IMAGING UPPER TERTIARY TO QUATERNARY DEPOSITS FROM NORTHERN BRAZIL APPLYING GROUND PENETRATING RADAR

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ABSTRACT Upper Tertiary to Quaternary deposits from northeastern Pará State, Brazil, were imaged with ground penetrating radar (GPR) and calibrated with geological data from a local cliff. The procedure allowed for the recognition of five radar facies (i.e., discontinuous parallel, continuous parallel, chaotic and reflection-free, oblique, and mound facies) that are organized into four radar units (referred to here as Units 1 to 4). Unit 1 includes mostly continuous parallel reflections and secondarily, discontinuous parallel and mound reflections, being correlatable at the cliff face to low-energy muddy lagoon and mud flat depositional settings. Unit 2 consists of continuous even parallel, discontinuous parallel, oblique, as well as chaotic and reflection-free facies, being related to low-energy muddy deposits interlayered with sands, which are attributed to tidal flats and channels. Units 3 and 4 include chaotic, reflection-free and, locally, discontinuous parallel radar facies, correlatable at the cliff face to massive sands, mostly representing aeolian coastal dunes. These units are bounded by continuous, high amplitude reflections that can be easily correlatable throughout the GPR profiles, serving as important stratigraphic markers. The GPR survey improved the reconstruction of the depositional environments through the recognition of tidal channel and point bar deposits within Unit 2, not present at the cliff face. The stratigraphic framework was also improved through the recognition of the discontinuity surface between Units 3 and 4, also not defined in previous studies, but which revealed to be a regionally significant stratigraphic marker attributed to a relative sea level fall.

Keywords: radar facies, stratigraphy, sea level change, Cenozoic, Northern Brazil

INTRODUCTION Although most of the documented application of ground penetrating radar (GPR) is focused on environmental, groundwater and geotechnical studies (e.g., Beres Jr. & Haeni 1991, Knoll *et al.* 1991, Greaves *et al.* 1996), many recent publications have highlighted GPR's use in sedimentary facies and stratigraphic analysis (e.g., Jol and Smith 1991, Gawthorpe *et al.* 1993, Bristow 1995a b, Olsen and Andreasen 1995, Bristow *et al.* 1996, Jol *et al.* 1996, Van Heteren & Van De Plassche 1997, Van Heteren *et al.* 1998, Fitzgerald & Van Heteren 1999). Despite these studies, the application of GPR to interpret the geological and sedimentological record still needs to be complemented by a larger number of case studies to tie the GPR reflections with sedimentary structures and depositional environments within systems characterized by complex facies relationships, as in coastal marine settings.

The main goal of the present work is to document the results of a GPR study performed in Tertiary and Quaternary deposits from northern Brazil, which successfully helped to better characterize facies distribution and understand the sequential evolution of estuarine deposits. We chose a geologically well-known area in order to assess the applicability of GPR equipment in studies focusing on the mapping of both facies architecture and discontinuity surfaces. Surface investigation using GPR requires knowledge of the radar properties of the materials being investigated, a well defined set of reflection patterns, and associated interpretations (Van Heteren *et al.* 1998). Therefore, an area at the Outeiro Island (Fig. 1) was selected considering the possibility to directly compare the geological data from a coastal cliff with the GPR reflections. The application of GPR methodology as a tool for helping analyzing facies patterns in

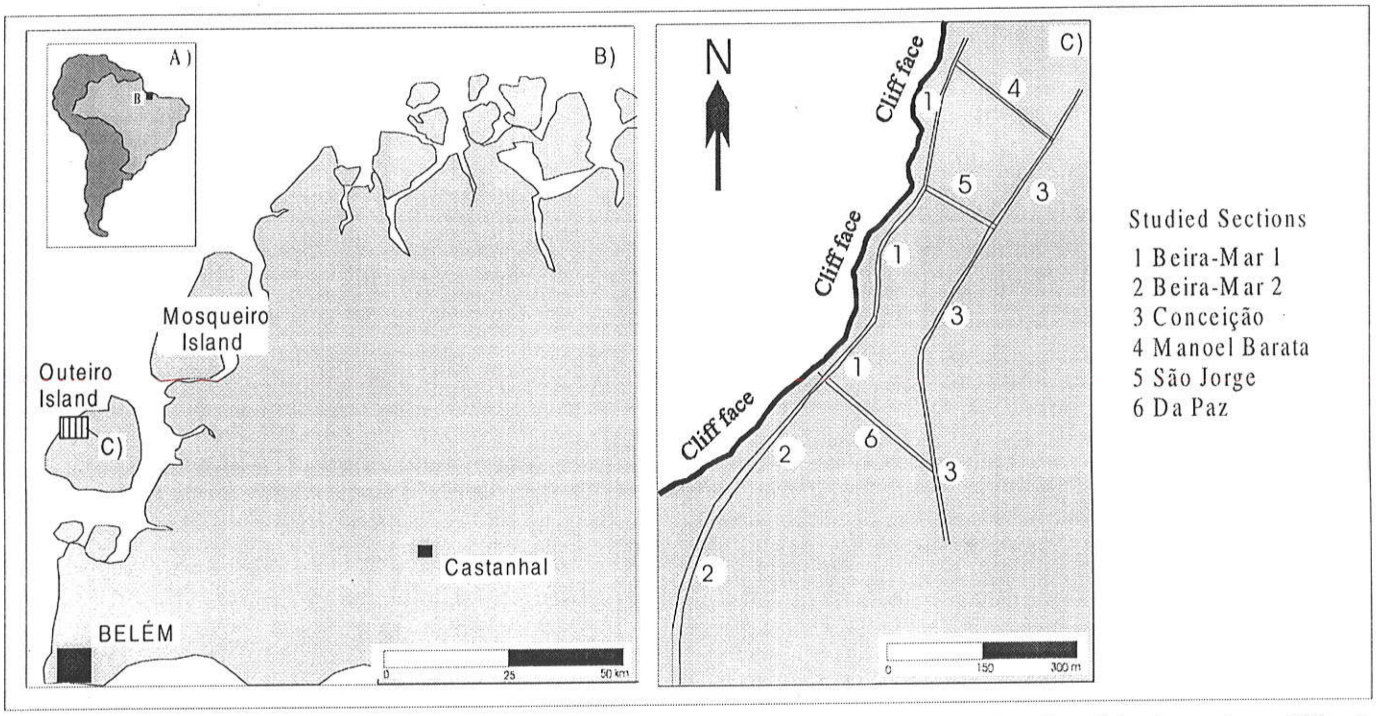

Figure 1 - A,B) Map showing the study area in northern Brazil. C) Location of the GPR sections along streets oriented parallel and normal to a cliff face in the town of Outeiro.

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sedimentary basins from northern Brazil has not been previously attempted yet. However, previous pioneering work done by Sauck *et al.* (1995a b) showed the feasibility of using GPR in the Amazon region. This was done despite the widespread opinion that it would not work because of the high clay content in the humid tropics. The tropical clays are highly leached by the intensive weathering and hence are very high resistivity, as contrasted with the conductive clays from temperate and sub-tropical climates. Thus, fine-grained sediments on old land surfaces in the Amazon region are not radar absorptive. The present study is a good example showing how GPR data can improve the geological interpretation from areas lacking widespread exposures.

STRATIGRAPHY AND PALEOENVIRONMENTAL FRAMEWORK OF THE STUDY SITE Previous studies of Tertiary to Quaternary deposits in the Bragantina Zone, northeastern Para State resulted in the recognition of three depositional sequences, referred to as Sequence A, Sequence B and Sequence C (Rossetti 2000). These deposits correspond respectively to the lithostratigraphic terms Pirabas Formation and lowermost portion of Barreiras Formation (Sequence A), middle to upper portions of the Barreiras Formation (Sequence B) and Post-Barreiras Deposits (Sequence C; Rossetti *et al.* 1989).

Sequence A consists of late-Oligocene to early Miocene limestones, black mudstones, and calcareous sandstones, which are interbedded with variegated mudstones and sandstones attributed to outer shelf, restricted shelf-lagoon, and mangrove-mud flat depositional environments. These deposits are interpreted as the record of a rise in relative sea level of nearly 40 to 50 meters above the present mean sea level, and which resulted in the flooding of an area nearly 150 km inland from the modern coastline. The base of this sequence is not exposed in the Bragantina Zone, but southward of this area it is an unconformity (SB1) either with Precambrian basement rocks or Cretaceous to early Tertiary (?) deposits of the Ipixuna Formation (Ferreira *et al.* 1984), being marked by a distinctive lateritic/bauxitic paleosoil. The sequence boundary at the top of Sequence A (i.e., SB2) is marked by a horizon of well-developed paleosoil characterized by roots, root marks and a lag of mudstone intraclasts and quartz pebbles of variable sizes, which is correlatable up to 600 km to the west (Rossetti 2000, 2001).

Sequence B consists of mid-Miocene deposits with variegated colors, which are mostly represented by widespread tidal channel, transgressive tidal flat and mangrove deposits, probably associated with estuarine systems (e.g., Rossetti 2001). The top of sequence B is a regional unconformity (SB3) caused by a significant drop in relative sea level that succeeded the transgression and resulted in a regionally extensive discontinuity surface marked by erosion and lateritic paleosoil.

Sequence C, of an uncertain age younger than the Pliocene, consists of fine-grained, massive sandstones and mudstones attributed to aeolian coastal dunes and embayments (Rossetti *et al.*1989, Rossetti 2001).

METHODS This study was based on stratigraphic data acquired on Outeiro Island, Bragantina Zone, with a Geophysical Survey Systems Inc. SIR-2 GPR. For easier operation, the survey was arranged according to pre-existing flat lying streets, and consisted of several lines parallel and normal to a coastal cliff (Fig. 1). In fact, this is the same area where the earlier studies by Sauck et al. (1995b) were done, except that they used the 100 Mhz antennae and a considerably greater range of 400 ns. The profiles were acquired using a monostatic 200 MHz antenna at a slow walking pace. The range of sedimentary features that can be seen on GPR records is very different for different antenna frequencies. Only the very large-scale features will be seen when antennae of 50 or 100 MHz are used, but penetration depths may be more than twice that for 200 MHz antennae. On the other hand, depths with a 300 or 500 MHz antenna system might be restricted to the uppermost 3-4 m, but would show very fine detail. Thus, antenna choice was a very important consideration, and the intermediate 200 MHz frequency revealed the best results for the purpose of this work. The equipment, operated by a 12-V battery, was run in a continuous recording mode, with a two-way travel time setting averaging 150 ns, which provided an estimated depth investigation to 12 m. To improve the image quality, the field data were analyzed using a RADAN software with different filters (Finite Impulse Response) being performed to remove bands of ringing and high frequency ("snow") noises, and enhance low frequency reflections. The same filters were used in all GPR profiles illustrated in this paper to allow a comparison of GPR facies characteristics.

The interpretation of GPR-reflections presented in this paper is based on correlation of the GPR signal with individual facies and key surfaces observed along the cliff face. The direct comparison and detailed correlation with the radar sections made throughout the study area enabled to calibrate the GPR data with the local sedimentology, providing a reliable geological interpretation for individual reflections and leading to a more precise stratigraphic framework for the Tertiary to Quaternary deposits at Outeiro Island. The GPR signal can be affected by rock-type and pore-water/clay content and chemistry, and its facies interpretation relies on the principles of seismic stratigraphy, which mostly include the identification of reflection configurations and terminations, internal reflection configuration and external geometry (Van Heteren *et al,* 1998, Beres Jr. and Haeni 1991). Radar stratigraphic procedure identifies radar sequences which are defined by packages of genetically related strata bounded by unconformities and their correlative conformities (i.e., radar boundaries), as well as to analyze the sedimentary facies and facies architecture in order to understand the lithology, depositional environments and stratigraphic evolution of this sedimentary succession.

RADAR FACIES Similarly to sedimentological facies analysis, the procedure used herein to analyze the GPR data set consisted in the identification of individual radar facies, which were grouped into radar units, interpreted to be representative of the depositional environments. Five radar facies were recognized in the study area based on distinctive reflection configurations. Comparisons with radar signals obtained from other areas documented in the literature (e.g., Bristow 1995 a b, Jol and Smith 1991, Van Heteren and Van de Okassche 1997, Pedley *et al.* 2000), added to direct sedimentological data collected from local cliffs (Rossetti 1989, Rossetti 2000), enabled one to interpret each individual radar facies.

Continuous parallel facies This radar facies (Fig. 2A,B) is dominated by closely-spaced, high-amplitude, continuous, parallel reflections that mostly occur as packages with a constant thickness averaging 2.5 m thick. Two types of parallel reflections were identified in the study area: even-parallel and wavy parallel. Even-parallel facies is the dominant one (Fig. 2A), and consists of a series of horizontal-layered, flat reflections overlying each other in the vertical direction. The wavy parallel facies (Fig. 2B) is characterized by reflections that drape over a lower irregular reflection, which gives an undulating appearance. The closely-spaced, continuous, parallel reflections of this radar facies are attributed to parallel-laminated argillites. Direct comparisons with the geological data collected from the cliff face are consistent with this interpretation because intervals with laminated argillites match well with the parallel reflections from the GPR sections recorded above them. In the cliffs, the intervals with parallel-laminated argillites show frequent alternations of well-sorted sand layers, which might be the reason why these muddy deposits show good GPR signal despite its thickness (up to 2.5 m). The wavy parallel reflections are attributed to mud deposition above a discontinuous surface at the boundary between stratigraphic units.

Discontinuous parallel facies Facies 2 (Fig. 2C) is the most frequent one, and consists of a series of closely-spaced, segmented, parallel reflections occurring in packages with estimated thickness around 3.5 m. The reflections are most commonly arranged as a succession of horizontal-layered, flat reflections, but there are areas dominated by reflections that are inclined, rather than horizontal, creating a complex disrupted pattern. At places, disruption is intense and results in steeply inclined to near-vertical segments of reflections. Facies 2 is correlatable with primarily parallel-laminated argillites, and

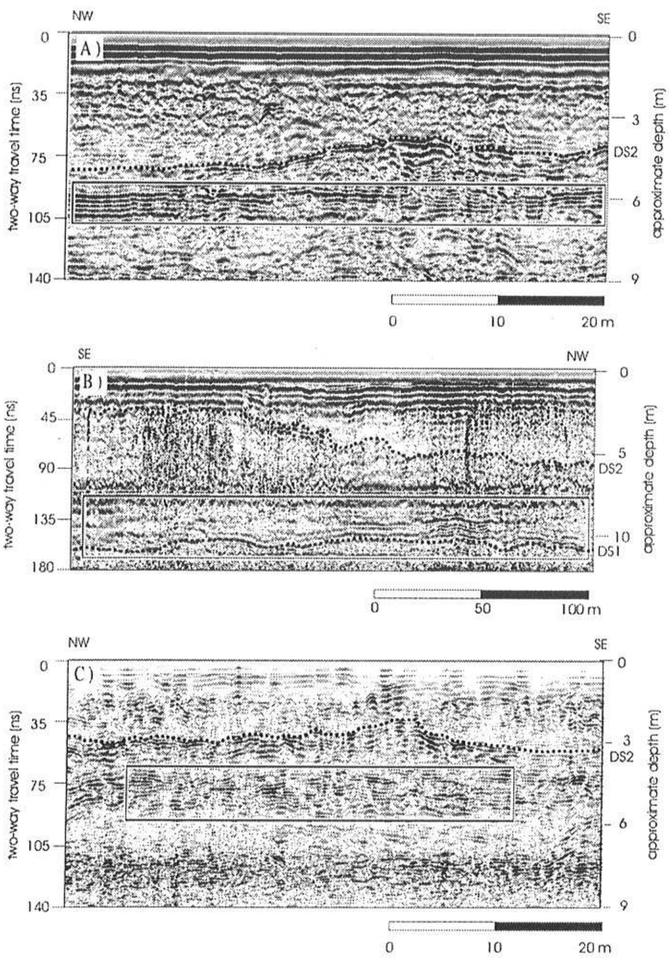

Figure 2 - Radar sections from the study area in the Outeiro Island, northern Brazil, illustrating: A) continuous even parallel reflections; B) continuous wavy parallel reflections; C) discontinuous parallel reflections. Dotted lines indicate discontinuity surfaces DS1 and DS2 between stratigraphic units.

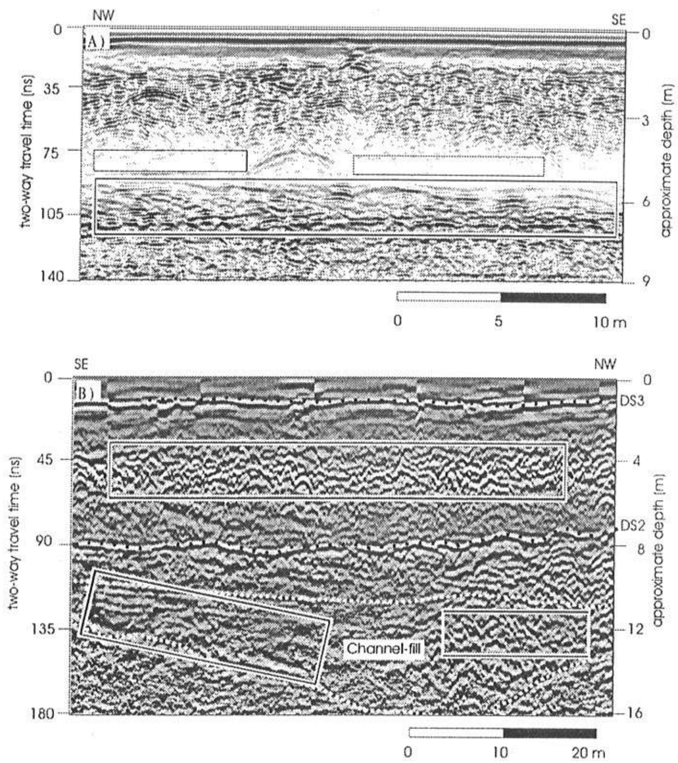

Figure 3 - Radar sections from the study area in the Outeiro Island, illustrating: A) low-angle dipping oblique reflections (lower box) and reflection-free zones (two upper boxes); and B) chaotic reflection (upper and lower right boxes) and large-scale, low-angle dipping oblique reflections within a channel fill shape (lower left box). The black dotted lines indicate bounding surfaces DS2 and DS3 described in the text and the white dotted line highlights the reflections with channel fill geometry.

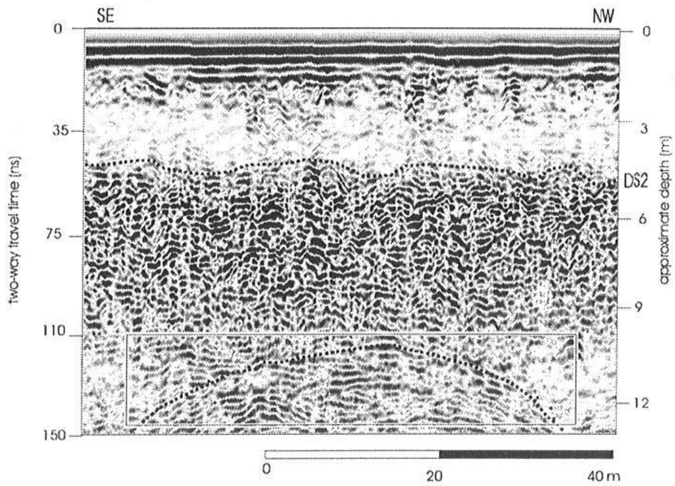

Figure 4 - Mound reflection observed in the Manoel Barata Section. See Figure 1 for location. The onlap of surrounding reflections against this mound geometry are indicated with arrows. Dotted line indicates the stratigraphic surface DS2 discussed in the text.

minor sand interbeds, that had their fabrics partially disturbed by weathering and/or pedogenesis. Individual, steeply-inclined to vertical reflections are linked in the cliff to blocks displaying steeply-inclined, laminated argillites attributed to syn-sedimentary slumping. Such features are common at a given stratigraphic horizon, and are overlain by entirely undisturbed, horizontal-bedded deposits.

Chaotic and reflection-free facies Facies 3 (Fig. 3 A,B) occurs in packages that are up to 5 m thick. It consists of low amplitude, discontinuous reflections that form widely-spaced, short segments typically displaying variable dip angles and directions. Not rarely, chaotic, poor reflections grade into areas displaying reflection-free configuration. Chaotic to reflection-free patterns were also observed closely associated within radar facies 3, occurring at its top and right below a continuous, high amplitude reflection DS1, described below. A chaotic configuration is a radar pattern often associated with massive or heterogeneous lithologies (e.g., Van Hetern *et al.* 1998). In the study area, this type of reflection corresponds to packages of massive sands having local, small to medium-scale, tidal-influenced cross stratification below the resolution of a 200 Mhz antenna used in this study. Data from the exposures along the cliff face allowed one to understand the lack of structures in this sandy deposit to a combination of factors including weathering, burrowing and pedogenesis. The chaotic reflections from the uppermost portion of the sections match well with a package of well sorted, well-rounded, very fine- to fine-grained sands, which are attributed to homogeneous coastal sand dunes according to previous interpretations (Rossetti *et al.* 1989, Rossetti 2000). The chaotic to reflection-free configurations that occur below a discontinuity surface DS1 correspond to an interval of massive argillites with abundant roots and root marks that grade downward into parallel-laminated argillites. Noteworthy is that, without the cliff control, there was no way to differentiate these massive argillites from the massive sand units.

Oblique facies Facies 4 (Fig. 3A,B) was observed only locally in the GPR profiles, occurring as lenses less than 100 m long and 2-3 m thick. It consists of a series of low-angle (<15^{o}) dipping reflections that are tangential-, and less commonly, sigmoidal-shaped. Oblique

Table 1 - Summary of the main characteristics of the radar stratigraphic facies recognized in the Outeiro area, with the proposed geological interpretation.

RADAR STRATIGRAPHIC UNIT	RADAR FACIES	GEOLOGICAL INTERPRETATION
UNIT 1	Continuous even parallel. Secondarily, discontinuous parallel, chaotic and reflection-free configuration	Low-energy, muddy flat and lagoon. Pedogenesis modification at the top
UNIT 2	Continuous even, and less commonly, wavy parallel. Secondarily, discontinuous parallel, oblique, chaotic and reflection-free configuration	Low-energy muddy flat with local bedform migration by tidal processes and intervening tidal channel with lateral accretion. Pedogenetic modification at the top
UNIT 3	Chaotic, reflection-free, and secondarily, discontinuous parallel	Eolian coastal dunes with interving low energy embayments or estuaries
UNIT 4	Chaotic and reflection-free	Eolian coastal dunes

reflections record accretion of a sedimentary unit following one preferential direction, which might be related to processes including bedform migration or lateral deposition in point bars.

Mound facies Facies 5 (Fig. 4) is well represented at three localities: Conceição Section (around the 800 m position), Beira Mar Section 1 (between 160-220 m), and Manoel Barata Section (between the horizontal distance 0-150 m and 310-320 m). It consists of convex-up geometries that form topographic buildups 20-30 m wide against which the surrounding reflections onlap. Within the mounds, individual reflections are either conformable to the external mound shape or display a complex of smaller-scale mounds (Fig. 4). The origin of these large-scale mound reflections are not well understood. Further investigation using a lower-frequency antenna is needed to allow more detailed interpretation. A preliminary interpretation invoked is that the mound-like reflections might record soft-sediment folds caused by large-scale slumpings, which would be consistent with the presence of slumped deposits from overlying strata as observed in the cliff face.

RADAR UNITS Similarly to seismic analysis, radar discontinuities were recognized by the analysis of different styles of reflection terminations. These discontinuities show good correlation with previously mapped stratigraphic surfaces attributed to sea level fluctuations and they were the clue to analyze the radar facies relationships, helping to better understand the complex architectural arrangement of the depositional environments in this sedimentary succession. Four radar units (presented below from bottom to top) were recognized in the study area (Fig. 5-6). Individual units are internally characterized by one or more radar facies described above, which are summarized in Table 1.

Unit 1 This unit has an approximate thickness ranging from 1 to 5 m. The lowermost portion shows poorly-defined reflections because it is at the limit of the 200 Mhz antenna resolution used in this investigation. The middle part is dominated by radar facies of fairly well defined reflections displaying discontinuous and, less commonly, continuous, even parallel configurations. Bright reflections occur locally throughout the package. The interval with continuous parallel reflection facies grades upward into a package dominated by discontinuous parallel, chaotic and reflection-free configurations. The geometry of this reflection shape can not be determined because the base is beyond the GPR resolution and the top is marked by a usually sharp, continuous, low to medium-amplitude radar reflection which truncates the underlying reflections. A striking feature of Unit 1 is the local presence of areas displaying mounded geometry that are in sharp contact with the surrounding reflections. They are: Beira-Mar Section 1, between horizontal distance of 160-220 m; and Manoel Barata Section, between horizontal distance of 0-150 m; see Figures 6B-D).

Unit 2 This unit reaches up to 8 m thick. It is defined at the base and top by sharp, continuous, commonly high amplitude reflections. It is noteworthy to mention that these reflections show frequent erosional truncation and onlap of the underlying and overlying reflections, respectively. Unit 2 consists of packages of reflections displaying geometries that range from sheet, sheet drape, lenticular, wedge to, locally, channel fill. Except for the channel fill, the shapes are internally characterized by different intergrading radar facies. The dominant facies is defined by continuous even parallel reflection configurations. At places where this pattern directly overlies the discontinuity surface at the top of unit 1, these reflections become dominantly wavy parallel. The continuous parallel styles of configurations are more commonly observed in the lowermost half of Unit 2, while its uppermost portion is dominated by discontinuous parallel reflections exhibiting segments that are steeply inclined to sub-vertical. Less commonly, this unit includes lenses of oblique, as well as chaotic and reflection-free facies. In the Conceição Section (Fig. 6A), sigmoidal oblique facies fills one side of a concave-up geometry circa 170 m wide and 4 m deep. In this case, the oblique reflections laterally grade into more chaotic patterns. Note the presence of areas displaying widening upward parallel continuous and discontinuous reflections, forming three cycles averaging 1 m thick, as in the southwest side of Fig. 6B.

Units 3 and 4 Unit 3 is up to 5 m thick, and is particularly well preserved within topographic lows developed along the continuous reflections that define the top of the underlying Unit 2. The absence of Unit 3 beyond these depressions results in its lateral discontinuity forming a series of isolated, lenticular shapes up to 900 m long. Unit 3 is internally represented mostly by chaotic to reflection-free radar facies that locally grade into discontinuous parallel facies. The top of Unit 3 is defined by another sharp, continuous reflection, which separates this unit from the overlying Unit 4. The latter is characterized by a package having an estimated thickness of up to 4 m in the GPR sections, and which is internally represented by dominantly chaotic, very bright GPR reflections.

SEDIMENTOLOGICAL AND STRATIGRAPHIC INTERPRETATION OF THE RADAR UNITS The GPR survey

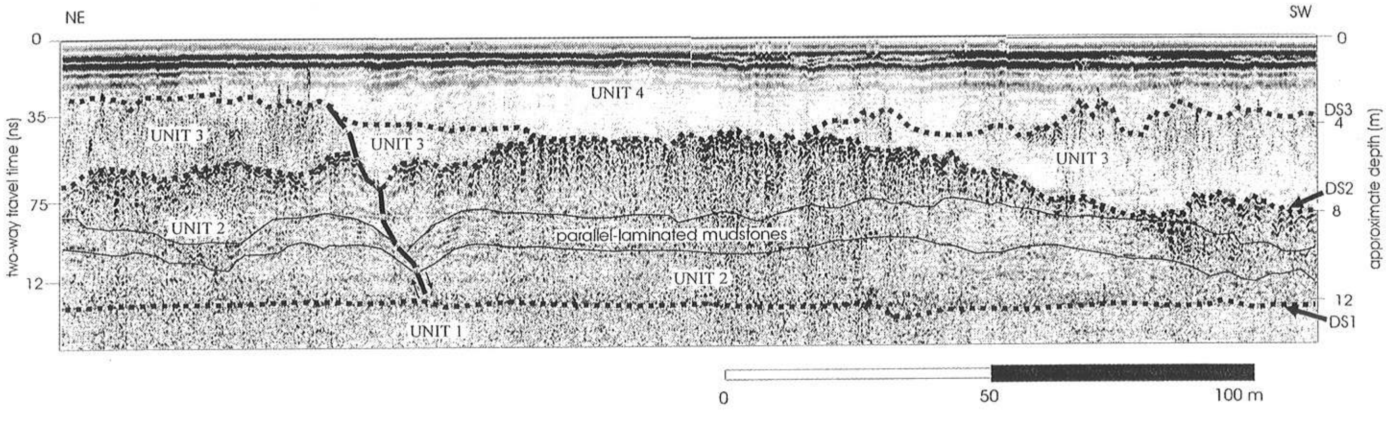

Figure 5 - GPR section from Outeiro Island collected along a line parallel to the cliff face. Location is between horizontal distance of 700-1000 m in Fig. 6B. Note the great lateral continuity of the bounding surfaces (DS1-DS3) between the stratigraphic units 1 to 4. A sub-vertical, thick dashed line indicates a proposed fault.

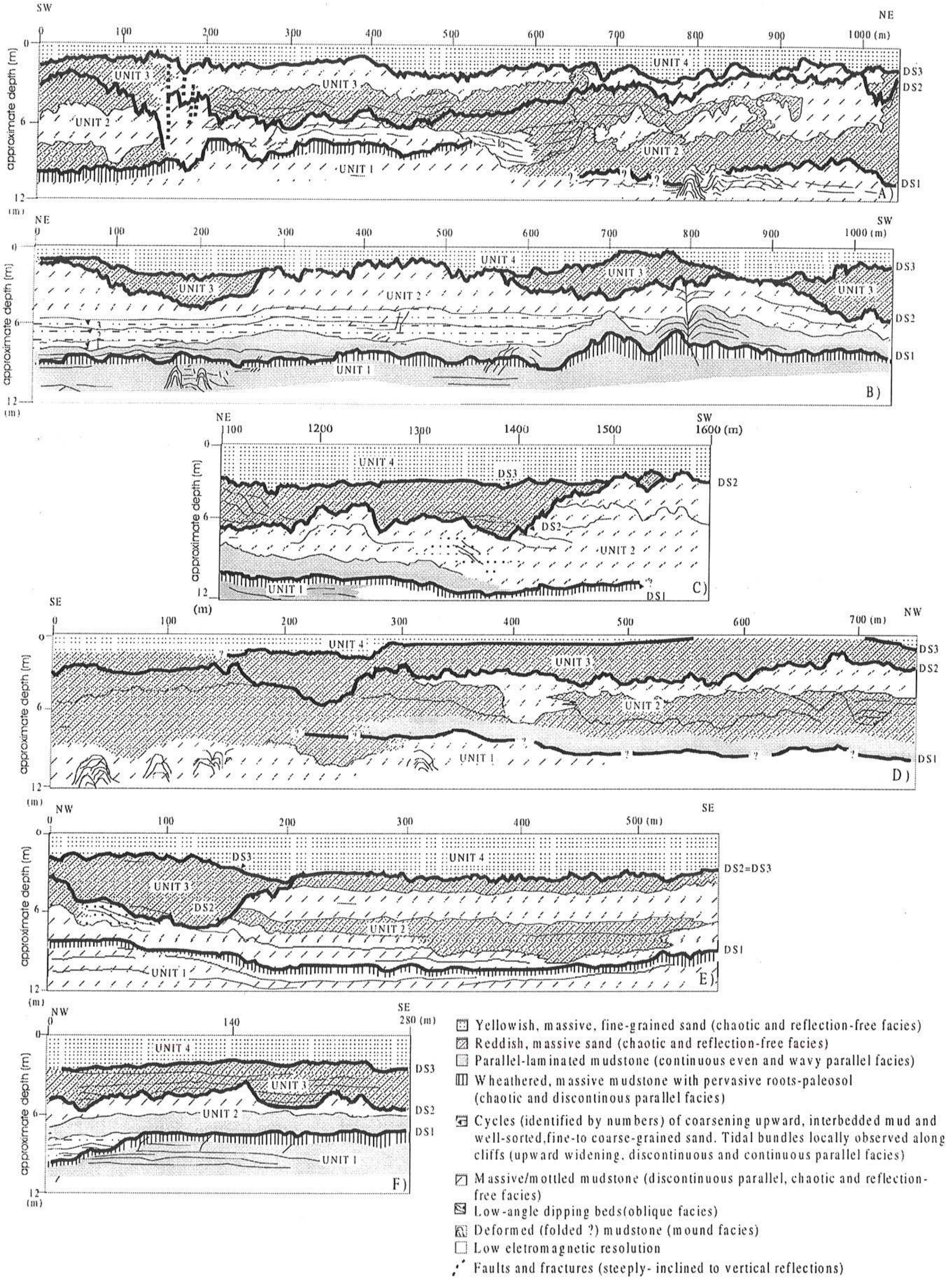

Figure 6 - Idealized schematic sections from the study area based on the GPR and geological data along Beira-Mar Section 1 and 2 (see Fig. 1 for location). A) Conceição Section; B) Beira-Mar Section 1; C) Beira-Mar Section 2; D) Manoel Barata Section; E) Da Paz Section; and F) São Jorge Section Notice the lateral continuity of surfaces DS1-DS3 that defines the stratigraphic units 1-4. See text for further explanations.

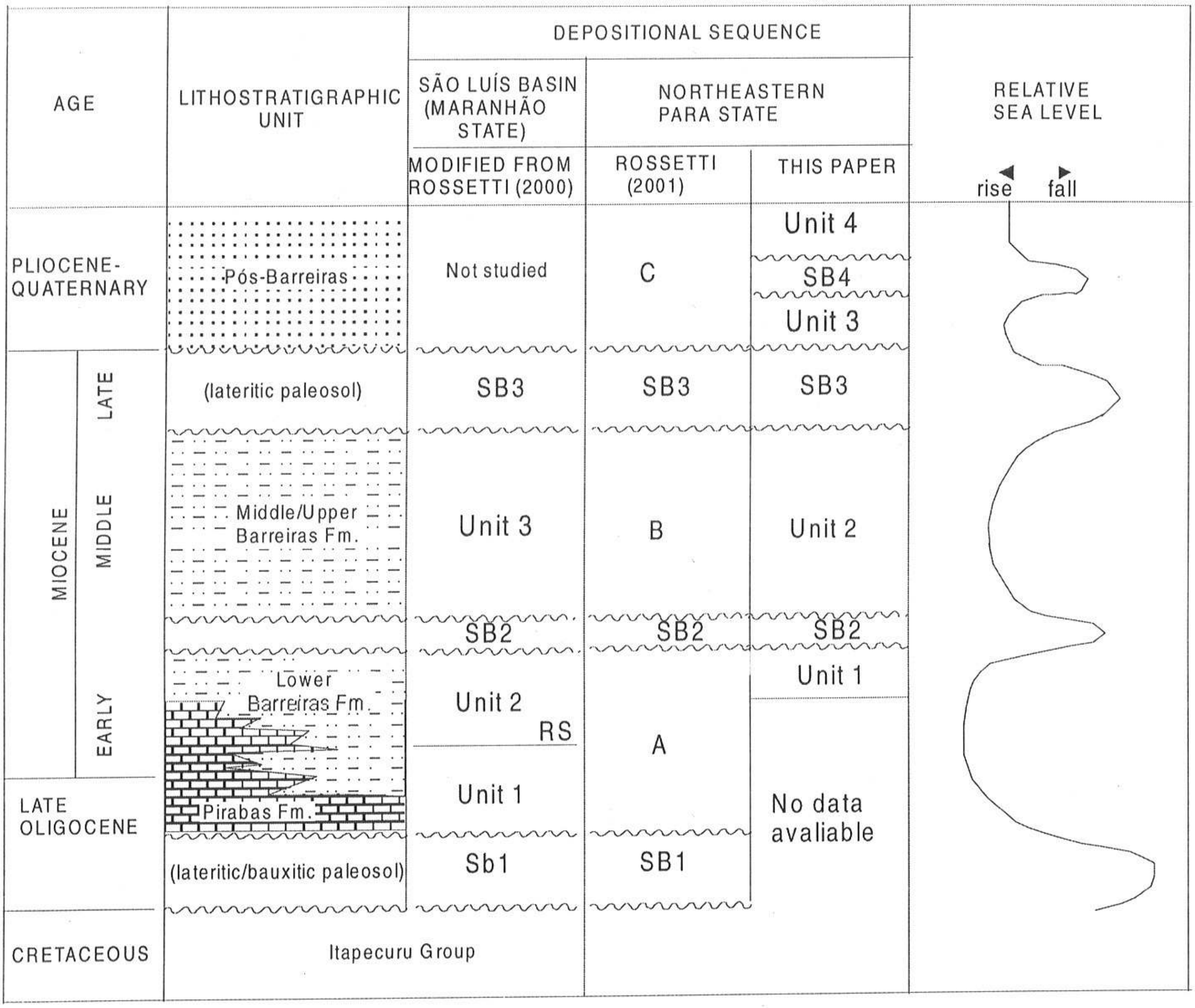

Figure 7 - Summary of the stratigraphic framework from the study area and its correlation with previously published Upper Tertiary to Quaternary stratigraphy charts from northern Brazil (Rossetti, 2000), where SB are sequence boundary and RS is a ravinement surface.

allowed the studied deposits to be subdivided into four units, which have good correlation with the stratigraphic units recognized along the northern Brazilian coast (Rossetti 2000, 2001; Fig. 7). Comparisons of radar and cliff data led to the conclusion that radar Unit 1 corresponds to the uppermost portion of Sequence A described in Rossetti (2001). Only the top of this sedimentary succession is represented in the radar sections, with the dominance of parallel reflections suggesting low energy, muddy depositional environments, probably associated with the lagoon and mud flat deposits that typify this stratigraphic interval at the cliff face. The continuous reflections at the top of radar Unit 1, and which truncate the underlying reflections, match well in the cliff face with the sequence boundary SB2 described in Rossetti (2001). The discontinuous, chaotic and reflection-free facies observed right below the continuous reflections are attributed to the presence of a paleosol horizon developed along the sequence boundary, as observed in the cliff face.

Radar Unit 2 is linked to the stratigraphic Sequence B of Rossetti *et al.* (1989) The dominance of sheet packages with continuous even parallel facies corresponds in the cliff face to muddy, laminated deposits formed in low-energy, muddy flats. Unit 2 has more frequent sand interbeds compared to Unit 1, which are arranged into coarsening upward cycles, identified in the radar sections by the cycles displaying widening upward, parallel reflections labeled 1 to 3 in Fig. 6B. Analysis of the cliff face shows the presence of cross-stratified sets having abundant mud drapes locally arranged in alternating thicker/thinner foreset packages, as well as abundant heterolithic beds, which are attributed to tidal processes (Rossetti *et al.* 1989, Rossetti 2001). Although only small- to medium-scale cross sets were observed on the cliff face, it is possible that the migration of larger bedforms locally produced large-scale (2-3 m thick) cross sets, as suggested by the presence of isolated lenses of oblique reflections. Considering these results, it is proposed that Unit 2 reflects sediment accumulation mainly along tidal flats. The laterally continuous coarsening-upward cycles observed in this unit are attributed to tidal flat transgressive pulses. The presence of large-scale, sigmoidal oblique facies within a channel fill reflection in the Conceição Section (Fig. 6A) is more likely attributed to lateral migration of a tidal point bar. As the laminated mud flat deposits mantled a paleotopography created by the continuous reflections related to sequence boundary SB2, wavy parallel reflections were produced. The more discontinuous parallel reflections from the uppermost portions of the unit matches with mottled deposits formed probably by the combination of weathering and pedogenesis. The steeply inclined to sub-vertical reflections suggest local bed disruption associated with slumpings, as confirmed by the study of the cliff face. The prominent continuous reflections at the top of Unit 2 match well with a discontinuity surface marked by

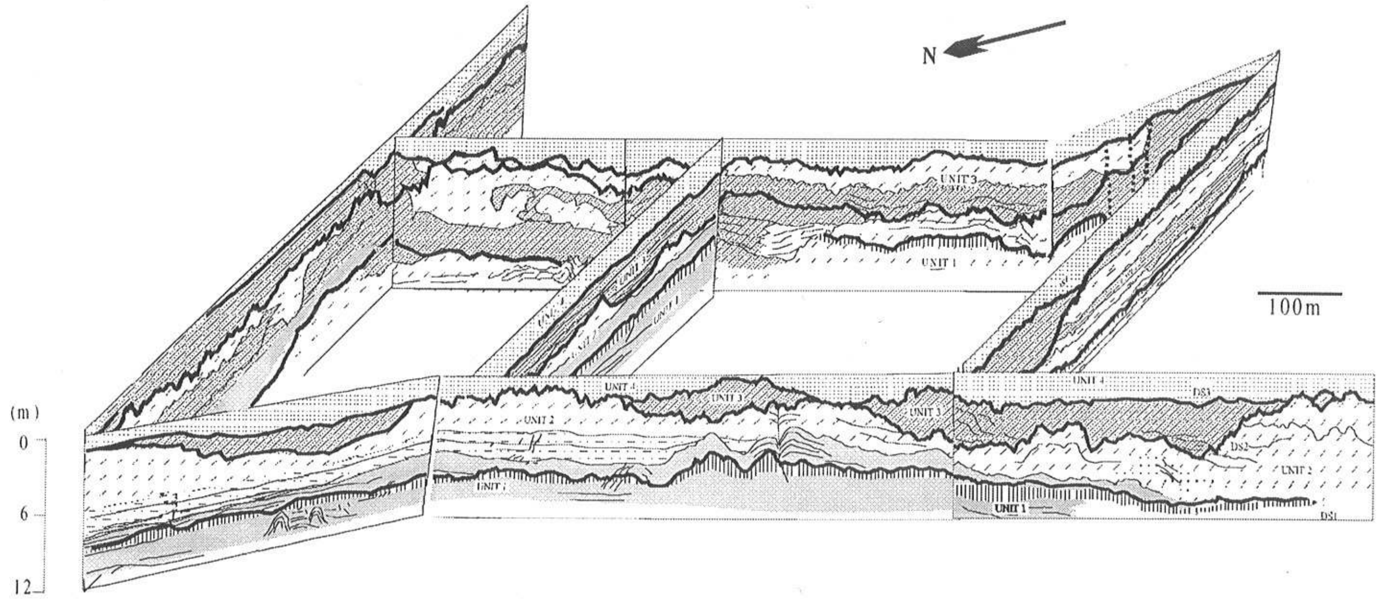

Figure 8 - Fence diagram showing the distribution of the radar facies and discontinuity surfaces throughout the study area. See legend in Fig. 6.

lateritic paleosol, attributed to sequence boundary SB3 in Rossetti (2000, 2001).

Units 3 and 4 correspond to Sequence C of Rossetti (2001). Although previous studies have described these deposits as representing genetically related strata bounded by regional unconformities (Rossetti 2001), the GPR imaging outside the cliff face allowed the recognition of a prominent discontinuity surface within this succession in places where the underlying unconformity SB3 is depressed. It is noteworthy to mention that our preliminary studies of Quaternary deposits exposed along the coast of Pará and Maranhão States suggest that this might be an important surface occurring throughout a distance of up to 600 km. Outcrop data show that this is an erosive surface, locally marked by a poorly developed lateritic paleosol separating underlying estuarine bay muds interfingered with massive sands from overlying coastal dune sands. Hence, Sequence C is subdivided into two stratigraphic units, which correspond to the radar units 3 and 4. Unit 3 defined in the study area. The chaotic reflections observed in Unit 3 are consistent with the dominance of massive lithologies. The high porosity of these sandy deposits, added to their position overlying less permeable strata of Unit 2 result in excellent aquifers. Despite the abundance of massive sands, Unit 3 also shows discontinuous parallel reflections that match with muddy estuarine/embayment deposits at the cliff face. The high degree of weathering of the uppermost portion of the cliff in the study area did not allow detailed study of these deposits. However, our preliminary investigation of correlatable deposits along the Brazilian coast revealed that the muddy deposits might indicate low energy mud settling in embayments or estuaries developed between areas with coastal dunes. The chaotic reflections of Unit 4 also indicate massive lithologies, and correspond to an interval dominated by eolian sands attributed to coastal dunes. Therefore, it is suggested that Units 3 and 4 might record distinct episodes of sediment deposition during the latest stages of the Tertiary and Quaternary. Following deposition of Unit 3 there was a break in sedimentation, which resulted in extensive erosion and soil development producing the uppermost unconformity SB4, which was in turn mantled by Unit 4.

IMPORTANCE OF GPR IN THE ANALYSIS OF THE ANCIENT RECORD The data presented here show how GPR imaging can be used to extend sedimentologic information from outcrops, thus allowing large-scale stratigraphic analysis of sedimentary facies and environments. Although this methodology has been applied as a tool to help analyzing the sedimentological record, most of the studies documented in the literature were concerned with holocene sedimentary environments, with particular emphasis on lacustrine, eolian and fluvial deposits (e.g., Bridge *et al.* 1988, Jol and Smith 1991, Huggenberger 1993, Beres *et al.* 1995, Bristow *et al.* 1996, Van Dam and Schlager 2000). Only a few publications have shown the application of GPR surveys in coastal depositional environments (Baker 1991, Jol *et al.* 1996, Van Heteren *et al.* 1998). The sedimentary record of this type of setting is complex due to the highly variable facies distribution both laterally and vertically. These characteristics difficult the reconstruction of depositional environments in areas where outcrops are discontinuous because the detailed delineation of architectural elements is greatly precluded.

The GPR subsurface investigation provided additional information to better reconstruct the depositional paleoenvironments of the study area, particularly within Unit 2, which was revealed to be faciologically more variable than initially thought based only on data collected at the cliff face. Hence, while previous studies documented tidal flat and mangrove deposits within Unit 2, the GPR survey led to the additional recognition of tidal channel and point bar deposits (e.g., in the Conceição and Manoel Barata sections, shown in Figures 6 and 7). The GPR profiles also provided a better overview of the distribution of facies and stratigraphic surfaces within the study area (Fig. 8). Hence, closer to the cliff face, Unit 1 consists mostly of continuous even and wavy parallel radar facies attributed to parallel-laminated mudstone. This facies grades into discontinuous parallel, chaotic and reflection-free facies farther away from the cliff, interpreted as massive/mottled mudstone. Such a change in facies pattern is related to deeper paleoweathering in relatively more inland areas associated with a paleosol horizon at the top of Unit 1 (i.e., SB2 of Rossetti 2001). A similar pattern is recognized within Unit 2, which shows wedges of continuous parallel reflections that onlap against the underlying SB2 and grade both upward and inland into discontinuous parallel, chaotic and reflection free radar facies. This change in radar facies is attributed to the better preservation of the sedimentary structures closer to the cliff face and downward in the section, which is probably due to the lateritic weathering associated with sequence boundary SB3.

Caution must be taken when analyzing GPR sections. Without lithological control from a cliff face, a significant stratigraphic surface could have been missed, as in the case of SB2, which separates deposits of similar, muddy composition in the radar profiles closer to the cliff. On the other hand, the application of GPR was important to detect the discontinuity surface at the top of Unit 3. This surface SB4 was not recognized as a stratigraphically significant surface in previous studies of the cliff face, which is due to the obliteration of the sedimentary features in the uppermost portions of the succession resulting from strong modern weathering. In addition, in some places the discontinuity surface at the top of Unit 3 is a composite surface that includes sequence boundaries 3 and 4, might lead one to misinterpret them as one stratigraphic surface. The GPR survey extended the geological information inland from the cliff face, where the two discontinuity surfaces SB3 and SB4, were better distinguished.

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