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Internal architecture of mixed tide- and storm-influenced deposits: an example from the Alcântara Formation, northern Brazil

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Abstract

The uppermost portion of the Itapecuru Group is exposed in the eastern margin of the São Luís Basin, northern Brazil, where it consists of two units: the Alcântara Formation (Cenomanian) and the Cujupe Formation (Late Cretaceous–early Tertiary? [Rossetti, D.F., Truckenbrodt, W., 1997. Revisão estratigráfica para os depósitos do Albiano–Terciário Inferior (?) na Bacia de São Luís (MA), norte do Brasil. Bol. Mus. Paraense Emílio Goeldi (Sér. Ciênc. Terra), in press]). The Alcântara Formation, which contains the large-scale structures discussed in this paper, consists of deposits attributed to mid- to upper-shoreface, foreshore, tidal channel, and lagoon/washover environments attributed to a regressive, barred shoreline. Several types of large-scale cross bedding (i.e., simple foreset, compound, mixed, undulatory, and intricately bounded) were recognized in the shoreface facies association. These structures are interpreted to record the interaction of storm and tidal processes. The storm influence is suggested by a combination of factors, mostly including: (a) the genetic association with other storm-generated sedimentary structures (i.e., swaley cross stratification and undulating parallel lamination with internal truncations); (b) the deposition on prominent surfaces formed by storm erosion, which are defined by large-scale, either symmetrical or asymmetrical scours arranged in a regular, repeating pattern; (c) the sedimentary features formed under combined (unidirectional and oscillatory) flow processes (e.g., compound/mixed bedding with superimposed either swaley cross sets or complexly truncating cross sets with highly undulating boundaries; large-scale, undulatory and intricately bounded cross beddings); and (d) the lateral change in structural styles within short distances, which records frequent modification from asymmetrical to symmetrical/nearly symmetrical bedform profiles (more likely to occur under storm-generated combined flows). The tidal signature is locally recognized by regularly spaced, thick/thin sandstone bundles defined by reactivation surfaces and/or mud drapes, which are attributed to tidal (ebb/flood) cycles. The analysis of paleocurrent distribution suggests that vigorous, southwestward-oriented storm flows interacted with local tidal currents on the shoreface to promote the landward transport of significant volumes of sand, which resulted in the large-scale cross stratification described in this paper. In addition, a secondary, southeastward-directed (oblique- to shore-parallel) combined flow would have periodically interacted with the main flow. The origin of this oblique- to shore-parallel flow is attributed to either the refraction of the main storm waves as they approached the paleocoastline or the interference of a separate storm episode, which competed with the major, landward-moving one. This complex storm flow pattern can be related to past penecontemporaneous seismic activity (i.e., tsunamis), as suggested by the paleogeography of the study area during the Cenomanian, combined with the structural history of the São Luís Basin and the sedimentary features recognized in the Alcântara Formation.

Keywords: tidal process; storm process; palaeoenviroment; estuary; stratigraphy; facies model

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1. Introduction

There are a number of studies documenting the internal structures produced by bedform migration in purely tidal-influenced settings (e.g., Allen, 1980; Boersma and Terwindt, 1981; Allen and Homewood, 1984). Similarly, an increasing number of papers have appeared in the sedimentological literature describing several styles of undulating lamination (i.e., undulating parallel lamination, swaley and hummocky cross stratification) formed in purely storm-influenced settings (e.g., Duke, 1985; McCrory and Walker, 1986). However, although there are many inferences of settings experiencing mixed tide and storm flow interaction in the ancient record (e.g., Johnson, 1977; Cant and Hein, 1986; Johnson and Baldwin, 1986; Bull and Cas, 1989; McKie, 1990; Duke and Prave, 1991), only a few publications have attempted to describe in detail the sedimentary imprint of such deposits (e.g., Fielding, 1989; McKie, 1990; Colquhoun, 1995). In particular, descriptions of large-scale strata formed by mixed tide and storm processes have been cursory (e.g., Chakraborty and Bose, 1990).

The Cenomanian deposits (Itapecuru Group) exposed in the Livramento Island Section (northern Brazil), though limited in thickness (i.e., 5–10 m in average), are laterally continuous for many hundreds of meters. The exceptional preservation of internal sedimentary structures provides an excellent opportunity for documenting large-scale, low-angle cross-bedded deposits from a mid- to upper-shoreface environment affected by both storm and tidal processes. Although the large-scale cross strata resemble those produced by the migration of tidal-generated bedforms (e.g., Allen, 1980; Allen and Homewood, 1984), their geometry and internal structures cannot be completely explained by applying only the model of time–velocity asymmetry attributed to tidal regimes. Instead, detailed sedimentological analysis suggests the coexistence of tidal currents and storm-generated, combined flows as the main control in their genesis.

2. Geological framework

The upper portion of the Itapecuru Group is well exposed in the vicinity of the town of Alcântara, São Luís Basin, northern Brazil (Fig. 1). This is an elongated, northwest/southeast-trending structure formed in the Brazilian Equatorial Margin as a result of the northeast/southwest regional extension related to the origin of the South Atlantic Ocean (Azevedo, 1991). Simple shear stress associated with lithospheric thinning led to initial rifting during the Aptian. Fluvio-deltaic deposits (Grajaú Formation) and black shales, limestones and anhydrite (Codó Formation) formed during this stage (Aranha et al., 1990; Fig. 2). The rifting occurred in the Albian, when the basin underwent a pull-apart phase owing to pronounced east/west extension caused by northeast/southwest and east/west strike-slip tectonism (Azevedo, 1991). The resulting sedimentary record is represented by fluvio-deltaic, coarse-grained sandstones of the lower portion of the Itapecuru Group (e.g., Carvalho, 1987; Aranha et al., 1990; Fig. 2). Fast sea floor spreading associated with the thermal decay of the plate during the Cenomanian to early Tertiary (?) caused northward tilting of the basin and deposition of transitional (estuarine) to inner shelf sandstones and mudstones of the upper portion of the Itapecuru Group. Although tectonic activity decreased during drifting, changes in spreading rates may have induced to seismological reactivations of main Aptian–Albian structural lineaments (Azevedo, 1991). These reactivations are recorded by several episodes of movements along east/west, northeast/southwest, and more recently, northeast/southwest-oriented strike-slip faults, which influenced the sedimentation of the Alcântara and Cujupe formations, as well as the Tertiary and even Pleistocene/Holocene units (Ferreira Junior et al., 1996).

Two stratigraphic units have been recognized in the uppermost portion of the Itapecuru Group exposed in the eastern São Luís Basin: the Alcântara Formation and the Cujupe Formation (Rossetti and Truckenbrodt, 1997). The Alcântara Formation is Cenomanian in age (Pedrão et al., 1993) and consists of an interval up to 35 m thick of well-lithified, calcite-cemented, olive–gray, pink to white, fine- to medium-grained sandstones, which are interbedded with brown to dark-red mudstones and minor gray to reddish limestones. The Cujupe Formation is of an uncertain age between the Late Cretaceous and early Tertiary (?), and consists of an interval up to 25 m thick of soft, commonly friable, pink, white or yellow, very fine- to fine-grained, feldspathic sandstones

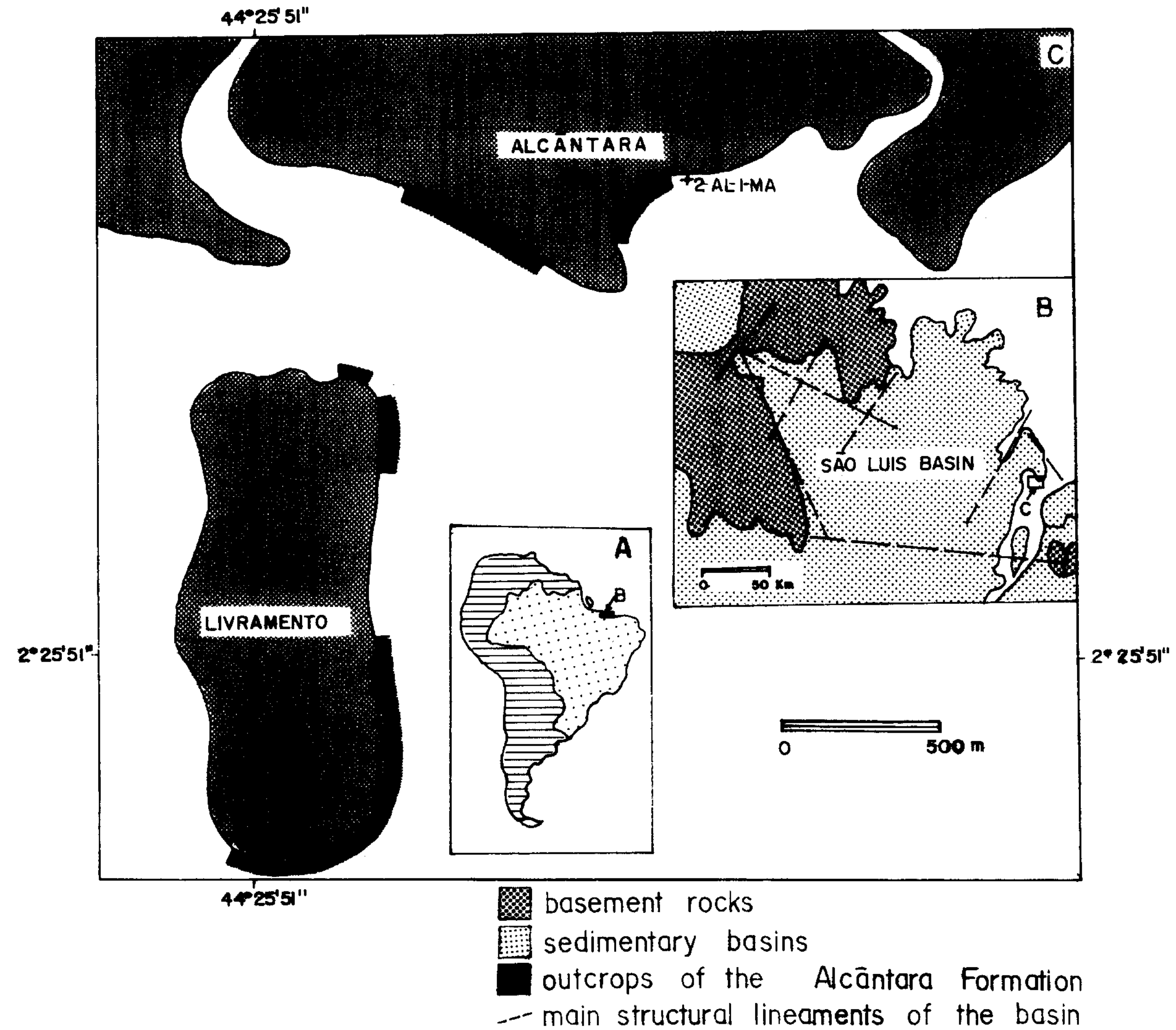

Fig. 1. Location map of the study area in the São Luís Basin, northern Brazil.

and arkoses, which are interbedded with purple to whitish shales. Both units are bounded by regional unconformities with erosional relief of about 30–45 m, which are interpreted to represent sequence boundaries formed during periods of lowstand in relative sea level at the base of incised paleovalleys (Rossetti, 1996a,b).

3. Depositional setting

The large-scale cross beddings described in this paper occur in the Alcântara Formation. Facies analysis and sequential evolution of this unit in the eastern São Luís Basin have been presented in detail by Rodrigues et al. (1990) and Rossetti (1996a,b); therefore, a brief summary is presented here. Four facies associations, assigned 1 to 4 (Figs. 3–6) were recognized and attributed to mid- to upper-shoreface, foreshore, tidal channel, and lagoon/washover depositional settings. The ichnofossils dominated by the traces of *Skolithos*, *Ophiomorpha*, *Planolites*, *Arenicolites*, *Cylindrychnus*, and *Thallassinoides* are consistent with deposition in a nearshore marine setting (Figs. 4–6).

AGE			ROCK TYPE	LITHOLOGY AND SEDIMENTARY SETTING	TECTONIC PHASE
LATE TERTIARY			BARREIRAS/ PIRABAS FORMATION	LIMESTONES, SANDSTONES AND SHALES (TRANSITIONAL/SHALLOW MARINE)	DRIFT
LATE CRETACEOUS/ EARLY TERTIARY		ITAPECURU GROUP	CUJUPE/ ALCÂNTARA FORMATION	SANDSTONES, SHALES, AND MINOR LIMESTONE (CONTINENTAL-SHALLOW MARINE)	
EARLY CRETACEOUS	ALBIAN	ITAPECURU GROUP	UNAMED UNIT	SANDSTONES AND CONGLOMERATES (FLUVIAL, DELTAIC)	RIFT
	APTIAN		CODO/ GRAJAU FORMATION	SANDSTONES, BLACK SHALES, LIMESTONES AND ANHYDRITE (FLUVIAL AND LACUSTRINE)	PRE-RIFT

Fig. 2. Stratigraphic chart and main tectonic stages of the São Luís Basin.

3.1. Facies association 1

This consists of amalgamated sandstone with a variety of laterally grading structures suggestive of storm and/or tidal processes, which are: (1) swaley cross stratification (Fig. 5B); (2) undulating parallel to low-angle cross lamination; (3) tabular cross stratification with reactivation surfaces/mud drapes that separate thick/thin sandstone bundle sequences (Fig. 5C); and (4) the large-scale low-angle cross bedding discussed in this paper. Highly disturbed intervals with faulted blocks, fractures and a variety of soft-sediment-deformed structures (e.g., contorted bedding, oversteepened cross bedding, loading, flame, sand volcanoes, pillar/dish) occur within these deposits (Fig. 5D). This association is interpreted to have formed in a high-energy, shallow marine environment above the storm wave base and close to the fair-weather wave transition, probably on the middle to upper shoreface (Rossetti, 1996a). Tidal influence is suggested by structures attributed to ebb/flood tidal bundle sequences (i.e., the alternating thick/thin sandstone bundles with reactivation surfaces/mud drapes).

3.2. Facies association 2

This association forms a single unit up to 5 m thick of fine- to medium-grained sandstone with horizontal to very low-angle, either northeast- or southwestward-oriented beach face lamination, and complex lamination. The latter consists of complexly intersecting, cross-laminated sets centimeters to decimeters thick and with a variety of features attributed to wave oscillation, including: (a) chevron lamination; (b) lamination with opposed-bundled upbuilding; (c) laminations that offshoot against adjacent sets; (d) laminations that contrast with the preserved ripple form; and (e) intricate, interwoven, cross-laminated sets (Fig. 6). This association is attributed to deposition in the transition to or above the fair-weather wave base, in the shallower waters of the foreshore zone (Rossetti, 1996a,b).

3.3. Facies association 3

This consists of cross-stratified sandstone with a basal undulating erosive surface mantled by lag of sandstone and/or mudstone intraclasts; though prominent at the outcrop scale, this erosive surface

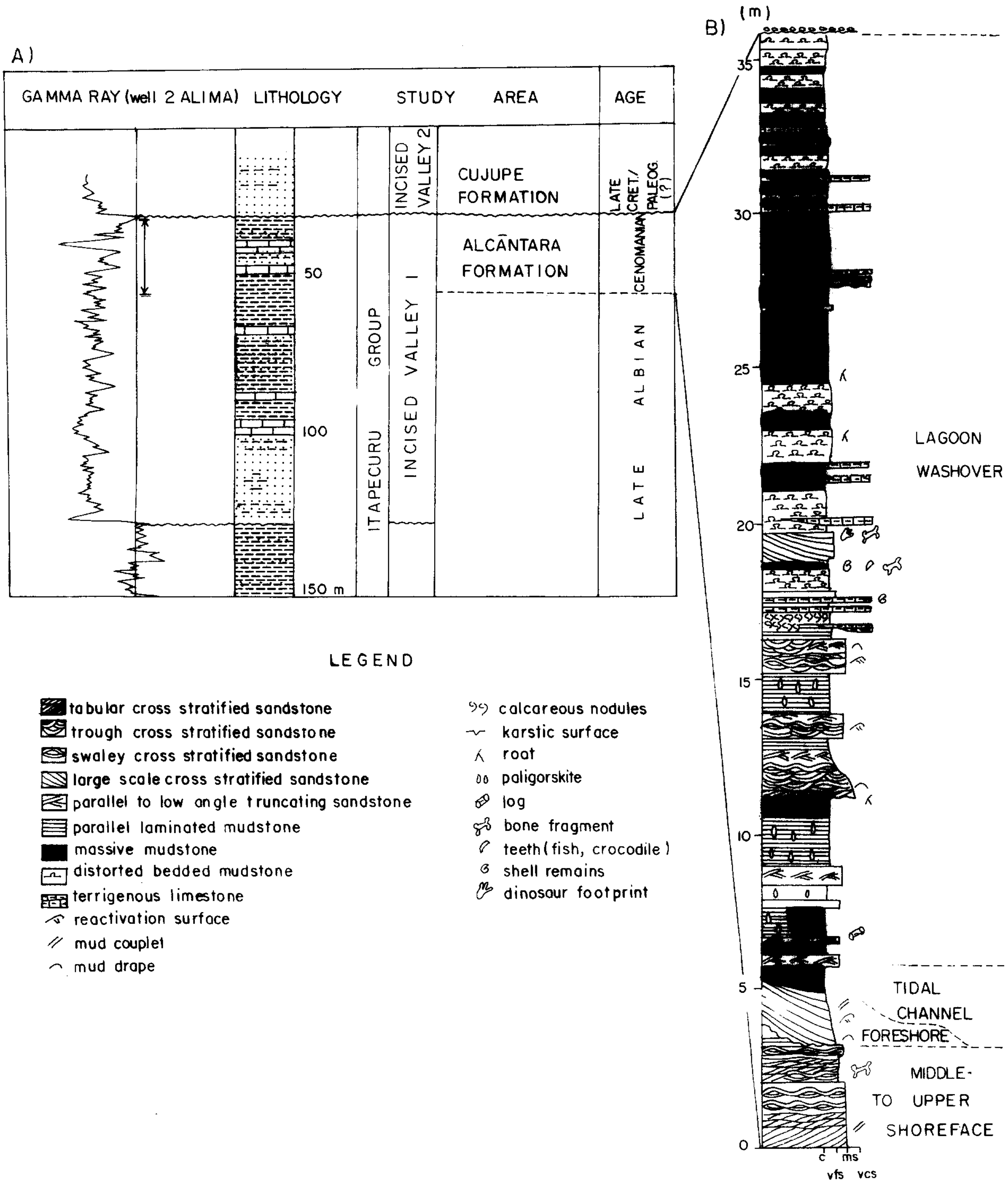

Fig. 3. (A) Stratigraphy of the Itapecuru Group in the eastern margin of the São Luis Basin (See Fig. 1 for well location). (B) Vertical section representative of the Alcântara Formation.

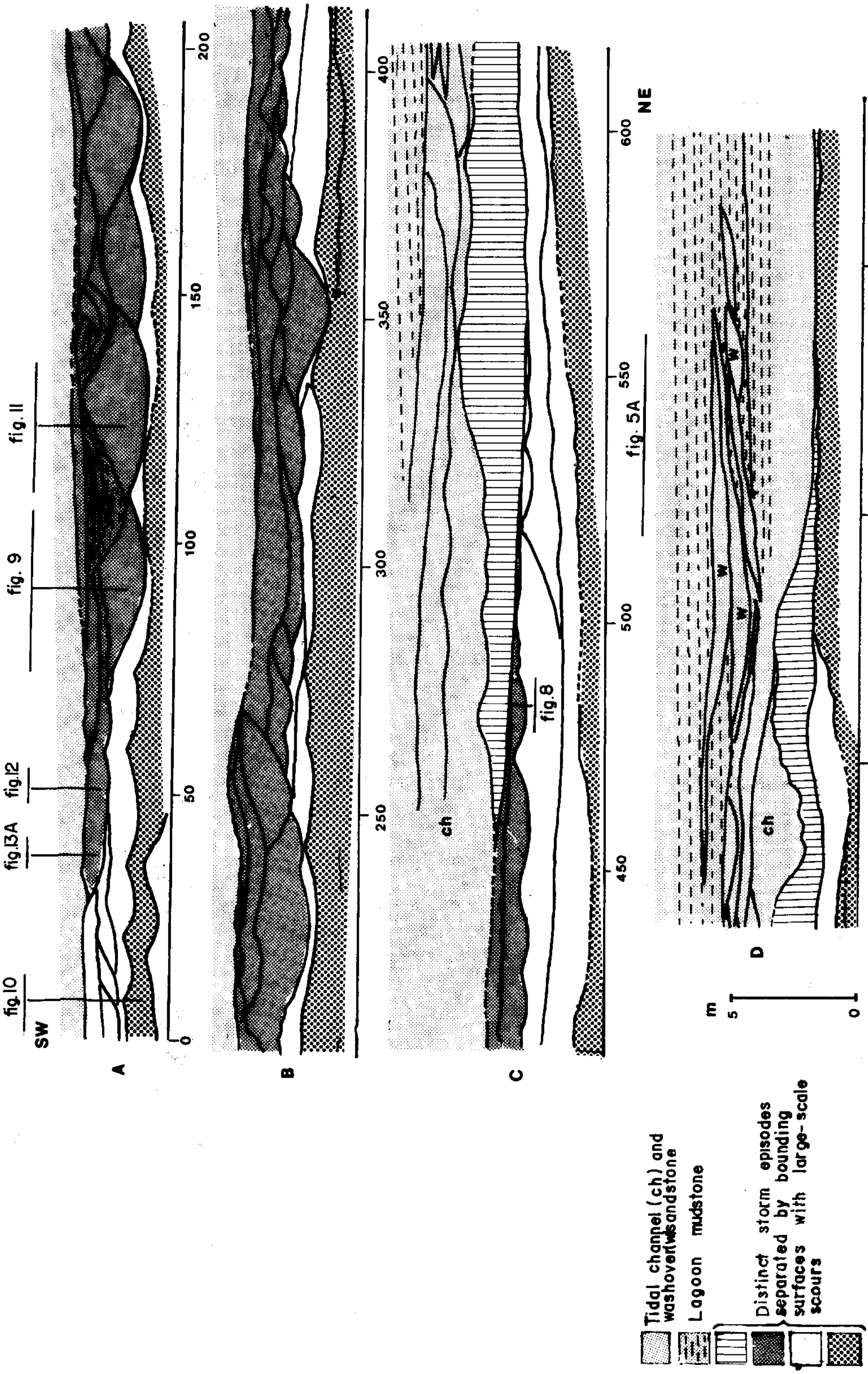

Fig. 4. Simplified geological section at the Livramento Island.

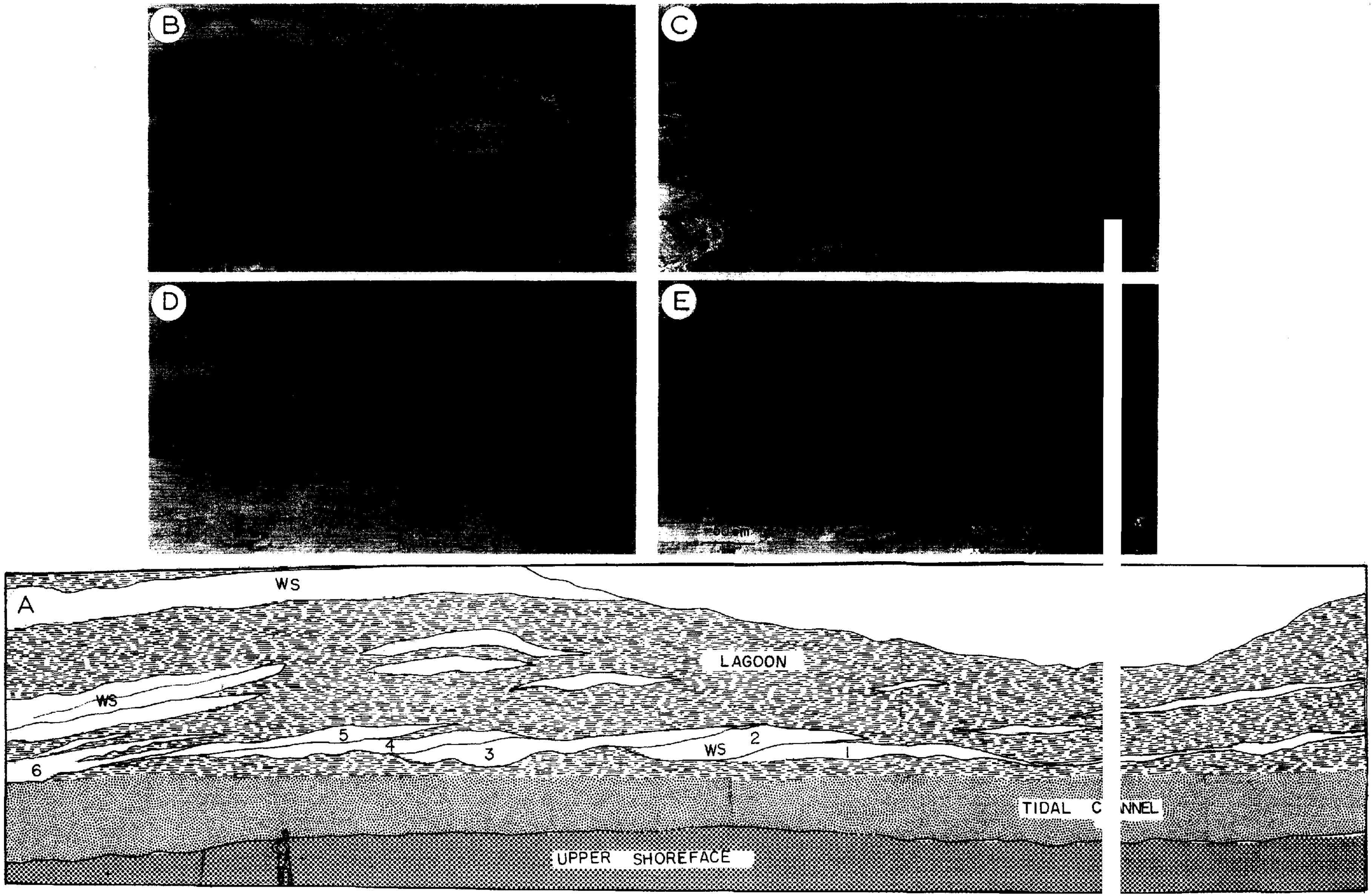

Fig. 5. (A) Drawing of photograph of mid- to upper-shoreface, tidal channel and lagoon/washover deposits of the Alcântara Formation (*WS* = washover fans; *1* to *6* represent the individual sandy lobes within the lagoonal mudstones; see location in Fig. 4). (*B*) Swaley cross-stratified sandstone (mid- to upper-shoreface association). (C) tabular cross-stratified sandstone with alternating thick/thin foreset packages defined by mud drapes and/or reactivation surfaces (mid- to upper-shoreface association). (D) Soft-sediment deformed interval sharply overlain by undeformed deposits (mid- to upper-shoreface association). (E) View of the lagoon deposits with washover sandstones.

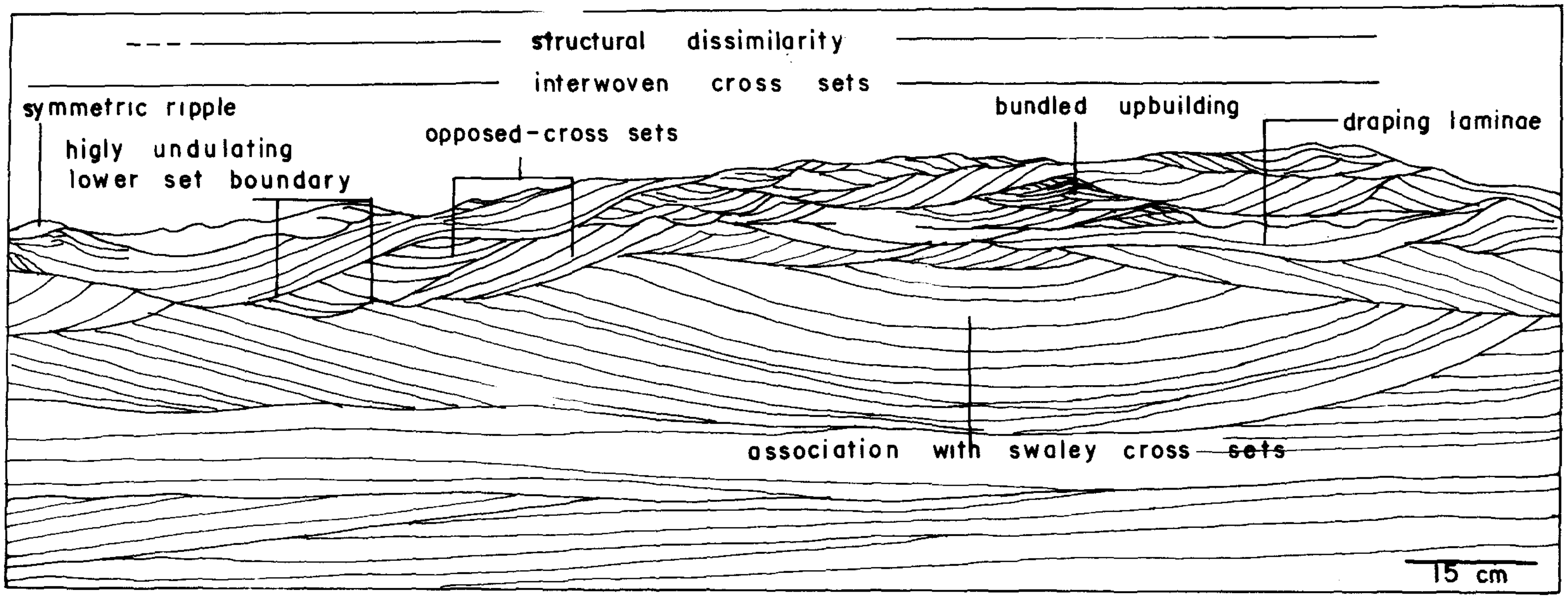

Fig. 6. Drawing of photograph of foreshore deposits showing the several internal structures attributed to wave oscillation.

occurs only at the Livramento Island Section. The deposits are several to many hundreds of meters wide and up to 4 m thick (Fig. 3B and Figs. 4 and 5A). The sandstone is moderately to well-sorted, fine- to medium-grained and internally shows medium-scale (average thickness = 0.40 m), mostly northeastward-oriented, tabular cross stratification. The cross beds show alternating thick/thin bundles, centimeters to several decimeters thick, and defined by mud drapes and/or reactivation surfaces, which are attributed to ebb/flood tidal fluctuations (Rossetti, 1996a). A tidal channel interpretation is proposed for this association with basis on the internal sedimentary features and the basal bounding surface with lag.

3.4. Facies association 4

This consists mostly of laminated, massive or contorted-bedded mudstone with minor sandstone and limestone (Fig. 3B and Figs. 4 and 5A,E). The sandstones are lenticular (lenses up to 2 m thick) and internally show low-angle, tabular and swaley/hummocky cross stratification, and undulating parallel lamination; directional structures from these deposits indicate southwest paleocurrent patterns. The limestone occurs as tabular layers or lenses (averaging 0.20 m in thickness) and displays several features (e.g., nodular fabric, root and root trace; microbreccia; microkarstic surface; and fenestral cavity/birdeyes) attributed to emergence, cementation in the vadose zone, and dissolution due to meteoric water (e.g., Platt and Wright, 1992; Tucker, 1994). The sedimentary structures of facies association 4, added to the presence of the ichnofossil *Gyrolithes*, suggest deposition in a low-energy, coastal setting with fluctuating marine and fresh water input, typical of lagoon and washover settings (Rossetti, 1996a).

The four facies associations of the Alcântara Formation, summarized in Table 1, are attributed to a regressive, barred shoreline (Rossetti, 1996a; Fig. 7). This was roughly southeast/northwest-oriented with land areas to the southeast, as suggested by: (1) the northeast/southwest orientation of beach face lamination; (2) the dominant northeast and subordinate southwest orientation of tidal cross sets; and (3) the southwest progradation of washover deposits (Rossetti, 1996a). The progradation of this barred shoreline is attributed to slow rise in relative sea level during the early highstand stage of the paleovalley evolution (Rossetti, 1996b).

4. Description of the large-scale cross beddings

These structures occur in the mid- to upper-shoreface deposits (facies association 1) of the Alcântara Formation. They consist of large-scale (1–3 m thick) sets of low-angle (10–12°), mostly southwestward-dipping (landward, according to the pro-

Table 1
Summary of the main characteristics of the four facies associations recognized in the Alcântara Formation exposed in the eastern São Luís Basin

Type	Description	Interpretation
1	Sandstones internally dominated by storm-generated, combined flow features (e.g., swaley/hummocky cross stratification, undulating parallel lamination, and large-scale cross stratification). Sandstones are amalgamated and form packages defined by bounding surfaces with regularly spaced scours up to 40 m wide, which are attributed to storm erosion.	Mid- to upper-shoreface
2	Sandstones with an abundance of fair-weather wave-generated structures, which coexist with horizontal to low-angle cross lamination.	Foreshore
3	Sandstone and mudstone with erosive, basal bounding surface, which are commonly concave-up shaped and have intraformational lag. The fill is represented by tidal-generated, sigmoidal cross-stratified sandstone, intraformational conglomerate with sandstone lenses, and heterolithic bedded deposits with features indicative of ebb/flood and neap/spring tidal cycles.	Tidal channel
4	Laminated and massive/deformed mudstones with synaeresis crack, root, and *Gyrolithes* trace fossil, which interfinger with minor layers and lenses of limestone with microkarstic surface, fenestral cavity, nodular fabric, mottling, microbrecciation, and root. Interbedded sandstone lenses with swaley, undulating parallel, and climbing ripple cross lamination.	Lagoon/washover

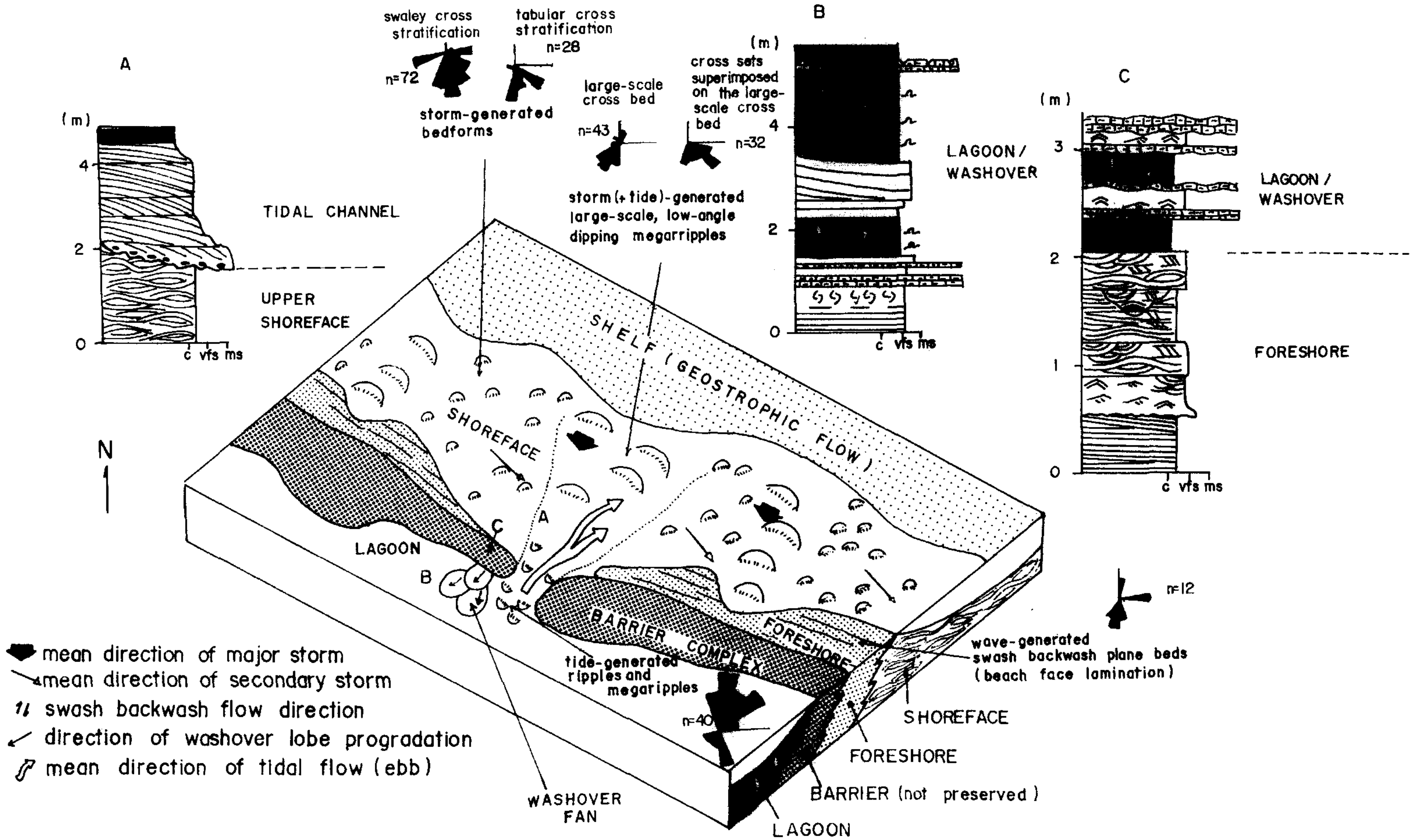

Fig. 7. Diagram illustrating the depositional setting proposed for the Alcântara Formation in the eastern of the São Luís Basin, with the schematic representation of flow distribution, as suggested by the internal sedimentary structures. The diagram also shows the bedforms and deposits formed in response to storm-generated combined flows approaching the tidal-influenced, prograding barred coast.

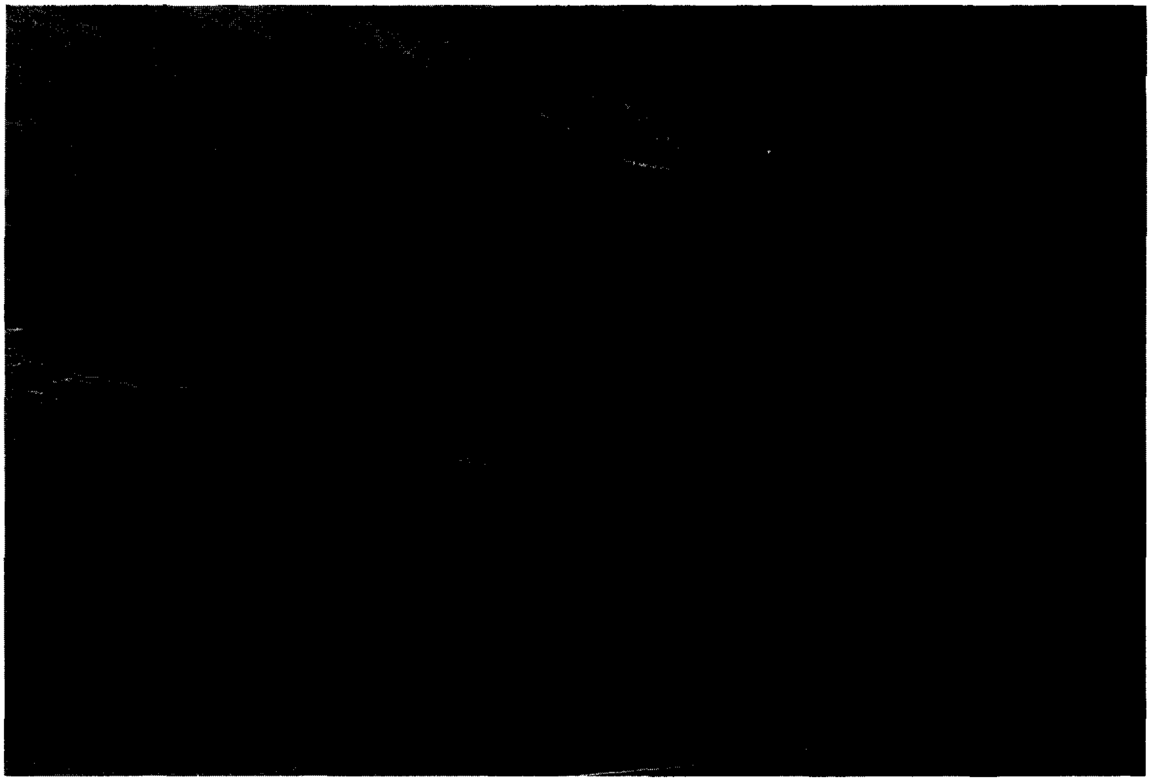

Fig. 8. View of a large-scale, symmetric scour with superimposed, ripple marks (arrows) cutting down into large-scale, low-angle cross-bedded sandstone. Note that the scours are mantled by a lag of intraclasts (see location in Fig. 4).

posed paleoshoreline) beds (Fig. 7) with a complex hierarchy of internal bounding surfaces, recognized on the basis of crosscutting relationships. The large-scale cross-stratified deposits form distinct intervals bounded by erosive surfaces with large-scale (up to 40 m wide) scours (the E_1 surfaces cited below) mantled by a lag of intraclasts. The scours (Fig. 8) are characterized by regularly spaced distribution, either symmetrical or asymmetrical shapes, and superimposed current and wave ripple marks, which altogether indicate erosion by storm waves (see later discussion). Within each interval, the large-scale cross beds are closely intergraded with swaley, tabular/trough cross stratification, and undulating parallel-laminated sandstones. The large-scale cross beds are particularly well developed in the central part of the Livramento Island Section (between 30 and 500 m in Fig. 4), where the scoured-bounding surface shows a broad concave-up configuration. Several styles were recognized, based on the internal sedimentary structures: (1) simple foreset bedding; (2) compound bedding; (3) mixed bedding; (4) undulatory bedding; and (5) intricate-bounded bedding.

4.1. Simple foreset bedding

This type of sedimentary feature consists exclusively of low-angle (5° to 8° in average) dipping foresets separated by discontinuity surfaces (Fig. 9A,B). Three hierarchies of bounding surfaces are internally recognized. First-order (E_1) surfaces bound the strata with simple foreset units. E_1 surfaces truncate second-order (E_2) surfaces. The latter occur either isolated or in groups of 3–5 sigmoidal- to tangential-shaped surfaces spaced at intervals averaging a few decimeters in thickness. E_2 surfaces truncate third-order (E_3) surfaces which, in turn, bound packages of foresets 5–10 cm thick. E_3 surfaces are only slightly discordant to the underlying foresets, being better defined if thin mud drapes and/or intraclasts

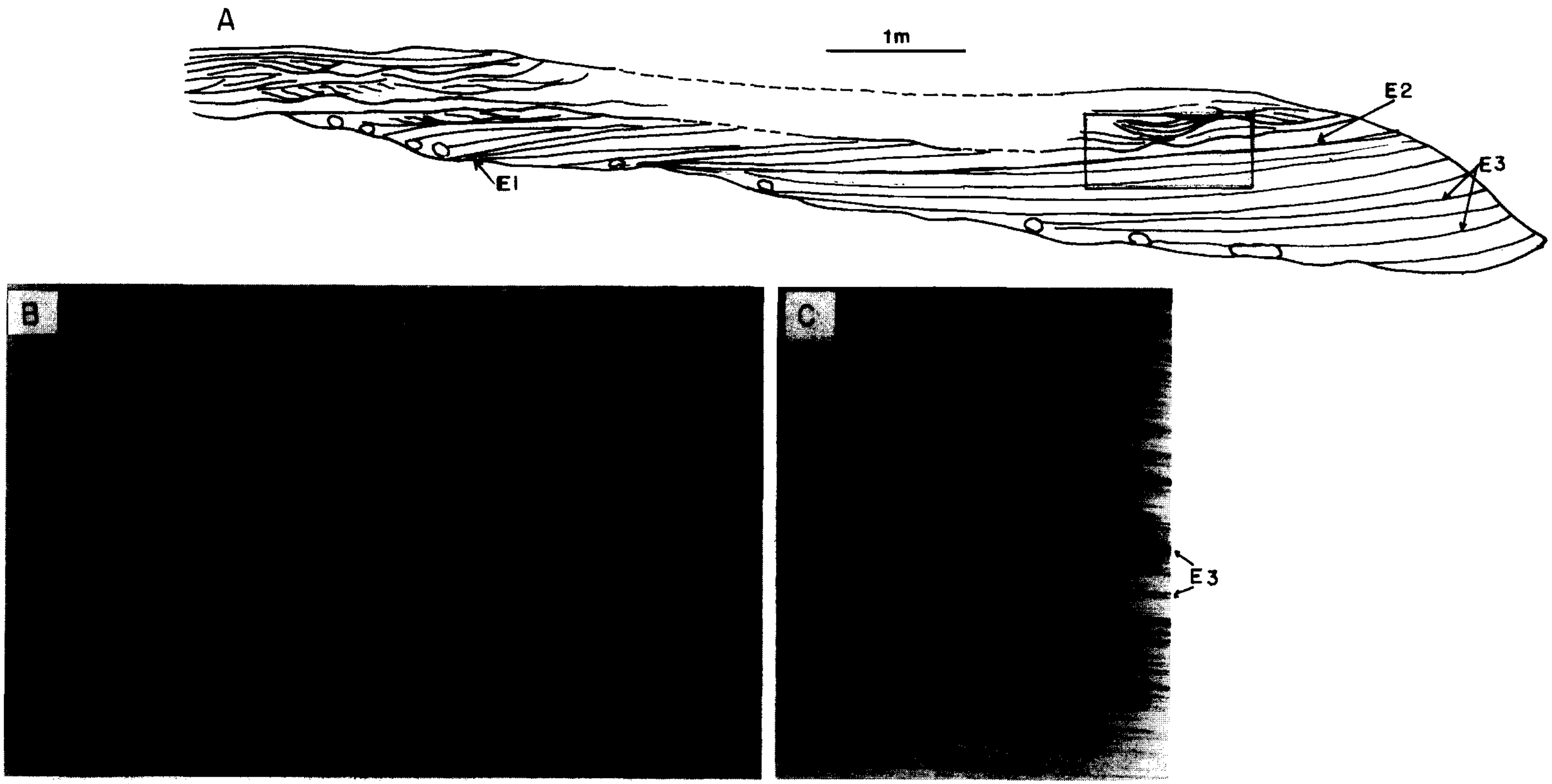

Fig. 9. (A, B) Large-scale, low-angle cross-bedded sandstone: simple foreset style (the inside box in A shows the location of B). (C) Detail of a simple foreset bedding showing well developed thick/thin sandstone packages within E_3 bounding surfaces. E_1–E_3 = bounding surfaces; see location in Fig. 4.

are present; locally, regularly spaced, thick/thin sandstone bundle sequences defined by reactivation surfaces and/or mud drapes are recognized (Fig. 9C). This type of surface may lose its erosive character laterally, becoming essentially conformable with the bedding. Both E_3 surfaces and internal foresets display concave-upward to sigmoidal shape.

4.2. Compound bedding

This is a type of structure defined by large-scale, gently dipping bedding (= master bedding) with superimposed, millimeter- to centimeter-scale, cross-laminated, and minor parallel-laminated sets and cosets (Fig. 10); the subsidiary cross sets dip southeast (i.e., oblique to shore parallel; Fig. 7). Four orders of bounding surfaces are identified, which are ranked E_1 to E_4. First-order (E_1) surfaces are the scoured surfaces at the set boundaries. Second-order (E_2) surfaces are defined as internal discontinuity truncated by E_1 surfaces, which in turn truncate E_3 surfaces. They are gently inclined (<10°), sigmoidal- to sinusoidal-shaped, and marked by 1–2 cm thick muddy partings, which locally thicken up to 10 cm. Most of the E_2 surfaces are located in a position that consistently coincides with the joining points between large scours developed along E_1 surfaces. Third-order (E_3) surfaces correspond to closely spaced, regularly distributed surfaces that bound cross- and parallel-laminated sets and cosets; thus, they are the surfaces that define the compound bedding. E_3 surfaces dip at angles averaging 7°, but which exceptionally reach up to 18°. Their shape is variable, ranging from roughly straight, tangential, sigmoidal, to sinusoidal. The subsidiary cross sets commonly ascend (climbing up the large-scale foresets), though descending cross sets are locally present. The climbing cross sets have highly undulating boundaries, occur even within very coarse- to pebbly-grained sandstones, and are particularly well developed in the uppermost reaches of the compound bedding, where they grade from parallel to low-angle cross laminations. Intervening ripples with either symmetrical or asymmetrical form show unidirectional (southeastward-oriented) cross laminae (Fig. 7). Finally, fourth-order (E_4) surfaces are defined as minor discontinuities that separate millimeter- to decimeter-thick packages of foreset laminations bounded by E_3 surfaces. E_4 surfaces are regularly spaced, highly tangential-shaped, and commonly marked by muddy partings.

4.3. Mixed bedding

This type of structure consists of a combination of simple foreset and compound bedding arranged in variable proportions (Fig. 11). Mixed bedding shows essentially the same hierarchy of internal bounding surfaces recognized within compound cross bedding; however, a number of intermediate, minor erosion surfaces may occur, increasing the degree of internal complexity. In addition, the climbing cross sets with undulating boundaries that occur in this structural style are replaced by and/or interbedded with small-

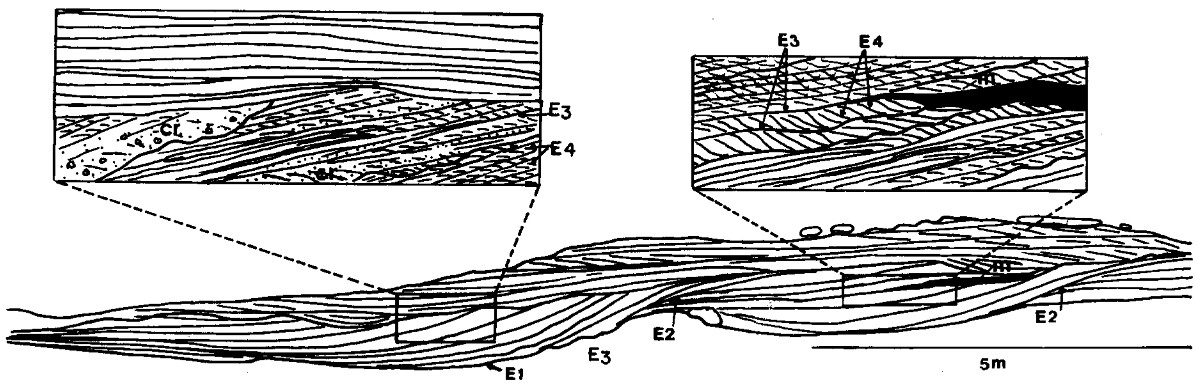

Fig. 10. Large-scale, low-angle cross-bedded sandstone: compound bedding style. The two blow outs illustrate details of the internal stratification, characterized by superimposed, climbing cross sets with undulating boundaries (E_3) and reactivation surfaces (E_4). (*cr* = coarse-grained cross-stratified sandstone; *m* = abnormally thick mudstone drape; E_1–E_4 = bounding surfaces; see location in Fig. 4.)

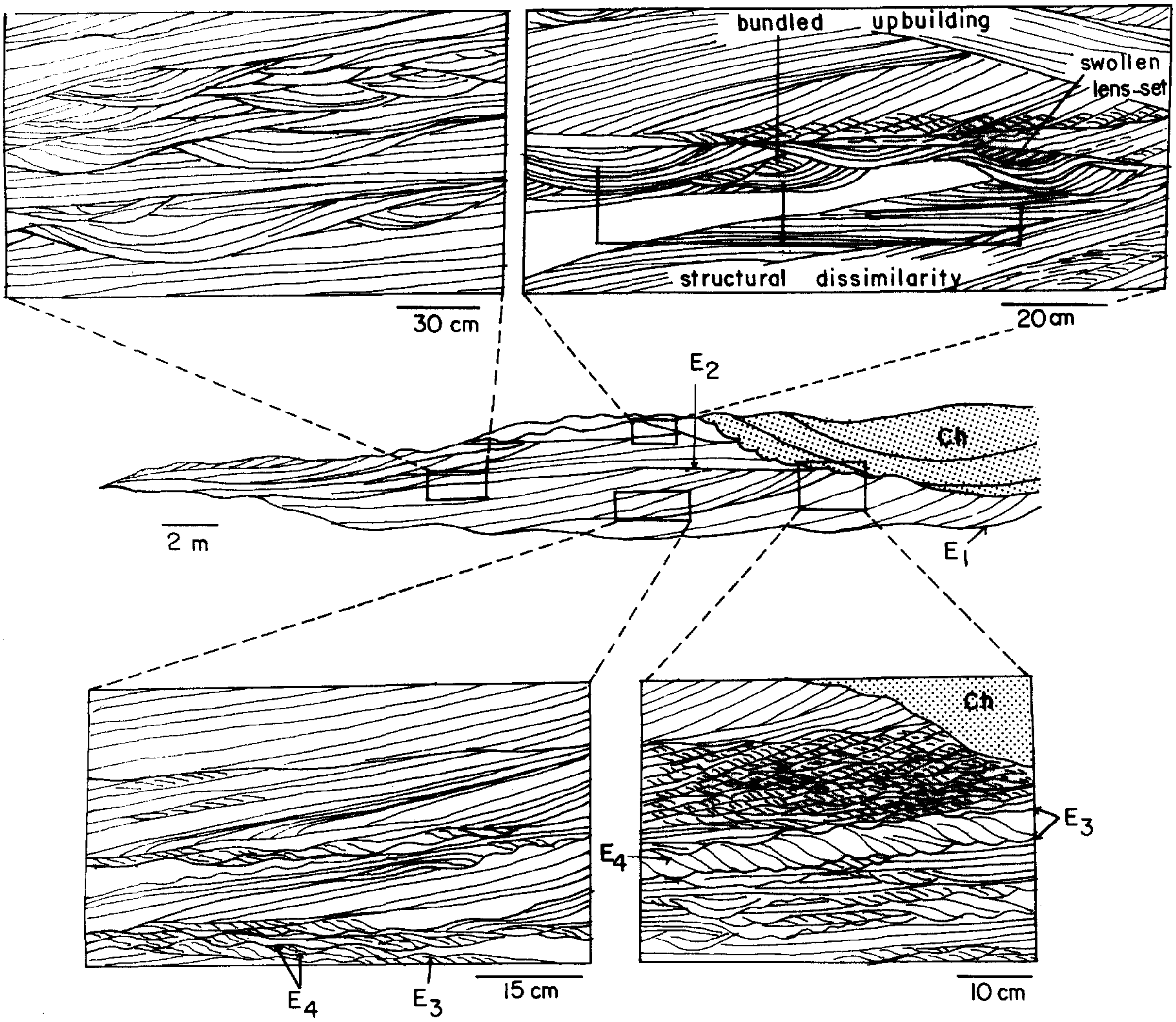

Fig. 11. Large-scale, low-angle cross-bedded sandstone: mixed bedding style. The two blow outs show details of the internal stratification characterized by alternating simple foreset and compound beddings. (*Ch* = channel; E_1–E_4 = bounding surfaces; see location in Fig. 4.)

to medium-scale, swaley cross sets (Fig. 11). Ripple and megaripple (mostly symmetrical) formsets are well preserved, being internally characterized by a variety of combined (unidirectional and oscillatory component) flow-generated features characterized by: (a) internal structures that change rapidly within short distances (structural dissimilarity); (b) laminations that dip in one direction that contrast with the symmetrical form sets; (c) oppositely dipping, bundled upbuilding laminations; (d) chevron laminations; and (e) swollen lens-like set laminations (Fig. 11).

4.4. Undulatory bedding

This type of structure consists of large-scale, low-angle cross bedding (<12°) bounded by heterolithic, undulating laminations that truncate one another by lateral thickening and condensation, forming swell-and-pinch-like laminations (Fig. 12); normal grading is observed between the undulatory laminae. The internal bounding surfaces of this type of structure are similar to those in the simple foreset beddings. The undulatory surfaces are ranked as E_3 surfaces; these are relatively steep on one side ('upflow'),

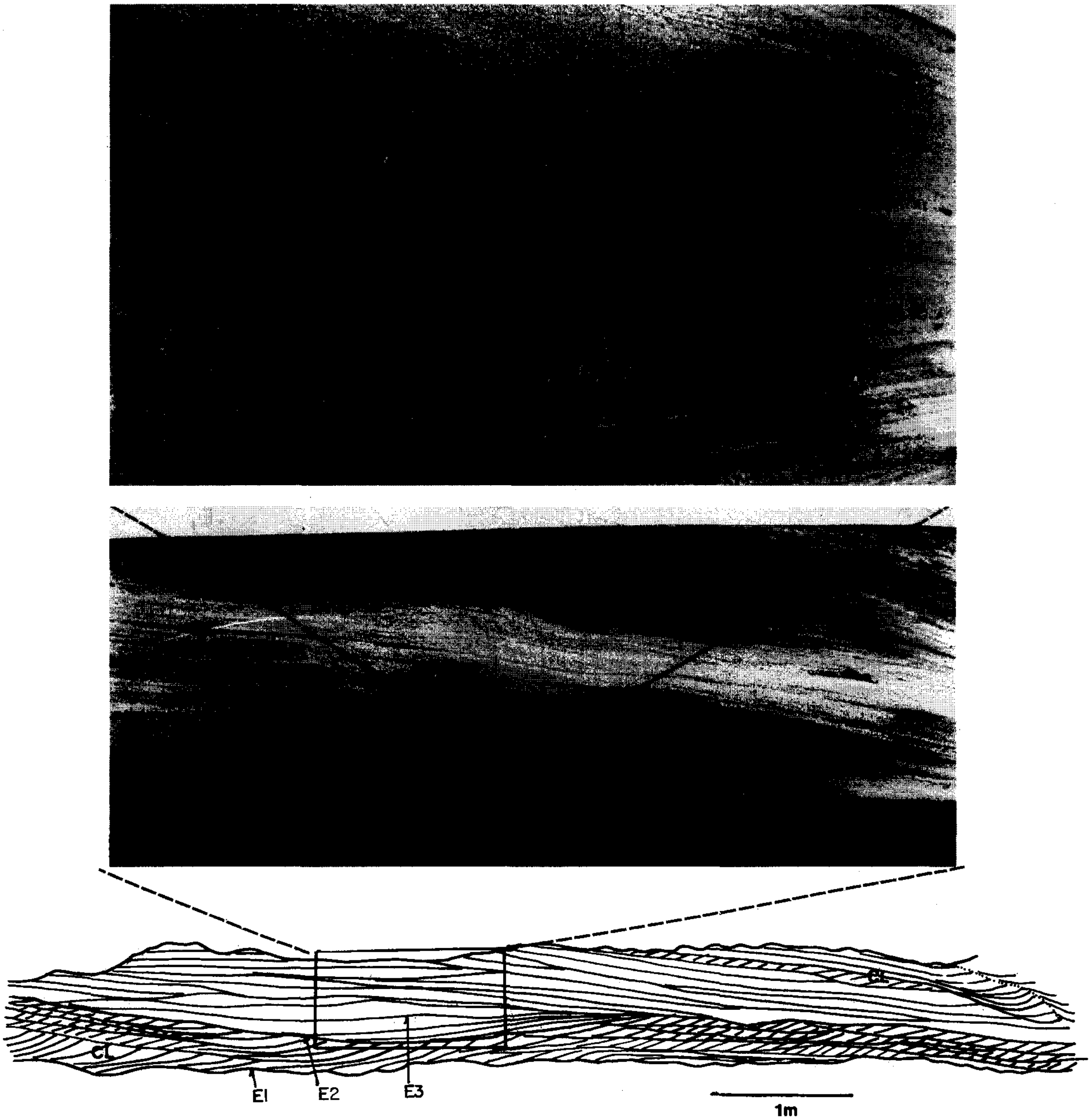

Fig. 12. Large-scale, low-angle cross-bedded sandstone: undulatory bedding style. Note the transition of this type of bedding into climbing cross sets (*CL*). (E_1–E_3 = bounding surfaces; see location in Fig. 4.)

but grade into very low-angle-dipping surfaces on the opposite side ('downflow'), where they also become closer-spaced. The strata bounded by the swell-and-pinch surfaces thin upward and show normal grading, which is particularly marked by the upward decrease in size of intraformational mudstone clasts (Fig. 12).

4.5. Intricately bounded bedding

This style of structure differs from the others in having decimeter-scale, cross-laminated and minor parallel-laminated sets bounded by catenary- to scoop-shaped E_3 erosion surfaces (Fig. 13). The

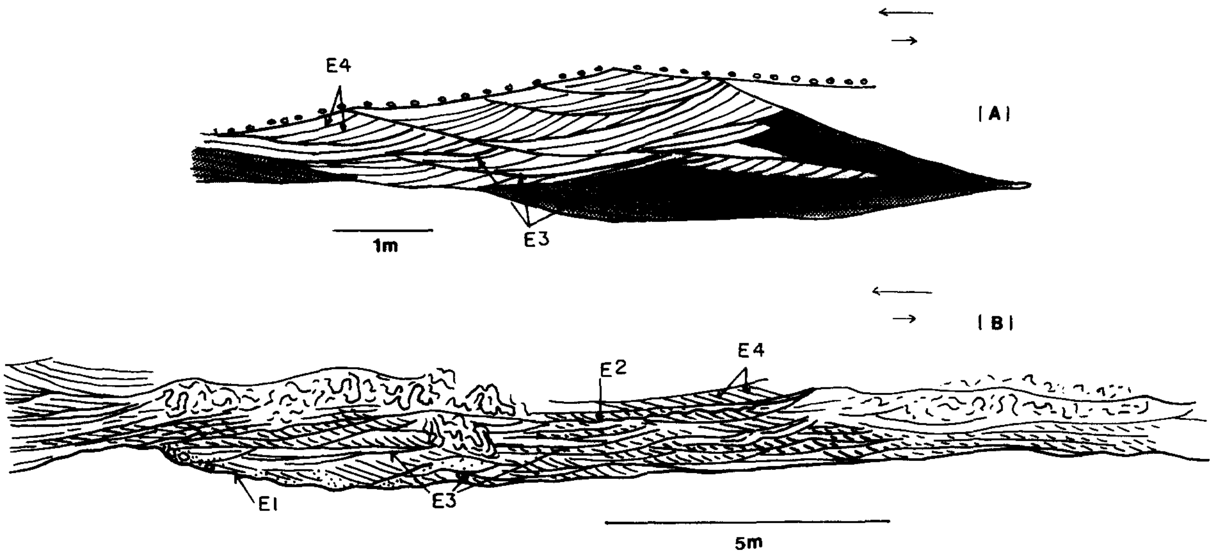

Fig. 13. Large-scale, low-angle cross-bedded sandstone: intricately bounded style with superimposed, oppositely dipping (A), and unidirectional (B) cross sets. (Long arrow = dominant flow direction; short arrow = subordinate flow direction; E_1–E_4 = bounding surfaces; see location of (A) in Fig. 4.)

cross sets of the intricate-bounded beddings are either oppositely dipping in a bundled-upbuilding pattern (Fig. 13A), or dip consistently in the dominant 'upflow' direction (Fig. 13B). Four bounding surfaces (E_1–E_4) are recognized internally. Similar to all the other styles large-scale cross beddings, the first-order (E_1) surfaces in this case bound the intricate-bounded strata, truncating lower-order surfaces. E_2 are nearly horizontal, undulating surfaces locally mantled by thin mudstone drapes. E_3 surfaces bound the internal sets, and thus they define this type of structure. E_4 are minor discontinuities with mudstone drapes that separate few centimeters thick foreset packages bounded by E_3 surfaces.

Among the large-scale structures described above, the compound and mixed types are the most common categories, occurring in almost equal proportion and together making up to 65% of the total volume. The three other styles (i.e., simple foreset, undulatory, and intricate-bounded beddings) make nearly 17%, 13%, and 5%, respectively. All these structures are closely interrelated, laterally succeeding one another within a single stratigraphic interval of the mid- to upper-shoreface setting. For instance, the following trend of large-scale structures occurs intergrading in the dominant flow direction: simple foreset bedding/compound bedding/mixed bedding/simple foreset bedding/undulatory bedding/intricately bounded bedding (Fig. 14).

5. Discussion

5.1. Sedimentary processes

The large-scale, low-angle cross beddings of the Livramento Island Section are attributed to the migration of large-scale bedforms (i.e., bars and/or megaripples) under highly unsteady flows (e.g., Mowbray and Visser, 1984; Chakraborty and Bose, 1990; Simpson and Eriksson, 1991). Similar deposits have been recorded from both tidal (e.g., Houbodt, 1968; Allen, 1980; Dalrymple, 1984), and less commonly, storm settings (e.g., Hobday and Reading, 1972; Swift, 1976; Flemming, 1988; Driese et al., 1991). The lateral coexistence of large-scale cross beddings with combined flow structures (e.g., swaley cross stratification, undulating parallel lamination) and tidal-generated structures (i.e., cross sets with thicker/thinner foreset bundle sequences) suggests a genesis linked to both tidal and storm processes. The sedimentary features associated with the several styles of large-scale cross beddings described here is consistent with such proposition. The tidal signature is particularly recorded in the simple foreset bedding

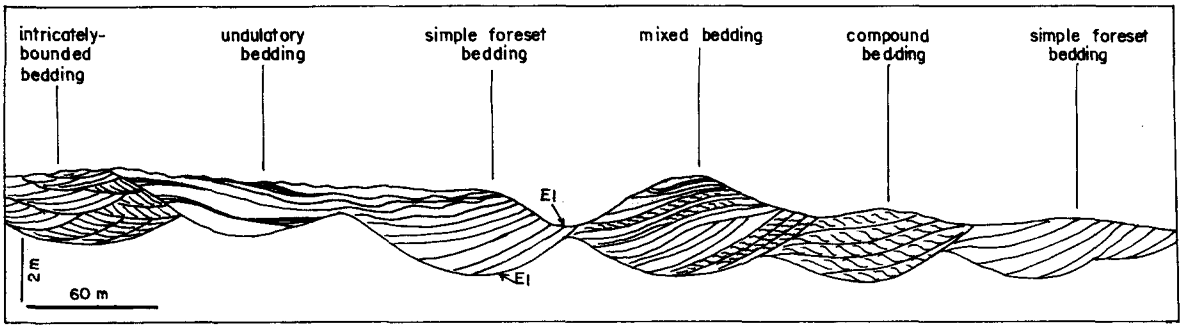

Fig. 14. Lateral change of structural styles of large-scale cross beddings found in the Livramento Island Section. (E_1 = bounding surface; see location in Fig. 4.)

by the thick/thin sandstone bundle sequences, which are diagnostic of ebb/flood tidal oscillations (e.g., Koster, 1983; Yang and Nio, 1985; Nio and Yang, 1991).

A number of features record the influence of storms during the genesis of the large-scale cross beddings. First, the dominance of large-scale cross stratification with very low dip angles (i.e., 10–12°) and the compound sets dominated by small-scale climbing, instead of descending, cross sets are better attributed to storm processes. This is suggested because storm-generated flows typically favor both bedforms with gently dipping slipfaces, and sediment-laden suspensions, which promote the development of abundant low-angle-dipping strata and climbing cross lamination, respectively (Nøttvedt and Kreisa, 1987; Arnott, 1992). Second, the undulatory bedding style is attributed to the action of oscillatory flows, based on comparisons with wave-generated structures (Boersma, 1970; de Raaf et al., 1977); however, the large scale of the undulatory sets of this instance is more consistent with the action of large, storm waves. Third, the lateral transition from compound and simple foreset beddings into intricately bounded bedding suggests rapid changes within short distances from asymmetric bedforms (with well-defined flow separation) to symmetric/nearly symmetric bedforms (with reduced or no flow separation), which is also consistent with a storm action. Subtle changes in flows were required to produce such features. The numerous downflow transitions from simple foreset bedding type show frequent changes in flow type even during the development of a single bedform. These characteristics are not common with purely tidal-influenced settings. Thus, it is more probable that storm-generated flows would have interacted with local tidal currents to temporarily reinforce and/or modify the bedform geometry, resulting in deposits characterized by laterally variable internal structures.

The storm influence during deposition of the large-scale cross beddings is further consistent with the details of the internal bounding surfaces. Hence, the scours in the E_1 bounding surfaces are better explained under storm conditions because of: (a) the presence of both symmetric and asymmetric shapes; (b) the large scale; (c) the regular, repetitive nature; and (d) the presence of both current and wave ripples. Such characteristics denote the coexistence of oscillatory and unidirectional motions, and the oscillation of large, thus more likely storm-generated flows. Similar features in the Silurian Whirlpool Sandstone of southern Ontario, Canada, have also been attributed to storm flows (Cheel and Middleton, 1993). During maximum strength, storm-enhanced tidal flows caused the downward erosion of the mid- to upper-shoreface (Fig. 15A), and promoted the development of the large-scale scours described herein (e.g., Swift et al., 1983). As the storm energy decreased, sediment was rapidly deposited, preserving the scoured surface (Fig. 15B). Intense storm scouring resulted in local channeling, which is recorded in the places where the bounding surfaces adopt a broad, concave-up configuration. Similar channels have been observed in other ancient shoreface settings (e.g., Duke et al., 1991).

The E_2 erosion surfaces of the large-scale cross beddings probably record changes in flow velocity as the bedforms migrated over the swaley morphology of the underlying E_1 bounding surfaces (Fig. 15B).

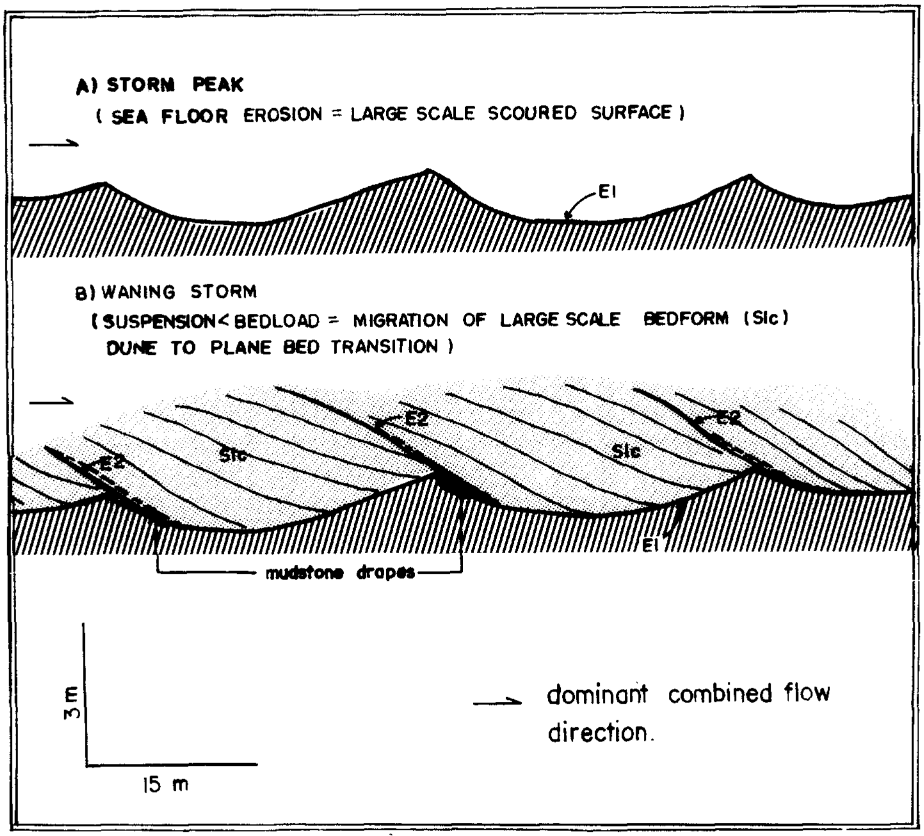

Fig. 15. Diagram illustrating the proposed origin of E_1 and E_2 bounding surfaces of the large-scale, low-angle cross beddings described in the text. (A) During maximum strength, storm-generated combined flow reworked the sea floor and produced erosion surfaces with large-scale, symmetrical and asymmetrical scours (E_1 bounding surfaces). (B) As the storm energy decreased, sediment was rapidly deposited, which resulted in the preservation of the scoured surfaces. The E_2 surfaces formed when the flow decelerated as it passed over the deeper scoured portion of the swales.

The occurrence of E_2 surfaces invariably at the connection between large-scale swales is consistent with this interpretation. Migrating bedforms would have slowed when passing from one swale to another due to flow deceleration, resulting in relatively steeper-dipping erosion surfaces, i.e., the E_2 type. The gently dipping E_3 surfaces are attributed to the climbing of smaller-scale bedforms on the slipface of larger ones. Based on comparisons with similar ancient shallow marine deposits (de Raaf et al., 1977), these cross sets are interpreted to have formed by the interaction of orbital and unidirectional flows, as shown by: (a) the highly undulating set boundaries; (b) the transition of unidirectional cross sets into cross sets with symmetrical profiles, but with internal features that frequently changed from bundled-upbuilding to chevron and swollen lens-like laminations; (c) the transition into swaley cross sets; and (d) the lateral gradation from parallel lamination to cross lamination with progressively increasing dip angles. The regularly spaced, E_4 surfaces that separate foreset packages reflect minor erosion on the lee face of superimposed bedforms due to short-term, but periodic fluctuations in flow velocity.

The shape of E_3 bounding surfaces can be used as a basis to interpret the flow conditions in which the large bedforms developed. Because these surfaces formed by the migration of smaller bedforms on the slipface of larger ones, their overall morphology roughly reflects the shape of the large bedform slipface. Based on this approximation, it is concluded that the large bedforms had very low-angle-dipping slipfaces with tangential to sigmoidal shapes. Similar bedforms are well known from settings in which suspended load dominates bedload (e.g., Collinson and Thompson, 1982). Such flow regime results in rapid vertical accretion, simultaneously with bedform migration under flow close to the dune–plane bed transition (e.g., Joppling, 1965; Bagnold, 1966).

The combination of upper flow regime conditions and low-angle-dipping slipfaces might explain the low frequency of descending cross sets in the large-scale cross beddings. It is proposed that as the dominant flow-oriented ripples reached the brink point of the large bedforms, sand was deposited either as parallel laminae or laminae dipping only slightly more steeply than the large bedform slipfaces. The dominance of ascending cross sets resulted from a combination of three factors: (a) rapid vertical bed accretion; (b) gently inclined slipfaces, which promoted the easy ascent of superimposed ripples; and (c) subordinate current strong enough to produce upstream-driven ripples.

5.2. Storm type

Following Bruun's rule (Bruun, 1962) many authors have argued that oceanic storms acting in nearshore areas result dominantly in erosion and offshore transport of suspended sediment (e.g., Brenchley and Newall, 1982; Swift et al., 1983; McCave, 1985). As a consequence, the ancient record of nearshore settings would be dominated by fair-weather deposits interrupted occasionally by erosive surfaces formed by the effect of storms (Hobday and Reading, 1972). Different mechanisms have been proposed to explain the offshore sand transport, mostly including surge ebb, wind-forced currents, wind-forced downwelling, coastal jets and turbidity currents (e.g., Morton, 1981; Brenchley and Newall, 1982; Swift et al., 1983; Walker, 1984; Brenchley et al., 1986).

The dominance of storm deposits in the shoreface setting of the Alcântara Formation and the analysis of the paleocurrent pattern make it impossible to adopt any of the above-mentioned interpretations for the study area. Considering the proposed paleocoast orientation, the southwestward-oriented, large-scale cross-bedded sandstone discussed herein indicates that the shoreface area was affected by a main landward-moving flow (Fig. 7). Detailed analysis of the internal sedimentary features in these beds suggests the influence of an external (i.e., storm) flow. The mechanisms responsible for an onshore, storm-driven flow is debatable. Erratic storm waves associated with pressure gradient formed by strong winds blowing over coastal waters of the continental shelf are refracted to nearly shore-normal directions in the nearshore area due to the shoaling effect (Duke et al., 1991). Thus, one hypothesis is that the interaction of such storm waves with flood-tidal currents would have produced the landward combined flows, which resulted in the large-scale structures described here. However, the development of such oceanic storms is unlikely in this case, considering the low paleolatitude (i.e., 5–8°S) of the North Brazilian coast during the deposition of the Alcântara Formation (Scotese et al., 1989). This paleolatitude rather indicates that the study area was located outside of the belt favorable for the development of oceanic storms, which is 10–45° for hurricanes and summer tropical storms and above 25° for winter storms (Marsaglia and Klein, 1983; Barron, 1989). Earthquake-generated storm waves (i.e., tsunamis) are thus invoked as an alternative mechanism to explain the storm deposits of the study area. This hypothesis is consistent with the tectonic history proposed for the São Luís Basin during the Late Cretaceous to early Tertiary, when changes in spreading rates induced seismological activities of previous structural lineaments (Azevedo, 1991). Seismic-induced storms are further supported by the presence of several, laterally continuous intervals with faulted blocks, fractures, and a variety of soft-sediment deformed structures between undisturbed deposits, as mentioned earlier. These features are attributed to the combined effects of fluidization, liquefaction, and shear stress formed shortly after deposition of horizontal sedimentary layers, and they are similar to earthquake-induced structures as reported by many workers (e.g., Seilacher, 1969; Sims, 1973; Mayall, 1983; Scott and Price, 1988; Ringrose, 1989).

The seismic-induced storm events would have also caused the development of an oblique- to nearly shore-parallel combined flow, as recorded by the southeastward orientation of both the cross sets superimposed on the large-scale cross beddings and the swaley cross stratification that occurs in asso-

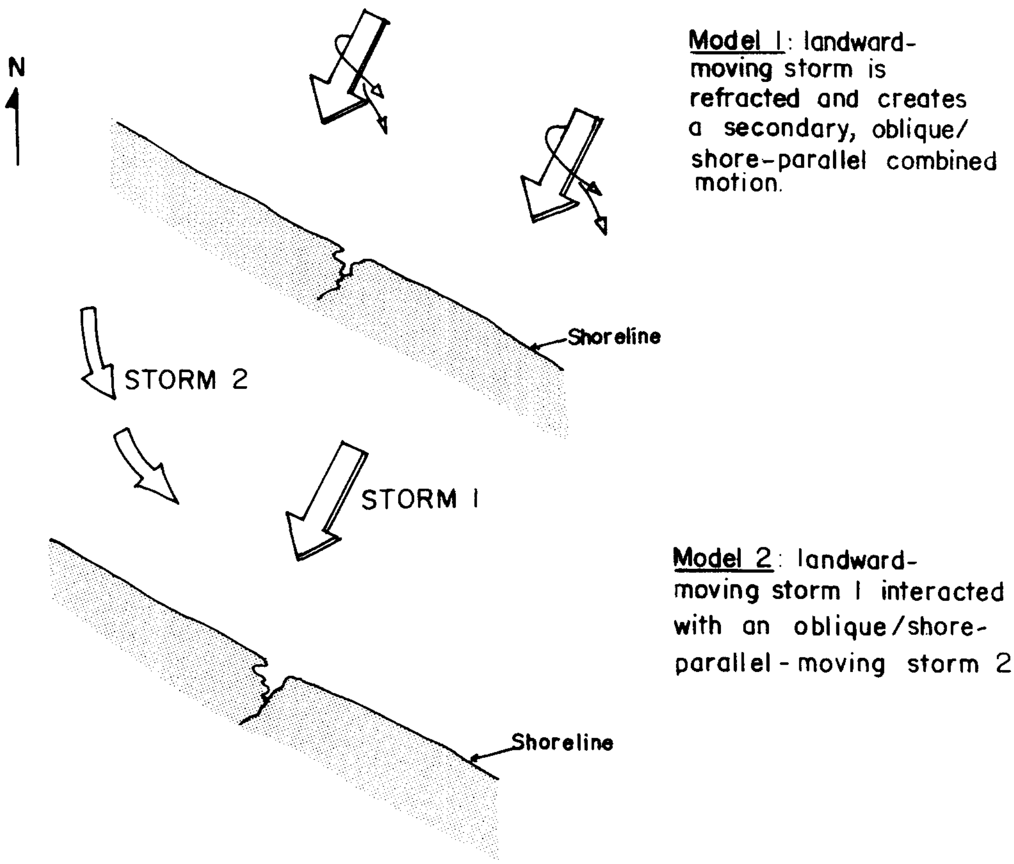

Fig. 16. Diagram illustrating two alternative models to explain the SW- and the SE-oriented, storm-generated, combined flow patterns of the study area.

ciation with these structures (Fig. 7). The origin of such flow pattern in the study area is not well understood; however, the main (landward) moving seismic-generated, storm waves might have been refracted as they approached the coastline, similarly to what has been documented with oceanic storms in many modern and ancient settings (e.g., Swift et al., 1972, 1983; Johnson, 1977; Brenchley et al., 1986; Snedden et al., 1988; Colquhoun, 1995). Alternatively, the southeast-oriented flow might have resulted from a separate, oblique- to shore-parallel storm episode, which would have competed with the major landward-moving storms (Fig. 16).

6. Conclusion

The several styles of large-scale, cross bedding in the mid- to upper-shoreface deposits of the Alcântara Formation exposed in the Livramento Island resulted from migration of large-scale bedforms with slipfaces tangential- to sigmoidal-shaped and profiles that changed rapidly from asymmetric to symmetric/nearly symmetric in the lateral direction. The build-up of such bedforms was favored by the development in a depositional setting experiencing both dominance of suspended load over bedload and highly unsteady flow conditions, close to the dune–plane bed transition. In this instance, such flow regime was promoted by vigorous, combined (unidirectional and oscillatory) flows produced by the interaction of severe storms with fair-weather (i.e., tidal) currents. The paucity of sedimentary structures diagnostic of tidal currents reflects intense reworking of fair-weather deposits during storms.

The introduction of large volumes of sand-size sediments needed to form the large-scale cross beddings discussed in this paper was due to the action of a main landward-moving storm combined with flood-tidal currents, as indicated by the dominance of southwestward paleocurrent orientation. An oblique to shore-parallel flow would have additionally contributed to the formation of the large-scale cross beddings. Such southeast-oriented flow records either the refraction of the main storm waves as they approached the paleocoast or a separate storm episode that would have competed with the main, landward-moving storm event. The paleogeographic reconstruction, the complex tectonic history of the São Luís Basin, and the presence of intervals strongly deformed within undisturbed deposits altogether point to penecontemporaneous seismic shocks as the main cause for these storm events.

The sedimentary features documented in this paper can help identifying similar deposits and reconstruct the flow dynamics in ancient depositional settings. Analogues in the geological record must be more widespread than documented at the moment, considering that tide- and storm-generated flows have been commonly observed to occur simultaneously in many modern marine settings (e.g., Swift et al., 1972, 1983; Stride, 1982; Belderson, 1986). The present study demonstrates that the recognition of mixed tide- and storm-influenced deposits will be unambiguous only if adequate, laterally continuous exposures with well preserved internal features are available.

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