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# *Ichnologic Signatures of Hyperpycnal Flow Deposits in Cretaceous River-dominated Deltas, Austral Basin, Southern Argentina*

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## ABSTRACT

Hyperpycnal flow deposits and associated facies in upper Cretaceous reservoirs of the Magallanes Formation in the Campo Boleadoras-Estancia Agua Fresca-Puesto Peter area of southern Patagonia, Argentina, are documented based on subsurface data. The study represents one of the first ichnologic characterizations of a deltaic system dominated by hyperpycnal processes. The fluvial-deltaic system was sourced from uplifted areas located in Central Patagonia and the Río Chico High and prograded toward the south and southeast. Integration of sedimentologic and ichnologic data allows establishing proximal-distal trends within a sediment transport system. The bulk of sandy hyperpycnal lobe deposits consists of coarse- to fine-grained sandstones that are either structureless or display a subtle parallel lamination that is commonly delineated by abundant plant remains. Vertical grain-size changes reflect flow fluctuations, with coarsening- and fining-upward intervals indicating waxing and waning flows, respectively. The concentration of plant remains indicates phytodetrital pulses in connection with direct fluvial discharges. These deposits are unburrowed to sparsely



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bioturbated, containing the *Thalassinoides* ichnofabric, which records opportunistic colonization during times of decreased sedimentation rate. However, the pervasive laminated fill of the burrows may reflect relatively high sedimentation rates, most likely because of suspension fallout of fine-grained material. The extreme compaction suggests burrow emplacement in a water-saturated soft substrate that underwent compaction subsequent to the bioturbation event. Associated heterolithic intervals contain the *Planolites-Teichichnus* ichnofabric, which characterizes marginal areas with respect to the hyperpycnal sand-rich lobes and times of quiescence between flows. During times of reduced sediment supply, material was reworked by wave processes, and hypopycnal conditions were dominant. The *Thalassinoides-Teichichnus* ichnofabric records colonization of these wave-reworked sandstone units, whereas the *Terebellina-Phycosiphon* ichnofabric reflects stable conditions that allowed intense bioturbation and the establishment of a moderately diverse benthic fauna. Fully marine offshore deposits are characterized by the *Teichichnus-Phycosiphon* ichnofabric, which display total biogenic reworking, high ichnodiversity, and a complex tiering structure.

## INTRODUCTION

Increased attention is being paid to river-flood-generated hyperpycnal flows as a mechanism of sediment transfer from river mouths to shelf and deep-sea areas (e.g., Mulder and Syvitski, 1995; Mulder et al., 2003; Plink-Björklund and Steel, 2004). Hyperpycnal flows create several stress factors, such as increased sedimentation rate, freshwater discharges, and high hydrodynamic energy that impact on the benthic faunas. However, the function played by these factors and the ichnology of hyperpycnal deposits have remained mostly underexplored. From an ichnologic standpoint, it is useful to differentiate two main depositional settings, where hyperpycnal flows are limiting factors on trace fossil distribution: deep marine and deltaic. The ichnology of deep-marine hyperpycnites has been analyzed by Ponce et al. (2007), Wetzel (2008), and Carmona and Ponce (2011). The ichnology of hyperpycnal flow deposits in deltaic systems is the focus of this study.

The Austral Basin (Figure 1) is one of the most important petroleum basins of Argentina (e.g., Biddle et al., 1986; Keeley and Light, 2008). The upper Cretaceous reservoirs of the Magallanes Formation in the Campo Boleadoras-Estancia Agua Fresca-Puesto Peter area have been analyzed based on an integration of ichnologic and sedimentologic data. As a result of this study, the function of hyperpycnal flows in sedimentary dynamics is underscored. The aim of this chapter is to document sedimentologic and ichnologic evidence that helps reinterpret the depositional mechanisms and sedimentary environments of the Magallanes Formation. This is one of the first studies that document in detail the ichnologic signatures of hyperpycnal flow deposits in a deltaic system. Accordingly, our observations in the Magallanes Formation may be of use to understand depositional dynamics in other successions formed in river-dominated deltas.

## GEOLOGIC SETTING AND PETROLEUM SYSTEMS

The Austral Basin, also known as Magallanes Basin, is located in the southernmost region of South America (Figure 1) and hosts up to 8000 m (26,247 ft) of rift (Triassic to middle–upper Jurassic), postrift (upper Jurassic to lower Cretaceous), and foreland (upper Cretaceous to Cenozoic) deposits. During this latter stage, the establishment of a fold and thrust belt resulted in the formation of a foredeep in the foreland basin (Figure 2). Sediment was sourced from uplifted areas in Central Patagonia and the Río Chico High located toward the northwest. Clastic wedges prograded toward the basin center, leading to a southeastern migration of the depocenters and forming a series of stacked sedimentary cycles controlled by regional tectonics.

Clastic wedges prograded from the north and northwest, and shoreface and deltaic deposits (Anita Formation) accumulated during the Campanian–Early Maastrichtian. Offshore mudstone and thin-bedded sandstone (Palermo Aike Formation) interfinger with the sandstone tongues toward the southeast. This succession is capped by the so-called D3 unconformity.

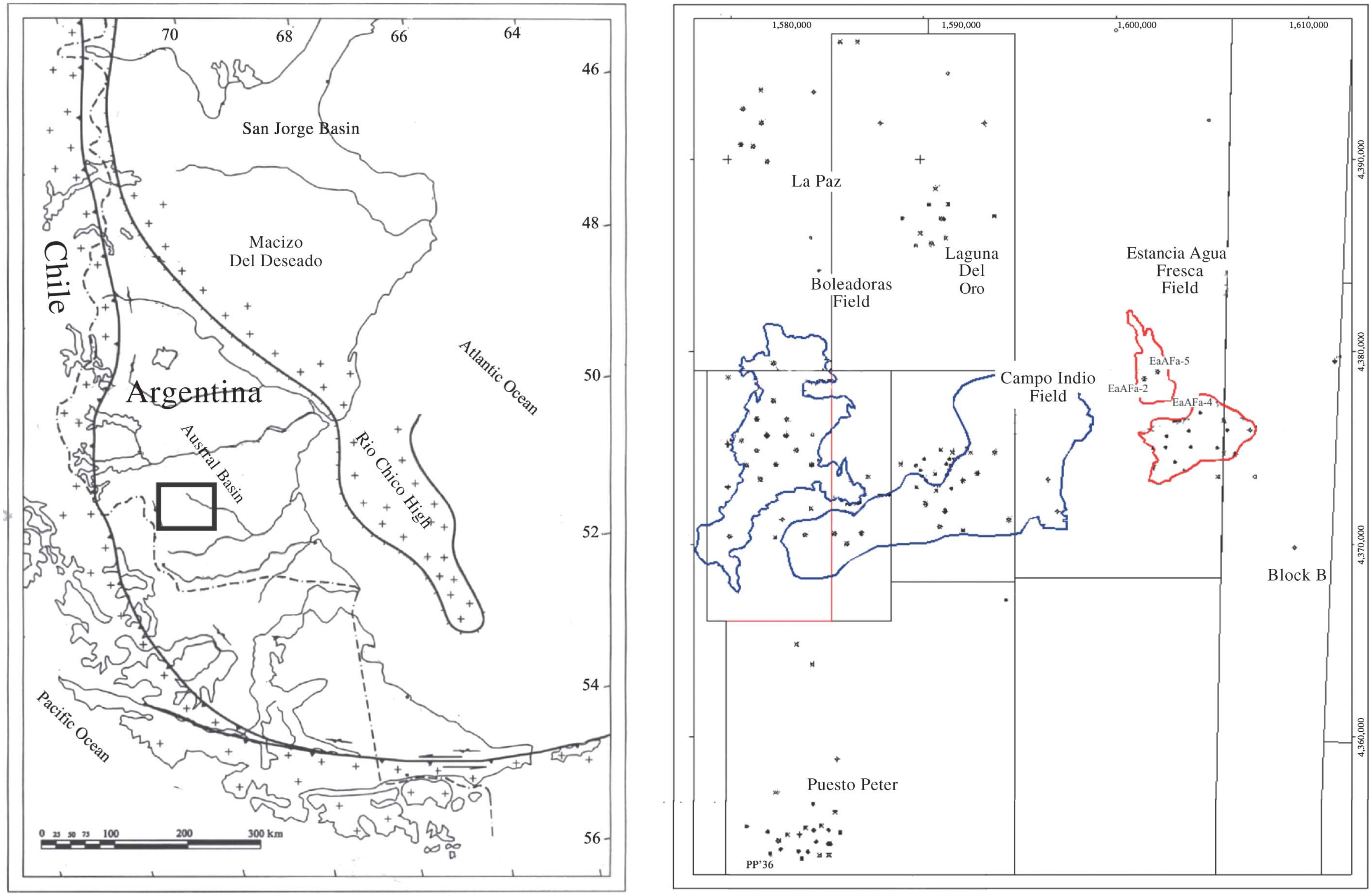


**FIGURE 1.** Location maps of the Austral Basin and the studied area in southern Argentina. EaAFa-2, EaAFa-4, EaAFa-5 = Estancia Agua Fresca well cores; PP'36 = Puesto Peter well core. Numbers at top and side of map at right indicate coordinates of the oil fields.

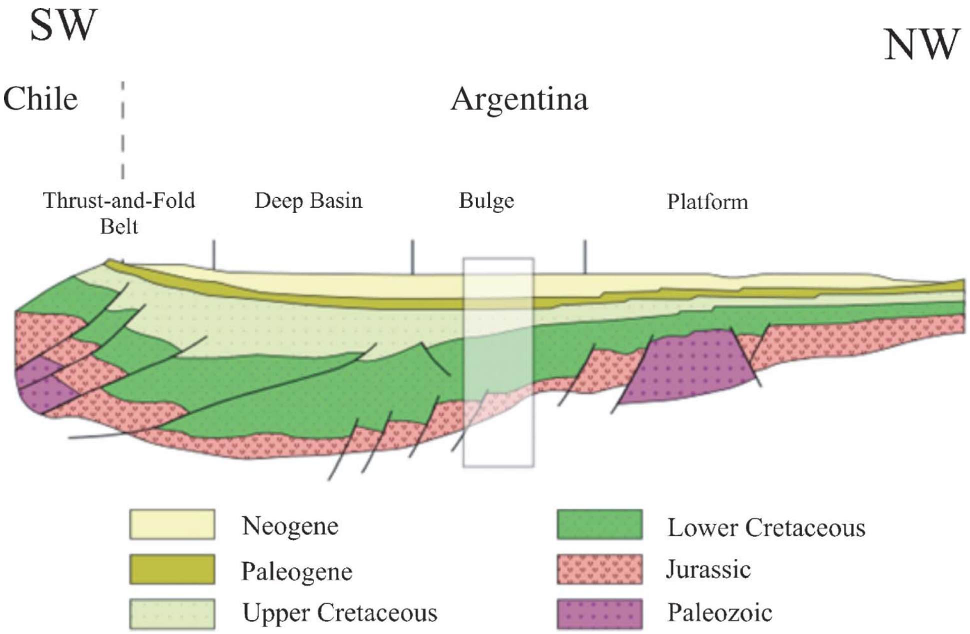


**FIGURE 2.** Tectonic setting of the Austral Basin. Box outlines position of the study area.

The Calafate sequence (Magallanes Formation, Upper Maastrichtian–Danian) occurs above this unconformity (Figure 3). During the rest of the Paleocene, the area was uplifted and the unconformity D4 was formed. Deep incisions were carved, leaving erosional remnants that favored formation of stratigraphic traps. Glauconite wackes accumulated during the Eocene transgression, forming the seal.

## SEDIMENTARY FACIES AND TRACE FOSSIL DISTRIBUTION

Our sedimentologic and ichnologic study is based on the analysis of 156.4 m (513.1 ft) of conventional cores and well logs from eight wells in an area of 200 km$^2$ (77 mi$^2$). The analyzed deposits correspond to the Lower Maastrichtian interval of the Magallanes Formation. Lower Maastrichtian deposits in the study area are stacked, forming a coarsening-upward succession, reflecting a prograding deltaic system during highstand (Figure 2). These deposits are bounded at the top by an erosional discontinuity related to the incision of estuarine valleys during a relative sea level fall. Logs from all wells in the study area were analyzed and correlated. Core information was matched with their log signatures. Sedimentary facies were distinguished based on lithology, physical sedimentary structures, and bed contacts. Three main facies have been defined: sandy hyperpycnal lobes, storm-influenced delta front and prodelta, and lower offshore. Our detailed trace fossil study was based on ichnotaxa identification, ethological and trophic types, population strategies, ichnodiversity, degree of bioturbation, and tiering structure. Degree of bioturbation was assessed following Taylor and Goldring (1993). In this scheme, a bioturbation index (BI), ranging from 0 (no bioturbation) to 6 (complete bioturbation), is defined. Five ichnofabrics were defined, characterized, and interpreted. Ichnofabrics were named after their most visible components and/or their most characteristic components (McIlroy, 2004). Ichnofabrics were placed in an ichnofacies context that allows their location into a paleoenvironmental framework. Environmental zonation and ichnofacies definitions of open-marine wave-dominated deposits follow the terminology of MacEachern et al. (1999). Standard terminology is used for environmental zonation of deltaic deposits (e.g., Bhattacharya, 2006). A comparison of ichnofabrics and ichnofacies from sandy hyperpycnal lobes, storm-influenced delta front and prodelta, and lower offshore allows the evaluation of benthic fauna response to different stress levels along a depositional gradient.

### *Sandy Hyperpycnal Lobes*

#### *Description*

The bulk of these deposits consists of coarse- to fine-grained sandstone that is either structureless or display a subtle parallel lamination that is commonly delineated by abundant plant remains. Hummocky cross-stratification and combined flow ripples are rare. Gradual changes in grain size are common, showing alternating coarsening- and fining-upward

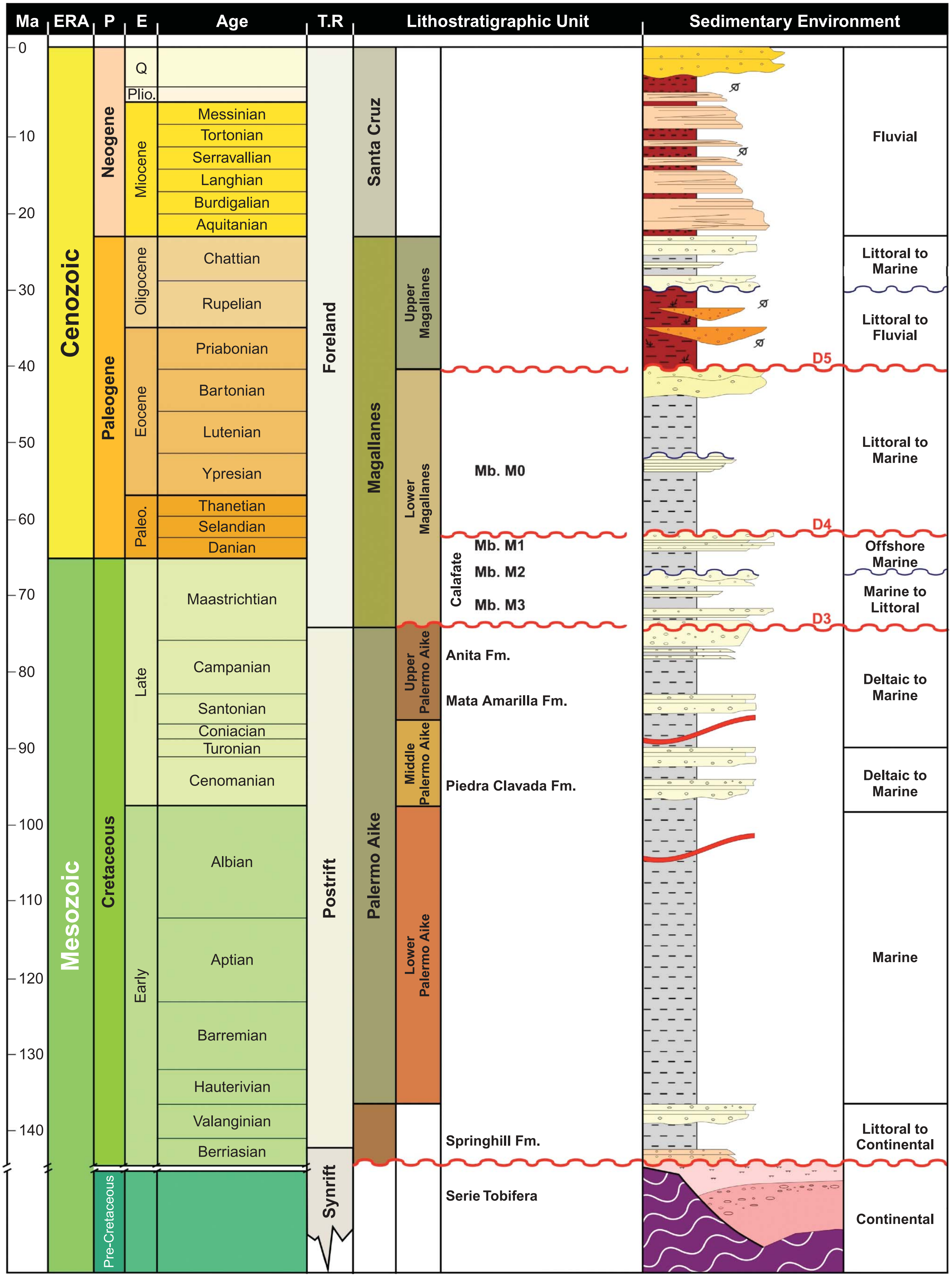


**FIGURE 3.** Stratigraphy of the Austral Basin in the studied region. P = period; E = Epoch; T.R = Tectonic Regime; Fm. = Formation; Q = Quaternary; Plio. = Pliocene; Paleo. = Paleocene; Mb. = Member; M = Magallanes; D3–D5 = unconformities.

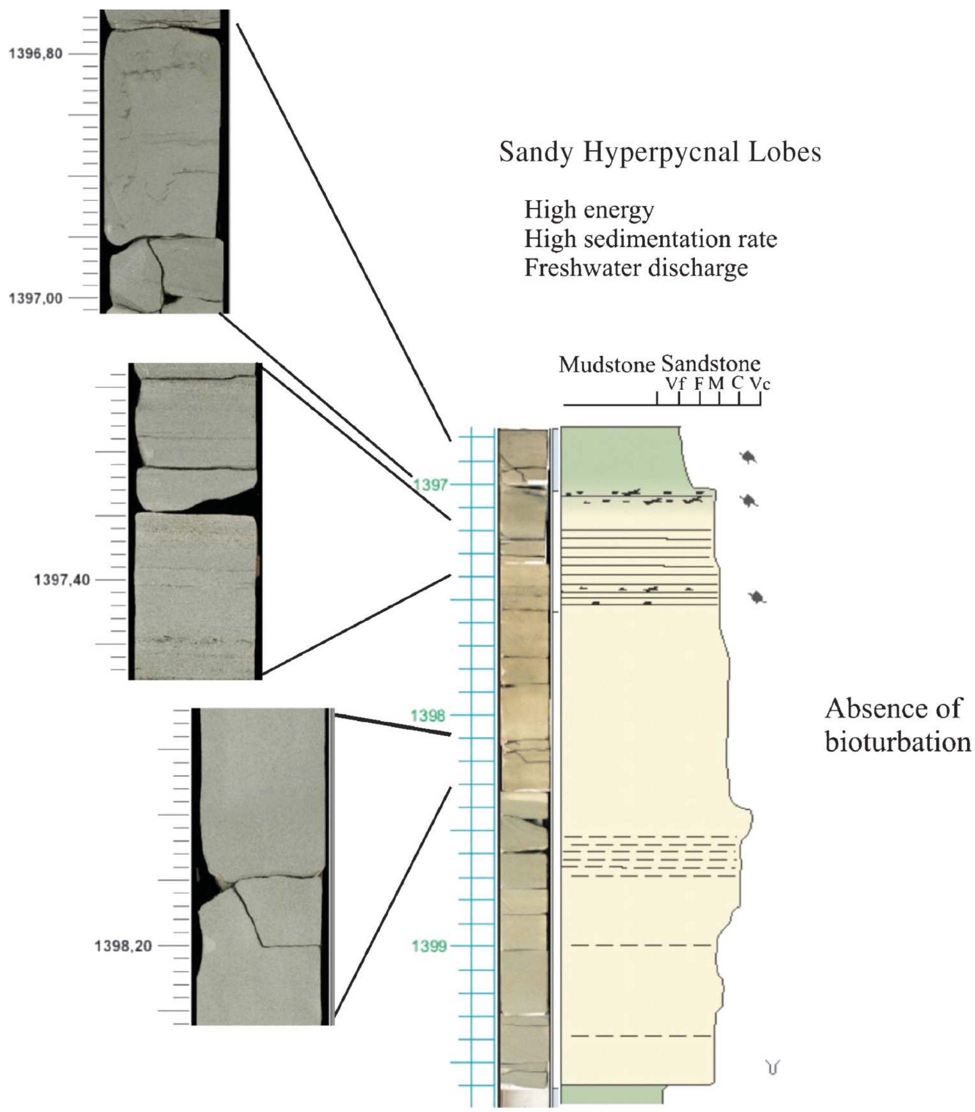


**FIGURE 4.** Sedimentologic attributes of internally complex sandstone deposits, interpreted as accumulated by long-lived and fluctuating hyperpycnal flows. Vf = very fine; F = fine; M = medium; C = coarse; Vc = very coarse. Numbers at left indicate core depths.

intervals (Figure 4). Erosive-based pebble conglomerate layers that contain bioclasts and flattened and deformed mudstone intraclasts occur at the base of very coarse- to coarse-grained sandstone units. Convolute lamination and fluid-escape structures are common throughout the interval. Discrete sandstone beds are difficult to identify, but amalgamated sandstone bedsets are up to 9.2 m (30.2 ft) thick. Sandstone bedsets are separated by intervals of dark gray, massive, or parallel-laminated mudstone-dominated units (up to 1.75 m [5.7 ft] thick) that may contain thinner sandstone layers (0.3–2 cm [0.12–0.79 in.] thick). These finer grained deposits contain syneresis cracks and plant remains. These deposits are present in well cores EaAFa-2, EaAFa-3, EaAFa-4, and EaAFa-5 of the Agua Fresca field in the central-eastern zone of the study area (Figure 1).

### *Ichnology*

Sandstone-dominated packages are unburrowed (Figure 4) to sparsely bioturbated and characterized by the *Thalassinoides* ichnofabric (Figure 5; Table 1). *Thalassinoides* is the dominant ichnogenus, consisting of burrow systems that contain both horizontal and vertical segments. Burrow walls are well defined and mud lined, although burrow fill is sandy, laminated, and passive. Burrows are extremely compacted, displaying flattened cross sections instead of circular or subcircular. The BI is typically 0–1 and, only locally, 2. Bioturbation is commonly restricted to the top of sandstone beds, and suites are typically monospecific, although *Ophiomorpha*, *Skolithos*, *Diplocraterion*, and *Palaeophycus* are present in places. The ichnofabric is dominated by dwelling structures of suspension feeders. These bioturbated deposits are

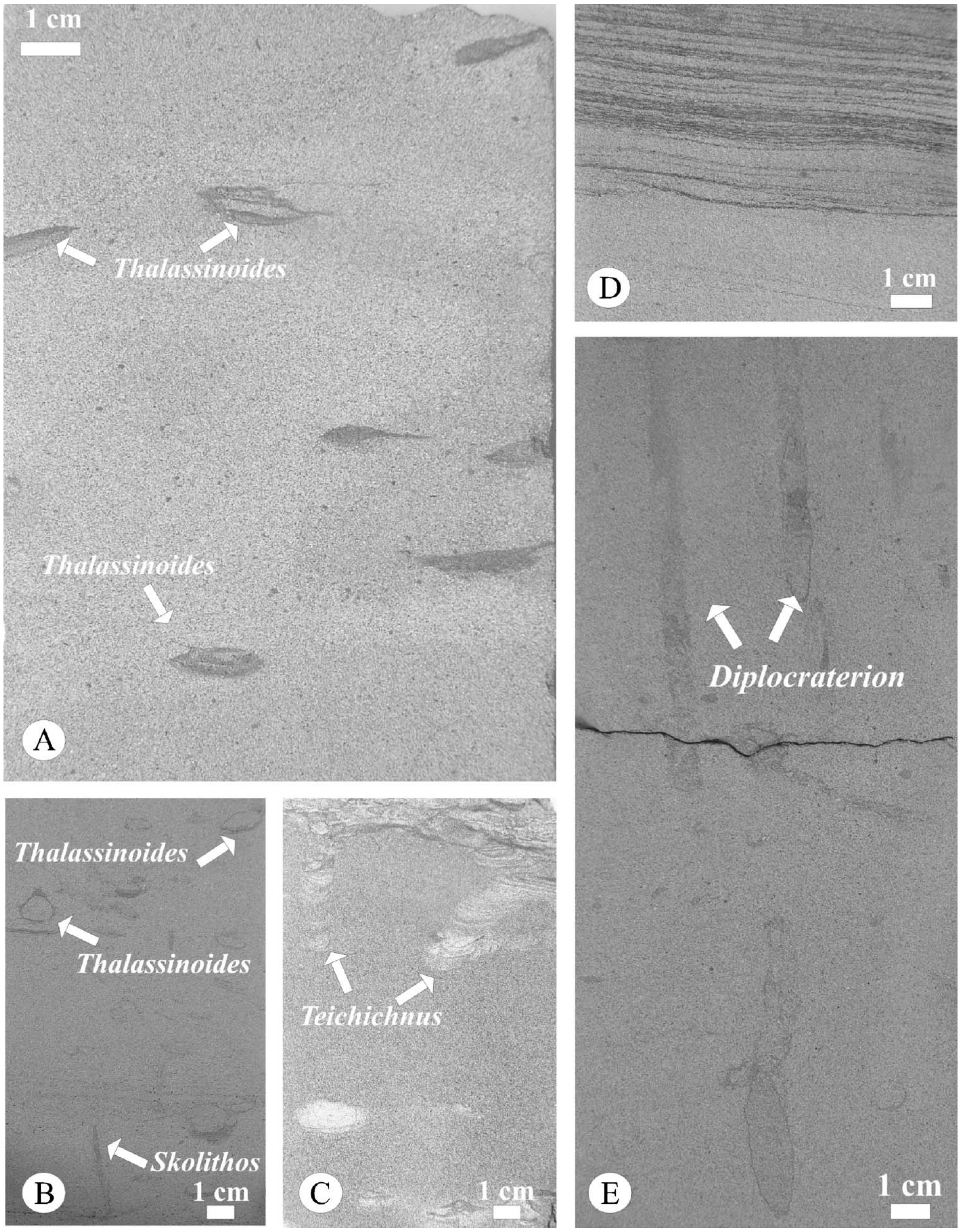


**FIGURE 5.** *Thalassinoides* ichnofabric in sandy hyperpycnal lobe deposits. (A) Highly compressed mud-lined *Thalassinoides,* showing infill with passive parallel lamination. EaAFa-4. (B) *Thalassinoides* and *Skolithos.* Note local subtle parallel lamination delineated by particulate carbonaceous material. EaAFa-2. (C) Retrusive *Teichichnus.* EaAFa-4. (D) Layers of particulate carbonaceous material, illustrating phytodetrital pulses. EaAFa-4. (E) Long, spreiten, U-shaped *Diplocraterion* burrows. EaAFa-4. EaAFa-2, EaAFa-4 = Estancia Agua Fresca well cores.

commonly interbedded with nonbioturbated structureless sandstone units. Tiering structure is very simple, displaying a dominance of deep-tier structures. *Palaeophycus* occupies shallow tiers, whereas *Thalassinoides*, *Ophiomorpha*, *Skolithos*, and *Diplocraterion* are deep-tier structures. In terms of archetypal ichnofacies, the *Thalassinoides* ichnofabric is representative of the *Skolithos* ichnofacies.

The associated thinner bedded sandstone and mudstone intervals contain the *Planolites*-*Teichichnus* ichnofabric (Figure 6; Table 1). *Planolites* and *Teichichnus* are commonly the only ichnogenera identified. Locally, *Thalassinoides* may occur. In contrast to the *Thalassinoides* ichnofabric, the *Planolites*-*Teichichnus* ichnofabric is dominated by feeding traces of deposit feeders. The BI of these finer grained deposits is typically 1–2. However, some intervals contain unbioturbated dark gray mudstone units. Tiering structure is very simple. *Planolites* and *Teichichnus* are shallow-tier structures, whereas *Thalassinoides* occupies deep tiers. The *Planolites*-*Teichichnus* ichnofabric illustrates a highly stressed expression of the *Cruziana* ichnofacies.

## *Interpretation*

Vertical grain-size changes reflect flow fluctuations, with coarsening- and fining-upward intervals indicating waxing and waning flows, respectively. This

**Table 1.** Summary of ichnologic and sedimentologic characteristics of the Magallanes Formation ichnofabrics.

| *Ichnofabric* | *Taxonomic Composition* | *Dominant Ethology and Trophic Type* | *Tiering* | *Bioturbation Index* | *Colonization Style* | *Depositional Conditions* | *Facies and Paleoenvironment* |
|---|---|---|---|---|---|---|---|
| *Thalassinoides* | Dominant: *Thalassinoides*; accessory: *Ophiomorpha*, *Skolithos*, *Diplocraterion*, *Palaeophycus*. | Dwelling structures of suspension feeders | Very simple | 0–1 (locally, 2) | Opportunistic colonization during times of decreased sedimentation rate | Waxing and waning flows (hyperpycnal discharges). Phytodetrital pulses. High suspended-sediment concentrations. Water-saturated soft grounds. High to relatively high energy. Sporadic reworking by oscillatory flows. Common salinity fluctuations. | Sand-rich hyperpycnal flow deposits. Deltaic lobes emplaced in distal delta front to proximal prodelta. |
| *Planolites-Teichichnus* | Dominant: *Planolites*, *Teichichnus*; accessory: *Thalassinoides*. | Feeding structures of deposit feeders | Very simple | 1–2 | Opportunistic colonization during interflow times | Low energy. Sporadic to common reworking by oscillatory flows. Common salinity fluctuations. | Sand-rich hyperpycnal flow deposits. Deltaic lobes emplaced in distal delta front to proximal prodelta. |
| *Thalassinoides-Teichichnus* | Dominant: *Thalassinoides, Teichichnus*; subordinate: *Rhizocorallium, Skolithos*, *Planolites*, *Asterosoma*. | Feeding structures of deposit feeders | Simple | 0–2 | Opportunistic colonization followed by climax populations | High suspended-sediment concentrations (hypopycnal discharges). Moderate energy. Common reworking by oscillatory flows. Sporadic salinity fluctuations. | Storm-dominated distal delta front to proximal prodelta. |
| *Terebellina-Phycosiphon* | Dominant: *Terebellina-Phycosiphon*; subordinate: *Planolites*, *Palaeophycus*, *Teichichnus*, *Thalassinoides*, *Zoophycos*, *Schaubcylindrichnus*. | Feeding structures of deposit feeders | Relatively well developed | 1–3 (locally, 4–5) | Opportunistic colonization followed by climax populations | High suspended-sediment concentrations (hypopycnal discharges). Moderate to low energy. Repeated reworking by oscillatory flows. Sporadic salinity fluctuations. | Storm-dominated distal delta front to proximal prodelta. |
| *Teichichnus-Phycosiphon* | Dominant: *Teichichnus*, *Phycosiphon*; subordinate: *Chondrites*, *Asterosoma*, *Planolites*; accessory: *Terebellina, Thalassinoides*, *Zoophycos*. | Feeding structures of deposit feeders | Complex | 6 | Climax populations | Low energy. Good oxygenation. Soft grounds. Negligible wave reworking. No salinity fluctuations. | Lower offshore |

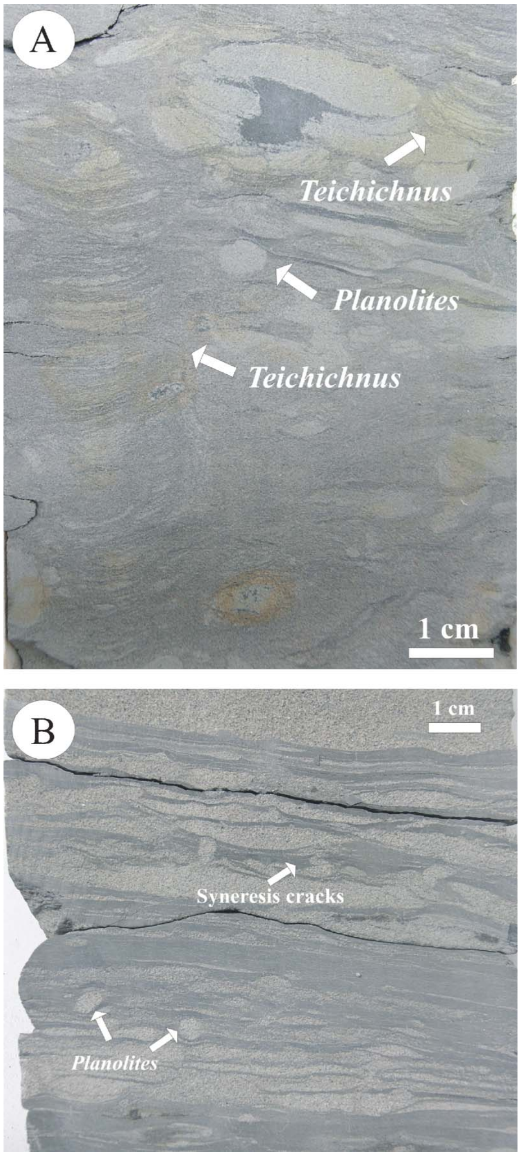


**FIGURE 6.** ***Planolites-Teichichnus*** **ichnofabric in hyperpycnal lobe deposits accumulated between flow events. (A) Moderately bioturbated deposits with deep and wide retrusive *Teichichnus* and isolated *Planolites*. Note discontinuous mudstone interbeds as a result of partial homogenization by bioturbation. EaAFa-4. (B) Sparsely bioturbated heterolithic deposits. Mudstone interbeds are continuous and well preserved. A low-density monospecific suite of *Planolites* is present in some of the mudstone interbeds. Note associated syneresis cracks. EaAFa-5. EaAFa-4, EaAFa-5 = Estancia Agua Fresca well cores.**

pattern results from a progressive increase in river discharge during waxing and peak flood stages followed by a waning flow stage (Mulder et al., 2003; Zavala et al., 2006; Soyinka and Slatt, 2008). The concentration of plant remains indicates phytodetrital pulses in connection with fluvial discharges (MacEachern et al., 2005). These deposits are interpreted as the result of turbulent flows of fluctuating energy and high suspended-sediment concentrations. Associated pebble conglomerate layers may indicate sediment bypass. This is also suggested by sandstone beds with asymptotic cross-stratification that may reflect fill of localized topographic lows. The local presence of hummocky cross-stratification and combined flow ripples indicates sand reworking by oscillatory flows and points to deposition above storm-wave base (Cheel and Leckie, 1993; Lamb et al., 2008). The syneresis cracks may reflect salinity fluctuations (Foster et al., 1955; Donovan and Foster, 1972). Interbedded dark gray massive or parallel-laminated mudstone and thin to very thin and very fine- to fine-grained sandstone accumulated during times of quiescence between flow events.

The *Thalassinoides* ichnofabric records opportunistic colonization in sand-rich hyperpycnal deposits. The characteristics of the ichnofauna (low ichnodiversity, dominance of dwelling burrows) and its presence at the top of massive beds suggest rapid colonization during times of decreased sedimentation rate. However, the pervasive laminated fill may reflect relatively high sedimentation rates, most likely caused by suspension fallout of fine-grained material. The extreme compaction suggests burrow emplacement in a water-saturated soft substrate that underwent compaction subsequent to the bioturbation event. The sparse bioturbation and simple tiering structure indicate short-term colonization windows. Low ichnodiversity and the presence of syneresis cracks are consistent with stress caused by dilution of marine salinity, specifically freshwater input during hyperpycnal discharges.

The dominance of feeding structures of deposit feeders in the *Planolites*-*Teichichnus* ichnofabric indicates exploitation of organic detritus in sediment accumulated during low-energy conditions. A low degree of bioturbation, preservation of thin-bedded sandstone layers, simple tiering structure, and low ichnodiversity suggest stressed conditions, most likely because of dilution of normal marine salinity caused by freshwater input. This is consistent with the presence of syneresis cracks and plant fragments.

In terms of bathymetry, ichnologic data indicate deposition in a shallow-marine environment. Elements typical of the distal *Cruziana* or the *Zoophycos* ichnofacies, which occur immediately above and below the storm-wave base, respectively (MacEachern et al., 1999), are absent. This is consistent with the localized presence of structures that indicate reworking of the sands by strong oscillatory flows, which point to flow emplacement well above the storm-wave base. However, intercalation of mudstone intervals indicates low-energy conditions in the absence of waves between flow events, suggesting deposition below fair-weather wave base most of the time. Therefore, integration of ichnologic and sedimentologic data indicates deposition in deltaic lobes emplaced in distal delta-front to proximal prodelta environments.

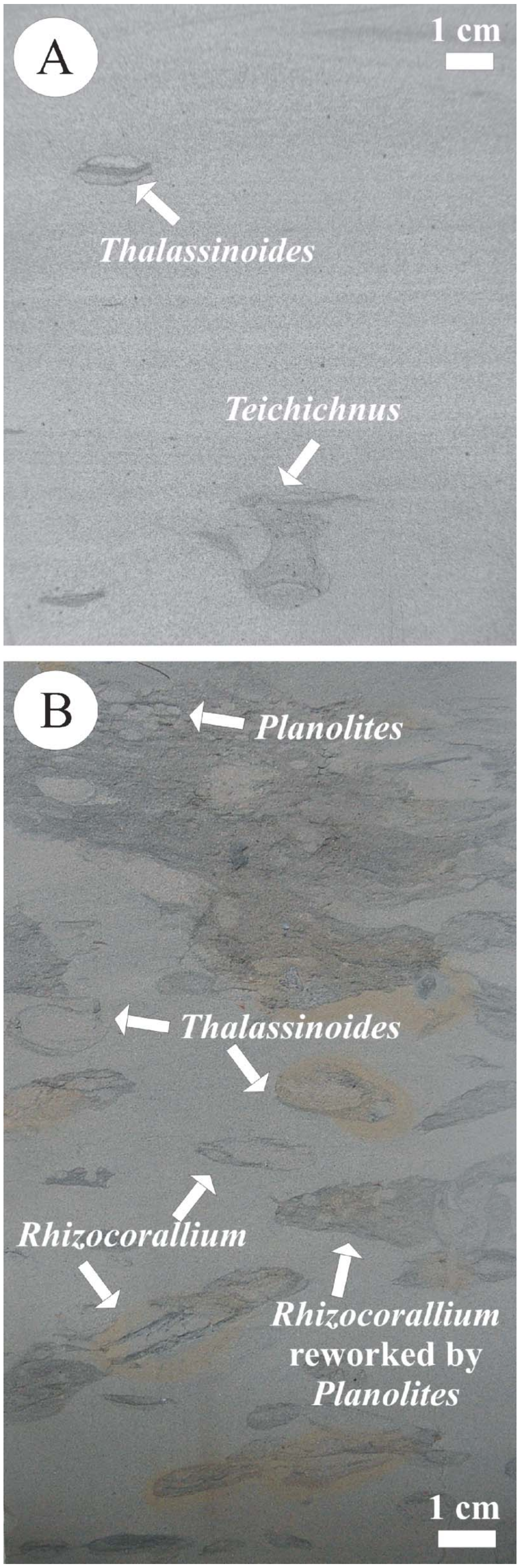


**FIGURE 7.** ***Thalassinoides-Teichichnus*** **ichnofabric in storm-influenced delta-front and prodelta deposits. (A) Sparsely bioturbated sandstone showing subtle hummocky cross-stratification. Protrusive** ***Teichichnus*** **and mud-lined** ***Thalassinoides*** **displaying infill with passive parallel lamination. (B) Moderately bioturbated sandstone showing an increase in bioturbation intensity toward the top. The fabric is dominated by** ***Thalassinoides*** **and** ***Rhizocorallium.*** ***Planolites*** **is concentrated either toward the top of the bed or inside** ***Rhizocorallium*** **burrows. Both photographs are from Estancia Agua Fresca well core EaAFa-3.**

### *Storm-influenced Delta Front and Prodelta*

#### *Description*

Sandy hyperpycnal lobe packages are locally interbedded and interfingered with silty very fine-grained sandstone with hummocky cross-stratification and combined flow-ripple cross-lamination and light gray mudstone. Sandstone beds are sharp and erosive based but have gradational tops. Hummocky sandstone may occur as 25- to 35-cm (9.8- to 13.8-in.)-thick discrete beds separated by 3- to 30-cm (1.9- to 11.8-in.)-thick mudstone-dominated units or amalgamated bedsets forming up to 1-m (0.39-in.)-thick packages. Thinner sandstone beds tend to form lenses. Syneresis cracks occur in the heterolithic intervals. These deposits occur in well cores EaAFa-3, EaAFa-4, and EaAFa-5 of the Agua Fresca field in the central-eastern zone of the study area.

#### *Ichnology*

Medium-bedded hummocky sandstone beds are either unburrowed or only bioturbated at the top, containing the *Thalassinoides*-*Teichichnus* ichnofabric (Figure 7; Table 1). *Thalassinoides*, *Teichichnus*, *Rhizocorallium*, *Skolithos*, *Planolites*, and *Asterosoma* are the most common ichnotaxa. *Thalassinoides* burrow segments are mostly horizontal and, less commonly, inclined. As in the case of the *Thalassinoides* ichnofabric of the sandy hyperpycnal lobe deposits, *Thalassinoides* has a mud lining and shows a laminated passive sandy fill. Locally, *Rhizocorallium* burrows are reworked by *Planolites*. The BI is 0–2 and, only locally, 3. The tiering structure is simple, showing the presence of both shallow- and deep-tier structures. *Asterosoma* and *Teichichnus* occupy shallow tiers, whereas *Ophiomorpha*, *Thalassinoides*, *Rhizocorallium*, *Planolites*, and

*Skolithos* are deep-tier structures. In terms of the ichnofacies model, the *Thalassinoides-Teichichnus* ichnofabric is included within a mixed *Skolithos-Cruziana* ichnofacies.

Mudstone intervals with thin layers of sandstone contain the *Terebellina-Phycosiphon* ichnofabric (Figure 8; Table 1). *Terebellina and Phycosiphon* are the dominant ichnotaxa. Subordinate components are *Planolites*, *Palaeophycus*, *Teichichnus*, *Thalassinoides*, *Zoophycos*, and *Schaubcylindrichnus*. Because it has been shown that the type specimen of *Terebellina* is a body fossil (Miller, 1995), the name is informally used to designate a trace fossil. *Phycosiphon* forms the background ichnofabric and is crosscut by the deeper tier structures, such as *Thalassinoides* and *Zoophycos*. *Terebellina* is easily visible because of its thick white wall. Degree of bioturbation in these deposits is highly variable, commonly 1–3, although some intervals may reach BIs of 4–5. Tiering structure is relatively well developed. Shallow-tier structures are *Terebellina*, *Planolites*, *Palaeophycus*, *Teichichnus*; the middle tier is occupied by *Schaubcylindrichnus* and *Phycosiphon*; and *Zoophycos* and *Thalassinoides* occupy the deep tier. The *Terebellina-Phycosiphon* ichnofabric illustrates the archetypal *Cruziana* ichnofacies.

### *Interpretation*

In contrast to the sandy hyperpycnal lobe intervals, these deposits display more abundant wave-generated structures, indicating that oscillatory flows were capable of reworking a substantial part of the material supplied by the distributary system. The lateral relationships between these deposits and the sand-rich hyperpycnal lobes suggest that oscillatory flows reworked the outer regions of the lobes. In addition, the vertical passage of hyperpycnal lobe deposits into intervals dominated by wave-reworked sandstone and suspension fallout mudstone indicates that basin processes were particularly effective during times of reduced sediment supply, when hypopycnal conditions were dominant. Although syneresis cracks are less common in this facies than in the hyperpycnal lobe deposits, their localized presence suggests that salinity fluctuations were important at times.

The *Thalassinoides-Teichichnus* ichnofabric records colonization of the wave-reworked sandstone units. As in the case of the *Thalassinoides* ichnofabric of the sandy hyperpycnal flow deposits, the laminated fill of the *Thalassinoides* burrows points to relatively high sedimentation rates. The low diversity of biogenic

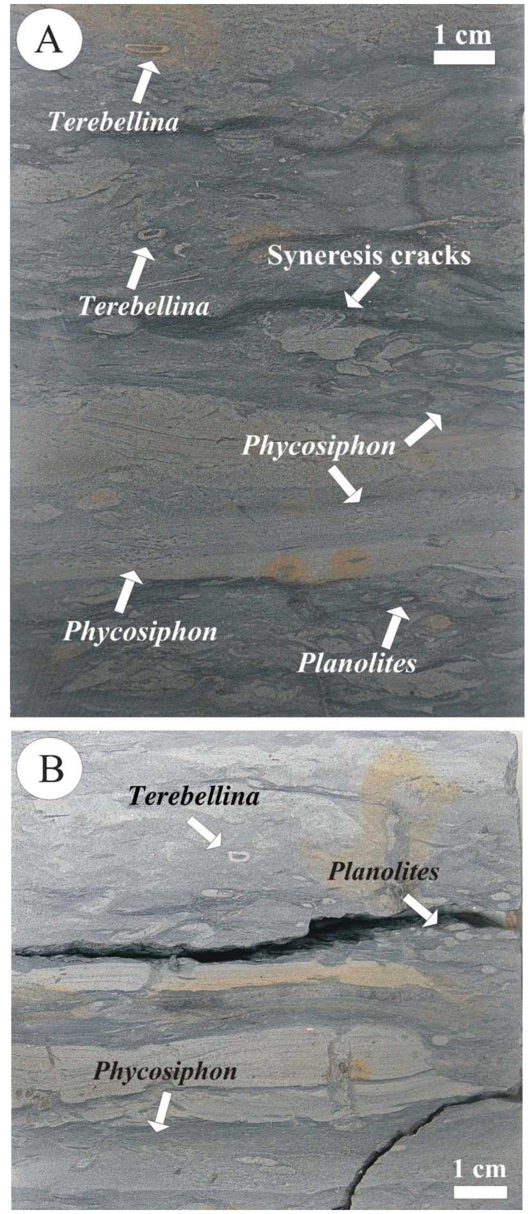


**FIGURE 8.** ***Terebellina-Phycosiphon*** **ichnofabric in storm-influenced delta-front and prodelta deposits. (A) Interbedded mudstone and combined flow-ripple cross-laminated sandstone. Fair-weather mudstone is intensely bioturbated, showing dominance of** ***Planolites*** **and** ***Terebellina*****. Interbedded sandstone shows locally preserved primary fabric and clusters of** ***Phycosiphon*****. Isolated and contorted sandstone lenses encased in mudstone may record biogenically reworked thin tempestites. Note associated syneresis cracks. (B) Interbedded mudstone and laterally discontinuous combined flow-ripple cross-laminated sandstone. Fair-weather mudstone is intensely bioturbated, showing dominance of** ***Planolites, Terebellina,*** **and clusters of** ***Phycosiphon*****. Both photos are from Estancia Agua Fresca well core EaAFa-3.**

structures and simple tiering structures are also indicative of stress conditions, most likely associated with freshets. However, the increase in degree of bioturbation indicates alternation of times of environmental stability, particularly during times of reduced sediment discharge.

The *Terebellina-Phycosiphon* ichnofabric indicates bioturbation during times of moderate- to low-energy conditions. The dominance of deposit-feeding structures, the locally high degree of bioturbation, the more complex tiering structure, and the increase in ichnodiversity levels point to a relatively stable setting and long-term colonization windows. In any case, trace fossil diversity is lower than in coeval open-marine deposits, total homogenization of the background fines is rarely attained, and syneresis cracks are locally present, suggesting that freshwater discharge was a controlling factor during deposition. An additional stress factor was represented by storms that caused repeated wave erosion of the substrate affecting the benthic fauna (e.g., Pemberton and Frey, 1984; Pemberton and MacEachern, 1997; Buatois et al., 2008).

With respect to water depth, these deposits were most likely emplaced similar to slightly deeper bathymetric zones than the sand-rich hyperpycnal lobes. Deposition well above storm-wave base is suggested by the widespread presence of wave-generated structures. As in the case of the hyperpycnal lobes, intercalation of mudstone intervals indicates alternation of low-energy conditions, suggesting that for the most part, deposition occurred below fair-weather wave base. In short, deposition in a storm-dominated distal delta front to proximal prodelta is the most likely environmental scenario.

## Lower Offshore

### Description

Lower offshore deposits are represented by intensely bioturbated mudstone forming a 6-m (19.7-ft)-thick interval. No physical sedimentary structures are preserved, and syneresis cracks were not observed. This facies has been observed in the PP'36 well core in the Puesto Peter zone, southwest corner of the study area.

### Ichnology

Primary sedimentary fabric has been totally obliterated by bioturbation. These deposits are characterized by the *Teichichnus-Phycosiphon* ichnofabric (Figure 9; Table 1), with these two ichnotaxa being the dominant components. The BI is 6. In contrast to ichnofabrics of the sandy hyperpycnal lobe deposits and the storm-influenced delta-front and prodelta deposits, this ichnofabric exhibits a complex tiering structure. The shallowest tier consists of an indistinct mottling that represents the background ichnofabric, reflecting emplacement in the water-saturated soupy substrate of the mixed zone. Shallow-tier structures (but deeper into the substrate than the mottling) are *Thalassinoides*, *Phycosiphon*, and *Zoophycos*. *Phycosiphon* tends to evenly cover the sediment, whereas *Thalassinoides* and *Zoophycos* show a patchy distribution. Midtier levels are represented by *Asterosoma*, *Planolites*, and *Terebellina*. The deep tier is occupied by *Chondrites*, *Teichichnus*, and another generation of *Thalassinoides*. In particular, the well-defined morphology and sharp burrow margins of *Teichichnus* and the absence of other trace fossils crosscutting this spreiten burrow indicate emplacement in deep and cohesive sediment zones. This ichnofabric is placed within a distal *Cruziana* ichnofacies.

### Interpretation

The intense bioturbation and the fine grain size indicate slow suspension fallout sedimentation under low-energy conditions well below the fair-weather wave base. If storm deposits were emplaced, these may have been totally reworked by biogenic activity. The dominance of deposit-feeding structures, the intense bioturbation, the highly complex tiering structure, the dominance of climax population strategies, and the high trace fossil diversity indicate a stable setting and long-term colonization windows. Ichnologic data suggest deposition under fully marine conditions; this is also supported by the absence of syneresis cracks. The high ichnodiversity and intense bioturbation indicate well-oxygenated bottom and interstitial waters.

Sedimentologic and ichnologic features indicate deposition in a lower offshore environment. The lack of stress factors and overall environmental stability indicate that sedimentation occurred far beyond the area of influence of hyperpycnal flows.

# DISCUSSION

The studied succession is interpreted as formed in a shallow-marine setting affected by sustained turbulent flows linked to a coeval fluvial distributary system and reworked by wave action. The fluvial-deltaic system was sourced from uplifted areas in Central

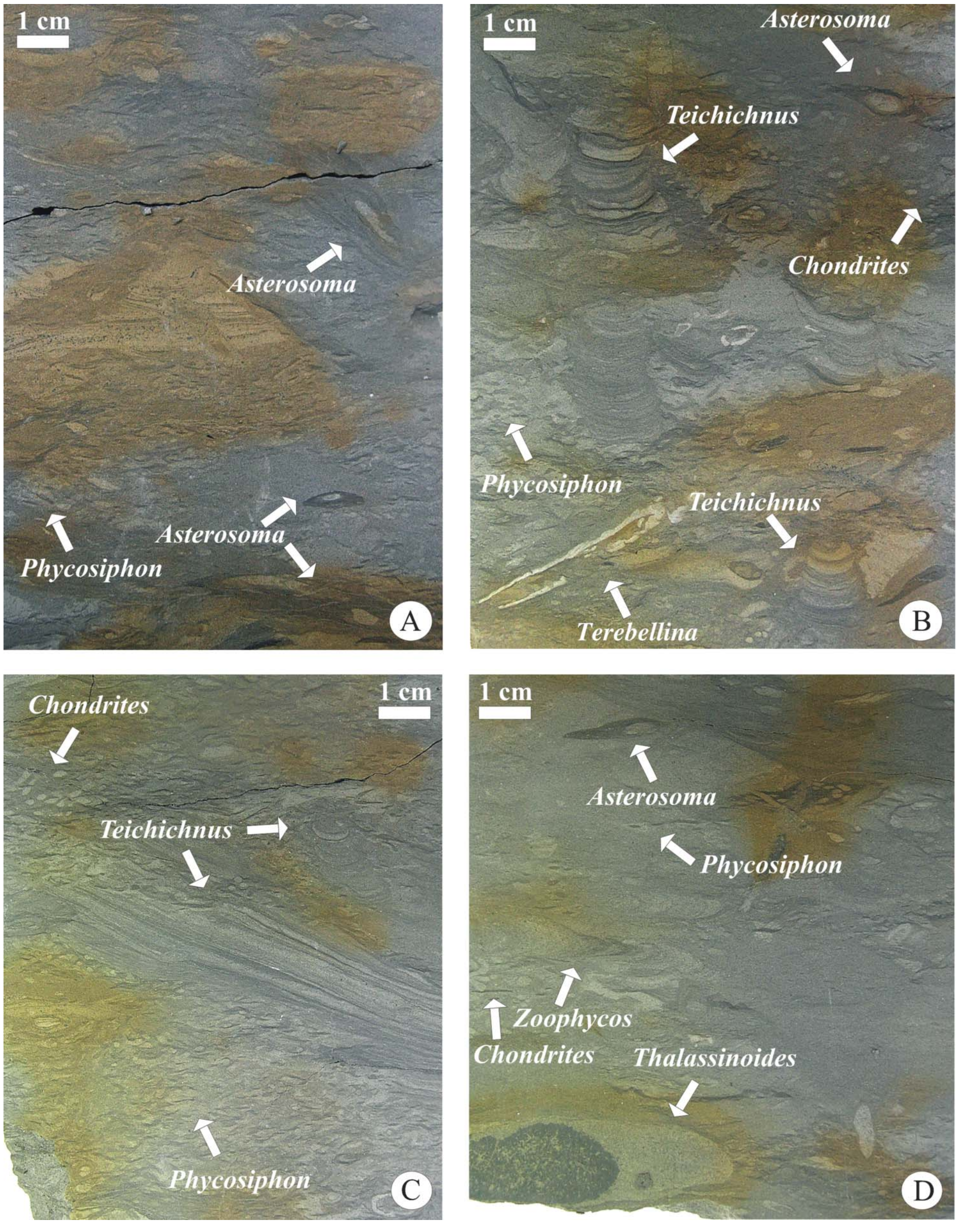


**FIGURE 9.** ***Teichichnus-Phycosiphon*** **ichnofabric in intensely bioturbated lower offshore mudstone. (A) Evenly distributed** ***Phycosiphon*** **crosscut by** ***Asterosoma*****. (B) Evenly distributed** ***Phycosiphon*** **crosscut by** ***Asterosoma*****,** ***Chondrites*****, and deep** ***Teichichnus*****. Note thick wall in** ***Terebellina*****. (C) Evenly distributed** ***Phycosiphon*** **crosscut by** ***Chondrites*** **and** ***Teichichnus*****. Note longitudinal view of** ***Teichichnus*** **spreiten that may be confused with primary sedimentary lamination. (D) Poorly preserved** ***Phycosiphon*** **intensely reworked by** ***Zoophycos*****,** ***Asterosoma*****,** ***Chondrites*****, and** ***Thalassinoides*****. All photographs are from Puesto Peter well core PP'36.**

Patagonia and the Río Chico High, was located northwest of the study area, and prograded toward the south and southeast (Figure 10). Extensive sand-rich lobes were formed in the Agua Fresca, La Paz, and Laguna del Oro fields. Deposits accumulated forming lobes that filled topographic lows, occasionally allowing the bypass of sand-rich flows into more distal areas of the Boleadoras field. Material supplied by the distributary system was reworked by wave action along the fringes of the deltaic lobe and during times of quiescence between hyperpycnal flows. Wave reworking of hyperpycnal flow deposits has been documented in both modern (e.g., Wright et al., 1988) and ancient (e.g., Pattison, 2005a, b) deposits. Toward the south in the Puesto Peter area, offshore environments were formed under fully marine conditions (Figure 10).

Integration of sedimentologic and ichnologic data allows establishing proximal-distal trends within a sediment transport system (Figure 11). High rates of sedimentation and freshwater discharge from a prograding river-dominated delta were among the most important stress factors that affected the benthic fauna. The *Thalassinoides* ichnofabric records opportunistic colonization of sand-rich hyperpycnal flow deposits in lobes emplaced in the distal delta front and the proximal prodelta. The *Planolites-Teichichnus* ichnofabric occurs in associated finer grained distal delta-front and proximal prodelta deposits that were formed lateral to the hyperpycnal sand-rich lobes

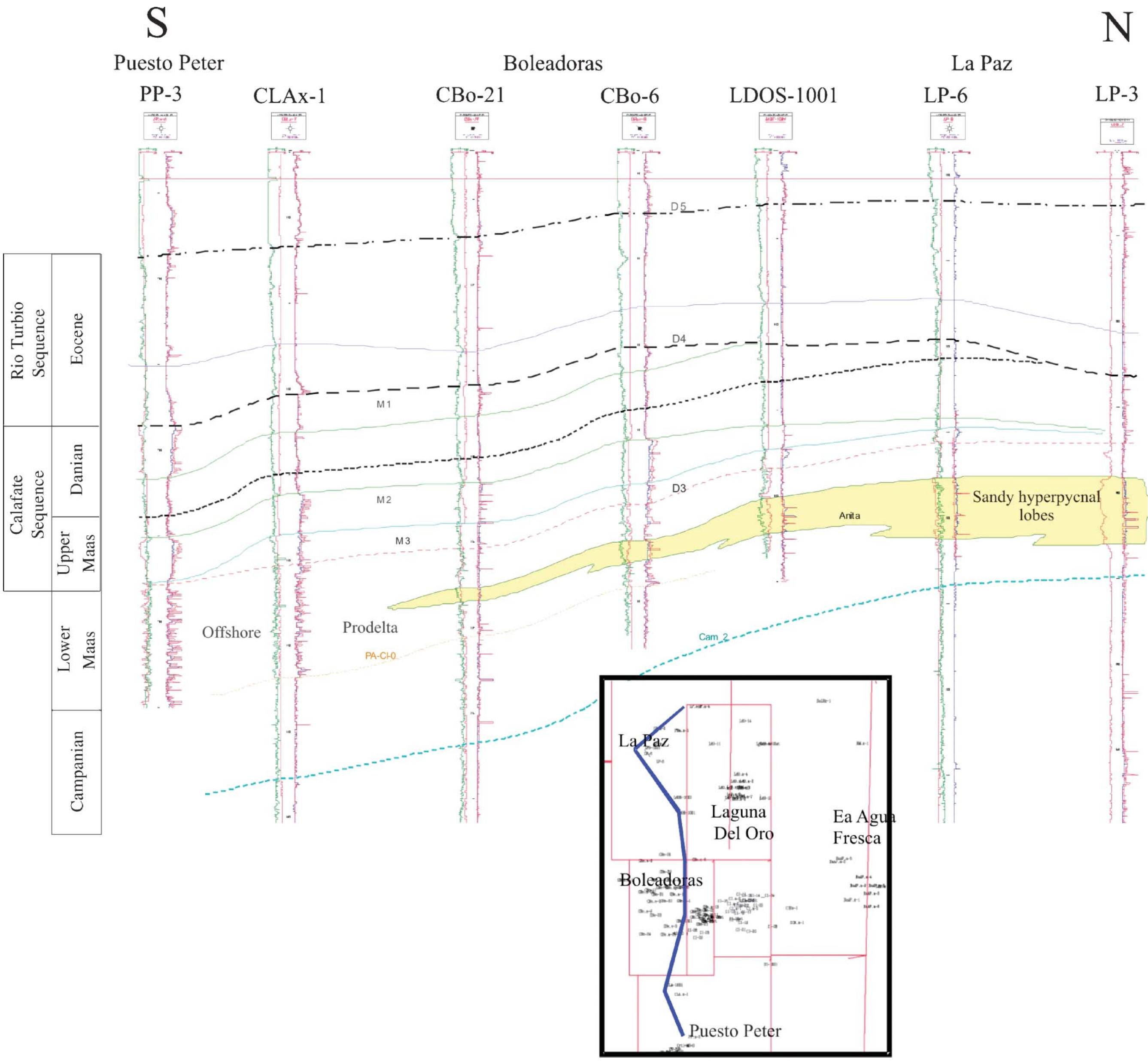


**FIGURE 10.** South-north cross section showing progradation toward the south. Extensive sand-rich lobes were formed in the La Paz field, whereas bypass sand-rich channels occurred toward the Boleadoras field. Toward the south in the Puesto Peter area, offshore deposits are predominant. Maas = Maastrichtian; Ea = Estancia; M = Magallanes; D3–D5 = unconformities; PP-3, CLAx-1, Cbo-21, CB0-6, LDOS-1001, LP-6, LP-3 = wells.

and during times of quiescence between flows by suspension fallout. The *Thalassinoides-Teichichnus* ichnofabric represents colonization of wave-reworked sandstone lobes. The *Terebellina-Phycosiphon* assemblage reflects stable conditions that allowed intense bioturbation and the establishment of a moderately diverse benthic fauna. During times of reduced sediment supply, material was reworked by wave processes and hypopycnal conditions were dominant. Finally, the *Teichichnus-Phycosiphon* ichnofabric represents intense bioturbation of lower offshore deposits.

Ichnofabrics vary along the sediment transport pathway and in times of dominance of hyperpycnal or hypopycnal conditions in response to a gradient in stress factors. Proximal positions and times of hyperpycnal conditions are characterized by rapid sedimentation and freshwater discharge. Distal positions and times of hypopycnal conditions are characterized by reduced sedimentation rates and normal salinity. Colonization windows were short-term in proximal positions and during times of hyperpycnal flows and long-term in distal positions and during

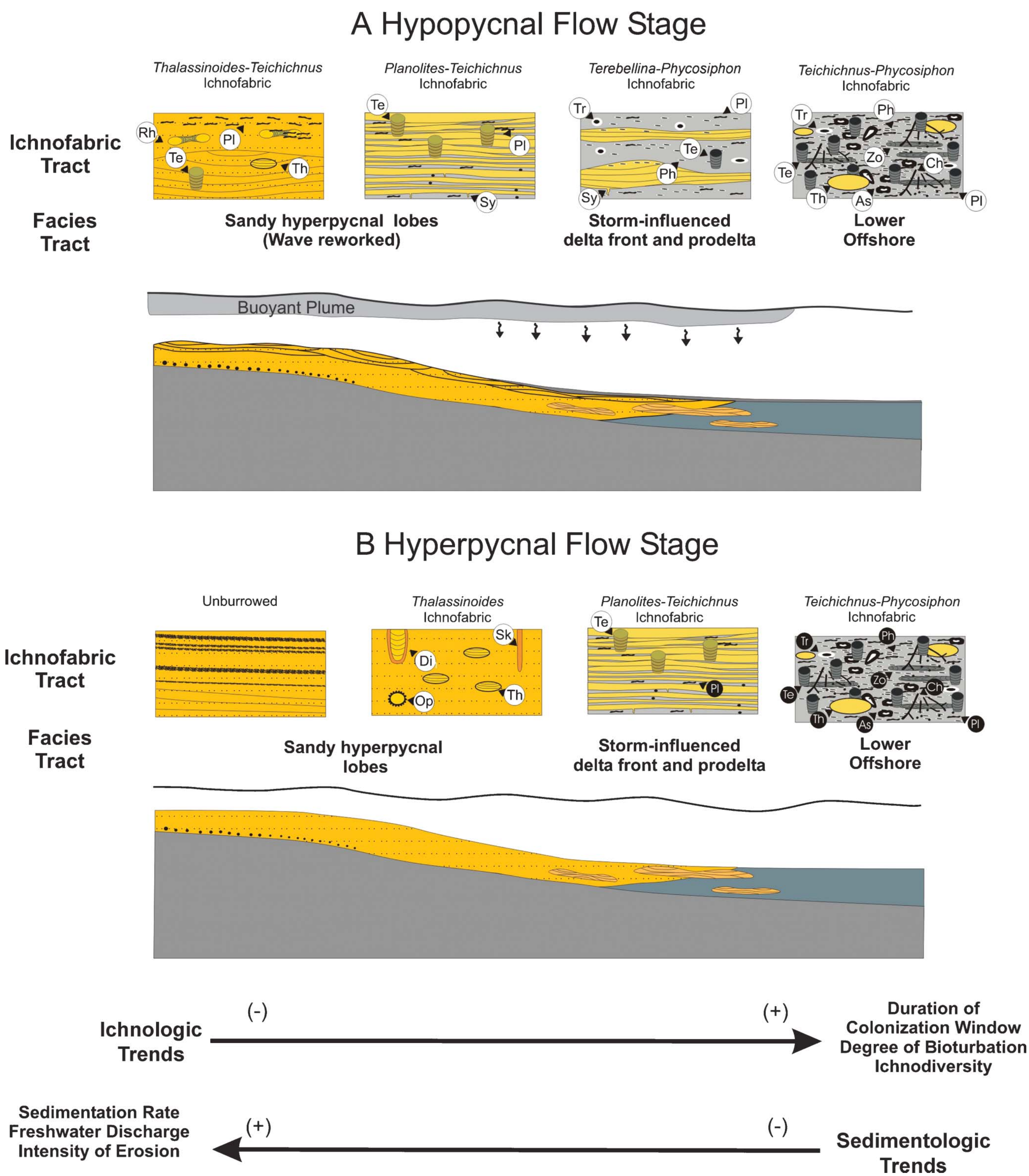


**FIGURE 11.** Paleoenvironmental distribution of the ichnofabrics and associated ichnologic and sedimentologic trends. Although the diagram illustrates proximal-distal relationships, these may also be understood not as simple bathymetric trends, but as radial trends from the inner zone to the margins of the lobe. Representative ichnogenera in the studied ichnofabrics include *Asterosoma* (As), *Chondrites* (Ch), *Diplocraterion* (Di), *Ophiomorpha* (Op), *Phycosiphon* (Ph), *Planolites* (Pl), *Rhizocorallium* (Rh), *Skolithos* (Sk), *Teichichnus* (Te), *Terebellina* (Tr), *Thalassinoides* (Th), and *Zoophycos* (Zo). Syneresis cracks (Sy) are commonly associated with the *Planolites-Teichichnus* and *Terebellina-Phycosiphon* ichnofabrics.

times of hypopycnal conditions. An increase in trace fossil diversity, intensity of bioturbation, tiering structure complexity, dominance of climax strategies, and dominance of deposit-feeding strategies is displayed along the transport pathway and as a response to the transition from hyperpycnal to hypopycnal conditions.

Freshwater discharge was conducive to limited biogenic activity, resulting in reduced trace fossil diversity and sparse bioturbation (e.g., Bhattacharya and MacEachern, 2009). High sedimentation rates also decrease animal activity. The laminated fill of *Thalassinoides* burrows is suggestive of rapid suspension fallout of fine-grained material. Phytodetrital pulses are evident in the sandy hyperpycnal lobes, as revealed by the high concentration of particulate plant fragments along bedding planes. In turn, phytodetrital pulses are linked to oxidation of organic carbon and oxygen depletion (MacEachern et al., 2005). However, in the Magallanes Formation, phytodetrital pulses did not seem to have been associated with oxygen depletion. This may have resulted from wave agitation in sand-rich lobes, which allowed the persistence of oxygenated bottom and interstitial waters. In addition to freshwater discharge, water turbidity represents another stress factor in river-dominated deltas. Deltas developed under hypopycnal conditions are commonly characterized by a buoyant plume leading to rapid flocculation of clays (Bates, 1953; Wright, 1977; Kineke et al., 1996). High suspended loads of fine-grained material related to river influx clog the filter-feeding apparatus of suspension feeders, therefore resulting in an impoverishment or direct suppression of the *Skolithos* ichnofacies (Gingras et al., 1998; MacEachern et al., 2005). In addition, accumulation of fluid muds in the distal delta-front and prodelta environment reduces boundary shear stress, preventing benthic organisms from constructing permanent structures or actively backfilling tunnels (Bhattacharya and MacEachern, 2009). Both buoyant plumes and fluid muds apparently were not important limiting factors in the present case. However, the sandy substrate of the hyperpycnal lobes seems to have been rich in water and very soft, as revealed by the extreme compaction of *Thalassinoides* burrows.

## CONCLUSIONS

1) Integration of sedimentologic and ichnologic data allows a more detailed characterization of the sedimentary facies and depositional dynamics of a river-dominated delta characterized by hyperpycnal flows. Five ichnofabrics have been defined in subsurface deposits of the upper Cretaceous Magallanes Formation.
2) The *Thalassinoides* ichnofabric records opportunistic colonization of sand-rich hyperpycnal lobes emplaced in the distal delta front and the proximal prodelta. The *Planolites-Teichichnus* ichnofabric occurs in associated finer grained deposits that were formed lateral to the hyperpycnal sand-rich lobes and during times of quiescence between flows by suspension fallout.
3) The *Thalassinoides-Teichichnus* ichnofabric represents colonization of wave-reworked sandstone lobes. The *Terebellina-Phycosiphon* assemblage reflects stable conditions that allowed intense bioturbation and the establishment of a moderately diverse benthic fauna. During times of reduced sediment supply, material was reworked by wave processes and hypopycnal conditions were dominant.
4) The *Teichichnus-Phycosiphon* ichnofabric represents intense bioturbation of lower offshore deposits. High ichnodiversity and intense bioturbation indicate normal marine salinity and well-oxygenated bottom and interstitial waters.
5) Ichnofabrics vary along the sediment transport pathway and in times of dominance of hyperpycnal or hypopycnal conditions in response to a gradient in stress factors. Colonization windows were short-term in proximal positions and during times of hyperpycnal flows and long-term in distal positions and during times of hypopycnal conditions. An increase in ichnodiversity, intensity of bioturbation, tiering structure complexity, dominance of climax strategies, and dominance of deposit-feeding strategies is displayed along the transport pathway and as a response to the transition from hyperpycnal to hypopycnal conditions.

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## REFERENCES CITED


Bates, C. C., 1953, Rational theory of delta formation: AAPG Bulletin, v. 37, p. 2119–2162.

Bhattacharya, J. P., 2006, Deltas, *in* H. Posamentier and R. G. Walker, eds., Facies models revisited: SEPM Special Publication 84, p. 237–292.

Bhattacharya, J. P., and J. A. MacEachern, 2009, Hyperpycnal rivers and prodeltaic shelves in the Cretaceous seaway of North America: Journal of Sedimentary Research, v. 79, p. 184–209, doi:10.2110/jsr.2009.026.

Biddle, K. T., M. A. Uliana, R. M. Mitchum, M. G. Fitzgerald, and R. C. Wright, 1986, The stratigraphic and structural evolution of the central and eastern Magallanes Basin, southern South America, *in* P. A. Allen and P. Homewood, eds., Foreland basins: International Association of Sedimentologists Special Publication 8, p. 41–61.

Buatois, L. A., N. Santiago, K. Parra, and R. Steel, 2008, Animal-substrate interactions in an Early Miocene wave-dominated tropical delta: Delineating environmental stresses and depositional dynamics (Tácata field, Eastern Venezuela): Journal of Sedimentary Research, v. 78, p. 458–479, doi:10.2110/jsr.2008.053.

Carmona, N. B., and J. J. Ponce, 2011, Ichnology and sedimentology of Miocene hyperpycnites of the Austral foreland basin (Tierra del Fuego, Argentina): Trace fossil distribution and paleoecological implications: *in* R. M. Slatt and C. Zavalla, eds., Sediment transfer from shelf to deep water—Revisiting the delivery system: AAPG Studies in Geology 61, p. 171–192.

Cheel, R. J., and D. A. Leckie, 1993, Hummocky cross-stratification: Sedimentology Review, v. 1, p. 103–122.

Donovan, R. N., and R. J. Foster, 1972, Subaqueous shrinkage cracks from the Caithness Flagstone Series (Middle Devonian) of Northeast Scotland: Journal of Sedimentary Petrology, v. 42, p. 309–317.

Foster, W. R., J. G. Savings, and J. M. Waite, 1955, Lattice expansion and rheological behavior relationships in water-montmorillonite systems: Proceedings of the Third National Conference on Clays and Clay Minerals: National Academy of Sciences, National Research Council Publication, v. 395, p. 296–316.

Gingras, M. K., J. A. MacEachern, and S. G. Pemberton, 1998, A comparative analysis of the ichnology of wave and river-dominated allomembers of the upper Cretaceous Dunvengan Formation: Bulletin of Canadian Petroleum Geology, v. 46, p. 51–73.

Keeley, M. L., and M. P. R. Light, 2008, Basin evolution and prospectivity of the Argentine continental margin: Journal of Petroleum Geology, v. 16, p. 451–464, doi:10.1111/j.1747-5457.1993.tb00352.x.

Kineke, G. C., R. W. Sternberg, J. H. Trowbridge, and W. R. Geyer, 1996, Fluid mud processes on the Amazon continental shelf: Continental Shelf Research, v. 16, p. 667–697, doi:10.1016/0278-4343(95)00050-X.

Lamb, M. P., P. M. Myrow, C. Lukens, K. Houck, and J. Strauss, 2008, Deposits from wave-influenced turbidity currents: Pennsylvanian Minturn Formation, Colorado: Journal of Sedimentary Research, v. 78, p. 480–498, doi:10.2110/jsr.2008.052.

MacEachern, J. A., B. A. Zaitlin, and S. G. Pemberton, 1999, A sharp-based sandstone of the Viking Formation, Joffre field, Alberta, Canada, criteria for recognition of transgressively incised shoreface complexes: Journal of Sedimentary Research, Section B, Stratigraphy and Global Studies, v. 69, p. 876–892.

MacEachern, J. A., K. L. Bann, J. P. Bhattacharya, and C. D. Howell Jr., 2005, Ichnology of deltas: Organism responses to the dynamic interplay of rivers, waves, storms, and tides, *in* L. Giosan and J. P. Bhattacharya, eds., River deltas: Concepts, models and examples: SEPM Special Publication 83, p. 49–85.

McIlroy, D., 2004, Some ichnological concepts, methodologies, applications and frontiers, *in* D. McIlroy, ed., The application of ichnology to paleoenvironmental and stratigraphic analysis: Geological Society (London) Special Publication 228, p. 3–27.

Miller, W. III., 1995, *Terebellina*; (= *Schaubcylindrichnus freyi* ichnosp. nov.) in Pleistocene outer-shelf mudrocks of northern California: Ichnos, v. 4, p. 141–149.

Mulder, T., and J. P. M. Syvitski, 1995, Turbidity currents generated at river mouths during exceptional discharges to the world oceans: Journal of Geology, v. 103, p. 285–299, doi:10.1086/629747.

Mulder, T., J. P. M. Syvitski, S. Migeon, J.-C. Faugères, and B. Savoye, 2003, Marine hyperpycnal flows: Initiation, behavior and related deposits—A review: Marine and Petroleum Geology, v. 20, p. 861–882, doi:10.1016/j.marpetgeo.2003.01.003.

Pattison, S. A. J., 2005a, Storm-influenced prodelta turbidite complex in the lower Kenilworth Member at Hatch Mesa, Book Cliffs, Utah: Implications for shallow marine facies models: Journal of Sedimentary Research, v. 75, p. 420–439, doi:10.2110/jsr.2005.033.

Pattison, S. A. J., 2005b, Isolated highstand shelf sandstone body of turbiditic origin, lower Kenilworth member, Cretaceous Western Interior, Book Cliffs, Utah: Sedimentary Geology, v. 177, p. 131–144, doi:10.1016/j.sedgeo.2005.02.005.

Pemberton, S. G., and R. W. Frey, 1984, Ichnology of storm-influenced shallow marine sequence, Cardium Formation (upper Cretaceous) at Seebe, Alberta, *in* D. F. Stott and D. J. Glass, eds., The Mesozoic of middle North America: Canadian Society of Petroleum Geologists Memoir 9, p. 281–304.

Pemberton, S. G., and J. A. MacEachern, 1997, The ichnological signature of storm deposits, the use of trace fossils in event stratigraphy, *in* C. E. Brett and G. C. Baird, eds., Paleontological events, stratigraphic, ecological and evolutionary implications: New York, New York, Columbia University Press, p. 73–109.

Plink-Björklund, P., and R. Steel, 2004, Initiation of turbidity currents: Outcrop evidence for Eocene hyperpycnal flow turbidites: Sedimentary Geology, v. 165, p. 29–52, doi:10.1016/j.sedgeo.2003.10.013.

Ponce, J. J., E. B. Olivero, D. R. Martinioni, and M. I. López Cabrera, 2007, Sustained and episodic gravity flow deposits and related bioturbation patterns in Paleogene turbidites (Tierra del Fuego, Argentina), *in* R. G. Bromley, L. A. Buatois, M. G. Mángano, J. F. Genise, and R. N. Melchor, eds., Sediment-organism interactions: A multifaceted ichnology: SEPM Special Publication 88, p. 253–266.

Soyinka, O., and R. M. Slatt, 2008, Identification and micro-stratigraphy of hyperpycnites and turbidites in Cretaceous Lewis Shale, Wyoming: Sedimentology, v. 55, p. 1117–1133, doi:10.1111/j.1365-3091.2007.00938.x.

Taylor, A., and R. Goldring, 1993, Description and analysis of bioturbation and ichnofabric: Journal of the Geological Society, v. 150, p. 141–148, doi:10.1144/gsjgs.150.1.0141.

Wetzel, A., 2008, Recent bioturbation in the deep South China Sea: A uniformitarian ichnologic approach: Palaios, v. 23, p. 601–615, doi:10.2110/palo.2007.p07-096r.

Wright, L. D., 1977, Sediment transport and deposition at river mouths: A synthesis: Bulletin of the Geological Society of America, v. 88, p. 857–868, doi:10.1130/0016-7606(1977)88<857:STADAR>2.0.CO;2.

Wright, L. D., W. J. Wiseman, B. D. Bornhold, D. B. Prior, J. N. Suhayda, G. H. Keller, Z.-S. Yang, and Y. B. Fan, 1988, Marine dispersal and deposition of Yellow River silts by gravity-driven underflows: Nature, v. 332, p. 629–632, doi:10.1038/332629a0.

Zavala, C., J. Ponce, M. Arcuri, D. Drittanti, H. Freije, and M. Asensio, 2006, Ancient lacustrine hyperpycnites: A depositional model from a case study in the Rayoso Formation (Cretaceous) of west-central Argentina: Journal of Sedimentary Research, v. 76, p. 40–58.