








Sedimentary Patterns and Spatial Distributions of Heavy Minerals along the Continental Shelf in the Espírito Santo State, Brazil

Padrões Sedimentares e Distribuição Espacial dos Minerais Pesados ao longo da Plataforma Continental no Estado do Espírito Santo, Brasil

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Abstract

Heavy minerals can be used as tools to better understand sedimentary patterns across continental shelves, in addition to their economic importance, where they form marine placers. This study investigates the spatial distributions of heavy minerals in sand deposits along the three different morpho-sedimentary compartments (i.e., Paleovalley Shelf, Doce river Shelf, and Abrolhos Shelf) of the Espírito Santo Continental Shelf, which presents distinct sedimentary regimes. A mineralogical characterization of 180 surface sediment samples allowed to identify fifteen different heavy mineral species across the study area, with a predominance of ilmenite. The qualitative characterization shows similar heavy mineral patterns among the three compartments, while their mineral proportion (quantitative analysis) is heterogeneous. Also, the supply and accommodation regimes do not responsible by influence the heavy mineral assemblages and sediment maturity. However, there is a significant relationship between supply regime (delta sedimentation) and higher average abundances of each heavy mineral species. With results found here is possible to affirm that marine placers are closely related to Holocene sedimentation.

Keywords: Mixed continental shelf; Marine placers; Supply regime

Resumo

Minerais pesados podem ser usados como ferramentas para entender melhor os padrões sedimentares nas plataformas continentais, além de sua importância econômica em locais onde formam placeres marinhos. Este estudo investiga a distribuição espacial dos minerais pesados, em depósitos arenosos, ao longo dos três diferentes compartimentos morfo-sedimentares (Plataforma de paleo-canal, Plataforma do Rio Doce; Plataforma de Abrolhos) da plataforma continental do Espírito Santo, os quais apresentam regimes sedimentares distintos. Para isso, através da caracterização mineralógica de 180 amostras de sedimento superficial, quinze espécies diferentes de minerais pesados foram identificadas em toda a área de estudo, com predominância da ilmenita. A distribuição espacial é heterogênea (quantitativo) em cada compartimento. No entanto, a distribuição de minerais pesados em cada um dos setores é semelhante (qualitativo). Os regimes de acomodação e suprimento não influenciam as assembleias de minerais pesados e nem sua maturidade composicional. No entanto, existe uma relação significativa entre o regime suprimento (sedimentação deltaica) e a concentração de cada uma das espécies de minerais pesados. Com os resultados encontrados aqui é possível afirmar que os placeres marinhos estão diretamente relacionados com sedimentação Holocênica.

Palavras-chave: Plataforma continental mista; Placeres marinhos; Regime de suprimento

1 Introduction

Heavy minerals have a density greater than 2.8 g/cm³ and are accessory minerals in sedimentary, igneous, and metamorphic rocks (Bates & Jackson 1980). These rocks are subjected to weathering processes, and the resulting sediment can be transported inside the shelf (Morton 1985). Heavy minerals are economically important when they are concentrated in sedimentary deposits (marine placers) (Komar 2007). Furthermore, the analysis of these minerals can be used as a tool to study provenance, sedimentary dispersion, and paleoenvironmental identification (Addad 2001; Qin et al. 2018; Tomazelli 1978; Vital & Guedes 2000).

Sediment distribution along continental shelf results from different processes acting in distinct temporal scales. In general, shelf sedimentation patterns are substantially influenced by sea-level changes, variations in sediment supply, wave-current processes, and carbonate production (Gao & Collins 2014). Moreover, terrigenous and carbonate sediments are distributed according to accommodation space, meta-oceanographic conditions, and sedimentary regime type. According to Swift, Phillips and Thorne (1991), siliciclastic continental shelves can be described in terms of the supply and accommodation regime. The shelf regime is defined based on high or low sediment input that can be related to regressive or transgressive coasts. Siliciclastic deposits predominate during the regression and lowstand stages, while carbonate deposits predominate during the transgression and highstand stages (Catuneanu 2002; Swift, Phillips & Thorne 1991; Wilson 1967). An exception to this pattern is a shelf with high sediment inputs during the transgressive or highstand stage, which is associated with a regressive coast (Catuneanu 2002).

The Espírito Santo Continental Shelf (ESCS) exhibits a complex lateral interaction between terrigenous, carbonate, and mixed sediments, and it is defined as a mixed sedimentation shelf by Bastos et al. (2015) and Vieira et al. (2019). Additionally, the Espírito Santo coast is known for the occurrence of heavy minerals in beach sediments, which are mostly associated with the erosion of the Barreiras Formation (Guarapari beaches) and the Rio Doce input (e.g., Regênciã beach) (Nascimento et al. 2011; Torezan & Vanuzzi 1997). Thus, this study investigates the spatial distributions of heavy minerals in sand deposits along the ESCS and evaluates this distribution while considering that the shelf presents distinct sedimentary regimes that are characterized by three different morpho-sedimentary compartments.

2 Geological Setting of the Study Area

The ESCS is located in the eastern Brazilian margin between the latitudes of 18° 20'S and 21° 18'S (Figure 1A). In geomorphological and geological terms, the continental margin terrace wedge can be subdivided into three different areas: the Precambrian hills, Neogene soft cliffs (Barreiras Formation), and Quaternary fluvio-marine plains (Martin et al. 1996). Three main sedimentary facies (terrigenous, mixed, and carbonate), were defined based on their carbonate composition (Larsonneur 1977 classification) by Vieira et al. (2019; Figure 1B). Mixed continental shelves typically exhibit terrigenous sediments along the coastline and carbonate domains mid-to outer-shelf (Dunbar & Dickens 2003). However, in the study area, the transition between terrigenous, carbonate, and mixed sediment facies is not always related to depth changes resulting from diverse environmental controls, i.e., sediment input, sea-level change, shelf morphology, shelf width, etc.

The ESCS can be subdivided into three sectors according to the sedimentary and morphological characteristics: the Paleovalley Shelf, Doce River Shelf, and Abrolhos Shelf (Bastos et al. 2015). The Paleovalley Shelf is located south of the Doce River Shelf, where the accommodation regime is dominant. The shelf and coastal morphologies are irregular along this sector, demonstrating the presence of paleovalleys and hardgrounds in the shelf, and unfilled estuaries and soft cliffs formed by the Neogene Barreiras formation along the coast. This accommodation regime along the ESCS does not represent an erosive shelf but the dominance of carbonate sedimentation, especially at water depths greater than 20 m (Bastos et al. 2015). The Doce River Shelf, in the north-center of the ESCS, has a supply regime with a high terrigenous sediment input. The bottom morphology is regular and is associated with a delta front and prodelta, following the Doce River deltaic plain along the coast (Bastos et al. 2015; Quaresma et al. 2015). The southern Abrolhos Shelf is located in the far north of the ESCS. This sector represents an enlargement of the eastern Brazilian shelf; it presents a supply regime along the inner shelf and an offshore carbonate regime (Bastos et al. 2015).

Although this complex mixed sediment system characterizes shelf sedimentation with extensive carbonate facies, two terrigenous sources to the shelf are also relevant in terms of heavy minerals supply: the Doce River, whose watershed cuts an important iron ore province (Iron Quadrangle-MG), the Precambrian hills, and the coastal

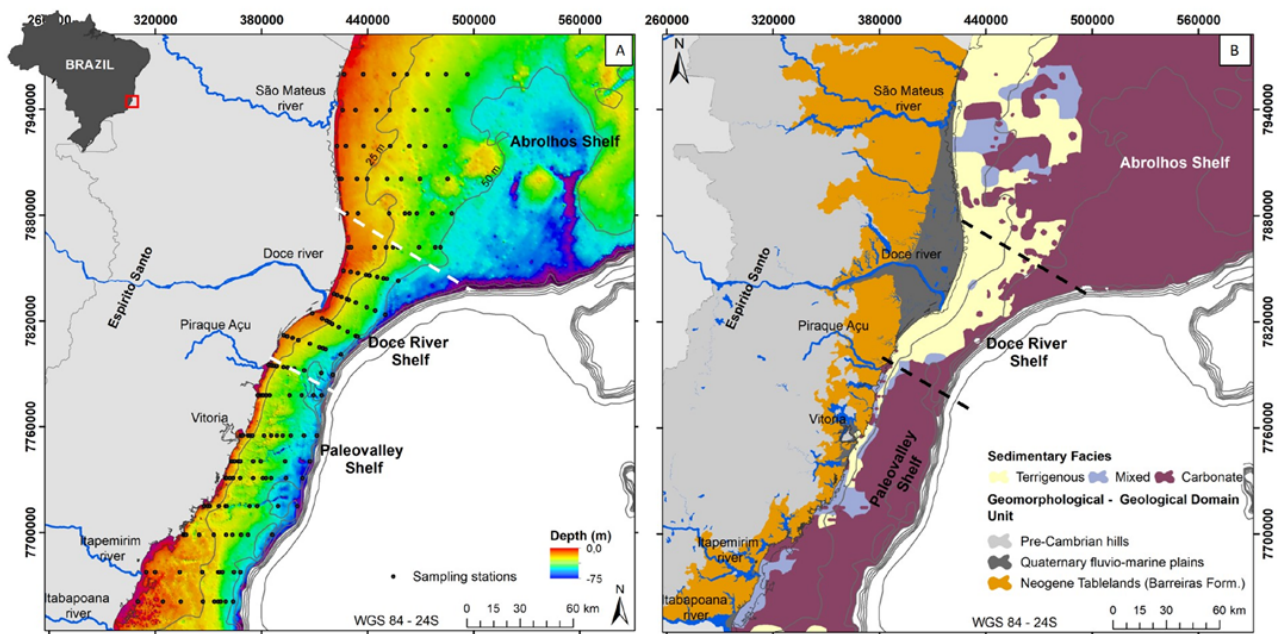


Figure 1 A. Bathymetric map with the three different morphological sectors of the ESCS based on Bastos et al. (2015) the black dots represent the locations of the planned sampling stations; B. Shelf sedimentary facies (based on Vieira et al. 2019) and coastal geological units. Coordinates are in universal transverse Mercator (UTM) (datum WGS84, 24S).

soft-cliffs formed by the Neogene Barreiras Formation, which is characterized by a deposit that underwent several cycles of transport and presents significant heavy mineral concentrations (Sousa et al. 2000). Most terrigenous sediments derived from the Doce River are deposited on the Doce River Shelf. However, carbonate sediments (authigenic) are predominant in the Paleovalley Shelf, and mixed sediments are more expressive on the inner Abrolhos Shelf (Bastos et al. 2015; Vieira et al. 2019).

3 Materials and Methods

A total of 180 surface samples were collected using a Van Veen grab sampler, ideal for sampling the surface layer of the bottom. The sampling stations were organized into 20 transects that were perpendicular to the coast. Nine samples were collected in each transect, based on pre-defined water depths, from 10 m to 50 m. The sampling design was established for a regular seabed sediment mapping project that aimed to define and study benthic habitats. Approximately 30% of the surface samples collected did not contain heavy minerals in their sand fractions (primarily in the Paleovalley Shelf).

The sediment samples were first washed to remove salts. After drying, they were wet sieved to separate the

sand and mud contents. Carbonate and organic matter were removed by applying HCL and H₂O₂, respectively, using the methods described by Dias (2004). The heavy mineral analysis was performed on the total sand fraction. The light and heavy minerals were separated with dense bromoform liquid using the gravimetric method (Dias 2004). At each sampling station, 300 random grains of heavy minerals were identified using a binocular microscope (GaleHouse 1971). However, some sediment samples did not contain 300 grains of heavy minerals (~30%); in this case, all available grains were analyzed. The heavy mineral contents were calculated for each sampling station. They were established according to the percentage of heavy minerals compared to the total weight of the sedimentary fraction analyzed (sand). The zircon–tourmaline–rutile (ZTR) index was calculated to measure the mineralogical maturity of the heavy mineral suites on the ESCS. This index is the sum of the zircon, tourmaline, and rutile contents in rocks and/or sedimentary deposits divided by the total identified translucent mineral contents and then multiplied by 100 (Hubert 1962). Mature sediments were defined as samples with ZTR values above 75%, while immature sediments presented ZTR values below 75% (Oni & Olatunji 2017; Sulieman et al. 2015).

4 Results

A total of 25,785 heavy mineral grains were separated and analyzed. These minerals were classified into 15 species: 11 translucent minerals and 4 opaque minerals (Figure 2). Limonite, hematite, and magnetite constitute the opaque group, where ilmenite is the predominant mineral across the ESCS. Moreover, the dominant translucent mineral in the study area is sillimanite. Zircon, tourmaline, epidote, monazite, garnet, staurolite, rutile, titanite, andalusite, and kyanite also constitute the translucent mineral group. The ZTR index was used to analyze the mineralogical maturity. The three distinct sectors displayed values below 75% (Table 1), being classified as compositionally immature sediments.

The spatial distributions of the heavy mineral types are heterogeneous in each ESCS sector. However, the assemblage of heavy minerals in each sector is similar take

into consideration the different heavy minerals each species average. In the accommodation sector as the Paleovalley Shelf, where there is space to accommodation of sediments, only the monazite (11.9 ± 18.7 , 58.9%), and garnet (7.7 ± 16 , 71.9%) demonstrate higher average abundances compared to those of the other two sectors (Table 2). Even in the supply sectors as inner Abrolhos and Doce River shelves, where sediments are deposited, there are differences in the distributions of these minerals. Among 15 heavy mineral types, nine species have a higher average abundance in the Abrolhos Shelf: andalusite (4.5 ± 5.4 , 75%), epidote (15 ± 9.9 , 44.5%), hematite (7.9 ± 5.9 , 40.3%), ilmenite (166.3 ± 42.6 , 41.4%), kyanite (2.3 ± 2.7 , 56.1%), sillimanite (32.1 ± 15.2 , 43.5%), staurolite (5.5 ± 3.7 , 50%), titanite (5 ± 4.5 , 58.8%), and tourmaline (18.3 ± 9.5 , 42.7%), while in Doce River shelf, limonite (44.8 ± 42 , 60.7%), magnetite (8.7 ± 13.5 , 65.9%), and rutile (3.9 ± 4.8 , 41.9%) stand out compared to the other sector distributions (Table 2).

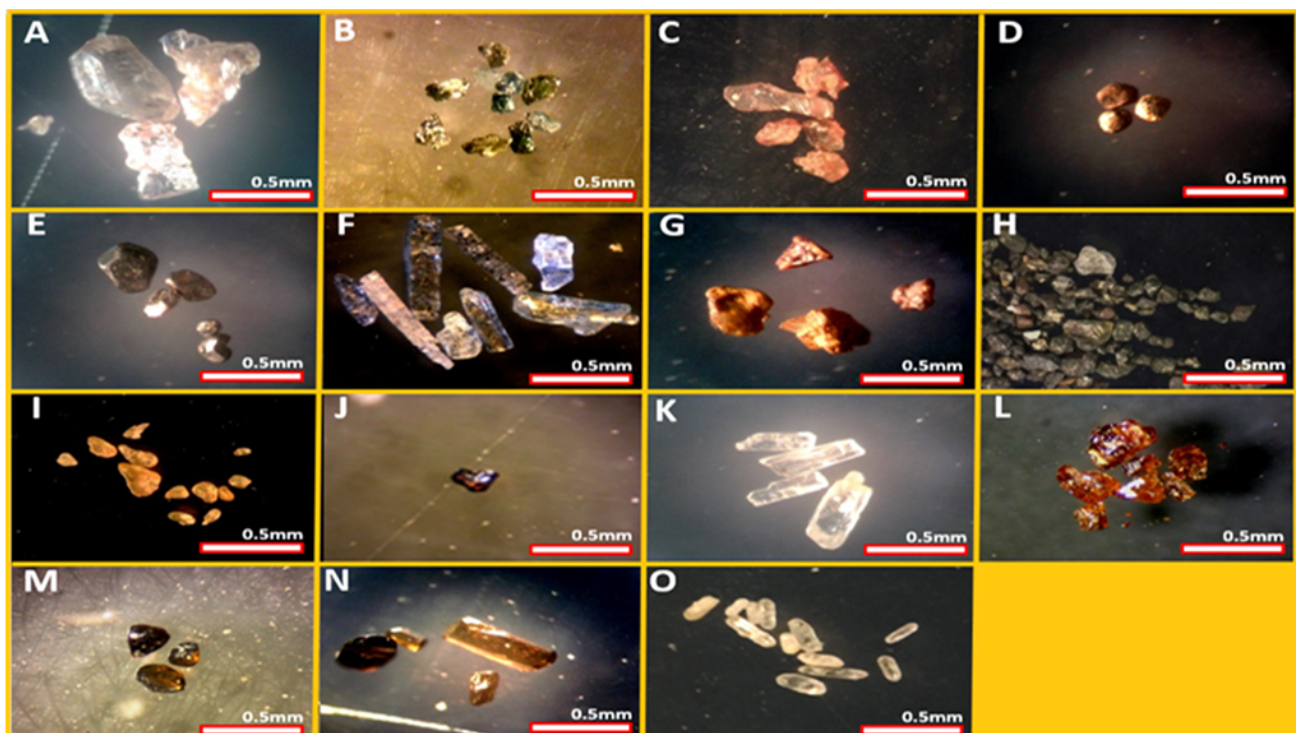


Figure 2 Binocular microscope photographs of heavy mineral grains identified in the ESCS (0.5 mm scale): A. Andalusite; B. Epidote; C. Garnet; D. Hematite; E. Ilmenite; F. Kyanite; G. Limonite; H. Magnetite; I. Monazite; J. Rutile; K. Sillimanite; L. Staurolite; M. Titanite; N. Tourmaline; O. Zircon.

Table 1 ZTR index average content in three sectors of the ESCS.

	Zircon average %(SD)	Tourmaline average %(SD)	Rutile average %(SD)	ZTR Index average %(SD)
Abrolhos Shelf	13.2(±6.5)	17.3(±2.6)	3.0(±11.5)	33.5(±7.7)
Doce River Shelf	17.8(±11.5)	17.6(±8.3)	5.8(±17.0)	41.2(±17.9)
Paleovalley Shelf	21.8(±16.8)	11.3(±16.2)	4.2(±6.2)	37.2(±9.2)

SD=Standard Deviation

Table 2 Heavy minerals content data in the study area.

	Abrolhos Shelf			Doce River Shelf			Paleovalley Shelf			All Samples- ESCS		
	Minimum	Maximum	Average (SD)	Minimum	Maximum	Average (SD)	Minimum	Maximum	Average (SD)	Minimum	Maximum	Average (SD)
Andalusite	0	23	4.5(±5.4)	0	7	0.5(±1.7)	0	24	1.0(±3.8)	0	24	1.7(±4)
Epidote	0	34	15(±9.9)	0	33	14.5(±8.9)	0	58	4.2(±9.9)	0	58	10.2(±10.8)
Garnet	0	8	1.1(±2.2)	0	23	1.9(±4.9)	0	63	7.7(±16)	0	63	4.2(±11.3)
Hematite	0	20	7.9(±5.9)	0	36	4.7(±7)	0	38	7(±9.3)	0	38	6.4(±7.9)
Ilmenite	33	220	166.3(±42.6)	10	213	119.9(±49.2)	7	233	114.8(±61.7)	7	233	128.5(±57.1)
Kyanite	0	10	2.3(±2.7)	0	8	1.7(±2.5)	0	2	0.1(±0.3)	0	10	1.1(±2.2)
Limonite	0	33	8.4(±10.9)	0	180	44.8(±42)	0	125	20.5(±32.8)	0	180	25.9(±35.7)
Magnetite	0	5	0.5(±1.4)	0	52	8.7(±13.5)	0	90	4(±15.4)	0	90	4.8(±13)
Monazite	0	15	5.7(±4.6)	0	22	2.6(±4.4)	0	79	11.9(±18.7)	0	79	7.3(±13.3)
Rutile	0	8	3(±2.6)	0	20	3.9(±4.8)	0	9	2.4(±2.9)	0	20	3(±3.6)
Sillimanite	0	63	32.1(±15.2)	4	67	24.1(±15.4)	0	83	17.5(±18.9)	0	83	23.1(±17.7)
Staurolite	0	13	5.5(±3.7)	0	22	5.4(±5.4)	0	5	0.1(±0.8)	0	22	3.2(±4.5)
Titanite	0	16	5(±4.5)	0	18	1.7(±3.9)	0	14	1.8(±3.0)	0	18	2.5(±3.9)
Tourmaline	0	44	18.3(±9.5)	0	83	17.4(±17.9)	0	69	7.1(±11.7)	0	83	13.2(±14.6)
Zircon	1	36	13.9(±9)	0	72	17.1(±18.9)	0	65	14.4(±15.9)	0	72	15.2(±15.7)

SD=Standard Deviation

The map and boxplots presented in Figure 3 show the heavy mineral amounts across the ESCS. According to Palma (1979), sedimentary deposits with 1% or more heavy mineral contents are classified as marine placers. The values varying between 0–3.6% were subdivided into three intervals. The highest heavy mineral contents dominated the mid-outer Doce River Shelf (30–50 m in water depth). The lowest heavy mineral contents were observed in the mid-outer Paleovalley Shelf. However, the inner Abrolhos Shelf (water depth < 30 m) expressed heavy mineral contents compared to the same water depth range of the other sectors.

5 Discussions

The source area is first subjected to weathering, and then the resulting sediments are transported, selected in accordance with the prevailing hydraulic conditions, and

deposited across the shelf (Morton 1985). Although there are different sedimentary regimes in the ESCS, there is no qualitative differentiation in the heavy mineral assemblages in the study area. The 15 heavy mineral species identified in the ESCS highlighted the predominance of ilmenite. However, each heavy mineral species is heterogeneously distributed in the ESCS sectors. The Doce River Shelf and Abrolhos Shelf (supply regime) exhibit higher average abundances compared to that of the Paleovalley Shelf (accommodation regime). The data illustrate that there is a quantitative heavy mineral assemblage differentiation between the sedimentary regimes. This difference, is likely due to the Doce River influence on riverine sediment discharge (modern and ancient), where more than 70% of the total ESCS riverine reaches a maximum of 133×10^6 tons in the wet season (Oliveira & Quaresma 2017). The ZTR index analyses demonstrated that the sedimentary deposits are immature (ZTR < 75%). This was the expected

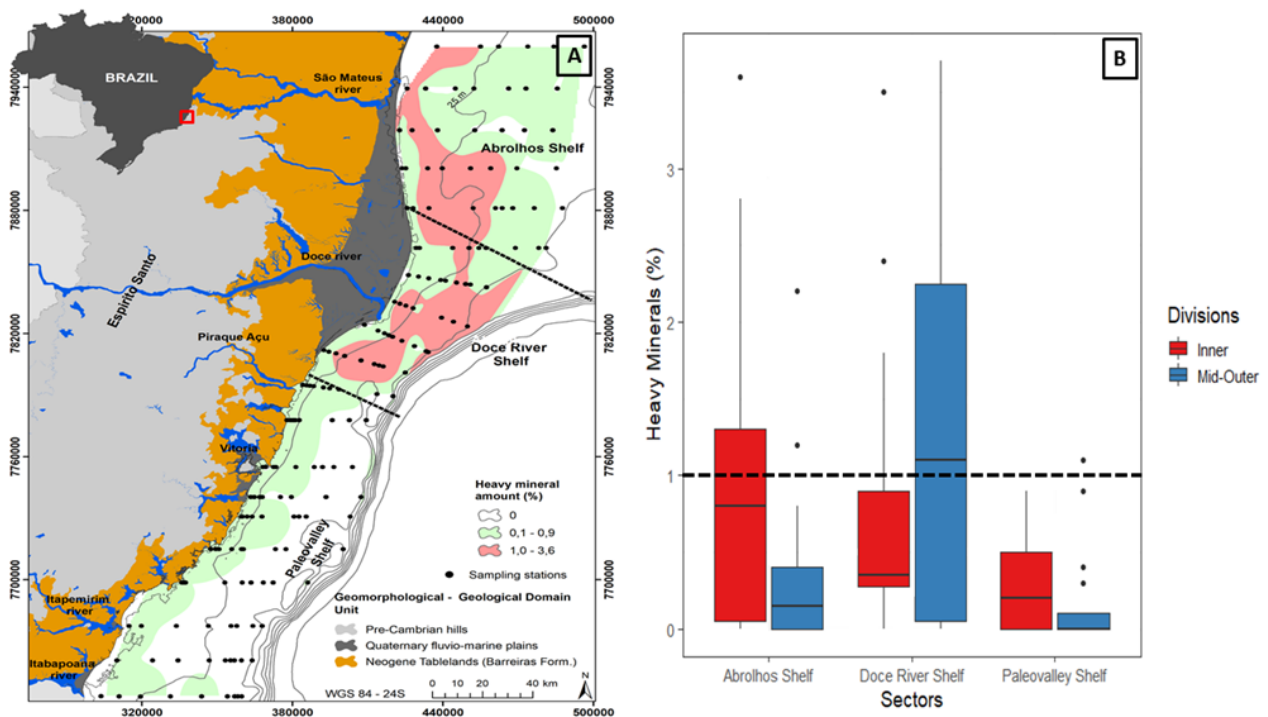


Figure 3 A. Morphotectonic map showing the distribution of heavy minerals along the ESCS; the black dots represent the samples used in this study. Coordinates are in UTM (datum WGS84, 24S); B. Boxplots showing the distributions of heavy minerals considering the morphological sector and water depth: the inner shelf represents a water depth of < 30 m, the mid-outer shelf represents a 30–50-m water depth, and the dashed black line ($\geq 1\%$) indicates a marine placer.

result due to the great variety of heavy minerals species that contain both stable and unstable minerals. The low ZTR index values suggest a short transport distance from the source area to the depositional environment and/or the low energy of the sedimentation environment (Hubert 1962; Oni & Olatunji 2017; Pettijohn et al. 1973; Sulieman et al. 2015).

It is necessary to include the physical environmental controls and sedimentary shelf characteristics to understand the relationship between the spatial distributions of the heavy minerals in sand deposits with distinct morpho-sedimentary in the study area. Dominguez (2009) described the Brazilian coast according to its sedimentary characteristics. The author subdivided it into the “starving coast” with low sediment inputs and/or erosive processes and sediment-fed delta with a high sedimentation rate. In the ESCS, the starved coast is represented by the Paleovalley Shelf (Bastos et al. 2015). Most of the heavy mineral deposits are observed along the inner shelf (water depth < 30 m), and they decrease towards the mid–outer shelf (30–50 m in water depth). This bathymetric control of the heavy mineral sand deposits directly reflects the accommo-

dation characteristics. The carbonate growth is inversely proportional to the input sedimentation rate; therefore, the Paleovalley Shelf is dominated by carbonate sedimentation in the mid-outer and offshore regions (Vieira et al. 2019). Shelf-widening characterizes the Abrolhos Shelf, and its distinct sedimentary patterns are also controlled by bathymetry. The mid-outer Abrolhos Shelf (accommodation) displays fewer heavy mineral deposits compared to that of the inner shelf (supply), and a transition is clearly defined by the sedimentary regime changes.

Marine placers in continental shelves worldwide have been associated with Holocene sedimentation and sea-level changes (Kudrass 2000). The lowest sea level increased the riverine inputs and erosive channel formations due to the high exposed shelf area. Afterwards, the continental shelves drowned due to sea-level rise. These deposits are directly related to the supply regime in the ESCS, which was observed in the mid-outer Doce River Shelf and inner Abrolhos Shelf. The seabed morphology across the Doce River Shelf is regular, including close to the shelf break, which suggests a deltaic lobe feature (Bastos et al. 2015). This can explain the presence of the marine

placer in the mid-outer Doce River Shelf and its association with the ancient Doce riverine (Holocene sedimentation). Furthermore, meteoceanographic conditions (i.e., winds, waves, storm events, etc.) influence the sedimentation distribution along the Doce River Shelf (Quaresma et al. 2015). Terrigenous deposits localized in the southern inner Abrolhos Shelf present a higher surface bulk density (~2.000 kg/m³) that indicates relict deposits (Quaresma et al. 2015). Furthermore, modern Doce River riverine terrigenous sands are strictly deposited near river mouths (Albino & Suguio 2010). This also corroborates that the sandy deposits in the northward Doce River mouth are relicts. Therefore, marine placers located in this area may be related to Holocene sedimentation.

6 Conclusions

In total, 15 distinct heavy minerals were identified in the ESCS, with a predominance of ilmenite. The different sedimentary regimes (supply and accommodation) did not qualitatively influence the heavy mineral assemblages or depositional maturity of the sediments (all immature deposits). However, there is a significant relationship between the supply regime and higher average abundances of heavy mineral species. Despite the modern terrigenous sediment input, the marine placers and their spatial distributions are exclusively related to the high sedimentation rate, which is related to the deltaic front and sea-level change (Holocene sedimentation).

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Author contributions

Adeildo de Assis Costa Junior: conceptualization; formal analysis; methodology; validation; writing-original draft; writing – review and editing; visualization. **Valéria da Silva Quaresma:** conceptualization; formal analysis, methodology; validation; writing original draft; funding acquisition; supervision; visualization; **Caio Vinicius Gabrig Turbay:** formal analysis, methodology; validation; **Natacha de Oliveira:** writing original draft- writing – review and editing. **Marcos Daniel de Almeida Leite:** collected data; methodology. **Fernanda Vedoato Vieira:** collected data; methodology. **Alex Cardoso Bastos:** conceptualization; formal analysis, methodology; validation; writing original draft; funding acquisition; supervision; visualization.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that may have influenced the work reported in this paper.

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