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First evidence of marine influence in the Cretaceous of the Amazonas Basin, Brazil

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Abstract

An integrated investigation emphasizing sedimentological and ichnological studies of Cretaceous deposits of the Alter do Chão Formation, exposed in the western Amazonas Basin, was undertaken with the aim of determining depositional environments. Four facies associations attributed to upper shoreface, foreshore, delta mouth bar, and lower/middle shoreface-prodelta depositional environments are recognized. The upper shoreface deposits were deposited by storm flows. They are interbedded with highly bioturbated sandstones displaying *Thalassinoides, Planolites* and *Diplocraterion* traces. The foreshore deposits, which are coarser-grained than the shoreface strata, are characterized by tabular sandstones displaying planar or trough cross-lamination/stratification, wavy/flaser lamination, and parallel lamination. These strata also contain an abundance of trace fossils. The delta mouth bar deposits comprise upward-coarsening beds displaying a lobed geometry. The lower/middle shoreface-prodelta settings consist of well-stratified, very fine-grained sandstones and mudstones deposited mostly by storm action. A wave-dominated delta system that prograded into a marine-influenced basin is supported for the study area. Therefore, in contrast to previous interpretations, it seems that a widespread Cretaceous transgression resulted in the submergence of large continental areas in the north of Brazil, affecting sediment deposition even in the innermost portions of the intracratonic Amazonas Basin.

Keywords: Cretaceous; Amazonas Basin; Marine influence; Sedimentary facies; Ichnology

1. Introduction

The distinction between open marine and continental strata in the geological record is, in general, straightforward, but the recognition of transitional depositional settings can be problematic because they produce sediments formed by a mixture of marine and non-marine processes. Interpretations are particularly problematic in successions that lack fossils, analysis of the depositional setting having to rely solely on an understanding of the physical sedimentary structures. Many papers published in recent years have contributed to our knowledge of the sedimentary imprint of marine processes, particularly involving tidal currents and storm waves (e.g., Boersma and Terwindt, 1981; Dott and Bourgeois, 1982; Walker, 1984; Yang and Nio, 1985; McCrory and Walker, 1986; Arnott and Southard, 1990; Leckie and Singh, 1991; Nio and Yang, 1991; Shanley et al., 1992; Arnott, 1992, 1993; Cheel and Middleton, 1993; Hadley and Elliot, 1993; Amos et al., 1996). As a result, many deposits recorded in the literature previously as continental may be partly of marine origin.

The sedimentological criteria that aid recognition of tidal and storm deposits have helped to provide new interpretations of many Cretaceous deposits exposed in the north Brazilian marginal basins, which are dominated by transitional marine deposits. Hence, a number of studies undertaken during the past ten years on exposures of Albian–Cenomanian rocks of the São Luís-Grajaú and Cametá (Marajó Graben System) basins, have demonstrated the significance of tidal currents and storm waves as dominant depositional agents, even in southernmost

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areas at the basin margins, located several hundreds of kilometres from the modern coastline (e.g., Rossetti, 1998; Rossetti et al., 2000; Rossetti and Santos Jr., 2003; Rossetti and Góes, 2004). They have shown that shallow-marine to transitional environments were extensive as a result of widespread marine incursions throughout these basins, in contrast to previous suggestions of an entirely continental origin (e.g., Petri and Fúlfaro, 1983). Transgressions of such magnitude should have had an influence on adjacent regions to the west in the intracratonic Amazonas Basin, which has been of low overall relief since at least the Cretaceous Period. However, no marine or marginal marine sediments have been recorded previously from the Cretaceous of this basin. The 500-m-thick Alter do Chão Formation is composed of siliciclastic red beds (sandstones and mudstones) that have been interpreted as continental in origin (e.g., Daemon, 1975; Dino et al., 1999), but a lack of widespread fossil collecting and sedimentological studies has precluded full recognition of the sedimentary processes that led to its development.

This paper provides a detailed description of the sedimentary features preserved in the Alter do Chão Formation where it crops out along the left side of the Amazonas River near Careiro Island, about 50 km to the east of Manaus, in the middle of the Amazonas Basin (Fig. 1). Our investigation has revealed a set of exposures with well-preserved physical and biogenic structures, allowing detailed interpretations of their mode of origin. Hitherto, studies of this nature had not been carried out on the formation, our knowledge of it having had to rely mostly on regional geological studies. In this paper, we integrate sedimentological and ichnological interpretations and conclude from these that the formation is not entirely continental in origin, features suggesting marine influence being abundant throughout the exposures. Our data lead us to suggest that Cretaceous transgressions might have been much more widespread in Brazilian territory than previously thought, resulting in the submergence of large continental areas, even within intracratonic basins.

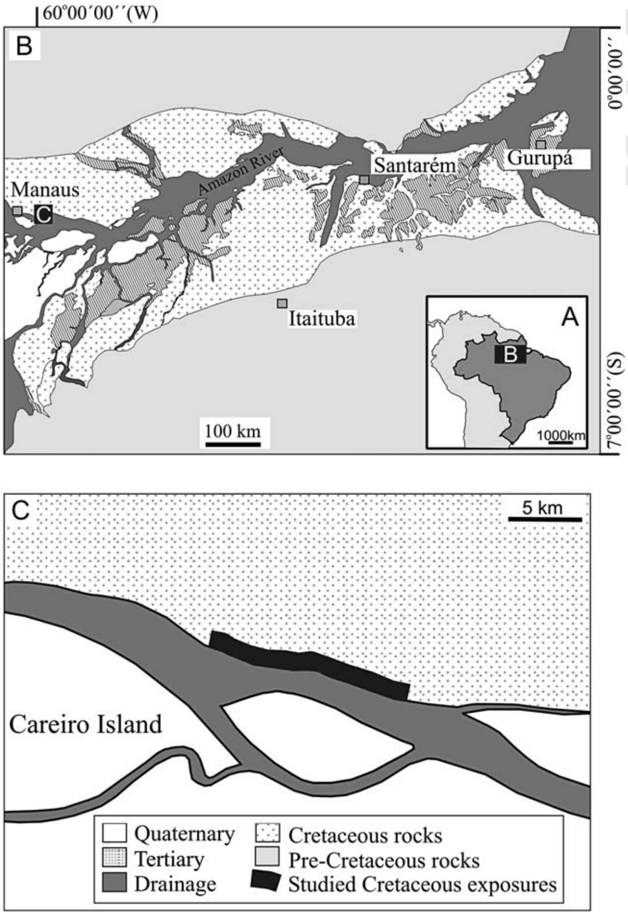


Fig. 1. A–C, location maps of the study area in Amazonas State, northern Brazil; the band of exposures of Cretaceous rocks along the riverbank to the north of the Careiro Island is shown in C.

2. Geological framework

The Amazonas Basin covers an area of up to 500,000 km^2, and is bounded by the Purus and Gurupá arcs to the west and east, which separate this basin from the Solimões and Marajó basins, respectively. It is limited to the north by the Guiana Shield and to the south by the Brazilian Shield. The basement comprises igneous, metamorphic and volcano-sedimentary rocks of the Maroni-Itacaiunas and Amazônia Central provinces, which correspond to the oldest rocks of the Amazon Craton (Teixeira et al., 1989; Tassinari and Macambira, 1999; Tassinari et al., 2000). Near the Purus Arch, this basin is underlain by Proterozoic sedimentary rocks belonging to the Purus Group (Eiras et al., 1993).

The structure of the Amazonas Basin is defined by an east–west and a southwest–northeast orientated central trough, bounded by two platforms located to the north and south. Its origin is related to a rifting event controlled by Early Paleozoic intraplate extension. As the rift evolved, four main phases of deposition took place, which alternated with periods of thermal subsidence. The main trough, where the depocenter is located, contains four sedimentary successions, collectively up to 6500 m thick, which developed during the Ordovician–Early Devonian, Devonian–Early Carboniferous, Middle Carboniferous–Permian and Mesozoic–Cenozoic. The last succession is up to 500 m thick, and consists of the Javari Group (Cunha et al., 1994; Eiras et al., 1994), formed due to east–west extension associated with both the evolution of the South Atlantic Ocean and the Andean Cordillera. The Alter do Chão Formation, the subject of this paper, records the Cretaceous sedimentation of this group. Defined for the first time by Kistler (1954), it comprises red-coloured sandstones, mudstones, conglomerates and intraformational breccias, traditionally attributed to high-energy, westward-flowing fluvial and lacustrine/deltaic systems (Daemon, 1975). Its Cretaceous age was first suggested on the basis of therapod teeth (Price, 1960), with later papers considering it as Cenomanian–Maastrichtian (Daemon and Contreras, 1971), and middle Albian–Turonian (Daemon, 1975). Subsurface information (e-logs and a few cores) from areas located a few kilometres from the localities reported here led to the recognition of two sedimentary successions within the formation: an upper Aptian/lower Albian meandering to anastomosed fluvial and eolian unit; and an upper Cenomanian fluvio-deltaic unit (Dino et al., 1999), the latter including the deposits described here.

3. Sedimentological and ichnological descriptions

The Alter do Chão Formation is exposed in the study area along a series of riverbanks that are up to 20 m high and, in general, several tens of metres long. Despite their discontinuous nature, which makes stratigraphic correlation difficult, these deposits display several internal features that provide good insights into the depositional processes. Furthermore, the strata are sufficiently well exposed and well preserved in the lower and middle reaches of the sections to provide information on facies relationships and, in some cases, geometry, thus allowing discussions of the depositional environment. Unfortunately, micropaleontological and palynological data that could help with the interpretation of the depositional setting are unavailable, but an abundance of ichnofauna aids discussion of the depositional processes and environments.

The deposits studied are typically red beds that are bounded at the top by a discontinuity surface with a mottled soil horizon that locally displays lateritic concretions. This surface is overlain by yellowish, fine- to coarse-grained friable sands, tentatively attributed to the Plio-Pleistocene Post-Barreiras sediments by comparison with similar deposits exposed in northeastern Amazonia (e.g., Rossetti et al., 1989; Rossetti and Góes, 2001). The exposures of the Alter do Chão Formation consist of moderately to well-sorted, fine- to coarse-grained, and locally conglomeratic, sandstones that are interbedded with thin layers of mudstones. A variety of sedimentary structures characterize the sandstones that, for descriptive purposes, can be regarded as 12 facies (Table 1). The mudstones are less variable, consisting of two sedimentary facies. The sandstones and mudstones can be organized into four facies associations, described below and summarized in Table 2. Facies associations A, B and D are widespread throughout the study area, while facies association C occurs only in the northwestern part, conformably overlying the other deposits.

3.1. Facies association A

These deposits (Fig. 2A–H) consist entirely of white to yellowish and light purple/red, very fine- to fine-grained sandstones that occur as a series of laterally continuous, tabular beds up to 3 m thick, with the whole association reaching up to 9 m thick. A variety of either well-stratified or massive sandy facies is present. Well-stratified sandstones form strata with lower boundaries that are typically undulating and erosional, and locally separated by thin mudstones or lags of mud chips and pebbles. Internally, these beds display large-scale, low-angle dipping strata (facies Su, see no. 1 in

Table 1
Summary of the sedimentary facies recognized in the study area, with the interpreted depositional processes

Sedimentary facies	Description	Depositional processes
Sqp	Well-sorted, fine-grained sandstone with quasi-planar lamination with frequent reactivation surfaces	Deposition of flat beds under variable upper flow regime with unidirectional and oscillatory motion
Su	Well-sorted, fine- to medium-grained sandstone with large scale, low-angle dipping stratification with frequent reactivation surfaces and/or mud drapes	Migration of large scale, but low amplitude bedforms under variable lower flow regime with unidirectional and oscillatory motion (the latter being subordinate)
Sw	Moderate to well-sorted, fine- to medium-grained sandstone with swaley cross-stratification and locally hummocky cross-stratification with frequent reactivation surfaces and/or mud drapes	Migration of sinuous-crested bedforms under variable, lower flow regime with unidirectional and oscillatory motion (with a greater contribution of the latter relative to facies Su)
Sx	Poorly to well-sorted, fine- to coarse-grained sandstone with planar and trough cross-stratification with frequent reactivation surfaces and/or mud drapes	Migration of straight- and sinuous-crested bedforms under unidirectional or variable lower flow regime with unidirectional and oscillatory motion (with a much greater contribution of the first relative to facies Sw)
Sl	Well-sorted, cross laminated-sandstone, locally with highly undulating set boundaries and internal reactivation surfaces/mud drapes	Migration of straight- and sinuous-crested bedforms (ripple scale) under unidirectional or variable lowest flow regime with unidirectional and oscillatory motion
Sb	Bioturbated sandstone	Loss of structure due to intense sediment deformation by biogenic reworking
Sp	Moderate to well-sorted, fine to coarse-grained sandstone with parallel lamination	Sand deposition under upper plane bed conditions
Sw/f	Well-sorted, fine- to medium-grained massive or cross-laminated sandstone interbedded with mudstone forming wavy and flaser lamination	Alternating mud deposition from suspension and bedload deposition under fluctuating flow energy
Sm	Moderate to well-sorted, very fine- to medium-grained massive sandstone	Rapid deposition, with no time for stratification of the sediments or post depositional destruction of the framework due to instabilities in the depositional setting
Sd	Moderate to well sorted, very fine- to medium-grained sandstone with soft sediment deformation including convolute folds and over-steep cross-strata.	Soft sediment deformation caused by water escape attributed to deposition at high sedimentation rates
Am	Massive, very fine-grained mudstone	Rapid accumulation in areas with high mud supply, soft sediment deformation
Al	Laminated mudstone	Mud settling from suspension in low energy depositional environments

Table 2
Summary of the main characteristics of facies associations in the study area, with the interpreted depositional settings

Facies association	Description	Depositional environment
A	Well-sorted, fine- to medium-grained sandstone bodies occurring as tabular, slightly undulating packages internally displaying a variety of undulating structures formed by combined storm flows (i.e., facies Sw, Sqp, and Su). Tabular and trough cross-stratified sandstones (facies Sx), cross-laminated sandstones (facies Sl) and hummocky cross-stratified sandstones (facies Sh) are locally present. Wave erosion is common. Degree of bioturbation may be very high, with main trace fossils including *Thalassinoides, Planolites* and *Diplocraterion.*	Upper shoreface
B	Tabular, well-sorted, medium to coarse-grained sandstone with planar and trough cross lamination/stratification (facies Sx), as well as wavy/flaser (facies Sw/f) and parallel lamination (facies Sp). Cross sets display internal reactivation surfaces with mud drapes separating foreset packages, and boundaries that are highly undulating. Opposed-dipping cross sets are locally present. Bioturbated sandstones (facies Sb), in which *Thalassinoides* are widespread, either as isolated burrows or complex networks of interconnecting branches associated with *Ophiomorpha*, *Planolites, Taenidium barretti*, and rare *Scoyenia*.	Foreshore
C	Moderate to well-sorted, very fine- to medium-grained, massive (facies Sm) or soft sediment deformed sandstones (facies Sd). Locally present are trough/tabular cross-stratified sandstone (facies Sx), swaley cross-stratification (facies Ss) and quasi-planar lamination (facies Sqp). The sandstones display lobate geometry, and are internally characterized by coarsening upward cycles. Lobes show depositional dip to the west/northwest and bi-directional flows pointing to the northwest and southeast. Reactivation surfaces and mud drapes are abundant within cross sets, as are combined flow laminations. *Taenidium barretti, Planolites,* occasional *Thalassinoides* and *Diplocraterion* occur.	Deltaic mouth bar
D	Alternation of massive, very fine-grained sandstones (facies Am) and laminated mudstones (facies Al) forming either fining or coarsening upward cycles. Fining upward cycles form slightly undulating beds with frequent internal truncation, locally forming swaley and hummocky cross stratification (facies Sw and Sh) that grade into quasi-planar lamination (facies Spq). Extremely bioturbated, but hard to identify individual traces, except for possible *Diplocraterion* (?)	Lower/middle shoreface/prodelta?

Fig. 2C, D) or, less commonly, swaley cross-stratification (facies Sw; Fig. 2G), both of which become laterally undulating, forming quasi-planar laminations (facies Sqp; Fig. 2C–F). Small-scale, hummocky cross-stratification, inserted in facis Sw, is only locally observed (Fig. 2E, F). Laterally, these facies grade into sandstones with small scale cross-stratification (facies Sx) and cross-lamination (facies Sl) displaying undulating lower set boundaries and also abundant internal reactivation surfaces, locally with mud drapes (Fig. 2H). The undulating sandstones are locally cut by broad, shallow scours that are up to 5 m deep and several tens of metres wide that are filled by sandstones also showing undulating stratification as described above.

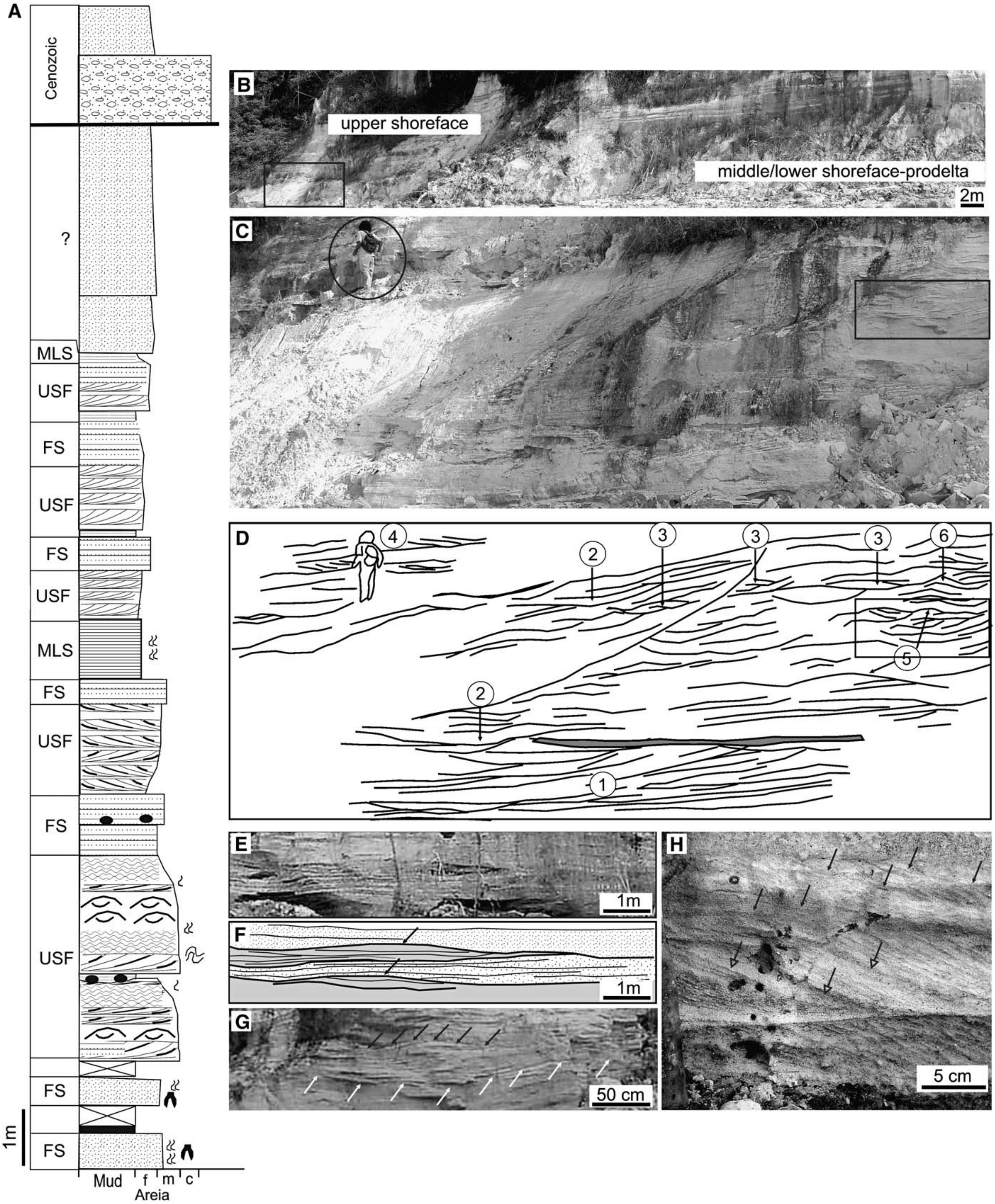
Interbedded with the stratified sandstones are highly bioturbated sandstones (facies Sb) that are fine-grained and well-sorted. The bioturbation is so intense that primary physical structures are not recognizable. Despite the intensity, there is a dominance of *Thalassinoides, Diplocraterion* (Fig. 3A, B) and *Planolites* traces. Two different classes of *Thalassinoides* burrow system may be distinguished by the average diameter of the galleries: smaller (7 mm), and larger (16 mm).

Measurements of azimuth dips of the cross-stratified sandstones reveal bi-directional flows orientated to either the northwest or the southeast (Fig. 3C).

3.2. Facies association B

This facies association is frequent at the base of the sections, forming laterally continuous, tabular sandstone beds that are up to 1.5 m thick and may show slightly undulating, locally erosional tops. It grades both laterally and vertically into facies association A, from which it is distinguished by

Fig. 2. Middle/lower shoreface/prodelta and upper shoreface deposits (facies associations D and A, respectively). A, measured vertical profile representative of these deposits in the study area (USF, upper shoreface-facies association A; FS, foreshore-facies association B; MLS, lower/middle shoreface–prodelta? facies association D). B, general view of an outcrop showing lateral gradation from middle/lower shoreface/prodelta sandstones and mudstones (right) to upper shoreface sandstones (left). Box on left locates C and D. C, D, detail of left side of B, with sandstones displaying a variety of undulating sedimentary structures attributed to wave action: 1, large-scale, truncating, low-angle dipping stratification; 2, swaley cross-stratification; 3, combined flow cross-stratification with highly undulating lower set boundaries and internal reactivation surfaces; 4, cross-stratified sandstone with reactivation surfaces and mud drapes; 5, slightly concave-up undulating stratification that truncates underlying laminae at a very low angle, similar to hummocky cross-stratification; 6, chevron stratification (figure for scale is 1.60 m tall; box in C and D locates G). E, F, detail of upper shoreface sandstones consisting of undulating, quasi-planar strata (facies Sqp) that become laterally convex upward (arrows), forming hummocky cross-stratification; patterns in F indicate successive beds defined by sharp undulating surfaces; note truncation of the strata below the hummocks. G, detail of swaley cross-stratification (see box on right-hand side of C and D for location); white arrows indicate a broad swale at the base of the strata; black arrows indicate strata that are slightly convex-up, indicating small-scale hummocky cross-stratification. H, medium-scale cross-sets with reactivation surfaces (open arrows) mantled by several cross-laminated sets with undulating set boundaries (closed arrows).


A
Cenozoic
?
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Mud
f
m
c
Areia
B
upper shoreface
middle/lower shoreface-prodelta
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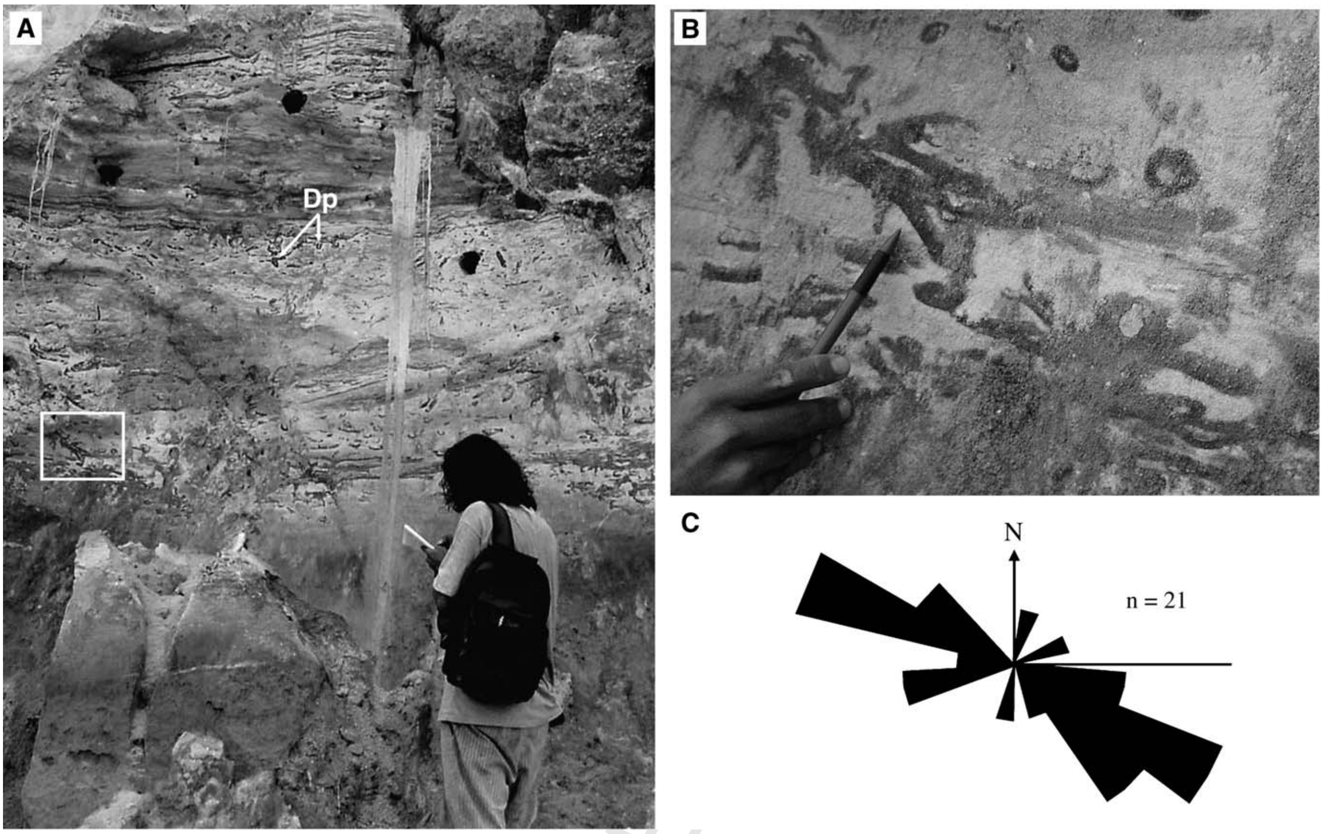


Fig. 3. A, general view of upper shoreface deposits characterized by highly bioturbated sandstones (facies Sb; Dp = *Diplocraterion*). B, detail of A illustrating *Thalassinoides* (see box in A for location). C, palaeocurrent distribution obtained from cross-stratified sandstones in upper shoreface deposits, indicating bi-directional, northwest/southeast-orientated flows.

the coarser grain size, forming thickening-upward successions. The sandstones are well sorted and, in general, fine- to medium-grained, though beds with coarse grain sizes are also frequent, in which case quartz granules and mud clasts are dispersed. Five sedimentary facies occur in this association, including, in order of abundance, bioturbated sandstone (Sb), planar and trough cross-laminated and cross-stratified sandstone (facies Sl and Sx, respectively), wavy/flaser laminated sandstone (facies Sw/f), and parallel-laminated sandstone (facies Sp). Facies Sl and Sx display mud drapes (Fig. 4A), undulating set boundaries and internal reactivation surfaces (Fig. 4B), as described in the other facies associations. Opposed-dipping cross sets are locally present. The sandstones in facies Sw/f are either massive or incipiently cross-laminated and display frequent symmetrical scours highlighted by mud layers (Fig. 4C).

A typical feature of all facies in this association is the variable degree of bioturbation, which can be very intense, as in facies Sb. Most of the deposits are reworked by the abundant, but monospecific *Thalassinoides* suite (Fig. 4D, E), which occur either as isolated burrows or as complex networks of interconnecting branches. Occasional *Ophiomorpha* may also be present (Fig. 4F). *Taenidium barretti* (Fig. 4H), *Planolites* (Fig. 4G), and rare *Scoyenia* (Fig. 4I), define the *Taenidium barretti* suite, overprinted by (Fig. 4H) or interbedded with (Fig. 4G) the *Thalassinoides* suite.

3.3. Facies association C

These deposits are characterized by well-sorted, very fine- to medium-grained sandstones, typically displaying a lobate geometry (Fig. 5A–C). Individual lobes are, in general, less than 2 m thick and up to 60 m long, and they may show an overall westward/northwestward depositional dip.

The sandstones are internally organized into coarsening-upward successions (Fig. 5A), as revealed by an inverse grading from very fine- to medium-grained sands or by a downward transition into massive mudstones. Where exposures allowed sufficient observation, the sandstone lobes were seen to be amalgamated, forming thicker sandy nuclei, which become laterally subdivided into several smaller lobes defined by thin (a few cm) argillite beds. Within an individual nucleus, the sandstones are either massive (facies Sm) or display soft sediment deformation (facies Sd; Fig. 5G), characterized mostly by convolute folds and over-steep cross-strata. Towards the margins, where the lobes are better defined, the sandstones are typically well-stratified, showing medium-scale (sets 0.2–0.3 cm thick, exceptionally 0.5 m thick) trough/tabular (Fig. 5D, E) and, less commonly, swaley cross stratification (facies Sx and Sw, respectively). Occurring with these structures at the lobe bases and edges are abundant tabular and trough cross-laminations (facies Sl). Palaeocurrent directions obtained from these strata record a wide

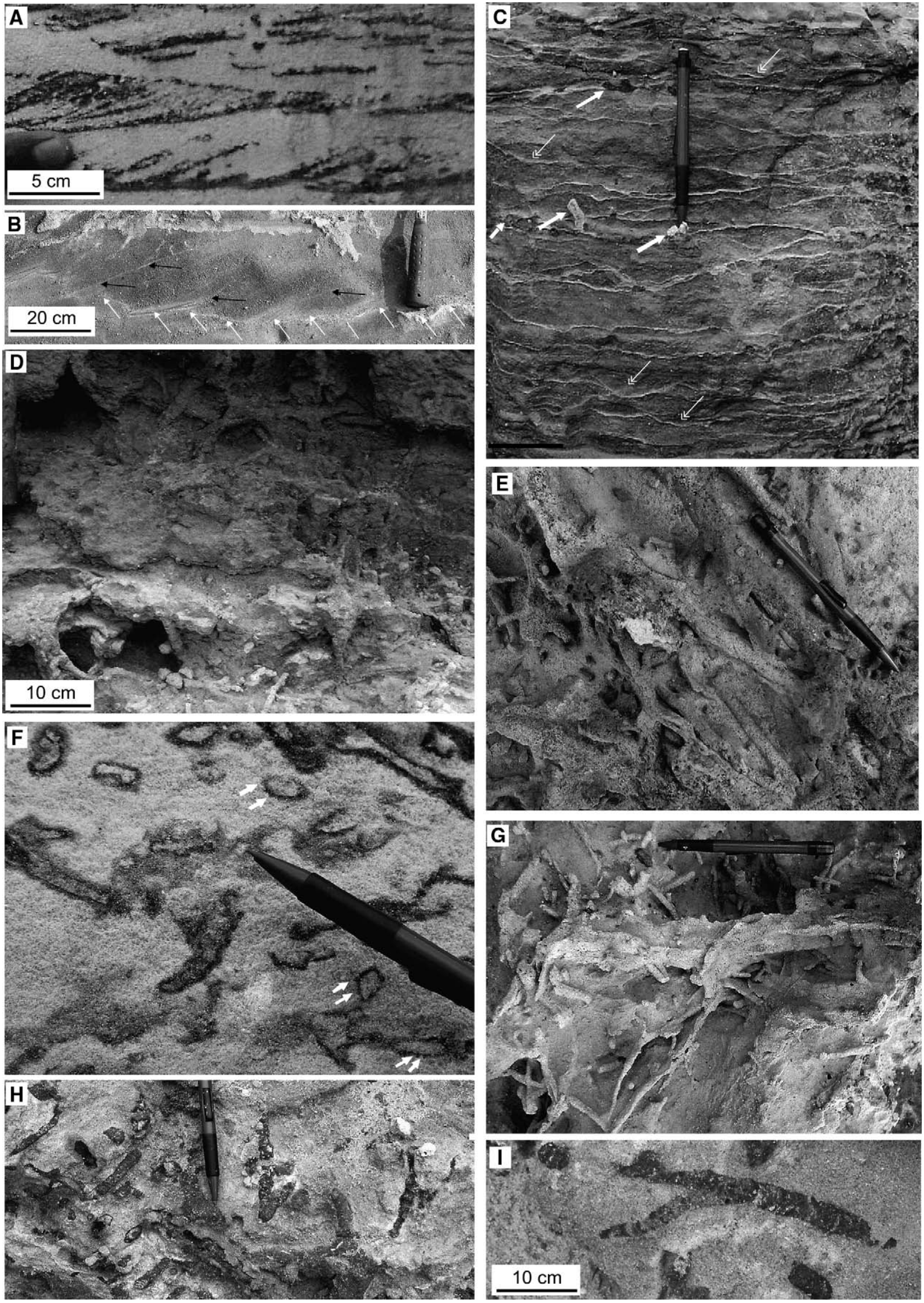


Fig. 4. Foreshore deposits (facies association D). A, low angle cross-lamination mantled by mud drapes. B, small-scale cross-stratification displaying undulating lower boundaries (white arrows) and internal reactivation surfaces locally with mud drapes (black arrows). C, wavy to flaser (light, undulating laminae) heterolithic sandstones typical of this facies association (white arrows with single head indicate trace fossils; those with double head indicate symmetrical scours); crenulated appearance of mud layers is due to presence of diminutive ripple marks (black arrows). D, E, branched traces of *Thallasinoides* in profile and plan views respectively. F, *Ophiomorpha*; white arrows indicate pellets surrounding trace walls. G, a mixture of *Planolites* and *Taenidium barretti*. H, *Taenidium barretti*. I, *Scoyenia*. Pen is 15 cm long.

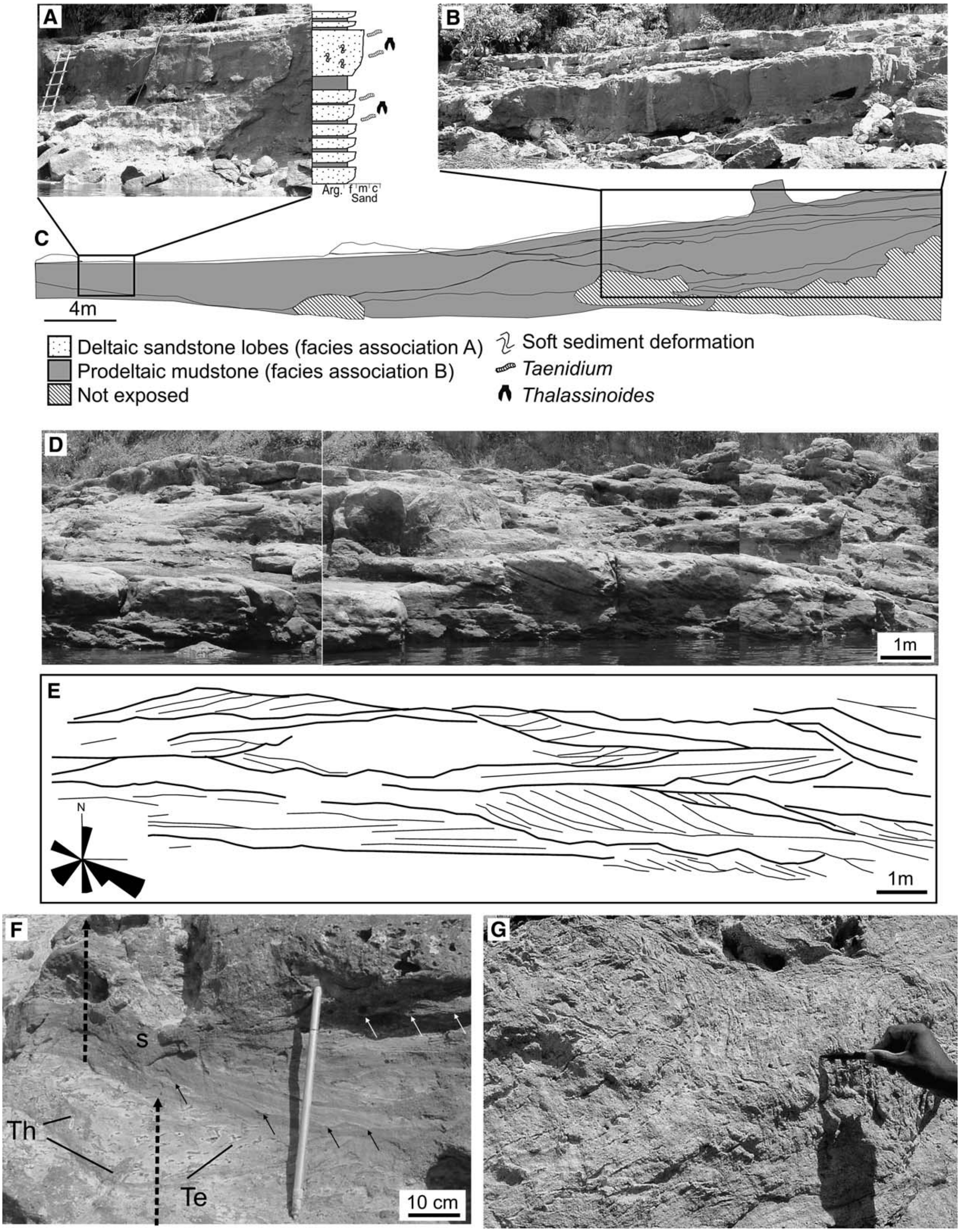


Fig. 5. Delta mouth bar deposits (facies association A). A–C, lobate geometry; note the typical coarsening upward successions in A, and the amalgamation of several lobes in C that dip slightly to the left of the sketch (i.e., to the west). D, E, photograph, with corresponding drawing, of a section characterized by amalgamated sandstone lobes displaying internal cross-stratification that dips in opposite directions, i.e., to the right (west) and left (east); these strata indicate a wide variation of flow, but with a main southeast-orientated mode (shown in left-hand corner; number of measurements, 8). F, detail of parts of two coarsening-upward successions (dashed arrows), illustrating finer grain-sizes at the base of the upper cycle displaying combined flow ripple cross laminations characterized by highly undulating lower set boundaries (black and white arrows); note also in this horizon the symmetrical scour caused by wave erosion (s) and intense bioturbation in the sandstone from the top of the lower cycle, where *Thalassinoides* (Th) and *Taenidium barretti* (Te) dominate. G, deformed sandstone (Facies Sd) from the nuclei of the lobes.

distribution of the flow, but with a mainly southeast-orientated mode (Fig. 5E).

A typical feature of the cross-sets is the presence of frequent reactivation surfaces mantled with mud drapes, as observed in the cross-sets of the other facies associations. In medium-scale cross-sets, these surfaces define foreset packages averaging 5–10 cm thick. The lower set boundaries of both medium- and small-scale strata are undulating, forming broad, shallow scours. Cross-lamination structures with highly undulating lower set boundaries and abundant reactivation surfaces may have evolved from quasi-planar laminations (facies Sqp) (Fig. 5F); in these cases, wavy-cut erosional scours are frequent.

The top of the beds or even the entire beds may be bioturbated, forming facies Sb (bioturbated sandstones). Recognizable trace fossils characterize an assemblage dominated by *Taenidium barretti* and *Planolites*. (Fig. 6A, B) and occasional, but locally abundant, small, flattened *Thalassinoides* galleries (Fig. 6A). Beds with a *Diplocraterion* ichnofabric are also observed (Fig. 6C, D). The ichnofabric is entirely dominated by horizontally-sectioned U-burrows with vertical spreiten, many revealing the curved end of the burrows. Burrow boundaries are invariably sharp-walled, suggesting colonization of firmgrounds (Pemberton and Frey, 1985; Bromley, 1996; Buatois et al., 2001).

3.4. Facies association D

This association forms units up to 3 m thick and includes fine-grained facies, consisting mostly of argillites, and very fine- to fine-grained sandstones. The strata form tabular to slightly undulating beds up to 0.2–0.3 m thick, which are interbedded with facies association A (Fig. 2A) or C (Fig. 5A–C). Internally, the lithologies are arranged into either cycles of sandstones that grade upward into mudstones or mudstones that grade up into sandstones. The mudstones display red to light brown colors, are mostly silty, and are either laminated (Al) or massive (Am). Laminated mudstones are interbedded with white or yellow, very-fine grained sandstones showing parallel and low-angle, quasi-planar laminations (Facies Sp). In these cases, the beds are undulating and display bases and tops that are slightly concave and convex, respectively, forming swaley and, locally, hummocky cross-stratification (facies Sw). Massive silty mudstones locally may show wavy, erosional surfaces superposed by successive smaller-scale scours (up to only few cm wide). The degree of bioturbation might be very high in the massive muddy lithologies, but individual traces could not be identified, except for spreiten-like, subvertical traces resembling *Diplocraterion* (?). Some beds, though, are only locally bioturbated.

4. Interpretation of sedimentary processes

Deposition by highly oscillatory flows is revealed by the dominance of different styles of cross-strata characterized by undulating lower set boundaries and abundant internal reactivation surfaces with mud drapes. Bi-directional flows, as indicated by palaeocurrent data, are also compatible with this interpretation. Two possibilities are currently considered here

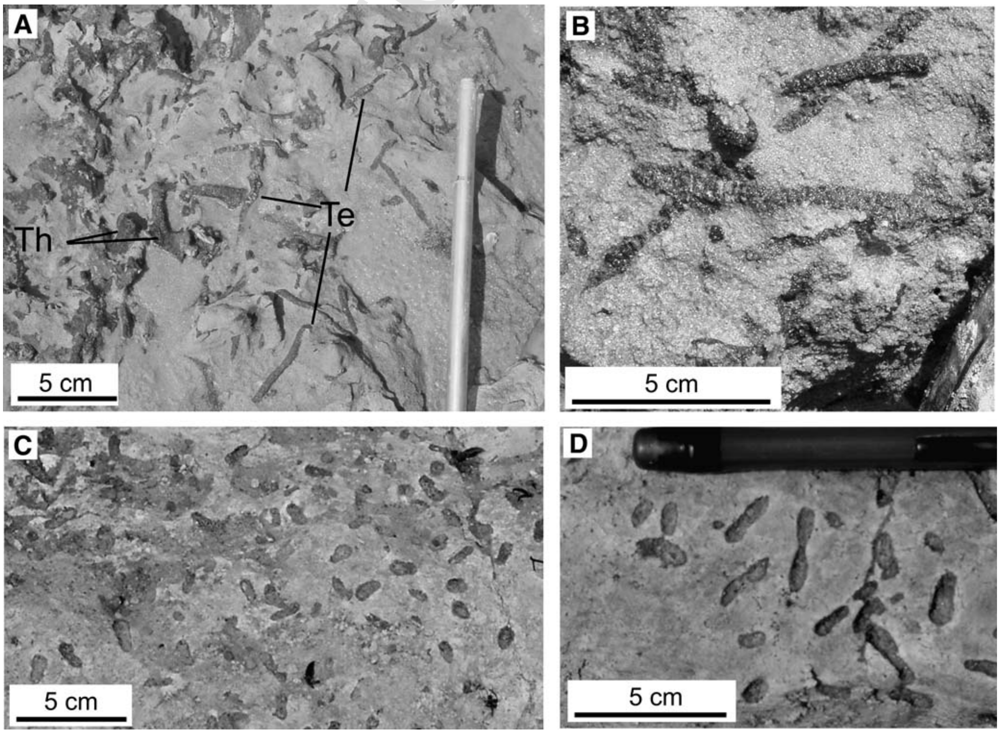


Fig. 6. Trace fossils typical of deltaic mouth bar deposits. A, sandstones from the top of a coarsening-upward cycle, with abundant trace fossils dominated by *Thalassinoides* (Th) and *Taenidium barretti* (Te). B, detail of *Taenidium barretti*. C, a view of the top of a sand bed with abundant *Diplocraterion*. D, detail of *Diplicraterion* from the surface shown in C. All figures show the trace fossils in plan view.

as the most likely causes: tidal currents and waves. Reactivation surfaces and mud drapes separating foreset packages are commonly recorded in association with tidal currents (Mowbray and Visser, 1984; Chakraborty and Bose, 1990; Simpson and Eriksson, 1991). However, several workers have claimed that similar features might be also due to wave action (e.g., Raaf et al., 1977; Arnott, 1992). In fact, differentiating between these processes in the geological record can be highly problematic, particularly in cases where there is a mixture of tidal and wave processes (e.g. Johnson and Baldwin, 1986; Harris and Eriksson, 1990; Amos et al., 1995; Colquhoun, 1995).

Interpreting the sedimentary signature of tidal currents is facilitated only when reactivation surfaces/mud drapes form a succession of alternating thicker and thinner foreset bundles that can be related to diurnal and monthly tidal periodicities (e.g. Allen, 1968; Yang and Nio, 1985; Kreisa and Moiola, 1986; Koster et al., 1987; Leckie and Singh, 1991). These features were not observed in the study area, but this absence cannot be used to preclude a tidal influence, as many ancient deposits attributed to tidal processes throughout the world do not show such diagnostic structure, even in subtidal settings where development of tidal bundles are more likely (Clifton, 1983; Yang and Nio, 1985; Koster et al., 1987).

Thus, although a tidal influence cannot be completely ruled out in this instance, the association of sedimentary features favours a wave-dominated influenced environment. This is suggested by the abundance of highly undulating structures, including swaley cross-stratification, with locally associated hummocky cross-stratification, and quasi-planar lamination. These features are considered typical of either oscillatory or combined flows with varying dominance of the unidirectional and orbital components. In particular, swaley cross-stratification indicates the action of larger than fair-weather waves, suggesting a storm-influenced setting (e.g., Allen and Pound, 1985; McCrory and Walker, 1986; Plint and Walker, 1987; Duke and Prave, 1991; Plint and Norris, 1991; Hadley and Elliot, 1993). This structure records the migration of low relief bedforms under storm-generated, combined flows (e.g., McCrory and Walker, 1986). The gradation from swaley cross-stratification to quasi-planar lamination and, locally, hummocky cross-stratification, is predicted in phase diagrams of combined flows, attesting to constant changes in the intensity of the unidirectional and oscillatory components (e.g., Nøttvedt and Kreisa, 1987; Arnott, 1992).

Considering this interpretation, the cross-sets displaying abundant reactivation surfaces and mud drapes are interpreted here to be more likely related to wave action than to tidal currents. These features are attributed to complex, short-term orientations of the flow and have been recorded in association with combined flows in many other storm settings (e.g., Swift et al., 1983; Nøttvedt and Kreisa, 1987; Arnott and Southard, 1990). The quasi-planar lamination may have formed during periods of upper flow regime and when the oscillatory motion was stronger than the unidirectional one (Arnott, 1992). Coexisting asymmetrical and symmetrical scours are also consistent with combined flows. In particular, cross-sets with reactivation surfaces and highly undulating lower boundaries are features of combined flow bedforms (e.g., Raaf et al., 1977). In this instance, the gradation of these structures from quasi-planar laminations records laterally decreasing flow energy.

The fact that the interbedded sandstone and argillite layers are not in sharp contact, as expected in tidal deposits (e.g. Visser, 1980), but rather grade vertically, is taken as further evidence in support of wave action in the study area, with the grading being attributed to waning energy flows associated with the passage of storms. The upward transition from large-scale, low-angle dipping strata to swaley and combined flow cross-strata is consistent with this process. Similar features have been observed in association with upper shoreface Cretaceous deposits in the São Luís-Grajaú Basin (e.g. Rossetti, 1997; Rossetti et al., 2000).

5. Discussion of the depositional settings

The sedimentological and ichnological data do not support the presence of continental palaeoenvironments in the Alter do Chão Formation as exposed in the study area. As discussed above, the set of sedimentary facies points to the prevalence of wave processes which, in association with the ichnological attributes, suggest deposition in environments not far from a shoreline and under the influence of significant wave (i.e., storm) action.

Although waves do form in some continental settings, such as in lakes and, locally, at the confluence of fluvial channels, the wave-influenced deposits exposed in the study area cannot be related to purely continental settings. This conclusion is based on the dominance of both wave-influenced sedimentary structures and of a *Thalassinoides* trace-fossil suite.

Thalassinoides is perhaps the most common burrow in ancient shallow marine and marginal marine environments, inhabiting dominantly silty-sandy substrates (Pemberton et al., 1992a, 2001). These burrows are assumed to have been produced by opportunistic, deposit-feeding thalassinidean crustaceans in post-Paleozoic rocks and by their ancestors, or by a crustacean with similar behaviour, in Paleozoic rocks (Sheenan and Schiefelbein, 1984; Watkins and Coorough, 1997; Ekdale and Bromley, 2003). By comparison, modern galleries similar to *Thalassinoides* are produced by thalassinidean shrimps that never abandon their burrows, growing-up inside and enlarging the burrow system, being the most common burrowing organisms of marine intertidal and shallow subtidal environments (Griffis and Suchanek, 1991). Although rare, *Thalassinoides* is also found in deep marine environments (Sheenan and Schiefelbein, 1984; Uchman, 1995; Buatois et al., 2001). Its facies-crossing character is a consequence of the opportunistic behaviour of a tracemaker able to support episodic or constant environmental changes (Wightman et al., 1987; Pemberton and Wightman, 1992). Although the geological record of *Thalassinoides* is overwhelmingly restricted to marine and brackish-water successions, there is one exception: Shukla et al. (2002) reported the presence of *Thalassinoides* in Quaternary deltaic and fluvial silt and sand deposits, apparently without marine influence. The only organisms that can produce similar burrows in continental settings are crabs, but in this case the galleries differ from those described here because they are much simpler, shallower and with fewer branches. Thus, the occurrence of *Thalassinoides* in the sedimentary record supports the inference of a depositional setting under the influence of marine processes. *Thalassinoides* became particularly widespread from the Mesozoic onwards, when their burrow systems were large and became more complex, forming mazes and boxworks (Frey, 1975; Bromley, 1996).

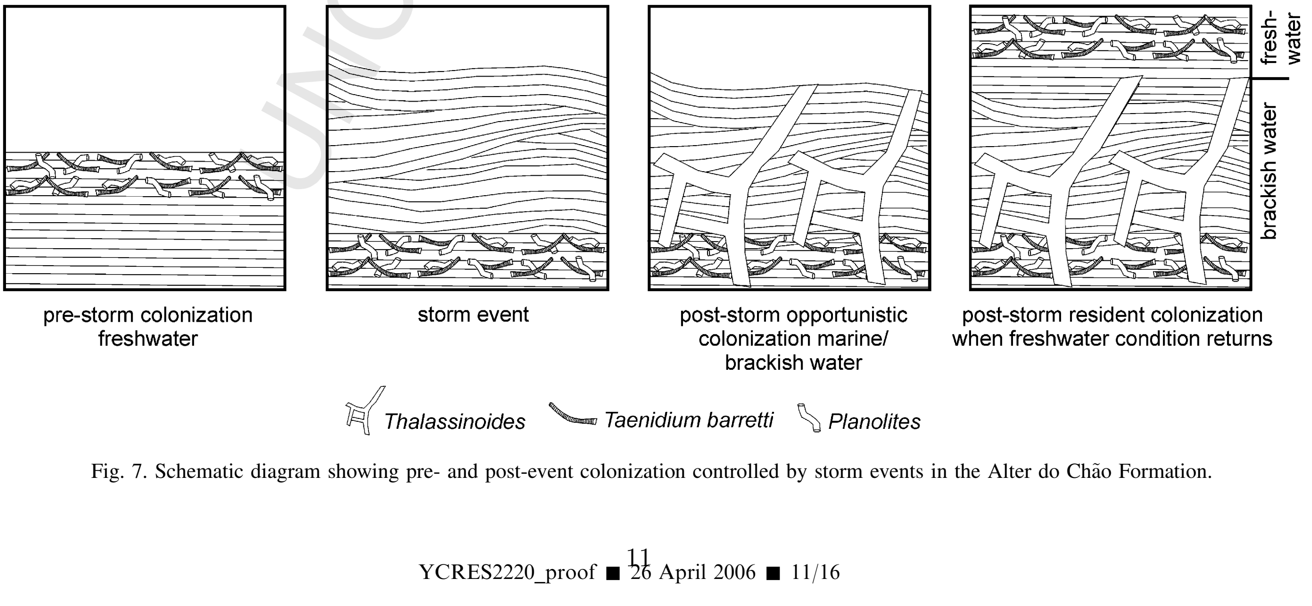
The complex arrangement of *Thalassinoides* burrows observed in facies association A, including burrow systems of different sizes, probably represents colonization by two major classes of individuals in a single population, revealing juvenile recruitment. This population strategy is common in brackish-water settings as a response to daily changes in controlling ecologic parameters dominated by extreme salinity fluctuations. Benthic communities of substrates affected by frequent salinity fluctuations, as occur in brackish-water systems, tend to consist of opportunistic elements with prevalent dwelling and feeding strategies (Ekdale et al., 1984; Pemberton and Wightman, 1992; Beynon and Pemberton, 1992; Pemberton et al., 1992b, 2001; Buatois et al., 1998; Gingras et al., 1999). The large burrows and reduced-size galleries of *Thalassinoides* in the same horizon, as recorded in this facies association, are thus comparable to brackish-water ichnofaunas (Wightman et al., 1987; Pemberton and Wightman, 1992; Pemberton et al., 2001; Buatois et al., 2005).

The highly bioturbated, monospecific *Thalassinoides* suite, as recorded particularly in facies association B, is consistent with this proposed depositional setting. Intense bioturbation *Thalassinoides* networks are expected to develop in moderate to low energy, shallow-marine to marginal-marine environments affected by occasional salinity fluctuations (stenohaline to polyhaline: Pemberton et al., 2001; Netto and Rossetti, 2003). In addition to the *Thalassinoides* suite, the presence of *Diplocraterion* in the deposits studied supports the influence of marine conditions, recording periods with a dominance of saline waters. On the other hand, the *Taenidium barretti* trace fossil in facies associations B and C attests to periods of predominantly freshwater influence, as this ichnospecies is characteristic of freshwater conditions (Buatois et al., 1998, 2002; Netto and Rossetti, 2003). When the salinity gradient reaches freshwater levels, a physiological barrier is erected to marine organisms and even those capable of enduring strong salinity fluctuations, such as the deep-burrowing *Thalassinoides*-producers, cannot survive. The successive alternation of *Taenidium barretti* with *Thalassinoides* in facies association B suggests relatively high salinity during coastal evolution, which is also compatible with the attribution of these deposits to foreshore settings (Fig. 7), as proposed in the following section.

Scarce, small and flattened *Thalassinoides* burrows, as occur in facies association C, are also good representatives of meso- to oligohaline waters in brackish-water settings (Pemberton et al., 2001; Netto and Rossetti, 2003; Buatois et al., 2005). However, the dominance of *Taenidium barretti* with only a few Thalassinoides in this facies association indicates a prevalence of freshwater to subaerial substrates (*Scoyenia* Ichnofacies: Pemberton and Frey, 1985; Buatois et al., 1998, 2002; Buatois and Mángano, 2004). The sharp-walled burrow boundaries of *Diplocraterion* observed in facies association C suggest colonization of firmgrounds and testify to substrate exhumation and temporary exposure before the next marine ingression (MacEachern et al., 1992; Pemberton et al., 2001; Netto and Rossetti, 2003).

A marine influx, probably resulting from storm events, would have brought in an opportunistic marine fauna, represented by the *Thalassinoides*-dominated ichnofauna, which rapidly colonized the substrate. Considering the very low trace fossil diversity and the mixed occurrence of saline and freshwater traces, it is suggested that deposition took place in environments experiencing a mixture of saline and freshwater flows, which are typical of brackish-water environments. In fact, it is common to observe the *Thalassinoides* suite cross-cutting substrates previously occupied by the *Taenidium-Planolites* suite, and vice-versa (Fig. 7).

The lack or scarcity of bioturbation in the strata with abundant sedimentary structures formed by wave action in the study area is to be expected, as the density of bioturbation varies from high in quiet, protected settings to rare in high-energy settings. Therefore, information from physical and



pre-storm colonization freshwater

storm event

post-storm opportunistic colonization marine/ brackish water

post-storm resident colonization when freshwater condition returns

Fig. 7. Schematic diagram showing pre- and post-event colonization controlled by storm events in the Alter do Chão Formation.

biogenic structures are complementary, and indicate the presence of depositional environments exposed to strong wave action during storms laterally coexisting with more protected settings.

Considering the limited lateral extend of the studied transect (only up to 15 km in length), reconstructing the depositional system is difficult. However, our suggested ichnological interpretation of mixed (i.e., freshwater and marine) water inflows conforms to a setting located in the transitional marine realm. The four facies associations conform to storm-influenced deltaic environments. A deltaic setting is particularly suggested by facies association C, which contains well-developed progradings and lobes indicative of deposition accompanying a rapid loss in energy related to the entrance of flows into a standing body of water, a process typical of distributary mouth bars. Massive and deformed sandstones in this association are consistent with a setting with a high sand inflow and gravity instability (e.g., Coleman, 1988; Orton and Reading, 1993; Glover and O'Beirne, 1994). Mouth bars deposits are characterized by high interstitial water pressure, which leads to intense fluidization and liquefaction, (e.g., Mills, 1983; Elliott, 1986; van Loon and Brodzikowski, 1987; Coleman, 1988), processes that produced the massive and deformed sandstones (facies Sm and Sd). In addition, mouth bars are places characterized by intense gravity instabilities promoted by the overloading of sands on muds (Shepard, 1955; Coleman and Prior, 1983; Elliott, 1986; Coleman, 1988). Mouth bars of many modern and ancient deltaic settings display such features (e.g., Nemec et al., 1988; Edwards, 1995). The small size of the sand lobes developed in the study area may be explained in the context of delta lobes entering shallow waters.

Two depositional models may be invoked to explain the strata studied: a wave-dominated delta and a wave-dominated estuary. The prevalence of brackish-water conditions favours an estuarine interpretation. Tidal channel deposits, however, which typify estuarine complexes, were not recognized in the study area. Furthermore, tidal currents are the main agents responsible for sediment deposition within estuaries, even in wave-dominated ones (e.g., Dalrymple et al., 1992), but the study area bears no conclusive evidence for tidal sedimentation.

Although an estuarine interpretation cannot be completely ruled out, the absence of criteria in support of tidal sedimentation, added to the abundance of sedimentary structures attributed to both fair-weather and storm waves, leads us to propose that a wave-dominated deltaic setting is more likely (Fig. 8). Like estuarine settings, wave-dominated deltas are characterized by a mixture of fluvial and marine inflows, thus stressed environments with brackish water conditions may develop.

Facies association D records the muddiest and therefore the lowest energy depositional setting of the study area. When these deposits occur interfingering with facies association C, they are interpreted as prodeltaic sediments. However, a large proportion of these deposits is genetically connected with facies associations A and B, when they are attributed to lower/middle shoreface settings. This interpretation is consistent with the presence of undulating sedimentary structures dominated by storm wave action. These structures suggest a low

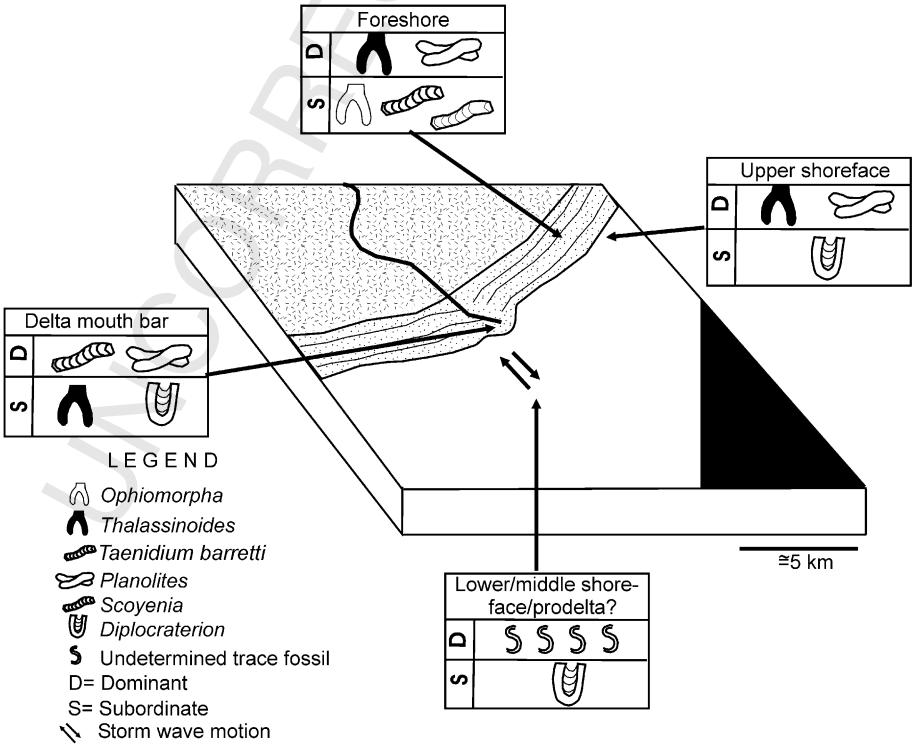


Fig. 8. A schematic block diagram illustrating the storm wave-dominated deltaic depositional system proposed for the Cretaceous deposits in the study area, with an indication of the ichnological characteristics of each sub-environment.

energy setting located below the fair-weather wave base but periodically affected by storm waves, favourable for preservation of hummocky cross-stratification (e.g. Walker, 1984; McCrory and Walker, 1986; Nøttvedt and Kreisa, 1987; Cheel and Leckie, 1993) and for intense biogenic reworking. Deposits of this facies association with scarce bioturbation probably record sedimentation in areas still under the effect of storm waves.

The spatial transition from facies association D to A and B further supports the above interpretation. Facies association A is also dominated by undulating structures, mostly represented by swaley cross-stratification. This structure is formed in a high energy environment above the storm wave base and close to the fair-weather wave transition, which within the proposed environmental context, is probably representative of the upper shoreface, as recorded in many other similar settings (Dott and Bourgeois, 1982; Walker, 1984; Allen and Pound, 1985; McCrory and Walker, 1986; Plint and Walker, 1987; Duke and Prave, 1991; Plint and Norris, 1991; Hadley and Elliot, 1993). The amalgamated nature of the sandstones bodies in facies association A is consistent with an upper shoreface setting, where erosion is frequent (Dott and Bourgeois, 1982; Brenchley et al., 1986).

The dominance of fair-weather wave structures in facies association B indicates deposition above fair-weather wave base, characterizing a shallower environment than indicated by facies associations A and D, being attributed to foreshore settings (e.g., Clifton et al., 1971; Driese et al., 1991). Thus, any deposits formed by storm action were subsequently reworked by fair-weather waves between storms. The abundance of fair-weather wave structures in these strata, as well as the presence of parallel lamination that might record beach face deposition, is consistent with this interpretation. Fair-weather conditions contributed to the widespread development of *Thalassinoides*, which reached their greatest abundance in these deposits. In this context, *Thalassinoides* represents the opportunistic post-storm colonization (Pemberton et al., 1992c, 2001), subsisting in the substrate while the salinity values permitted (oligohaline waters: see Wignall, 1991; Netto and Rossetti, 2003). The *Taenidium-Planolites* suite is a relict of the original resident non-marine endofauna, characterizing pre-storm colonization, when freshwater conditions apparently prevailed (Fig. 7). The fact that facies association B overlies upper shoreface strata, forming coarsening-upward successions, in addition to its coarser-grained nature relative to those deposits, further supports a setting located closer to the coastline, adjacent to the shoreface.

Unfortunately, our palaeocurrent data are too few to provide a reliable determination of flow pattern. However, it is possible to infer a coast orientated roughly in a northeast–southwest direction and a continental influx from the northwest, as suggested by the main southeastward mode recorded from delta lobe deposits. This coastline would have been affected by storm waves oscillating between northwest and southeast. Marine conditions might, therefore, have prevailed to the east or southeast of the study area. If this is correct, then correlatable deposits located in those areas should record increased evidence of marine influence, a hypothesis that must be tested in future investigations.

6. Conclusion

The traditional view that the Cretaceous deposits of the intracratonic Amazonas Basin are entirely continental in nature might be a result of a lack of detailed sedimentological studies. The sedimentological and ichnological data presented herein suggest that, after the Permo-Carboniferous marine incursion that gave rise to the Itaituba limestones, the Amazonas Basin might also have experienced a marine incursion during the Cretaceous. The magnitude of this transgression and the route by which marine waters entered the basin are issues that need to be discussed in the light of a much larger volume of information. However, the data available from our study allow us to suggest a palaeoenvironmental model in which continental flows from the northwest formed a wave-dominated delta system that prograded into a basin connected to the marine realm to the east or southeast. This model must be tested by further investigations of deposits of the Alter do Chão Formation in the central and eastern areas of the Amazonas Basin. Despite the limited potential for the recovery of fossils, given the red-bed nature of the formation, it is necessary to search for localities that might yield microfossils in order to improve the depositional model.

Uncited references

Buatois et al., in press

Acknowledgments

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