Application of the GPR method in the stratigraphic characterization of Atalaia Beach, Salinas - PA

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Abstract

Ground penetrating radar (GPR) was used to study the stratigraphy of Atalaia beach in northeastern Pará State. The GPR data, obtained by three acquisitions with an antenna frequency of 200 MHz, showed the presence of eight radarfacies, indicating a complex stratigraphy. In this work, the region of interest (during the upper Miocene) is considered to have had a tidal environment and a eustatic sea level well below that of today, this entire area was considered Unit 1. In Unit 2, the identified radar facies indicate deposition in alluvial fans and on the shoreline surface, particularly inland, suggesting marine transgression. The presence of reflection patterns interpreted as paleodunes suggests a rapid rise of the ocean, which curiously is reflection-free in much of the area. Later, another regression through a sequence boundary where the sea level reaches the current elevation, where the radarfacies corresponding transition deposits of foreshore and eaolian deposits, in addition to dunes and paleochannels, it was called unit 3.

Introduction

Coastal areas are regions subject to constant morphodynamic changes, resulting in an unstable environmental system (Leite, 2010). These areas provide valuable information for understanding geologic evolution through time, sea level changes, and other important geologic events on a global scale.

Stratigraphy aims to study, describe, interpret, and classify different rock layers, and new concepts and methods for studying the subsurface have emerged. One of these methods is seismostratigraphy, which uses seismic techniques to study strata and is fundamental to understanding sequence stratigraphy.

Jol & Smith (1991) and Beres & Haeni (1991) implies that depositional environments can be interpreted by making analogies between radar records and seismic data. The ground penetrating radar (GPR) method provides high-resolution profiles that provide information on geologic, hydrologic, and lithofacies boundaries and has the advantage of rapid data acquisition (Ulriksen, 1982).

The use of GPR to characterize the stratigraphy of coastal regions is widely employed in Brazil, with numerous published studies aiming for this purpose (Teixeira et al., 2020; Rossetti et al., 2001; Rodriguez, 2006; Silva et al., 2010; Caldas et al., 2006; Rocha et al., 2013; Tamura et al., 2008; Heteren et al., 2002). Consequently, it contributes with additional information about specific areas that cannot be directly analyzed by examining the strata.

Geological context

In the northeastern region of Pará, Brazil, the Upper Tertiary and Quaternary deposits are represented by the Pirabas Formation, the Barreiras Formation, the Post-Barreiras sediments, Recent sediments (de Fátima Rossetti, 2001), and lateritic paleosol. It should be noted that deposition within these units has been affected by strong tectonic influences (Rossetti & Góes, 2004), including the generation and reactivation of normal and slip faults (Costa et al., 1993), as well as by fluctuations in relative sea level.

On the basis of lithostratigraphic criteria in outcrops of the Bragantina and Pará platforms, Rossetti & Góes (2001) presented a subdivision of this sedimentary package into three depositional sequences.

The deepest part refers to the Pirabas Formation, composed of carbonate rocks and interlocked with the Barreiras Formation at the late-oligocene. This unit indicates sedimentation in a progradational marginal marine system whose lower boundary consists of Precambrian rocks and a paleosol laterite/bauxite.

The Barreiras Formation follows, a group composed of sandy-clayey and occasionally conglomeratic sediments. It is characterized by deposits of alluvial to marine transitional fans, strongly influenced by tidal channels and mangroves, suggesting deposition in an estuarine environment.

Finally, the sediments post-Barreiras, which date from the Pliocene/Quaternary, show a diverse depositional environment. They include partly eaolian deposits and later show a greater facies diversity than originally thought, including deposits of beach ridges and muddy tidal flats. Silva et al. (2004) identified four distinct morphologies: coastal plateau, estuarine plains, tidal flats, and coastal plains.

The flow dynamics in the coastal regions of northern Brazil are primarily influenced by tidal currents and river discharge. As a result, estuarine morphology with tidal flats and associated mangroves are present in these areas (Martins, 1987).

Materials and Method

The GPR method uses the propagation of electromagnetic waves from a transmitting antenna, which propagates through the area of interest, undergoing reflection, refraction, and diffraction. The waves returning to the surface are detected by a receiving antenna, which may be the same antenna, and provide information about the subsurface (Davis & Annan, 1989).

The study area is approximately 220 km away from Belém. Atalaia Beach is located on the island of the same name, which belongs to the municipality of Salinópolis (figure 1). It is bordered by a tidal channel to the west, the Sampaio River to the south, the Arepopó Bay to the east, and the Atlantic Ocean to the north (Gregório, 2004).

Figure 1 – Location map of Atalaia Beach and the position of GPR acquisitions.

Data were collected using the TerraSIRch (Subsurface Interface Radar) System-3000 instrument from Geophysical Survey System Inc. equipped with a shielded 200 MHz antenna. Three measurement lines were conducted in the area of interest: two in Atalho do Atalaia street (Line 1 and Line 2) and one in the westernmost part of the island, a more urbanized location marked as Line 3 in the image. The common offset method was applied in a continuous and constant velocity mode to obtain records of lateral and vertical variations.

Since the data collection was conducted without the help of GPS, it was necessary to obtain information on terrain elevation from digital elevation models (DEM). Topographies were provided by OpenTopography through the QGIS software, using data from sources such as the Shuttle Radar Topography Mission (SRTM), Alos Palsar, GLO-30 Copernicus, and the website of the Instituto Nacional de Pesquisa Espacias (INPE) website through the Topodata project. All DEMs had a resolution of about 30 meters, and the elevation value used in this work was the arithmetic mean of the mentioned DEMs. Finally, the collected data were integrated together with the GPR data and the coordinates from GPS.

The radargrams were processed using the ReflexWin software, following the following routine:

- Remove header gain
- Subtract-mean (dewow)
- AGC-Gain
- Static correction
- Bandpassfrequency
- Trace normalize
- Correct 3D-topography

The interpretations were performed by identifying, separating, and analyzing the reflection patterns and comparing them with the existing literature and understanding of the local geology. The depth values are only for qualitative purposes, as no specific technique was employed to create a velocity model. A value of 0.1 m/ns was used as a general approximation for velocity.

Results

Profile 1A

Profile 1 was divided into two radar sections, the first of which was 320 m long and covered the entire length of the beach and the beginning of the paved shortcut. Five archetypes were identified by acquiring data perpendicular to the coastline.

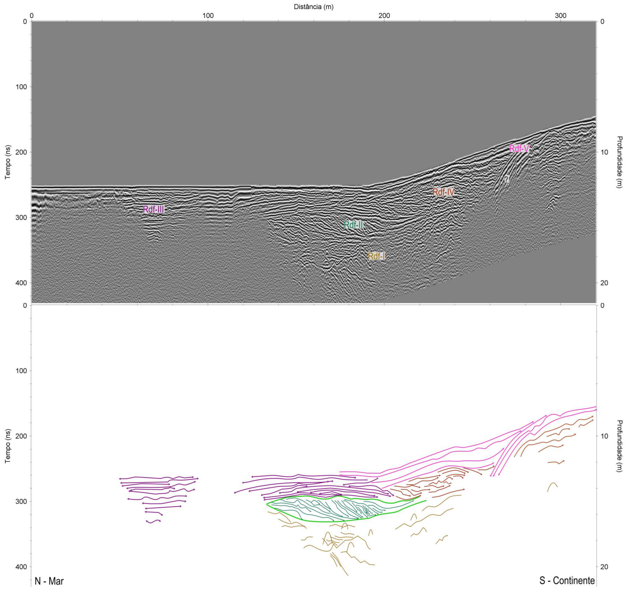

Figure 2 – Radar profile of the first 320 meters of acquisition 1, showing the various radarfacies encountered. Rdf-I: Paleo Tidal Flat; Rdf- II: Washover fan Deposits; Rdf- III: foreshore; Rdf- IV: shoreface; Rdf-V: aeolian deposits.

The Rdf-I shows discontinuous reflections, a chaotic pattern, and varied amplitudes and directions, including some diffractions. In the interpretation, it suggests deposition in a tidal flat, where the hyperbolas are associated with the presence of muddy sediments, plant remains, and bioclasts. It may also indicate an environment influenced by continental factors.

Rdf- II shows an accumulation of sigmoidal oblique reflectors that downlap towards the continent and filling an external sigmoidal geometry. This has been associated with deposition in washover fan formed by the overflow of barrier islands during tidal waves and storms.

Rdf- III shows flat reflections with good amplitude, vertically juxtaposed and with a continuous characteristic. At a particular location, a slope is observed that is influenced by deposition on an irregular substrate and correlates with deposition in the foreshore, the part of the beach environment between low and high tide.

Rdf- IV is laterally discontinuous with moderate contrast and is characterized by subparallel and irregular reflections. It exhibits an upward concave-convex shape similar to hummocky features. These reflections correlate with the depositional environments of the shoreline surface, which represent a larger accommodation space that is consistently below sea level.

Rdf-V shows good lateral continuity and high amplitude, confined to the upper part of the profiles with matching and subparallel geometry. In some cases, terminations can overlap. This pattern is commonly associated with aeolian deposition.

Profile 1B

In the second part of Profile 1, which covers a distance of 280 meters, the data was collected entirely over the asphalt surface.

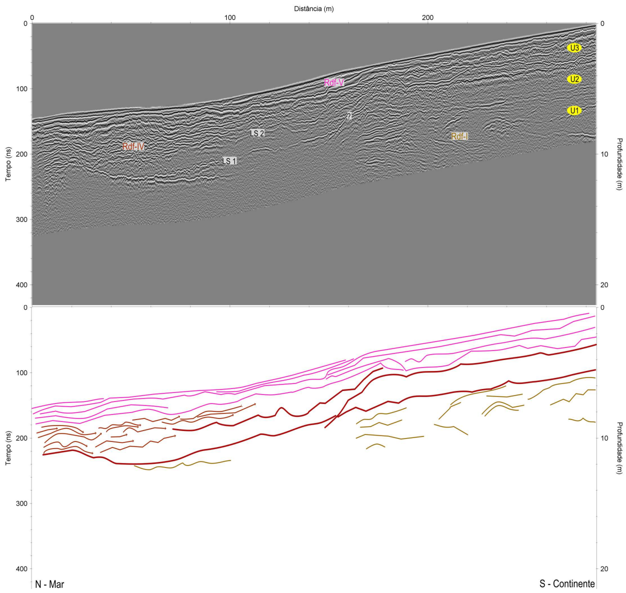

Figure 3 – Radar profile showing the last 280 meters of acquisition 1, indicating the location of the radarfacies. Rdf-I: Paleo Tidal Flat; Rdf- IV: shoreface; Rdf-V: aeolian deposits. In addition to the presence of sequence boundaries (LS1 and LS2) and the units in which they were separated.

There are no new radarfacies, but some clear reflections with high amplitude and good lateral continuity were observed. These reflections were irregular throughout the profile and deepened in certain places and even had a concave shape. They were interpreted as sequence boundaries (LS) and labeled LS1 for the lower region and LS2 for the upper region. Based on these sequence boundaries, the profile can be divided into three units. Unit 1 (U1) represents the lower part, characterized by low-amplitude and chaotic radarfacies. Unit 2 (U2) represents the middle part, and Unit 3 (U3) consists mainly of Rdf-V facies.

Profile 2

The line of acquisition for this data was slightly perpendicular to the coastline and became parallel from the middle to the end, giving a more horizontal and orderly pattern.

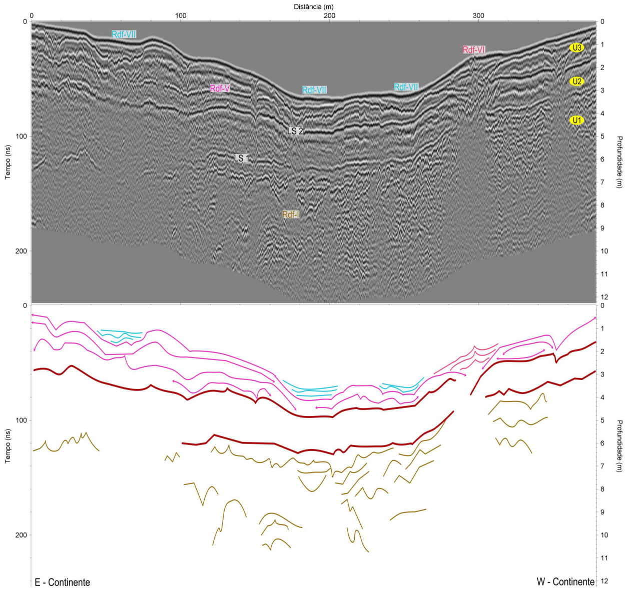

Figure 4 – Radar profile for acquisition 2. Rdf-I: Paleo Tidal Flat; Rdf-V: aeolian deposits; Rdf- VI: dunes; Rdf- VII: paleochannel and lagoons. Sequence boundaries and units are labeled.

This section also has two sequence boundaries, probably related to those observed in the previous profile. It is possible to divide this section into three units that have similar characteristics to those already presented.

Unit 3 maintains the Rdf-V facies but also shows two additional radarfacies not identified in the previous profiles. Rdf- VI shows parallel patterns, triangular geometry, low lateral continuity, and overlapping reflections. On the other hand, Rdf-VIII is characterized by a set of reflectors with a concave external geometric base that is also filled with concave reflectors. Immediately below this facies there is signal attenuation, a characteristic also observed in the work of (Tamura et al., 2008). Considering the environment of this section together with studies by other authors, it can be inferred that these radarfacies represent lagoons, paleo-tidal channels, and dunes. It is worth noting that the presence of asphalt smooths the features in this area.

Profile 3

Data collection occurred approximately 2 km from the previous profiles, in a more anthropogenically influenced area, perpendicular to the coastline. This section is found to have similar characteristics to the previous profiles, with two sequence boundaries and in the upper part with aeolian deposits.

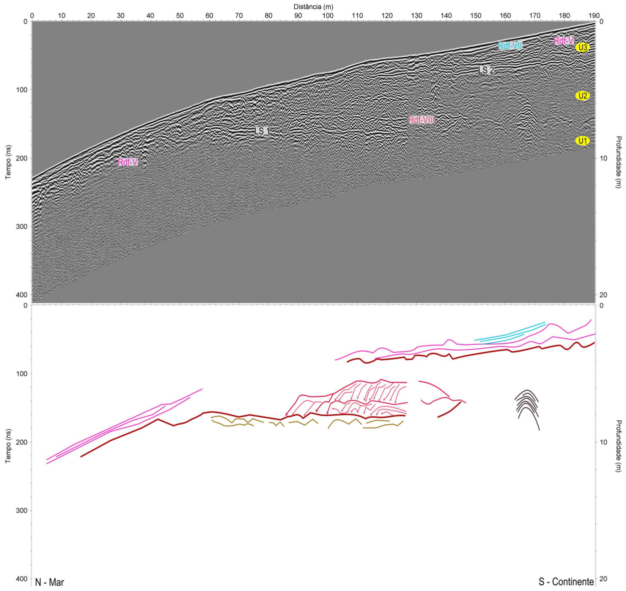

Figure 5 – Radar profile for acquisition 3. Rdf-V: aeolian deposits; Rdf- VII: paleochannel; Rdf- VIII: paleodunes. Identifies sequence boundaries and unit separation present in the other profiles.

A new radarfacies, designated Rdf-VIII, has been identified. It exhibits an external sigmoidal geometry filled with a series of patterns characterized by oblique reflections that oscillate between tangential, sigmoidal, and complex sigmoidal shapes. There is a horizontal reflection between the lenses of the external sigmoid, suggesting that they are superimposed structures, the lower portion being more flattened, while the upper part has a greater vertical thickness. We consider paleodunes to be the likely cause of this pattern. In addition, locally juxtaposed hyperbolas were observed, already noted in the work of Rossetti & Góes (2001) and defined as the presence of large boulders.

Discussions and Conclusions

The units found in the profiles can be correlated because they share common sets of radarfacies. Unit 1, located in the basal part of the radar, shows a strongly attenuated signal with chaotic reflections present in all the recorded profiles.

Unit 2 has a feature without reflections, an area without a series of radarfacies. In certain places there are changes in this pattern, but it is probably influenced by processes in other layers, since it is only visible when the upper layer has an anomaly.

Unit 3, located in the upper part of the profile, has a variety of radarfacies, but is predominantly Rdf-V, indicating aeolian deposits.

No sequence boundaries can be discerned in Profile 1A, making units delineation difficult. However, there is a variation of deposits characteristic of beach environments. Post-barrier island deposits we have Rdf-I which are associated with tidal flats, typical of very flat and low-energy coastal environments. Washover fan deposits are also associated with the lagoon side of the barriers and occur when waves reach the top of the barriers and carry sediments inland. This suggests that the post-beach barriers were farther forward than they are today, indicating a lower sea level.

There are two representatives for the deposits located in the marine part of the barriers: the foreshore and the shoreface, which were correlated with Rdf- III and Rdf- IV, respectively. The foreshore refers to the intertidal zone, which is influenced by both high and low tides, and consists largely of sandy deposits with parallel stratification that slopes slightly toward the sea. However, Rdf- III has a completely horizontal configuration, with a slight dip at the end of the deposits interpreted as the result of deposition on a steep base. The shoreface corresponds to deposition in the part of the beach that is always inundated by the sea. As can be seen in figure 2 and figure 3, these radar patterns are found far inland, indicating marine transgression originating in Rdf- II. During a period of even higher sea level, the deposits of Rdf- IV were finally formed.

The study area thus exhibits a diverse stratigraphic architecture that includes marine, aeolian, transitional, and possibly continental depositional environments, along with eight radarfacies, local features, and sequence boundaries that help suggest geomorphologic structures. This study relied solely on the literature of other authors to support its interpretations. Therefore, for future projects in this area, we recommend the use of other methods to better support the results. These methods could include the use of vibracores to obtain sediment samples, antennas with different frequencies to obtain higher resolution in shallow subsurface areas, and the use of common midpoint (CMP) acquisition to determine true depth and layer thickness.

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