Geotemas, Pau dos Ferros, RN, Brasil
ISSN: 2236-255X, v. 16, 2026.

DETAILED GEOMORPHOLOGICAL CHARACTERIZATION AND ASSOCIATED RISK IN THE RASA PALEO-CLIFF, RJ

Caracterização geomorfológica detalhada e riscos associados na paleofalésia da Praia Rasa, RJ

Caracterización geomorfológica detallada y riesgos asociados en el paleocantil de Praia Rasa, RJ

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https://doi.org/10.33237/2236-255X.2026.7439

Article History
Received: 25 august, 2025
Accepted: 26 december, 2025
Published: 22 february, 2026

ABSTRACT

The paleocliff of Praia Rasa, located at the municipal boundary between Cabo Frio and Armação dos Búzios (Rio de Janeiro state), represents the southernmost occurrence of cliffs developed in Barreiras Group deposits along the Brazilian coast, constituting a feature of significant geomorphological and environmental importance on the coastline of Rio de Janeiro state. In this context, the objective of this study was to integrate a critical literature review with detailed aerial photogrammetric mapping, aiming to characterize the morphology of the escarpment, identify signs of instability, and assess land use and land cover. From the three-dimensional products, topographic profiles and slopes were extracted, and additional cartographic products were generated, which supported a supervised classification of land use and land cover. The results indicate a scenario of anthropogenic pressure in which increased urban density near the crest, road cuts on the slopes, and fragmentation of vegetation cover are associated with morphological features such as a straight-line alignment of the escarpment, talus deposits, and incision by gullies, evidencing active retreat in weakly consolidated materials. According to the legal framework, the feature meets the criteria for a Permanent Preservation Area, requiring setback zones, adequate stormwater drainage, vegetation maintenance and restoration, and periodic monitoring. The study aimed to provide a technical-scientific basis applicable to local land use planning and risk management.

Keywords: Coastal cliff; UAV; Barreiras Group; Permanent Preservation Area (APP).

RESUMO

A paleofalésia da Praia Rasa, situada no limite municipal entre Cabo Frio e Armação dos Búzios (RJ), representa a ocorrência meridional de falésias desenvolvidas em depósitos do Grupo Barreiras no litoral brasileiro, conferindo uma feição de elevada relevância geomorfológica e ambiental no litoral do estado do Rio de Janeiro. Diante desse contexto, o objetivo do estudo foi integrar uma revisão crítica da literatura e o mapeamento de detalhe por aerofotogrametria, visando caracterizar a morfologia da escarpa, identificar indícios de instabilidade e avaliar o uso e cobertura do solo. A partir dos produtos tridimensionais, foram extraídos perfis topográficos e declividades, além de gerar demais produtos cartográficos, que subsidiaram a classificação supervisionada do uso e cobertura do solo. Os resultados indicam um cenário de pressão antrópica, no qual o adensamento urbano junto à crista, os cortes viários nas vertentes e a fragmentação da cobertura vegetal se associam a feições morfológicas como alinhamento retilíneo da escarpa, depósitos de tálus e dissecação por sulcos, evidenciando recuo ativo em materiais pouco consolidados. À luz do arcabouço legal, a feição atende aos critérios de Área de Preservação Permanente, demandando faixas de recuo, drenagem pluvial adequada, manutenção e restauração da vegetação e monitoramento periódico. O estudo buscou oferecer uma base técnico-científica aplicável ao planejamento e à gestão do risco para a localidade.

Palavras-chave: falésia; ARP; Grupo Barreiras, Área de Preservação Permanente.

RESUMEN

El paleocantil de Praia Rasa, situado en el límite entre Cabo Frio y Armação dos Búzios (estado de Río de Janeiro, Brasil), representa la ocurrencia meridional conocida de acantilados costeros desarrollados sobre depósitos Barreiras a lo largo de la costa brasileña constituyendo una forma del relieve de elevada relevancia geomorfológica y ambiental en la costa del estado de Río de Janeiro. En este contexto, el objetivo del estudio fue integrar una revisión crítica de la literatura con un mapeo detallado mediante aerofotogrametría, con el fin de caracterizar la morfología de la escarpa, identificar indicios de inestabilidad y evaluar el uso y la cobertura del suelo. A partir de los productos tridimensionales se extrajeron perfiles topográficos y pendientes, además de generar ortomosaicos y cartografía temática, que sirvieron de base para la clasificación supervisada del uso y la cobertura del suelo. Los resultados indican un escenario de creciente presión antrópica, en el que la expansión urbana próxima a la cresta, los cortes viales en las vertientes y la fragmentación de la cobertura vegetal se asocian con rasgos morfológicos como el alineamiento rectilíneo de la escarpa, depósitos de talud y disección por surcos, evidenciando un retroceso activo en materiales poco consolidados. A la luz del marco legal vigente, la feición cumple los criterios de Área de Preservación Permanente, requiriendo franjas de protección, drenaje pluvial adecuado, mantenimiento y restauración de la vegetación y monitoreo periódico. El estudio ofrece una base técnico-científica para apoyar la planificación ambiental y la gestión del riesgo a escala local y en otras áreas con ocurrencia de falésias sometidas a ocupación humana.

Palabras clave: Acantilado costero; RPAS; Grupo Barreiras; Área de Preservación Permanente (APP).

1 INTRODUCTION

Cliffs are geomorphological features of great geo-environmental importance, characterized by steep ramps or near-vertical scarps sculpted into the coastal margin (Suguio, 1988; 1992; Vilas Boas et al., 2001; Terefenko et al., 2024). Their origin and development are closely linked to the erosive dynamics of waves and marine currents, to subaerial processes (precipitation, surface runoff), and, in some places, to tectonic factors that influence the uplift or subsidence of blocks (Bird, 2008; Maia et al., 2022). In the Quaternary context, sea level variations conditioned cyclic phases of erosion followed by stabilization, such that many cliffs are active on the present-day coastline, while others correspond to fossilized cliffs or paleo-cliffs, indicative of ancient shorelines abandoned by marine regression in the late Holocene (Moura-Fé, 2014; Maia et al., 2022).

In Brazil, cliffs occur from the Ceará coast to the northern coast of Rio de Janeiro state. Most predominantly and contiguously on the Northeast coast, there is the so-called “Tabuleiros Coast” (Costa dos Tabuleiros in Muehe, 2001), extending from Rio Grande do Norte to Bahia, with active scarps that can reach tens of meters in height (e.g., the cliffs of Pipa, RN and Barra de Tabatinga, PB) and that are widely recognized for their scenic and touristic value. In contrast, on the Southeast coast the occurrences are more limited, with only a few escarpment features that are active. These are usually associated with Cenozoic sediments of the Barreiras Group or related units, which outcrop discontinuously from southern Espírito Santo to northern Rio de Janeiro (Alheiros et al., 1988; Morais, 2001; Mello, 2019; Ferreira, 2020).

The Barreiras Group consists of poorly consolidated siliciclastic deposits of Miocene-Pliocene age, accumulated in continental to transitional environments during major eustatic variations in the Neogene (Arai, 2006; Nunes et al., 2011; Nunes et al., 2019; Rossetti, 2009). It is a lithostratigraphic unit distributed almost continuously along approximately 4,000 km of the Brazilian coast, from Amapá state to Rio de Janeiro state (Amador, 1982; Bezerra et al., 2006). These deposits form extensive coastal tablelands (high, flattened surfaces between 20 and 50 m in elevation), whose edges generally end in abrupt scarps of up to approximately 25° inclination (Santos Junior et al., 2015). They exhibit great internal heterogeneity of facies and structures, resulting from multiple fluvio-deltaic and marine depositional cycles during the Neogene (Nunes et al., 2011; Garcia, 2015).

The complexity regarding ages and evolutionary processes has led several authors to prefer the designation Barreiras Group instead of “Formation,” reflecting the arrangement of correlated sedimentary subunits within the sequence (Alheiros, 1988; Silva and Machado, 2014; Silva et al., 2020). In the Brazilian Southeast, few investigations have detailed the local characteristics of the Barreiras Group. Among these, notable works include Morais (2001, 2006), on Barreiras facies in northern Rio de Janeiro state, and Mello (2019), on the compartmentalization of Barreiras tablelands in southern Espírito Santo. Geomorphological studies using detailed mapping methods (such as Pereira et al., 2024) are even rarer, highlighting a research gap on the topic.

Despite their scientific and scenic importance, cliffs and paleo-cliffs suffer intense anthropogenic pressures from real estate developments, urban expansion, and mass tourism, which increase their vulnerability and the geotechnical risks associated with inappropriate land use (Brito, 2005; Silva et al., 2020). Construction at the top or base of these slopes can exacerbate erosive processes, increase the load on the slopes, and compromise the stability of the scarps. In the Brazilian context, many coastal cliffs of poorly consolidated materials already have a history of collapses or landslides. A tragic example occurred in 2020 at Praia de Pipa (RN), when the collapse of part of an active cliff weakened by marine erosion at the base caused the death of three people (Moreira, 2020). This episode highlighted the urgency of properly assessing and managing geomorphological risk in occupied cliff areas.

The paleocliff of Praia Rasa, the focus of this study, represents an emblematic case. Located at the municipal boundary between Cabo Frio and Armação dos Búzios (Rio de Janeiro), it is a set of relict coastal scarps corresponding to the southern limit of the occurrence of Barreiras cliffs along the Brazilian coast. Given the above, this work aims to integrate an updated review of cliffs in Barreiras deposits, map the morphology of the Praia Rasa paleocliff, diagnose signs of instability and retreat, assess land use and land cover, and discuss the need for its classification as a Permanent Preservation Area and risk management. The area is under intense territorial pressure characterized by strong real estate speculation, land disputes, and irregular settlements associated with urban expansion between Cabo Frio and Armação dos Búzios. It is an area with increasing human presence, new road construction, and development projects near the escarpment edge, which amplifies the exposure of populations and infrastructure to geomorphological instability processes. The lack of systematic detailed-scale studies and technical tools for land use planning contributes to the normalization of risk and the recurrence of socio-environmental conflicts.

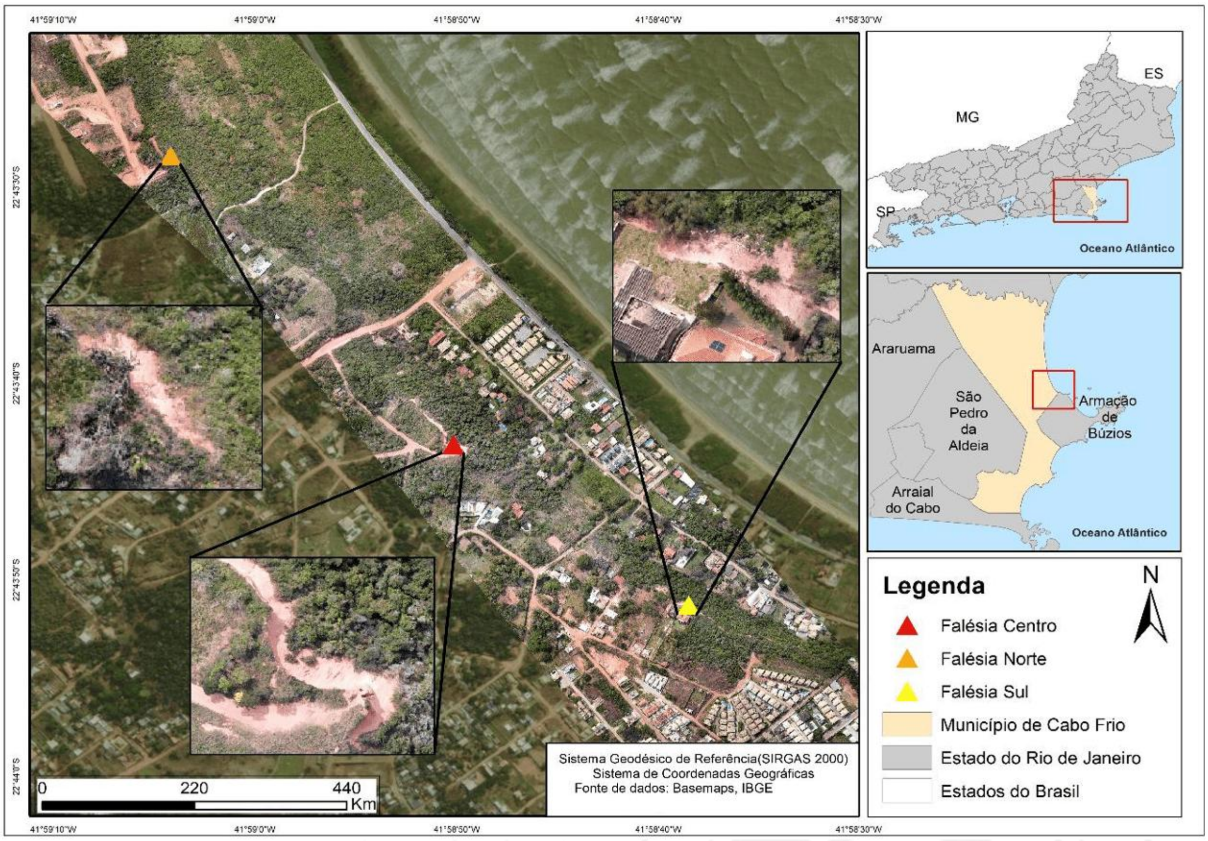
2 MATERIALS AND METHODS

The methodological strategy adopted combined three main stages: a literature review; acquisition of aerial images by an unmanned aerial vehicle (UAV) and photogrammetric processing with 3D modeling of the study area; and integrated analysis of geomorphological and land use data.

2.1 Study Area

The study area is located at Praia Rasa, north of the municipality of Armação dos Búzios and south of the Tamoios district (Cabo Frio), on the eastern coast of Rio de Janeiro state (Figure 01). Along the analyzed stretch, three main erosive scarp sectors were identified, here referred to as South Cliff, Central Cliff, and North Cliff, which correspond to the segments of the paleocliff mapped in this study. Each sector features a higher promontory or crest followed by a steep decline towards the coastal plain, forming segments of the relict escarpment.

Figure 01 – Location map of the study area with insets of orthorectified images of the escarpment segments.



Source: Basemaps, IBGE. Authors.

2.2. Literature Review and Preliminary Analysis

Initially, a literature review was conducted on coastal cliffs and the Barreiras Group to obtain a representative overview of the Brazilian coast. This review aimed to consolidate concepts and criteria for identifying relict and active cliffs, understanding their morphodynamics and their relationship to the compartmentalization of the regional relief, as documented in books, dissertations, theses, and academic articles (e.g., Suguio, 1992; Moura-Fé, 2014; Mello, 2019; Maia et al., 2022, among others). It served to establish diagnostic criteria and working hypotheses to guide the identification and comparison of cliffs/paleocliffs, their association with the Barreiras deposits, and the interpretation of field data.

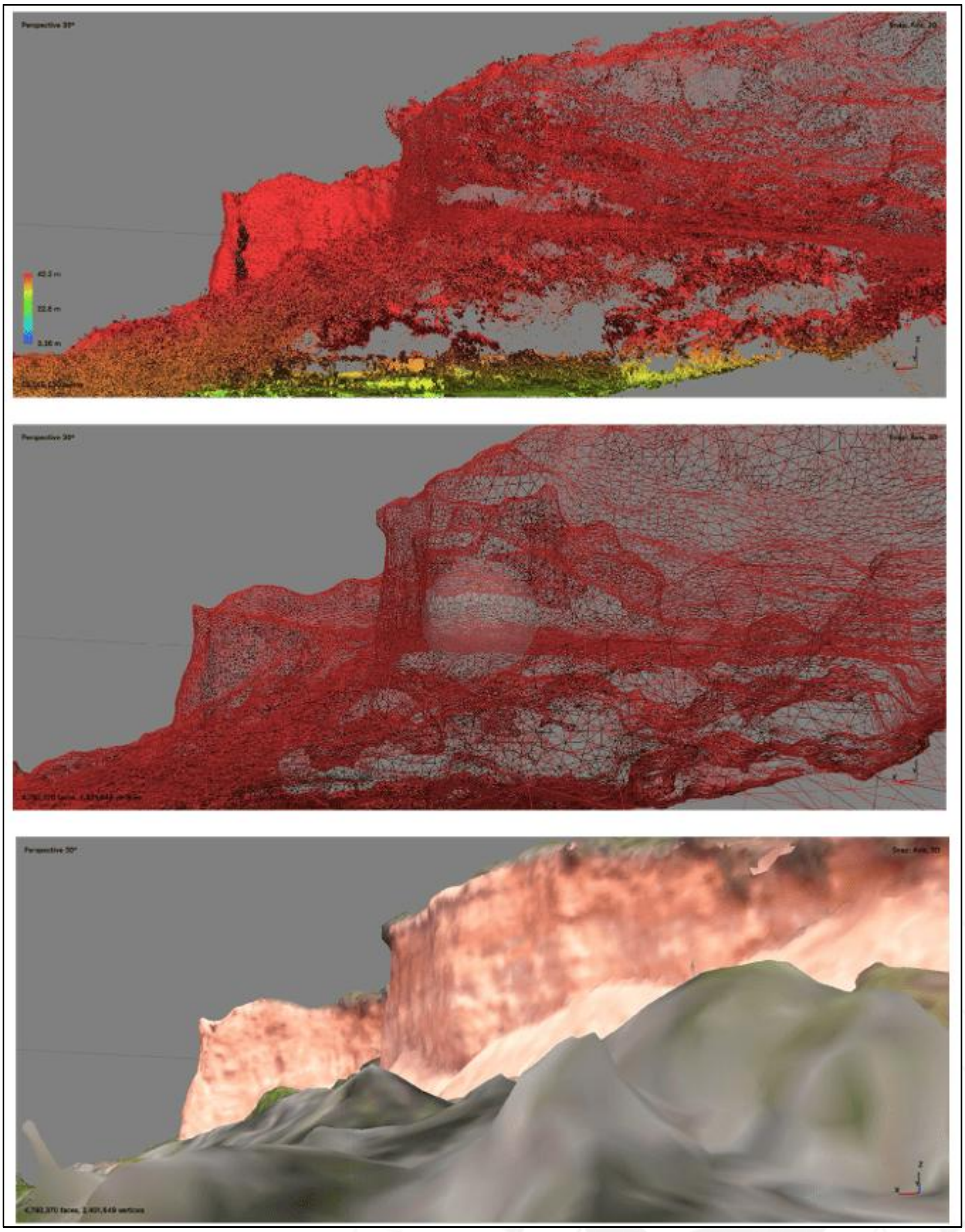
2.3. Aerial Photogrammetric Survey

To map the paleocliff and its morphology, a high-resolution aerial photogrammetric survey using a UAV was carried out. Planning began with the analysis of satellite images (Google Earth Pro) and an SRTM terrain model to delimit the area of interest, covering the escarpment and adjacent terrain, and to estimate the flight altitude. Then, an automated flight plan was prepared in the Map Pilot Pro app, defining a coverage grid that ensured wide image overlap. Acquisition parameters were: flight altitude of 120 m, front/side overlap of 80% and 70%, resulting in an average Ground Sample Distance (GSD) of 3.3 cm/pixel. The total area surveyed was 0.6 km².

The UAV employed was a DJI Air 2S model. For safety reasons, no ground control points (GCPs) were placed in the area, as prolonged team presence in conflict-prone or difficult-to-access zones was avoided. In the absence of ground control points, the relative planimetric accuracy of the drone's GNSS (3 to 5 m) was adopted along with altimetric reference points identified in Google Earth Pro, which integrates SRTM and LiDAR data with advanced processing algorithms. These controls reduced the initial altimetric errors and were sufficient for the objectives of the survey.

The aerial images were processed using Agisoft Metashape 2.1.2 software, employing digital photogrammetry techniques based on Structure from Motion (SfM) for three-dimensional reconstruction (Guisado-Pintado et al., 2019).

Figure 02 – Different phases of the aerophotogrammetric processing, with an oblique view of the cliff escarpment in the survey area, simulating the view of an in situ observer. In descending order: Dense Point Cloud, Triangular Mesh, and Textured Model, steps of the 3D model processing.



Source: Authors.

Processing steps included photo alignment, generation of a dense point cloud, a polygon mesh, and a georeferenced orthomosaic. Some of the products generated were a

Digital Surface Model (DSM) and a Digital Elevation Model (DEM) with spatial resolution of approx. 13 cm, a textured triangular mesh (approx. 4.7 million faces) representing the escarpments in 3D (Figure 02), and a high-definition orthophotomosaic (pixel = 3.3 cm). Point editing of the dense cloud was performed to remove noise (spurious points) by applying reconstruction and reprojection filters within the software. From these products, topographic profiles and slopes were extracted, and the orthomosaic was used to generate a land use and land cover map within a GIS environment (ArcGIS 10.8).

3 RESULTS AND DISCUSSION

3.1. Geological and geomorphological framework

The literature review encompassed a wide range of studies addressing the Barreiras Group/Formation and associated cliffs, covering different sectors of the Brazilian coastline. In general terms, there is broad consensus that Barreiras sediments represent an essentially Neogene depositional pattern, with ages ranging from the Lower Miocene to the Upper Pliocene (23 to 2.5 million years). Most authors describe sandy to sandy-clayey lithologies, poorly consolidated, frequently exhibiting reddish or yellowish mottling as a result of weathering and ferruginous oxidation. In some localities, conglomeratic horizons at the base and lateritic crusts at the top are reported, indicating distinct depositional pulses followed by cementation processes (e.g., Furrier et al., 2006).

The origin of Barreiras sediments is interpreted in different ways. Many studies suggest predominantly continental fluvial-deltaic input, whereas others highlight coastal marine influence during transgressive phases (Arai, 2006; Nunes et al., 2011). This duality reflects major Neogene eustatic movements that controlled depositional regimes. Accordingly, the Barreiras Group is understood as a polyphasic deposit, resulting from the progradation of deltaic and fluvial systems interspersed with transgressive events, which explains its extensive distribution along thousands of kilometers of the Brazilian coast and its marked local facies variability.

A noteworthy aspect identified in the review concerns terminological differences. In northeastern Brazil, where Barreiras outcrops form expressive active cliffs, the term “Barreiras Formation” is commonly used (e.g., Bezerra et al., 2006; Mansur et al., 2012; Moura-Fé, 2014; Morais, 2020; Maia et al., 2022) to designate locally continuous sedimentary units, sometimes incorporating subunit nomenclature. In contrast, in broader regional contexts or when emphasizing depositional heterogeneity, several authors prefer the term "Barreiras Group" (e.g., Rodrigues et al., 2020), reinforcing the interpretation of a set of correlated sedimentary layers rather than a single homogeneous formation. From a geomorphological perspective, the reviewed studies consistently highlight coastal tablelands as the dominant landforms and coastal cliffs as features associated with the margins of these tablelands, where the Barreiras sedimentary package is exposed.

3.2. Regional and local physical-environmental characterization

Adopting an integrated landscape perspective requires consideration of geological, pedological, biogeographical, climatic, and sociocultural aspects, which together condition the observed landforms. Geologically, the region lies within the Búzios Complex, a Meso–Neoproterozoic metamorphic unit composed predominantly of paragneisses (Heilbron et al., 1982; Fonseca et al., 1998). Along the Búzios headland, coastal gneisses outcrop at elevations between 30 and 80 m, whereas to the west lies the Quaternary lowland of Cabo Frio. Barreiras Group sediments unconformably overlie portions of the crystalline basement, forming tablelands and gentle hills, resulting in a locally diverse lithological framework: Precambrian crystalline rocks (granitoid gneisses and migmatites) on the peninsula and substrate, partially covered by Neogene sandy-clayey Barreiras deposits (CPRM, 2016). This mixed geology shapes a landscape in which rounded hills developed on resistant lithologies contrast with escarpments and gullies carved into less consolidated sedimentary deposits.

In the immediate vicinity of the paleocliff, strongly weathered Proterozoic paragneisses and schists crop out (CPRM, 2016), upon which sandy-conglomeratic sedimentary packages attributed to the Barreiras Group are superposed (Morais, 2001). This lithological heterogeneity creates contrasts in resistance and permeability: metamorphic rocks form more resistant hills and rocky shores, while Paleogene–Neogene sediments, being less consolidated, give rise to escarpments and ravines.

According to Morais (2001) and Morais et al. (2006), the origin or reactivation of this paleocliff dates back to approximately 5.1 ka BP, when mean sea level reached about +3 m relative to present during the Holocene transgressive maximum. Subsequent marine regression permanently exposed the escarpment, which is now located roughly 300 m inland, separated from the modern shoreline by a narrow coastal plain. This landform conditioned the development of a unique ecosystem at its base, locally known as the "stone mangrove," a term used by Morais (2001) and Mansur et al. (2012) to describe a mangrove established on rocky slabs, far from river mouths. This mangrove is sustained by diffuse freshwater discharge from the Barreiras aquifer within the adjacent cliff (Mansur et al., 2012). Although of high ecological and scientific relevance, this environment is currently highly degraded and reduced due to anthropogenic actions such as deforestation and illegal landfilling.

From a pedological standpoint, the area encompasses distinct soil compartments correlated with relief. On the Quaternary coastal plain, Quartzarenic Neosols (acidic, nutrient-poor quartz sands) with sparse restinga vegetation predominate, along with Haplic Gleysols in marshy sectors subject to periodic flooding (Dantas et al., 2009). At the cliff foot and on steep slopes, shallow and young soils such as Eutrophic Regolithic Neosols and Cambisols occur, whereas the tops of the regional tablelands are dominated by Yellow Latosols and Yellow Argisols (Fontana et al., 2022). Together, this soil diversity reflects the interaction between relief, parent material, and climate, influencing both vegetation distribution and local erosional processes.

The region's natural vegetation was originally classified as Lowland Semideciduous Seasonal Forest (Veloso et al., 1991), also referred to as Coastal Semideciduous Forest (Farág, 1999). This transitional forest formation has a canopy approximately 8 to 12 m high, with some emergent trees reaching 15 to 18 m, and exhibits partial leaf loss during the dry season. Currently, due to fragmentation and land occupation, this native vegetation persists only sparsely and in secondary stages on the cliff and adjacent slopes. Regional studies indicate that, on coastal tableland tops, the original vegetation has largely been replaced by pasture or sparse secondary growth due to poor soils, while remnant native flora survives on slopes under specific edaphoclimatic conditions (Dantas et al., 2009).

The area includes a semi-arid enclave (Köppen BSh), atypical for its latitude, resulting from the Cabo Frio upwelling system (Coe and Carvalho, 2013). Average annual rainfall is low (approximately 800 mm), with a prolonged dry season, while potential evaporation exceeds 1,200 mm per year, producing a marked water deficit and maintaining semi-arid landscape conditions (Coe et al., 2007). Persistent northeasterly trade winds, laden with marine aerosols, promote soil salinization and influence vegetation physiognomy, which displays stunted growth and coriaceous leaves. This regime also intensifies aeolian erosion in exposed areas. Consequently, the dry and windy climate hampers vegetation recovery, allowing erosion to advance more rapidly than revegetation in deforested areas.

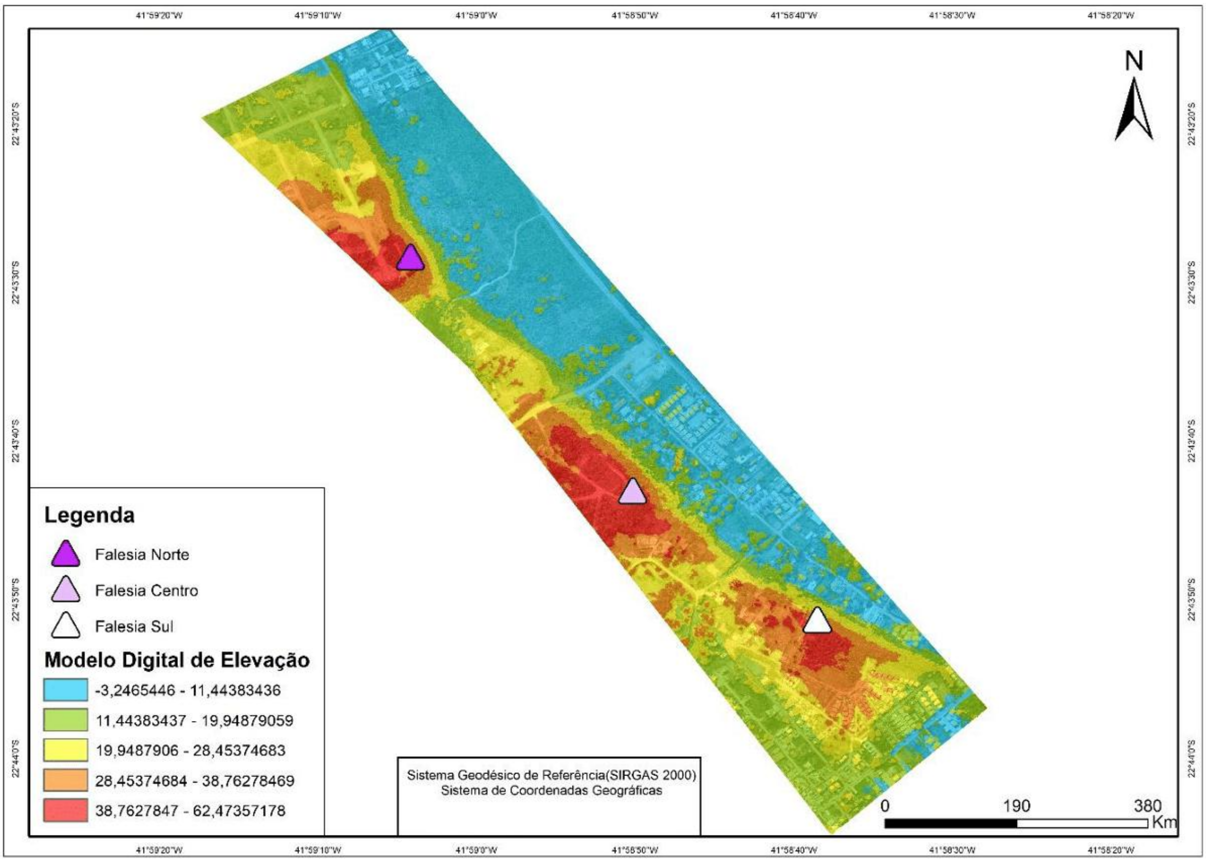
From a sociocultural perspective, the Rasa area is home to remnant traditional communities, including quilombola groups and artisanal fishers, who have historically relied on resources from the coastal plain and cliff environments. In recent decades, however, these communities have experienced strong pressure from the urban expansion of Búzios, one of the main tourist destinations in Rio de Janeiro state (Pereira, 2013). Real estate developments and irregular occupations have encroached upon traditional lands, generating land conflicts and reports of territorial dispossession, as documented by JFRJ (2024) and Vaz (2021). Beyond sociocultural impacts, the occupation of the cliff edge by houses and roads increases geological risk, given the inherent instability of steep, poorly consolidated slopes. Satellite imagery and field inspections confirm deforestation along the cliff belt and constructions very close to the edge (Folha dos Lagos, 2018).

3.3. Geomorphological analysis of the Rasa cliffs

The analysis focused on characterizing escarpment morphometry (heights, slopes, transverse profiles) and identifying evidence of ongoing erosional processes or instabilities. For descriptive purposes, three main segments were considered: South, Central, and North cliffs, corresponding to the highlighted elevations along the escarpment alignment (Figure 03). Topographic profiles extracted from the DEM for each segment are illustrated in Figure 6, which also indicates their positions along the cliff crest.

Overall, the results show that the paleocliff forms an approximately rectilinear SE–NW-trending alignment, with a total length of about 1 km. Crest elevations range from 35 to 55 m above sea level, while the adjacent plain at the cliff foot lies between 2 and 5 m. The South Profile (southeastern extremity) reveals a maximum relative height of 39 m. In this sector, the escarpment displays extremely steep slopes, with nearly vertical sections reaching 90° over short stretches. The mean slope between base and crest, integrating less steep segments, ranges from 40° to 52% (two estimates obtained for subsections of the profile) (Figure 06).

Figure 03 – Map derived from the Digital Elevation Model of the study area



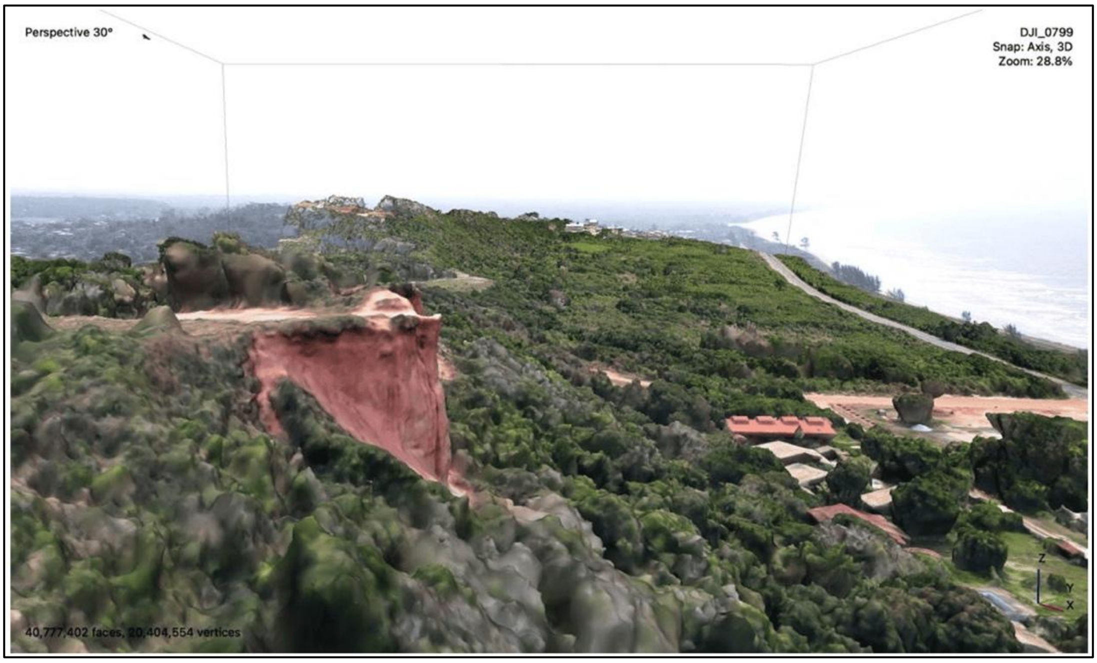
Source: SIRGAS (2000). Authors.

Field observations indicate that the exposed face consists of clayey layers interbedded with gravelly levels, with evidence of recent collapses. Blocks and debris accumulate at the base, forming a talus deposit. This debris slope indicates that gravitational processes such as slab detachment and shallow slides are actively contributing to cliff retreat. Notably, in the southern sector, urban occupation occurs very close to the edge, with a residence located only a few meters from the precipice on clayey soil, also visible in the transverse profile. This proximity constitutes a geotechnical risk situation, in which crack propagation or sudden face collapse could directly affect the structure.

The Central Profile corresponds to the highest portion of the paleocliff, reaching approximately 55 m of relative height. As shown in Figure 06, this segment exhibits a steep and imposing face: the upper 16 m approach slopes of 84°, effectively forming a near-vertical wall. Below this, the slope remains steep, resulting in an average inclination of 42° from crest to base. This is the most continuous and steepest section among the three segments.

Photointerpretation and oblique UAV imagery (Figures 04 and 05) reveal different exposed lithofacies, including subhorizontal layers of polymict conglomerates and sandy-clayey sandstones, with cream to reddish tones typical of the Barreiras Group in the region (Morais, 2001). Unlike the southern and northern segments, the central profile lacks nearby occupation at the cliff edge. Nevertheless, natural instability is evident, as sediment accumulates at the angle of repose over vegetation at the base of the bare escarpment, suggesting small-scale slides.

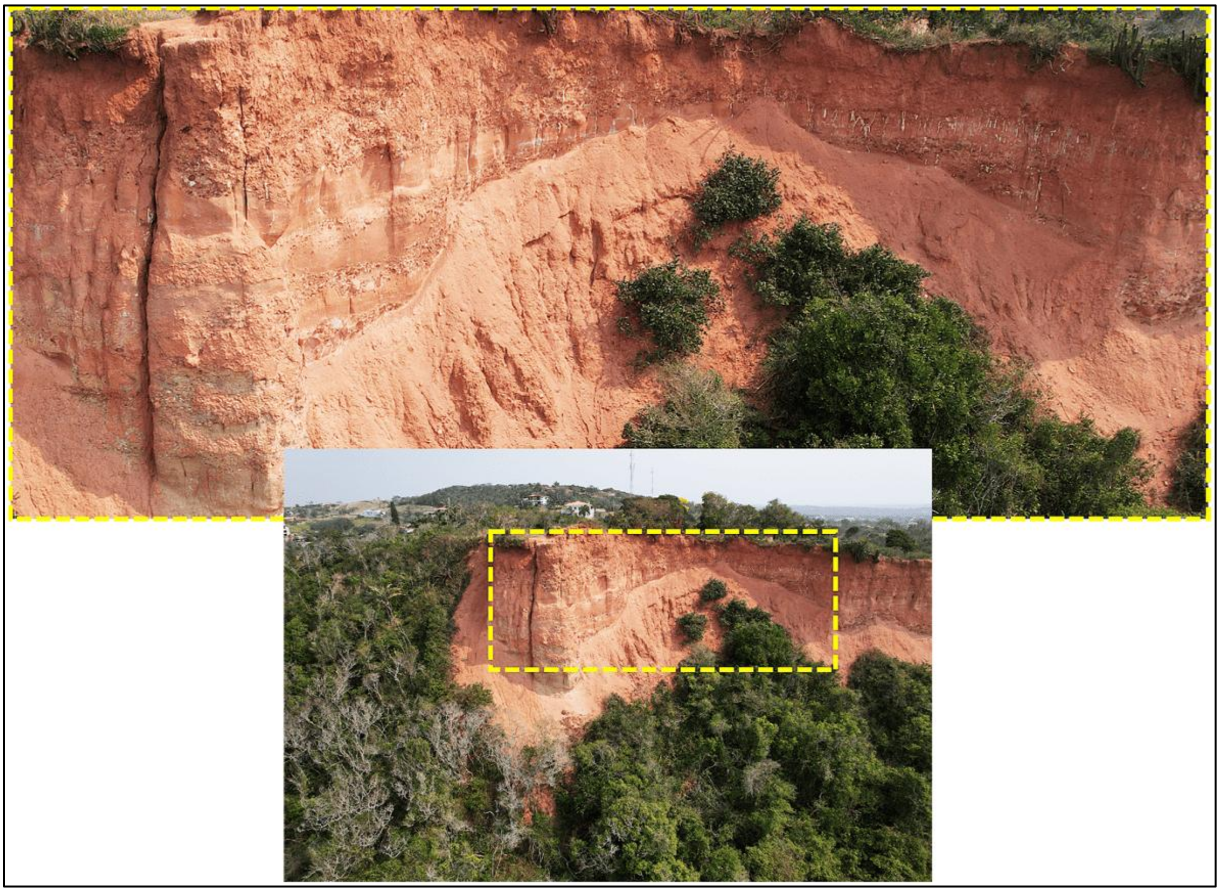
Figure 04 – Fusion of the textured model and oblique aerial image showing the Central Cliff escarpment



Source: Authors.

The North Profile (northwestern extremity) presents somewhat different characteristics. The escarpment height reaches 41 m, intermediate between the other segments. The overall mean slope from crest to base is approximately 32°, lower than in the other profiles, likely due to the presence of a sedimentary ramp at the base, where collapsed materials have gradually accumulated (Figure 06). However, the upper portion of the northern profile includes a 20 m-high steep section with a slope of 52°, indicating a still significant escarpment. In this sector, the cliff base connects more smoothly to the plain through colluvial deposits and broader footslopes, allowing greater vegetation cover upslope. This suggests that the northern sector may be relatively more stabilized, possibly due to a slightly concave morphology that retains material and reduces exposure to surface runoff and gravitational movements.

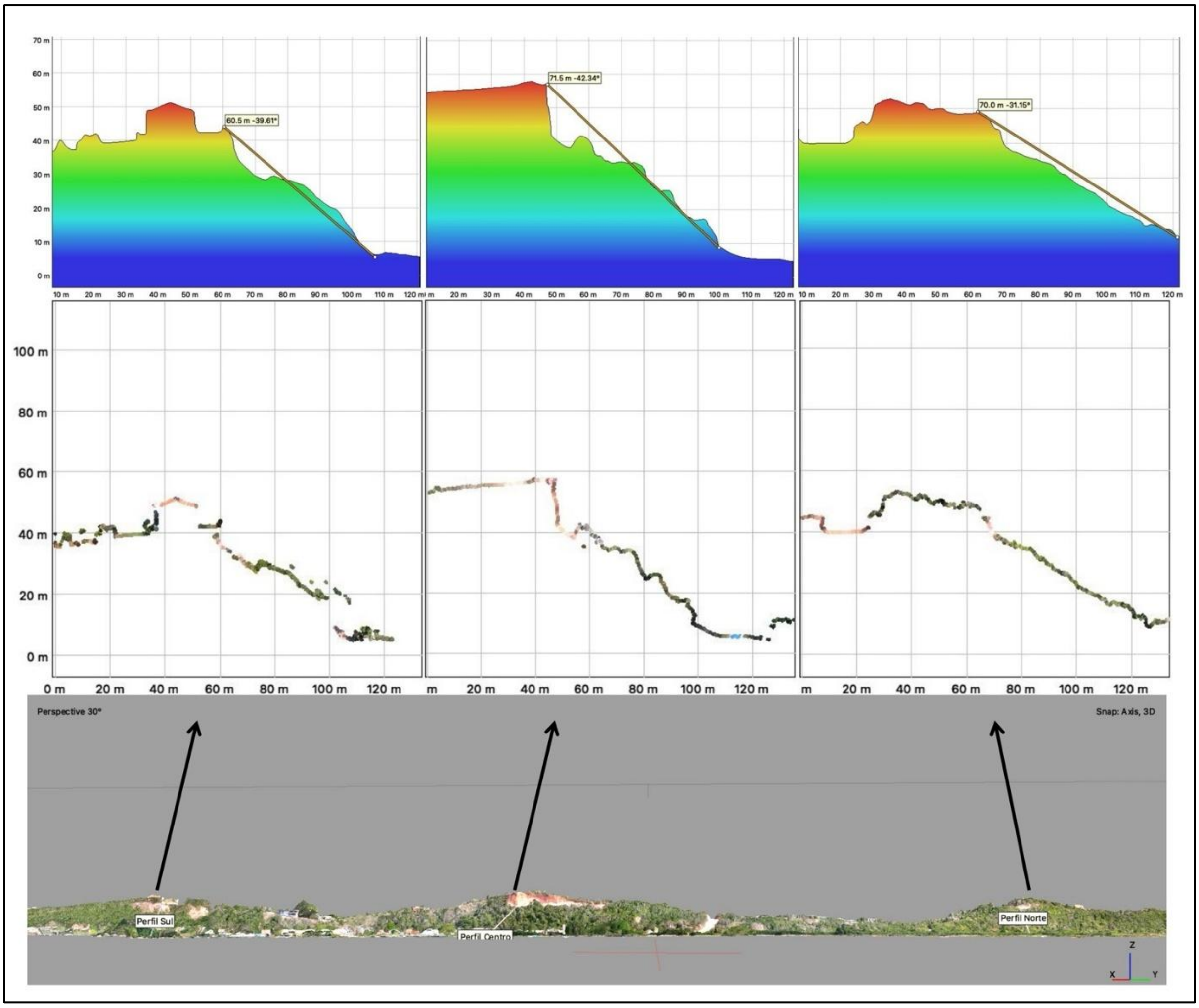
Figure 05 – Frontal view of the central paleocliff showing different lithofacies.



Source: Authors.

Integrated analysis of the three profiles reinforces that the Praia Rasa paleocliff retains geomorphological attributes typical of this landform along the Brazilian coast: steep escarpments, talus deposits at the base, and a continuous linear crest. The distribution of talus deposits indicates that, although it is a “fossil” cliff (i.e., no longer directly affected by wave action), the escarpment remains active, retreating through gravitational processes and pluvial erosion. In poorly consolidated materials such as those of the Barreiras Group, fossil cliffs commonly continue to retreat for centuries after being isolated from marine action (Brito, 2005).

Figure 06 – Southern, central, and northern topographic profiles derived from the Digital Elevation Model and textured point cloud. At the bottom of the figure, a frontal view of the textured 3D model shows arrows indicating the profile locations along the escarpment crest

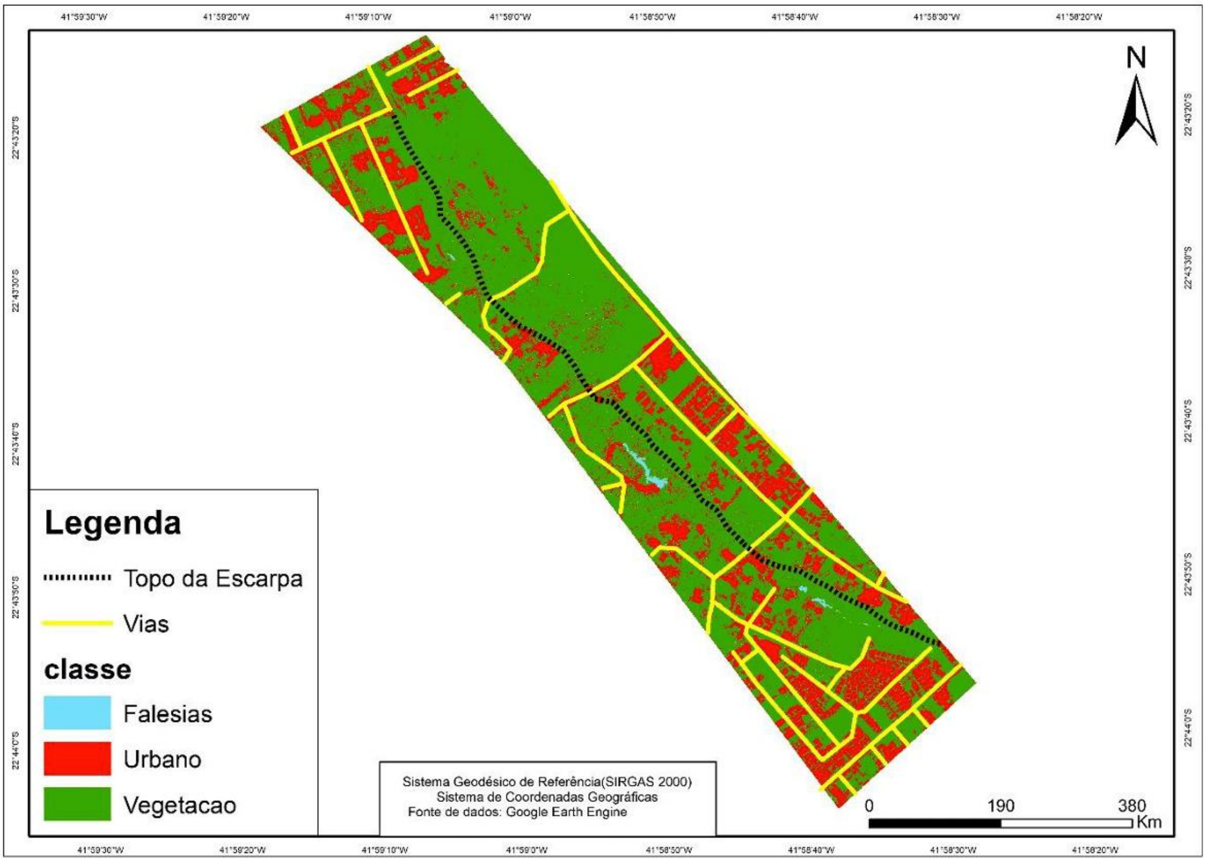


Source: Authors.

In this case, the topographic elevation and the relatively short interval since the transgressive episode (approximately 5 ka, according to Mansur et al., 2012) explain why the cliff morphology remains well preserved. The exposure of inclined sedimentary layers and erosional contacts further suggests that detailed sedimentological studies could extract valuable information on Miocene–Pliocene paleoenvironments in the region. However, within the scope of this work, the emphasis lies on practical environmental implications: confirmation of the coastal cliff nature of this escarpment reinforces its legal classification as a Permanent Preservation Area and the need for preventive risk management. Continued erosional retreat implies that areas at the cliff top may collapse in the future, especially under triggers such as intense rainfall or construction-related vibrations, if stabilization measures or appropriate land use controls are not implemented.

The land use and land cover map (Figure 07) synthesizes anthropogenic pressure on the paleocliff and its surroundings. Supervised classification using the Random Forest algorithm achieved high accuracy (Kappa ≈ 0.83) and distinguished three main classes: urban/built-up areas, vegetation (native or regenerating), and exposed cliff surface. Vegetation occupies approximately 70.4% of the mapped area (≈ 0.417 km²), concentrated on slopes and undeveloped portions of the plain. Urbanized areas account for 29.3% (≈ 0.173 km²), predominantly on the escarpment crest and along marginal roads. Exposed cliff surfaces represent only 0.4% (≈ 0.0022 km²), restricted to a narrow linear strip of bare soil and outcrops along the escarpment. Functionally, the predominance of vegetation suggests a stabilizing role on slopes, whereas the substantial extent of urban use indicates potential risk associated with land occupation near the relief edge.

Figure 07 – Land use and land cover map of the studied perimeter



Source: Authors.

Spatial interpretation of the map reveals critical proximity of developments to the cliff crest, particularly in the central-southern sector, where subdivisions approach within 5 to 10 m of the break of slope. Road and trail cuts on the slope and signs of recent deforestation are also evident, consistent with local news reports from 2018 (Folha dos Lagos, 2018). Such interventions reduce soil cohesion, intensify concentrated runoff, and may act as instability triggers, especially when combined with additional loading from buildings and vegetation removal.

These observations confirm a pattern of occupation-induced degradation at the cliff top, where impermeabilization, concentrated infiltration, and vibrations favor cracking, gully formation, and mass movements (Silva et al., 2020; Câmara and Silva, 2021), creating a risk scenario that demands land-use regulation and preventive measures consistent with the fragility of the landform.

4 FINAL CONSIDERATIONS

This study characterized the Praia Rasa paleocliff as a relict coastal escarpment carved into Barreiras Group sediments and formed under a higher Holocene sea level. It represents a singular occurrence in southeastern Brazil and appears to mark the southernmost limit of Barreiras-associated cliffs along the Brazilian coast. Preserved morphology, exposure of typical lithofacies, and evidence of retreat driven by subaerial processes confirm its cliff nature, despite its current disconnection from active coastal processes. Talus deposits, gullies, and exposed soil segments indicate ongoing instability and support the geomorphological and functional interpretation of the feature.

From a territorial perspective, its classification as a Permanent Preservation Area under CONAMA Resolution 303/2002 and the Brazilian Forest Code is unequivocal. This requires strict land-use control, particularly at the upper edge of the escarpment, where encroachment by subdivisions, vegetation suppression, and construction near the slope have been documented.

Regarding risk management, preventive priorities include establishing setback zones and protective easements at the crest, implementing stormwater drainage systems that prevent flow concentration on the escarpment, maintaining continuous vegetation cover, and promoting restoration with native species in degraded sections. In critical areas, periodic geomorphological monitoring of stability through topographic surveys or aerial photogrammetry represents a viable future approach, along with adaptation measures or assisted relocation of dwellings exposed to risk when necessary.

Cliff conservation also safeguards ecosystem services and local sociocultural values.

The stone mangrove and aquifer discharges at the base depend on the geomorphological integrity of the escarpment, while traditional quilombola and artisanal fishing communities should be actively involved in management decisions.

In summary, this work provides a preliminary technical-scientific foundation for the comprehensive protection of the Praia Rasa paleocliff and for mitigating associated risks, contributing practical guidelines for environmental planning and offering a methodological reference for analogous coastal sectors in southeastern Brazil.

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