SEISMIC-INDUCED DISTURBANCES IN LATE CRETACEOUS ROCKS OF THE SÃO LUÍS BASIN, MARANHÃO STATE, BRAZIL

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ABSTRACT - Unusual deposits including faults of small displacements, fractures, soft sediment deformation and channel-like (i.e. concave-shaped) structures occurring within undisturbed estuarine strata of the uppermost Itapecurú Formation are attributed to penecontemporaneous sediment disturbances produced by water escape and slumping mechanisms. Such features are considered to be the result of externally-triggered processes associated with seismic shock episodes that affected unconsolidated and/or semiconsolidated deposits. It is possible that seismically-induced movements preferentially affected those areas of the estuary experiencing overloading due to constant sand influx (e.g., tidal deltas, bayhead deltas), which were naturally more susceptible to sediment failure.

KEY WORDS: *Penecontemporaneous disturbances, Seismicity, Late Cretaceous, Itapecurú Formation, Brazil.*

RESUMO - Falhas de pequeno rejeito, fraturas, estruturas de deformação e em forma de canal (côncava) ocorrendo em estratos não perturbados de origem estuarina da parte superior da Formação Itapecurú são atribuídos a perturbações penecontemporâneas à sedimentação, produzidas por mecanismos envolvendo escape de água e escorregamentos. Estas feições são consideradas como resultantes de processos externos, associados com episódios de abalos sísmicos, afetando depósitos não consolidados e/ou semiconsolidados. É possível que movimentos sismicamente induzidos tenham afetado preferencialmente aquelas áreas do estuário já caracterizadas por sobrecarga devido ao constante aporte de areia, naturalmente mais favoráveis à deformação.

PALAVRAS CHAVES: *Perturbações penecontemporâneas, Sismicidade, Cretáceo Superior, Formação Itapecurú, Brasil.*

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INTRODUCTION

The sedimentary record of deposits formed under influence of penecontemporaneous seismic activity has only partly been investigated throughout the Brazilian basins (Raja Gabaglia 1991; Riccomini *et al.* 1991; Coimbra *et al.* 1992; Fernandes & Coimbra 1993). The subject of this paper is the description of probably seismic-induced, disturbed deposits exposed along the Cujupe Pier Road and vicinities of the town of Alcântara, 15 Km north of São Luís, Maranhão State, northern Brazil (Figure 1). Disturbance in these deposits is recorded by various types of brittle and ductile sediment deformation. Particularly well developed are channel-like structures, defined as disturbed strata bounded by basal, gently curved-up discordances.

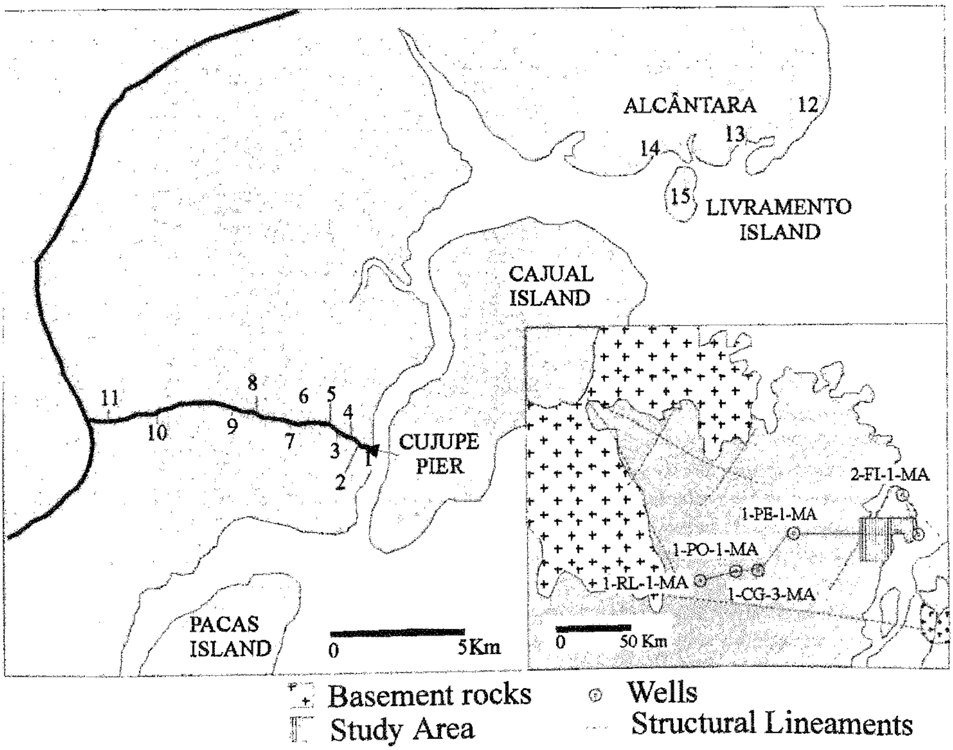

Figure 1 - Map showing location of the study area. (1-11 = location of the geological sections).

The deposits investigated here are located in the eastern portion of the São Luís Basin. This is a NW/SE-oriented structural feature formed by simple shear and strike-slip stress (pull-apart phase) along the Brazilian North Equatorial Margin as a result of the split up of South America and Africa continents in the late Jurassic to early Cretaceous. The sedimentary record of the São Luís Basin is represented by the Codó-Grajaú (Aptian), Lower Itapecurú (Albian), and Upper Itapecurú (Cenomanian to early Tertiary?) formations (Aranha *et al.* 1990; Lima 1994). The Upper Itapecurú Formation is represented in the study area by two estuarine successions belonging to distinct incised valley sequences (Figure 2). The Lower Succession consists of strata circa 30-35 m thick, which are subdivided into 4 facies associations representing tide and/or storm-influenced depositional settings, including: upper shoreface, foreshore, tidal channel, and lagoon/washover complex (Figure 3). High resolution sequence stratigraphic analysis revealed that these settings are confined to the same stratigraphic level, which records a prograding, barred-coastline, probably associated with a wave-dominated estuarine system. The Upper Succession encompasses up to 25 m of deposits comprised entirely of tidal-influenced lithosomes, including: channel, point bar, shoal/sand flat, ebb delta, and subtidal lagoon/bay fill complex. The architectural arrangement of this succession indicates a complex estuarine fill, which reflects environmental (i.e., supply) changes and/or high frequency fluctuations in relative sea level within a main transgressive/regressive cycle. As a result of such fluctuations, the estuary underwent to morphological changes through time, shifting from a wave-dominated to a tide-dominated type. The disturbed deposits documented here occur at distinct stratigraphic levels within both lithological successions described above. For more information about the paleoenvironmental and stratigraphic interpretation of these exposures refer to Rossetti (1996).

DESCRIPTION OF THE STRUCTURES

Unusual deposits in the Lower Estuarine Succession are represented by faulted-blocks of small displacements (averaging 0.20-0.30 cm) and numerous, locally sand-filled, fractures (Figure 4). These features occur in

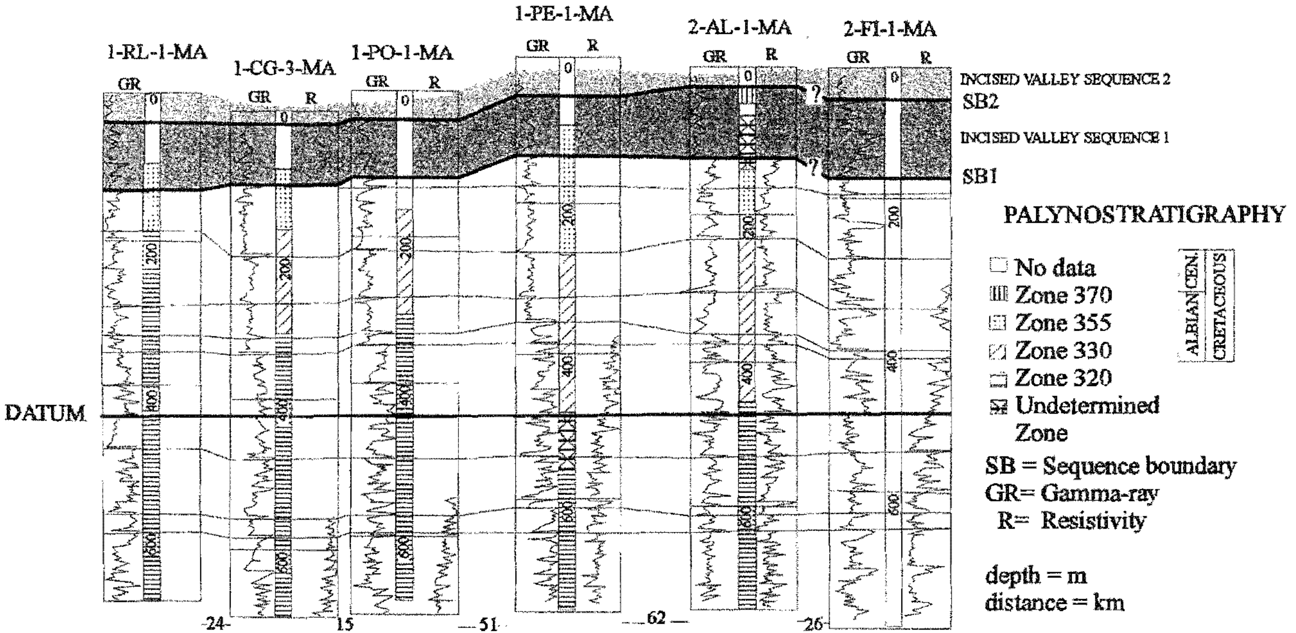

Figure 2 - Subsurface distribution of the two incised valley sequences containing the Lower (sequence I) and Upper (sequence 2) estuarine successions.

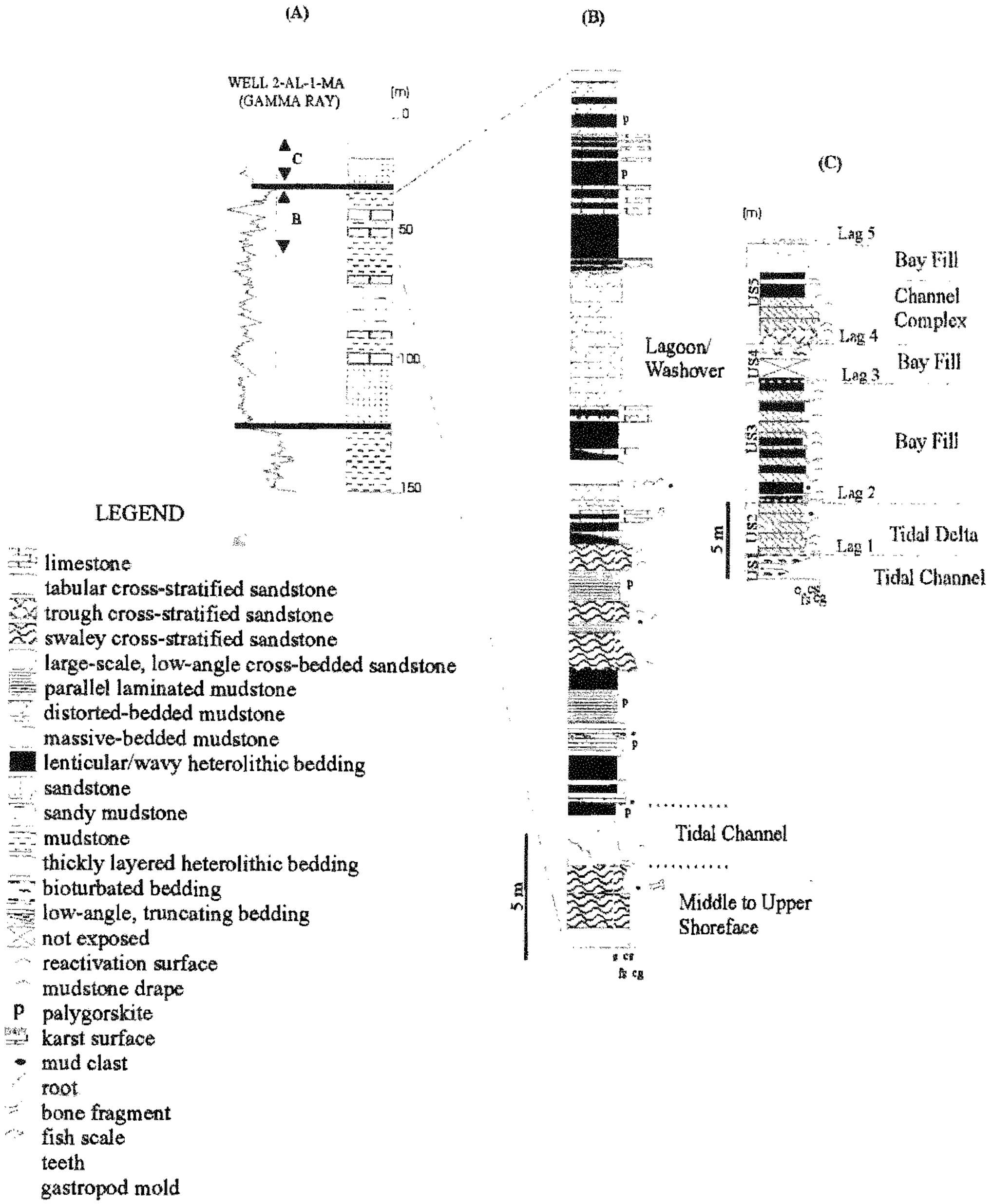

Figure 3 - A) Gamma-ray log and inferred lithology from well 1-AL-1-MA showing the proposed correlation with the studied surface sections; B) measured composite vertical profile of the Lower Estuarine Successio with the main sedimentary features and interpreted depositional settings; C) vertical profile of the Upper Estuarine Succession measured at section. The stratigraphic intervals (US1-US5) bounded by key erosive surfac draped by lag deposits suggest that the Upper Succession represent a complex estuarine fill (Rossetti, 1996). (See figure 1 for location of the well).

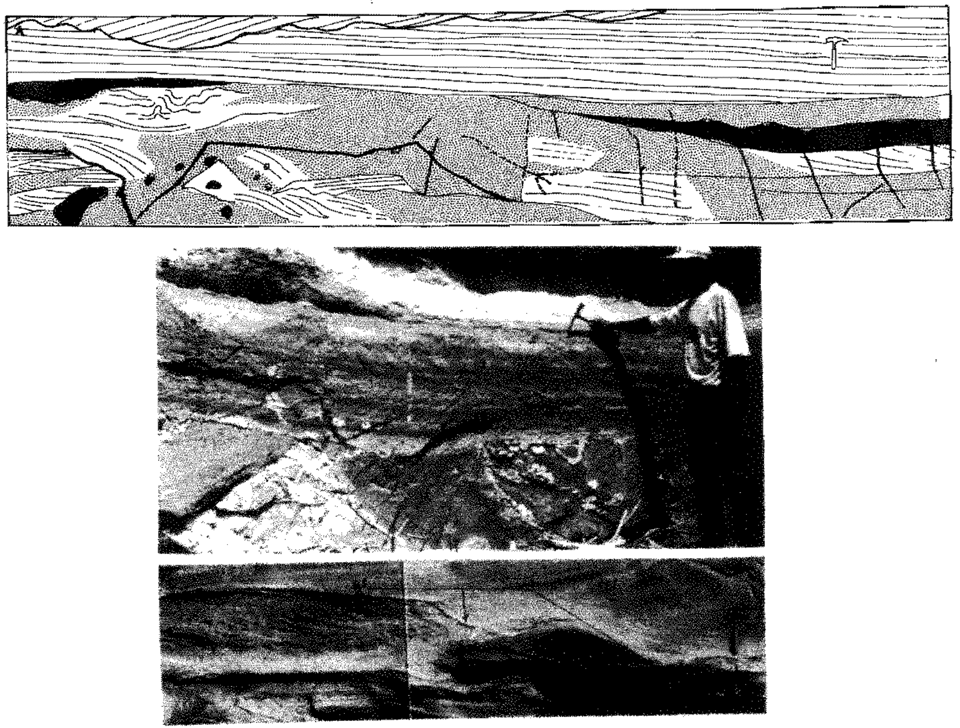

Figure 4 - Disturbed features from the Lower Estuarine Succession, depicting: A,B) faulted-blocks, fractures, and liquefied strata (light, stippled areas). Notice the sharp contact with overlying, undisturbed deposits; and C) sandstone-filled, locally branched-fractures (sf) cutting into cross-stratified shoreface sandstones. (dark, stippled area = mudstone layers/clasts; thick continuous, straight lines = well-developed fractures; thick hatched straight lines = incipient fractures).

Figure 5 - Deformed sandstones. A,B) soft-sediment fold; C,D) dyke (d), oversteepened cross bedding (ov), liquefied layer (ll), liquefied channel (lc), and pillar (p); E)sand volcano (sv).

association with sandstones displaying variable types of soft sediment deformed structures similar to those described by Lowe (1975), which include: fluidized and/or liquefied layers and channels, soft sediment folds, dikes, sand volcanoes, flames, loading and individual pillar/dish structures (Figure 5). Soft sediment folds include well developed synclines and anticlines, as well as oversteepened cross beddings (Figure 5D). Noticeably, all the structures mentioned above are enclosed within invariably undisturbed strata. The thickness of the deformed strata in this lower estuarine succession ranges from few centimeters up to 1 m.

Disturbed strata are even better preserved in the Upper Estuarine Succession, particularly along the Cujupe Pier Road, where they present the following characteristics:

(a) A channel-like geometry, defined by a concave-up-shaped, basal discordant surface (Figure 6-8). This discordance has a relief averaging 20°-30° with respect to the regional bedding, and it is represented by either a single or a composite surface. This latter is formed by the superposition of surfaces successively cutting into one another. These gently curved features reach 150 m wide and nearly 6 m thick;

(b) Composite surfaces at the base of the channel-like deposits separate packets of deformed strata with well-developed soft sediment folds. These are sharply truncated by the immediately overlying surfaces (Figure 6);

(c) The lithological composition of the strata contained by the discordance is either identical or only slightly muddier than the deposits above and below the structure;

(d) The channel-like strata occur in several distinctive stratigraphic levels surrounded by invariably undisturbed deposits;

(e) Within the channel-like feature, deposits immediately overlying the basal discordance are locally deformed into contorted and/or folded beds. However, deformation is confined to the lowest part of the channel-like strata; upward, beds are either undisturbed or display only minor deformation, which invariably disappear in the upward direction;

(f) The channel-like strata form beds that are commonly parallel to sub-parallel to the basal discordance, with the beds onlaping against the walls of the "channels". Bedding is progressively less curved upward, with the uppermost layers becoming horizontal at the top of the structure. In places, strata contained by the curved discordances are steeply dipping at an angle that ranges from 10° to 30° (Figure 9);

g) Strata from the disturbed interval may contain intraformational, collapsed boulders measuring up to 3 m in diameter (Figure 6-7).

In addition to the channel-like strata described above, another type of unusual deposit occurs in the Upper Sequence. It consists of strongly deformed, heterolithic-bedded strata that form breccias. At one place along the Cujupe Pier Road, heterolithic-bedded layers were only slightly disrupted, forming a package of angular clasts averaging 5 m thick. These deposits are surrounded vertically by undisturbed strata.

GENESIS OF THE STRUCTURES

Since the deposits described above are limited to intervals bounded by undisturbed strata, a tectonic origin resulting from post-depositional fault movements was not considered to be plausible. This characteristic indicates that deformation took place simultaneously or immediately following sediment deposition. Hence, the interpretation of the structures described above is more compatible with penecontemporaneous disturbances affecting sediments in an unconsolidated and/or semiconsolidaded state.

The soft sediment deformation of the lower estuarine succession records water escape from highly saturated-sediments. This process results from intergranular movements (Williams 1960) associated with sediment liquefaction and/or fluidization (Lowe 1975; Johnson 1977; Van Loon & Brodzikowski 1987).

The concave-up-shaped structures, though resembling channel geometry, had a more complex genesis than simply by channel scouring. Comparisons with many modern and ancient examples (e. g. Seilacher & Meischner 1968; Collinson & Thompson 1982), indicate that these gently curved features can be attributed to disturbances caused by slump processes. The basal discordance that defines the structure reflects slump shear planes along which the sediment mass failed (slump scars). The deformed deposits immediately overlying the basal plane resulted from mass movement during

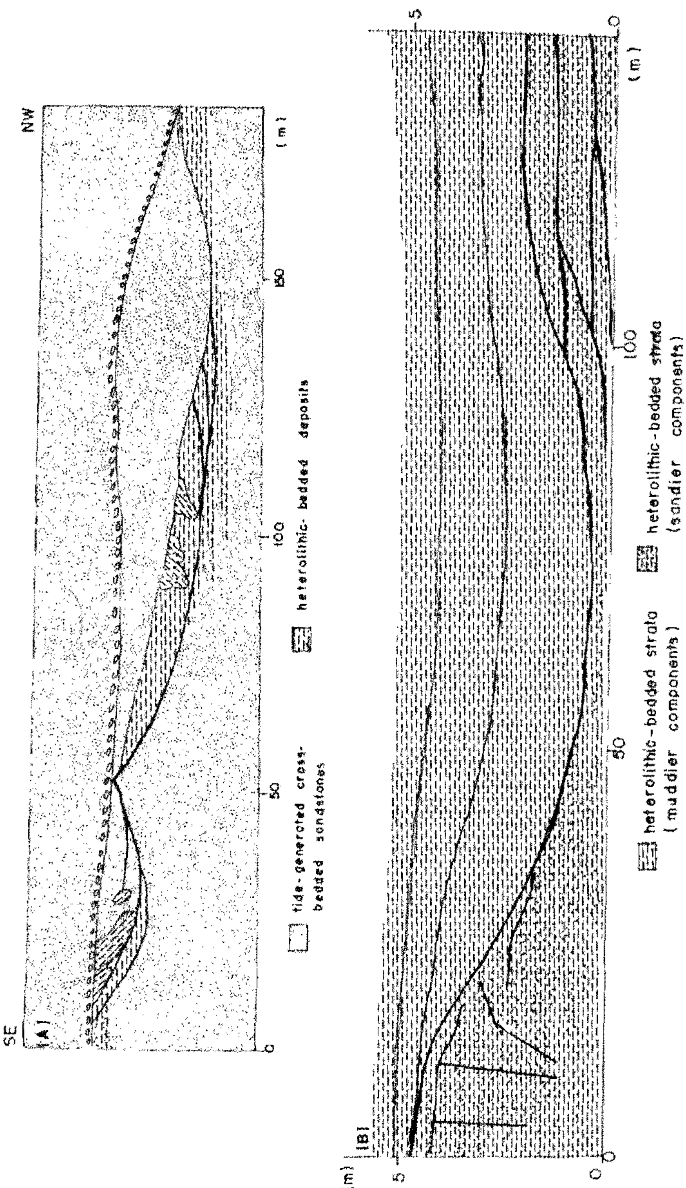

Figure 6 - a,b) Channel like deposits from the Upper Estuarine Succession defined by a lower composite discordance formed by erosive surfaces superimposed into one another.

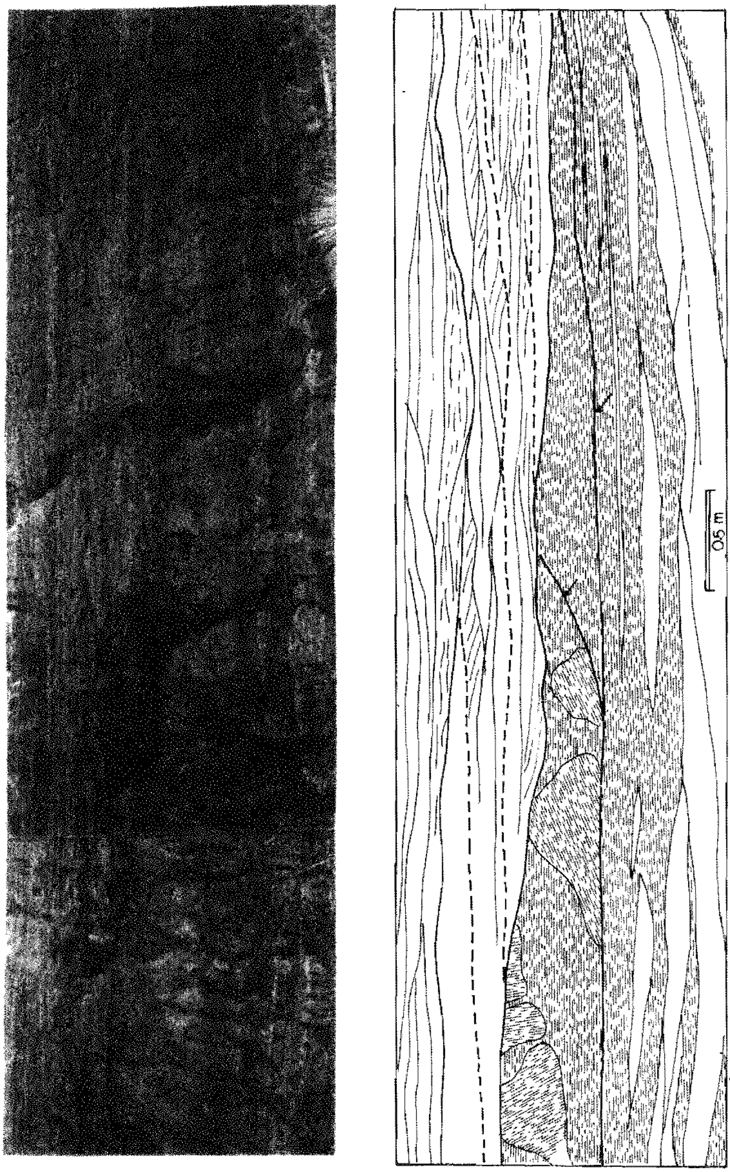

Figure 7 - Well-developed shears and large collapsed blocks within mudstone layers. Note that the disturbed interval is underlain and overlain by completely undisturbed deposits.

Figure 8 - Shear planes developed at the bottom of the channel-like packet shown in figure 6b (lower, right side). Note the soft sediment folds within strata bounded by the shear planes. Also observe that the degree of sediment deformation subtly decreases in the upward direction away from the shears.

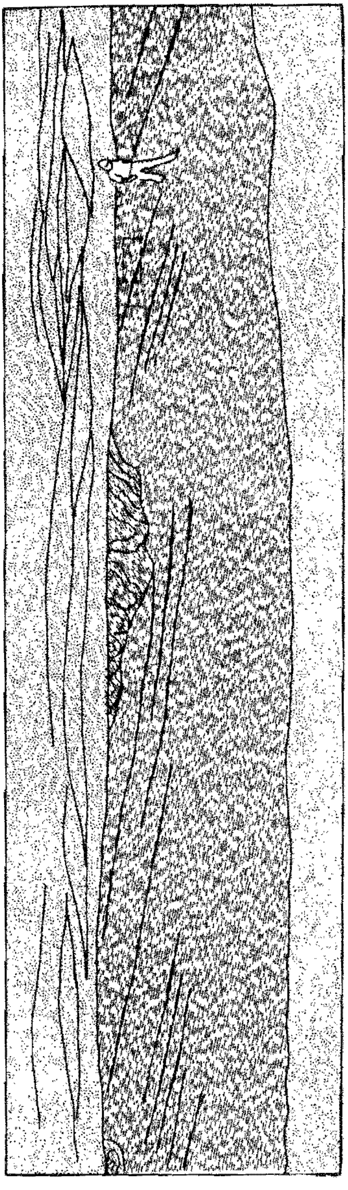

Figure 9 - Oversteepened mudstone packet with large, collapsed blocks displaying high degree of soft sediment deformation.

the slumping. The deformed strata immediately underlying the discordance at some places were formed by overpressure caused by slumping of the sediment mass (Laird 1968).

CAUSES OF THE DISTURBANCES

Slumpings and soft sediment deformation take place if: a) deposits are susceptible to deformation; and b) there is a trigger of sufficient strength to cause the deposit to fail downward and/or change its physical state from solid-like to liquid-like (Allen 1986). Events meeting such requirements chiefly include: sudden-sediment loading, gravity-induced mass movement, storm impact, and earthquake.

Processes involving sediment loading and gravity- induced movements are responsible for several types of deformed structures in deltaic settings. In particular, the collapse depressions spontaneously formed in interdistributary bay areas (Colleman & Prior 1982) are features comparable to the channel-like structures described here. Despite the resemblance, these processes are not typical of estuarine lithossomes. On the other hand, sediment loading and/or gravity movements may potentially develop in wave dominated-estuarine areas experiencing high sedimentation rates, such as bayhead deltas (upper estuary) and tidal deltas (estuary mouth). Similarly to deltaic settings, these portions of the estuaries might experience sediment instability due to overloading resulting from constant sand influx into muddier, central bay areas. However, even considering such environmental condition, this mechanism can not respond for all the unusual features observed in the study area, as deposits overlying the disturbed strata do not necessarily show contrasting lithologies. In particular, faulted and fractured strata overlain by undisturbed, but lithologically comparable deposits are inconsistent with overloading processes. Therefore, an alternative mechanism is required to explain the sediment disturbances.

An origin linked to storm impact also seems to be unsuitable to explain all the unusual deposits from the study area, which leave us with the third possibility, i.e., earthquakes as the most probable trigger mechanism responsible for the disturbances. The storm hypothesis is promptly ruled out at least in the case of the Upper Succession because of its overall lack of storm-generated features. In contrast, storm impact could account for sediment disturbances in the Lower Succession, where there is a number of sedimentary features (hummocky/swaley cross stratification; undulating parallel lamination; coarse-grained, combined flow-generated lamination; erosive surfaces presenting large scale, regularly distributed, symmetrical and asymmetrical scours) indicative of large scale wave activity attributed to vigorous storms (Rossetti 1996). However, these catastrophic events also seem to have had a primary tectonic trigger. Storm events result from both tectonic and non-tectonic seismic shocks (Johnson 1977). The first is produced by earthquakes (i.e., tsunamis), whereas the second results from oceanic pressure gradient. The formation of oceanic storms during the deposition of the Lower Succession conflicts with the current Mesozoic paleogeographic maps (Barron *et al.* 1981; Ziegler *et al.*1983). During the Late Cretaceous, the Brazilian north equatorial margin was located in a position out of the zone of commonly expected hurricanes caused by cyclonic wind circulation (i.e., the 10°-45° latitudinal belt). Based on these considerations, it is intriguing to invoke tectonic seismic shocks as the most likely mechanism inducing the storms (i.e., tsunamis), although the data presented here do not allow any definitive conclusions.

Considering the foregoing discussions, the penecontemporaneous disturbances reported herein are more properly related to earthquakes. The occurrence of disturbed deposits at different stratigraphic levels implies repetitive periods of seismic activity affecting sedimentation pattern in the study area. Perhaps, contemporaneous seismological events enhanced the potential to sediment failure and soft deformation in those areas of the estuary naturally favored to gravity-induced sediment instability. Examples of similar seismic-triggered structures occur in Silurian rocks of western Ireland (Laird, 1968), in sediments of Van Norman Lake, California (Sims 1973), in lacustrine sediments of the East Anatolian Fault, Turkey (Hempton & Dewey 1982), and in several Late Cretaceous deposits of Brazil (Raja Gabaglia 1991; Riccomini *et al.* 1991; Coimbra *et al.* 1992; Fernandes & Coimbra 1993).

CONCLUSION

The unusual strata from the lower and upper estuarine successions of the Itapecuru Formation exposed in the São Luís Basin are attributed to penecontemporaneous disturbances. Because either internal or external factors may sufficiently disturb the primary features resulting similar products, unreaveling the direct connection between penecontemporaneous disturbances and a particular causual mechanism is commonly problematic. However, considering the paleoenvironmental reconstruction of these rocks, the association of several brittle and ductile structures within a single stratigraphic interval appears to be more readily explained as resulting from the influence of forces related with seismic shocks. Seismically-induced tectonic movements probably caused liquefaction and/or fluidization of the water-laden sediments, as well as create shear planes along which the sediment failed.

In the particular case of the Lower Succession, additional evidence for seismicity is provided by strata that record periods of severe storm episodes. Given the paleogeographic location of the Brazilian north coast since the late Cretaceous, it appears to be more likely that such vigorous storms represent tsunamis as opposed to naturally-induced, oceanic pressure gradient.

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