Ocean and Coastal Research

ORIGINAL ARTICLE
Special Article Collection
Sousa, Carreira & Fonseca (eds), Subsidies for ecosystem-based management in an offshore oil and gas exploration area, Santos Basin, Brazil
http://doi.org/10.1590/2675-2824071.22064agfj
ISSN 2675-2824

Santos Basin continental shelf morphology, sedimentology, and slope sediment distribution

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ABSTRACT

The ocean bottom morphology, depth, sediment grain size, sediment sorting, carbonate content, and water depth are used to compose seafloor maps as support for biological studies. Sediments are reworked by waves and currents and accumulate according to the hydrodynamic level on the continental shelf. In contrast, sediments are accumulated by pelagic settling, mass wasting, turbidity flows, and boundary currents on the slope. Sea level oscillations during the Quaternary also played an important role in modifying the shelf seabed's morphology and sedimentary mosaic composition. The work addresses these topics in the Santos Basin based on extensive bathymetric data, shallow seismic records, and stratified bottom sediment samples in water depths ranging from 25 to 2,400m, as part of The Santos Basin Regional Environmental Characterization Project (PCR-BS). The main objective is to provide broad background information on the sedimentology and morphology of Santos Basin, focusing on the continental shelf. The morphology, sediment supply, shelf orientation, and ocean climate imprint the Santos Basin's characteristics. The Northern shelf sector is the most dynamic because of the narrow shelf, steep gradient, and East-West shoreline orientation, providing conditions for storm waves to approach and mobilize sediment in the ocean bottom shallow than 50 m water depth. The Southern sector of the shelf is much broader than the Northern sector; it displays a gentler gradient, and its orientation is Northeast-Southwest; therefore, less subject to storm waves than the Northern sector.

Descriptors: São Paulo plateau, Seafloor maps, Grain size and facies, Carbonate content, sediment sorting, São Paulo plateau.

INTRODUCTION

The Santos Basin is the largest offshore sedimentary basin in the Western South Atlantic, developed during the rifting of South American and African plates, covering an area of 350,000 km^2, and extending from the coastline down to 3,000 m water depth and sediment thickness up to 15 km (Mio et al., 2005). It is one of the most relevant sedimentary basins at the Brazilian margin due to many ports' activity and the pre-salt oil fields reservoirs exploration.

Its continental shelf (Figure 1) comprises an area of 134,000 km^2. It extends from shore to the shelf break at 200m water depth. It is narrower in Cabo Frio's Northern limit (75 km) and wider from São Sebastião Island (220 km) toward the South till Florianópolis Island. Because of distinct shelf width, orientation, and sediment properties from North to South, we propose a division into Northern and Southern sectors. The deeper portion of the basin comprises the slope and the São Paulo Plateau. Because of the considerable amount of data, the focal point of this research is the continental shelf. In contrast, in the slope and

Submitted: 31-May-2022
Approved: 27-Jan-2023

Associate Editor: Renato Carreira

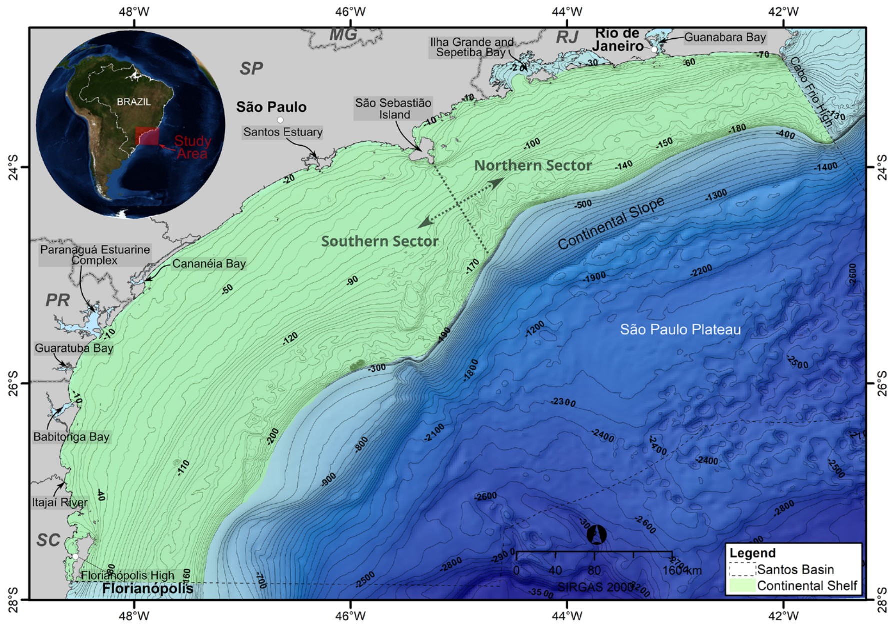

Figure 1. Santos Basin location. The continental shelf, extending up to 200 m water depth, is highlighted in green.

the São Paulo Plateau, only grain size and carbonate content distribution will be explored because of the reduced amount of data.

The shelf morphology was described by the pioneer works of Zembruscki (1979) and Martins and Coutinho (1981) as very smooth, with low angle inclination. At the outer shelf, morphology is highly influenced by bioconstructions and features related to sea-level oscillations, such as beach rocks (Figueiredo Jr. and Tessler, 2004; Reis et al., 2013). Sediments are mainly composed of siliciclastic sands at the inner and middle shelves, with extensive mud facies toward the South and biogenic gravel patches toward the North at the outer and shelf break (Kowsmann and Costa, 1979).

As one of the Santos Basin Regional Environmental Characterization (PCR-BS) (2019-2023) objectives, we compiled bathymetric and sediment datasets.

Several authors relate sediment quality to the benthos community and the geochemical process inside the sediment. According to Aller (1988, 2014), marine sediments under oxygenated bottom water are permanently or periodically inhabited by benthos and endobenthos communities. During their grazing and feeding activities, they can transport sediment particles, burrowings, and tube constructions and consequently irrigate the sediment with nutrients and oxygenated water. As a result of burrowing, the two-dimensional sediment surface becomes a three-dimensional body for geochemical reactions. Sediment porosity and permeability depend on grain size, sediment sorting, layers stratification, and degree of bioturbation.

In the North Atlantic, in water depths between 250 and 3,000 m, along the East coast of North America, Etter and Grassie (1992), based on 558 box-corers demonstrated that in deep-sea benthic species, diversity varies geographically and bathymetrically, where the nature of sediment should be essential in structuring deep-sea communities. Because deposit feeders rely on sediments for nutrition and comprise most deep-sea organisms, the composition of soft sediment communities is influenced by sediment particle size.

However, according to Snelgrove and Butman (1994), there is little evidence that sediment grain size alone is the primary determinant of infaunal species distribution. Other factors may include organic and microbial content, food supply, and trophic interactions. Common sense indicates that deposit feeders are more abundant in muddy habitats and suspension feeders dominate sandy habitats. Grain size covaries with organic matter content, pore-water chemistry, and microbial abundance and composition. Because these parameters are influenced by the near-bed flow regime, further looking at sediment and environment dynamics is essential.

Considering the findings of the above-cited authors, this paper has the primary objective of providing broad background information on the sedimentology and morphology of Santos Basin with a focus on the continental shelf.

METHODS

Environmental Setting

The shallow and deep-water meteoceanographic processes that influence Santos Basin geomorphology and sediment composition, like waves, currents, and water masses, are thoroughly discussed by Dottori et al. (2023) and Silveira et al. (2023).

The bathymetric map was derived from 891,979 data points from the Brazilian Navy's sounding sheets, 10,014 points from nautical charts, and gridded surface cells of the Brazilian Continental Shelf Research Program (LEPLAC). All these data had the same cartographic projection and were reduced to the same *datum*. We used the Inverse Distance Weighted (IDW) interpolation method to grid the final regional bathymetric surface with a cell size of 2 km.

To complement morphology data and identify ocean bottom features, 12,269 km of Sub Bottom Profiler (SBP) data at frequencies of 3.5 and 12 kHz were acquired during PCR-BS project. SBP data was also used to identify sedimentary facies, such as bioclastic, sand, and muddy facies. Time-Variant Gain-TVG and the negative amplitudes were corrected as proposed by Chu and Hufhagle (2006) and Taner et al. (1994).

Triplicate surface sediment samples were collected during PCR-BS cruise one at eighty-eight stations along eight transects at specific isobaths (25, 50, 75, 100, 150, 400, 700, 1000, 1300, 1900, and 2,400 m) and eleven stations in the São Paulo Plateau, totalizing 297 samples (red dots in Figure 2). A box-corer of 50x50x50 cm and a mega van Veen grab of 90x92x55 cm (231 L) were used. Sediments were sampled in three depth strata: 0-2 cm, 2-10 cm, and 0-10 cm. In the laboratory, after homogenization, the sediment fraction of 0-10 cm was frozen and dried before grain size and carbonate content analysis.

For grain size analyses, a fraction of 1 g was used in a laser grain sizer (Malvern Mastersizer 2000 particle size analyzer). Each sediment sample was first sieved through a 1 and 2 mm mesh sizes and then analyzed with a Malvern Mastersizer 2000. Particles larger than 1 mm and 2 mm were weighed and added manually to the Gradistat program, to compute the statistical parameters according to the Folk and Ward (1957) equations. The carbonate sediment was not eliminated before grain size analysis. Another fraction of 10 g was used for acid digestion with Hydrochloric Acid reduction at 10% volume to calculate carbonate content.

In addition to the PCR-BS data, 7,740 grain size analyses and 3,404 carbonate content records from historical datasets were added to the data bank (green dots in Figure 2). The sediment data from the PCR-BS project is derived from the upper 10cm of sediment strata, while for the historical datasets, there was no control. However, because the samples from historical datasets were collected by grab samplers, sediment strata would probably reach at most 20 to 30 cm below the surface. Despite the diverse methodology used in sediment analyses of historical and PCR-BS data, results were compared, and the similarity between historical data and nearby PCR-BS data points was high.

RESULTS

Shelf Morphology

The Santos Basin continental shelf exhibits a variable relief of smooth and monotonous surfaces. It is notable a widening of the continental shelf in the central portion, off Santos Estuary (220 km), and a narrowing in Cabo Frio (75 km). The inner and middle shelves have smooth and gently undulating surfaces. In contrast, the outer shelf between 70 and 200 m exhibits a rough surface in the Northern sector and is substantially less rugged in the Southern sector (Figure 3).

The mean shelf slope is 0.08°. In the Northern sector, between Cabo Frio and São Sebastião Island, the declivities range from 0 to 3°. A rugged relief from Cabo Frio to off Cananéia Bay prevails at the middle and outer shelves. Toward the South, the mean slope doesn't exceed 1.5°. The geomorphological features richness increases toward shallow waters, mainly at bay mouth entrances. A great variety of bottom features as bay-mouth sand shoals (Figure 4I), ebb-tidal deltas (Figure 4III), island downstream side sand shoals or submerged spits that indicate drift direction (Figures 4I and II), modern channels, sand wave fields defined by undulating topography (Figures 4I and III), rocky outcrops, incised valleys (Figure 4II and III) are noted all over the inner shelf.

The SBP data complements the regional bathymetric map aspect and detailed bottom and sub-bottom features as morphologies, sizes, and extensions (Figure 5). Other features were highlighted exclusively in the SBP records as an extensive erosive feature in the head of the Cananéia Canyon (Zembruscki, 1979, Figure 5IV). The erosive area is 6 km wide at the shelf break inside the Cananéia Canyon head.

Sediments grain size and facies

Grain size analysis of triplicate samples collected during the PCR-BS cruise reveals the occurrence of very coarse sands to muds, with the predominance of sand-sized sediments on the continental shelf. In contrast, sediments are mostly muddy in the slope and São Paulo Plateau (Figure 6). From the inner shelf to the outer shelf, a trendline indicates a decrease in grain size towards the deeper areas, while on the slope, no grain size variation was detected. For the whole basin, the trendline suggests a decrease in grain size towards the deep.

When considering the historical and PCR-BS data, the sandy facies predominates on the shelf (Figure 7). In the Northern sector, it covers the whole shelf with a small area of muddy sediment in the middle shelf. In the Southern sector, the sandier facies is more restricted to the inner and middle shelf. In the slope and plateau, sands are more frequent in the upper and middle slopes in

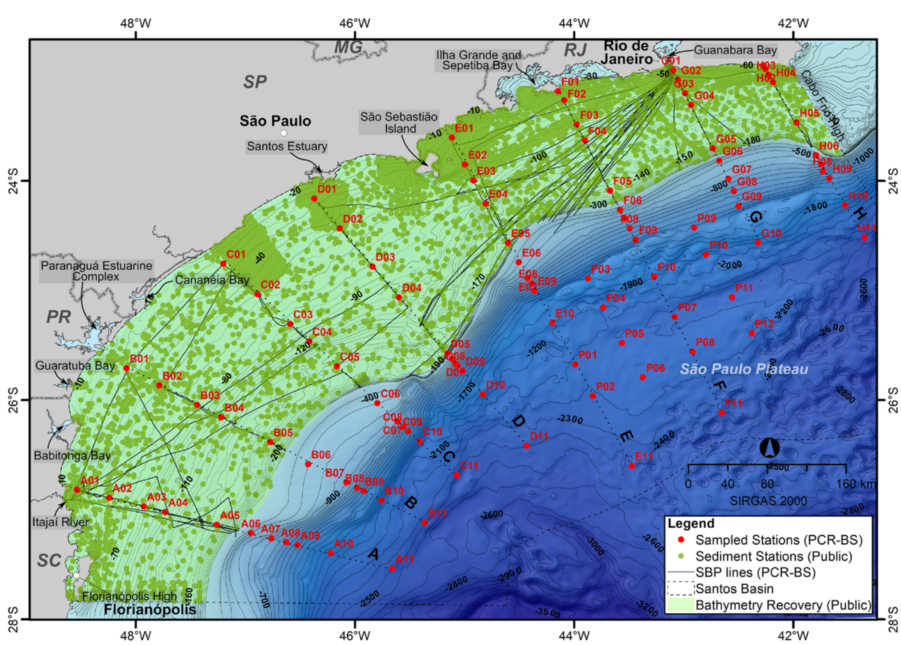

Figure 2. Sediment data points locations. Red dots are PCR-BS stations, while green dots correspond to historical public data. The light green area represents the area of detailed bathymetry derived from public data on the continental shelf. The black lines correspond to SBP track lines during PCR-BS cruise one. The blue area corresponds to the slope and São Paulo Plateau.

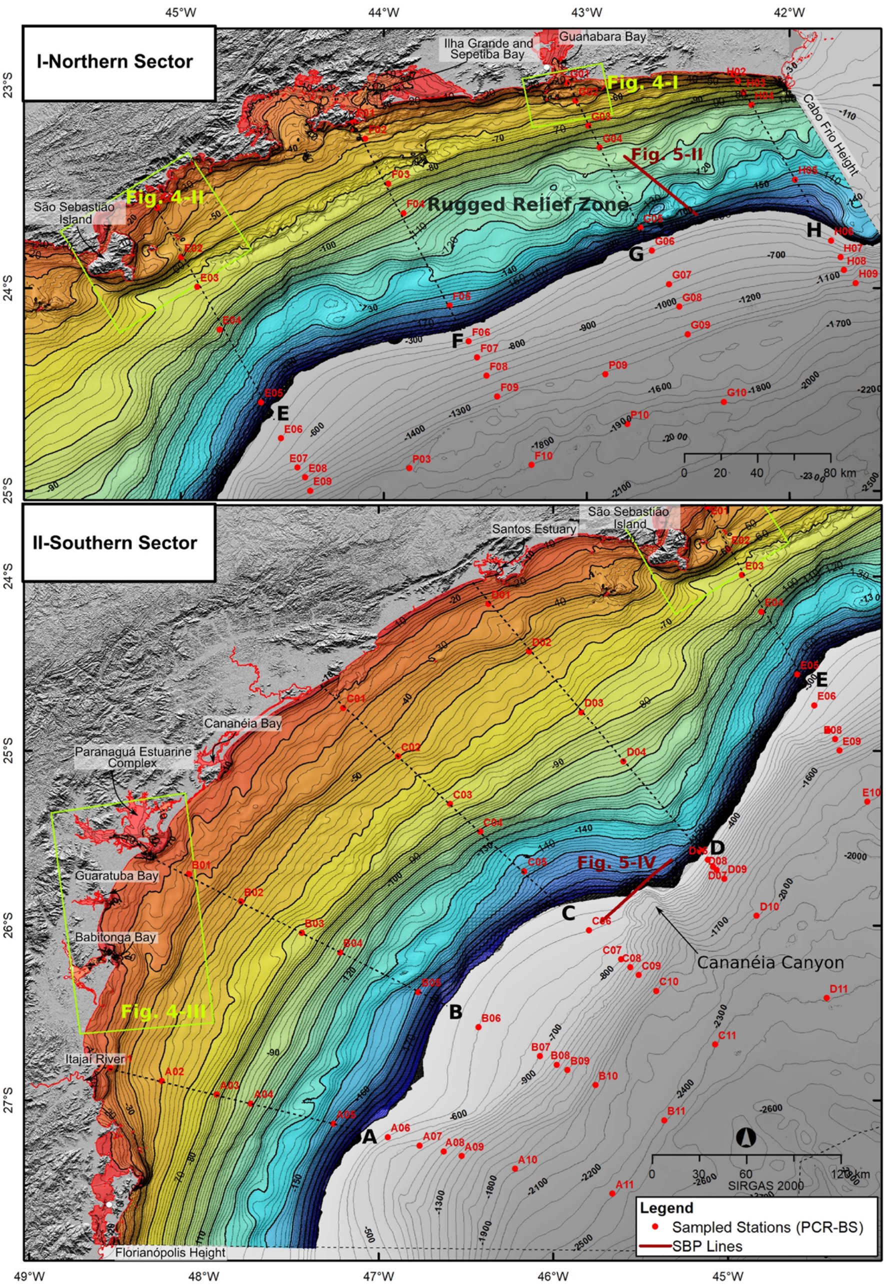

Figure 3. Bathymetric map of Santos Basin. The colored area is the continental self, divided from the slope (grey area) by the 200m isobath. The focus of the paper is on the continental. Green squares indicate examples of geomorphological features, and dashed lines are the transects. Continental topography is derived from SRTM database.

the Northern sector despite being predominately muddy.

On the shelf, the muddy facies appears in two main areas. The largest one exhibits an elongated shape, up to 100 km wide and becoming narrower towards the North. It occupies the outer shelf and shelf break from Florianópolis to Santos Estuary. The smaller muddy facies is observed in shallower waters, between 100 and 135 m, and extends from São Sebastião Island to Guanabara Bay.

Considering only the PCR-BS samples, the muddy facies predominates on the slope and São

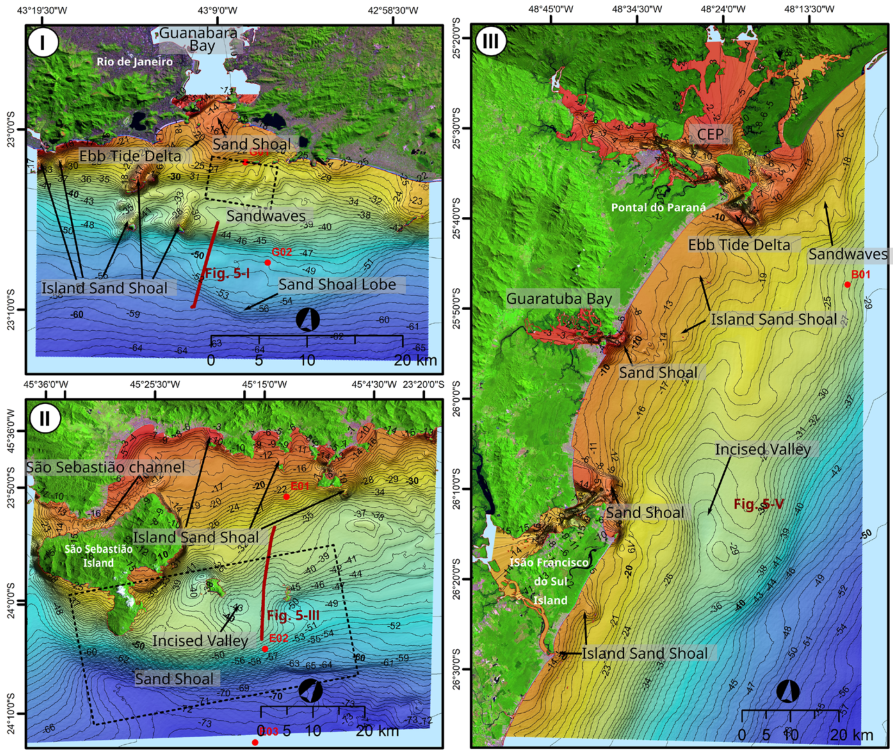

Figure 4. Examples of the main geomorphological features at the inner shelf. I- Sand shoals, sand shoal lobe, island downstream side sand shoal or submerged spits, and sand waves fields. II- Sand shoals and incised valley close to São Sebastião Island. III- well-defined incised valley close to São Francisco do Sul Island.

Paulo Plateau, except in samples collected along transect G and a few other samples from the Northern and Southern sectors (Figures 3 and 7).

Sediment sorting

Grain size sorting varies from well-sorted to very poorly sorted. The well-sorted, moderately well-sorted, and moderately sorted sediments are all located in areas shallower than 30 m (Figure 8). Beyond the 30m isobath, all samples are poorly to very poorly sorted. In the shelf muddy facies, all samples were classified as poorly sorted.

The wave base is the water depth where orbital movements associated with surface waves reach the bottom and may start resuspending sediments and consequently improve grain sorting. In the slope, because of the pelagic settling of bioclastic particles in a muddy environment and siliciclastic particles of various sizes transported by turbidity currents and contour currents, the grain sorting is not elevated.

According to Berger and Heath (1968), bioturbation rates are faster than accumulation rates contributing to the occurrence of poorly sorted sediments on the slope. Therefore, the poor and very poor sorting at the slope could also be related either to the pelagic settling of a variety of grain-sizes or active bioturbation of sediment layers.

Carbonate Content

In this research, the carbonate content by weight in sediment uses the classification proposed by Larsonneur (1977) and modified by Dias (1996) (Table 1).

Carbonate content in the basin increases from the inner to the outer shelf and from the upper slope to the lower slope and São Paulo Plateau (Figure 9). The highest carbonate content occurs in sediment from the outer shelf and shelf-break at 150 m, as indicated by the shelf's trendline. The slope trendline indicates increasing concentration towards the deep ocean.

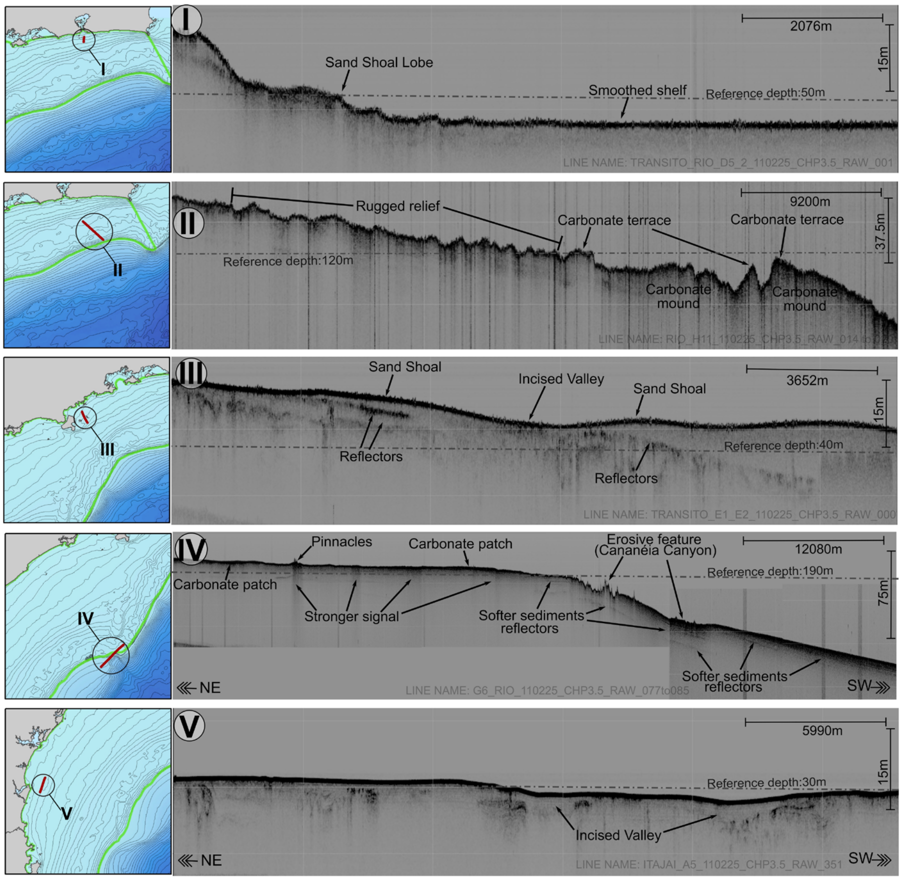

Figure 5. Geomorphological features mapped by the sub-bottom profiler (SBP). A few buried features, such as channels, are also shown. A reference depth line is added to identify water depth.

In the shallow shelf, the carbonate is dominated by bivalves and gastropod shells, while in the outer shelf and shelf-break, calcareous algae, bryozoans, and Halimeda predominate. At the slope, crustacea, mollusks, and planktonic foraminifera are the predominant carbonate source. In contrast, in water depths between 2,000 and 2,400 m, carbonate is mainly derived from planktonic foraminifera and pteropod shells.

On the shelf, carbonate facies dominate the outer and the shelf break area from North to South, with an interruption on the heads of the Cananéia canyon, which is covered by the muddy sediments (Figure 10). The carbonate content is higher in the Northern sector and decreases toward the South.

Mean grain size and carbonate content along the transects

Along the eight transects, A to H, and at selected depths (Figure 2), the mean grain size and carbonate content were plotted following the ocean bottom topography and distance from the shoreline (Figure 11).

The distance between the shoreline and the 2,400 m isobath varies from 200 km (transects G and H) to 300 km (transects A, B, C and D), reaching 400 km at transects E and F. The slope topography in all transects has a concave profile. The slope gradient is higher in the Northern sector, than in the Southern sector.

In the Southern sector (transects A, B, C and D), samples taken in shallow water (20 – 50 m) exhibit mean grain size smaller than 400 µm, while in

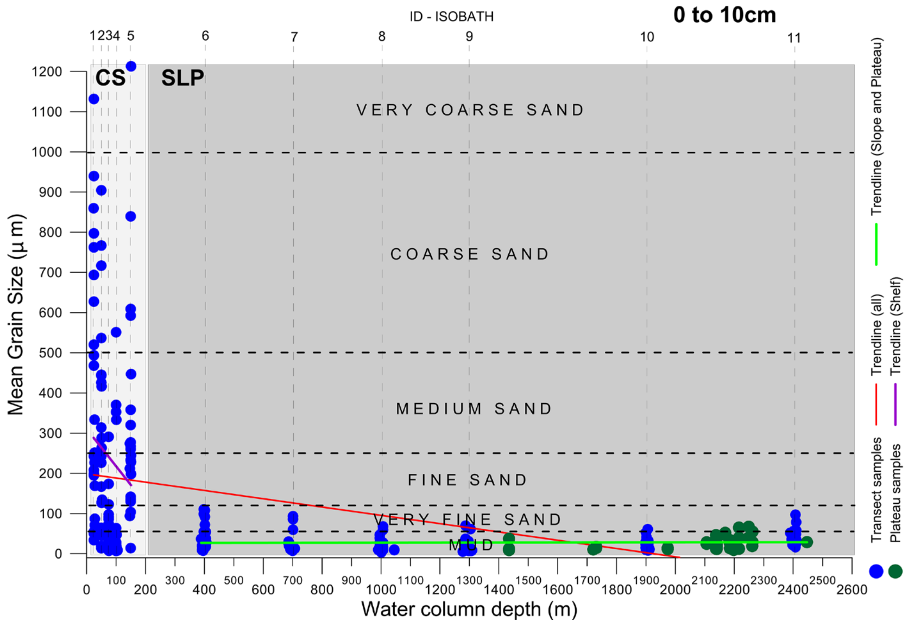

Figure 6. Mean grain size classification of the top 10 cm from the grab sampler of the PCR-BS cruises. Samples of all eleven transects and the São Paulo Plateau are represented. Blue dots represent samples from the shelf and slope. Green dots represent samples from São Paulo Plateau. Continental Shelf samples (CS) are represented in the clear area. Continental Slope samples (SLP) are represented in the darker area. The numbers on top indicate the transects.

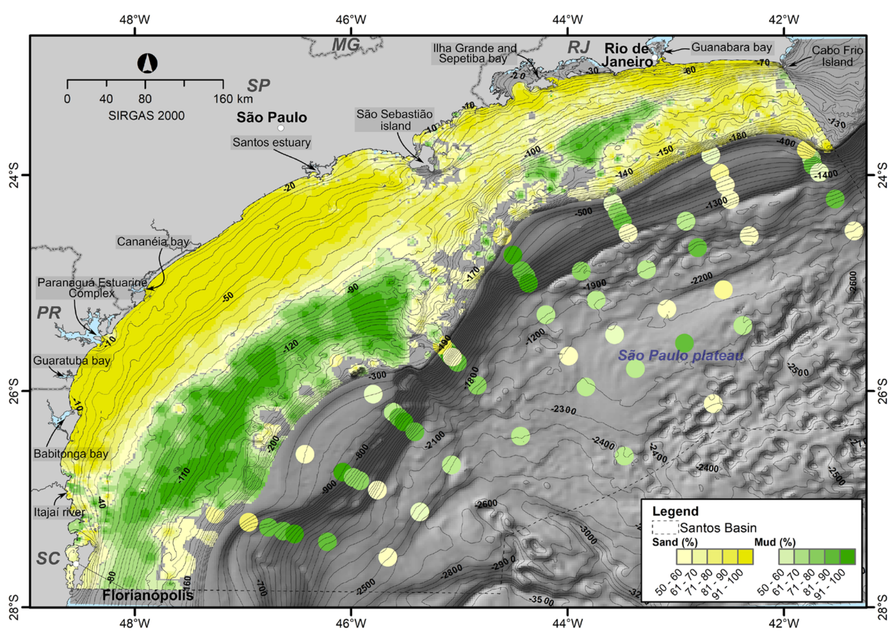

Figure 7. Distribution of sandy and muddy facies in the continental shelf and slope. On the shelf, historical and PCR-BS samples were considered, while at the slope and São Paulo Plateau, only samples from the PCR-BS project were included. The yellowish colors represent the predominance of sandy facies, while greenish colors represent muddy facies.

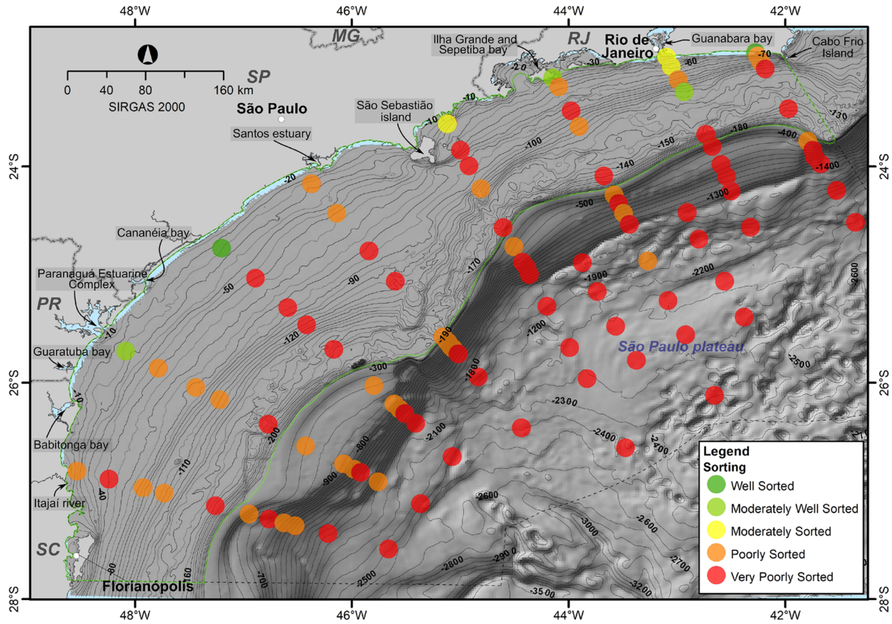

Figure 8. Grain size sorting on the shelf, slope, and São Paulo Plateau based only on the top 0-10cm of PCR-BS samples.

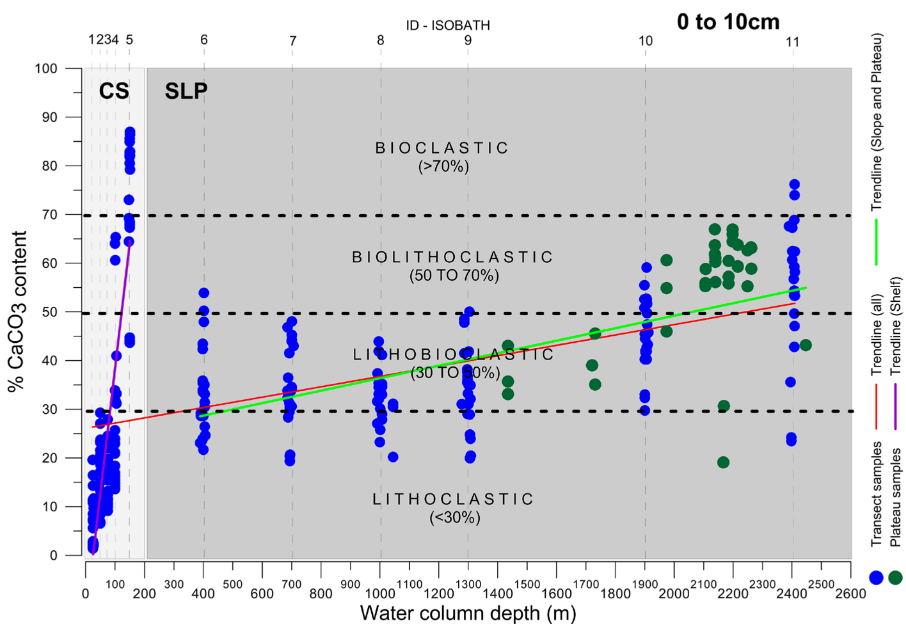

Figure 9. Carbonate content in the top 10 cm of sediment. The figure represents carbonate content along the eleven transects at a specific isobath from 20 to 2,400 m. Green dots represent samples from São Paulo Plateau. Continental Shelf samples (CS) are represented in the clear area. Continental Slope samples (SLP) are represented in the darker area. The numbers on top indicate the transects.

the Northern sector (transects E, F, G and H) their mean grain size is mostly greater than 400 µm, reaching values close to 1200 µm.

Towards the shelf break, there is a decrease in grain size, except at 150 m water depth, where there is always an abrupt increase in grain size in

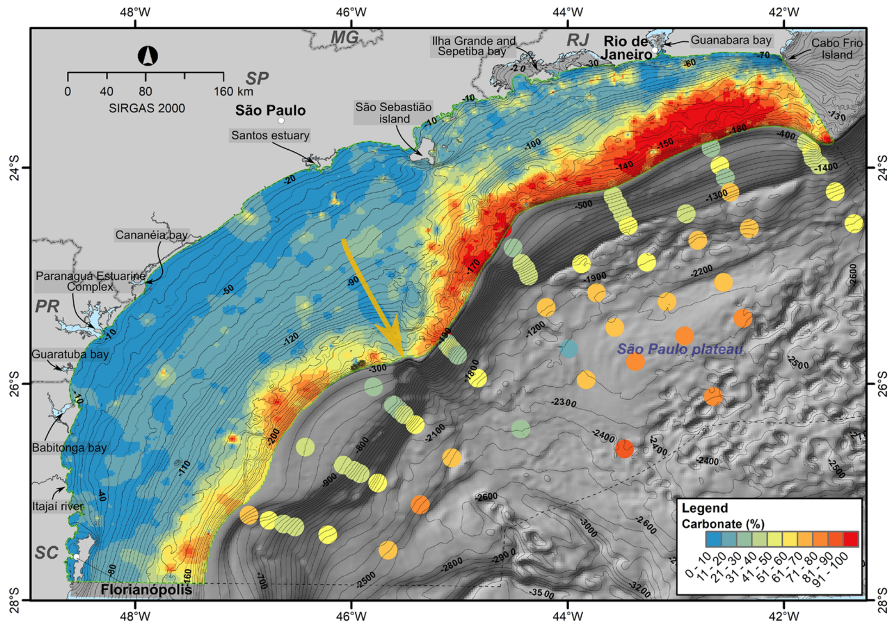

Figure 10. Carbonate content at the continental shelf, slope, and São Paulo Plateau. The arrow indicates an interruption of the carbonate domain at Cananeia's Canyon Heads.

the outer shelf carbonate facies. Beyond the shelf break mean grain size stays under 400 µm.

In shallow water (20-100 m), carbonate content remains mostly below 20%, abruptly increasing at 150 m, reaching 60-80% or even higher values. Beyond the shelf break, samples from transects A, B, C, D, and F present decreasing carbonate content followed by a gradual increase to deeper waters (Figure 11). In transects, G and H carbonate content stays between 60 and 80% beyond the shelf break.

In transects F, G, and H, at the deepest stations, carbonate content in the upper sediment layer (0 to 2 cm) is higher than the underlying sediment (2 to 10 cm) (Figure 11).

DISCUSSION

The continental shelf of Santos Basin presents a great variety of morphological features and is mostly of small relief, like Campos Basin at the Northern sector border (Figueiredo Jr. et al., 2016). Martins and Coutinho (1981) related the main features of the Santos Basin shelf to terrigenous deposits reworked during the Holocene transgression. Still, this unprecedented new seabed analysis reveals a much more complex relation between morphology, sediment composition, hydrodynamics, and sea-level changes.

The shelf morphology has a significant effect on sediment distribution and selection. The narrow shelf (100 km wide) and steep ocean bottom in the Northern sector (Figure 3I) allow the approach of energetic waves, promoting a mean grain size increase up to 800 µm and better selection toward shore starting at 50 m isobath (Figures 8, and 11). Stations 01 and 02 in transects E, F, G, and H, are expected to have a biota characteristic of this energetic environment. The Southern sector is much broader (200 km), wave energy is smaller than in the Northern sector, and grain size ranges between 200 to 300 µm.

Besides grain size and sorting, the bottom morphology has features that indicate sediment dynamics as ebb-tidal deltas at Guanabara's Bay and Paranaguá Bay entrances (Figures 4I and 5I) superimposed by a set of sand waves and island downstream side sand shoals or submerged drifts, denoting drift direction. These features demonstrate how energetic the waves in the Northern sector are and indicate that sediment is being transported toward the shore. Sand shoals can also be observed next to São Sebastião Island (Figures 4II and 5III) and near São Francisco do

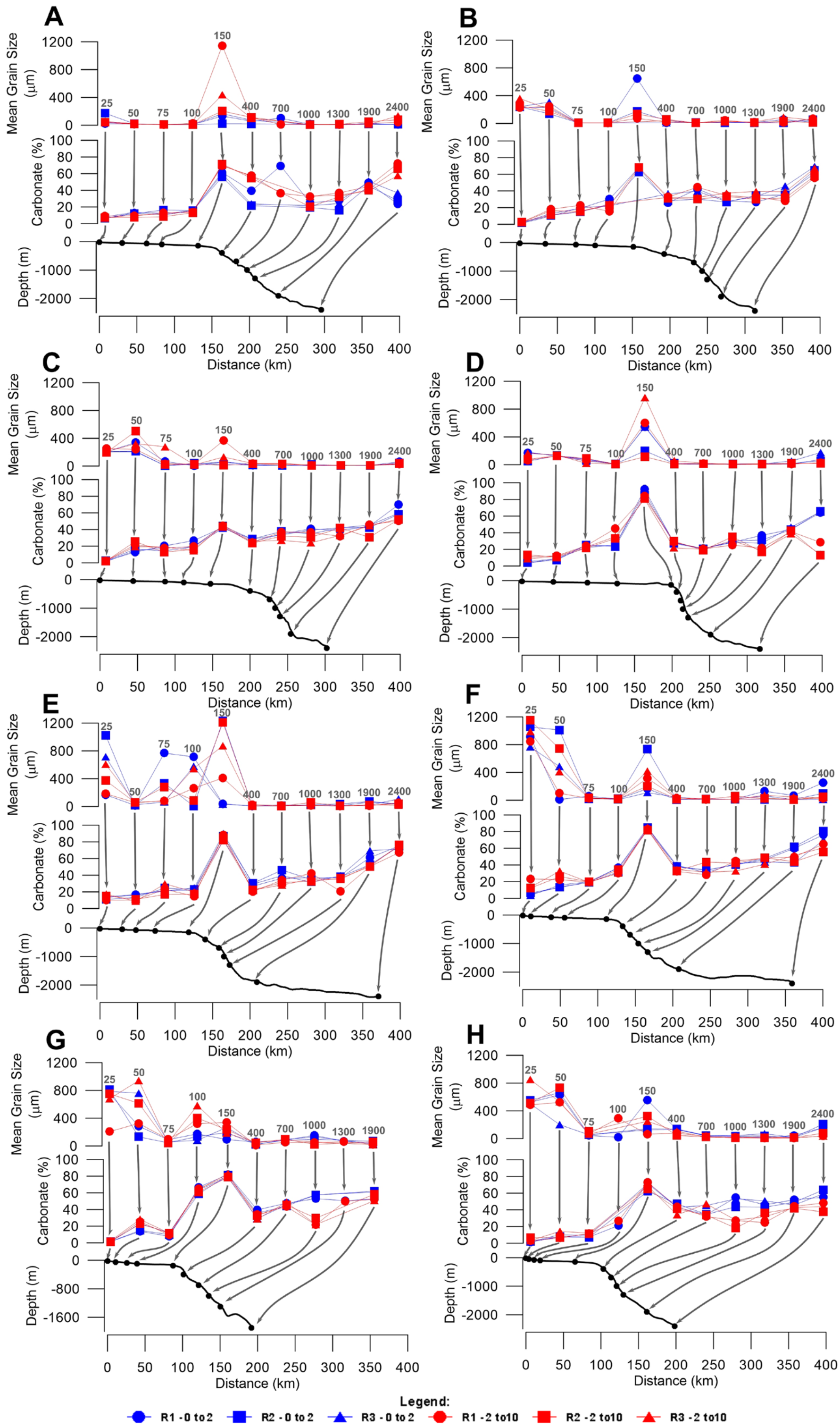

Figure 11. Mean grain size, carbonate content, bottom topography, and distance from shoreline represent the eight transects from South (A) to North (H). The blue symbols refer to the top sediment fraction from 0 to 2 cm. The red symbols refer to sediment fractions from 2 to 10 cm deep. R1, R2, and R3 are replicas. Numbers on top of the mean grain size line indicate the water depth of sample collection.

Sul Island. The position and orientation (SW-NE) of the submerged drift behind the islands agree with the main longshore transport that flows northward due to wave action (Trombetta et al., 2020). Remanent relict features of low sea level have also been detected as paleochannels or incised valleys (Figure 4 I, II, and 5V).

Sand waves located at the estuarine system mouths would be the morphodynamics response of tidal and coastal currents, waves, and their influence on longshore transport (Gao and Collins, 2014). Incised valleys are frequently found features at the Santos Basin seabed and are evidence of lower sea-level continental drainage systems (Furtado and Conti, 2006; Artusi and Figueiredo Jr., 2007; Conti and Furtado, 2009; Friederichs et al., 2013; Reis et al., 2013; Riva, 2015).

The rough relief of the ocean bottom in the outer shelf between 70 and 200 m that extends from Cabo Frio to Florianópolis (Figures 3I and II) is characteristic of the carbonatic facies with overgrowing calcareous algae forming terraces and pinnacles (Figures 5II and IV). Grain size in carbonatic facies is coarser than the surrounding facies and thus should have a specific biota.

Indeed, the Northern sector middle and outer shelf present several carbonate bioconstructions fields (Cavalcanti et al., 2012; Reis et al., 2013). These massive structures are similar to the rhodolith and coralline algae reef patches observed at Campos (Lopes et al., 2014; Tâmega et al., 2014; Figueiredo Jr. et al., 2016; Curbelo-Fernandez et al., 2017) and Espírito Santo (Bastos et al., 2015; Vieira et al., 2019; Oliveira et al., 2020) basins, including aggregates, terraces, pinnacles, rhodoliths mounds, crustose calcareous algae, bryozoans, gastropods, bivalves, and others, creating a rough relief in the ocean bottom (Figures 3I and 5II).

Carbonate facies also occur on the slope and are more concentrated in the São Paulo Plateau, being quite different from those observed on the shelf. They are predominantly formed by the pelagic deposition of foraminifera and pteropods, forming extensive vasa in the ocean bottom. So, while on the outer shelf the carbonate is constructed as an irregular relief, in the deep ocean, it creates a drape over the ocean bottom, as seen in Figure 11. The upper 0-2 cm layer is richer in carbonate content than the underlying 2-10 cm layer.

Siliciclastic sand facies predominate in the inner and middle shelf as a function of a more energetic environment and supply from land as river discharge and coastal erosion (Figure 7). The sand facies is carbonatic on the slope and São Paulo Plateau, since calcium carbonate grains are considered in the grain size analysis.

The muddy facies cover two main areas of the continental shelf. According to Carreira et al. (2023), muddy sediments in the mid-shelf, mainly along the 100 m isobath, are enriched in organic matter with great potential to be used by benthic organisms. The most extensive mud deposit is located in the Southern sector (Figure 7) in the outer shelf and shelf break. According to Mahiques et al. (2010), the source for this facies is the La Plata River sediment plume. Indeed, Dottori et al. (2022) indicate that the large volume of fresh water in the Coastal Water (CW) has the La Plata River as a strong candidate for its origin. As this muddy facies prograde northward with the Brazilian Coastal Current (BCC), it is captured by the heads of the Cananéia Canyon and conducted to the upper slope (Figure 7).

The smaller muddy facies in the Northern sector is bordered by sand facies shoreward and carbonate facies in the outer shelf and shelf break. The origin of this muddy facies is attributed to sediments derived from Guanabara Bay and Sepetiba Bay (Lazzari et al., 2019). In the deeper areas, the muddy facies extend over the slope and São Paulo Plateau, with some occurrences of sandy facies on the Northern slope.

CONCLUSION

The morphology, sediment supply, shelf orientation, and ocean climate imprint the Santos Basin's characteristics. The Northern shelf sector is the most dynamic because of the narrow shelf, steep gradient, and shoreline orientation almost East-West, providing conditions for storm waves to approach and mobilize sediment in the ocean bottom shallow than 50 m water depth. Therefore, there is a predominance of sandy facies on the inner and middle shelf, with a narrow strip of muddy facies on the middle shelf. In the outer shelf and shelf-break predominates the carbonate facies of bioconstructions.

The Southern sector of the shelf is much broader than the Northern sector; it has a small gradient, and its orientation is Northeast-Southwest, therefore, less energetic than the Northern sector. The sandy facies occupy the inner and middle shelf, while the muddy facies occupy the outer shelf and shelf break.

On the slope and São Paulo Plateau predominates the muddy facies, except for a portion of the slope in the Northern sector and a portion of the plateau.

In conclusion, many factors act in the shelf and deep ocean to determine the bottom morphology, grain size, grain sorting, its nature if carbonate or lithoclastic and consequently conditioning oxygen irrigation of sediment, nutrient preservation, and living conditions for biota.

ACKNOWLEDGMENTS

The authors are grateful to PETROBRAS, RD&I investments clauses of the Brazilian National Agency of Petroleum, Natural Gas and Biofuels (ANP) for fieldwork support during the Santos Basin Regional Environmental Characterization Project (PCR-BS) and laboratory analysis. To Foundation in Support of the University of São Paulo (FUSP) for financial resources covering equipment purchase and maintenance, scholarship, travel, and others. We also thank the Brazilian Navy for providing the historical bathymetric and sediment dataset. A special thanks to the trainee undergraduate students Gabriela de Jesus Rocha, Leonardo Junius Chapeta Santos, Fernanda Scofano Pinheiro, Thais Guterres Soares, Jonathan de Souza Silva de Araujo, Stephanie Tavares Venâncio dos Santos and the master-degree students Natalia de Jesus Lopes Chaves and Amanda Bourguignon Cecilio for performing the grain-size analysis. We are grateful to Daniel Leite Moreira and Silvia Helena de Mello e Souza for reviewing an earlier version of this paper and to the OCR reviewers who contributed to the significant improvement of this article.

AUTHOR CONTRIBUTIONS

A.G.F.JR.: Project Administration; Investigation; Writing – original draft; Writing – review & editing.

J.C.C: Methodology; Investigation; Writing – original draft; Writing – review & editing.

J.R.S.F.: Investigation; Figures; Writing – review & editing.

REFERENCES

ALLER, R. C. 1988. Benthic fauna and biogeochemical processes in marine sediments: the role of burrow structures. *In:* BLACKBURN, T. H. & SORENSEN, J. (eds.). *Nitrogen cycling in coastal marine environments*. New York: Wiley, pp. 301-338.

ALLER, R. C. 2014. Sedimentary diagenesis, depositional environments, and benthic fluxes. *Treatise on geochemistry.* 2nd ed. Amsterdam: Elsevier Ltd., v. 8, pp. 293-334.

ARTUSI, L. & FIGUEIREDO JUNIOR, A. G. 2007. Sismoestratigrafia rasa da plataforma continental de Cabo Frio – Araruama – RJ. *Revista Brasileira de Geofísica,* 25(Suppl 1), 7-16, DOI: https://doi.org/10.1590/S0102--261X2007000500002

BASTOS, A. C., QUARESMA, V. S., MARANGONI, M. B., D'AGOSTINI, D. P., BOURGUIGNON, S. N. & CETTO, P. H., et al. 2015. Shelf morphology as an indicator of sedimentary regimes: a synthesis from a mixed siliciclastic-carbonate shelf on the eastern Brazilian margin. *Journal of South American Earth Sciences*, 63, 125-136, DOI: https://doi.org/10.1016/j.jsames.2015.07.003

BERGER, W. H. & HEATH, G. R. 1968. Vertical mixing in pelagic sediments. *Journal of Marine Research*, 26, 134-143.

BILÓ, T. C., SILVEIRA, I. C. A., BELO, W. C., CASTRO, B. M. & PIOLA, A. R. 2014. Methods for estimating the velocities of the Brazil current in the pre-salt reservoir area off southeast Brazil (23∘S-26∘S). *Ocean Dynamics,* 64, 1431-1446. DOI: https://doi.org/10.1007/s10236-014-0761-2

CARREIRA, R. S., LAZZARI, L., CECCOPIERI, M., ROXO, L., MARTINS, D., FONSECA, G., VIEIRA, D. C. & MASSONE, C. G. Sedimentary provinces of organic matter accumulation in the Santos Basin, SW Atlantic: insights from multiple bulk proxies and machine learning analysis. *Ocean and Coastal Research*, this issue.

CAVALCANTI, G. H., CAROLINA, R., ARANTES, M. & LOIOLA, L. L. 2012. Caracterização ambiental das formações carbonáticas na rota do gasoduto Cernambi- -Cabiúnas (Anexo II.5.2-1). Rio de Janeiro: IBAMA. Available at: http://licenciamento.ibama.gov.br/Petroleo/Producao/Producao%20-%20Bacia%20de%20Santos%20-%20Gasoduto%20Rota%202%20(Rota%20Cabiunas)%20-%20Petrorbas/ - EIA.zip - EIA.rev01 - Anexos - Anexo II.5.2-1 - CARAC. AMB. DAS FORMAÇÕES CARBONÁTICAS NA ROTA DO GASODUTO Acessed in: 21/02/2022

CECILIO, R. O. & DILLENBURG, S. R. 2020. An ocean wind-wave climatology for the Southern Brazilian Shelf. Part I: Problem presentation and model validation. *Dynamics of Atmospheres and Oceans*, 89, 101101, DOI: https://doi.org/10.1016/j.dynatmoce.2019.101101

CONTI, L. A. & FURTADO, V. V. 2009. Topographic registers of paleo-valleys on the southeastern Brazilian continental shelf. *Brazilian Journal of Oceanography,* 57(2), 113-121, DOI: https://doi.org/10.1590/s1679-87592009000200004

CURBELO-FERNANDEZ, M. P., GIUSTINA, I. D., LOIOLA, L. DE L., ARANTES, R. C. M., MOURA, R. B., BARBOZA, C. A. M., NUNES, F. S., TÂMEGA, F. T. S., HENRIQUES, M. C. M. O., FIGUEIREDO, M. A. O., FALCÃO, A. P. C. & ROSSO, S. 2017. *Biota de fundos carbonáticos da plataforma continental da Bacia de Campos: algas calcárias e fauna associada. In:* CURBELO-FERNANDEZ, M. P. & BRAGA, A. (eds.). *Comunidades demersais e bioconstrutores.* Amsterdam: Elsevier Ltd, pp. 15-42, DOI: https://doi.org/10.1016/b978-85-352-7295-6.50002-6

DOTTORI, M., SASAKI, D. K., SILVA, D. A., GIOVANNINO, S. R., PINTO, A. P. & GNAMAH, M., et al. 2022. Hydrographic structure of the continental shelf in Santos Basin and its causes: the SANAGU and SANSED campaigns (2019). *Ocean Coastal Research,* 12. Available at: https://www.scielo.br/j/ocr/a/wWqcHpyLTpnNVT4GXR8BsLB/?format=pdf&lang=en

ETTER, R. J. & GRASSIE, J. F. 1992. Patterns of species diversity in the deep sea as a function of sediment particle size diversity. *Nature, Letters to Nature*, 360, 576-578.

FIGUEIREDO JUNIOR, A. G., PACHECO, C. E. P., VASCONCELOS, S. C. & SILVA, F. T. 2016. Continental shelf geomorphology and sedimentology. *Geology and Geomorphology*, 13-31, DOI: https://doi.org/10.1016/b978-85-352-8444-7.50009-3

FIGUEIREDO JUNIOR, A. G. & TESSLER, M. 2004. *Topografia e composição do substrato marinho da região Sudeste-Sul do Brasil - Série documentos Revizee: Score Sul.* São Paulo: Instituto Oceanográfico.

FRIEDERICHS, Y. L., REIS, A. T., SILVA, C. G., TOULEMONDE, B., MAIA, C. R. M. & GUERRA, J. V. 2013. Arquitetura sísmica do sistema fluvio-estuarino da Baía de Sepetiba preservado na estratigrafia rasa da plataforma adjacente, Rio de Janeiro, Brasil. *Brazilian Journal of Geology,* 43(1), 124-138, DOI: https://doi.org/10.5327/Z2317-48892013000100011

FURTADO, L. A. & CONTI, V. V. 2006. Geomorfologia da Plataforma Continental do Estado de São Paulo. *Revista Brasileira de Geociências,* 36(2), 8.

GAO, S. & COLLINS, M. B. 2014. Holocene sedimentary systems on continental shelves. *Marine Geology,* 352, 268-294, DOI: https://doi.org/10.1016/j.margeo.2014.03.021

KOWSMANN, R. O. & COSTA, M. P. A. 1979. Sedimentação quaternária da margem continental brasileira e áreas oceânicas adjacentes. In: *Reconhecimento global da margem continental brasileira*. Rio de Janeiro: PETROBRAS/CENPES, pp. 1-55.

LAZZARI, L., WAGENER, A. L. R., CARREIRA, R. S., GODOY, J. M. O., CARRASCO, G., LOTT, C. T., MAUAD, C. R., EGLINTON, T. I., MCINTYRE, C., NASCIMENTO, G. S. & BOYLE E. A. 2019. Climate variability and sea level change during the Holocene: Insights from an inorganic multi-proxy approach in the SE Brazilian continental shelf. *Quaternary International,* 508, 125-141, DOI: https://doi.org/10.1016/j.quaint.2018.11.011

LEGEAIS, J. F., OLLITRAULT, M. & ARHAN, M. 2013. Lagrangian observations in the Intermediate Western Boundary Current of the South Atlantic. *Deep Sea Research Part II: Topical Studies in Oceanography,* 85, 109-126, DOI: https://doi.org/10.1016/j.dsr2.2012.07.028

LOPES, M. C., TADEU DOS REIS, A. & GUIZAN SILVA, C. 2014. Paleodrenagem e estratigrafia dos sistemas deposicionais Pleistoceno Superior Holoceno da plataforma norte fluminense, bacia de Campos. *In: VII Simpósio Brasileiro de Geofísica.* 2016 Oct 25-27, Ouro Preto, Minas Gerais, Brasil. Ouro Preto: SBG, pp. 1-6, DOI: https://doi.org/10.22564/7simbgf2016.107

MIO, E., CHANG, H. K. & CORRÊA, F. S. 2005. Integração de métodos geofísicos na modelagem crustal da Bacia de Santos. *Revista Brasileira de Geofísica*, 23(3), 275-284.

MAHIQUES, M. M., DE MELLO E SOUSA, S. H., FURTADO, V. V., TESSLER, M. G., TOLEDO, F. A. L., BURONE, L., ET al. 2010. The Southern Brazilian shelf: general characteristics, quaternary evolution and sediment distribution. *Brazilian Journal of Oceanography*, 58, 25-34, DOI: https://doi.org/10.1590/s1679-87592010000600004

MAHIQUES, M. M., LOBO, F. J., SCHATTNER, U., LÓPEZ-QUIRÓS, A., ROCHA, C. B. & DIAS, R. J. S., MONTOYA-MONTES, I. & VIEIRA, A. C. B. 2022. Geomorphological imprint of opposing ocean bottom currents, a case study from the southeastern Brazilian Atlantic margin. *Marine Geology,* 444, 106715, DOI: https://doi.org/10.1016/j.margeo.2021.106715

MARTINS, L. R. & COUTINHO, P. N. 1981. The Brazilian continental margin. *Earth-Science Reviews*, 17(1-2), 87-107, DOI: https://doi.org/10.1016/0012-8252(81)90007-6

MÉMERY, L., ARHAN, M., ALVAREZ-SALGADO, X. A., MESSIAS, M. J., MERCIER, H., CASTRO, C. G. & RIOS, A. F. 2000. The water masses along the western boundary of the south and equatorial Atlantic. *Progress in Oceanography*, 47(1), 69-98, DOI: https://doi.org/10.1016/S0079-6611(00)00032-X

OLIVEIRA, N., BASTOS, A. C., QUARESMA, V. S. & VIEIRA, F. V. 2020. The use of Benthic Terrain Modeler (BTM) in the characterization of continental shelf habitats. *Geo-Marine Letters,* 40, 1087-1097, DOI: https://doi.org/10.1007/s00367-020-00642-y

REIS, A. T., MAIA, R. M. C., SILVA, C. G., RABINEAU, M., GUERRA, J. V., GORINI, C., AYRES, A., ARANTES-OLIVEIRA, R., BENABDELLOUAHED, M., SIMÕES, I. & TARDIN, R. 2013. Origin of step-like and lobate seafloor features along the continental shelf off Rio de Janeiro State, Santos basin-Brazil. *Geomorphology,* 203, 25-45, DOI: https://doi.org/10.1016/j.geomorph.2013.04.037

RIVA, V. C. D. 2015. Paleodrainage mapping of the São Paulo southern continental shelf on the Santos basin. *In: 14th International Congress of the Brazilian Geophysical Society held.* 2015 Aug 3-6, Rio de Janeiro, Rio de Janeiro, Brasil. Rio de Janeiro: Sociedade Brasileira de Geofísica, pp. 420-423, DOI: https://doi.org/10.1190/sbgf2015-083

SILVEIRA, I. C. A., LAZANEO, C. Z., AMORIM, J. P. M., SILVA, M. B., BERNARDO, P. S. & MARTINS, R. C.,GUERRA, L. A. A. & MOREIRA, D. L. 2023. Oceanographic conditions of the continental slope and deep waters in Santos Basin: the SANSED cruise (winter 2019). *Ocean and Coastal Research*, 71(Suppl 3), e23008.

SILVEIRA, I. C. A., SCHMIDT, A. C. K., CAMPOS, E. J. D., GODOI, S. S. & IKEDA, Y. 2000. A corrente do Brasil ao largo da costa leste brasileira. *Brazilian Journal of Oceanography*, 48(2), 171-183, DOI: https://doi.org/10.1590/S1679-87592000000200008

SNELGROVE, P. V. R. & BUTMAN, C. A. 1994. Animal-sediment relationships revised: cause versus effect. *Oceanography and Marine Biology: an Annual Review*, 32, 111-177.

SOUZA, R. B. & ROBINSON, I. S. 2004. Lagrangian and satellite observations of the Brazilian Coastal Current. *Continental Shelf Research*, 24(2), 241-262, DOI: https://doi.org/10.1016/j.csr.2003.10.001

STRAMMA, L. 1989. The Brazil current transport south of 23°S. *Deep Sea Research Part A: Oceanographic Research Papers*, 36(4), 639-646, DOI: https://doi.org/10.1016/0198-0149(89)90012-5

STRAMMA, L. & ENGLAND, M. 1999. On the water masses and mean circulation of the South Atlantic *Ocean. Journal of Geophysical Research Oceans*, 104(C9), 20863-20883, DOI: https://doi.org/10.1029/1999JC900139

TÂMEGA, F. T. S., BASSI, D., FIGUEIREDO, M. A. O. & CHERKINSKI, A. 2014. Deep-water rhodolith bed from central Brazilian continental shelf, Campos Basin: coralline algal and faunal taxonomic composition. Galaxea*, Journal of Coral Reef Studies*, 16(1), 21-31, DOI: https://doi.org/10.3755/galaxea.16.21

TROMBETTA, T. B., MARQUES, W. C., GUIMARÃES, R. C. & COSTI, J. 2020. An overview of longshore sediment transport on the Brazilian coast. *Regional Studies in Marine Science,* 35, 101099, DOI: https://doi.org/10.1016/j.rsma.2020.101099

VIEIRA, F. V., BASTOS, A. C., QUARESMA, V. S., LEITE, M. D., COSTA, A., OLIVEIRA, K. S. S., DALVI, C. F., BAHIA, R. G., HOLZ, V. L., MOURA, R. L. & AMADO FILHO, G. M. 2019. Along-shelf changes in mixed carbonate-siliciclastic sedimentation patterns. *Continental Shelf Research,* 187, 103964, DOI: https://doi.org/10.1016/j.csr.2019.103964

ZEMBRUSCKI, S. G. 1979. *Geomorfologia da Margem Continental Sul Brasileira e das Bacias Oceânicas Adjacentes.* Rio de Janeiro: Projeto REMAC.