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ANALYSIS OF THE EROSIVE BEHAVIOR AND SEDIMENTOLOGICAL CHARACTERIZATION OF THE SANDY BAR AT THE MOUTH OF THE ITABAPOANA RIVER, PRESIDENTE KENNEDY-ES

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ABSTRACT
The state of Espírito Santo, despite being the smallest in the Southeast region, presents a significant diversity in the variations between the effects of retrogradation and coastal progradation. This dynamic is influenced by a complex interplay of variable factors, such as coastal geomorphology, hydrodynamics, and geology, which directly affect coastal cities and their development. The objectives of this study are to understand the phenomenon of coastal erosion and to analyze the morphological behavior of the sandy bar at the mouth of the Itabapoana River and at Praia das Neves, generating relevant information for the preservation of the coastal environment and minimizing material losses in urban areas adjacent to the sea. This work used tools such as the Ground Penetrating Radar (GPR) for the interpretation of radarfacies, as well as remote sensing and satellite image geoprocessing methodologies, combined with sedimentological characterization studies applied to Environmental Geology. The integration of GPR data revealed a complex sedimentary dynamic, with reflectors that indicate the progradation of beach deposits, as well as eolian, fluvial and marine influences, observing the presence of filled paleochannels and fluvial deposits. The analysis of satellite images allowed us to identify variations in the morphology of the beach and the location of the sandy bar at the mouth of the Itabapoana River, which shows migration patterns in a north-south direction. The compilation of the results suggests that coastal erosion in the region is cyclical, alternating between moments of progradation and retrogradation throughout the analyzed period, reflecting a complex coastal environment that involves climatic factors and marine and fluvial dynamics. The sediments analyzed were well selected, ranging from fine to medium fraction, with heavy fine sediments from the Araçuaí-Ribeira Orogen, showing low textural maturity.

Keywords: Remote Sensing. GPR. Sedimentology. Coastal Erosion.

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INTRODUCTION

For decades, the discussion about the consequences of climate change, such as the intensification of natural phenomena, has been widely addressed by academics, government agencies, and NGOs. Catastrophes are reported with increasing frequency, both due to natural agents — such as currents generated by waves and tides, winds, storms, weathering and erosion — and to modifications caused by anthropic agents, such as disorderly occupation, suppression of vegetation and changes in the landscape (Albino et al., 2006; Teixeira et al., 2009; Albino et al., 2010).

In the coastal region of Brazil, which extends for about 8,000 km and is home to capitals and cities of great economic relevance, the damage caused by erosion generates concern among the population and the authorities. Although erosion is a natural phenomenon, the way humans deal with this issue is crucial for the maintenance and prevention of new disasters (Albino et al., 2006; Teixeira et al., 2009; Albino et al., 2018).

In view of this scenario, Praia das Neves was chosen as the object of study. Despite suffering little anthropic change, the bibliographic analysis and satellite images revealed an intense variation of the coastline. Conversations with local residents indicated that the city government has implemented actions to mitigate the advances of the sea and dunes, such as landfills in the Post-Beach and Coast strip, since the region is dominated by coastal paleocords.

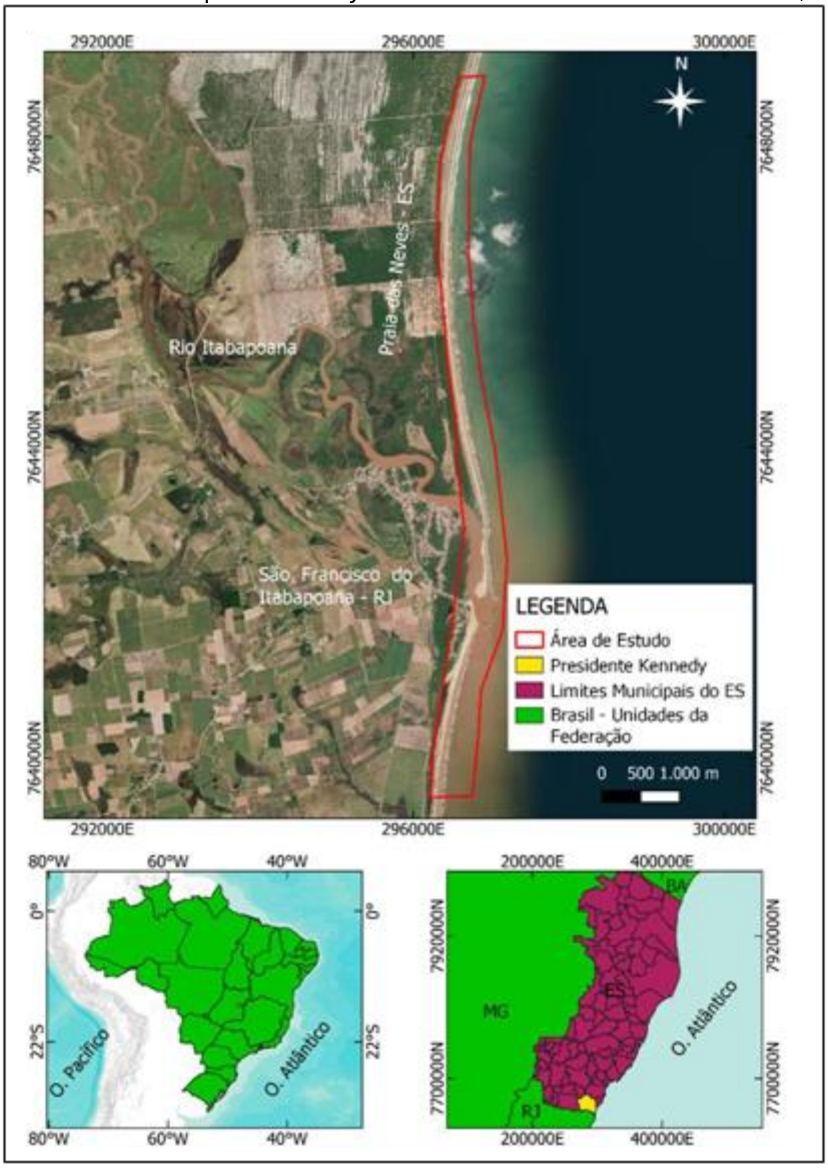
This study is relevant, as there are few similar works in the area, and offers the opportunity to transform academic research into material that helps to understand and visualize local erosive effects, in addition to informing the population about the prevention of future events. Thus, the research contributes with information on remote sensing, sedimentological characterization and geophysical applications, supporting the development of municipalities, the well-being of the population and the sustainable maintenance of the coastal region.

LOCATION OF THE AREA

The study was carried out in the region of the mouth of the Itabapoana River, which marks the border between the states of Espírito Santo and Rio de Janeiro, specifically in the municipal limits of Presidente Kennedy (ES) and São Francisco do Itabapoana (RJ) (Figure 1). The activities were concentrated at Praia das Neves, located on the Espírito Santo side.

The study area is accessible by the Governador Mário Covas Highway (BR-101), in Cachoeiro de Itapemirim (ES). Heading south, between km 421 and 422, is the cloverleaf that gives access to the municipality of Presidente Kennedy. From this interchange, it is possible to access the ES-162 road, which leads to the city center. To get to Praia das Neves, you must follow the ES-060, which, in the south direction, leads to the district of Praia das Neves.

Figure 1: Location map of the study area. Scale 1:50000. Source: Author, 2023.



OBJECTIVES

The general objective of this study was to interpret and analyze the evolution of the sandy bar in the region of the mouth of the Itabapoana River. To better understand the coastal effects of retrogradation and progradation in the study area, satellite image geoprocessing was used, allowing the definition of the evolution of the coastal margin of sediments.

The specific objectives of this work included the elaboration of thematic maps that illustrate the evolution of the sandy bar and the coastal margin, in order to evaluate the dynamics of the coastal morphology; the use of geophysical data (GPR) to obtain information on the behavior of sedimentation in the subsurface; sedimentological characterization through sample collection, using existing methodologies to understand minerals and their depositional characteristics; and the generation of coherent information to promote the preservation of the coastal environment of fluvial-marine interaction, aiming to inform authorities and the local population of the region of the mouth of the Itabapoana River.

LOCAL GEOLOGY

According to Heilbron et al. (2016) and Nascimento (2018), Holocene Quaternary littoral deposits are widely observed along the north coast of Rio de Janeiro and south of the Espírito Santo portion. These deposits can have a thickness ranging from tens of meters to kilometers, especially near the mouths of rivers, bars and sandy paleocords. It is an environment characterized by depositional interactions (Figure 2) between fluvial-marine and aeolian processes, which highlights the complexity of the effects of shoreline reworking (Rocha and Fernandez, 2013; Sousa et al., 2017; Albino et al., 2018).

Figure 2: Praia das Neves, Presidente Kennedy-ES. (A) sandy bar at the mouth of the Itabapoana River (B) post-beach zone with wind interaction (C) beach zone in front of the district's waterfront. Source: Author, 2023.

Sandy paleocords are recent sedimentary records, resulting from eustatic variation in sea level, with the most significant change occurring about five thousand years ago, when there was a variation of approximately four meters. These deposits mark old beach lines and are reworked by fluvial and aeolian systems, which alter the morphology of the paleocords. The sandy bar, in turn, is formed due to the estuarine fluvial-marine interaction, depositing sediments at the mouths of the rivers (Teixeira et al., 2009; Heilbron et al., 2016; Albino et al., 2018).

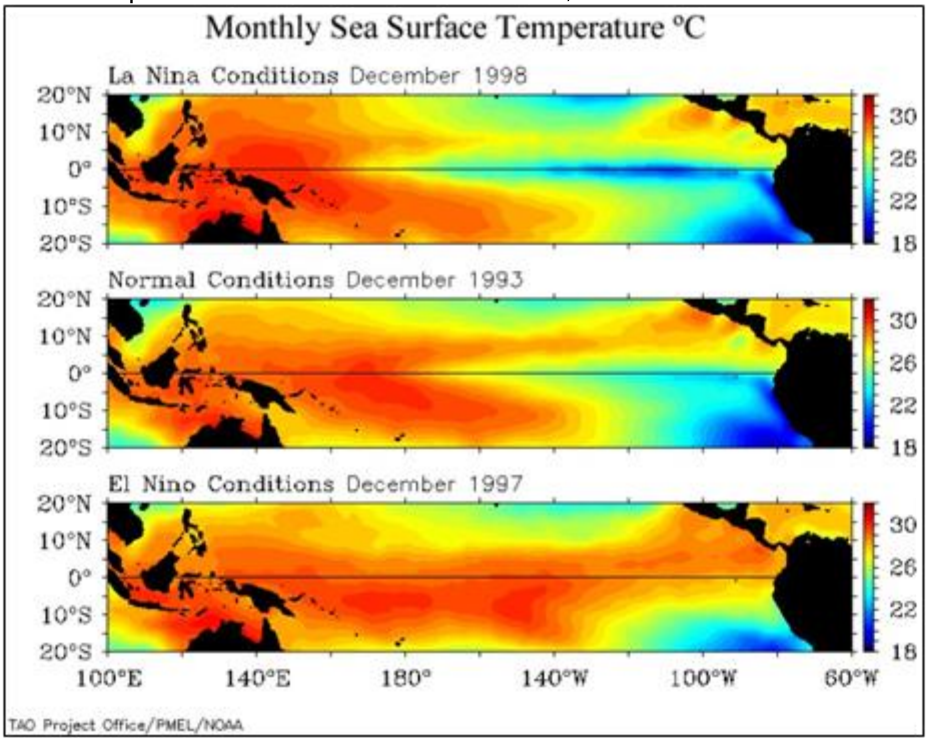
The composition of the Quaternary sediments is, in general, well selected, ranging from medium to coarse, with a predominance of quartz. Heavy minerals, seashells, and silt rich in organic matter are also found. Sedimentary structures are characterized by parallel flat laminations, as well as coastal and aeolian surfaces, with finer graining (Heilbron et al., 2016; Sousa et al., 2017; Nascimento, 2018).

Although there are few studies in the research area and nearby, authors such as Souza et al. (2017) characterized the particle size fractions and described the heavy minerals present in São Francisco do Itabapoana (RJ). Nascimento (2018) used GPR to investigate paleocords. The environment is predominantly composed of fine to medium sands, of marine and fluvial origin. Identified minerals include amphibole, apatite, biotite, kyanite, epidote, spinel, staurolite, garnet, ilmenite, limonite, monazite, muscovite, pyroxene, rutile, sillimanite, tourmaline, and zircon.

COASTAL EROSION

In view of the national scenario, several beaches and cities along the Brazilian coast are being severely affected, in part, by anthropogenic actions, such as disorderly occupation and the suppression of vegetation, in addition to the intensification of climatic phenomena, among which El Niño stands out. This seasonal natural phenomenon, characterized by the increase in the average temperature of the waters of the equatorial Pacific (Figure 3), causes changes in global atmospheric circulation systems, affecting moisture transport, temperatures, and precipitation (NOAA, 2023; CPTEC/INPE, 2023).

Figure 3: Sea surface temperator in ºC under normal conditions, in El Nino and La Nina.Source: NOAA, 2023.



The effects of El Niño generate catastrophic consequences from North to South of Brazil, a country of continental dimensions located on the South American Shelf. As it is an underdeveloped and unequal nation, many regions do not have disaster prevention plans or adequate infrastructure or urban planning to deal with these climatic events, even if they are provided for in federal, state and municipal guidelines (Teixeira, 2009; Albino et al., 2018; Nascimento, 2018).

In the North of the country, severe drought results in the drying up of rivers, compromising the main means of local socioeconomic transport: the river. Meanwhile, the South and Southeast regions face strong storms (Figure 4), caused by low atmospheric pressure zones that favor the formation of cyclones; in 2023 alone, more than a dozen of these events have already been recorded (Teixeira, 2009; Albino et al., 2018; Nascimento, 2018; NOAA, 2023; CPTEC/INPE, 2023).

It is also important to mention the La Niña phenomenon, which occurs seasonally, but less frequently than El Niño. La Niña is characterized by the cooling of waters in the Pacific Ocean (Figure 3), near the coast of Peru. This phenomenon alters the global atmospheric circulation, resulting in a lower evaporation rate, which translates into lower precipitation rates, greater drought, and changes in wind patterns, affecting the global climate. In Brazil, the impacts of these changes include drought and heat waves in the South, cold and dry to humid weather in the Southeast, and hot and humid temperatures, with higher precipitation, in the North of the country (NOAA, 2023; CPTEC/INPE, 2023).

Figure 4: Illustration of different regions of Brazil, with strong erosive aspects. (A) Campeche Beach, Florianópolis-SC (B) Massaguaçu Beach, Caraguatatuba-SP (C) Ponta Negra Beach, Natal-RN (D) Atafona Beach, São João da Barra-RJ. Source: Regional journalistic sites.

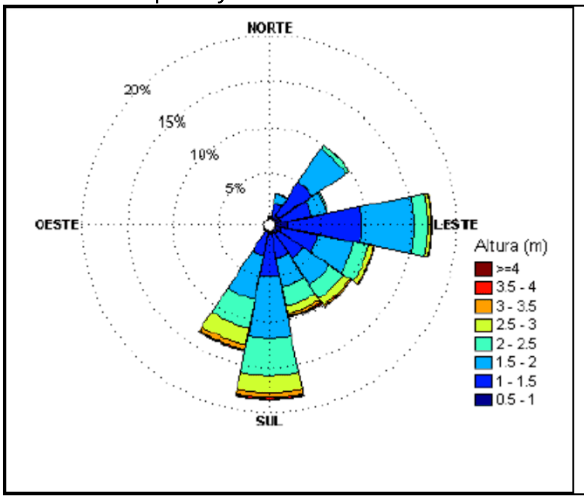
The state of Espírito Santo, although it is the smallest in the Southeast region, presents a significant variation in the effects of coastal retrogradation and progradation, resulting from a complex interaction of factors, such as coastal geomorphology, hydrodynamics and geology. These factors directly impact coastal cities and their development. In the north of the state, localities such as Conceição da Barra, Regência, Marataízes and Presidente Kennedy face a strong erosive trend (Figure 5), a reality frequently reported by the press and evidenced by the Ministry of the Environment (MMA) project entitled "Overview of Coastal Erosion in Brazil" (Albino et al., 2018; Nascimento, 2018).

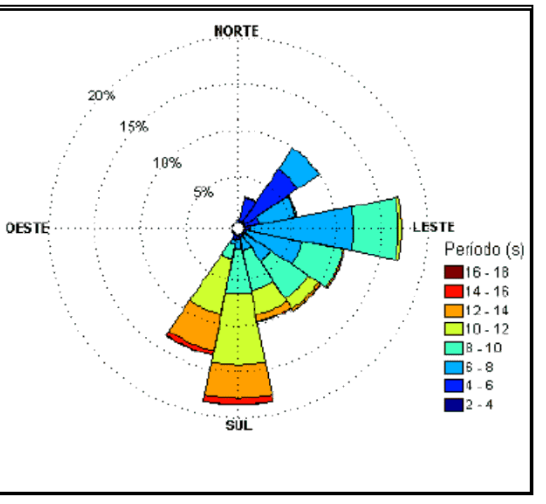
Figure 5: Illustration of different regions of the state of ES, with strong erosive aspects. (A) stretch of highway grounded Anchieta-ES (B) Highway eroded by waves at UBU Beach (C) Areia Preta Beach, Guarapari-ES (D) Neves Beach in 1970 (E) Neves Beach in 2013 (F) Snows Beach in 2022. Source: Regional journalistic sites and Civil Defense.

Praia das Neves, in Presidente Kennedy, is located in a coastal area composed of Quaternary fluvial-marine plains. The presence of the mouth of the Itabapoana River increases the susceptibility to coastal erosion, aggravated by the coastal cords, which promote migrations and dune formation, especially due to the intense winds characteristic of this region, the windiest in the state. This Quaternary plain has a beach classified between the intermediate and dissipative morphodynamic stages, inserted in Sector 5 of the subdivision of coastal morphology, which extends from the north bank of the Itabapoana River to the Itapemirim River (Albino et al., 2018).

The tidal regime is micro-tide, with a maximum amplitude of 1.7 m. During the summer and spring, the wind regime is dominated by the South Atlantic Anticyclone, resulting in prevailing winds from the east (E) and northeast (NE) directions, characterizing a dissipative coast (DHN 2015 Apud Albino et al., 2018). As illustrated in Figure 6, in autumn and winter, polar fronts coming from the south move towards the north, generating waves from the southeast (SE) and south (S), which are more intense than the prevailing winds. These waves can reach up to 2.0 m in stormy conditions (Albino et al., 2018; Nascimento, 2018).

Figure 6: (Left) Graph of the height and direction of the waves throughout the year (Right) graph with the period in seconds of the frequency of the waves. Source: Civil Defense.





MATERIALS AND METHODS

The methodology occurred according to six main stages: bibliographic survey, geoprocessing, geophysical survey, sample collection, granulometric analysis and sedimentological description. Each step is described below.

BIBLIOGRAPHIC SURVEY

The work began with a bibliographic survey, focusing on the search for studies related to the area of Presidente Kennedy, Praia das Neves-ES. However, it was observed that there was a scarcity of research on the subject in the region, which led to the consultation of works with similar themes carried out in various parts of Brazil, addressing topics such as geophysical characterization, geoprocessing, granulometric and stratigraphic analyses and geological units. In the course of applying the methodologies, new research was occasionally carried out to complement relevant information from studies in similar settings.

GEOPROCESSING

In this stage, the QGIS geoprocessing and remote sensing program, version 3.22, was used. The satellite images were obtained free of charge from the Earth Explorer portal, maintained by the USGS (United States Geological Survey), and acquired through the LANDSAT 5 (L5) and LANDSAT 8 (L8) satellites, covering the period from 2000 to 2010 and 2013 to 2023, with 0% cloud cover and multispectral resolution of 30 m.

The processing was carried out based on methodologies partially adapted from the works of Akel (2010) and Rodrigues & Souza Filho (2011). For LANDSAT 5, the band composition was R4-G5-B3, while for LANDSAT 8 it was R5-G6-B4. The reclassification aimed to highlight the reflectance of sediments, especially in sandy strips, restinga vegetation and urban sprawl. After generating new images in raster format, the study area was cut, identifying the pixel values. Then, using the table reclassification tool, batch processing was performed, assigning values of 0 and 1 to the pixels (Table 1).

Table 1: Determination of pixel values for table reclassification processing. Source: Author, 2023.

Pixel Value	Determined value for Reclassification	Environment described
0 – 14000	0	Vegetation, water and city
14000 – 40000	1	Sediments (beach and bar)

Finally, the images reclassified in matrix format were vectorized and transformed into vector files using the tools available in QGIS. This process allowed the evaluation of the extent of the sediments in the study area, in square meters. The maps generated for each year evaluated were made on a graphic scale of 1:90,000, following the Universal Transverse Mercator projection system, with the Horizontal Datum WGS84/Zone 24S, as presented throughout the work.

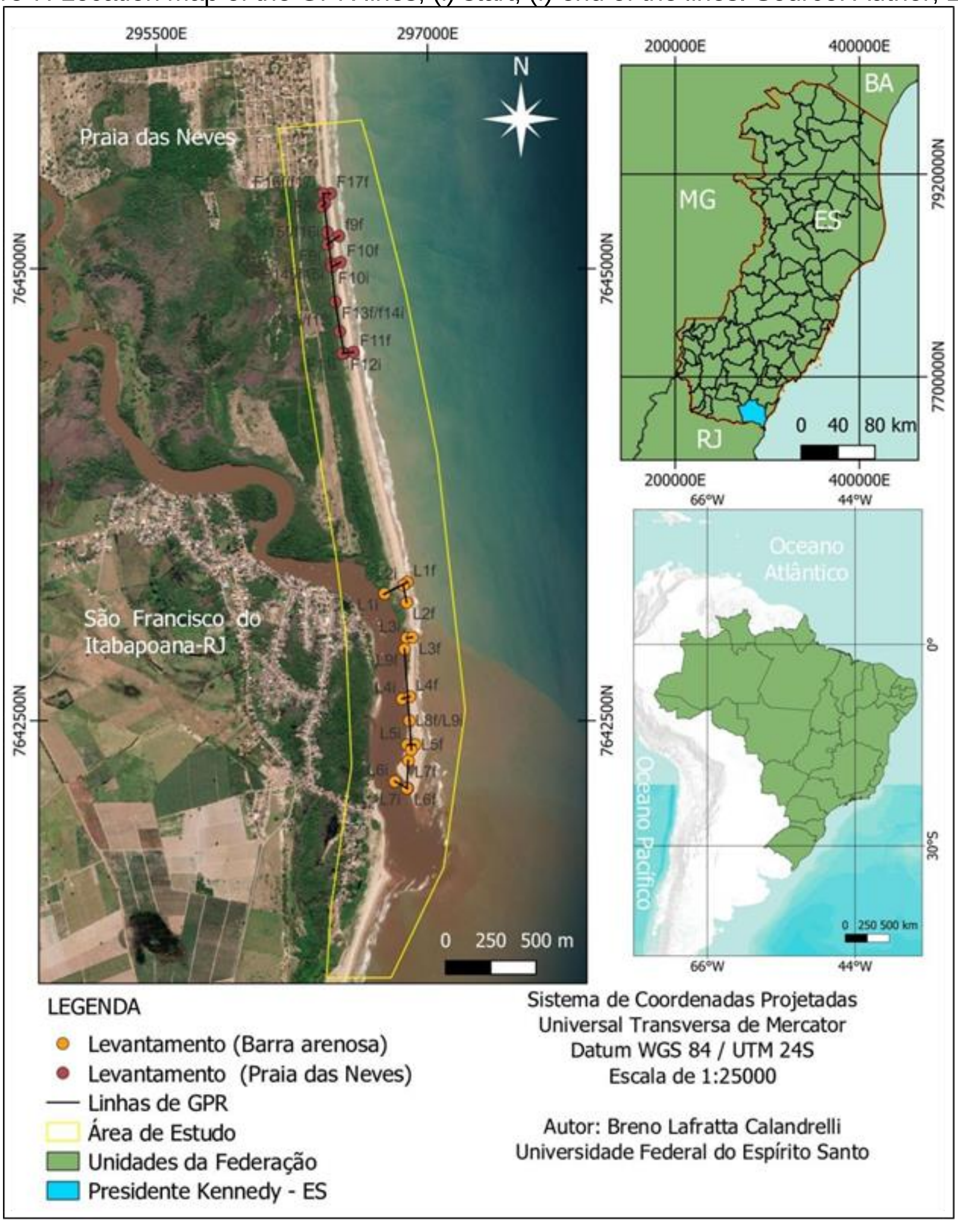
GEOPHYSICAL SURVEY (GPR)

Georadar, or GPR (Ground Penetrating Radar), is a geophysical method that emits a short pulse of electromagnetic waves with the fixed frequency of the transmitting antenna, directed to the ground. Part of this wave is reflected off the horizons, depending on differences in the electrical properties of the material, while the other part propagates and dissipates in the middle. These variations occur due to the presence of fresh or salt water and are related to factors such as sedimentological variations (grain size), porosity, and compaction. The reflected wave is captured by the antenna receiver, which amplifies, digitizes and stores the signal in the equipment, generating a 2D image of the transect traveled, allowing the visualization of the substrate in the subsurface on the equipment's display (Kearey, Brooks and Hill, 2009; Duarte, 2016; Leandro, 2018).

The survey was carried out using a georadar data acquisition system (Figure 4). The equipment, model SIR-2000 from Geophysical Survey Systems, Inc. (GSSI),™ was available from the Department of Geology (DGEO) and was attached to a 200 MHz antenna and a distance meter.

During the fieldwork (Figure 7), more than eighteen lines were collected. However, due to the little variation of reflectors between them, only five lines, with lengths ranging from tens to hundreds of meters, will be presented, contemplating the variations of environments and reflectors in the study area.

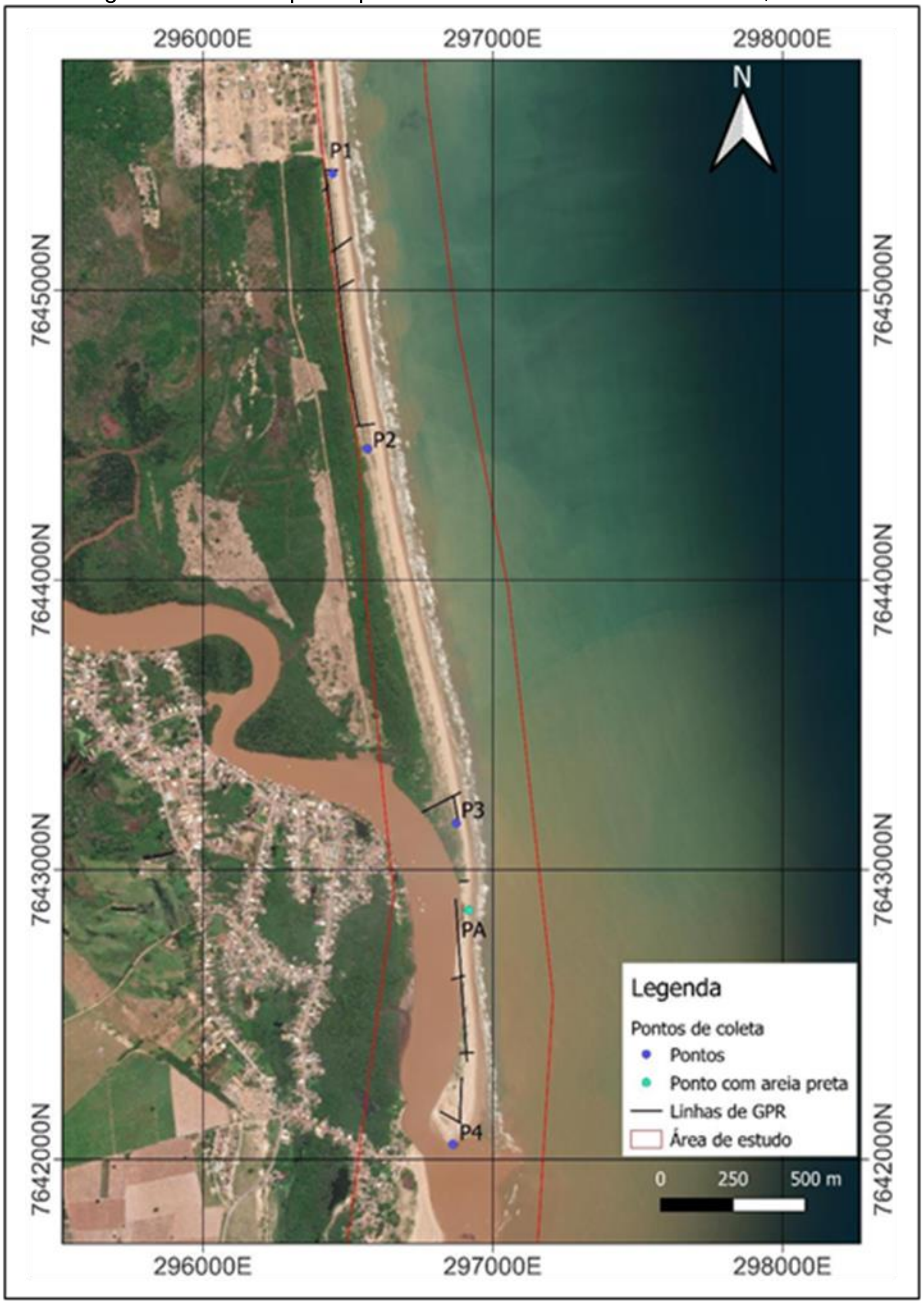
Figure 7: Location map of the GPR lines, (i) start, (f) end of the lines. Source: Author, 2023.



SAMPLE COLLECTION

The samples were collected at five points: two along Praia das Neves (P1 and P2), one in an interaction zone between the beach and the sandy bar (P3), one in the sandy bar near the mouth of the Itabapoana River (P4), and the black sand sample was collected in the center of the bar (PA) (Figure 8).

Figure 8: Point map sampled with GPR lines. Source: Author, 2023.



Two samples were taken at the points, one of 0-20 cm and between 80-100 cm

(Figure 8), the PA point only on the surface. To perform the drilling at the collection sites, the use of swollen and mechanical auger was used to remove discarded material and the manual auger that helped in the recovery of the samples at the desired depth.

PARTICLE SIZE ANALYSIS

For the granulometric analysis, the same methodology adopted by Vicente et al. (2010), Sousa et al. (2017) Duarte (2020) and according to NBR 7181 was used. The samples were homogenized, separated into portions of 400 grams and dried in an oven for 30 hours at 60º C. Then, the samples were quartered by hand and each sample was sieved with the aid of an automatic sieve shaker for 10 to 15 minutes and with a frequency of 15 Hz.

To perform the particle size separation of the sediments, a specific group of sieves was used with the particle size ranges given in mesh (opening in mm), namely: 10 (2.00 mm), 16 (1.18 mm), 20 (0.84 mm), 30 (0.60 mm), 40 (0.42 mm), 60 (0.250 mm) and 100 (0.149 mm). 120 (0.125 mm). 200 (0.074 mm). The calculation of the statistical parameter for the phi curve was made according to the classification of Folk and Ward (1957).

MINERALOGICAL DESCRIPTION

The description of the collected sediments was performed using an Oleman binocular stereomicroscope, available at the Sedimentology Laboratory of the Department of Geology of UFES. For a better understanding of the sedimentary grains, the general description included all the minerals present at each point, based on the references of Pereira et al. (2005), Sousa et al. (2017), Chaves et al. (2011) and Costa (2018). Parameters such as degree of roundness, sphericity and color were considered in order to identify the minerals present.

RESULTS

The results of the geoprocessing studies, geophysical survey, granulometric analysis and mineralogical description are presented below.

GEOPROCESSING

In view of the methodology employed, through data interpretations and consequently production of thematic maps (figures 9 and 10), it was possible to analyze the results. The two main targets of study were considered, being coastal erosion or definition of the extension of the sand strip, the morphology and behavior of the coastal zone at the mouth of the Itabapoana River.

Starting from the evolution of the sandy bar, a migration and variation in the morphology of the bar at the mouth of the river is clear. By following a pattern over the years, it is possible to delimit a polygon of coordinates 7644000N and 7641000N, 296000E and 298000E or the green square in figures 8 and 9. It is in this quadrant where, strictly speaking, the sandy bar evolves morphologically and moves, as observed in the orange color in the satellite images of the years obtained (figures 8 and 9).

According to figure 7, the sandy bar migrates southwards in (2000) and reaches the apex of southward migration in (2002). In the next few years (2004), (2006) and (2008), the displacement changes direction drastically, migrating slowly to the north, reaching the apex of displacement in (2010). In figure 8 in (2013), the sandy bar again drastically changes its direction, migrating back south, slowly, until the present day being again in the extreme south (2023).

It is worth mentioning that in (2006) there was a rupture of the bar, allowing an increase in the flow of the river and consequently a smaller extension of the sandy strip, as well as the formation of a small lagoon that in the following years was dry, according to the migration from the mouth to the north. Also, there is a great variation in the shape that the mouth of the river presents, for now narrower with a few meters and for now wider with tens of meters.

In relation to the erosive behavior of the sandy strip of beach, beforehand, there is a great variation in the dimensions of the sedimentary contribution that shapes the coastal zone south of ES and north of RJ, over the years. Through a visual definition of the variation of the beach extension, it was observed that there is a cyclicity almost every two to four years, where there are changes in progradation (Marine regression) and coastal retrogradation (Marine transgression).

According to figure 9 between (2000) and (2002) there is a retrograde trend, greater coastal erosion, that is, a decrease in the extension of the beach and sediment deposition. From (2002) to (2004) a progradational trend, then in (2006) again the retrogradational trend with the complete erosion of the bar at the mouth of the river. By the year (2013) the coastal progradation will predominate, slowly fattening the sandy strip and the recomposition of the bar until the year (2013).

In relation to figure 10, in the period from (2013) to the year (2017), coastal retrogradation occurs again, to follow the trend of coastal progradation until (2019), where it presents the highest sedimentary contribution and extension of the sandy strip. Between

(2019) and (2021) there is a subtle erosive trend, that is, starting another cycle of coastal retrogradation, which until the year (2023) is intensified and consequently a decrease in the sandy strip.

Therefore, in view of the results obtained from the processing of satellite images, in addition to the visualization of the differences in the morphological behavior of the sandy bar and beach, over the years, described above, the data can be complemented by means of table 2. These are information in square kilometers, about the dimension of the sand strip and its variation, based on the methodology used in this work, from the calculation of the area of the vectors by geoprocessing.

According to the table below, it is possible to observe in a mathematical quantity the cyclicity of the events, that is, for now an increase and for now a decrease in the coastal sedimentary contribution present in the place. A higher sedimentary input was identified in the years (2019) and (2021), compared to the other years analyzed, and a lower sedimentary input or a trend of coastal erosion, in the years (2002), (2006) and (2023).

Table 2: Area of the sandy strip in each year of the study, after the geoprocessing of satellite images. Source: Author, 2023.

Year	Area (km²)
2000	1,26
2002	0,82
2004	1,21
2006	0,88
2008	1,38
2010	1,45
2013	1,48
2015	1,40
2017	1,29
2019	1,64
2021	1,60
2023	0,84

Figure 9: Maps generated from satellite image geoprocessing, the beach strip (yellow), the region of the mouth of the Itabapoana River and no data (black). Source: Author, 2023.

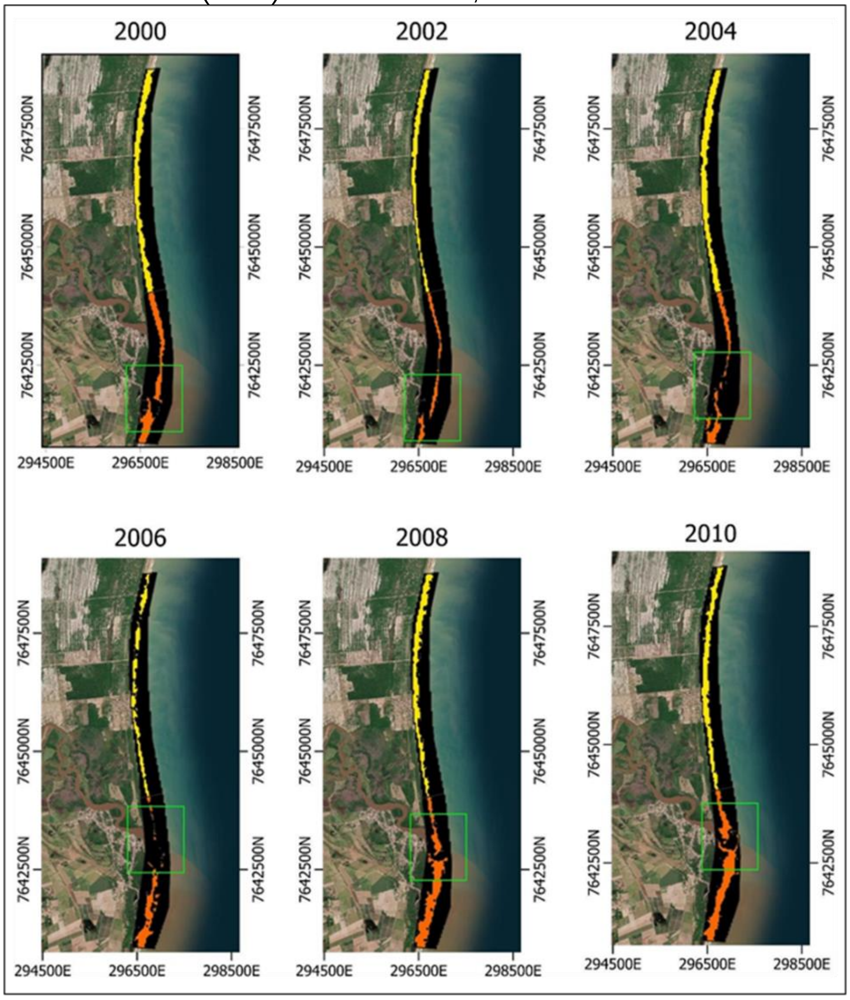
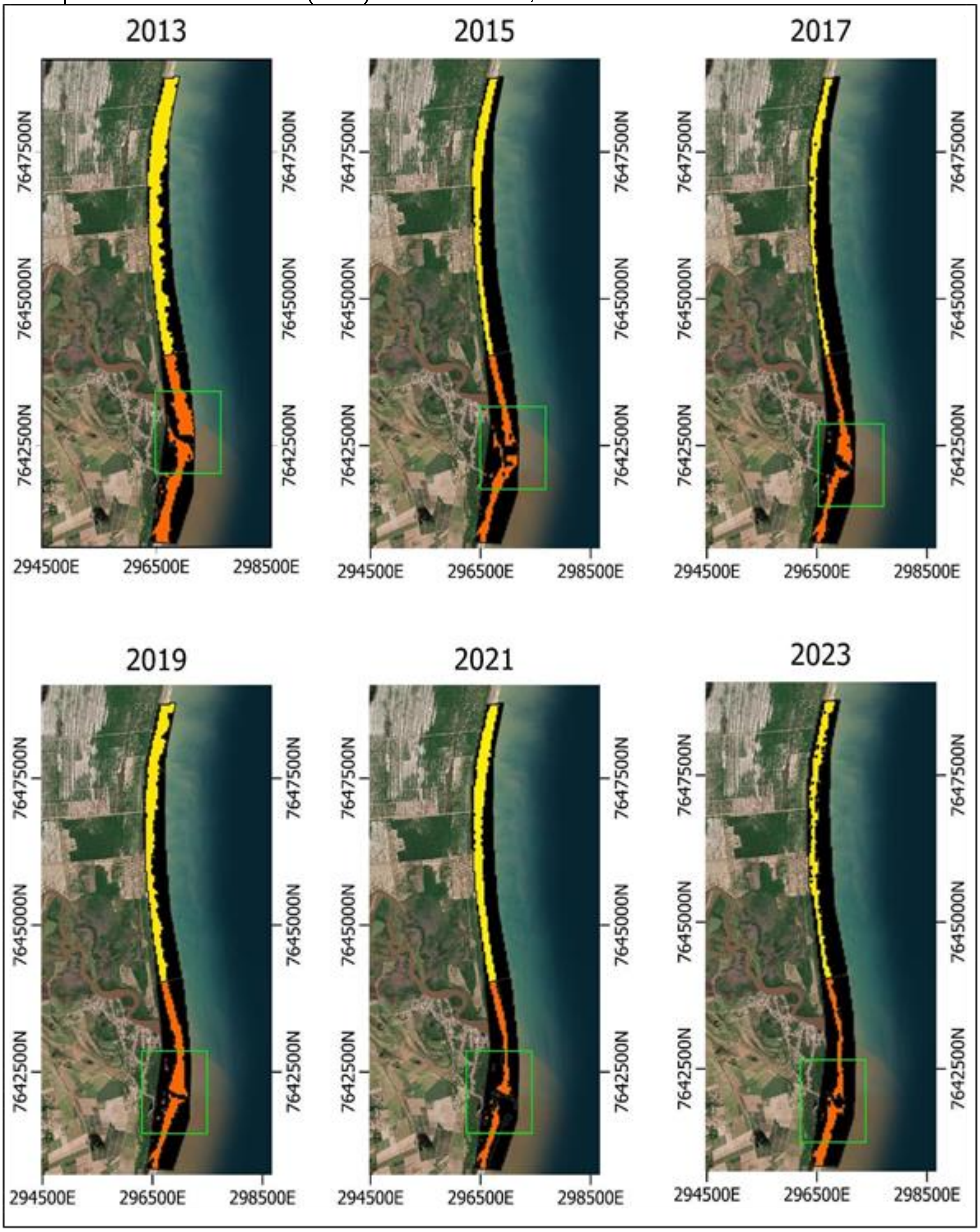


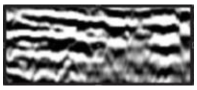
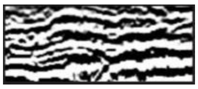
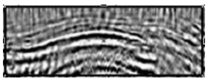
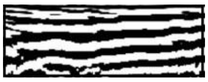
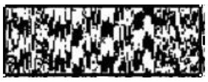
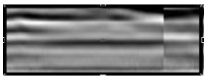
Figure 10: Maps generated from satellite image geoprocessing, the beach strip (yellow), the region of the mouth of the Itabapoana River and no data (black). Source: Author, 2023.



GEOPHYSICAL SURVEY

The geophysical data, respectively, the GPR lines, were analyzed, interpreted and described, in full, using as a parameter the radarfacies shown in table 3, indicating the main reflectors identified. This framework was based on works by authors such as Ribeiro and Rosas (2006), Muehe (2011), Rocha and Fernandes (2013), Leandro (2018) and Nascimento (2018), who use GPR in the coastal environment. The reflectors can be repeated in different ways, along each raised line. Seven radarfacie were defined, where their reflectors are imaged and correspond to an interpretation of a specific zone, of an environment based on the description of the main highlighted characteristics, which are equivalent to interaction zones, marine, fluvial-marine and eolian.

Table 3: Identification and characterization of radarfacies of GPR images. Source: Author, 2023.

Radarfaces	Description	Reflector	Interpretation
RF – 01	Wavy concave little continuous		Area between marshes
RF – 02	Corrugated, non-continuous with concave/convex pattern		Influence-bearing post-beach zone of storms
RF – 03	Sub horizontal, convex and continuous, predominant at depths of up to 2m.		Dune and wind capping
RF – 04	Horizontal, parallel to sub-horizontal, low-angle and not very continuous.		Fluvial
RF – 05	Horizontal, parallel to sub-horizontal, low-angle and continuous.		River
RF – 06	Low-angle sub-horizontal, parallel to sigmoidal and sub-continuous.		Beach /post beach area
RF – 07	Noise of varying amplitude, related to medium to high depths (at a height of 2m).		Presence from brackis h water
RF – 08	Horizontal parallel and continuous.	 	Aquamarine in beach area.

For a better understanding of the GPR lines and their interpreted radarfacies, figure 11 shows the total delimitation of each facie radar, in lines 01, 04, 06, 09 and 17. These lines were defined due to their better quality, greater representativeness compared to the other lines interpreted and the limitation of pages in this work. It is noteworthy that the Rf-07 are reflectors, with varied noise, possibly related to the presence of the water table.

Line 01 contains architectural elements with reflectors interpreted as fluvial to the west (Rf-05) near the Itabapoana River, referring to the deposition of seasonal sediments, according to rainy or dry seasons. While the radarfacie Rf – 03, it was interpreted and attested in the field, that there are wind deposits (Dunes). Then towards the sea, the Rf-02 radarfacies corresponds to the post-beach zone, an environment in which there is an abrupt tidal variation, as a result of storm surges (confirmed by local residents). Subsequently, the Rf-01 radarfacies, the intertidal zone (Unsaturated sediments), where sediments are constantly reworked by the action of waves and tides according to the lunar cycle. At the end of line 01, to the east, is the radarfacie Rf-08, which is a beach area saturated with water, being exposed due to low tide.

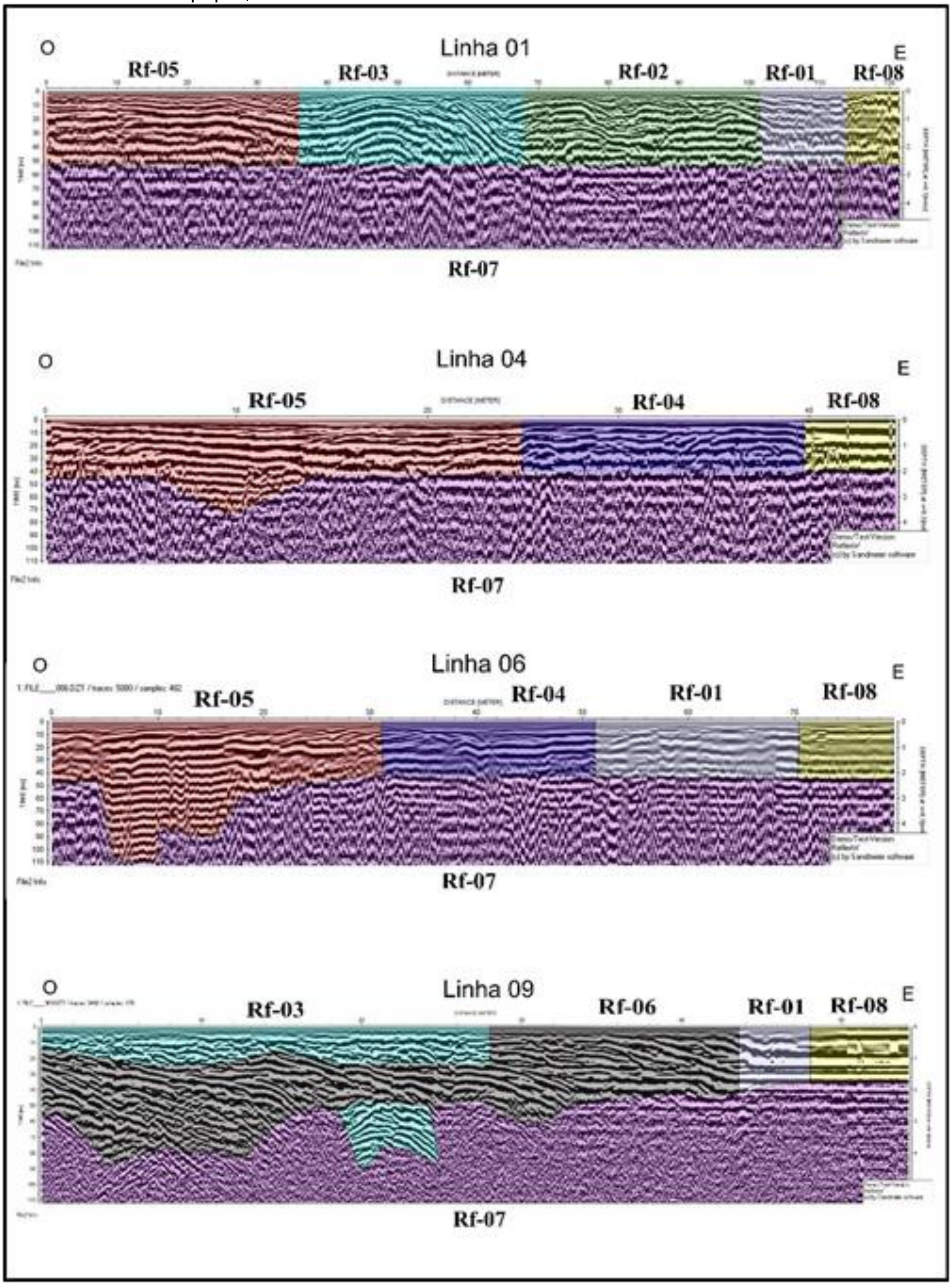
Line 04 represents the middle of the sandy bar, between the Itabapoana River to the west and the sea to the east. At the western end of the line, the Rf-05 radarfacies shows reflectors, with characteristics of fluvial deposits, and it is possible to correlate with a paleochannel, due to the concave erosion of the reflectors. Next, the Rf-04 radarfacies occurs, equivalent to an environment of fluvial-marine interaction, where the rupture of the bar was observed in certain periods, as shown in figure 11 (2006). At the eastern end is the radarfacie Rf-08, being a beach area with saturated sediments and a stronger reflection.

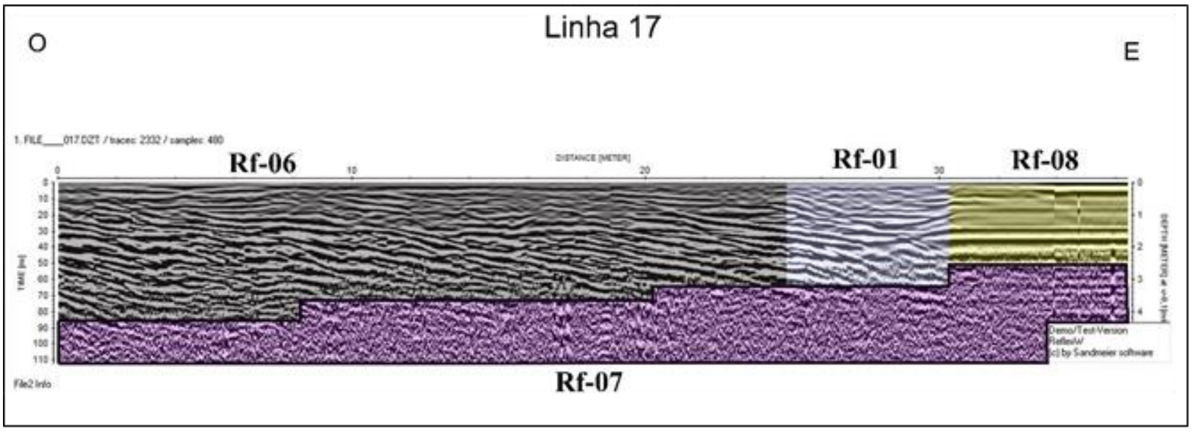
Line 06 is located at the end of the sandy bar with the mouth of the Itabapoana River, in the left portion of the line, there is a very good reflection and greater depth, without noise, being represented by Rf-05, that is, reflectors of an exclusively fluvial environment. The Rf-04 radarfacies, on the other hand, has reflectors, which can be defined as radarfacies of a fluvial-marine interaction environment. But to the east, towards the sea, there are reflectors, probably unsaturated, Rf-01 that bring an intertidal zone, in constant coastal reworking. Finally, at the eastern end, we have the Rf-08, which are radarfacies that reflect the beach area, saturated, being exposed due to the action of the dry tide.

Line 09, on the other hand, stands out because, despite being in an environment similar to line 17, it has the Rf-03 radarfacie, well marked, demonstrating an environment of intense wind reworking, with little similarity of the reflected structures. The low-angle sub-horizontal reflections stand out in the Rf-06 radarfacie, repeated from Rf-01 and Rf-08 reaching the sea.

Finally, line 17, in its western portion and a large part of the line, is composed of the radarfacies Rf-06, being the beach zone for post-beach, where the reflectors dive at a low angle towards the sea, indicating marine regression (Progradation). At the eastern end, the radars Rf-01 and Rf-08, already described, is the beach zone (Unsaturated and saturated) and may have stronger reflectors, as well as disturbance of the layers as a result of the waves. The Rf-07 radarfacies is present in the three lines described, where they have strong reflectors with noise, so it is assumed that they are saturated sediments, that is, the phreatic visible from 2 to 3m deep, probably a mixture of brackish water.

Figure 11: Interpretation of the reflectors and correlation with the radarfacies present in GPR lines 01, 04, 06, 09 and 17. Author of the paper, 2023.





MINERALOGICAL DESCRIPTION

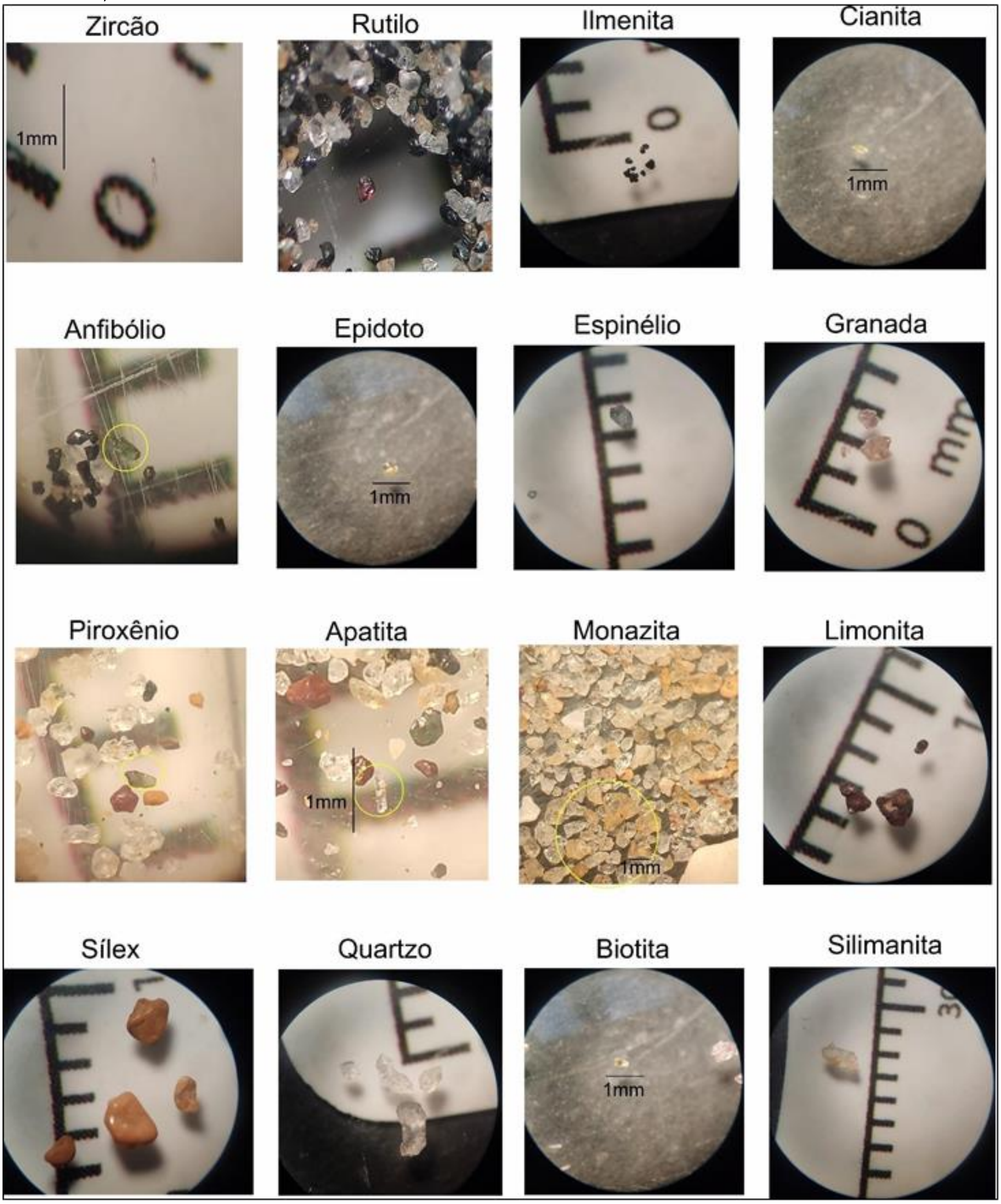
The minerals found in the magnifying glass analysis in the sedimentology laboratory allowed the identification and description of the main minerals present in the samples. No quantification was performed in percentage of each mineral found. It can be highlighted that the estuarine environment, of fluvial-eolian-marine interaction is characterized by sediments of fine to medium granulometric fraction, with greater angularity and low sphericity. Because they are transported in suspension, they end up not predominating physical weathering between the grains, therefore, being more fractured and angular.

Soon a wide variety of heavy minerals occurs, as shown in figure 12. The description of each mineral is contained in Table 4, following the morphology parameters of the grains. It is worth mentioning the large amount of monazite, quartz and heavy minerals. Also, the main difference to make the identification and visual distinction mainly of quartz and monazite, were parameters such as color, with monazite brownish and quartz colorless, the degree of greater angularity of quartz and lower angular and greater brightness of monazite, as well as quartz grains are less rounded in relation to monazite and quartz does not exhibit evident cleavage, while monazite may show imperfect cleavage.

Table 4: Description of the identified minerals. Source: Author, 2023.

Name	Diagnostic features
Zircon	Prismatic and colorless grains, less than 0.4mm.
Rutile	Intense red grains, matte edges and sub-metallic interior, underrounded.
Ilmenite	Tabular, sub-rounded grains of black color.
Kyanite	Euhedral prismatic grains with cleavage. They can be colorless, green to pale blue tones.
Pyroxene	Under-rounded grains, brownish green to translucent in color.
Epidote	Yellowish green grains, rounded grain.
Spinel	Rounded to sub-rounded specimens of blue color and translucent.
Grenada	Under-rounded grains, light pink to colorless in color.
Amphibole.	It has a dark green to black color, with anhedral and angular grains.
Apatite	Elongated, colorless, prismatic grains of vitreous luster.
Monazite	Rounder grains, reddish-brown to yellowish in color, intense, with a silky to glassy luster.
Limonite	They have rounded to sub-rounded grains, quite angular and irregular. Its color varies from red to ochre.
Quartz	Colorless grains are very angular and low sphericity.
Flint	Large rounded to sub-rounded grains light brown to beige in color.
Biotite	The mineral is golden to greenish with luster. Small, lamellar grains in basal cleavage.
Sillimanite	Elongated and angular specimens with some streaks. It is yellowish to yellowish in color predominant colorless.

Figure 12: Photo of the minerals identified by means of the magnifying glass in the sedimentology laboratory. Source: Author, 2023.



PARTICLE SIZE ANALYSIS

The granulometric analysis indicated that the environment is predominantly composed of medium sand in most of the samples. Table 5 presents a summary of the particle size fraction and the degree of selection for each point.

Table 5: Synthesis of particle size and selection data. Author of the paper, 2023. Source: Author, 2023.

Sample	Particle Size Fraction Predominant	Degree of selection
P1A	Medium sand	Well Selected
P1B	Medium sand	Well Selected
P2A	Medium sand	Well Selected
P2B	Medium sand	Well Selected
P3A	Medium sand	Well Selected
P3B	Medium sand	Well Selected
P4A	Medium sand	Well Selected
P4B	Medium sand	Well Selected
PA - Areia Preta	Fine sand	Well Selected

DISCUSSION

In view of the results presented above, based on data from geoprocessing, geophysics, mineralogical description and granulometric analysis, it is necessary to discuss the interpretations obtained and compare them with several studies cited in the bibliographic survey.

The interpretations of the maps generated from the satellite images indicated a cyclicity of two to four years in coastal progradation and retrogradation events, with variations in sedimentary input along the coast in the period studied. A complex morphodynamic dynamic was also observed, with constructive and destructive cycles in the mouth of the Itabapoana River, presenting a migration in the North-South direction in a cycle of approximately ten years. Compared to the study by Ribeiro (2006), which describes events of erosion and enlargement of the coast, a simultaneous but distinct behavior was observed at Praia das Neves. While Ribeiro observed erosion at the mouth of the Paraíba do Sul River and fattening of the beach strip along the coast, at Praia das Neves, the behavior is different. The work of Albino et al. (2018) identified a high risk index of retrograde events, but did not explore progradation cycles.

In the interpretations of the GPR lines, radarfacies were identified and described based on previous works, such as Nascimento (2018), who studied structures in the sandy paleocords near the study area. Nascimento identified two main radarfacies: an upper one, with reflections facing the ocean, indicating a marine regression, and a lower one, with reflections facing the continent, suggesting a retrogradation. Comparing with the reflections observed in the present study, similar trends in coastal progradation with slopes to the ocean were found. In addition, other lines indicated the presence of aeolian and river structures and old beach terraces, suggesting past beach levels and intense reworking due to high tides, storms and winds.

In the granulometric analysis, the curves indicated a predominance of medium sand in most of the sampled points, except at the point where black sand was collected, composed of fine and heavy sediments, consistent with a deltaic system of fluvial-eolian-marine interaction. This predominance of medium sand reflects the environment of selective transport of fine particles in suspension, which results in grains with lower sphericity and greater angularity. Compared to the study by Sousa et al. (2017), the granulometric characteristics observed converge, suggesting a greater control of the sedimentary input by the river, which can reduce the marine influence and the currents from North to South. However, in storm events, this balance can change, altering the behavior of the sedimentary input.

From the mineralogical point of view, the samples collected showed a predominance of quartz, monazite, rutile, zircon, ilmenite, limonite, sillimanite, apatite, spinel, kyanite, biotite, among others. The morphology of the minerals is consistent with studies by Sousa et al. (2017), Costa Junior (2018) and Chaves (2011), carried out close to the study area, which suggests a nearby source area, intensively reworked by the modeling agents.

The mineralogical diversity is directly associated with the source area, which includes several lithologies of the Araçuaí-Ribeira Orogen, such as orthogneissic, paragneissic, charnockite, Neoproterozoic plutonism, alkaline rocks, among others, with different ages and compositions. These types of rocks were described by Fontes et al. (1981), Duarte et al. (2012), Heilbron et al. (2016), and Mendes et al. (2022), and their descriptions are compatible with the resistant minerals found in the samples collected.

Table 6: Correlation between the climatic regime and erosive behavior in the study area. Source: Author's production based on NOAA, 2023.

Anus	Area (km²)	Regime Climatic
2000	1,26	La Niña
2002	0,82	Neuter
2004	1,21	Neuter
2006	0,88	Neuter
2008	1,38	La Niña
2010	1,45	The Child
2013	1,48	Neuter
2015	1,4	Neuter
2017	1,29	Neuter

2019	1,64	Neuter
2021	1,6	La Niña
2023	0,84	El Niño

As global cyclical events occur, there is a relationship between erosive and depositional processes and climatic phenomena, such as El Niño and La Niña, which affect meteorological conditions around the world. It is possible to try to establish a correlation between these phenomena and the events of greater or lesser coastal sedimentary input. There is a greater tendency for significant sedimentary input during La Niña events and in neutral periods, as well as a change in the cycle after these events. In contrast, there is a more erosive trend, or lower sedimentary input, in El Niño years. This can be explained by the increase in cyclones and strong storms, which bring large volumes of rainfall and undertows, intensifying the dynamics and erosion of the local coastal zone.

There are several ways to mitigate and remediate the impacts of coastal erosion in coastal cities. The Federal Constitution, through Law No. 7,661 of May 16, 1988, and Decree No. 5,300 of December 7, 2004, which institutes and regulates the National Coastal Management Plan (PNGC), delegate to States and Municipalities the responsibility of planning, preserving, inspecting and executing preventive works in coastal zones. According to Souza (2009), in areas of low risk of erosion, monitoring, preservation of the local ecosystem and small anthropogenic interventions are sufficient to minimize the impacts. However, in high-risk areas, such as areas where the city is already close to the beach, river mouths and paleocords, more severe interventions are necessary, such as specialized containment works or landfill, relocation of houses and structures, incentive to preservation, creation of vegetation zones delimiting the city from the coastal area and, if necessary, the recovery of frontal dunes.

CONCLUSION

Finally, after the development of the results and discussion, it is evident the need to present some conclusions, starting with the products generated from the satellite images. In the analyzed period, which covers approximately 20 years, the behavior of the sandy bar at the mouth of the Itabapoana River, in relation to the morphology and sedimentary input on the beach, shows great variety. A migration of the river mouth along the North-South axis is observed for approximately a decade.

These environments are intensely reworked by fluvial, eolian and marine agents, being even more influenced by climatic cycles. This results in a cyclicity characterized by large periods of coastal progradation or marine regression. However, coastal retrogradation is intense, especially in this complex depositional environment, where several factors influence the construction and destruction of the coastal zone.

GPR analyses confirmed the presence of structures that record the coastal sedimentary. Compared to other studies, it can be stated that the interpreted structures do indeed reflect what is visible on the surface and are in accordance with the observed depositional environments. In addition, standard radarfacies were defined for a better characterization of the reflectors in relation to similar studies.

The mineral analysis consisted of the identification of minerals in grains, which corroborate previous studies in the area. It was possible to relate the minerals to the source area, which are the AROS lithologies. The low textural maturity of the grains, characterized by low sphericity and high angularity, indicates the proximity to the source area and the low transport energy (suspension transport). The grains have a fine to medium particle size fraction, a high degree of selection and are more spherical/shock-worn. It is believed that the main responsible for the local sedimentary contribution is the fluvial environment, with reworking by North-South currents and strong S-SE undertows.

Taking into account all the methods applied in this work, it is suggested that, in order to deliver future research products with greater precision, methodologies such as X-ray diffraction (XRD) should be employed for a better understanding of the composition of the fine heavy minerals of the beach; the use of other particle size tests, such as density, for the separation of specific minerals and quantification in percentage; the geoprocessing method with specific complements of the ArcGIS software for the generation of the erosive vulnerability map of the local coast; the performance of tide, wave and rainfall surveys over time, seeking correlations to identify the main erosive agent; conducting studies during the summer season (rainy), since the research was carried out in winter and autumn (dry); and the realization of more studies using satellite images since the 1980s, investigating the beginning of captures by the LANDSAT 5 satellite and exploring more the intriguing phenomenon of the cyclicity of deposition and erosion events, which have average intervals of 2 to 4 years.

Finally, it is essential to maintain and plan the coastal zone, where more than half of the planet's population resides, in order to minimize anthropogenic impacts, preserve and reconstitute local vegetation, which play a crucial role in dissipating wave energy, in addition to establishing policies that promote sustainable socio-environmental development.

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