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Research Article

Sedimentary dynamics and erosion on tide-modified mixed beaches in Northeast Brazil

Dinâmica sedimentar e erosão em praias mistas modificadas por maré no Nordeste do Brasil

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Abstract: Coastal erosion is a relevant concern along the semi-arid coast of Northeastern Brazil, where tide-modified mixed siliciclastic–carbonate beaches exhibit seasonal variability and increasing anthropogenic pressure. This study aims to analyze the seasonal sedimentary dynamics of Peroba and Picos beaches, located in Icapuí, Ceará. Sediment samples were collected during four field campaigns, in March, May, September, and November 2024, and analyzed for grain-size distribution, calcium carbonate content, and sediment classification. The results indicate a predominance of very fine to fine sands on both beaches, with Peroba showing lower grain-size variability throughout the analyzed period and Picos exhibiting more pronounced spatial and seasonal variability. Calcium carbonate was higher for the backshore of Peroba, with a mean of 71.5%, while Picos showed greater fluctuations, especially in specific sectors and field campaigns. Sediment classification indicated the predominance of fine to very fine lithoclastic and lithobioclastic sands in Peroba, whereas Picos showed greater sedimentary class diversity, with up to ten distinct classes, including bioclastic and mixed classes. These results indicate distinct morphosedimentary responses between the two beaches, associated with seasonality, hydrodynamics, sediment availability, and local morphosedimentary controls. Finally, the importance of integrated sedimentological analyses and continuous monitoring is emphasized to improve the understanding of sediment sources, transport processes, seasonal redistribution, and long-term coastal evolution.

Keywords: Sediment Dynamics; Bioclastics sediments; Sandy Beaches; Grain Size Analysis

Resumo: A erosão costeira constitui uma preocupação relevante ao longo da costa semiárida do Nordeste do Brasil, onde praias mistas siliciclásticas-carbonáticas modificadas por maré apresentam variabilidade sazonal e crescente pressão antropogênica. Este estudo tem como objetivo analisar a dinâmica sedimentar sazonal das praias de Peroba e Picos, localizadas em Icapuí, Ceará. Amostras de sedimentos foram coletadas durante quatro campanhas de campo, em março, maio, setembro e novembro de 2024, e analisadas quanto à distribuição granulométrica, ao teor de carbonato de cálcio e à classificação sedimentar. Os resultados indicam o predomínio de areias muito finas a finas em ambas as praias, com Peroba apresentando menor variabilidade granulométrica ao longo do período analisado e Picos exibindo variabilidade espacial e sazonal mais pronunciada. Os teores de carbonato de cálcio foram mais elevados no pós-praia de Peroba, com valores médios de 71,5%, enquanto Picos apresentou maiores flutuações, especialmente em setores e campanhas específicas. A classificação sedimentar indicou o predomínio de areias litoclásticas e litobioclásticas finas a muito finas em Peroba, enquanto Picos apresentou maior diversidade de classes sedimentares, com até dez classes distintas, incluindo classes bioclásticas e mistas. Esses resultados indicam respostas morfossedimentares distintas entre as duas praias, associadas à sazonalidade, à hidrodinâmica, à disponibilidade sedimentar e aos controles morfossedimentares locais. Ressalta-se, por fim, a importância de análises sedimentológicas integradas e do monitoramento contínuo para aprimorar a compreensão das fontes sedimentares, dos processos de transporte, da redistribuição sazonal e da evolução costeira de longo prazo.

Palavras-chave: Dinâmica Sedimentar; Sedimentos Bioclásticos, Praias Arenosas, Análise Granulométrica

1. Introduction

The coastal zone, a dynamic interface between the continent and the ocean, is characterized by natural processes and anthropogenic pressures that continuously transform its landscapes. This sensitive environment has been increasingly affected by factors such as unplanned urban growth, the expansion of impervious surfaces, the construction of coastal structures, and global climate change, which together result in cumulative effects on coastal morphology and ecosystems (Small and Nicholls, 2003; Morais et al., 2008; Neumann et al., 2015; Andrew et al., 2019; McMichael et al., 2020; Lacerda Barros et al., 2021a; Lacerda Barros et al., 2021b; Lv et al., 2021; Lacerda Barros et al., 2024b).

Among the most significant processes is coastal erosion, which results from the combined influence of global drivers, local morphodynamic conditions, sediment availability, and human interventions. Global factors such as sea-level rise, climate change, and changes in storm frequency and intensity may increase shoreline instability and exposure to marine flooding, especially in densely occupied coastal areas (Muehe, 2006; Luijendijk et al., 2018; Vousdoukas et al., 2020; Pang et al., 2023; Vasconcelos et al., 2024). However, shoreline retreat is not solely controlled by sea-level rise, as coastal responses are strongly mediated by local morphology, sediment budgets, and human-induced changes to sediment supply (Le Cozannet et al., 2014; Cooper et al., 2020). Local factors, including coastal occupation, river damming, uncontrolled sediment extraction, and rigid coastal protection structures may disrupt sediment pathways and intensify beach erosion and shoreline retreat (Bird, 2008; Roebeling et al., 2011; Paula, 2015; Kuriyama and Banno, 2016). These impacts compromise fragile ecosystems such as dunes, cliffs, and mangroves, while exposing human communities to increasing risks of flooding and shoreline retreat.

The problem of coastal erosion in Brazil is particularly severe along the northeastern shoreline, with Ceará being one of the most affected states. All its 20 coastal municipalities exhibit sections undergoing severe erosion. Of the state's 573 km coastline, approximately 30% is already in an erosive state, and another 17% shows an erosional trend, totaling 47% of the coast under degradation (CEARÁ, 2024). These findings confirm the tendency previously indicated by Morais et al. (2018), who estimated that nearly 50% of the Ceará coastline was undergoing erosional processes. The impacts are extensive, affecting ecosystems, urban infrastructure, and economic activities such as tourism and fishing, while also posing risks to the health and safety of coastal populations, reinforcing the urgency of management and mitigation measures.

Sandy beaches play a crucial role in dissipating wave energy and protecting the shoreline. These dynamic sedimentary systems are composed of materials ranging from pebbles to sand sediments (Bird, 2008), with morphology resulting from the interaction between hydrodynamic processes, sediment characteristics, and topographic variability (Wright and Short, 1984; Masselink and Short, 1993; Leal-Alves et al., 2020; Ton et al., 2021; Jackson et al., 2022; Vallarino Castillo et al., 2023). Along the coast of Ceará, approximately 50% of the beaches are classified as tide-modified (RTR > 3), exhibiting wide intertidal zones, predominantly fine sediments, and low-energy conditions (Pinheiro et al., 2016).

Over the past century, numerous sedimentological studies have contributed to advancing the understanding of coastal sediment dynamics. Classical works such as those by Folk and Ward (1957), Mason and Folk (1958), Friedman (1961, 1967, 1979), and Duane (1964) established fundamental parameters for the statistical analysis of sediments. More recent research, including studies by Ouillon (2018), McFall (2019), Laignel et al. (2023), Matsumoto and Young (2023), Shi et al. (2023), Tang et al. (2023), Kontakiotis et al. (2024), and Karlonienė et al. (2024), has expanded this scope by incorporating new methods and approaches in coastal environments. In Brazil, notable contributions include the works of Martins (1965, 1967), Suguio (1973), Ponçano (1986), Corrêa and Ponzi (1978), as well as more contemporary studies by Martins (2003), Bulhões and Estrada (2011), Quinamo (2013), Jesus and Andrade (2013), Jesus et al. (2014), Cunha et al. (2017), Silva et al. (2019), De Oliveira Souza and Perez Filho (2019), Motta et al. (2018), Oliveira et al. (2018), Da Câmara et al. (2021), and Lacerda Barros et al. (2024a).

These studies provide essential support for coastal planning and management, serving as a foundation for more effective and integrated public policies. When combined with technical assessments and institutional action, this knowledge becomes a strategic tool for mitigating the impacts of erosion and promoting the sustainability of coastal territories.

The present study aims to investigate sediment dynamics and the textural variation of sediments on mixed (siliciclastic–carbonate) beaches, tide-modified and under erosive conditions, located in the Peroba and Picos sectors of the Icapuí municipality, on the eastern coast of Ceará. The analysis seeks to understand how morphological factors (presence of rocky promontories) and anthropogenic influences (coastal occupation) affect the processes of erosion, deposition, and redistribution of siliciclastic and bioclastic sediments.

2. Study Area

The study area is in Icapuí, on the eastern coast of the state of Ceará, approximately 203 km from the state capital, Fortaleza, in Brazil. The municipality is part of Sector 1 – Eastern Coast, according to the Coastal Management Program of the State of Ceará (GERCO-CE). It borders the state of Rio Grande do Norte to the east and the municipality of Aracati to the west and south. The coastline extends for about 46 km and comprises 14 beaches distributed across the districts of Icapuí (seat), Ibicuitaba, and Manibu (Meireles et al., 2016) (Figure 1 and Figure 2).

The area under analysis is entirely located within *the Área de Proteção Ambiental (APA) Berçário da Vida Marinha (*Marine Life Nursery Environmental Protection Area), a state-level Sustainable Use Conservation Unit. Predominantly marine, this APA is part of a local mosaic of conservation units, situated between two municipal APAs: the APA da Ponta Grossa and the APA do Manguezal da Barra Grande.

The section under analysis is in the emerged portion of the Potiguar Basin, featuring geological outcrops from the basin's drift phase. The main formations include the Jandaíra Formation (Cretaceous age, composed of limestone), the Barreiras Formation (Miocene, consisting of conglomerates and sandstones), and the Potengi Formation (Quaternary, composed of eolian sandstones) (Ximenes Neto et al., 2024). These formations support cliffs and paleocliffs along the coast, giving rise to geomorphological features of great significance.

The study area includes Holocene environments that play a key role in shaping the present landscape through sedimentary and geomorphological processes, particularly a Late Holocene marine terrace (Ximenes Neto et al., 2024). This terrace, located between the paleocliffs and the present shoreline, is crucial for understanding erosion and sedimentation processes, providing valuable insights for the management and conservation of the coastal zone.

The Icapuí Coastal Plain exhibits geomorphological features resulting from Quaternary sea-level variations, including Holocene marine terraces, dunes, cliffs, paleocliffs, beaches, lagoons, and coastal lakes. Its formation and evolution are associated with global marine regression and transgression events that occurred at the end of the Quaternary (Meireles, 1991; Meireles and Santos, 2014; Ceará, 2016; Ximenes Neto et al., 2024). Some areas receive sediments from coastal dunes and mass movements, making cliffs and dunes essential sediment sources for coastal dynamics (Morais et al., 2006; Pinheiro et al., 2016; Lacerda Barros et al., 2024b). The climate in northeastern Brazil is influenced by the Intertropical Convergence Zone (ITCZ), where the northeast and southeast trade winds converge. Rainfall occurs mainly between February and May, with a dry season prevailing for the rest of the year, showing variations due to the El Niño–Southern Oscillation (ENSO) phenomenon (Marengo et al., 2017). Intermittent surface drainage and the semiarid climate contribute to the low sediment availability for the beach system and the continental shelf of Ceará (Morais and Pinheiro, 2011). According to the Fundação Cearense de Meteorologia e Recursos Hídricos (FUNCEME), the historical average precipitation in Icapuí between 1988 and 2023 was 714 mm annually (FUNCEME, 2024).

Tides along the coast of Ceará are semidiurnal, with average amplitudes of 3.2 m in a mesotidal environment (Morais, 1981; Maia, 1998; Pinheiro et al., 2016). In Icapuí, according to the Tide Table for Porto de Areia Branca–TERMISA, published by the Directorate of Hydrography and Navigation of the Brazilian Navy, tidal amplitudes can reach up to 3.8 m (BRASIL, 2026).

According to the Wavewatch III model, waves in the area reach their peak between December and March, with heights of up to 2.2 m (Lacerda Barros, 2018), the highest height being recorded in February 2016. During the other months, wave heights ranged between 0.8 m and 1.5 m, with periods varying from 4.1 s to 9.9 s. Swell waves exhibit periods between 10 s and 11.5 s.

In Ceará, Sea-type waves predominate, accounting for 72% of occurrences, while Swell-type waves represent 28% (Carvalho et al., 2007). The regional longshore drift along the eastern coast of Ceará is generally described as predominantly east–west, favoring sediment transport toward the Aracati sector (Morais et al., 2006; Pinheiro et al., 2016; Morais et al., 2018).

The coast of Icapuí is currently undergoing intense erosional processes that have been extensively documented over the past decades (Morais et al., 2006; Morais et al., 2018; Lacerda Barros, 2018; Lacerda Barros et al., 2021a; Lacerda Barros et al., 2024b). This scenario particularly affects the cliff and beach sectors located in Redonda, Peroba, and Picos (Chacanza et al., 2022; 2023). These processes are associated with both natural dynamics and the intensification of anthropogenic pressures, such as coastal occupation. In response to this situation, localized interventions, such as sandbags, wooden stakes, and riprap, have been implemented in certain areas, although often without integrated planning, resulting in collateral effects on the adjacent coastal dynamics.

3. Materials and methods

For the execution of this study, four main stages were defined (Figure 3), during which surface sediment samples were collected and analyzed along six morphological profiles (S1 to S6) perpendicular to the shoreline in 2024. Sampling was conducted across three different beach compartments: the backshore, the foreshore, and the nearshore zones. The analyzed section extends approximately 3.5 km along the SL, allowing for a detailed characterization of the sedimentological conditions in different sectors of the study area.

3.1. Sampling Point Selection

The selection of sampling points was based on the presence of sections showing evidence of coastal erosion and the occurrence of coastal protection structures on beaches of siliciclastic–carbonate composition.

The analyzed area encompasses two beaches, Picos and Peroba, divided into six sections spaced approximately 500 m apart: S1 to S3 correspond to Picos Beach, and S4 to S6 to Peroba Beach. The two beaches are separated by the presence of a promontory, which may influence and control the action of coastal and sedimentary processes in the region. This division enabled a detailed comparative assessment of the different areas along the investigated shoreline, considering local variations in environmental conditions and prevailing sedimentary processes.

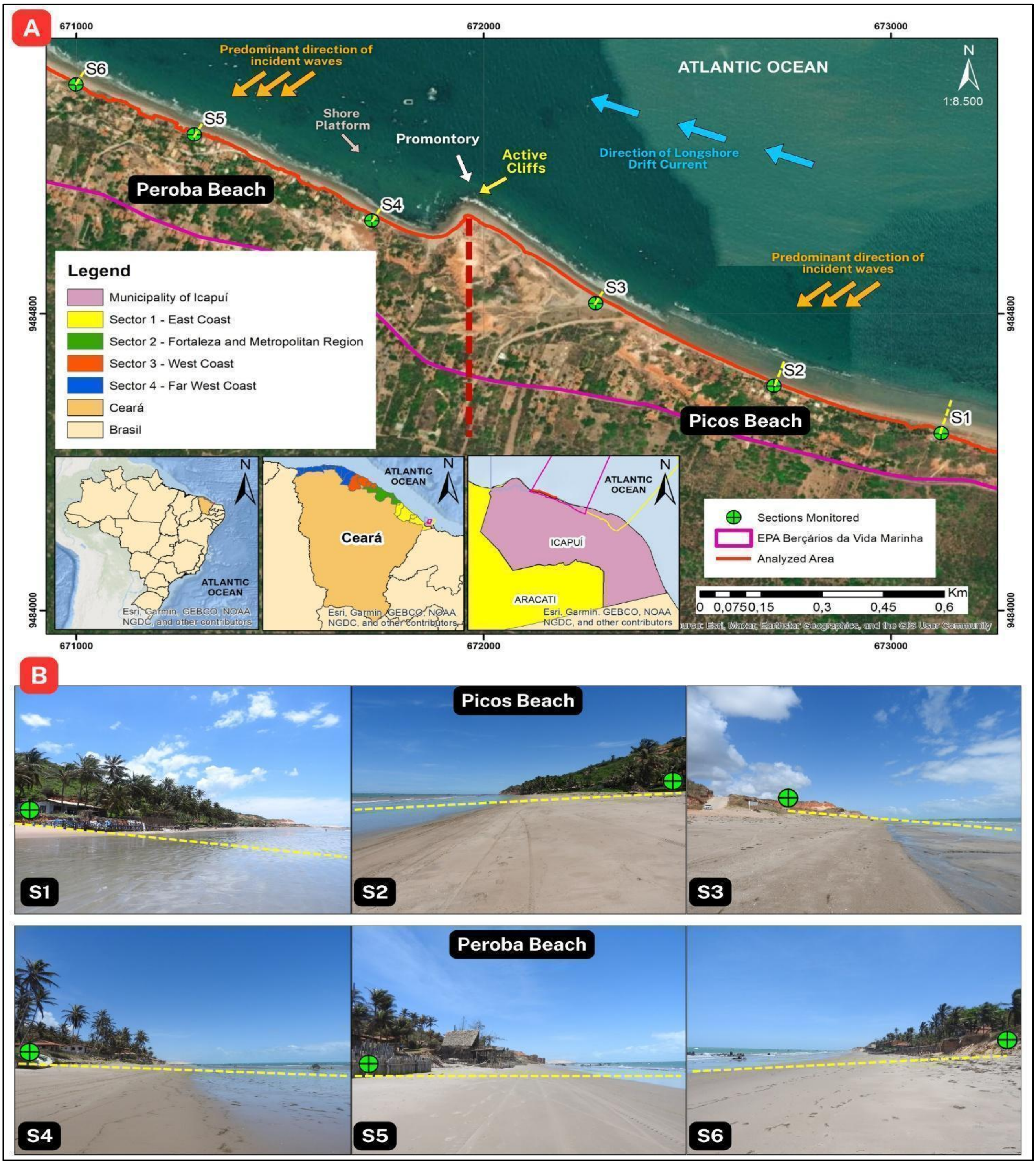

Figure 1. A) Location map of the study area, indicating the monitored sections and sediment sampling points along Peroba and Picos beaches. B) Visual depiction of the morphological conditions and coastal occupation in each monitored section; the yellow dashed line represents the monitored beach profiles, while the green markers indicate the approximate position of each section in the field photographs.

Figure 2. Aerial views of Picos Beach (left) and Peroba Beach (right), highlighting the beach–cliff system, coastal occupation, and submerged abrasion platforms in Peroba. The red dashed line marks the spatial limits of the study area considered in this research.

3.2. Sample Collection

Sampling was conducted during two distinct periods, considering the hydroclimatological seasonality of the region in 2024: the rainy season and the dry season. The rainy season covered the months of March and May, while the dry season included September and November, totaling 72 surface samples distributed across 18 sampling points (Figure 4).

Surface sediment samples were collected from the uppermost 2–5 cm of the substrate using a plastic spatula/manual sampler. Approximately 300 g of sediment were collected at each sampling point, stored in labeled plastic bags, and transported to the laboratory. Backshore and foreshore samples were collected manually from the exposed beach surface, whereas nearshore samples were obtained during low spring tide in the shallow submerged/intertidal zone.

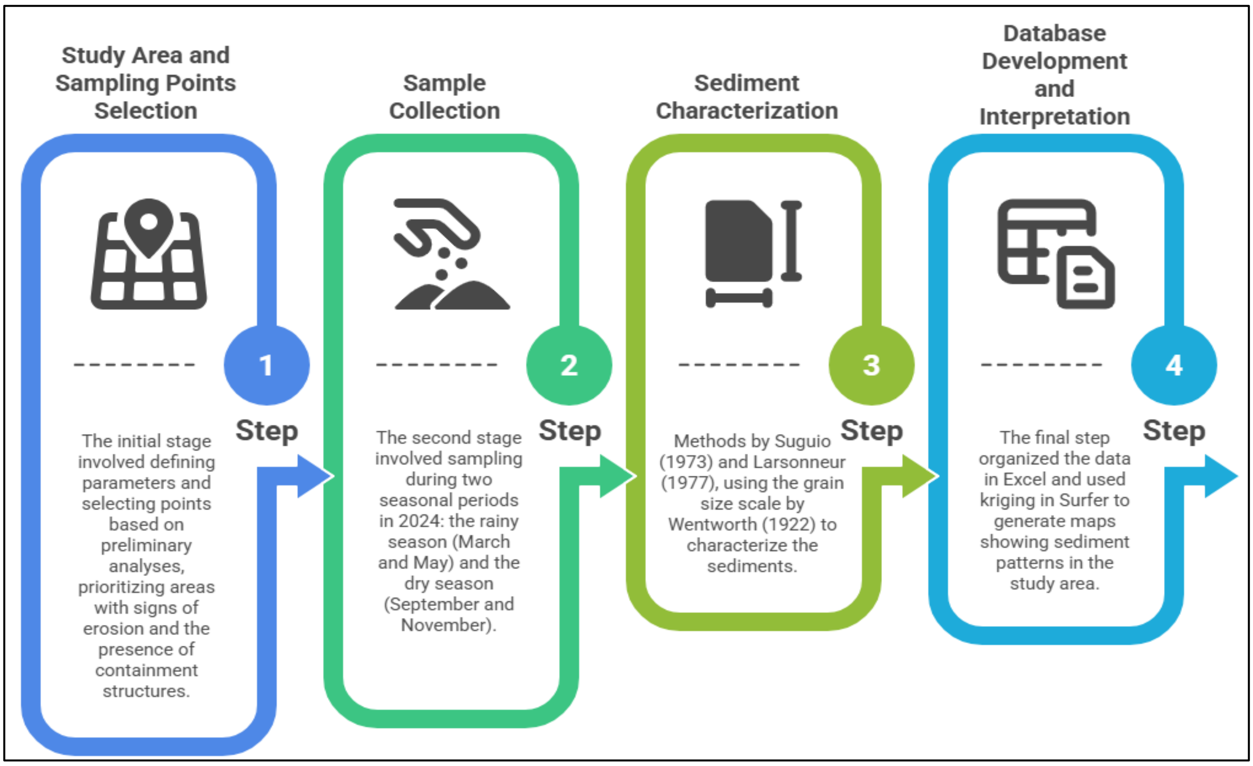

Figure 3. Summary flowchart of the methodological steps applied in the study. Adapted from Napkin AI.

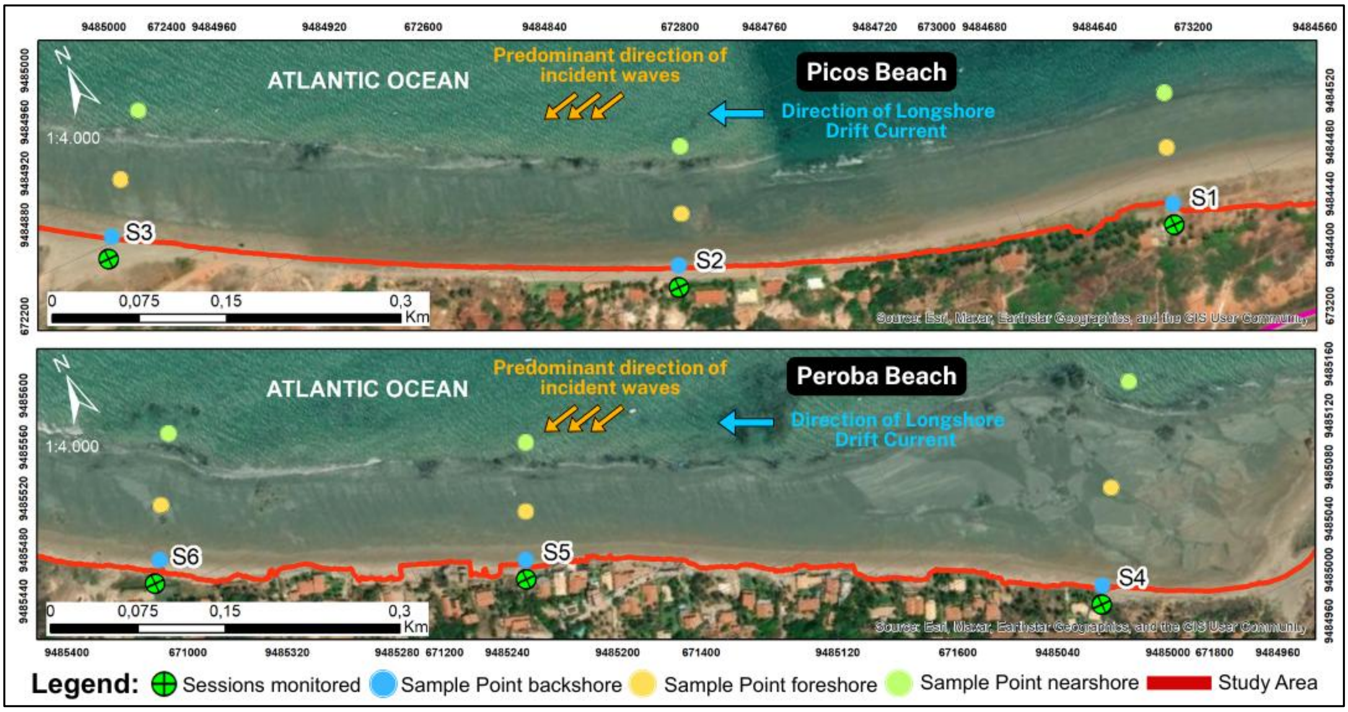

Figure 4. Monitored sections and sediment sampling points along Picos and Peroba beaches. Blue, yellow, and light-green circles indicate backshore, foreshore, and nearshore samples, respectively. The red line marks the study area limits.

3.3. Sediment Characterization

Granulometric analysis was performed following the methodological approach of Suguio (1973), based on the Wentworth (1922) grain-size scale and on classical sedimentological principles for the description of siliciclastic sediments (Folk, 1974). The data were processed using the Sistema de Informação Granulométrica — SIGRAN (Sousa et al., 2019), developed by the Laboratório de Geologia e Geomorfologia Costeira e Oceânica (LGCO), Universidade Estadual do Ceará (UECE). Previous studies on coastal sedimentology in Ceará have applied similar granulometric procedures to characterize mixed siliciclastic–carbonate deposits in coastal and beach–dune systems (Ximenes Neto, 2020; Ximenes Neto et al., 2021). In this study, SIGRAN was used as an operational tool to calculate the sedimentological statistical parameters proposed by Folk and Ward (1957), particularly median grain size and sorting degree.

Given the mixed siliciclastic–carbonate nature of the study area, characterized by the simultaneous occurrence of siliciclastic and bioclastic grains, skewness and kurtosis were not used; these parameters may be affected by variations in grain shape, density and origin, leading to unreliable interpretations of sedimentary processes in heterogeneous deposits (Ximenes Neto et al., 2024). Therefore, the analysis focused on median grain size and sorting degree.

Calcium carbonate content was determined using the Bernard calcimeter method (Lamas et al., 2005) at the Laboratório de Oceanografia Geológica of the Instituto de Ciências do Mar (Labomar), Universidade Federal do Ceará (UFC). The samples were classified according to the sedimentological scheme modified from Larsonneur (1977) and adapted by Dias (1996), which is suitable for mixed coastal environments and has been applied in previous studies such as De Falco et al. (2017), Ximenes Neto et al. (2024, 2026) and Lacerda Barros et al. (2024a). This scheme distinguishes sediments based on calcium carbonate content into four main classes: lithoclastic (<30%), lithobioclastic (30–50%), biolithoclastic (50–70%), and bioclastic (>70%). The compositional classification was complemented by granulometric analysis, especially median grain size and sorting degree.

The qualitative identification of grain types was performed through optical microscopy, using representative sediment samples selected according to variations in calcium carbonate content and grain-size characteristics. The analysis focused on the visual recognition of carbonate and siliciclastic components, including gastropod fragments, foraminifera, and calcareous/coralline algae, based on morphological attributes described in specialized literature (Milliman, 1974; Souza et al., 2011; Lacerda Barros et al., 2024a). This procedure was used as qualitative support for the interpretation of sediment composition, sediment sources, and depositional conditions, and was not intended as a detailed taxonomic classification of the biogenic components.

3.4. Interpretation

The sedimentological database described above was organized using Microsoft Excel. To spatially represent the obtained results, kriging interpolation was applied using the Surfer software. For cartographic representation and spatial organization of the sampling design, the shoreline position was defined using the wet/dry line as a proxy, corresponding to the visible boundary between the dry beach surface and the recently wetted intertidal zone, following the shoreline indicator framework discussed by Leatherman (2003) and Boak and Turner (2005). This shoreline proxy was used to support the spatial delimitation of the Peroba and Picos beach sectors and the representation of sediment sampling points along the beach compartments.

The kriging method was chosen due to its ability to handle the spatial heterogeneity of samples and to minimize errors associated with interpolation (Oliveira et al., 2018). This technique enabled the generation of detailed maps showing the spatial distribution of sedimentary parameters, contributing significantly to the identification of patterns and trends throughout the study area.

4. Results

4.1. Grain Size and Statistical Parameters

At Picos Beach, sediments predominantly range from very fine to fine sand, with lower grain-size variability observed in the backshore sectors and higher heterogeneity in the foreshore and nearshore zones (Figs. 4–6). During the rainy season, represented by the March and May sampling campaigns, the samples indicated a predominance of very fine sand in March (45%), with 67% of the samples classified as moderately well sorted. In May, greater granulometric diversity was recorded, with an even distribution among very fine, fine, and medium sands (33.3% each), as well as an increase in sediment uniformity, with 78% of the samples classified as moderately well sorted. In the second semester, marked by the dry period and stronger winds, fine sand became dominant in September (89%), accompanied by a higher proportion of poorly sorted sediments (56%), reflecting greater textural heterogeneity and sediment reworking. In November, fine sand still predominated (45%), but with a partial return to more uniform sorting conditions, with 56% of the samples classified as moderately well sorted.

At Peroba Beach, grain size remained more stable throughout the year, with a predominance of very fine sand, particularly during the first semester (67% in March and May). The sorting degree also reflected this stability, with a predominance of well-sorted sediments (56% in March), suggesting a more uniform depositional environment. In September, very fine sand continued to dominate (56%), although greater variability in both grain size and sorting was observed, indicating changes in environmental energy. In November, an increase in the fine sand fraction (45%) was recorded, with 45% of the samples well sorted, suggesting higher transport competence but still limited to fine-grained sediments.

Most samples consisted of well- to moderately well-sorted sediments (Figure 5), indicating the predominance of materials with good granulometric uniformity. Occasional occurrences of poorly sorted sediments were recorded, irregularly distributed across sectors and sampling campaigns, revealing variability in the sorting degree throughout the analyzed period.

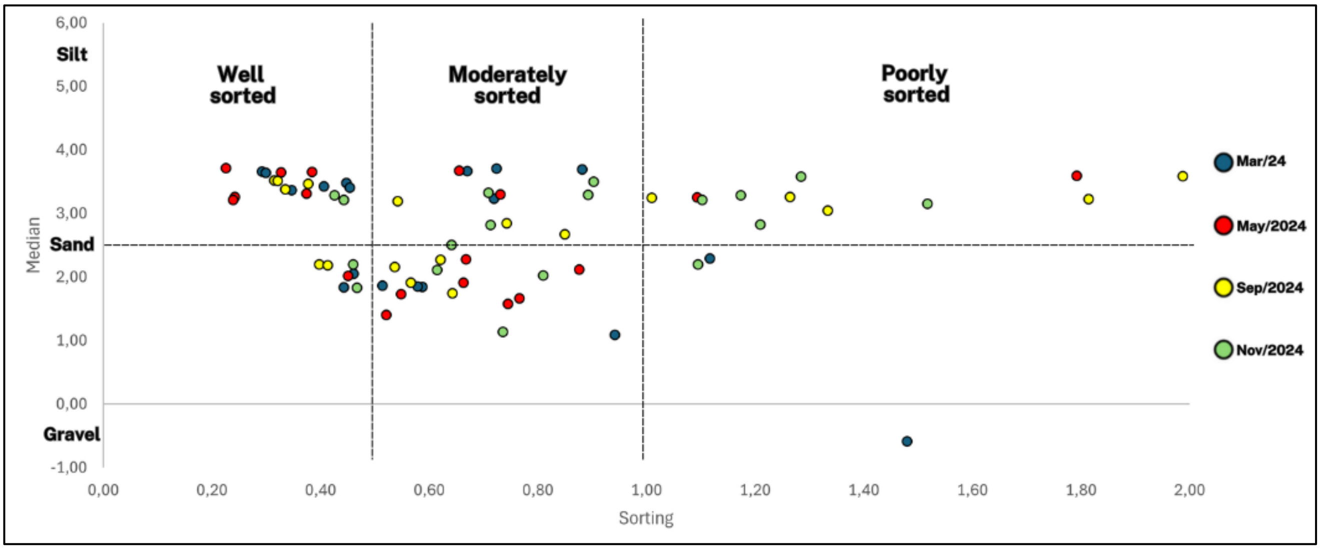

Figure 5. Median versus sorting diagram of sediment samples collected between March and November 2024, showing granulometric variation according to sorting classes.

In summary, the results indicated that Picos exhibits greater seasonal variability, with very fine sand predominating in March, a balanced distribution of very fine, fine, and medium sand in May, and fine sand predominating in September and November. Moderately well-sorted sediments prevailed in March, May, and November, while poorly sorted sediments were more frequent in September. In contrast, Peroba maintained higher textural homogeneity, with a predominance of very fine sands and a more consistent sorting pattern throughout the analyzed period (Figure 6). Figure 7 organizes these patterns by morphological compartments (backshore, foreshore, and nearshore), highlighting the differences among sectors, months, and beaches.

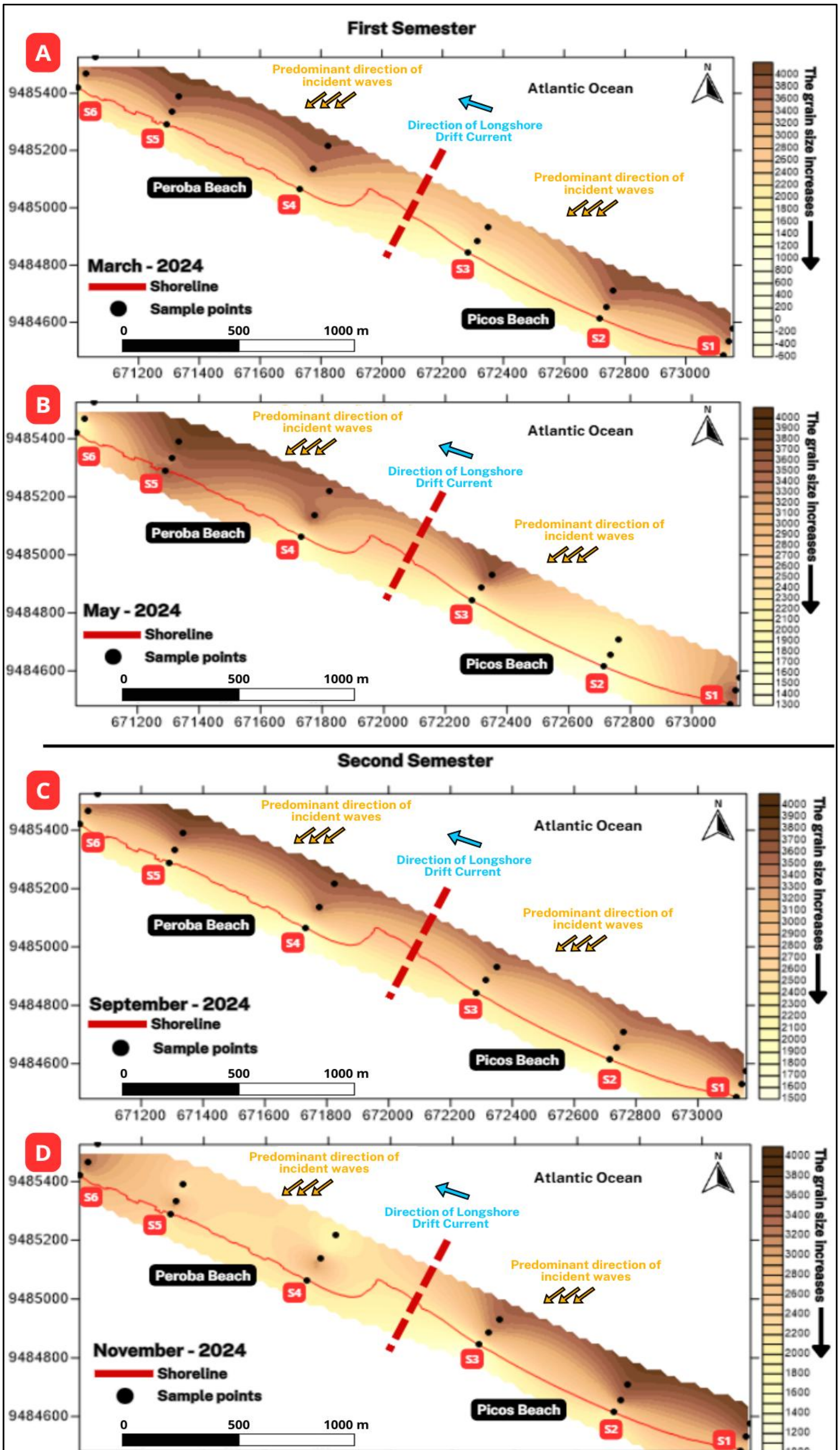

Figure 6. Kriging interpolation map showing median grain size (D50, μm) distribution.

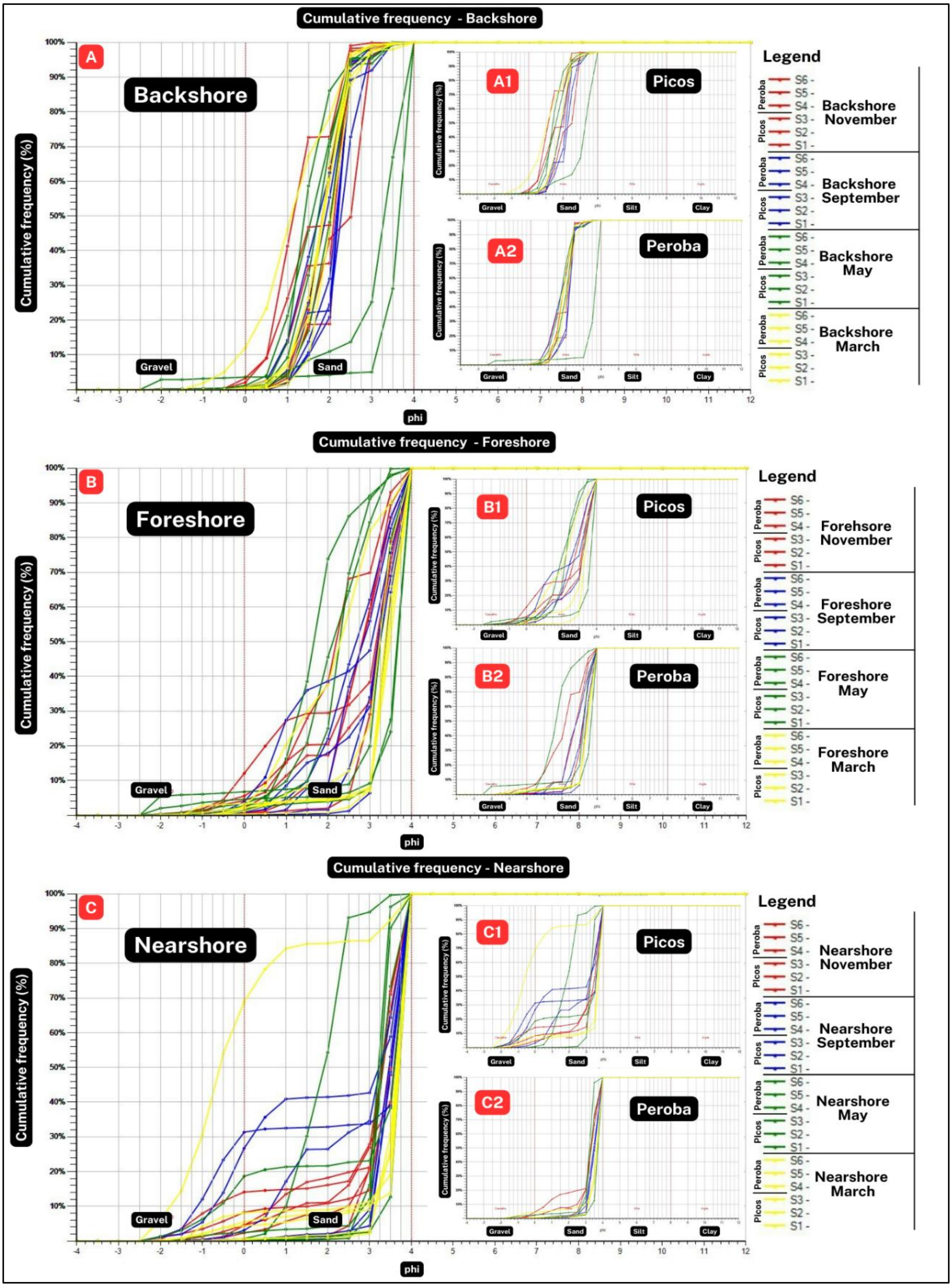

Figure 7. Cumulative frequency curves for sediments collected from the Backshore (A), Foreshore (B), and Nearshore (C) zones of Picos and Peroba beaches. A1 and A2 provide detailed results for the Backshore of Picos and Peroba, respectively; B1 and B2 show details for the Foreshore of Picos and Peroba, respectively; and C1 and C2 present details for the Nearshore of Picos and Peroba.

4.2. Calcium carbonate

The analysis of calcium carbonate content (%) revealed clear differences between Picos and Peroba beaches (Figure 8). In the backshore, the highest mean values were observed, with 71% in Peroba and 54% in Picos, indicating a higher concentration of carbonate-rich sediments in the backshore of Peroba and a slightly greater variability in Picos, which reached 82% in sector S3.

The foreshore exhibited pronounced fluctuations. In Picos, the mean calcium carbonate content was 44%, higher than that recorded in Peroba (34%), confirming a greater input and mobility of bioclastic sediments. In the nearshore, the lowest contents prevailed, with averages of 34% in Picos and 25% in Peroba. Overall, Picos showed greater spatial and temporal variability in carbonate content, whereas Peroba was characterized by stability in the backshore and a more pronounced reduction in the foreshore.

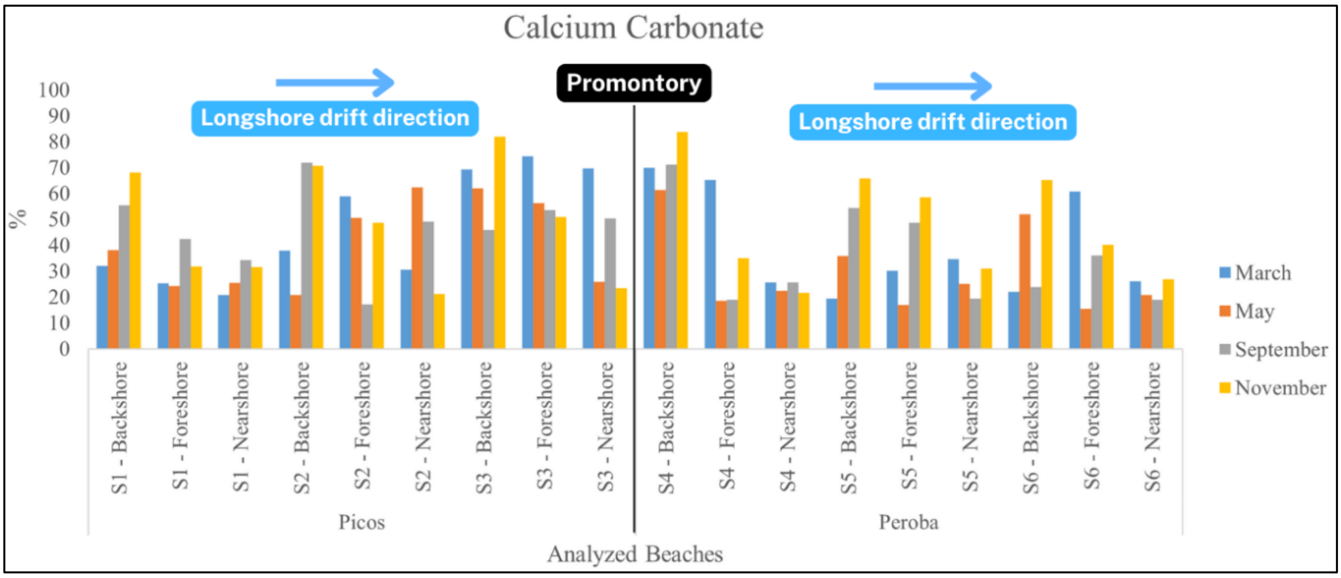

Figure 8. Calcium carbonate content (%) at Picos (S1–S3) and Peroba (S4–S6) beaches between March and November 2024, considering the different beach sectors (backshore, foreshore, and nearshore) and the direction of the longshore drift.

The comparison between the two beaches shows that Peroba exhibited higher and more stable mean calcium carbonate contents in the backshore sector, whereas Picos displayed greater dispersion among sectors, with lower mean contents in the foreshore and nearshore. Overall, the backshore sectors showed the highest carbonate contents, followed by the foreshore and, finally, the nearshore sectors, which presented the lowest calcium carbonate contents and the smallest variation over time (Figure 9).

In addition to the statistical analysis of calcium carbonate content and granulometric variability, representative samples were selected to illustrate the main compositional and textural characteristics of the sediments observed on Peroba and Picos beaches. These samples capture the contrasts between carbonate-rich and mixed siliciclastic–carbonate assemblages, highlighting the presence of biogenic components such as gastropod fragments, foraminifera, and calcareous algae embedded within a siliciclastic matrix. The photographic records qualitatively depict sedimentary heterogeneity across different beach compartments and seasonal periods, providing visual support for the interpretation of sediment sources and depositional conditions (Figure 10).

Accordingly, selected sampling points were used to represent the main sedimentological contrasts observed in the study area: the highest and lowest $CaCO_3$ contents, an intermediate condition close to the overall mean, and contrasting grain-size classes, including very coarse and very fine sediments.

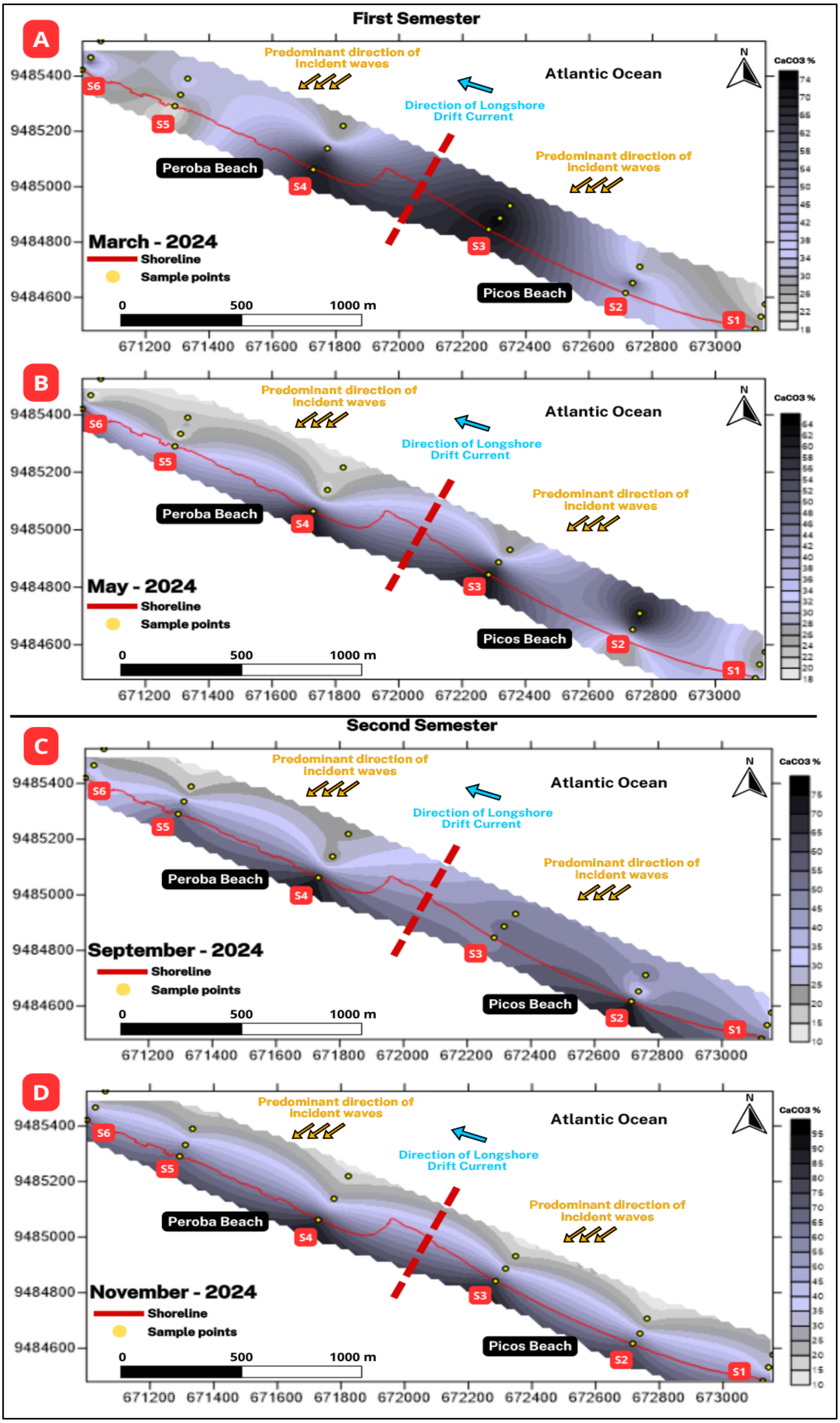

Figure 9. Kriging interpolation maps showing the spatial distribution of calcium carbonate content ($CaCO_3$%).

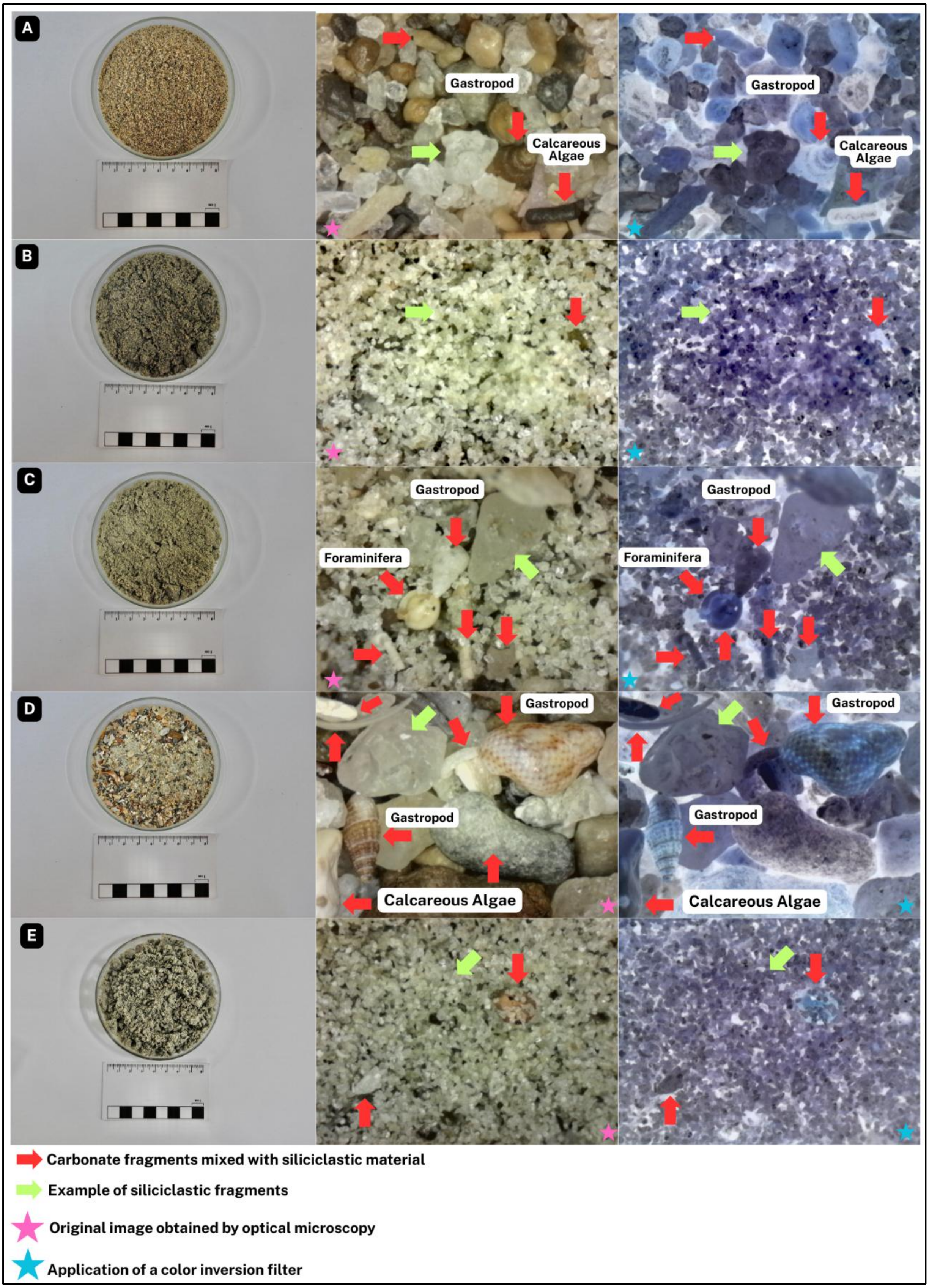

Figure 10. Sediment samples observed using optical microscopy, showing the variation between carbonate and siliciclastic components. On the left, an overview of the samples; in the center, original images identifying gastropods, foraminifera, and coralline algae; and on the right, images with color inversion filters to enhance contrast.

4.3. Textural and compositional classification of unconsolidated sediments

At Picos Beach, Sector 1 was characterized by the occurrence of three main sedimentary classes throughout the year. In March, the backshore exhibited medium lithobioclastic sand, while the foreshore and nearshore were composed of fine to very fine lithoclastic sand. In May, all zones displayed fine to very fine lithobioclastic or lithoclastic sand, a pattern that persisted in September. In November, the predominant sedimentary classes were fine to very fine biolithoclastic sand in the backshore and fine to very fine lithobioclastic sand in the other zones.

In Sector 2, the backshore in March was characterized by medium lithobioclastic sand, the foreshore by fine to very fine biolithoclastic sand, and the nearshore by fine to very fine lithobioclastic sand. In May, the predominant sedimentary classes were medium lithoclastic sand in the backshore, fine to very fine biolithoclastic sand in the foreshore, and fine to very fine biolithoclastic sand in the nearshore. In September, sedimentary classes such as medium bioclastic sand, fine to very fine lithoclastic sand, and fine to very fine lithobioclastic sand were observed. In November, fine to very fine bioclastic sand dominated in the backshore, fine to very fine lithobioclastic sand in the foreshore, and fine to very fine lithoclastic sand in the nearshore.

Sector 3 showed the greatest variability among subenvironments. In March, sedimentary classes included coarse to very coarse biolithoclastic sand in the backshore, fine to very fine bioclastic sand in the foreshore, and fine to very fine lithobioclastic sand in the nearshore. In May, the distribution comprised medium biolithoclastic, fine to very fine biolithoclastic, and fine to very fine lithoclastic sands, respectively. In September, fine to very fine lithobioclastic sand predominated in the backshore and nearshore, and fine to very fine biolithoclastic sand in the foreshore. In November, coarse to very coarse bioclastic sand occurred in the backshore, fine to very fine biolithoclastic sand in the foreshore, and fine to very fine lithoclastic sand in the nearshore.

At Peroba Beach, Sector 4 presented medium biolithoclastic sand in the backshore, fine to very fine biolithoclastic sand in the foreshore, and fine to very fine lithoclastic sand in the nearshore. In May, all zones exhibited fine to very fine lithoclastic sand. In September, the backshore contained medium bioclastic sand, while the foreshore and nearshore remained composed of fine to very fine lithoclastic sand. In November, the sedimentary classes were fine to very fine bioclastic sand in the backshore, fine to very fine lithobioclastic sand in the foreshore, and fine to very fine lithoclastic sand in the nearshore.

Sector 5 was characterized in March by fine to very fine lithoclastic sand across all zones. In May, sedimentary classes varied between fine to very fine lithobioclastic sand in the backshore, fine to very fine lithoclastic sand in the foreshore, and fine to very fine lithoclastic sand in the nearshore. In September, the backshore exhibited fine to very fine biolithoclastic sand, the foreshore fine to very fine lithobioclastic sand, and the nearshore fine to very fine lithoclastic sand. In November, medium biolithoclastic, fine to very fine biolithoclastic, and fine to very fine lithobioclastic sands were recorded, respectively.

Finally, in Sector 6, sedimentary classes included medium lithoclastic sand in the backshore, fine to very fine biolithoclastic sand in the foreshore, and fine to very fine lithoclastic sand in the nearshore. In May, fine to very fine biolithoclastic, medium lithoclastic, and fine to very fine lithoclastic sands predominated. In September, all zones exhibited fine to very fine lithoclastic or fine to very fine lithobioclastic sands. In November, sedimentary classes consisted of fine to very fine biolithoclastic, fine to very fine lithobioclastic, and fine to very fine biolithoclastic sands, respectively.

Figure 11 presents the kriging interpolation map displaying the spatial distribution of sedimentary classes across the study area. This approach allows the identification of occurrence patterns and sedimentological variations, providing a detailed visualization of the zones where specific sedimentary classes predominate and the transitions between different sediment types.

Table 1 summarizes the textural and compositional sediment classes by beach, sector, month, and morphological compartment. The results show greater variability at Picos Beach, especially in sector S3, and a more recurrent pattern of fine to very fine lithoclastic and lithobioclastic sands at Peroba Beach, mainly in the foreshore and nearshore. This synthesis supports the comparison of spatial and seasonal differences between the two beaches.

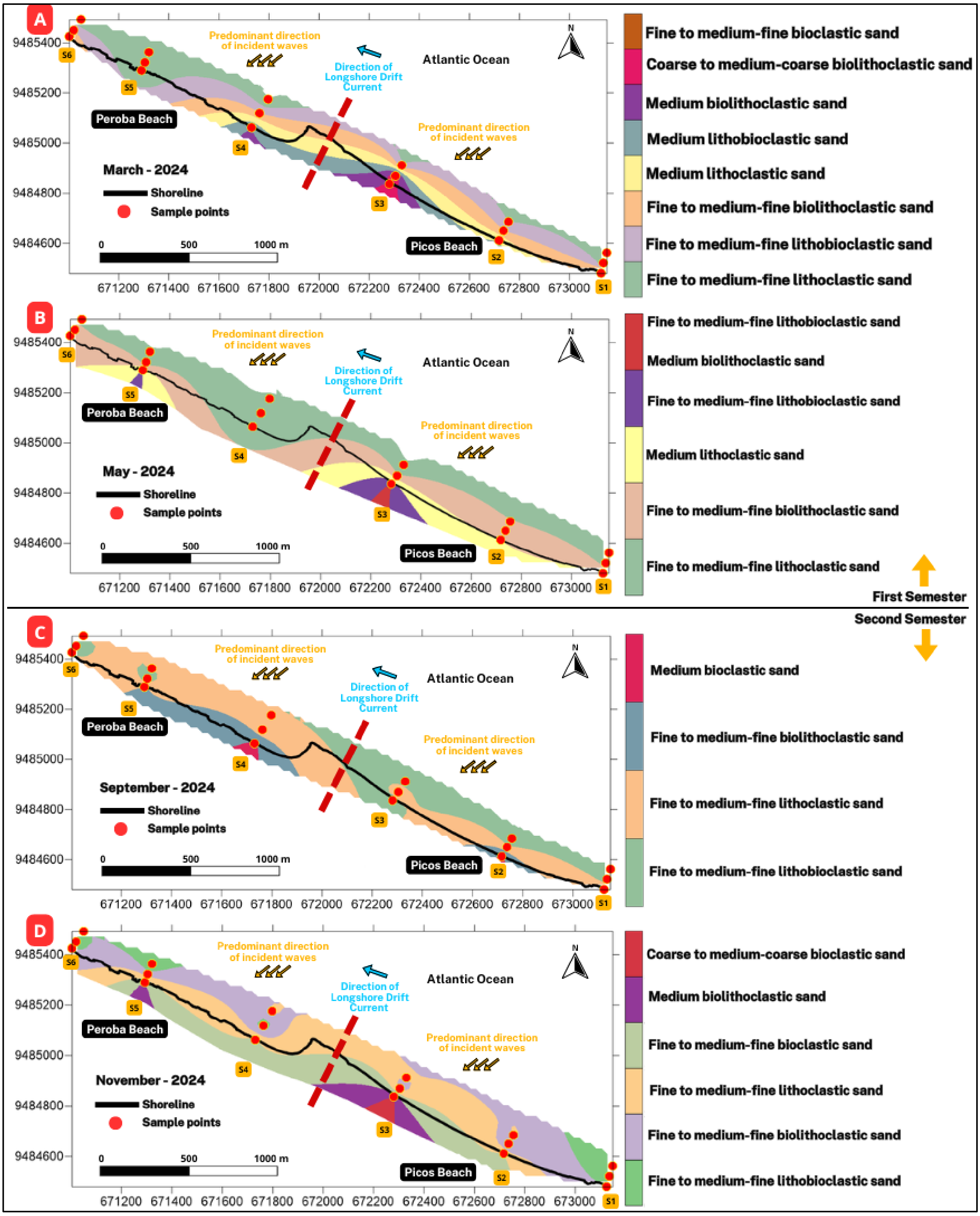

Figure 11. Kriging interpolation maps showing the spatial distribution of sedimentary classes along Peroba and Picos beaches during the first and second semesters of 2024: March (A), May (B), September (C), and November (D). The black line indicates the shoreline position, which was defined using the wet/dry line as a proxy, corresponding to the visible boundary between the dry beach surface and the recently wetted intertidal zone, following the shoreline indicator framework discussed by Leatherman (2003) and Boak and Turner (2005). The yellow circles represent sediment sampling points, and the red dashed line indicates the approximate cartographic separation between the Peroba and Picos beach

sectors. Blue arrows indicate the dominant longshore drift direction, orange arrows indicate the predominant direction of incident waves, and scale bars are expressed in meters.

Table 1: Textural and compositional sediment classes by beach, sector, month, and beach compartment.

Beach	Sector	Month	backshore	foreshore	nearshore
Picos	S1	March	Medium lithobioclastic sand	Fine to very fine lithoclastic sand	Fine to very fine lithoclastic sand
Picos	S1	May	Fine to very fine lithobioclastic/ lithoclastic sand	Fine to very fine lithobioclastic/ lithoclastic sand	Fine to very fine lithobioclastic/ lithoclastic sand
Picos	S1	September	Fine to very fine lithobioclastic/ lithoclastic sand	Fine to very fine lithobioclastic/ lithoclastic sand	Fine to very fine lithobioclastic/ lithoclastic sand
Picos	S1	November	Fine to very fine biolithoclastic sand	Fine to very fine lithobioclastic sand	Fine to very fine lithobioclastic sand
Picos	S2	March	Medium lithobioclastic sand	Fine to very fine biolithoclastic sand	Fine to very fine lithobioclastic sand
Picos	S2	May	Medium lithoclastic sand	Fine to very fine biolithoclastic sand	Fine to very fine biolithoclastic sand
Picos	S2	September	Medium bioclastic sand	Fine to very fine lithoclastic sand	Fine to very fine lithobioclastic sand
Picos	S2	November	Fine to very fine bioclastic sand	Fine to very fine lithobioclastic sand	Fine to very fine lithoclastic sand
Picos	S3	March	Coarse to very coarse biolithoclastic sand	Fine to very fine bioclastic sand	Fine to very fine lithobioclastic sand
Picos	S3	May	Medium biolithoclastic sand	Fine to very fine biolithoclastic sand	Fine to very fine lithoclastic sand
Picos	S3	September	Fine to very fine lithobioclastic sand	Fine to very fine biolithoclastic sand	Fine to very fine lithobioclastic sand
Picos	S3	November	Coarse to very coarse bioclastic sand	Fine to very fine biolithoclastic sand	Fine to very fine lithoclastic sand
Peroba	S4	March	Medium biolithoclastic sand	Fine to very fine biolithoclastic sand	Fine to very fine lithoclastic sand
Peroba	S4	May	Fine to very fine lithoclastic sand	Fine to very fine lithoclastic sand	Fine to very fine lithoclastic sand
Peroba	S4	September	Medium bioclastic sand	Fine to very fine lithoclastic sand	Fine to very fine lithoclastic sand
Peroba	S4	November	Fine to very fine bioclastic sand	Fine to very fine lithobioclastic sand	Fine to very fine lithoclastic sand
Peroba	S5	March	Fine to very fine lithoclastic sand	Fine to very fine lithoclastic sand	Fine to very fine lithoclastic sand

Peroba	S5	May	Fine to very fine lithobioclastic sand	Fine to very fine lithoclastic sand	Fine to very fine lithoclastic sand
Peroba	S5	September	Fine to very fine biolithoclastic sand	Fine to very fine lithobioclastic sand	Fine to very fine lithoclastic sand
Peroba	S5	November	Medium biolithoclastic sand	Fine to very fine biolithoclastic sand	Fine to very fine lithobioclastic sand
Peroba	S6	March	Medium lithoclastic sand	Fine to very fine biolithoclastic sand	Fine to very fine lithoclastic sand
Peroba	S6	May	Fine to very fine biolithoclastic sand	Medium lithoclastic sand	Fine to very fine lithoclastic sand
Peroba	S6	September	Fine to very fine lithoclastic/lithobioclastic sand	Fine to very fine lithoclastic/lithobioclastic sand	Fine to very fine lithoclastic/lithobioclastic sand
Peroba	S6	November	Fine to very fine biolithoclastic sand	Fine to very fine lithobioclastic sand	Fine to very fine biolithoclastic sand

5. Discussion

5.1. Textural and Compositional Patterns of Tide-Modified Mixed Beaches

The interpretation of the results obtained for Picos and Peroba beaches must be understood in light of the specific characteristics of tide-modified mixed coastal environments. These systems exhibit complex sedimentary dynamics resulting from the interaction between hydrodynamic processes and the dual composition of sediments, combining lithoclastic and bioclastic fractions. These textural properties acquire particular relevance in such environments, where the tidal regime acts as a key agent of sediment redistribution and reworking. In the present study, a reduction in the degree of sorting was observed during the second half of the year, particularly in September, when the proportion of poorly sorted sediments increased.

In the study area, the mixed character of the sediments is evident from the coexistence of lithoclastic and bioclastic components in the analyzed samples, as indicated by calcium carbonate contents and the visual identification of biogenic fragments under optical microscopy. Along the semi-arid Brazilian coast, beach sedimentation has commonly been interpreted as predominantly siliciclastic, although recent studies have identified mixed and carbonate-rich patterns in the Aracati–Icapuí shelf–coast system (Ciarlini and Morais, 2014; Ximenes Neto et al., 2018; Ximenes Neto, 2020; Ximenes Neto et al., 2021; Lacerda Barros et al., 2024a).

Along the semi-arid Brazilian coast, beach sediments have traditionally been described as predominantly siliciclastic, although carbonate components may also occur locally (Guerra, 2014; Paula et al., 2015; Pinheiro et al., 2016). However, recent studies have revealed mixed and even carbonate-rich patterns, such as those identified in the Aracati–Icapuí shelf–coast system (Ximenes Neto et al., 2018; Ximenes Neto, 2020), corroborated by records of carbonate sediments in the Potiguar Basin associated with the presence of coralline algae (Vital et al., 2005; Moura, 2014; Ciarlini and Morais, 2014). The literature further indicates that current sedimentation in these areas cannot be explained solely by modern hydrodynamics, but is also influenced by geomorphological controls inherited from Quaternary marine transgression and regression cycles (Meireles, 1991; Meireles and Santos, 2014; Ceará, 2016; Ximenes Neto et al., 2024).

This compositional complexity is reinforced by the occurrence of *Halimeda* banks on the shallow shelf of Icapuí (Colares, 2009; Monteiro, 2011; Carneiro and Morais, 2016), favored by low terrigenous input (Morais and Pinheiro, 2011), the semi-arid climate (Lacerda Barros, 2018), shelf morphology (Morais et al., 2020), and high carbonate production in shallow habitats (Ciarlini and Morais, 2014). In this context, Lacerda Barros et al., (2024a) also emphasize that the interaction between terrigenous and biogenic sources is a key factor shaping the mixed composition of beach and shallow shelf deposits in northeastern Brazil.

Both Picos and Peroba beaches exhibit a tendency toward mixed sedimentation, with the coexistence of bioclastic (carbonate) and terrigenous material (Figure 12). This hybrid composition likely contributes to the observed textural variability, particularly during periods of heightened hydrodynamic energy or differentiated sediment input.

The spatial differences in calcium carbonate content may reflect local morphosedimentary controls. In Peroba, higher carbonate concentrations in the backshore may be associated with the retention of bioclastic fragments in the upper-beach compartment, influenced by beach morphology, coastal occupation, and rocky or abrasion-platform substrates (Bird, 2008; Trenhaile, 2016; Claudino-Sales et al., 2018; Lacerda Barros et al., 2024a). In Picos, the higher carbonate content in the foreshore and its greater variability may indicate more active redistribution of bioclastic material across the intertidal zone, associated with wave action, tidal modulation, longshore transport, and the promontory separating the two beach sectors (Masselink and Short, 1993; Hurst et al., 2015; Claudino-Sales et al., 2018; Lacerda Barros et al., 2024a). These interpretations should be considered cautiously, since carbonate distribution also depends on sediment availability, hydrodynamic energy, beach morphology, and local geological inheritance (De Falco et al., 2017; Ximenes Neto et al., 2024; Lacerda Barros et al., 2024a).

From an environmental standpoint, the mixed depositional nature and pronounced seasonality observed in this study indicate complex sedimentary responses along the Icapuí coast. In Peroba, the lower grain-size variability and predominance of fine to very fine sediments indicate a more recurrent textural pattern, but this condition should not be interpreted alone as evidence of higher erosional susceptibility. Beach response depends on the interaction among sediment availability, beach morphology, hydrodynamic forcing, longshore transport, and anthropogenic occupation (Komar, 1998; Masselink and Short, 1993; Short, 1999; Cooper and Pilkey, 2004; Bird, 2008; Masselink et al., 2011; Paula and Farrapeira Neto, 2017; Pinheiro et al., 2016; Cooper et al., 2020; Lacerda Barros et al., 2024a). In Picos, the greater granulometric and compositional variability indicates a more heterogeneous sedimentary setting, although episodic erosion still occurs along the monitored stretch.

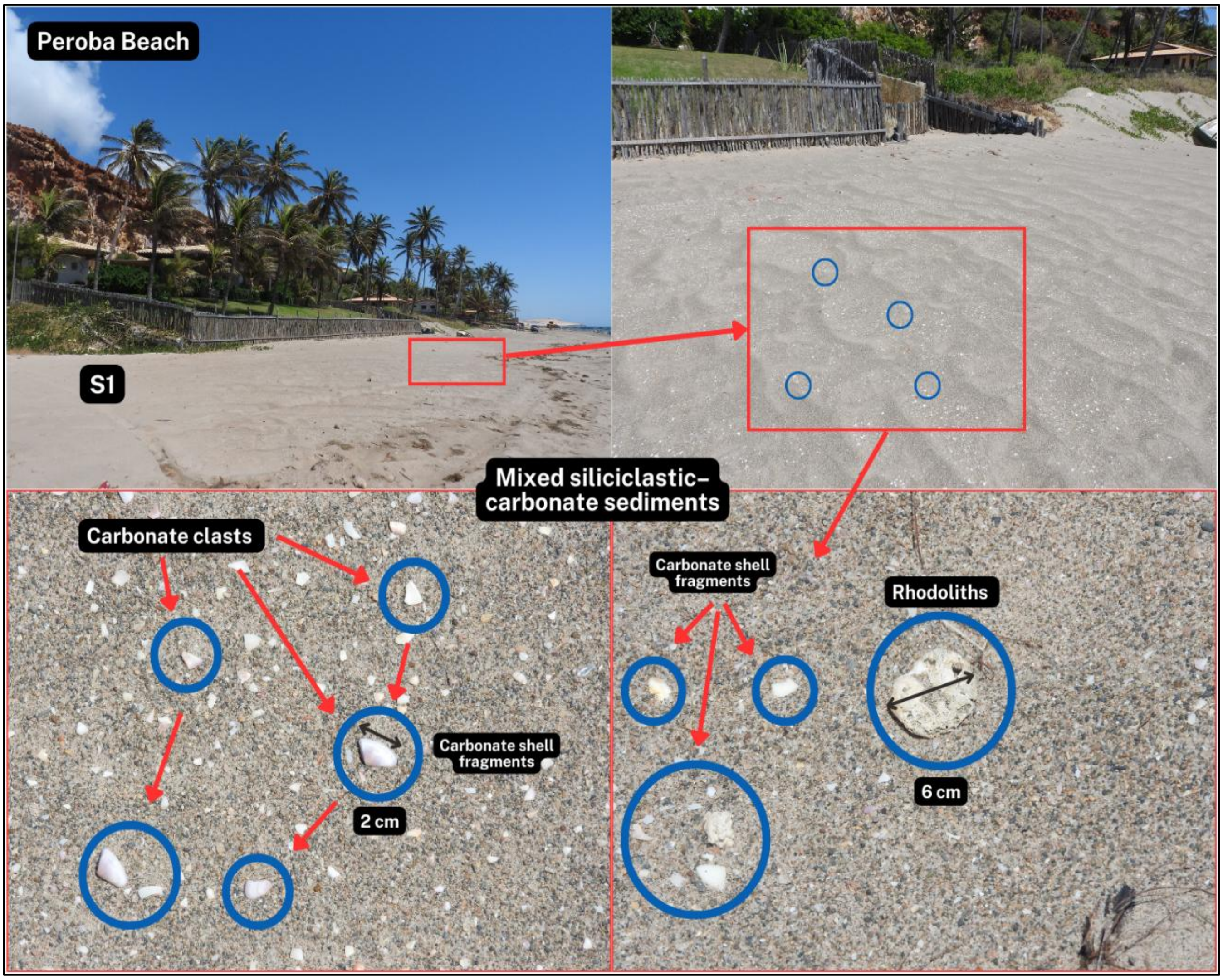

Figure 12. View of Peroba Beach (S1) showing details of mixed siliciclastic–carbonate sediments. Shell fragments and rhodoliths are visible across the beach surface, highlighting the textural and compositional heterogeneity of the deposit.

5.2. Environmental and Coastal Management Implications

Studies on the coastal dynamics of Icapuí (Oliveira, 2012; Lacerda Barros, 2018; Chacanza et al., 2022; Chacanza et al., 2023; Lacerda Barros et al., 2021a; Lacerda Barros et al., 2024a, 2024b) indicate that Picos and Peroba beaches are part of a broader mixed depositional system influenced by both natural processes and anthropogenic factors. The predominance of fine sandy sediments associated with bioclastic fragments, combined with low recent terrigenous input, explained by the semi-arid climate and the structural inheritance of the Potiguar Basin, makes the coastal equilibrium particularly fragile (Schwarzer et al., 2006). The erosion of active cliffs and the redistribution of sediments toward the inner continental shelf reinforce the connection between continental and marine processes, showing that local interventions can affect the entire sediment cell and the broader environment (Pinheiro et al., 2016; Morais et al., 2018; Claudino-Sales et al., 2018; Soares et al., 2021).

These differences have direct implications for coastal management. In Peroba, the higher environmental vulnerability underscores the need for stricter preventive measures, as highlighted by Chacanza et al., (2024). Key actions include restricting occupation in high-risk areas, controlling coastal impermeabilization, and implementing continuous monitoring programs capable of anticipating critical erosive events. Such programs may integrate Citizen Science methodologies, complementing traditional approaches already applied in the region. In Picos, where sedimentary variability provides greater natural buffering capacity, management strategies should focus on tracking seasonal dynamics, protecting cliffs from accelerated erosion, and maintaining surface drainage corridors to reduce concentrated sediment input and preserve system stability.

More broadly, the coexistence of stability and retreat phases along the Icapuí coastline demonstrates the need for adaptive management and planning tools. Beach width and morphological variability are also relevant parameters for assessing recreational function and supporting local coastal management, particularly in beaches affected by erosion and seasonal sediment redistribution (Paula et al., 2022). The Plano Diretor Urbano (Urban Master Plan), the Integrated Coastal Zone Management Plans, and other mechanisms linked to the Plano Nacional de Gerenciamento Costeiro (National Coastal Management Plan – PNGC) can directly benefit from sedimentological and morphodynamic data, whether to delineate priority conservation zones, regulate the construction of coastal infrastructure, or identify areas where carbonate-rich sediments make the preservation of marine habitats indispensable.

The textural and compositional patterns identified in this study should be interpreted as indicators of morphosedimentary variability rather than as direct measures of erosion risk. The differences observed between Peroba and Picos suggest that each beach sector responds differently to the interaction among sediment availability, beach morphology, tidal modulation, wave action, longshore transport, wind-driven processes, and local geological controls (Masselink and Short, 1993; Bird, 2008; Pinheiro et al., 2016; Cooper et al., 2020; Lacerda Barros et al., 2024a).

In Peroba, the lower grain-size variability and the recurrent predominance of fine to very fine sediments indicate a more homogeneous textural pattern throughout the analyzed period. However, this condition should not be interpreted in isolation as evidence of greater erosional susceptibility, since beach response also depends on sediment budget, nearshore morphology, hydrodynamic forcing, coastal occupation, and the presence of hard substrates or coastal protection structures.

In Picos, the greater textural and compositional variability, including the alternation among lithoclastic, lithobioclastic, biolithoclastic, and bioclastic sedimentary classes, may reflect a more heterogeneous morphosedimentary setting, possibly influenced by local controls such as the promontory, rocky outcrops, wave transformation processes, and seasonal changes in sediment redistribution.

Therefore, although the sedimentological results provide relevant evidence for understanding local beach dynamics, future studies integrating hydrodynamic monitoring, morphometric surveys, nearshore bathymetry, and shoreline-change analysis are needed to better constrain the mechanisms controlling sediment redistribution and erosional responses in Peroba and Picos.

Table 2 summarizes the main sedimentological contrasts between Peroba and Picos beaches and presents their possible morphosedimentary implications. Rather than classifying erosion risk directly, the table highlights how grain size, sorting, sedimentary classes, seasonal variability, and local controls may help explain the different sedimentary responses observed in each beach sector.

Table 2. Comparative sedimentological synthesis of Peroba and Picos beaches, highlighting grain size, sorting, sedimentary classes, seasonal variability, and possible morphosedimentary implications.

Parameter	Peroba Beach	Picos Beach	Interpretative implication
Mean grain size	Predominance of very fine sand, especially in March and May	Greater grain-size variability, with very fine, fine, and medium sand occurring throughout the year	Peroba shows a more recurrent fine-grained pattern, while Picos presents greater textural variability
Sorting degree	Predominance of well- to moderately well-sorted sediments	Moderately to poorly sorted sediments, especially in September	Sorting patterns suggest different degrees of sediment reworking between the two beaches
Sedimentary classes	Lower diversity, with frequent occurrence of fine	Higher diversity, including lithoclastic, lithobioclastic,	Picos shows greater textural-compositional heterogeneity,

	to very fine lithoclastic and lithobioclastic sands	biolithoclastic, and bioclastic classes	while Peroba presents a more recurrent sedimentary pattern
Seasonal variation	Lower seasonal variation in sedimentological parameters	Greater seasonal variation, especially in grain size, sorting, and sedimentary classes	Seasonal changes are more evident in Picos and may reflect stronger spatial variability in sediment redistribution
Local controls	More recurrent fine-grained deposits and coastal occupation adjacent to and locally extending into the upper beach sector	Greater influence of sectoral heterogeneity, promontory effects, and rocky/submerged substrates	Differences between beaches should be interpreted in relation to hydrodynamic forcing, sediment availability, morphology, and local geological controls

6. Conclusions

The sedimentological analysis of Peroba and Picos beaches revealed distinct patterns in grain-size distribution and calcium carbonate content, and sedimentary class diversity, indicating the combined influence of seasonality, hydrodynamics, sediment availability, and local morphosedimentary controls on beach dynamics.

From a granulometric perspective, both beaches are dominated by very fine to fine sands, associated with low-to moderate-energy conditions. However, Peroba displayed lower grain-size variability throughout the analyzed period, whereas Picos exhibited more pronounced spatial and seasonal variability. Calcium carbonate contents were higher in the backshore sector of Peroba, with mean values of 71.5%, while Picos showed greater fluctuations, especially in specific sectors and sampling periods.

The textural and compositional classification of the sediments also revealed marked contrasts between the two sites. Peroba was dominated by fine to very fine lithoclastic and lithobioclastic sands, displaying a more recurrent sedimentary pattern throughout the year. In contrast, Picos presented greater sedimentary class diversity, with up to ten distinct classes, including bioclastic and mixed classes, indicating a more heterogeneous depositional setting and stronger seasonal variability.

Overall, the results show that Peroba presents lower grain-size variability and a recurrent predominance of fine to very fine sediments, whereas Picos is characterized by greater granulometric and compositional heterogeneity, with higher sedimentary class diversity and more pronounced seasonal variability. These differences indicate distinct morphosedimentary responses between the two beaches but should not be interpreted as direct measures of erosional vulnerability or resilience; beach behavior also depends on sediment availability, hydrodynamic forcing, beach morphology, longshore transport, wind-driven processes, and local geological controls. Therefore, integrated sedimentological analyses combining grain size, carbonate content, and sedimentary class identification are essential for understanding the complexity of coastal dynamics and may provide technical support for future coastal management assessments. Furthermore, continuous monitoring integrating sedimentological, hydrodynamic, morphometric, morphoscopic, nearshore bathymetric, and shoreline-change data is needed to improve the understanding of sediment sources, transport processes, seasonal redistribution, and long-term coastal evolution.

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Declaration of Use of Artificial Intelligence: During the preparation of this manuscript, the authors used the GPT-5.5 PLUS Thinking tool to improve the grammar and fluency of the text and to assist with translation into English. The English version was subsequently reviewed by a professional translator. The authors also used the Napkin AI tool to prepare the graphic shown in Figure 03. After using these tools, the author critically reviewed and edited all content, assuming full and complete responsibility for the published manuscript, including any inaccuracies or errors.

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