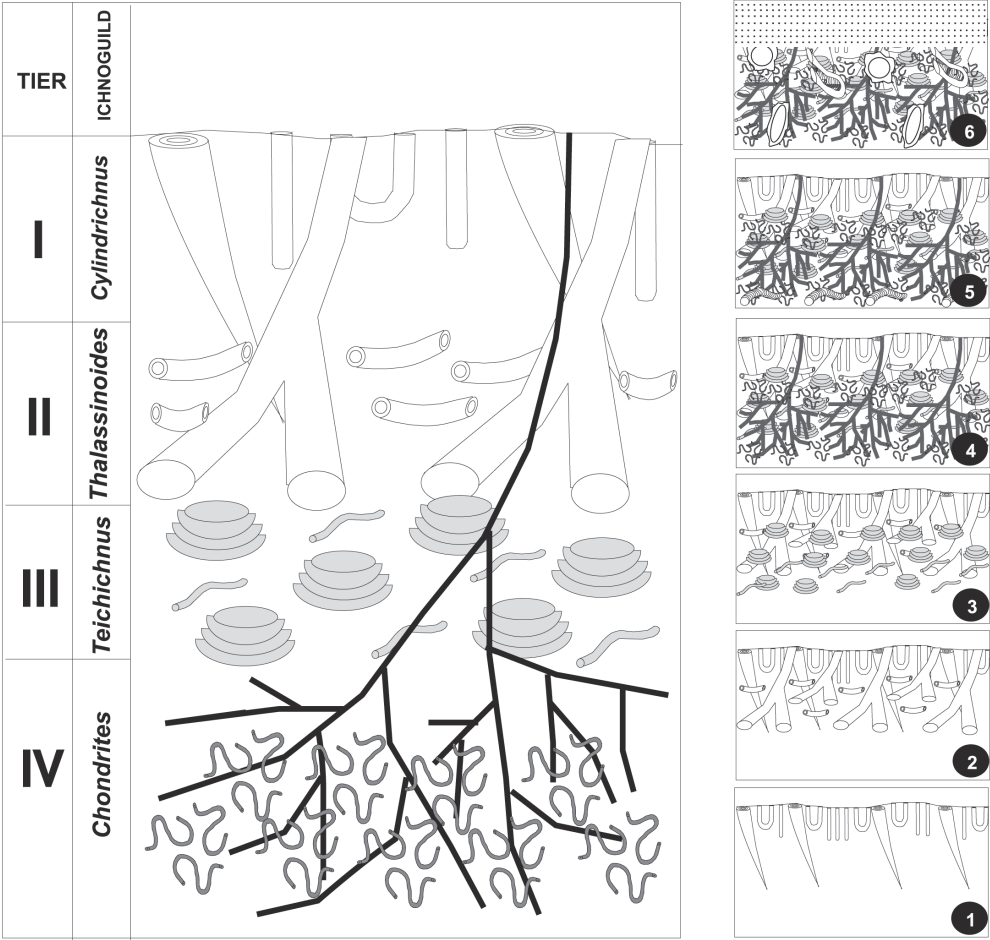
#### *Thalassinoides-Teichichnus* composite ichnofabric

This ichnofabric occurs in the finer-grained deposits that constitute the upper half of facies association CH, from 6.18 to 7.35 m of the exposed sedimentary succession (Figures 3C and 10). It contains abundant *Thalassinoides*, *Teichichnus* and *Palaeophycus*, and isolated *Ophiomorpha*, *Planolites* and *Taenidium* (Figure 10). Dwelling and feeding structures are the main behavioral patterns. The tiering structure here is less complex than those of the *Teichichnus*-dominated composite ichnofabric. *Ophiomorpha* burrows appear to represent initial colonization, however the shallowest tier is not preserved. *Thalassinoides*, *Palaeophycus*, *Teichichnus*, *Planolites* and *Taenidium* occupy the medial tier, crosscutting the *Ophiomorpha* burrows. Diversity is low, but the degree of bioturbation is high (BI5, Taylor & Goldring, 1993), suggesting again a depauperate Cruziana ichnocoenosis. Such characteristics support deposition in restricted environments, such as lagoons and bays associated with estuarine settings.

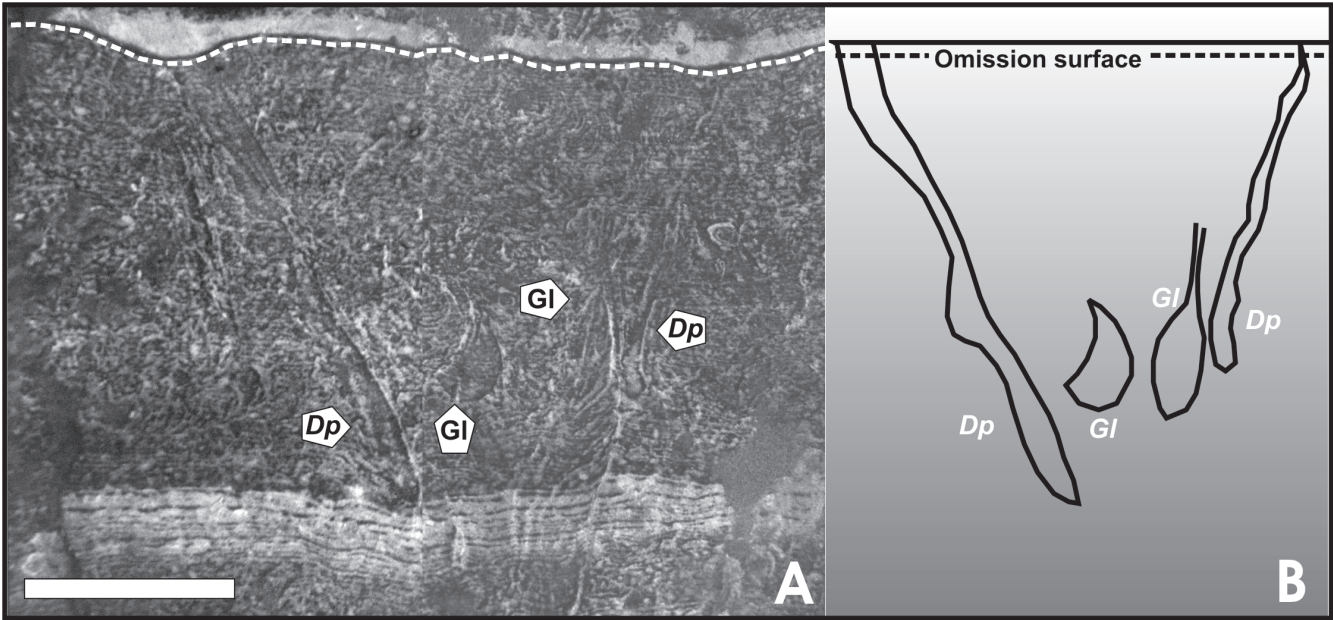


**Figure 6.** Coarsening-upward cycles of SH facies association of Lower Barreiras succession (Unit 1) hosting the complex *Teichichnus*-dominated composite ichnofabric. **Ch** = *Chondrites*; **Cy** = *Cylindrichnus*; **Pa** = *Palaeophycus*; **Pl** = *Planolites*; **Op** = *Ophiomorpha*; **Ph** = *Phycosiphon*; **Rh** = *Rhizocorallium*; **Te** = *Teichichnus*; **Th** = *Thalassinoides*. Scale bar = 10 cm.





**Figure 7.** Tiering diagram of the *Teichichnus*-dominated composite ichnofabric and the successive stages of substrate occupation. Initial colonization by vertical burrows (1) occupies the shallowest tier, increasing the substrate with organic-rich matter and opening the way to deeper colonization by deposit feeders (2 and 3). The deepest tier usually is poor-oxygenated, limiting aerobic life but favoring scavengers and chemosymbionts (4, 5). Out of scale.



**Figure 8.** A. General aspect of the Glossifungites suite. Bar scale: 10 cm. B. Schematic draw showing longness of *Diplocraterion* (*Dp*) and the tear drop-shape burrows (*Gl*) and its close relationship with the erosional surface on the top, characterizing an omission surface (*sensu* MacEachern *et al.*, 1992).

## GENERAL DISCUSSION

Marginal marine environments characteristically display steep salinity gradients due to variability in amounts of freshwater inputs, rainfall, evaporation, tidal range and salinity content in adjacent coastal waters, as well as variations in coastal morphology, wind direction and velocities (Pemberton & Wightman, 1992). Salinity fluctuations generate physiologically stressful conditions for a great number of organisms, and together with changes in turbulence and turbidity of water, oxygen content, temperature, and substrate exposure, influence the distribution of benthic fauna in estuarine environments (Pemberton *et al.*, 2002). Accordingly, benthic communities of substrates affected by salinity fluctuations tend to consist of opportunistic elements, typical

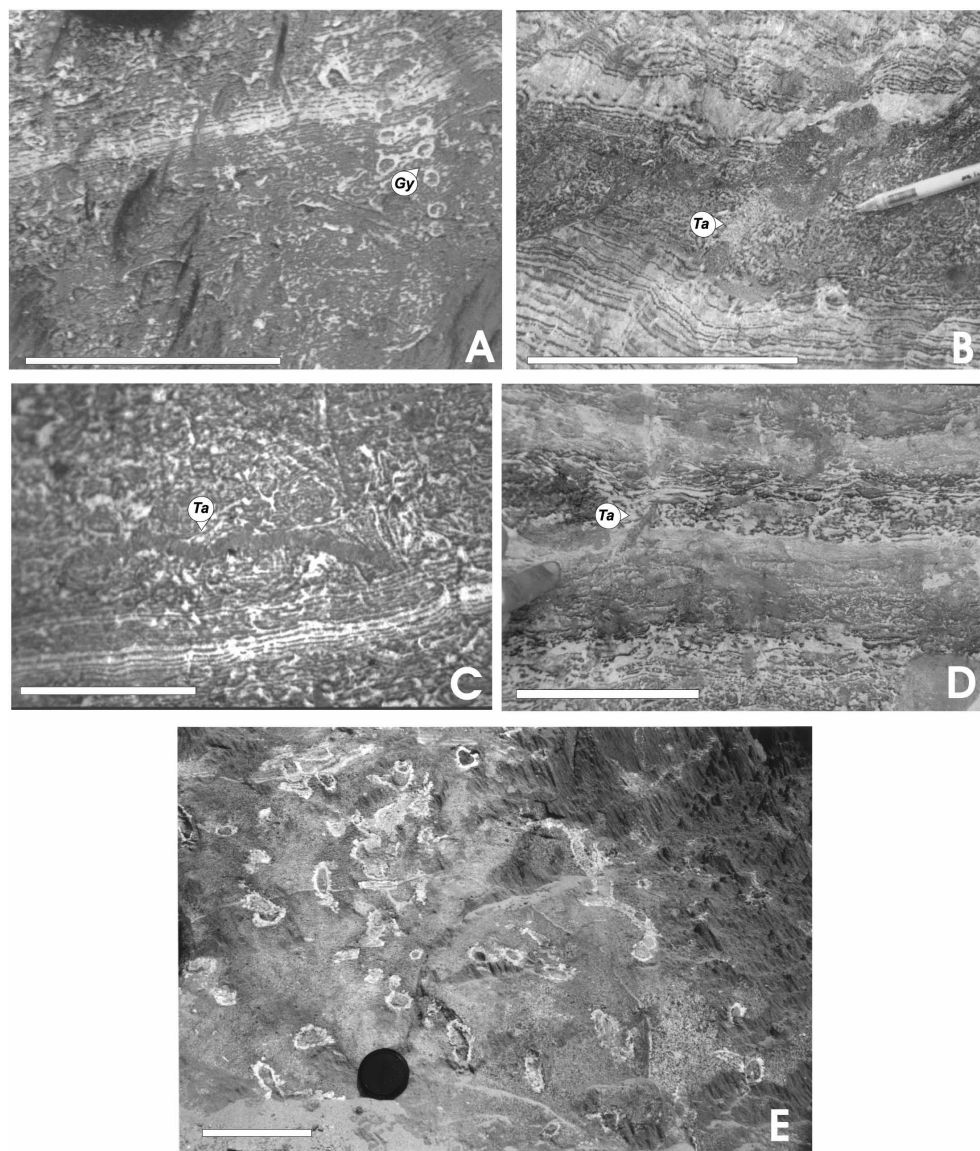
of brackish-water environments. Brackish-water faunas are characterized by: (i) low organic diversity; (ii) small size of organisms; (iii) high density of individuals; (iv) trophic generalists; (v) burrowing organisms that excavate deep inside the sediments and make morphologically simple structures; (vi) burrowing activity chiefly for dwelling and feeding purposes (Ekdale *et al.*, 1984; Pemberton & Wightman, 1992; Beynon & Pemberton, 1992; Pemberton *et al.*, 1992b, 2002; Buatois *et al.*, 1998b; Gingras *et al.*, 1999).

As many of the benthic fauna that inhabits brackish-water settings is composed of infaunal organisms, most of the characteristics cited above are well reflected in the ichnological record. Thus, ichnodiversity in brackish-water environments decreases, being critical in areas of salinity lower than to 5 ppm, in which only estuarine endemic

organisms (oligohalines) can survive (Figure 11). The density of bioturbation varies from high in quiet, protected settings, to low, in high-energy settings and poorly-oxygenated muds. Bioturbation is commonly more pervasive towards the seaward-influenced side of the estuary.

The oxygen-content of the substrate plays an important role in faunal distribution in brackish-water environments. Poorly-oxygenated substrates normally inhibit occupation by organisms dependent upon oxygen-content from pore water for respiration. The development of low-oxygen substrates in brackish-water settings creates an extra constraint for infaunal occupation. In extreme circumstances, only biogenic structures made by chemosymbionts are preserved.

The ichnofabrics recorded in the Lower Barreiras reflect most of the above-mentioned characteristics, including: (i) low ichnodiversity; (ii) dominant dwelling and feeding behavior patterns; (iii) simple structures made by trophic generalists; and (iv) both vertical and horizontal burrows in the same assemblage. These features correspond to the mixed *Skolithos*-*Cruziana* ichnocoenosis and, in specific cases, to an impoverished



**Figure 9.** Monospecific ichnofabrics recorded in the Unit 1: the *Gyrolithes* ichnofabric (A), reworking the *Teichichnus*-dominated ichnofabric; the *Taenidium* ichnofabric, superimposed to the *Teichichnus*-dominated (B, C) and to the *Thalassinoides*-*Teichichnus* (D) ichnofabrics; and the *Ophiomorpha* ichnofabric (E), showing the characteristic thick pelleted-wall of *O. nodosa*. Gy = *Gyrolithes*; Ta = *Taenidium*. Scale bar = 10 cm.



Cruziana assemblage, both commonly preserved in brackish-water influenced settings (Pemberton *et al.*, 1992a, 1997; Buatois & Mángano, 2000). The trace fossil assemblages recorded in the study area are equivalent to suites observed in the more seaward-influenced side of many estuarine settings (Pemberton & Wightman, 1992; Pemberton *et al.*, 1992b, 2002; Ranger & Pemberton, 1992; MacEachern & Pemberton, 1994). Recently, Pemberton *et al.* (2002) proposed a schematic profile of the general traits common to brackish water ichnofacies. Some trends presented in this profile match with the ones observed in the Lower Barreiras succession, such as: (i) the occurrence of monospecific associations, particularly *Gyrolithes*; (ii) the presence of a general brackish suite, represented herein by the *Teichichnus*-dominated ichnofabric; and (iii) the occurrence of a mixed *Skolithos*-*Cylindrichnus* association, represented by the *Cylindrichnus*-*Skolithos* ichnofabric. In addition, thin sandy layers with discrete cryptobioturbation are sporadically observed in the study area.

A similar ichnofauna occurs in inclined heterolithic stratification (IHS) from the southern part of the Miocene Solimões Formation that crops out along the Acre River, near the city of Rio Branco (Acre State), northwestern Brazil (Gingras *et al.*, 2002). A complex ichnofabric is recorded in the upper part of that unit, composed of *Ophiomorpha*, *Thalassinoides*, *Arenicolites*, *Chondrites*, *Planolites*, *Scolicia*, *Teichichnus*, *Lockeia*, *Cylindrichnus*, *Diplocraterion*, *Trichichnus* and also ?*Gyrolithes*. Only *Scolicia*, *Lockeia* and *Trichichnus* were not recognized in the Lower Miocene Barreiras Formation, which otherwise contains *Taenidium* and *Palaeophycus*. Gingras *et al.* (2002) interpreted the ichnofauna as generated in a marginal marine channel, under tidally-influenced and mesohaline water conditions, recording seasonal or annual cyclic sedimentary events, as reflected by the IHS beds.

Despite minimal difference in trace fossil composition, the SH facies association from the Barreiras Formation is highly comparable with the 5.1 to 7.0 m interval of the Solimões Formation (Gingras *et al.*, 2002). Both exhibit: (i) an erosional unconformity with the underlying deposits, evidenced by erosional truncation; (ii) a change from unburrowed to poorly bioturbated sands and highly bioturbated silty deposits (BI 5-6, Taylor & Goldring, 1993), primary mixed *Skolithos*-*Cruziana* and impoverished *Cruziana* assemblages; and (iii) a *Glossifungites* assemblage demarcating a discontinuity between the underlying and the overlying sets of cyclic sedimentation. The shoaled upper IHS sets of the Solimões Formation show a prograding character, which can be observed in the figured strip log (Gingras *et al.*, 2002, fig. 3, p. 594) and in the 5.1 to 7.0 m

interval interpretation. The same prograding character is observed in the SH coarse-grained cycles of the Lower Barreiras Formation. Finally, both units show cyclic sedimentation resulting from alternating marine and freshwater influxes.

The freshwater influx in the Lower Barreiras succession can be evaluated by the presence of monospecific associations of *Gyrolithes* and *Taenidium*, the former commonly related to areas undergone to extreme salinity fluctuations (Gernant, 1972; Powell, 1977; Ranger & Pemberton, 1988, 1992; Strobl, 1988; Beynon & Pemberton, 1992; Pemberton *et al.*, 1997, 2002), and the latter consistent with periods of freshwater to continental conditions (Taylor & Gawthorpe, 1993) (Figure 12). Otherwise, marine influx would have brought fully saline opportunistic fauna, represented by the *Ophiomorpha*-*Diplocraterion* and *Cylindrichnus*-*Skolithos* ichnofabrics, as well as the *Cylindrichnus*-*Skolithos* suite of the *Teichichnus*-dominated ichnofauna, which rapidly colonized the substrate and maintained itself while salinity values were higher than those of mesohaline conditions. Below that, only euryhaline opportunists and endemic estuarine fauna can survive, and diversity is at a minimum (Figure 11). However, the overall bioturbation index may remain high. Both groups characterize the typical brackish water fauna, represented in the Lower Barreiras by the *Thalassinoides*-*Ophiomorpha*, the *Thalassinoides*-*Teichichnus*, and the *Teichichnus*-dominated ichnofabrics (Figure 12).

Freshwater influx reduces not only diversity, but also the degree of bioturbation, as extreme salinity fluctuation normally constraints animal distribution. In freshwater and continental environments, monospecific assemblages and low degree of bioturbation are common and may suggest colonization during short periods of time. Otherwise, the medium to high degree of bioturbation and the complex

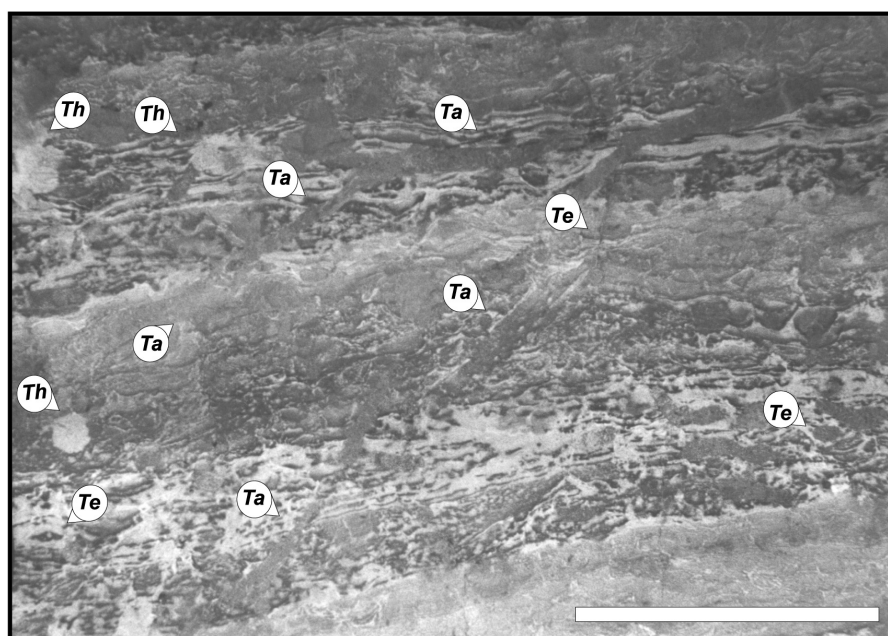
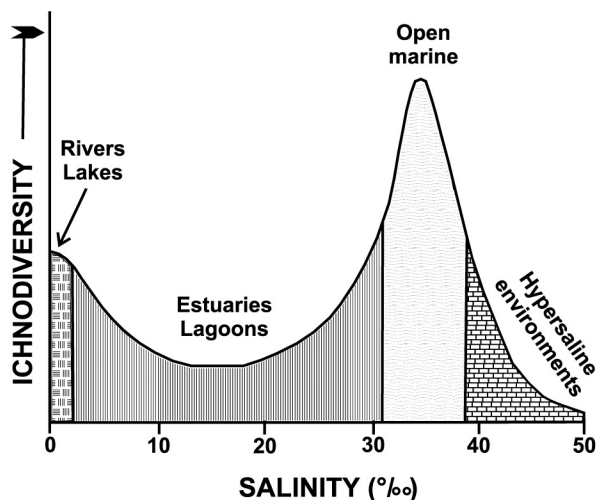
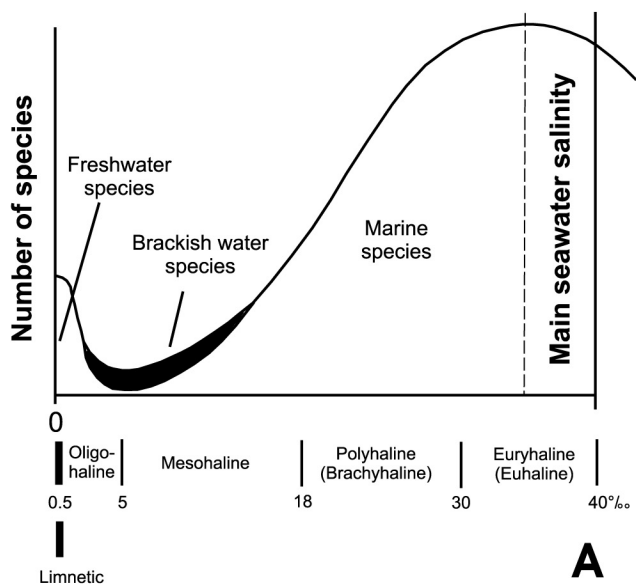


Figure 10. The *Thalassinoides*-*Teichichnus* composite ichnofabric. *Pa* = *Palaeophycus*; *Pl* = *Planolites*; *Ta* = *Taenidium*; *Te* = *Teichichnus*; *Th* = *Thalassinoides*. Scale bar = 10 cm.

ichnofabric observed in brackish-water settings need a long-term period of time involved in substrate colonization. Intense reworking obscured the record of older biogenic structures. This suggests continuous, albeit slow, vertical accretion and a certain stability of bottom conditions. This in turn requires a period of time longer than the six-hours daily tidal cycles. Thus, cyclic alternation between muddy silt deposits highly bioturbated with the complex *Teichichnus*-dominated ichnofabric and the crosscutting *Gyrolithes* and *Taenidium* ichnofabrics may reflect seasonal sedimentation and salinity fluctuations, probably recording spring and neap tidal cycles.



**Figure 11.** Effects of salinity in diversity and species distribution, according to the saline zones in estuaries (A) and their reflex in ichnodiversity (B). Modified after Ekdale (1988) and Pickerill & Brenchley (1991).

## CONCLUSIONS

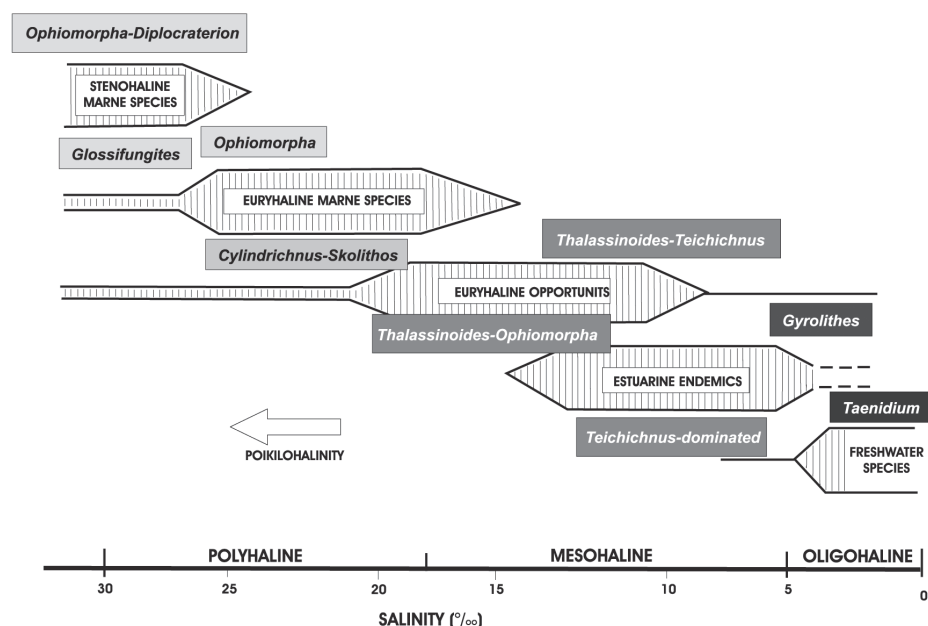
The ichnofauna observed in the Lower Barreiras Formation (Early Miocene) represents burrowing of sediment by infaunal invertebrate organisms adapted to brackish-water conditions. The vertical distribution of ichnofabrics along the entire succession denotes frequent salinity fluctuations, sometimes extreme, which varied from the lowest salt wedge to freshwater and continental conditions. The presence of fully marine organisms comprising a mixed *Skolithos*-*Cruziana* ichnocoenosis and of a complex, highly bioturbated ichnofabric typical of an impoverished *Cruziana* assemblage indicate deposition in the seaward portion of a wave-dominated estuary, probably in the inner estuary mouth. Rhythmic alternation between *Teichichnus*-dominated ichnofabrics and the superimposed *Gyrolithes*/*Taenidium* ichnofabrics reinforce a tidal influence during deposition. The presence of *Gyrolithes* superimposed over the complex, highly bioturbated assemblage established in the silt muddy deposits of the coarsening-upward cycles from facies association SH and its close association with *Taenidium*, suggest periods of extreme salinity fluctuations, when salinity values were at a minimum and a lowest salt wedge could be recorded in the inner zone of the estuary mouth complex. In addition, the complex ichnofabrics resulting from strong bioturbation in silty to muddy deposits (i.e., *Teichichnus*-dominated and *Thalassinoides*-*Teichichnus* ichnofabrics) requires a long-term development period. It allows characterize the rhythmic deposition of coarse-grained deposits of SH coarsening-upward cycles as resultant of seasonal cyclic events, which probably reflect annual spring and neap tidal cycles.

In general, fully marine ichnofabrics are replaced upward by brackish water assemblages, which are, in turn, mostly reworked by freshwater to terrestrial assemblages. The upward recurrence of trace fossil associations is consistent with the prograding character of the SH facies association, as recorded by the coarsening-upward cycles just overlying the surface from where the *Glossifungites* ichnofabric descends. Despite its well-known stratigraphic significance, the *Glossifungites* ichnofabric in the Unit 1 of the Lower Barreiras Formation showed a very local occurrence, suggesting that the erosional surface is of limited significance in terms of regionally sea-level influx.

## ACKNOWLEDGMENTS

This work was supported by grants from the FUNTEC/SECTAM (project 06/97) and from the PPGeo UNISINOS (project 3.00.006/1-0). Museu Goeldi is acknowledged for providing the logistical support. Rodrigo Dias Lima is also acknowledged for his assistance and friendship during the field trip. Special thanks to John-Paul Zonneveld, Luis Buatois and an anonymous reviewer for manuscript review, and to Maria Gabriela Mángano, Paulo Paim, Ubiratan Faccini and Patricia Balistieri, for helpful technical discussion.





**Figure 12.** Classification of estuarine zones and the faunal distribution, and a tentative ichnofabric allocation, according their occurrence in the Lower Barreiras succession deposits (modified after Knox, 1986).

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Received July, 2003; accepted November, 2003