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Sedimentological Patterns of the Beach-Inner Continental Shelf System of Icapuí, CE (NE-Brazil)

Padrões Sedimentológicos do Sistema Praia-Plataforma Continental Interna de Icapuí, CE (NE-Brasil)

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Abstract: The aim of this study was to analyze the sedimentary patterns of the shallow continental beach-shelf system adjacent to Ponta Grossa (Icapuí, Ceará - Potiguar Basin) to verify aspects of the contribution of terrigenous vs. marine sedimentation. The methodology consisted of analyzing 154 samples collected between Ponta Grossa and Peroba. The samples were analyzed for granulometry, calcium carbonate, texture and grain identification for subsequent analysis of statistical parameters. Sedimentation is predominantly of a mixed nature (carbonate-siliciclastic), with a tendency for fine to very fine sand to predominate near the coastline. In the more distant sectors (mainly to the north and southeast of Ponta Grossa), sedimentation of coarser fractions predominates, including fragments of the Barreiras Formation. Also noteworthy is the high percentage of carbonate sediments in these ultra-shallow waters, reaching values of almost 100% $CaCO_3$ on the shallow shelf and more than 80% $CaCO_3$ in the beach area. This shows the geomorphic control of the promontories on the adjacent offshore morphosedimentary conformation, with the topobathymetry deriving from the evolution of the Potiguar Basin, sea level variation and modern coastal processes (aerodynamics and hydrodynamics). As such, these aspects seem to favor the predominance of carbonate sedimentation, even though there are several points of terrigenous sediment input on the coastline (e.g. erosion of cliffs, dunes).

Keywords: Mixed Sedimentation; Shore Platform; Headlands.

Resumo: O objetivo deste estudo foi analisar os padrões sedimentares do sistema praia-plataforma continental rasa adjacente à Ponta Grossa (Icapuí, Ceará - Bacia Potiguar) com o intuito de verificar aspectos de contribuição de sedimentação terrígena x marinha. A metodologia consistiu na análise de 154 amostras coletadas entre Ponta Grossa e Peroba. As amostras foram analisadas quanto à granulometria, carbonato de cálcio, textura e identificação de grãos para posterior análise dos parâmetros estatísticos. A sedimentação é predominantemente de natureza mista (carbonático-siliciclástico), com tendência de preponderância de areia fina a muito fina nas proximidades da linha de costa. Nos setores mais distantes (e principalmente ao norte e sotamar da Ponta Grossa) predomina a sedimentação de frações mais grossas, verificando-se inclusive fragmentos da Formação Barreiras. Destaca-se também a grande presença de sedimentos carbonáticos nessas águas ultra-rasas, atingindo valores de quase 100% de CaCO3 na plataforma rasa e mais de 80% na faixa praial de $CaCO_3$. Desta forma, fica evidenciado o controle geomórfico dos promontórios na conformação morfossedimentar *offshore* adjacente, sendo a topobatimetria derivada da evolução da Bacia Potiguar, variação do nível do mar e processos costeiros modernos (aerodinâmica e hidrodinâmica). Sendo assim, estes aspectos parecem favorecer a predominância da sedimentação carbonática, mesmo sendo verificados diversos pontos de aporte de sedimentos terrígenos na linha de costa (por exemplo, erosão de falésias, dunas).

Palavras-chave: Sedimentação Mista; Plataformas Abrasivas; Promontórios.

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1. Introduction

The continental shelf is configured as a submerged extension of the continents, with genesis associated with tectonic control, relative sea level oscillations during the Quaternary, local geology, topography, coastal dynamics, as well as the characteristic biological control of these submerged systems (Cainelli; Mohriak, 1999; Morais, 2000; Harris et al., 2014). In general, the continental shelves of the Brazilian Continental Margin are of the Atlantic type, typical of less seismically active regions (Burchette; Wrigth, 1992; Silva et al., 2004). This characteristic can be seen in the stretch that comprises the Ceará continental shelf, which has a relatively flat relief (interrupted by some morphological patterns, such as incised valleys), with an extension that varies between 100 km and 40 km, respectively in the sectors located on the border with the states of Piauí and Rio Grande do Norte (Morais et al., 2020). It is also divided into three sectors: Coreaú, Mundaú and Jaguaribe (Morais et al., 2020). The latter includes the shallow shelf of Icapuí, in the Potiguar Basin.

The continental shelf of Ceará is characterized by the occurrence of underwater dunes, escarpments/patamars, paleochannels, beachrocks, reefs and rocky outcrops associated with the crystalline basement and Cenozoic deposits (Freire, 1985; Morais, 2000; Monteiro, 2011; Silva, 2015; Ximenes Neto et al., 2018; Morais et al., 2020, Pinheiro et al.,2023). Sedimentation is influenced by the semi-arid climate, with reduced fluvial input and a low volume of silty-clay material contributed by continental drainages (Morais; Pinheiro, 2011; Pinheiro et al., 2020). The low sea level conditions during the Wisconsin glacial (Arz et al., 1998; Nace et al., 2014) and the subsequent drowning of the shelf during the Holocene Transgression favored the formation of the current mixed depositional system, with modern sediments rich in bioclastics mixed with siliciclastics of a mainly reliquary/palimpsest nature (Ximenes Neto et al., 2018). Thus, the bioclastics are mostly made up of fragments of calcareous algae such as *Halimeda Incrassata* and Corallinaceas, while the siliciclastics are predominantly represented by quartz sands and heavy minerals (Coutinho; Morais, 1970; Freire; Cavalcanti, 1998; Carneiro; Morais, 2016).

The Icapuí continental shelf is narrow, shallow and clearly influenced by the structural heritage of the Potiguar Basin, such as the occurrence of cliffs on the promontories which show neotectonic influence, mainly in the Barreiras Formation which occurs in the basal parts of the cliffs (Freire, 1985; Morais, 2000). Consequently, this sector of the Ceará coast is characterized by having an inner continental shelf with reduced slope gradients and ultra-dissipative beaches, with morphodynamics controlled predominantly by tidal variations and transverse sediment transport (Pinheiro et al., 2016); factors which may favor the high occurrence of bioclastics in the coastal system (Barros, 2018; Ximenes et al., 2018). In addition, there are modern sources of terrigenous sedimentation for the coastal system, via wind by-pass and mass movements of the cliffs (Silva, 2022).

Thus, the justification and objective of this research is to analyze the sedimentary patterns of the shallow continental beach-shelf system adjacent to Ponta Grossa (Icapuí, Ceará - Potiguar Basin) in order to verify aspects of the contribution of terrestrial vs. marine sedimentation. This perspective is important because it provides input on the main sedimentary supply that occurs in this coastal and shallow-marine environment. Studies that analyze the morphosedimentary processes between the beach-shelf system are scarce and at the same time necessary to understand how coastal morphology and processes can interfere with sedimentary patterns in shallow areas.

According to Pinheiro et al. (2019), interference in these sedimentary patterns in submerged environments or those subject to periodic flooding can have repercussions on future changes in geohabitats, such as the meadows of needle grass (*Halodule wrightii*), the main food of manatees (*Trichechus manatus*) that occur in the region (Moretz-Sohn, 2013). At the same time, the beaches located in Redonda and Peroba are undergoing accelerated erosion processes, with an erosion rate of between 2.72 and 6.51 m/year (Leite and Almeida, 2023). As such, the presence of rockfill structures to stabilize the coastline is noteworthy, as well as small private containment structures (Barros et al., 2021; Chacanza et al., 2022). In addition to this, it is important to carry out detailed sedimentary studies to identify possible siliciclastic deposits on the shallow shelf, which could support proposals for nature-based recovery and rehabilitation, considering the area's high ecological and social relevance.

2. Methodology

2.1 Study Area

The study area is located on the coastal stretch between Peroba and Ponta Grossa beaches, encompassing the beach and its adjacent inner continental shelf (depth <10 m), in the municipality of Icapuí (Figure 1). It comprises the Potiguar Basin and the Jaguaribe sector of the Ceará shelf. The Jaguaribe sector is the narrowest section of the Ceará continental

shelf (~ 40 km wide) and displays the largest number of high-energy unconsolidated bottom forms (e.g. underwater dunes) (Morais et al., 2020). In Icapuí, the Barreiras Formation is also found on the inner continental shelf.

The Potiguar Basin is located at the eastern end of the Brazilian Equatorial Margin, comprising an emerged segment and a submerged segment. The submerged structural framework includes two main grabens, separated by internal highs and bordered by the Touros and Aracati platforms (shallow basement) (Mohriak, 2003; Vital et al., 2005). In its submerged extension, it is characterized as a mixed shelf composed of a cover of siliciclastic, carbonate-siliciclastic and carbonate sediments (Vital et al., 2005). Alignments subparallel to the direction of the shelf approach the contact between the shallow basement and the submerged Potiguar Basin (Silva Filho, 2007).

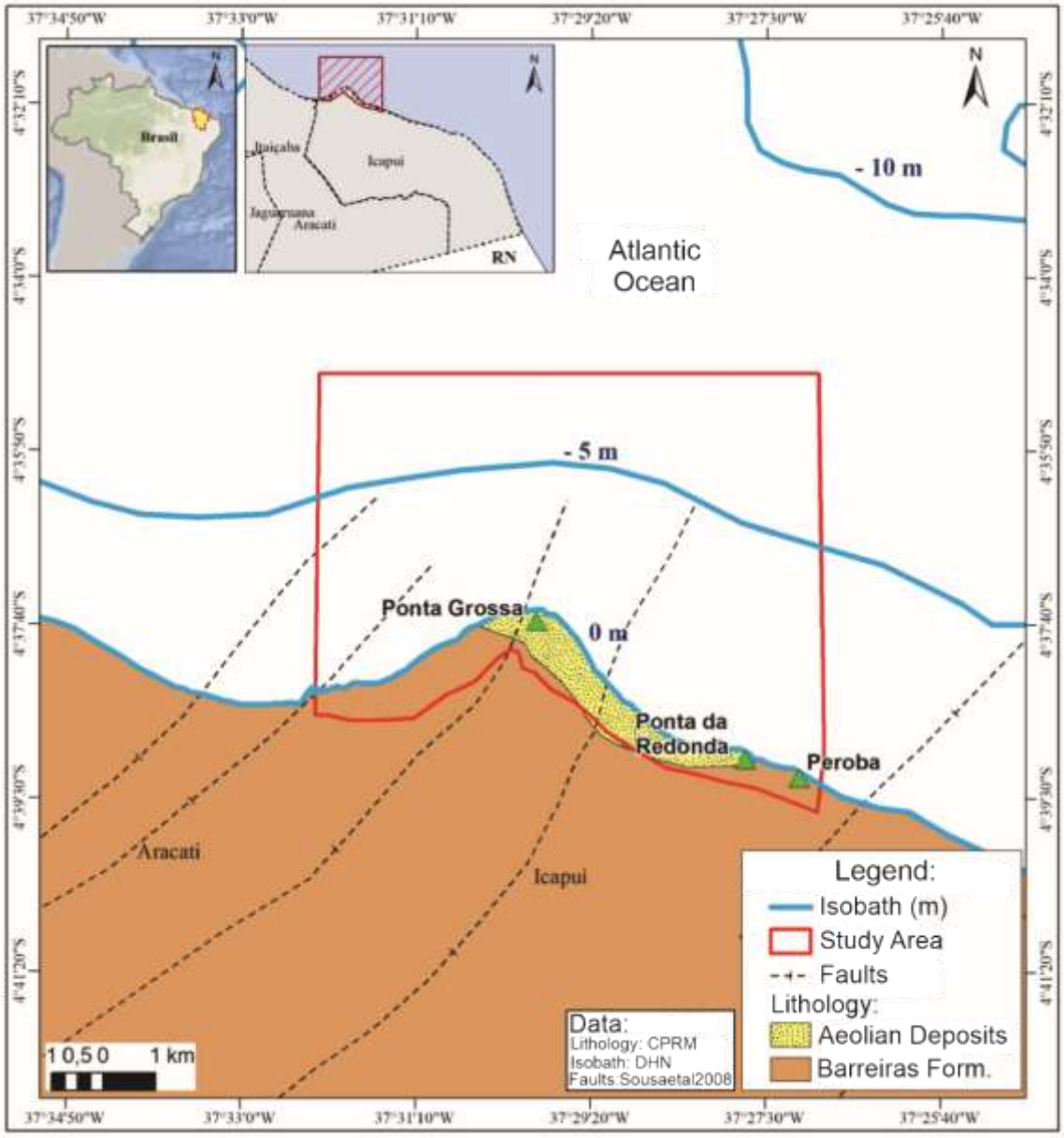

Figure 1 – Study area.
Source: Lithology (CPRM/ Cavalcante et al., 2003), Depth (DHN), Faults (Sousa et al., 2008).

Along the coastal area studied, the presence of cliffs is notable; these erosive features are formed basically by the combination of marine and sub-aerial hydrodynamic processes (e.g. precipitation) that occur on the rocks that outcrop in the coastal region. As characterized by Sousa et al., (2008) The outcrops are made up of various geological formations, with a predominance of siliciclastic sedimentary rocks correlating to the Barreiras Formation (Miocene) and the Potengi Formation (Quaternary). In addition to these, there are carbonate rocks from the Jandaíra Formation (Cretaceous) in some sectors of the cliff base. The structural influence is clearly evident in the cliffs, with a Neogene-age stress field responsible for the emergence of faults, folds, fractures and hydroplastic structures (Sousa et al., 2008). It should be emphasized that Silva (2022), in a sedimentological and geochronological study, named these Quaternary deposits that are superimposed on the Barreiras as Post-Barreiras Sediments.

The coastline is characterized by beaches preceded by active and inactive cliffs, with differences in height and degrees of resistance and with sectors with direct input of material from coastal dunes and/or products of mass movement; consequently, cliffs and dunes are important sources of siliciclastic sediments for coastal dynamics (Figure 2) (Morais et al., 2006; Pinheiro et al., 2016).

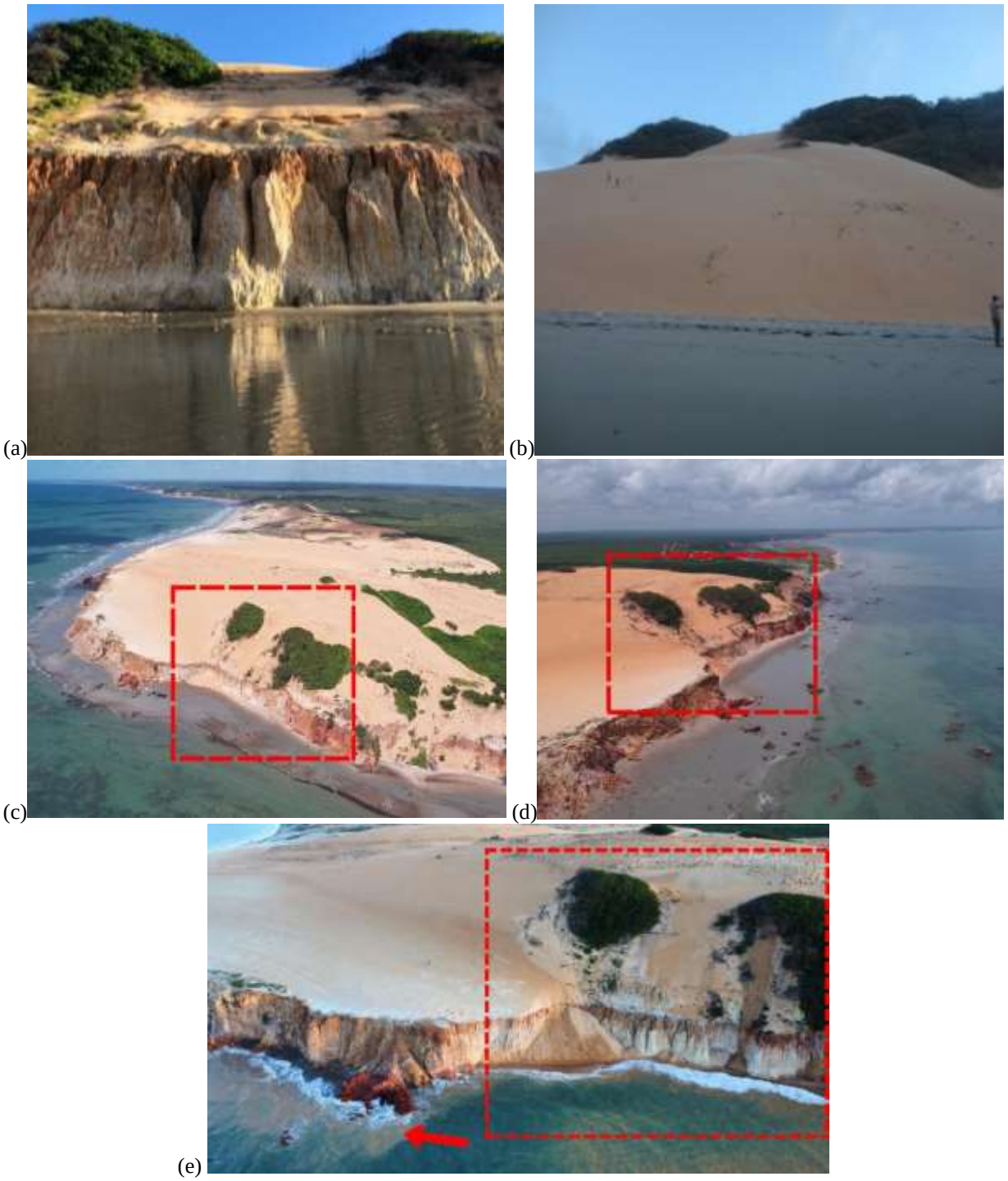

Figure 2 – Cliffs at Praia de Ponta Grossa in different configurations, in a) the cliffs are active on the beach; in b) the dunes due to the wind bypass are superimposed on the cliff scarp, noting the contribution of siliciclastic sediments to the streambed; in c) and d) it is possible to observe the same stretch at low tide and e) high tide, where the red arrow indicates the presence of suspended sediments.
Source: Barros, E.L (a-2020; b-2008; d-2023) and Leisner, M. (c-2023; d-2024).

The regional climate of northeastern Brazil is governed by the Intertropical Convergence Zone (ITCZ), where the northeast and southeast trade winds from the Atlantic converge. The rainfall regime is seasonal and well demarcated, with annual precipitation concentrated from February to May, and drought the rest of the year, and may show interannual variability associated with the El Niño Southern Oscillation (Marengo et al., 2017). Intermittent surface drainage, associated with semi-arid climates, results in a low terrigenous contribution to the Ceará continental shelf (Morais; Pinheiro, 2011).

The large-scale circulation of the Northeast Brazilian Continental Shelf includes the North Brazil Current (CNB), which tends to flow continuously in a northwesterly direction (from February to June) off the northern coast of South America, near the continental shelf break (Condie, 1991; Silveira et al., 1994; Nace et al., 2014). The shelf swells and circulations are mainly associated with the shear stress of the trade winds, which is closely related to the dynamics of the ITCZ (Morais et al., 2006). Waves with greater energy also reach the coast of Ceará, being associated with the action of extratropical hurricanes from the Northern Hemisphere, with repercussions on the period of sea surges between December and March (Paula et al., 2015).

Wave heights in the area, based on data from the Wavewatch III model, are highest between the months of December and March, reaching up to 2.2 m (Barros, 2018). The highest heights were identified in February 2016 (Barros, 2018). In the other months of the year, the heights vary between 0.8 m and 1.5 m, with periods ranging from 4.1 s to 9.9 s. Swell waves have periods ranging from 10 s to 11.5 s. Sea swells predominate in Ceará, accounting for 72% of occurrences, while Swell swells account for 28% (Carvalho et al., 2007). The tides are semi-diurnal, with amplitudes that can reach a maximum of 3.7 m during syzygy, and minimum of 1 m in the quadrature, according to tide table records from the Port of Areia Branca, in Rio Grande do Norte.

2.2 Identification and analysis of sedimentary patterns

The data collection area was divided between the beach and the inner shelf (<10m) between Peroba and Ponta Grossa. Surface samples were collected in 16 sectors between the base of the cliff/dunes and the foreshore, totaling 45 samples (Figures 3, 4 and 5). These samples from the beach system were correlated with those collected in the submerged sector of the shelf to verify the morphosedimentary interaction. On the continental shelf, an area of 59.804 km² was delimited, taking into account the consolidated substrates (abrasion platforms), unconsolidated substrates and structural features identified on the geological maps, considering the location of the area in the Potiguar Sedimentary Basin. Samples of the marine substrate were collected using a Van Veen-type sampler, distributed in a grid with a spacing of 500 meters subdivided between the -4 m and -8 m isolines. A total of 109 samples were collected from 19/01/2011 to 01/03/2013.

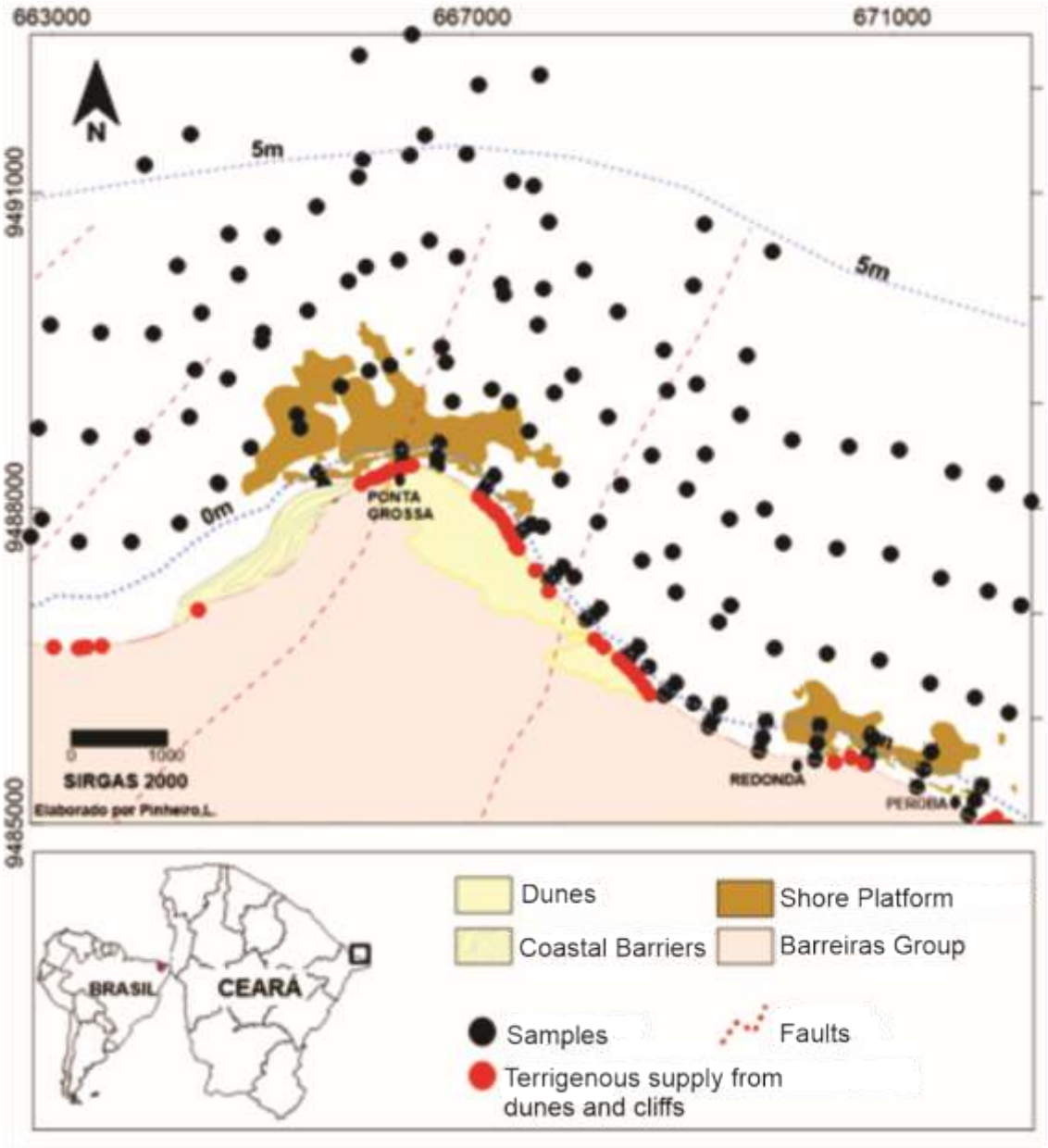

Figure 3 – Sampling grid for sediment collections on the shallow continental shelf and beach strip. Source: Lithology (CPRM/ Cavalcante et al., 2003), DHN (depths), Sousa et al., 2008 (faults).

The sediment samples were analyzed using Suguio's (1973) mechanical and wet sieving method for the textural and granulometric characterization of the sediments. The percentage of calcium carbonate was obtained using the modified Bernard Calcimeter method (Soares, 2017). After statistical treatments, the sedimentary facies were classified based on Larsonneur (Dias, 1996). The main components of the siliciclastic and bioclastic sediments were described using microscopic analysis. Walks along the beach were carried out using a GPS navigation receiver to map locations with direct input of terrigenous sediment from the dunes and cliffs. To assess possible interference in sedimentation in the beach x shelf sector, abrasion platforms were mapped using Google Earth images from 2022 in QGIS 3.22. The maps were drawn up using Kriging interpolation, with scale control depending on the density of the sampling mesh.

3. Results and discussion

3.1 Sedimentological distribution

The analyses of the sedimentological distribution were organized into two topics: one on the characterization of the beach environment and the other on the continental shelf environment.

3.2 Beach

An analysis of the median (D50) of the 45 samples shows a predominance of very fine sand (44%) and medium sand (40%). Spatially, it should be emphasized that there is a predominance of finer sands in the updrift stretch of Ponta Grossa and that the downdrift of Ponta Grossa shows a tendency towards an increase in granulometric size (Figure 4a). The average calcium carbonate content was 44%, with values ranging from 3% to 83%. In terms of spatial distribution, there is a predominance of values below 50%, especially at the three ends, Peroba-Redonda-Ponta Grossa. In contrast, the stretches southeast of Ponta Grossa and Peroba show areas with higher CaCO3 levels (above 50%) (Figure 4b). Thus, according to Larsonneur's (1977) classification (Dias, 1996) there is a predominance of fine to very fine and medium biolithoclastic sand, both with 22.2% each. Fine to very fine lithoclastic sand and fine to very fine lithobioclastic sand also stand out with 17.8% and 13.3%, respectively.

3.3 Shallow Shelf

An analysis of the median (D50) of the 109 samples shows a predominance of medium sand (56.6%), very fine sand (18%), fine sand (15%) and coarse sand and gravel (11%). It should be noted that in the sector between Ponta Grossa and Ponta da Redonda, especially close to the coastline, there is a predominance of the finest fractions (fine to very fine sand). The northern sector offshore of Ponta Grossa shows a distribution of larger sediments (medium sand to gravel) (Figure 4a).

The average calcium carbonate content was 73%. However, the values varied between 98.6% and 25.1%. The spatial distribution of calcium carbonate showed the following trends: lowest values (<65%) near the coastline and offshore of Ponta Grossa, while the rest of the area showed the highest calcium carbonate values (>65%) (Figure 4b). The only place that doesn't follow this pattern is the northeast area of Ponta Grossa, where the high levels of calcium carbonate (>70%) move towards the coastline (Figure 4b). Therefore, according to Larsonneur's (1977) classification (Dias, 1996), there is a predominance of fine to very fine bioclastic sand (44.4%), medium bioclastic sand (14.8%) and fine to very fine biolithoclastic sand (12%) (Figure 5).

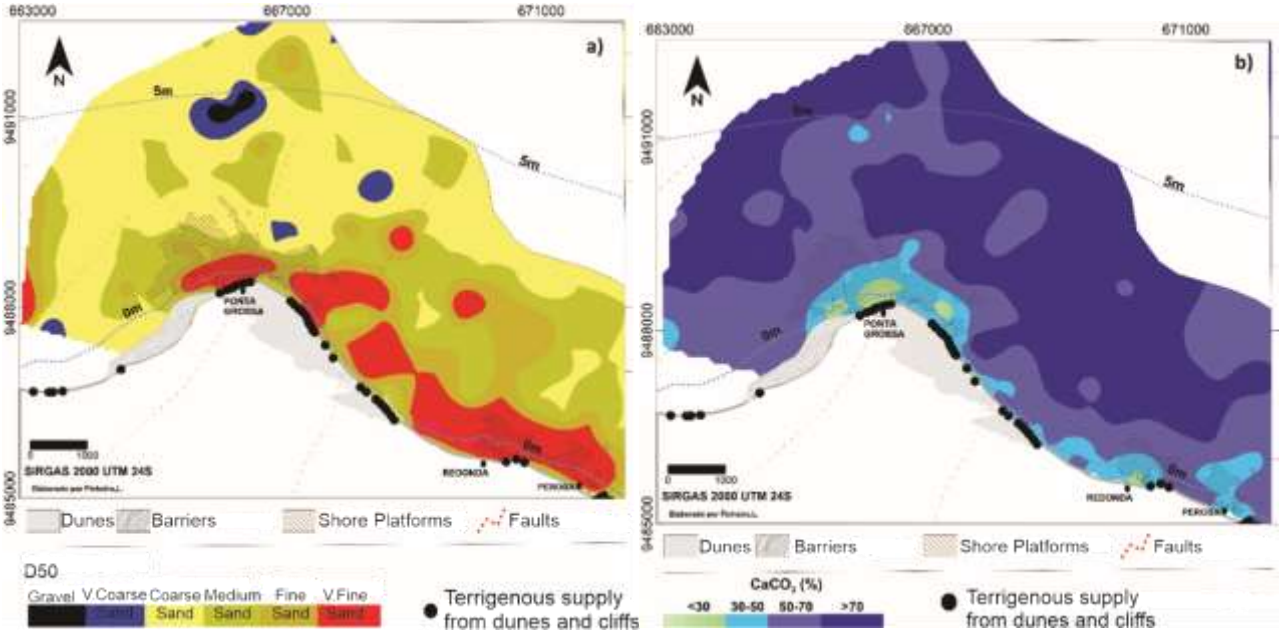

Figure 4 – a) Spatial distribution of the D50; b) Percentage of Calcium Carbonate present in the sediments. Source: Authors (2024).

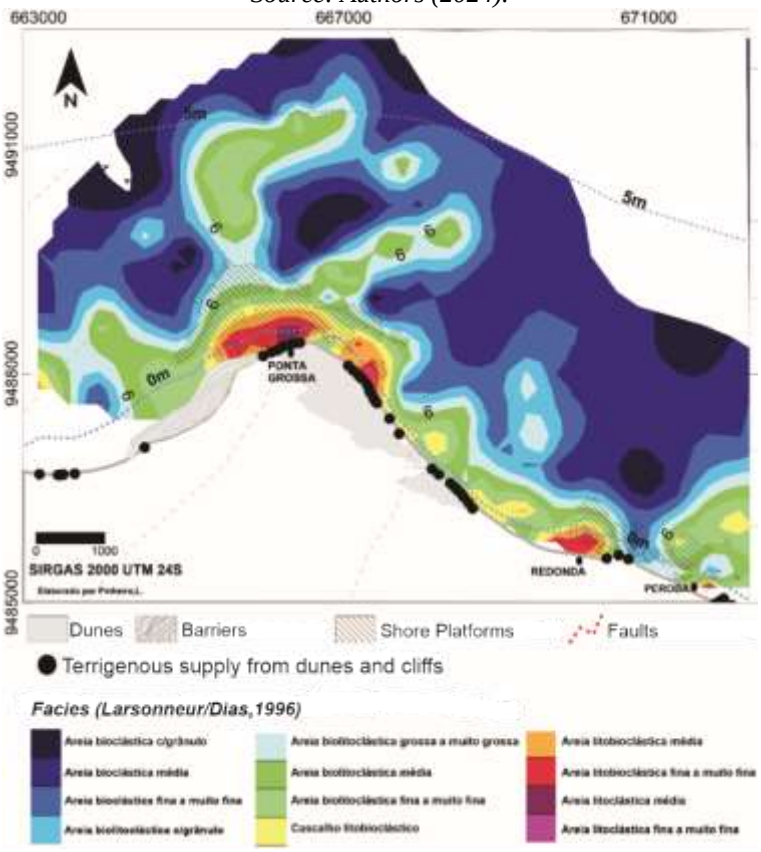

Figure 5 – Sedimentary patterns of the Icapuí inner continental shelf-beach system. Source: Authors (2024).

3.4 Types of grain

The main components in the sediments analyzed were bioclasts, followed by siliciclastics. The former are mainly represented by red (coralline) and green (*Halimeda*) calcareous algae, mollusks (e.g. bivalves), echinoderms (e.g. sea urchins), bryozoans and corals. It should be noted that the bioclastic fragments of calcareous algae are well distributed throughout the shelf analyzed. The siliciclastics are mainly associated with quartz grains and fragments of the Barreiras Formation. The materials belonging to the Barreiras Formation occur ~2.6 km away from Ponta Grossa at a depth of ~6.5m. In addition, high concentrations of *Halimeda* algae (branched stalks with well-preserved articles) occur ~2.7 km away from Ponta da Redonda at a depth of ~4.5m (Figure 6).

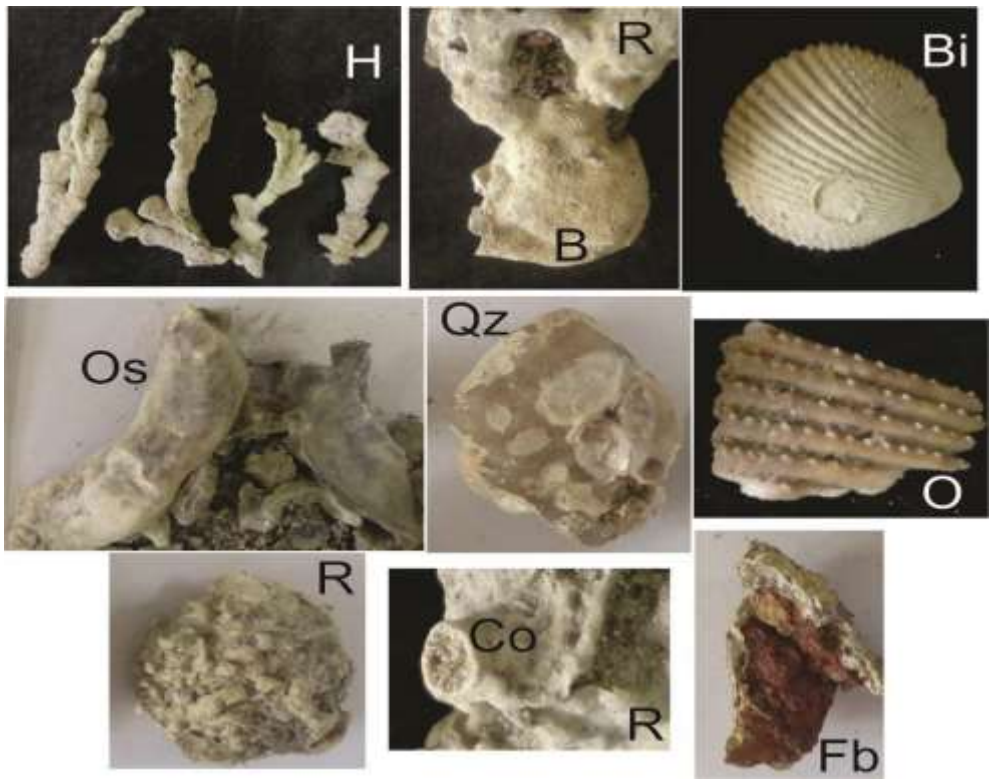

Figure 6 – Main components identified in the sediments: R - rhodolith (red calcareous algae), B - bryozoan, Bi - bivalve, Qz - quartz, O - sea urchin, H - Halimeda, Os - oysters, Co - coral, Fb - fragment of the Barreiras Formation. Source: Authors (2024).

The beach and the shallow shelf adjacent to the Ponta Grossa, Peroba and Redonda promontories show a mixed depositional pattern (mixture of siliciclastic and carbonate), with the deposits close to the coastline having a mixed siliciclastic-carbonate deposition; moving offshore, the bioclastic influence increases, thus creating a mixed carbonate-siliciclastic and sometimes entirely carbonate deposition. This carbonate materials in the beach system and in ultra-shallow waters is not well documented in the literature for the semi-arid coast, with emphasis on studies of the metropolitan region of Fortaleza (Guerra, 2014; Paula et al., 2015; Pinheiro et al., 2016), which were in an entirely siliciclastic system.

The mixed to eminently carbonate deposition in this study area follows the pattern suggested for the stretch of continental shelf adjacent to Aracati and Icapuí, as pointed out by Ximenes Neto et al. (2018) and for the Icapuí coast (Ximenes Neto, 2020). However, no work to date has sought to integrate the beach-shelf interaction from a morphosedimentary point of view. Several studies carried out on the continental shelf of the Potiguar Basin have verified the high occurrence of carbonate facies, mainly related to calcareous algae, such as Vital et al. (2005), Moura (2014) and Ciarlini and Morais (2014).

Colares (2009), Monteiro (2011) and Carneiro and Morais (2016) highlight the high occurrence of banks of green calcareous algae of the *Halimeda* genus on the Icapuí continental shelf, mainly between 12-25m deep. However, *Halimeda* can also occur in shallower areas, as found in this study. Consequently, it is emphasized that the low input of terrigenous sediments (Morais; Pinheiro, 2011), the semi-arid climate (Barros, 2018), the morphology of the continental shelf (Morais et al., 2020) and carbonate production by benthic habitats in ultra-shallow waters (Ciarlini; Morais, 2014) have led to the creation of a coast rich in marine sediments. A greater presence of terrigenous sediments was to be expected due to the area having important sectors of coastal cliffs with mass movements, so this fact was associated with two factors: i) the Barreiras Formation, which supports a large part of the bases of the cliffs, has a lower degree of erodibility than the other coastal cliffs in Ceará, such as Morro Branco, Canoa Quebrada, Ponta do Maceió, Pacheco (Rodrigues et al., 2020; Rodrigues, 2021; Leisner et al., 2023), thus does not supply a high volume of siliciclastics to the beach system on a short time scale; ii) coastal transport, which plays a key role in the dispersal of sediments, such as wind transport that occurs predominantly towards the continent (with the exception of specific stretches such as Ponta Grossa, where avalanches of aeolian sediments into the beach environment are observed) (Barros, 2018), in addition to longitudinal transport that favors modern mixing between siliciclastics and carbonates, as observed in the coastal barrier system slightly downdrift of Ponta Grossa.

The geomorphic aspects through the layout of a coastline with promontories and abrasive platforms (Figure 7 a;b) led to the establishment of an area of low slope in the shallow marine sector (Oliveira, 2012; Barros, 2014; Barros, 2018; Rodrigues, 2021), especially in front of Ponta Grossa. This factor can be seen in the presence of some fragments of the Barreiras Formation collected in the submerged samples. Thus, according to Ximenes Neto (2020), the sectors of the Ceará coast that have a low slope at the beach-platform interface provide greater connectivity with the carbonate sedimentation of the platform, a factor that may favor the establishment of a coastline of a mixed nature.

(a)  (b) 

Figure 7 – a) Beach strip with reduced slope at Redonda; b) Abrasion platforms adjacent to the tip of Redonda. Source: Authors (2024).

4. Final considerations

With regard to the sedimentary patterns of the beach-shelf system, a mixed nature (mixture of carbonate and siliciclastic sediments) was evident, with emphasis on the high presence of carbonates not only on the shelf, but also in the beach system, where the latter showed values of up to ~80% CaCO3. Near the coastline between Ponta Grossa and Redonda there was a predominance of fine to very fine sand, and in the offshore sector to the Ponta Grossa Promontory there was an increase in the influence of coarse fractions. Among these larger fractions are rock fragments from the Barreiras Formation.

The morphosedimentary aspects are products of the geomorphic conformation of this sector of the Potiguar Basin, just as in the Serras do Mel and Mossoró there is a succession of topographic highs and a structurally controlled lowered sector (Maia et al., 2014), aspects that extend into the shallow shelf sector and consequently favor the establishment of carbonate habitats in shallow waters and close to the beach system. Other factors influencing the mixed nature of this area are sea level variation and modern coastal processes (aerodynamics and hydrodynamics).

The results of this article present important implications for coastal and marine management, as well as for the conservation of ecosystems, especially in areas subject to erosion processes in advanced stages, such as the Redonda and Peroba beaches. The analysis and understanding of sedimentary patterns and their interaction with environmental and

anthropogenic factors allows for the development of specific strategies to deal with coastal erosion and promote the resilience of coastal communities and marine habitats. Finally, the continued importance of sedimentological and morphosedimentary studies for sustainable and effective management of the coastal zone and the marine environment is highlighted, with a view to conserving natural resources and protecting ecosystems in the face of climate change and anthropogenic activity.

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