Morphology of the eastern continental slope of Ceará, Brazilian equatorial margin

Morfologia do talude continental leste do Ceará, margem equatorial brasileira

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Abstract

Mapping the seafloor is a global objective of the United Nations Decade of Ocean Science. In the case of the Brazilian Equatorial Margin (BEM), a region considered an emerging petroleum province, understanding the seafloor is even more urgent and essential to minimize geological risks in offshore infrastructure projects and to monitor environmentally sensitive areas. This research aims to investigate the morphology of the continental slope off the eastern coast of the state of Ceará, in the sector adjacent to the Jaguaribe River, within the BEM. To achieve this, multibeam bathymetric data acquired through the SeabedMap Project and a seismic volume provided by the ANP were analyzed to characterize the main submarine features and assess geological and oceanographic processes influencing seabed stability. A total of 13 submarine canyons with “V” and “U”-shaped profiles were identified. Nine canyons were classified as being in a transitional evolutionary stage, and four in a mature stage. Their lengths range from 11.2 to 45.1 km, widths from 1 to 4.1 km, and depths between 0.2 and 0.5 km. Four of the canyons are sinuous, and two exhibit a slope of 8°, which is above the regional average. Additional features mapped include gullies ranging from 0.45 to 5.1 km in length, mass movement deposits with semicircular and triangular geometries, five circular depressions, dunes, and several sediment ridges. The mapping of these features provided key insights into the geological and oceanographic processes shaping the deep marine depositional environment in the region. The results offer valuable information to support marine spatial planning, mitigate risks associated with the installation of submarine cables and pipelines in unstable areas, and contribute to future research on geohabitats and to the environmental management of this portion of the continental slope of the equatorial Atlantic.

Keywords: Submarine canyons; Multibeam bathymetry; Marine geomorphology.

Resumo

Mapear o fundo marinho é um objetivo global da Década do Oceano. No caso da margem equatorial brasileira (MEB), região considerada uma província petrolífera emergente, conhecer o fundo marinho é ainda mais urgente e essencial para minimizar riscos geológicos em projetos de infraestrutura offshore e monitorar áreas ambientalmente sensíveis. Esta pesquisa objetiva compreender a morfologia do talude continental leste do estado do Ceará, setor adjacente ao Rio Jaguaribe, na MEB. Para tal propósito, foram utilizados dados de batimetria multifeixe adquiridos pelo Projeto *SeabedMap* e um volume sísmico concedido pela ANP. Os dados foram analisados a fim de caracterizar as principais feições submarinas e avaliar processos geológicos e oceanográficos que influenciam a estabilidade do fundo. Foram identificados 13 cânions submarinos de perfis em “V” e “U”. Nove cânions foram classificados em estágio evolutivo de transição e quatro cânions, em estágio maduro. Seus comprimentos variam de 11,2 a 45,1 km, larguras de 1 a 4,1 km e profundidades entre 0,2 e 0,5 km. Quatro deles apresentam sinuosidade acima de 1,1 e dois exibem inclinação de 8°, sendo este valor superior à média regional. Também foram mapeadas ravinas com 0,45 a 5,1 km de extensão, movimentos de massa (com formatos semicirculares e triangulares), cinco depressões circulares, dunas e diversas cadeias sedimentares. O mapeamento destas feições proporcionou conhecimento sobre os processos geológicos e oceanográficos que moldam o ambiente deposicional marinho profundo da região. Os resultados fornecem subsídios que podem auxiliar no planejamento espacial marinho, na prevenção de riscos associados à instalação de cabos e dutos submarinos em áreas instáveis, além de contribuírem para futuras pesquisas em geohabitats e para a gestão ambiental dessa região do talude continental do Atlântico equatorial.

Palavras-chave: Cânions submarinos; Batimetria multifeixe; Geomorfologia marinha.

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1. Introduction

Mapping the seabed is one of the main goals of the Decade of Ocean Science for Sustainable Development (2021–2030), promoted by the United Nations (Coley 2022, Wölfl et al. 2019). Among the strategic actions that make up this initiative is the Seabed 2030 project, an international effort aimed at mapping 100% of the ocean floor by 2030. The proposal seeks to fill significant gaps in the knowledge of global submarine morphology, promoting open access to data and fostering public policies and sustainable actions based on science (Mayer et al. 2018, 2020).

Knowing the morphology of the seabed is fundamental for various areas of knowledge and for strategic economic sectors (Dove et al. 2020). Submarine relief directly influences ocean circulation patterns, sedimentary processes, the connectivity of benthic habitats, and ecosystem dynamics (Domínguez-Carrió et al. 2022, De Almeida et al. 2023). The detailed description of these features is also essential for marine spatial planning, the identification of areas vulnerable to erosion or geological instability (Sun et al. 2025), and the assessment of risks associated with the installation of submarine cables (He et al. 2025), oil pipelines, offshore energy structures, and even carbon capture and storage (CCS) systems (Bian et al. 2021, Iswara & Afriansyah 2022, Lin et al. 2024).

The morphology of the continental slope represents, on a global scale, an important transition zone between the shallow continental shelf and the deeper oceanic regions (Shepard 1937, Heezen & Hollister 1971). Among the features associated with continental slopes, submarine canyons stand out for their geomorphological complexity, their importance in the processes of erosion, deposition and transport of sediments, and for being recognized as biodiversity hotspots (Shepard 1965, Prather et al. 2017). These structures function as gravity flow conduits, allowing sediments and organic matter to be transferred from coastal areas to deeper basins (Milliman & Syvitski 1992). These structures serve as conduits for gravity flow, facilitating the transfer of sediments and organic matter from coastal regions to deeper basins (Milliman & Syvitski 1992).

The discovery of hydrocarbons in deep waters off the margins of the equatorial Atlantic, including the Brazilian Equatorial Margin (BEM) and its African counterpart, as well as the Guiana-Suriname-French Guiana margin, confirms the importance of these areas as new exploratory frontiers (Maia de Almeida et al. 2020). This has drawn attention to the Equatorial Atlantic as an emerging oil province.

Furthermore, it is noteworthy that the BEM, especially the Ceará and Potiguar Basins, harbors important submarine communication cable routes, being considered an important region for international data traffic (Bragion et al. 2023).

However, despite the strategic, economic, and environmental importance of the deep waters of the Potiguar Basin, there are considerable gaps in knowledge about the morphology of its continental slope and the sedimentary processes associated with this deep marine environment. This lack of studies hinders the assessment of geological risks, as well as the conservation of ecosystems and the sustainable economic exploitation of its resources.

Thus, this research aims at a detailed geomorphological characterization of a region of the continental slope of the Potiguar Basin, adjacent to the Jaguaribe River (Ceará) (Fig. 1), and an understanding of the oceanographic processes acting in this region, considered a new exploratory frontier. For these purposes, reflection seismic and multibeam bathymetry data were used to answer the following scientific questions:

- What is the morphology of the continental slope adjacent to the Jaguaribe River, on the Brazilian equatorial margin?

- At what evolutionary stage are the mapped submarine canyons?

- Are there features that make the area unstable for the installation of offshore infrastructure?

- How can we understand oceanographic processes based on the identified features? How can oceanographic processes be comprehended based on the identified features?

Additionally, this study correlates local features with those mapped globally, filling some of the scientific gaps regarding the morphology of the seabed in the Potiguar Basin. In particular, it addresses the eastern continental slope of Ceará, contributing to the sustainable management of the region's natural resources and advancing knowledge about the Brazilian Equatorial Margin.

Specifically, it focuses on the eastern continental slope of Ceará, thereby contributing to the sustainable management of the region's natural resources and the advancement of knowledge concerning the Brazilian Equatorial Margin.

2. Geological characterization of the area

The formation of the South Atlantic continental margin, and especially the Brazilian equatorial region, is associated with the fragmentation of Gondwana and the opening of the Atlantic Ocean during the Mesozoic era. This process resulted from the reactivation of crustal weakness systems and the intrusion of basaltic magma from the upper mantle, key factors in the development of rifts that marked the beginning of oceanic opening (Keary & Vine 1996).

In this context, the BEM presents very diverse sedimentary basins, such as the Amazon River mouth, Pará-Maranhão, Barreirinhas, Ceará, and Potiguar basins (Schrank & De Ros 2015, Pinheiro et al., 2020). Each basin exhibits its own structural and stratigraphic characteristics due to the episodes of extension and subsidence that shaped the Brazilian Equatorial Margin. These differences influence the exploratory potential and reinforce the need for specific studies to understand its evolution and economic viability (Matos 2000, Mohriak et al. 2003, Tavares et al. 2020).

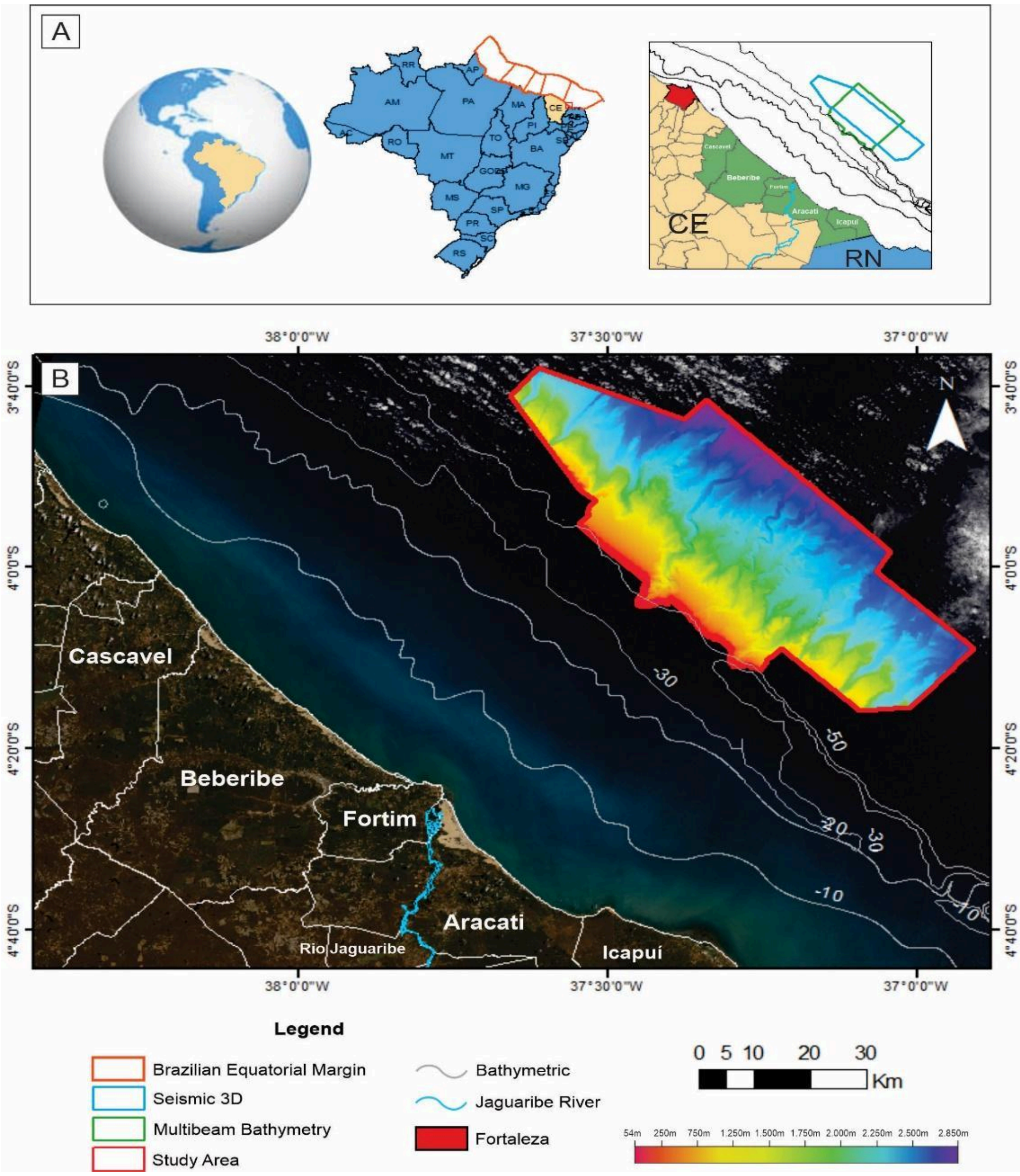

Figure 1 – A) Location map of the study area, situated in the far west region of the Potiguar Basin, specifically on the eastern continental slope of Ceará State. B) Compilation of study area data (bathymetric and seismic) adjacent to the Jaguaribe River (CE). On the continental shelf, contour lines are shown at 10 m intervals. (Landsat image, RGB432 composition).

Located within the BEM, the Potiguar Basin presents an evolutionary history marked by rifting and subsidence processes that originated its sedimentary structures. During the initial rifting phase, the development of semi-grabens created conditions for the accumulation of sediments from both continental and marine sources (Matos 1992). As the basin stabilized, continuous subsidence allowed the deposition of thick sedimentary sequences, which organized themselves into varied depositional systems, including deltas, turbidites, and pelagic deposits, recording sea-level oscillations and paleoenvironmental changes (Pessoa Neto et al. 2007). This sedimentary dynamic, in synergy with tectonic events, established the conditions for the generation of hydrocarbon resources, making the Potiguar Basin an area of high geological and economic importance.

The Continental Shelf of Ceará (CSCE) has depths varying up to 100 m and an average slope of around 2 m/km. The relief is predominantly shallow and slightly undulating, with the presence of irregular forms associated with algal reefs. The features reflect the combined influence of tectonic and volcanic processes, in addition to the geological and climatic conditions of the adjacent emerged area (Dias 2011). Regarding width, the CSCE is considered narrow, with an average of 63 km (Freire 1985).

According to Morais et al. (2019), the CSCE is subdivided into three geomorphological sectors according to physiographic, morphostructural, sedimentological and morphological aspects, namely: Coreaú, Mundaú and Jaguaribe.

In this study, the description focuses on the Jaguaribe sector, since the research area is entirely within this portion of the CSCE. The Jaguaribe sector is located between the Fortaleza Promontory and the mouth of the Manibú River (Morais et al. 2019). It has the narrowest platform in Ceará, approximately 40 km wide in front of Icapuí, and has a large number of unconsolidated, high-energy bottom forms, such as underwater dunes (Maia de Almeida et al. 2016, Morais et al. 2019).

In the vicinity of the mouth of the Jaguaribe River, there are transverse dune fields, oblique dune fields, reef formations, and beachrock lines (Maia de Almeida et al. 2016), and near the municipality of Icapuí, there is the Barreiras Formation on the inner shelf as an abrasion platform, marine pillars, and blocks (Morais et al. 2019). Transverse and oblique dune fields, reef formations, and beachrock lines are present in the vicinity of the Jaguaribe River mouth (Maia de Almeida et al. 2016). Near the municipality of Icapuí, the Barreiras Formation manifests on the inner shelf as an abrasion platform, marine pillars, and blocks (Morais et al. 2019).

3. Material and Methods

3.1 Material

The dataset consists of a seismic volume granted by the National Agency of Petroleum, Natural Gas and Biofuels (ANP), and high-resolution bathymetric data collected in June and July of 2022 with a Kongsberg Multibeam Echosounder (ME) 122 aboard the Brazilian Navy's Hydrographic Oceanographic Ship Cruzeiro do Sul (NHo CS-H38) (Fig. 2C).

During the acquisition of bathymetric data, each survey line had a 20% overlap to minimize gaps and ensure continuous coverage. In addition, sound velocity data in the water column were acquired using XBTs (Expendable Bathythermographs). The adjustment process involved using the XBT information to correct the sound velocity profile, ensuring that the acquired bathymetric data accurately represent the seabed topography. This correction was necessary to guarantee the accuracy and reliability of the acquired bathymetric data.

The seismic data (0276-BCE2-BPOT-100) consists of a time-migrated post-stack seismic volume (Kirchhoff – PSTM) with a resolution of 12.5 m x 25 m, covering an area of 2,257.7 km². This data was acquired in the year 2000 by TGS and made public by ANP in 2010. It is approximately 33 Gb in size. The acquisition was performed using the marine reflection seismic method, utilizing air-gun seismic sources that emit low-frequency acoustic pulses (less than 100 Hz). The waves reflected by the geological interfaces were recorded by hydrophones arranged on towed seismic cables, allowing the acquisition of a three-dimensional record of the seabed. The penetration of the seismic signal reaches an average of 3 to 5 seconds of double time (TWT), corresponding to approximately 3 to 6 km of depth, which allows the identification of tectono-sedimentary structures on the continental slope (Martins 2001).

3.2 Methods

The seismic data obtained were entered into the Petrel program. Initially, quality control was performed to verify the conformity of the data with the research proposal. After this step, the seismic volume was cut, keeping only the region of interest, since the information at greater depths was not the object of interpretation in this study. The processing focused on the extraction and analysis of the bathymetry derived from the seabed reflector. Furthermore, an adjustment was made to the frequency histogram for better visualization of the target reflector, while the volume was performed with 8 bits in the project; then, the seismic interpretation and characterization of the seabed could begin (Fig. 2A).

During the interpretation, the first result was obtained from the construction of a 3D surface representing the seabed, through horizon mapping. For this, the automatic interpretation tool (autotracking 3D) was used on the X-lines from 1910 to 9630 and the Inlines from 987 to 1898 (Fig. 2C). Simultaneously, an evaluation of the automatic and manual interpretation was performed in the sectors not adequately mapped, using the “manual interpretation” tool (Fig. 2B). Taking into account the average speed of sound in water as 1480 m/s, the generated surface was converted to the depth domain, which allowed integration with bathymetric data.

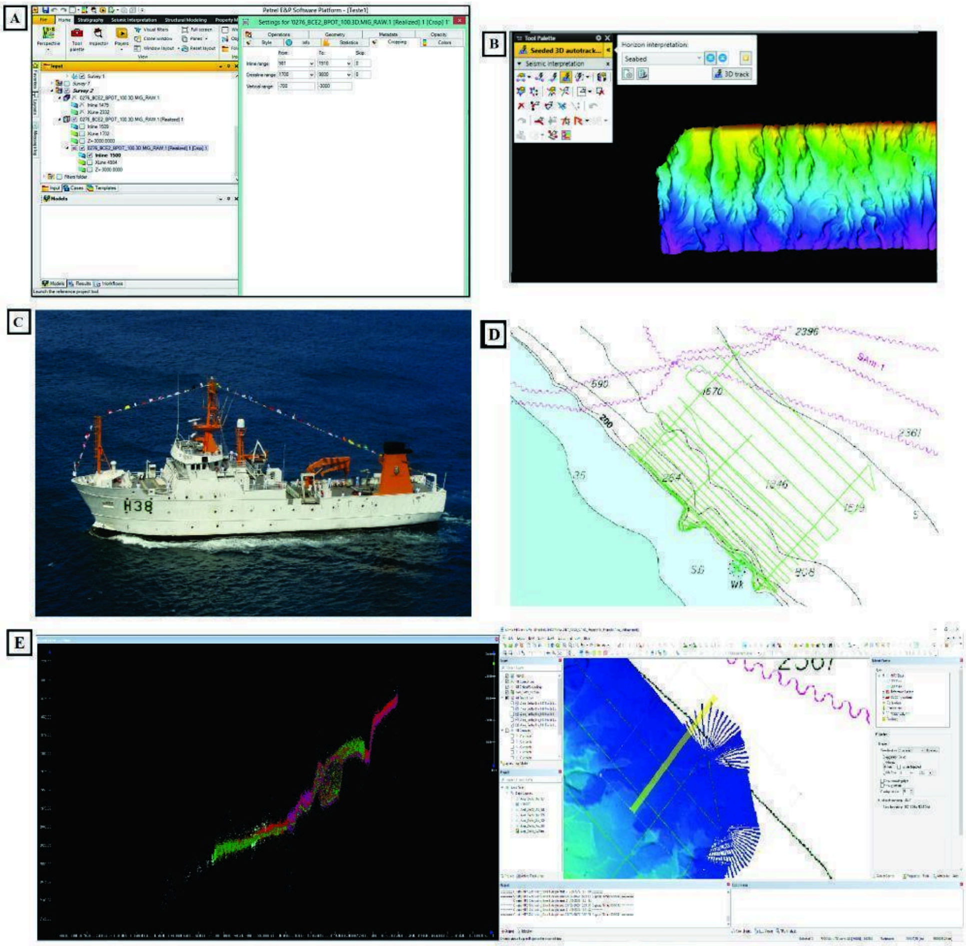

Figure 2 - (A) Visualization of the seismic volume cut with focus on the first reflectors. (B) Use of the automatic seismic interpretation tool (Seeded 3D autotracking). (C) Vessel Hydrographic Oceanographic Ship Cruzeiro do Sul (NHo CS-H38) of the Brazilian Navy. (D) Acquisition lines of bathymetric data. (E) Example of the processing of multibeam data using the Caris software.

The multibeam data were processed using Caris HIPS and SIPS 11 software (Fig. 2E). First, the data were filtered, and sensor error checking, parameter correction, and removal of incorrect and/or discrepant data were performed. The Combined Uncertainty and Bathymetry Estimator (CUBE) automatic processing method with a 25 m resolution grid was used to generate the Digital Terrain Model (DTM). According to Teledyne CARIS, bathymetry processing methods, such as the CUBE algorithm, allow the generation of surfaces with multiple hypotheses to represent the seabed. This method evaluates the uncertainty associated with the data and allows the acceptance or exclusion of depth variations, resulting in more efficient filtering and a better representation of submarine morphology (NOAA 2022).

After converting the interpreted surface depth from seismic data in Petrel and processing the bathymetric data in Caris, both surfaces were converted to the same reference system and resampled to a final 25 × 25 m grid, ensuring spatial compatibility between the datasets. The vertical uncertainty considered was based on the accuracy of the multibeam data, adopted as the main reference for the morphological characterization of the seabed. The resulting surfaces were exported in georeferenced raster format (GeoTIFF) and imported into ArcGIS®, where they were combined and analyzed to create maps and measure the features of the study area.

Subsequently, the geomorphological features were identified and classified based on the integrated bathymetric surface. The analysis allowed for three-dimensional visualization and the extraction of topographic profiles. Initially, submarine canyons were visually mapped along the continental slope and named according to the continental locations situated in front of them, with the support of Google Earth Pro and the shapefiles of the study area. For morphometric characterization, parameters such as depth, length, width, and distance from the head to the continent were measured using ArcGIS® measurement tools. Sinuosity was calculated by the ratio between the actual length of the canyon axis (L) and the linear distance between the head and the mouth (D), according to $S = L/D$. Values greater than 1.05 indicated sinuous canyons, while values close to 1 corresponded to rectilinear forms. Concavity was evaluated from longitudinal profiles, considering gradient variations along the thalweg. These parameters, combined with visual analysis and seismic amplitude attributes, supported the classification and description of the geomorphological features of the continental slope.

4. Results

4.1 Seafloor Characterization of the Eastern Continental Slope off Ceará

The analyzed bathymetric survey covers depths ranging from approximately 33 m to 2,750 m, corresponding to the actual limits of the available dataset (Fig. 3). The continental slope begins at variable depths between 50 and 100 m, reflecting the regional morphological differences observed along the Ceará continental shelf. The study area encompasses a portion of the eastern Ceará slope, approximately 96 km long and 40 km wide, where several morphological features were identified along the transition between the outer shelf and the upper slope. Bathymetric profiles across the continental slope exhibit both convex shapes (profiles 3–3’, 4–4’, and 7–7’) and concave shapes (profiles 5–5’, 6–6’, 8–8’, 9–9’, and 10–10’) (Fig. 4). The longitudinal profile 1–1’ is located at the transition between the middle and lower (deeper) portions of the slope and displays gullies, scarps, sediment ridges, and a higher concentration of sedimentary deposits (Fig. 3). In contrast, profile 2–2’ represents the transition between the upper and middle slope, showing features such as mass-movement deposits, dunes, gullies, and sediment accumulations, although less abundant than in the area represented by profile 1–1’.

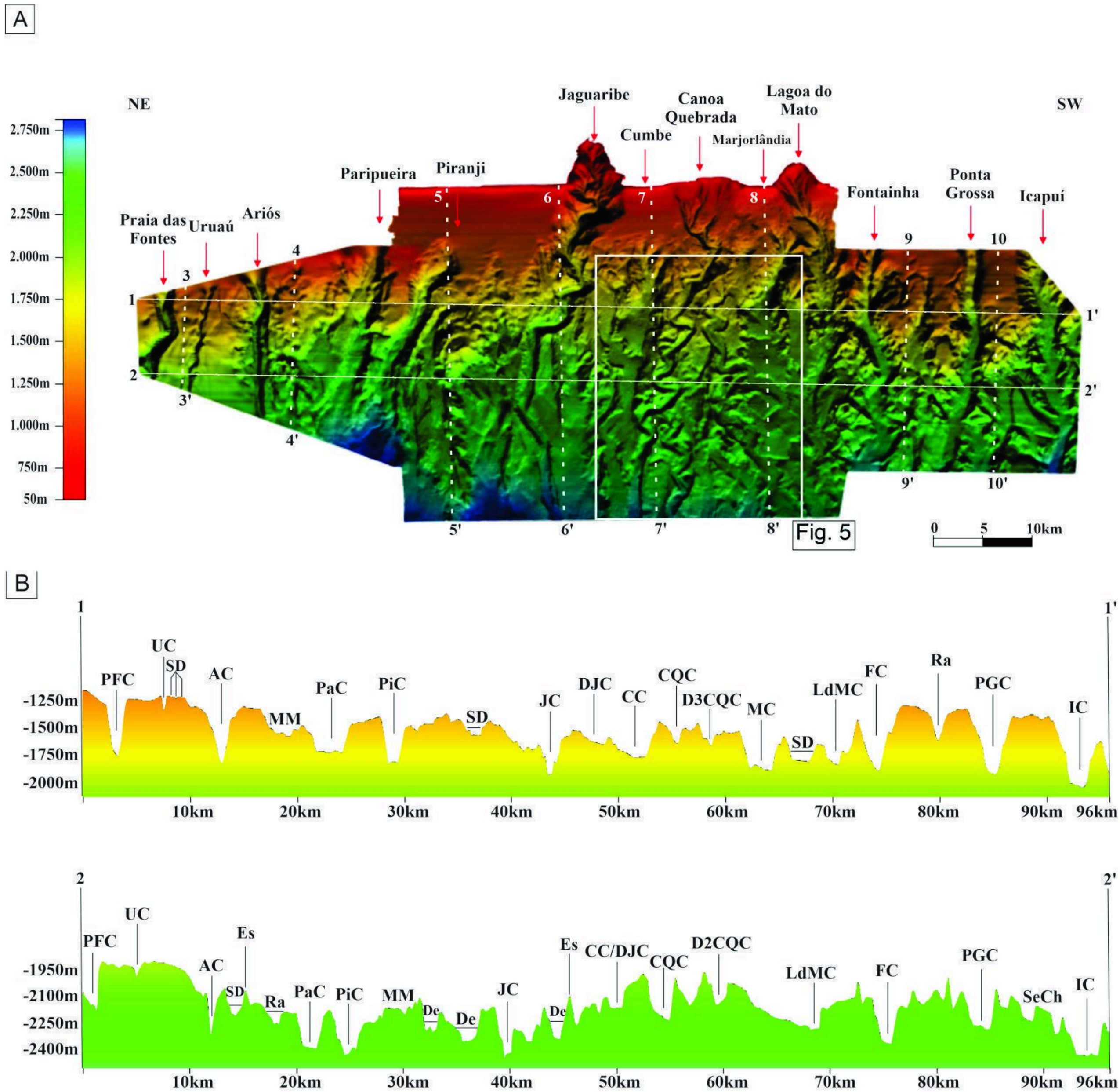

Figure 3 - A) Seabed surface of the continental slope in the study area. Steep morphology, average of 7°, and dip to the NE. The numbers in white and black indicate the ends of the profiles. B) Longitudinal bathymetric profiles (continuous lines) 1-1’ and 2-2’ (AC = Ariós Canyon, SeCh = Sedimentary Chain, CC = Cumbe Canyon, CQC = Canoa Quebrada Canyon, FC = Fontainha Canyon, IC = Icapuí Canyon, JC = Jaguaribe Canyon, LdMC = Lagoa do Mato Canyon, MC = Marjorlândia Canyon, PaC = Paripueira Canyon, PFC = Praia das Fontes Canyon, PGC = Ponta Grossa Canyon, PiC = Piranji Canyon, UC = Uruaú Canyon, D2CQC and D3CQC = Distributary of the Canoa Quebrada Canyon, DJC = Distributary of the Jaguaribe Canyon, SD = Sedimentary Deposit, Es = Escarpment, MM = Mass Movement, Ra = Ravine).

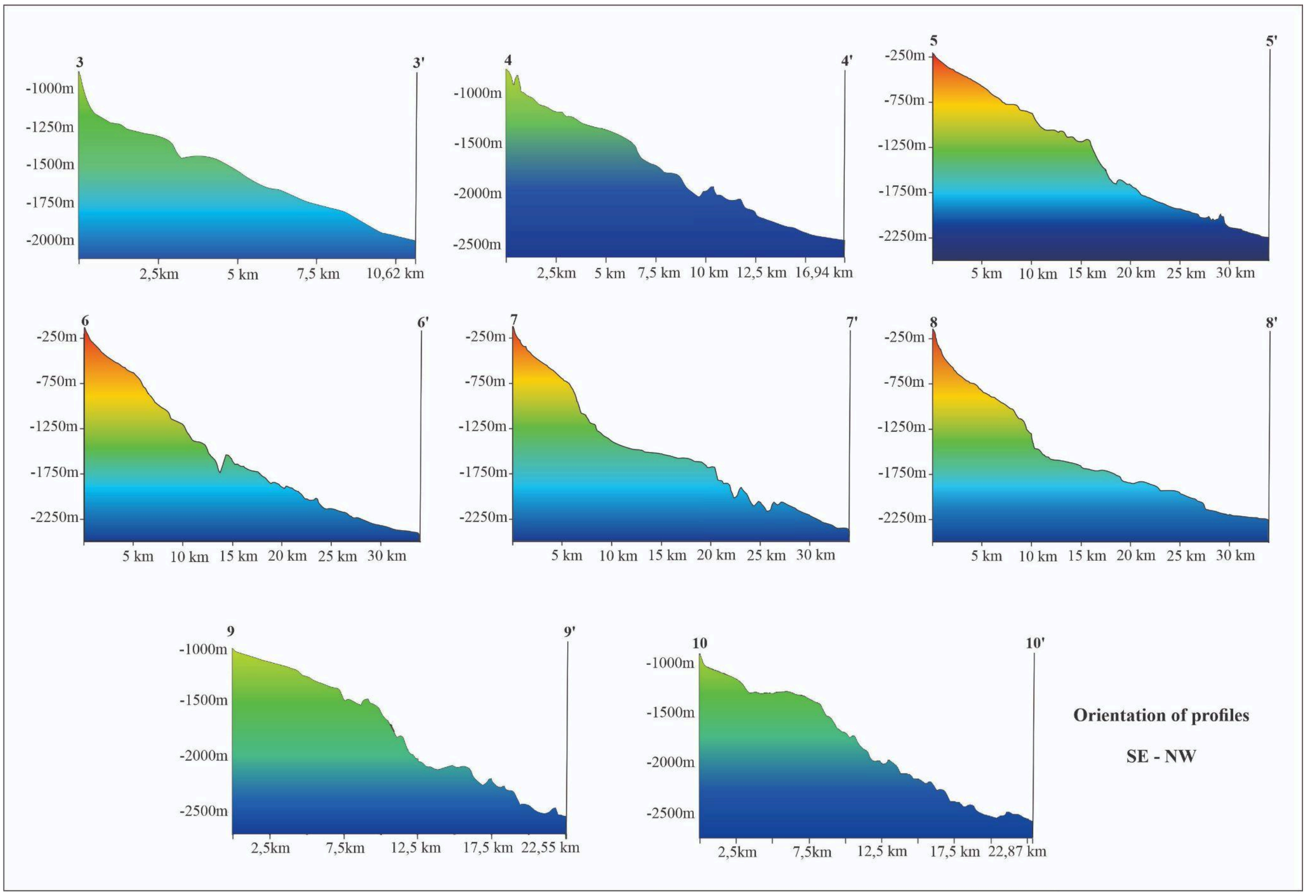

Figure 4 – Cross-sectional profiles along the continental slope of the study area. For location, see Fig. 3(A).

4.2 Submarine Canyons of the Eastern Continental Slope off Ceará

A total of 13 submarine canyons were identified along the studied continental slope, arranged roughly parallel to each other. Most canyon thalwegs are oriented toward the northeast, indicating a regional trend of erosive flow in the same direction (Fig. 3A).

The canyons range in length from 11,218 m to 45,197 m, with the Canoa Quebrada Canyon being the longest, extending for more than 45 km (Fig. 3A; Table 1). In contrast, the Praia das Fontes Canyon is the shortest, measuring 11,218 m (Fig. 3A; Table 1). These values, however, are limited by the spatial extent of the bathymetric data.

To obtain a more detailed characterization of canyon width, measurements were taken at both the canyon heads and distal portions. Among the fully mapped canyons, the Jaguaribe Canyon exhibits the widest head (4,594 m), while the Majorlândia Canyon has the narrowest (1,518 m). At the distal portions, the Paripueira Canyon stands out as the widest (3,473 m), whereas Majorlândia remains the narrowest (1,193 m) (Table 1).

Average canyon depths were estimated from cross-sections perpendicular to the canyon walls, with an average of four sections per canyon evenly distributed along their length. Based on these profiles, the Uruaú Canyon is the shallowest, with an average depth of 151 m, whereas the Jaguaribe Canyon is the deepest, reaching approximately 365 m (Fig. 3). Considering the minimum and maximum depths measured along the longitudinal profiles, the Pirangi Canyon has the shallowest head, starting at a depth of 1,120 m, while the Jaguaribe Canyon reaches the deepest waters, down to 4,200 m (Fig. 3).

The sinuosity index (SI) of each canyon was calculated as the ratio between its total thalweg length and its thalweg straight length. SI values lower than 1.1 indicate a nearly straight canyon, while values equal to or greater than 1.1 characterize sinuous canyons (Janocko et al. 2013).

Table 1 – Main morphometric characteristics of the canyons.

Canyon	Maximum depth (m)	Minimum depth (m)	Average depth (m)	Length (km)	Width at the head (m)	Width at the mouth (m)	Guideline (Straight Line) (km)	Slope	Sinuosity
Ariós	3,800	2,050	495	15,5	1,866	578	14.9	6°	1.04
Canoa Quebrada	4,050	1,350	255	43,4	1,273	1,729	30.3	4.4°	1.43
Cumbe	3,550	1,150	265	30,7	1,269	2,275	28.8	6.9°	1.07
Fontainha	4,000	1,450	305	23,8	702	2,042	22.4	5.7°	1.06
Icapuí	4,100	2,200	282	23,1	2,748	1,684	22.8	4.5°	1.01
Jaguaribe	4,200	1,680	365	45,1	4,594	1,786	36.9	4.9°	1.22
Lagoa do Mato	3,500	1,400	177	35,8	4,125	1,404	34.4	6.7°	1.04
Majorlândia	3,800	1,400	237	33,3	1,518	1,193	30.9	5.5°	1.08
Paripueira	3,750	1,250	402	20,5	2,207	3,473	19.9	8°	1.03
Piranji	4,000	1,120	400	25,4	1,879	2,863	23.7	7.2°	1.07
Ponta Grossa	3,900	1,700	442	22,8	1,874	2,976	22.4	5.2°	1.02
Praia das Fontes	3,300	1,910	455	11,2	2,110	2,045	9.2	7°	1.22
Uruaú	3,100	1,210	151	12,7	715	959	11.4	8°	1.12

For canyon classification, we calculated the mean sinuosity index across individual canyons, which resulted in an average value of 1.1. Accordingly, the canyons Icapuí, Ponta Grossa, Paripueira, Lagoa do Mato, Ariós, Fontainha, Cumbe, Pirangi, and Majorlândia show below-average sinuosity, while Uruaú, Praia das Fontes, Jaguaribe, Canoa Quebrada, and the distributary branches of Canoa Quebrada display higher sinuosity values. Among them, the Canoa Quebrada distributary III stands out as the most sinuous feature (SI = 1.22) in the study area (Fig. 5).

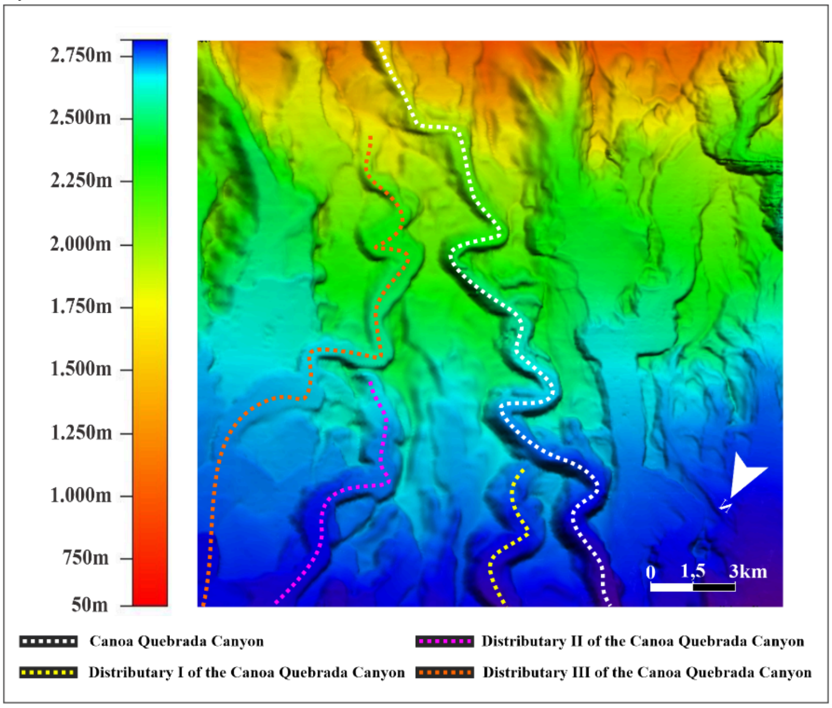

Figure 5 – Canoa Quebrada Canyon and its distributaries. For location, see Fig. 3(A).

The average slope is 7°, with the Paripueira and Uruaú canyons having the steepest slopes (8°). An inverse relationship between canyon slope and sinuosity is observed—more sinuous canyons tend to have gentler gradients. For instance, the Canoa Quebrada Canyon is the most sinuous and least steep, while the Jaguaribe Canyon, the second most sinuous, also shows one of the lowest average gradients (Table 1). The analysis of bathymetric profiles also contributes to identifying the evolutionary stages of the continental slope. One approach for classification involves the cross-sectional canyon shapes (Garone 2018). U-shaped canyons with slightly flattened floors (e.g., the Canoa Quebrada Canyon; Fig. 6B) and V-shaped canyons (e.g., the Ariós Canyon; Fig. 6C) were identified..

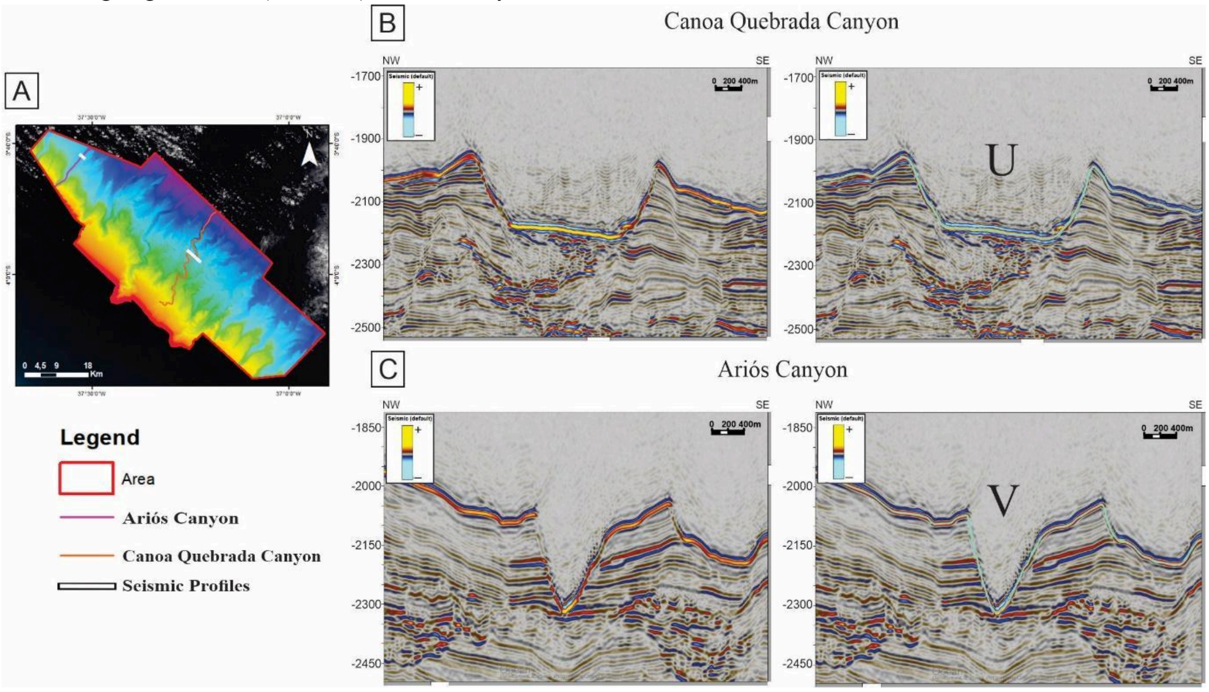

Figure 6 – (A) Location of seismic profiles in the study area. (B) Seismic profile of the Canoa Quebrada Canyon showing a U-shaped morphology with a slightly flat bottom. (C) Seismic profile of the Ariós Canyon showing a V-shaped morphology.

4.3 Other Deep-Water Features

In addition to the submarine canyons, other geomorphological features were recognized on the continental slope, mainly within the inter-canyon areas. These structures vary in dimension and morphology (e.g.: Lawrence & Aaron 2020). They include gullies, mass-movement features, sediment ridges, and circular depressions, all of which display variations in size and shape. Gullies correspond to small erosional channels formed by concentrated flows and bottom currents, responsible for incision and sediment redistribution along the slope (Canals et al. 2006). Mass-movement features are associated with gravitational slope instability and are characterized by scarps, displaced blocks, and rupture surfaces typical of submarine landslides and debris flows (Mosher et al. 2010). Sediment ridges were interpreted as elongated, wavy forms likely related to bottom-current activity and fine sediment deposition. Circular depressions correspond to negative relief features (Hovland 1981a, Hovland et al. 2010).

4.3.1 Gullies

In the upper portion of the slope, several gullies were observed (Fig. 7 and 8), including one located parallel between the Ponta Grossa and Fontainha canyons (Fig. 7A). This feature was classified as a gully because it exhibits smaller depth and length, lacks a well-defined head, and displays a simple linear profile without direct connection to the main thalweg of the adjacent canyons. This gully widens downslope, measuring 722 m (Fig. 9B) across its upper portion and 3,532 m in its lower segment (Fig. 9C). Its head is located 2,895 m away from the heads of the corresponding canyons, and its total length is 5,085 m. Based on its length and incision degree, it is considered the most developed gully in the study area, although its dimensions are still smaller than those of fully developed canyons.

The gully, located between the Lagoa do Mato and Majorlândia canyons (Fig. 7C), originates 2,727 m from the slope break and has an average width of 645 m. It is 2,531 m long and remains straight and uniform along its entire course. Relative to the Lagoa do Mato Canyon, Gully 2 forms an angle of approximately 45°.

Between the Canoa Quebrada and Cumbe canyons, there are gullies that converge toward the Cumbe Canyon at an angle of roughly 45°. Among these, one larger gully measures 2,020 m in length and 800 m in average width, while another is 1,294 m long and 527 m wide on average.

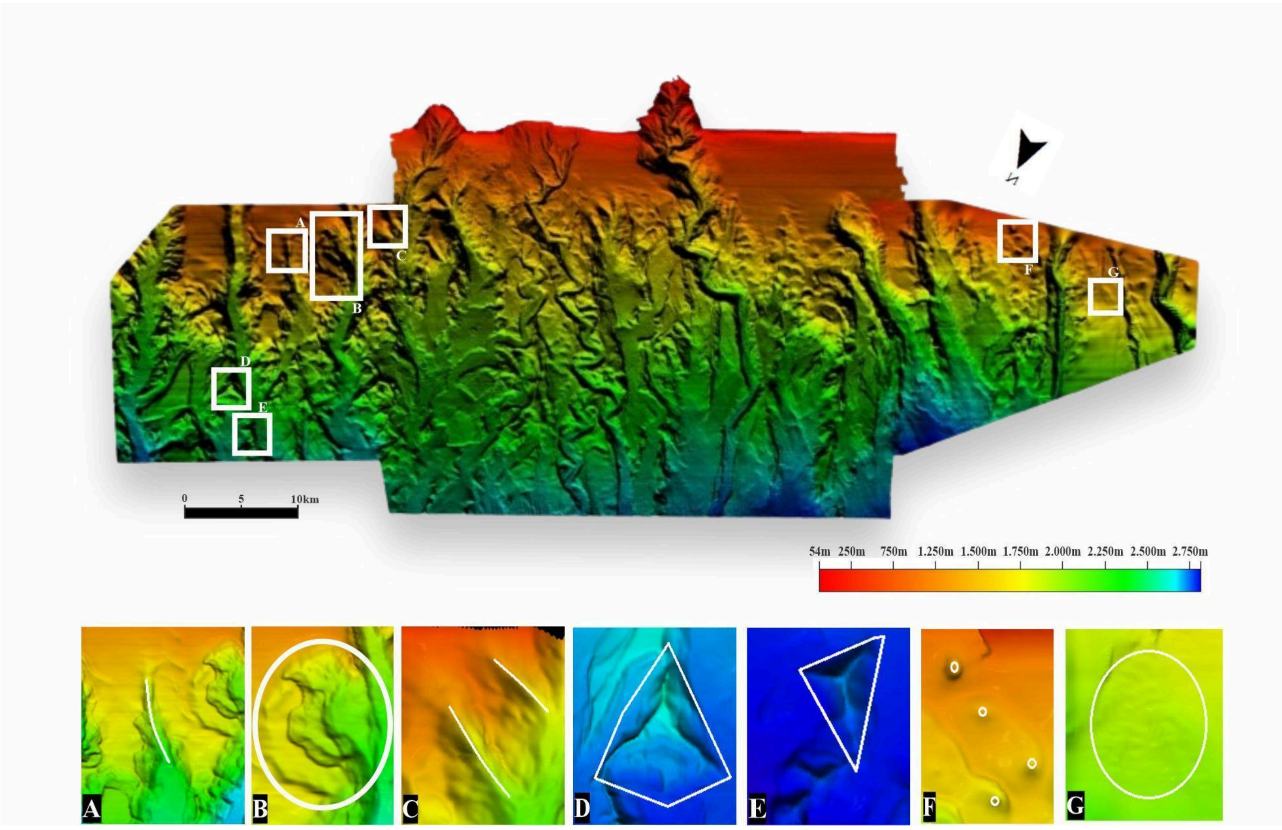

Figure 7 – Representation of the seafloor surface with highlighted features. (A) and (C) Gullies; (B) Mass-movement features; (D) and (E) Sedimentary chains; (F) Circular depressions; and (G) Dunes.

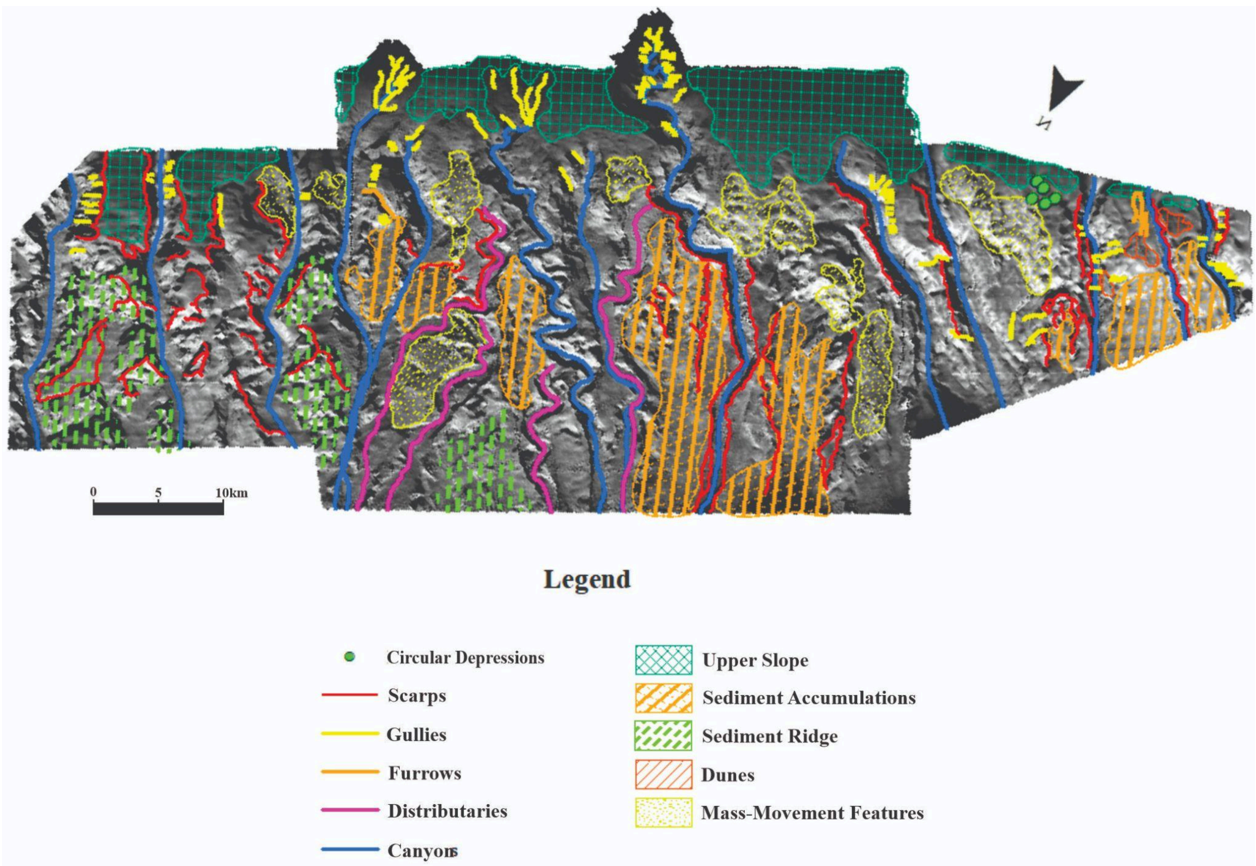

Figure 8 – Study area with the compilation of all morphological features interpreted in this research

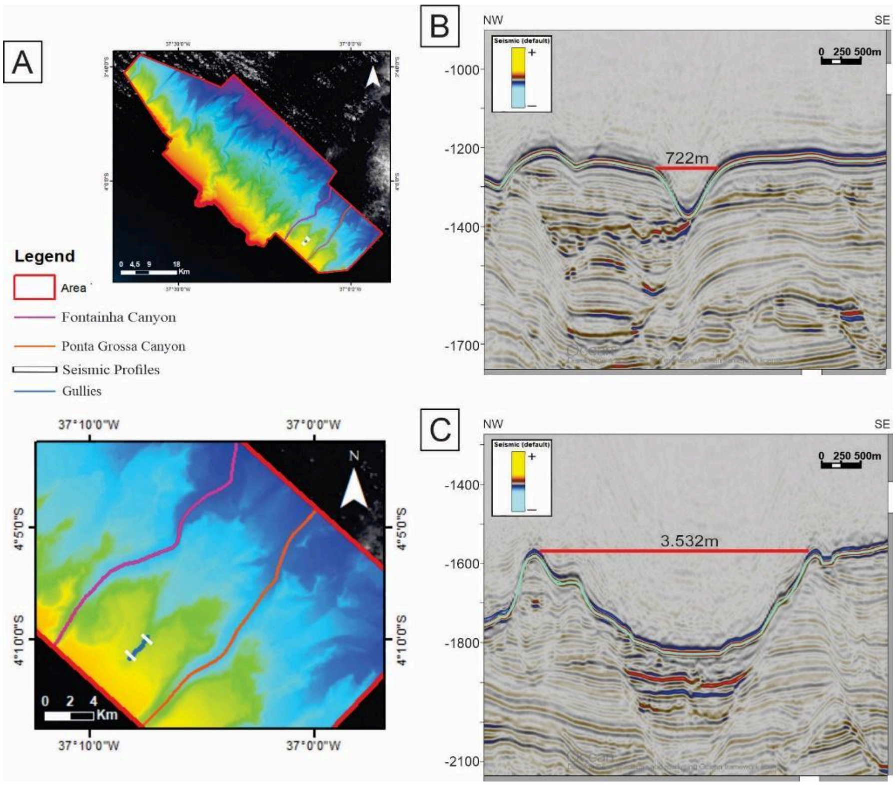

Figure 9 – (A) Location of the seismic profile of the gully in the study area. (B) Seismic profile of the upper portion of the gully. (C) Seismic profile of the lower portion of the gully.

4.3.2 Mass-Movement Features

Nine areas showing evidence of mass movements were identified within the study area (Fig. 8). On the eastern wall, near the head of the Fontainha Canyon, the first landslide structure presents a semicircular shape with a radius of 4,627 m. Adjacent to the Lagoa do Mato Canyon, a second mass-movement zone is also semicircular, with a radius of 2,226 m (Fig. 7B). The remaining unstable areas show stepped morphologies and triangular shapes, with widths ranging from 1,838 to 5,073 m and slopes exceeding 6°, associated with well-defined scarps along their upper portions (Fig. 10).

These features differ from the cyclic steps described by Lawrence & Aaron (2020), which display rhythmic and continuous patterns of crests and troughs, gentle slopes (2°–4°), and a depositional character. In contrast, the morphologies observed in this study are erosional and gravitational in nature, with disorganized distribution and clear basal rupture—typical characteristics of submarine mass-movement processes.

4.3.3 Sediment Ridges

Sediment ridges were also identified in several locations across the study area, but they are most abundant in the lower part of the continental slope between the Icapuí and Ponta Grossa canyons, where three well-defined ridges occur (Figs. 7D, and 7E).

Morphologically, these ridges correspond to irregular sediment accumulations that vary in width, length, and orientation, often displaying triangular or slightly curvilinear shapes. Unlike the elongated and parallel forms described by Lawrence & Aaron (2020), the sediment ridges identified here exhibit a more discontinuous and asymmetric arrangement, influenced by local topography and by the interaction with adjacent canyon structures.

This interpretation is consistent with the morphological patterns described by Maia de Almeida et al. (2015) for the Potiguar Basin margin, where such features reflect the combined action of depositional bottom currents and gravitational sediment redistribution processes.

Among the mapped features, the ridge located along the wall of the lower portion of the Ponta Grossa Canyon stands out. It occurs in a relatively flattened area compared to the surroundings (Fig. 11), displaying a well-defined triangular shape, 1,452 m in width and 2,213 m in length (Fig. 7E).

4.3.4 Circular Depressions

Five circular depressions were identified in the analyzed area, all located between the Paripueira and Ariós canyons and grouped together in a single cluster (Figs. 7F and 12). The largest depression measures 445 m in diameter, while the others have diameters of 157 m, 219 m, 232 m, and 262 m.

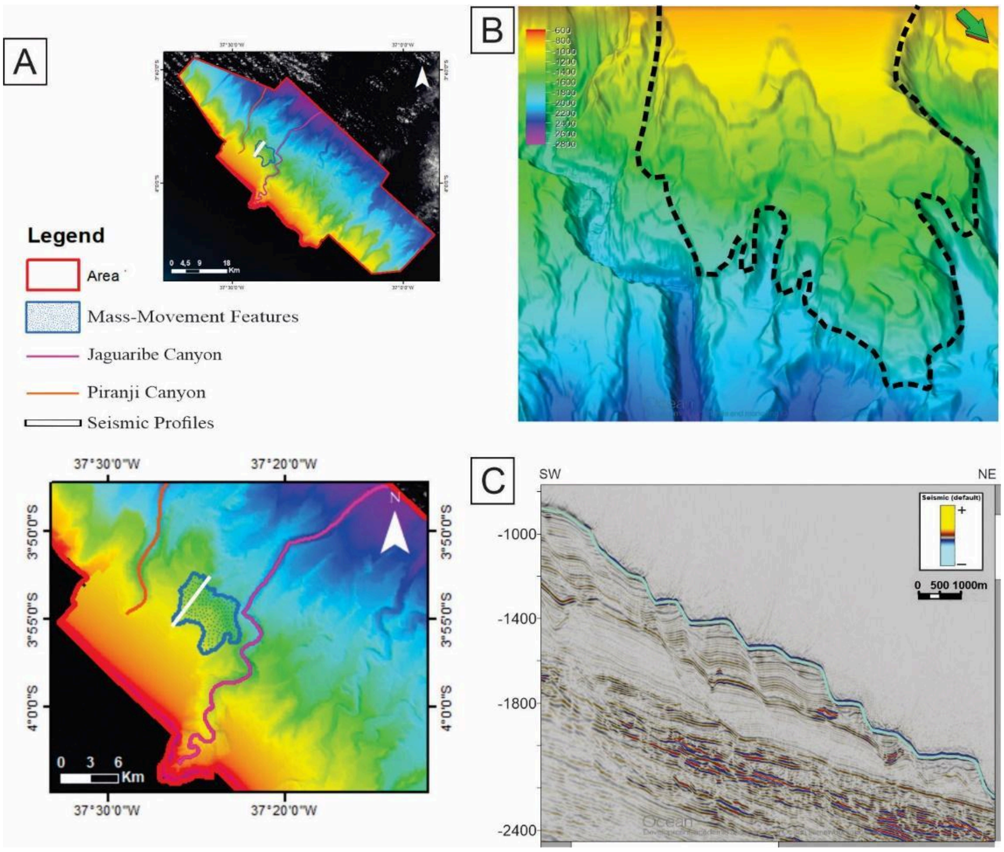

Figure 10 – (A) Location of the seismic profile showing a mass-movement feature. (B) 3D frontal view of the stepped mass-movement pattern. (C) Seismic profile of the stepped mass-movement pattern.

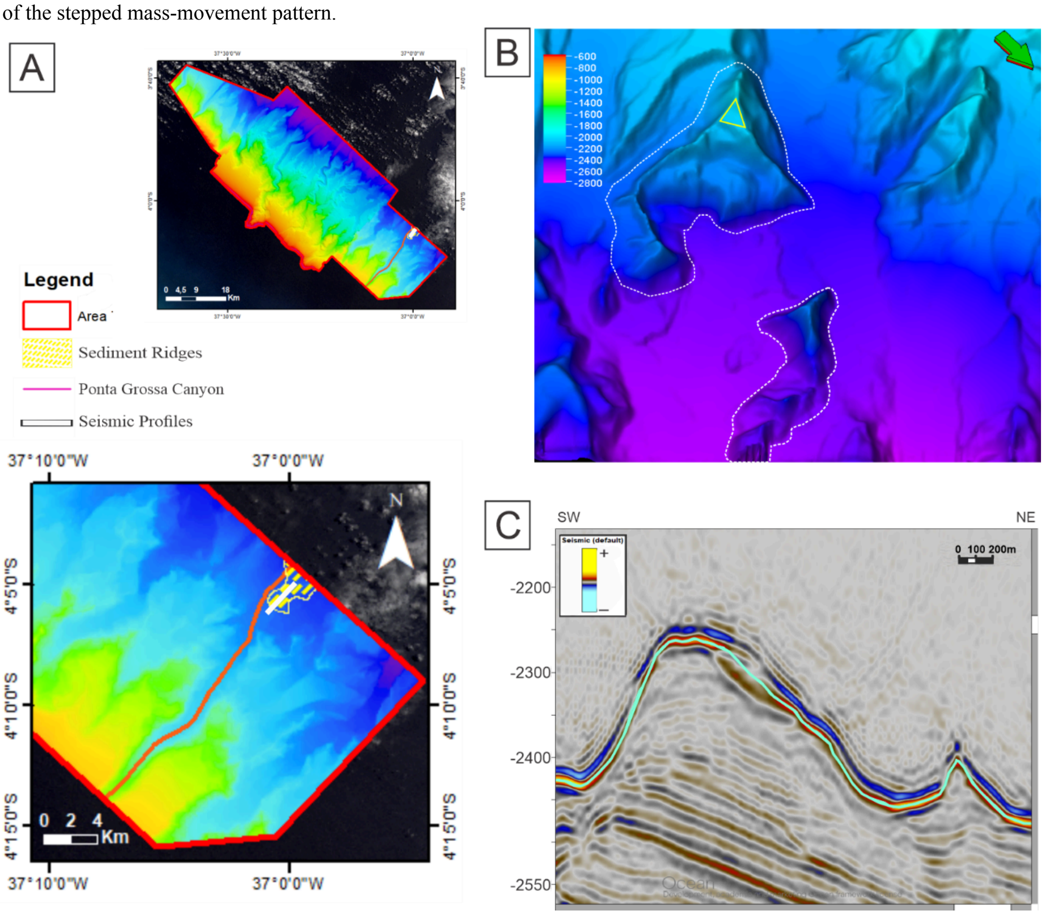

Figure 11 – (A) Location of the sedimentary chain in the study area. (B) 3D visualization of the sedimentary chain with a triangular shape. (C) Seismic profile of the sedimentary chain.

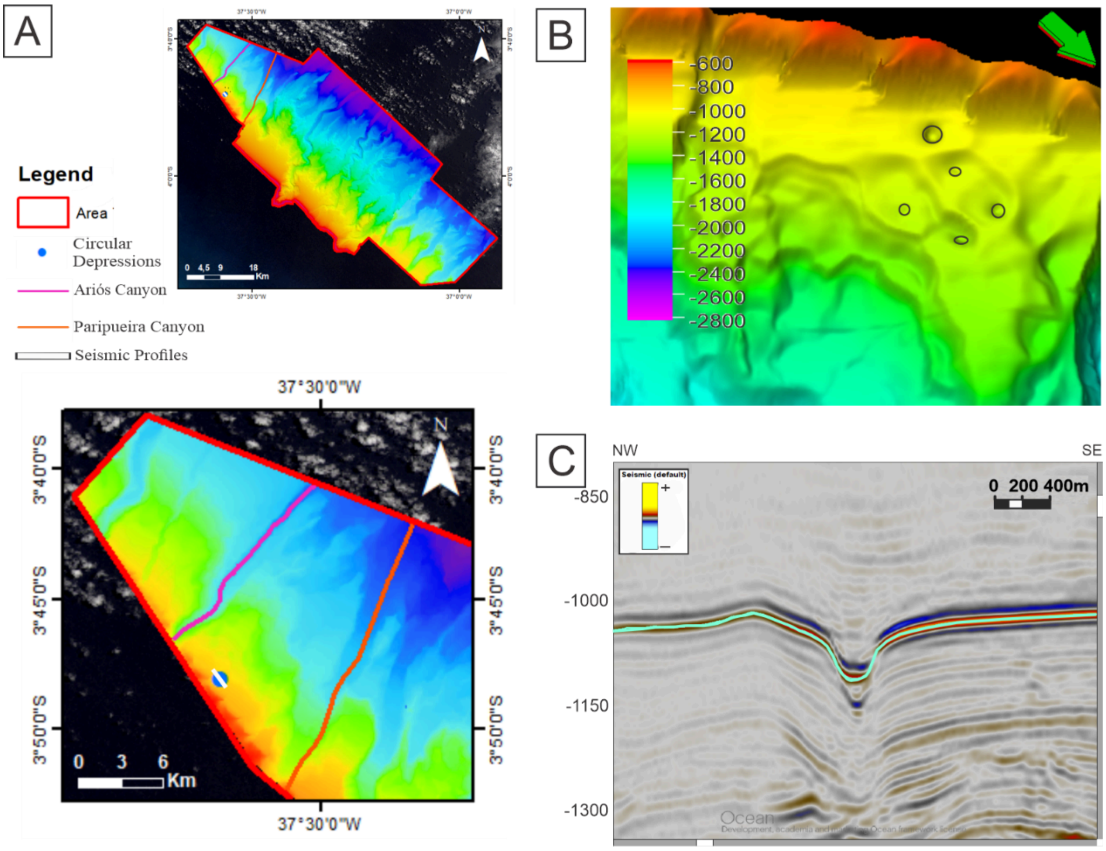

Figure 12 – (A) Location of the circular depression feature and seismic profile. (B) 3D view of the five circular depressions. (C) Seismic profile of the circular depression.

4.3.5 Dunes

The study area also includes features identified as dune fields, with three main occurrences (Fig. 13A)—two located in the upper portion of the slope and one in the intermediate region.

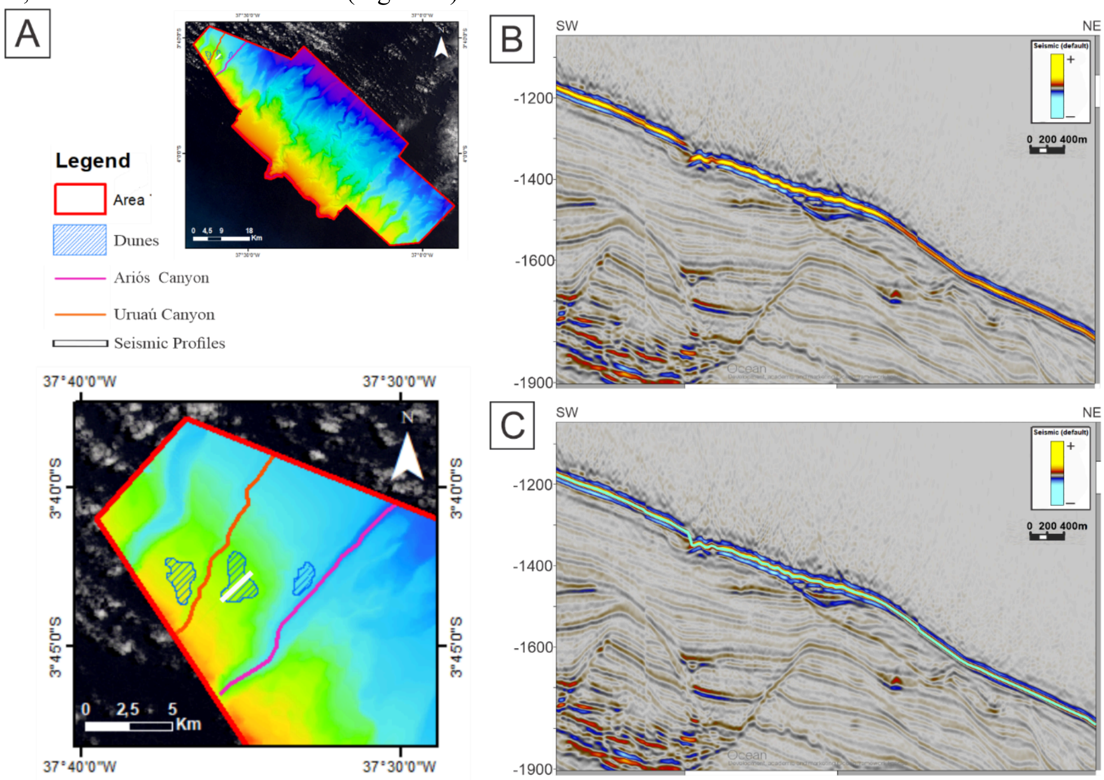

Figure 13 – (A) Location of the seismic profile of the dune field. (B) Seismic profile of the dune field without interpretation. (C) Seismic profile of the dune field with interpretation.

The first dune field covers an area of 2.81 km², with an average crest-to-crest spacing of approximately 98 m. The second dune field, adjacent to the wall of the Uruaú Canyon, measures 1,584 m in length and has an average spacing between crests of about 85 m (Figs. 7G and 13). The third dune field is located near the wall of the Ariós Canyon, with a length of 2,167 m and an average crest spacing of approximately 91 m (Fig. 8).

5. Discussion

Based on the geometry and morphological patterns of the continental slope in the study area, several submarine geomorphological features were interpreted. These features shape a deep-water environment characterized by high heterogeneity and a wide range of forms and dimensions. Among these, submarine canyons stand out as the most prominent.

5.1. Submarine Canyons

5.1.1. Evolutionary Stages

Maia de Almeida et al. (2015) conducted a morphological characterization of the continental slope in the northern sector of the Potiguar Basin, demonstrating that the formation and development of submarine canyons in that region conform to the model proposed by Farre et al. (1983) and Puga-Bernabéu et al. (2011). Given that the present study area lies within the same geological framework and exhibits similar geomorphological configurations, the same theoretical model was applied. This approach allows a better understanding of the evolutionary stages of submarine canyons, which can be classified as incipient, transitional, or mature. This classification considers variations in canyon geometry, morphometric parameters, and the multiple sedimentary processes that shape their relief (e.g.: Farre et al. 1983, Puga-Bernabéu et al. 2011).

Unlike the findings of Maia de Almeida et al. (2015), the criteria used to classify canyons as incipient were not identified in the present study area. The incipient stage involves preconditioning factors such as the presence of downslope erosive flows, low sediment strength, tectonic structures, or zones of geological weakness that lead to localized slope failure and the initiation of nascent submarine canyons (Puga-Bernabéu et al. 2011).

Conversely, based on geomorphological configuration and incision patterns, most of the canyons identified in the study area—Ariós, Cumbe, Fontainha, Icapuí, Lagoa do Mato, Majorlândia, Paripueira, Ponta Grossa, Pirangi, and Uruaú—are interpreted to be in a transitional stage (Farre et al. 1983). Incision patterns were recognized from variations in canyon depth and cross-sectional shape, indicating ongoing vertical excavation, evolving canyon heads, and V-shaped profiles typical of intermediate stages of canyon development, in which vertical erosion still exceeds lateral widening. These features also show upslope growth toward the shelf break, suggesting that erosional and depositional processes have not yet reached full maturity. The similarity to the upper portion of the São Francisco Canyon (SFC) in the Sergipe-Alagoas Basin (Ribeiro et al. 2021) reinforces this classification. Although the São Francisco Canyon is widely recognized as a mature feature along its main course, different developmental stages coexist along its extent. As observed in the upper part of that canyon, the features in the study area exhibit partial incision, evolving heads, and developing channel systems, reflecting the multiphase dynamics of excavation and sedimentation typical of the transitional stage. Thus, similar to the São Francisco Canyon, the canyons adjacent to the Jaguaribe River illustrate how comparable processes of regressive erosion and sediment supply can generate internal variations in canyon development.

Additionally, some canyons—Canoa Quebrada, Jaguaribe, and Praia das Fontes—were classified as mature, as they are both deep and sinuous (e.g.: Maia de Almeida et al. 2015). In this mature stage, canyon erosion style may shift, initiating incision at the shelf break, as observed in the Jaguaribe Canyon (Fig. 3) (Farre et al. 1983).

According to Puga-Bernabéu et al. (2011), canyon length is a relevant variable for determining its evolutionary stage, as length, when analyzed together with canyon morphology, provides insight into its developmental phase. The Canoa Quebrada and Jaguaribe canyons were fully mapped, allowing accurate measurement of their total lengths and other geomorphological parameters. These canyons exhibit the greatest linear extensions and the highest sinuosity indices, as well as U-shaped cross sections—typical characteristics of features in the mature stage (Farre et al. 1983, Puga-Bernabéu et al. 2011).

Among the studied canyons, six (Ponta Grossa, Fontainha, Lagoa do Mato, Majorlândia, Pirangi, and Paripueira), along with the Canoa Quebrada distributary branches, have widened to the point that measuring their distal widths was no longer feasible. According to Farre et al. (1983), incision depth typically increases with greater sediment transport, which promotes gravity flows capable of deepening the canyon. However, in the present case, the observed lateral expansion suggests a reduction in effective incision, possibly resulting from partial wall collapse and sediment accumulation rather than increased transport. This dynamic indicates a morphological evolution stage where vertical excavation gives way to lateral widening, reflecting both structural adjustments and the influence of sedimentary and gravitational factors that continuously reshape canyon geometry.

The formation and evolution of submarine canyons are directly associated with climatic and oceanographic processes—such as rainfall patterns and marine currents—that control sediment supply and circulation on continental shelves (Heezen & Hollister 1971, Emery, 1968). Fluvial input, for instance, promotes both canyon excavation and subsequent infilling, whereas ocean currents contribute to sediment redistribution, generating features of variable depths (Mosher & Piper 2007). Overall, the interaction between inherited geomorphological characteristics, sediment availability, and current energy results in features of comparable depths, even across different latitudes.

Furthermore, Table 1 presents the sinuosity indices of the canyons in the study area. Among the morphometric parameters observed, a high sinuosity index is strong evidence of a canyon in a mature evolutionary stage (Maia de Almeida et al. 2015), as seen in the Uruaú, Praia das Fontes, Jaguaribe, and Canoa Quebrada canyons.

The sinuosity of submarine canyons also directly influences the development of distributary channels, which commonly originate at confluence points along the outer margins of canyon bends. Studies from Australia and the Bahamas indicate that highly sinuous canyons tend to develop short, narrow, shallow, and less sinuous distributaries, whereas straighter canyons favor more direct flows that transport sediments toward deeper regions (Huang et al. 2014, Tournadour et al. 2017). In contrast, the present study area exhibits a distinct pattern: the Canoa Quebrada and Jaguaribe canyons, which show the highest sinuosity values (1.43 and 1.22, respectively), have long and sinuous distributaries, differing from the trends described in the literature (Fig. 3). This configuration suggests the occurrence of less energetic but more recurrent turbidity flows capable of promoting greater lateral migration and elongation of distributary channels. Similarly, studies on the Nazaré and Setúbal canyons (Portugal) highlight how canyon geometry and sinuosity influence sedimentation and erosion patterns along their courses and distributaries (Wynn et al. 2007, Puga-Bernabéu et al. 2011). However, in contrast with the literature, the Canoa Quebrada distributary exhibits a high sinuosity index, reinforcing the interpretation that less intense yet more frequent turbidity flows affect sediment dynamics along the eastern Ceará margin (Kane et al. 2008, Crisóstomo-Figueroa et al. 2024).

Regarding cross-sectional shapes, V-shaped profiles represent transitional-stage features where erosional activity is less intense, whereas U-shaped profiles indicate a mature stage, resulting from enhanced erosional processes that promote canyon deepening and widening (Farre et al. 1983). Consequently, the V-shaped profile of the Pirangi Canyon supports its classification as a transitional canyon, while the Canoa Quebrada Canyon, which exhibits both a high sinuosity index and a U-shaped profile, is corroborated as a mature canyon.

5.1.2. Canyon Depth and Connectivity Analysis

In the BEM, Oliveira Júnior (2019) mapped and characterized 431 submarine canyons, observing an overall mean depth of 142 m. In this context, it is noteworthy that canyons along the Eastern Margin are generally deeper, followed by those along the Northern Margin. This distribution is related to sediment dynamics and current patterns along the Brazilian coast, which redistribute material differently, leading to variations in incision and canyon morphology.

In the study area, the overall mean canyon depth reaches 325 m, a value considerably higher than the average reported by Oliveira Júnior (2019). This difference reflects the influence of local oceanographic and sedimentary conditions, such as lower terrigenous input and higher energy of the contour currents, which reduce deposition rates and enhance erosive processes. Consequently, the canyons in the region exhibit greater incision and relative depth, a pattern also observed on the northern slope of the Potiguar Basin (Maia de Almeida et al. 2015). The convergence of these factors—sediment supply, ocean current energy, and inherited geomorphology—explains the occurrence of features with similar depths, even if spatially distinct (Milliman & Syvitski 1992, Maia de Almeida et al. 2017).

Regarding the incision pattern, it is known that it results from both local conditions and broader processes acting on the equatorial brazilian margin. Relating each canyon's depth, it is observed that those connected to the continental shelf and with large heads (Table 1) have the greatest mean depths (e.g.: Oliveira Júnior 2019). In the present study, at least two of the thirteen analyzed canyons (Jaguaribe and Lagoa do Mato) show connectivity with the continental shelf. On the other hand, some canyons whose heads could not be identified due to data limitations exhibit high mean incision depths, suggesting that they may also be connected to the shelf. Among these canyons without visible heads, Icapuí stands out, which has the largest upper width (2,748 m) and, at the same time, is among the shallowest of the slope (282 m depth) (Table 1). Based on these characteristics, it is suggested that this canyon is connected to the continental shelf.

5.2 Other Deep-Water Features

5.2.1 Gullies and Mass Movements: Potential Submarine Geohazard Areas

Gullies, also known as headward-eroding channels, are defined as short morphological conduits that erode the seafloor and are smaller than canyons (Garone 2018). They typically lack tributaries and are located on continental slopes and fault scarps (Corrêa 2021). This definition applies to the gullies identified in the study area, including the feature located between the Ponta Grossa and Fontainha canyons, which is characterized by shallow depth, absence of a well-defined head, and simple linear morphology.

Identifying gullies and observing their behavior on the continental slope is crucial for understanding other seafloor structures, such as submarine canyons.

Canyons exhibiting mass movement characteristics, such as gullies along their lateral walls, are generally wider (Nelson et al., 2011), as observed in the Cumbe Canyon, which is among the widest canyons (2,231 m) and shows gullies incising its lateral walls.

According to Pratson et al. (1994), linear gullies typically converge near canyon heads at low angles, as observed between the Lagoa do Mato and Majorlândia canyons (Fig. 7D). Once a linear gully forms, it can channel subsequent turbidity flows along the same path (Spinelli & Field 2001).

The study area contains gullies of various sizes (see Section 4.3.1). Literature indicates that small gullies play a key role in the initiation and development of canyons, often occurring near shelf breaks or slope bases (Bourget et al. 2014, Kristoffersen et al. 2007).

On continental slopes, several physical processes occur, including erosive ones, frequently associated with unstable structures such as mass movements (Pratson et al. 1996, Retegui et al. 2024). These active or relic landslides were identified throughout the study area, where mass movement zones cover approximately 148 km² and sediment deposits extend over ~303 km².

These structures are significant for the safety of offshore operations and submarine cable installations, as features such as slides and slumps can pose substantial geological hazards (Freitas et al. 2001). Understanding mass movement types, including debris flows and penetrative slides, is essential for assessing risks associated with these features (Dourado et al. 2013).

According to McAdoo et al. (2000), submarine landslides are an important mechanism in the formation and downslope transport of large volumes of sediment along continental slopes. Among the mechanisms responsible for the genesis of these geomorphic features are sediment deposition and erosion resulting from gravity-driven flows interacting with an irregular seafloor (Garone 2018).

From these processes, remnant regions may occasionally stand out, referred to as sedimentary ridges (Maia de Almeida et al. 2015), as interpreted in the lower portion of the continental slope in the study area, indicating that this region has undergone more intense erosional activity.

5.2.2 Circular Features: Influence of Bottom Currents?

Circular features observed in this study resemble pockmarks. However, pockmarks are traditionally associated with fluid migration from the subsurface to the seafloor (Andresen & Huuse 2011), whereas the circular features in the study area show no evidence of gas or fluid migration in seismic profiles.

Typically, pockmarks are circular or oval depressions, ranging from 100 to 400 m in diameter (King & Maclean 1970, Chand et al. 2009), and can be randomly distributed in shallow areas or aligned in linear chains in deeper regions (Dandapath et al. 2010). They are often associated with faults or fractures, which act as preferred pathways for subsurface fluid migration (Hovland 1981, Hovland et al. 2010). In contrast, the absence of acoustic anomalies and the continuous reflectors observed in seismic profiles suggest a stable sedimentary environment with no evidence of active fluid escape. Discontinuous seismic features and acoustic anomalies, such as gas chimneys and attenuation zones, are typical indicators of active fluid migration, which are not observed here (Gay et al. 2007, Cartwright et al. 2007).

In the study area, evidence suggests that these depressions may have formed due to bottom current processes, similar to patterns described by Maestrelli et al. (2020) in the Ceará Basin, where depression trails result from cyclic steps. In such environments, the interaction between contour currents, velocity changes, and substrate heterogeneities can produce circular or elongated depressions, with distribution and dimensions dependent on current intensity and direction (Stow et al. 2009).

Additionally, considering the spatial distribution of circular depressions—concentrated in the area near the Ariós Canyon—and their proximity to mass-wasting regions, it is possible that part of these features is associated with repetitive depositional processes and seafloor instabilities, similar to the cyclic steps described by Maestrelli et al. (2020) and Lawrence & Aaron (2020). These structures may result from alternating deposition and erosion induced by turbidity flows or pulsating contour currents, promoting the development of aligned and stepped depressions on the continental slope. While no acoustic anomalies indicate active fluid migration, the morphology and geomorphological context suggest that combined hydrodynamic and gravitational processes played a key role in their formation.

Thus, the circular features observed do not display characteristics typical of pockmarks, as there is no evidence of subsurface fluid flow. Instead, the most plausible hypothesis is that they represent depressions formed by hydrodynamic processes, possibly linked to the action of intense contour or bottom currents (e.g.: Maestrelli et al. 2020). High-resolution seismic data could further investigate the subsurface of these features to confirm this hypothesis.

5.2.3 Subaqueous Dunes: Recording Seafloor Currents

Subaqueous dunes are sedimentary features found in various marine environments, including the upper continental slope and deeper areas, forming predominantly under persistent bottom currents and occasionally modified by residual turbidity flows (Reeder et al. 2011, Wynn & Stow 2002). In the study area, two of the three mapped dune fields occur on the upper slope, while the third is located in the lower slope, suggesting the influence of multiple current regimes along the depth gradient (Fig. 13). Dunes in deeper areas are associated with zones below gullies and along canyon flanks, indicating that sediment reworking was driven by the interaction of bottom currents and decreasing gravity flows, responsible for sediment redistribution along the slope (Wynn & Stow 2002).

Analysis of crest orientation shows a general south–north alignment in the shallower dune field (650–800 m), possibly related to slope gradient and/or the presence of gullies and fractures acting as flow corridors (Wynn & Stow 2002). In this sense, the south-north orientation may reflect bottom currents originating in the east and flowing westward, such as the North Brazil Undercurrent (SNB) (Schott et al. 2005), or result from a sum of different flow vectors modulated by local morphology, such as incisions and ravines on the slope and differences in depth in the S-N direction.

In the deeper dune fields (800–1,550 m), crest orientation is NW–SE. Some marine systems exhibit multiple bottom current orientations, producing overlapping dune fields or dunes with different crest directions (Reeder et al. 2011). Therefore, the differentiated arrangement of dune fields in the study area suggests variations in current regime or a dominant flow phase (Wynn & Stow 2002). Compared to regions such as the South China Sea, where fine to medium sand dunes can exceed 350 m in wavelength (Reeder et al. 2011), the smaller dimensions observed locally (<100 m crest spacing) indicate a relatively low-energy regime or conditions specific to this slope sector. Accordingly, NW–SE dune fields likely developed under SW–NE bottom currents, consistent with canyon orientation and slope inclination, while current morphology may reflect episodic reworking by higher-density sediment flows.

The presence of subaqueous dunes at different slope depths and with variable crest orientations evidences a dynamic and heterogeneous environment, influenced by structural orientation (incisions, gullies), slope gradient, and current regime. Crest orientation analysis provides a preliminary inference of flow direction, though secondary or multiple sedimentation cycles cannot be excluded (Wynn & Stow 2002).

5.4 Compilation of Continental Slope Geomorphological Features Adjacent to the Jaguaribe River: Support for Exploration, Marine Spatial Planning (MSP), and Regional Sustainability

The study area adjacent to the Jaguaribe River exhibits a diverse set of geomorphological features, reflecting the complex interplay of depositional and erosional processes along the continental slope. Gullies were identified in the upper sectors, often near canyon heads, showing significant variations in width and length, such as the gully located between the Ponta Grossa and Fontainha Canyons, which reaches 5,085 m in length and up to 2,940 m in width. In the upper portion, mass-wasting features are also observed at different evolutionary stages, including semicircular landslides near the Fontainha and Lagoa do Mato Canyons and triangular-shaped collapse areas with widths ranging from 1,838 m to 5,073 m. Furthermore, sedimentary ridges were predominantly mapped in the lower portion of the slope, particularly between the Icapuí and Ponta Grossa Canyons, including a prominent triangular feature measuring 1,452 m in width and 2,213 m in length. Additionally, five circular depressions were cataloged between the Paripueira and Ariós Canyons, with diameters ranging from 157 to 445 m and no evidence of fluid escape.

Regarding depositional features associated with current dynamics and gravity-driven flows, dune fields stand out in the upper and middle portions of the slope, with average crest spacing between 85 m and 98 m. Furrows and sedimentary deposits were also observed, as well as canyons and their distributaries arranged at different morphological stages. In general, the upper slope is characterized by a gentle inclination, concentrating canyon heads and some gullies, whereas the middle and lower slope host most of the other features, such as mass-wasting areas, sedimentary ridges, and dunes. This compartmentalization reinforces the influence of slope gradient, ocean currents, and gravity-driven flows on the evolution and configuration of the submarine landscape.

In summary, the integrated characterization of geomorphological features along the continental slope adjacent to the Jaguaribe River reveals a dynamic, multiphase system in which erosional, depositional, and gravitational processes interact complexly along the bathymetric gradient. The spatial organization of these features—from gullies and canyon heads on the upper slope to sedimentary ridges, dunes, and mass-wasting areas in deeper portions—reflects the combined influence of structural morphology and regional hydrodynamics.

This compartmentalization and morphological diversity have direct implications for assessing geohazards, MSP, and the responsible exploitation of natural resources, as they allow the identification of unstable areas, sediment corridors, and potential geohabitats. Thus, beyond merely describing individual features, this synthesis highlights the importance of an integrated understanding of the submarine landscape as a strategic tool for environmental management and sustainable development of the Ceará continental margin.

The characterization of these features also has direct implications for understanding geohabitats (sensu Rengstorf et al. 2019), as each structure (canyons, gullies, dunes, etc.) can provide specific substrate conditions, nutrient circulation, and environmental heterogeneity, supporting diverse benthic communities. Gullies, for example, may concentrate currents rich in organic matter, while canyons act as sediment transport corridors, influencing the distribution of organisms and connectivity among marine communities across different depth gradients (Freiwald et al. 2019).

From a sedimentary and exploration perspective, the presence of turbidite fans or contourite deposits along the slope may indicate areas with potential hydrocarbon storage (Maestrelli et al. 2020). Gravity-driven flows, turbidity currents, and contour currents can generate sediment layers with relatively uniform grain size and good porosity, forming potential subsurface reservoirs (Prather et al. 2020). Consequently, detailed mapping of features such as mass-wasting areas or sedimentary ridges contributes to understanding depositional architecture, helping to identify analogs of exploration targets and areas with higher hydrocarbon accumulation potential.

Simultaneously, geomorphological characterization and understanding of sediment dynamics are essential for marine spatial planning, especially in coastal-oceanic regions that may support multiple uses (Sardá et al. 2020). This research supports the identification of benthic geohabitats of ecological relevance, guiding management decisions, delimitation of fishing areas, submarine cable routes, and potential offshore energy installations. Moreover, identifying regions subject to unstable processes, such as mass-wasting, is crucial for risk prevention and establishing maritime occupation guidelines.

6. Conclusions

The geomorphological characterization of the eastern Ceará continental slope highlights a remarkable variety of submarine features, including 13 canyons, sedimentary ridges, five circular depressions, nine mass-wasting zones, as well as several gullies and three dune fields. This geomorphological diversity underscores the complex and dynamic nature of the study area, where erosional and depositional processes act in a coupled and interdependent manner.

The identified submarine canyons are predominantly in a transitional stage, with some already exhibiting characteristics of mature canyons (Jaguaribe and Canoa Quebrada). The presence of gullies, mass-wasting areas, sedimentary deposits, and dunes along the slope corroborates the notion of an active system, shaped by gravity-driven flows and bottom currents that influence local morphology.

The detection of potentially unstable structures, such as landslides and gullies, highlights the need for careful consideration of possible geohazards. These areas may pose risks to offshore infrastructure installations (e.g.: oil exploration, wind farms, and submarine cable deployments) due to the susceptibility to collapses and substrate instabilities.

The results obtained in this study are unprecedented for the eastern Ceará continental slope, providing a comprehensive overview of the main submerged features and contributing to the scientific understanding of a deep marine depositional environment that remains poorly studied. These findings offer valuable support for future research on geohabitats, as well as for the planning of submarine cables and pipelines, naval operations, geohazard assessments, and environmental management. Furthermore, the mapping and monitoring of potential economically relevant analog deposits, such as turbidite and contourite systems, highlight the practical significance of the data collected, supporting exploratory activities and marine spatial planning, thereby contributing to the safe and sustainable development of activities in the region.

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M.L.S.N.: Writing – original draft, Writing – review & editing

G.A.M.M.: Writing – original draft, Writing – review & editing

J.C.A.N.: Data curation, Writing – original draft, Writing – review & editing

H.V.: Data curation, Funding acquisition, Project administration, Resources, Software, Supervision, Writing – original draft, Writing – review & editing

N.M.A.: Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Visualization, Writing – original draft, Writing – review & editing

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