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Technical report

Cabo Branco Cliff – João Pessoa, PB: Geomorphological characterization and associated erosional processes

Falésia de Cabo Branco - João Pessoa, PB: Caracterização geomorfológica e processos erosivos associados

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Abstract: Several active coastal cliffs have been undergoing erosional processes that cause risks and may comprise public roads and the safety of the local population and tourists. A representative example of this situation is the Cabo Branco Cliff, in João Pessoa (PB), Brazil, which recently had rock armour was placed along the coastline as a measure to reduce the erosion. In view of this, this study aims to characterize and evaluate the retraction of the escarpment, considering factors such as the rock control of the Barreiras Formation and the effects of human interventions on the top (asphalt waterproofing) and base (rock armour) of the coastal cliff. A photogrammetric survey was carried out with a drone to generate a high-resolution digital surface model (DSM) (7 cm-resolution mesh). Geomechanical tests were performed with an analog rebound hammer in some sectors of the cliff. Physical resistance tests were also performed by measuring rebound values with an analog rebound hammer. The fieldwork allowed a detailed description of erosion processes. The results indicate that the cliff's retrogradation is maintained due to persistent erosion by gravitational collapse. At present, the effectiveness of rock armour will be most noticeable in maintaining the talus deposits, since the top of the cliff will continue to recede, likely compromising even more public facilities installed there. In the long term, sea defense will be more effective in reducing the accelerated erosion of the cliff due to the change in profile and topographic gradient.

Keywords: Cliff; Erosion; Collapse; Risk.

Resumo: Muitas falésias ativas vêm passando por processos erosivos, causando riscos e comprometendo vias públicas e a segurança da população local e turistas. Um exemplo representativo desta situação é a falésia de Cabo Branco, em João Pessoa (PB), Brasil, que recebeu recentemente um anteparo erosivo em sua base como medida de contenção à erosão. Diante o exposto, o objetivo deste trabalho é caracterizar e avaliar a retração da escarpa considerando os fatores condicionantes das rochas da Formação Barreiras e os efeitos das intervenções antrópicas no topo (impermeabilização asfáltica) e na base (enrocamento). Foram realizados levantamento fotogramétrico com drone para gerar um modelo digital de superfície (MDS) de alta resolução (malha de 7 cm). Testes geomecânicos também foram realizados com esclerômetro analógico em alguns setores da falésia. O trabalho de campo permitiu a descrição detalhada de processos erosivos. Os resultados apontam para a manutenção da retrogradação da falésia em função da persistência da erosão por colapso gravitacional. No momento, a efetividade do anteparo erosivo será mais perceptível na manutenção dos depósitos de tálus, já que o topo da falésia continuará retroagindo, comprometendo ainda mais equipamentos públicos ali instalados. A longo prazo, o anteparo erosivo será mais efetivo na redução da erosão acelerada da falésia em virtude da mudança de perfil e gradiente topográfico.

Palavras-chave: Falésia; Erosão; Colapso; Risco.

1. Introduction

Coastal escarpments are widespread across the globe and can occur in a variety of lithotypes (Carpenter et al., 2014; Bird, 2016). Their evolution is generally controlled by coastal erosive processes and the properties of the constituent materials (Rogers et al., 2012; Duguet et al., 2021; Bergillos et al., 2022), i.e. the combined action of waves, rainfall, groundwater flow, beach geometry, tectonics, and lithology (Young & Carilli, 2019; Furlan, 2014; Lee, 2008; Masselink). In tectonic active margins, cliffs located along the coasts represent an exception, as their formation is primarily controlled by tectonic activity, which generates steep morphologies (Arróspide et al., 2023). Several factors explain the variability in cliff erosion rates, such as structural control, rock body geometry, wave energy (Blanco-Chao et al., 2014; Bird, 2016), and rock resistance (Prémaillon et al., 2018).

Cliffs serve as important indicators of sea-level change throughout the Quaternary, influencing coastal physiography and sediment dynamics (Davidson-Arnott, 2010). Moreover, the deposits supporting these escarpments play a significant role in the morphostratigraphic record, contributing to the understanding of sedimentary environment evolution throughout the Cenozoic (Rossetti et al., 2013a; Bezerra et al., 2020). It is important to emphasize that even on passive margins, neotectonic effects can be observed in Neogene and Quaternary sedimentary units (Blanco-Chao et al., 2014; Maia and Bezerra, 214; Rossetti et al. 2013b; Furrier, 2006; Marques, 2024). In this context, neotectonic effects include fracturing and displacements resulting from compressive deformation (Marques et al., 2024), which may locally induce dissection, adding to other factors that influence the erodibility of cliffs (Maia et al., 2022; 2024).

This study presents an analysis of the geomorphological context and erodibility of the Cabo Branco cliff in João Pessoa, Paraíba. This cliff is steep and developed in friable sedimentary rocks, situated along a narrow beach strip. For these reasons, it exhibits a high rate of erodibility, and the factors promoting such processes will be addressed in this report. The analysis will be based on the extraction of morphological data from a digital surface model (DSM) and on the acquisition of geomechanical data (rebound hardness) from the outcropping rocks, as well as on the description and classification of erosional processes and morphometric data related to the escarpment's morphology.

The guiding premise lies in detailing the geomorphological processes that trigger cliff erosion. It is important to note that although this relationship may seem obvious—given the frequent association between cliff retreat and wave-induced erosion—it is necessary to understand the rheology and its relationship with geomorphology. In this regard, different facies, degrees of diagenesis and laterization, as well as the extent of deformation and fracturing of the Barreiras Formation, may influence the predominance of specific erosional processes. Therefore, this study aims to characterize and assess the retreat process of the escarpment considering the conditioning factors associated with the rocks comprising the Barreiras Formation and the impacts of anthropogenic interventions at the top (asphalt impermeabilization) and base (rock armour) of the cliff.

2. Study Area

The Cabo Branco cliff is located within the urban area of the municipality of João Pessoa, situated in the central sector of the Paraíba coastline, northeastern Brazil. In this region, the coastline exhibits a north–south orientation and is characterized by a succession of headlands and embayments, with the presence of cliffs sculpted in rocks of the Barreiras Formation and overlying post-Barreiras sediments (Figure 01).

Figure 01. Location of the study area. A: South America and Brazil, highlighting the state of Paraíba in yellow and the city of João Pessoa (red dot). B: Coastal zone of João Pessoa.C: Study area: Cabo Branco cliffs.

The Barreiras Formation is a sedimentary unit deposited during the Neogene (Rossetti, Bezerra, & Dominguez, 2013), extending along the Brazilian coastline from the state of Rio de Janeiro to Amapá (Suguio & Nogueira, 1999). Regarding depositional environments, several authors have attributed a continental origin to the sediments of the Barreiras Formation (Mabesoone, 1972; Bigarella, 1975; Lima, Vilas Boas, & Bezerra, 2006), although transitional and marine environments are considered predominant (Arai, 2006; Rossetti & Góes, 2013; Gandini et al., 2014; Gandini et al., 2017). The origin, associated with the depositional setting, may primarily determine textural and mineralogical variations, and consequently, the lithological characteristics. These aspects, in turn, when combined with weathering and subsequent diagenetic processes, can influence the resistance of the lithology to erosional forces, resulting in different geomorphological signatures observed in cliffs along the northeastern Brazilian coast. Rossetti and Dominguez (2012) classified the sedimentary deposits of the Barreiras Formation into ten facies associations, predominantly transitional marine in origin.

According to Rossetti et al. (2007), the facies variations within the Barreiras Formation reveal deposition influenced by continental, transitional, and marine depositional systems. From a tectonic perspective, the works of Bezerra et al. (1998, 2001), Bezerra & Vita-Finzi (2000), Barreto et al. (2002), Lima et al. (2006), Nogueira et al. (2006), Moura Lima et al. (2010), Furrier et al. (2006), and Maia & Bezerra (2024) have demonstrated the influence of Cenozoic and neotectonic activity on the brittle deformation of the Barreiras Formation in northeastern Brazil. This deformation has been described as sets of joints, fractures, and NE–SW and NW–SE faults, associated with strike-slip and normal fault movements, both syn- and post-depositional.

The study area features a hot and humid tropical climate, classified as As according to Köppen (Nascimento et al., 2016), with a mean annual precipitation of approximately 1800 mm (Crispim et al., 2010). The region is characterized by two well-defined seasonal periods: a rainy season from March to August, and a dry season extending from September to February. The area is also influenced year-round by southeast trade winds, as well as by the Intertropical Convergence Zone (ITCZ) during the drier months (Santos & Santos, 2013). The wave dynamics along this sector of the Paraíba coast are characterized by waves predominantly from the east and east-southeast, with average significant wave heights ranging from 1.0 to 1.5 meters, based on coastal modeling using historical data (1948–2008) (Silva et al., 2024).

Crispim et al. (2010) reported a significant increase in erosional events at the Cabo Branco cliff following the installation of a retaining wall at its base, constructed by the João Pessoa municipal government in 2020. In addition to the exposure of claystone outcrops, partial collapses were recorded along Avenida Cabo Branco as recently as 2022 (Jornal da Paraíba, 2022).

3. Materials and Methods

The aerial photogrammetric survey was conducted using a DJI Mavic 3 Pro drone equipped with a 24 mm, 20 MP camera. The data acquisition followed standard photogrammetric protocol, adapted to the cliff environment (photos captured in nadir view, at 45°, and at 0° angles). For all angular intervals, a frontal and lateral image overlap of 80% was applied.

The collected data were processed using Metashape Agisoft PhotoScan, employing the Structure from Motion (SfM) algorithm, which enabled the generation of a high-resolution model (18.1 points per m²) representing the morphological and textural characteristics of the escarpment (Figure 02).

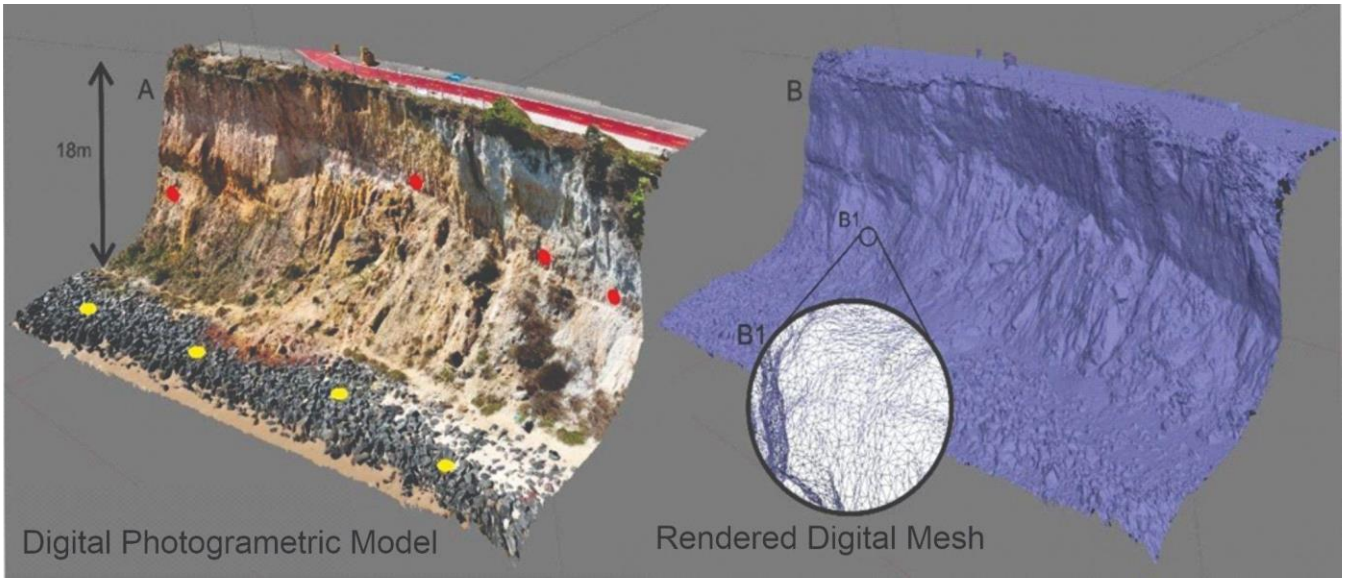

Figure 02. High-resolution photogrammetric digital model of the Cabo Branco cliff – João Pessoa, Paraíba (PB). In A, yellow points represent measurement locations on the riprap, while red points indicate measurement locations on the cliff face.

Non-destructive hardness tests were performed on rock surfaces (both cliff and riprap) using a Schmidt Hammer (Sclerometer) MKT-1015, standard Type N model, with an impact energy of 2.207 Nm (or 2.207 J) and a compressive strength range of 10 to 70 N/mm² (or MPa). The measurements from the geomechanical tests are expressed as rebound values (R), a percentage-based number that reflects the surface hardness upon impact of the piston, calculated using the following formula:

$$Rh = \frac{x2}{x1} \times 100,$$

where the rebound number (Rh) corresponds to the rebound value, where x_2 represents the maximum spring extension at rebound and x_1 the maximum spring extension. This value is directly related to the uniaxial compressive strength (UCS) of the rock (Basu & Aydin, 2005). The rebound reading is influenced by the orientation of the hammer during testing. Measurements taken with the Schmidt Hammer positioned perpendicularly to a horizontal surface are automatically adjusted by the device; however, in cases where the piston is oriented downward (+90° or +45°) or upward (–90° or –45°), the values must be corrected according to standardized correction tables (Basu & Aydin, 2005; Aydin, 2009).

On the cliff face, the selected points were located along the lateritic sectors of the cliff, where a sub-metric columnar reddish mottling was observed. The acquisition methodology employed in this study followed ASTM standards (American Society for Testing and Materials) (ASTM, 2001; Aydin & Basu, 2005), with ten measurements taken at each selected point, maintaining a minimum spacing of one piston diameter, and avoiding fractures and irregular surfaces. The tests were conducted in the nearly horizontal lateritic zones of the sandstone rocks supporting the escarpment. It is worth noting that attempts to measure rebound values in non-lateritic facies were unsuccessful, as values were below 10 (the minimum detectable by the equipment). In this sector, measurements were taken along a linear profile following the lateritic level, totaling eight acquisition points (80 measurements), with the Schmidt Hammer, operated in a horizontal position (Figure 04).

In the rock amour located at the base of the escarpment, measurements were taken along its length on igneous (granitoid) rock blocks. A total of ten points (100 measurements) were selected in this sector. Data acquisition in this area was conducted with the piston in a downward (+90°) position, and the values were corrected accordingly.

From a morphostructural perspective, the escarpment was classified based on cliff morphology following Maia et al. (2024), and a description was made of both morphological and structural aspects, including lateritic levels and exposed fracture planes. Within this analysis, vertical fracture sets were identified and grouped to evaluate potential correlations with erosional processes. Based on direct visual inspection, recent gravitational collapse scars were also identified, along with their corresponding talus deposits. Additional processes such as toppling and block collapse were also recognized and described.

4. Results

The data obtained from direct measurements using the Schmidt Hammer revealed the physical resistance values of the exposed rocks on the escarpment, as well as those composing the rock armour. The rebound values (R) recorded on the escarpment sectors were relatively low (< 20), likely due to the low degree of diagenesis, characteristic of friable rocks, as observed in this area. In certain sectors, due to the very low cohesion of the rock, the instrument was unable to register any rebound value. Given these observations, it is considered that these rocks can only sustain steep escarpments under specific conditions, particularly when the base exhibits high erodibility.

In contrast, the rebound values of the granite rock blocks comprising the rock armour exhibited greater variability, with values ranging from 34 to 71 (Figure 03).

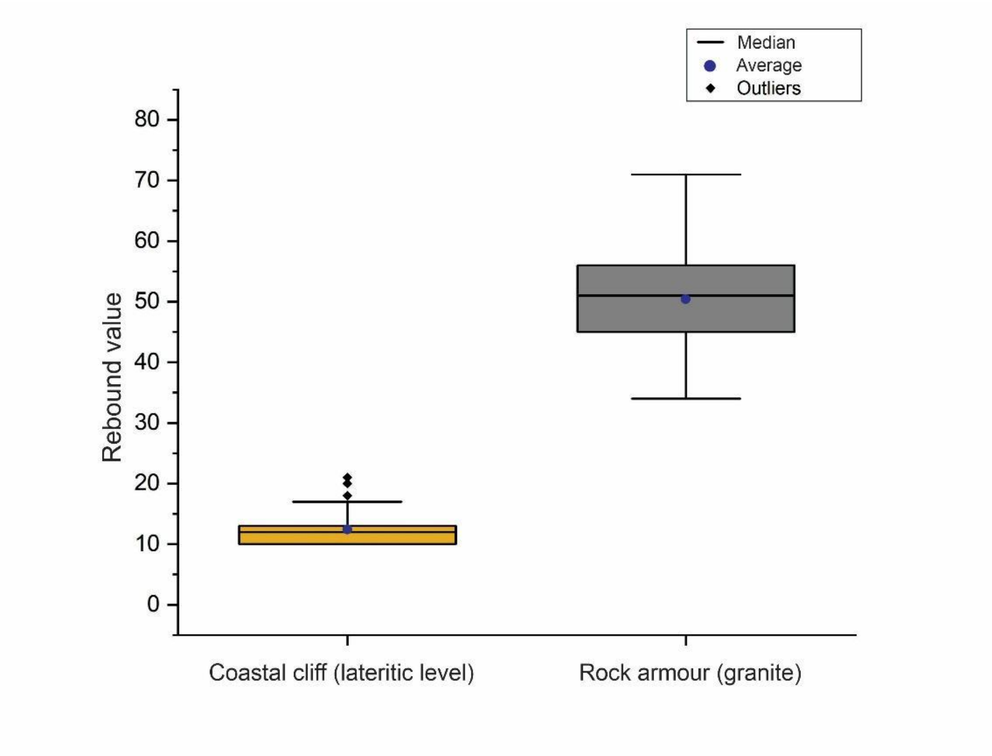

Figure 03. Boxplot of rebound values measured in the lateritic levels of the Cabo Branco cliff – João Pessoa, Paraíba (PB), and in the rocks composing the rock armour.

The low rebound values recorded on the cliff face indicate incipient diagenesis and also partial laterization, both of which contribute to the disaggregation of the escarpment through fracturing that ultimately leads to gravitational collapse. In the upper portion of the cliff, due to the unconsolidated nature of the sediments, it was not possible to carry out measurements. This is a common occurrence in very steep escarpments composed of exposed friable rocks, where the weight of the escarpment itself contributes to its breakdown and eventual collapse.

In the case under analysis, this type of process results from two primary controlling factors. The first is associated with the degree of rock diagenesis, and the second, with the rate of cliff retreat. Even in escarpments carved into rocks with a low degree of diagenesis—as is the case with the outcropping facies of the Barreiras Formation and post-Barreiras sediments at Cabo Branco—the cliff can remain steep under conditions of high base erodibility (Figure 04).

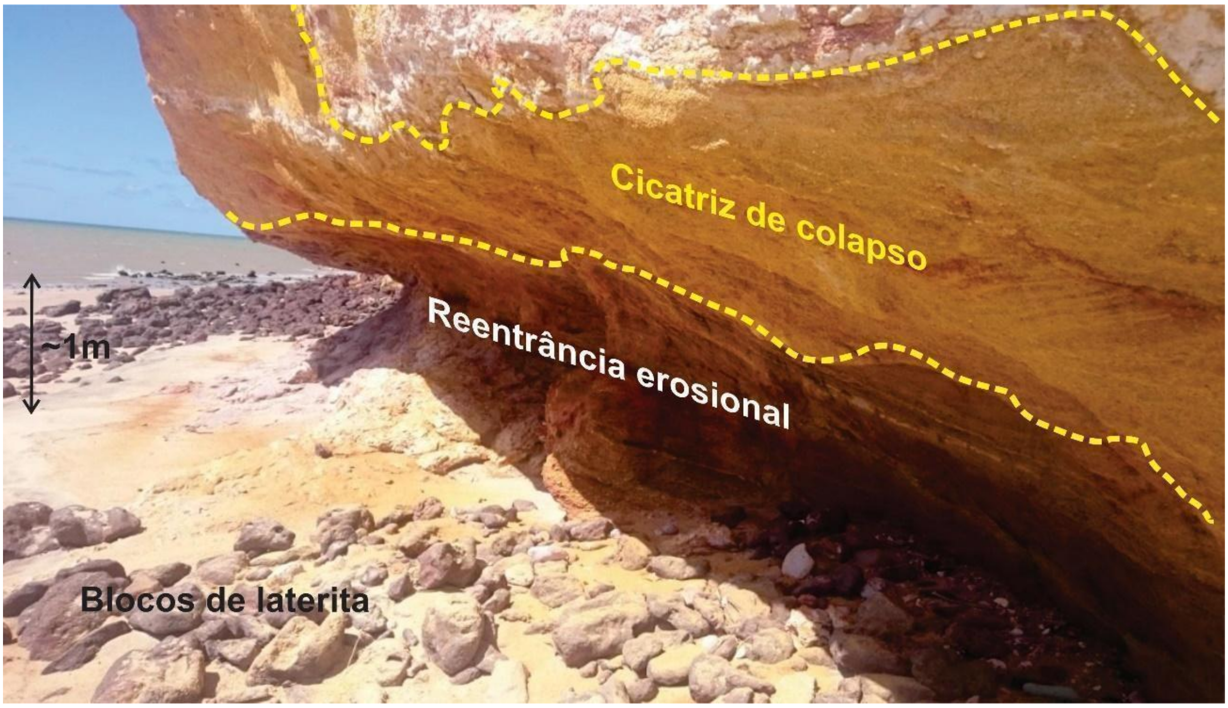

Figure 04. Erosional indentation at the base of the Cabo Branco cliff – João Pessoa – PB. Interpretation based on a photograph by Nóbrega Júnior, 2016.

The degree of diagenesis of the Barreiras Formation rocks in the study area reveals a brittle mechanical behavior, which favors sporadic movements, such as those that lead to gravitational collapse. This behavior necessitates the maintenance of a steep escarpment, where the self-weight of the cliff generates shear stress near the failure threshold, resulting in parallel fracturing, followed by disaggregation and collapse. These processes occur in two main forms: toppling, when vertical fracturing isolates a column, and direct collapse, when failure occurs along a detachment surface (Maia et al., 2022). Both mechanisms result in the formation of talus ramps.

The rockfall, flaking, and toppling generates impact at the cliff base, which, in rocks with lower diagenetic development—as in this case—leads to the disintegration of friable rocks and sediments, leaving behind only blocks with a higher degree of laterization. In locations with more cohesive lateritic stratigraphic levels, block production can lead to the formation of a natural buttress at the base of the cliff, as observed at Pipa Beach in Rio Grande do Norte (RN). In contrast, at the Cabo Branco cliff, prior to the installation of the protective structure, talus deposits were entirely removed by direct tidal action, due to the narrow beach profile and absence of a berm zone in this sector.

With the cliff base now protected by an artificial erosion-control structure, the ravinement process, already initiated, has become concentrated in the upper portion of the escarpment, where the presence of unconsolidated deposits is evident. Such deposits are common across several cliffs in Northeastern Brazil (e.g., Redonda–CE, Beberibe–CE, Pipa–RN, Barra de Tabatinga–RN). At the base, the talus deposits, now sheltered by the structure, have begun to be colonized by arboreal vegetation (Figure 05 – A2).

Figure 05. Comparative analysis (2021–2025) of vegetation on talus deposits at the base of the Cabo Branco cliff – PB.

The retreat of the more friable layer at the top of the cliff has led to localized structural failures and the closure of traffic lanes along sections of Cabo Branco Avenue. During the rainy seasons, the deepening of gullies tends to occur in the more friable portions of the Barreiras Formation. In contrast, at points where laterization is more pronounced, erosional interfluves in the form of narrow ridges are formed.

As the escarpment undergoes lateral retreat, it maintains a steep topographic gradient. In areas with narrow beaches lacking a berm zone, high tide results in direct wave impact at the cliff base, creating the necessary conditions for sustaining the steep profile of the scarp. Two key processes contribute to this dynamic, both promoting gravitational collapse of the escarpment. The first involves the formation of erosional embayments at the cliff base, driven by direct wave action. The second relates to the continuous removal of the talus ramp, which accumulates as a product of gravitational collapse.

This footwall erosion eliminates the natural support structure provided by talus deposits, leaving the cliff face fully exposed and thus more susceptible to disintegration through processes such as slab detachment, block fall, and toppling.

Within this context of continuous scarp retreat and talus removal, the conditions favoring collapse-induced erosion persist, occurring at a faster rate than rill and gully development (as seen in Figure 07, zoomed Detail B). This is primarily because the degree of laterization, though incipient, is sufficient to uphold the integrity of the cliff face. Nonetheless, it is important to emphasize that this dynamic requires a high retreat rate; otherwise, gullies may have enough time to evolve into more pronounced erosional features, such as badlands, which are typically observed in more stable cliff systems.

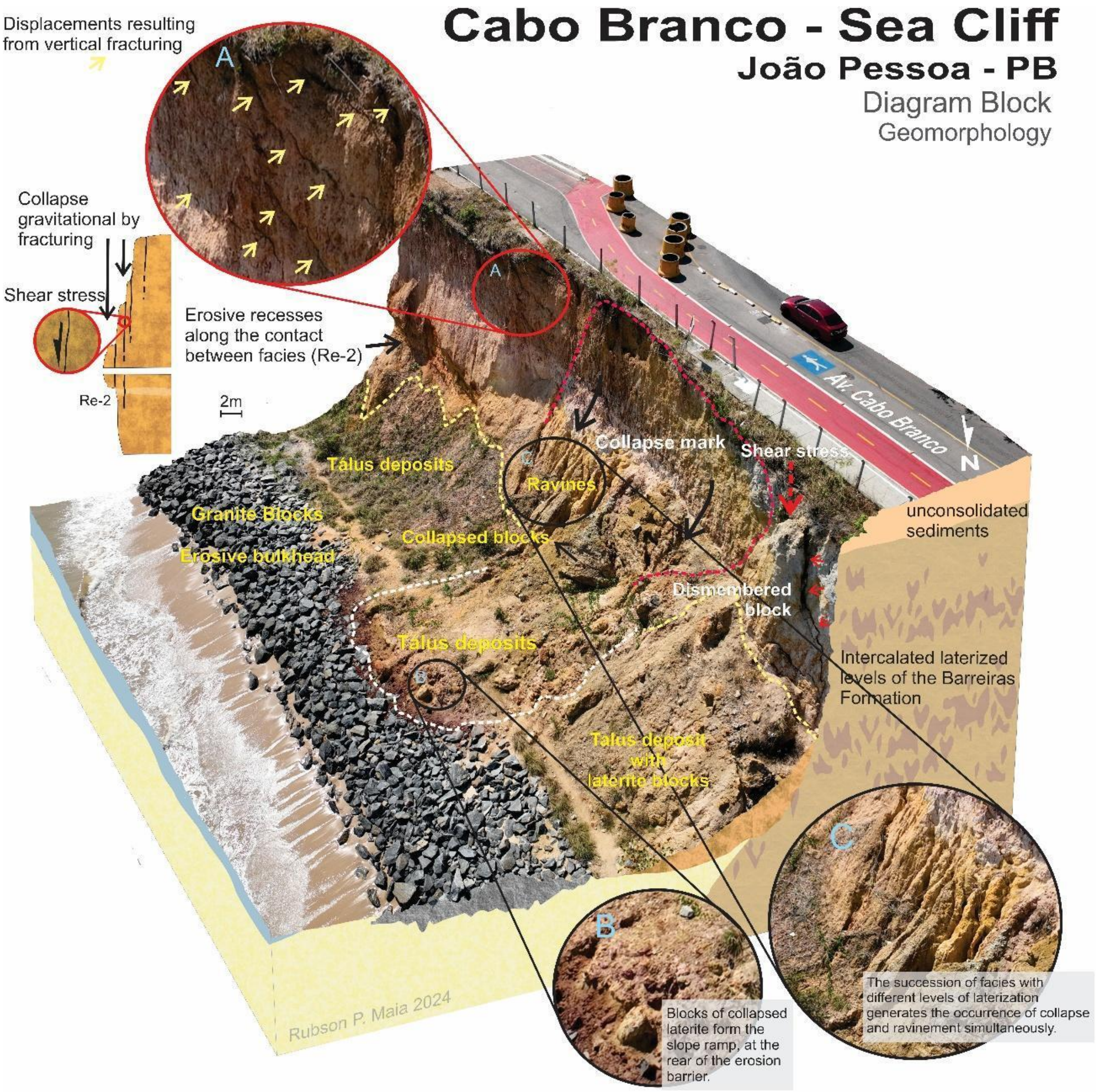

Figure 07. Geomorphological Block Diagram of the Cabo Branco Cliff in João Pessoa – Paraíba. The drawing adjacent to the enlarged area A (red circle) represents a cross-section of the scarp along vertical detachment fractures. In B (black circle), the collapse of lateritic blocks forming the talus ramp is depicted. In representation C (black circles), a succession of facies with varying degrees of lateritization is observed. Re-2 denotes the second erosional embayment formed at the contact zone between sedimentary layers. The red dashed line indicates the scar of the most recent collapse event. The yellow dashed line marks the contact zone between the talus deposits and the steep escarpment, while the white dashed line represents recently accumulated talus deposits resulting from the latest collapse. The digital model was generated using aerial photogrammetry techniques.

Considering the protection provided by the installation of an erosion control structure, such as a rock revetment (2020), at the base of the cliff, both the topography and the profile of the escarpment may be altered from a steep to a concave, rilled form, as demonstrated in the model shown in Figure 8. As long as the talus deposits are preserved, gravitational collapse of the escarpment will continue during the initial years. However, as the top of the cliff retreats while the base remains stable, the slope angle of the escarpment will no longer favor gravitational collapse processes. Once the escarpment adopts a more concave profile, with the top retreating more than the base and a slope gradient around 50%, the shear stress responsible for the formation of vertical fractures will decrease. This occurs because the new, wider base better accommodates the stress resulting from the weight of the escarpment itself. In this way, the escarpment becomes progressively more stable in terms of collapse-induced erosion. The new slope profile will promote surface runoff and rilling at the escarpment. The presence of these features may serve as indicators of a gradual shift in processes and reflect the effectiveness of erosion control measures, particularly when analyzed over long-term periods (greater than 30 years).

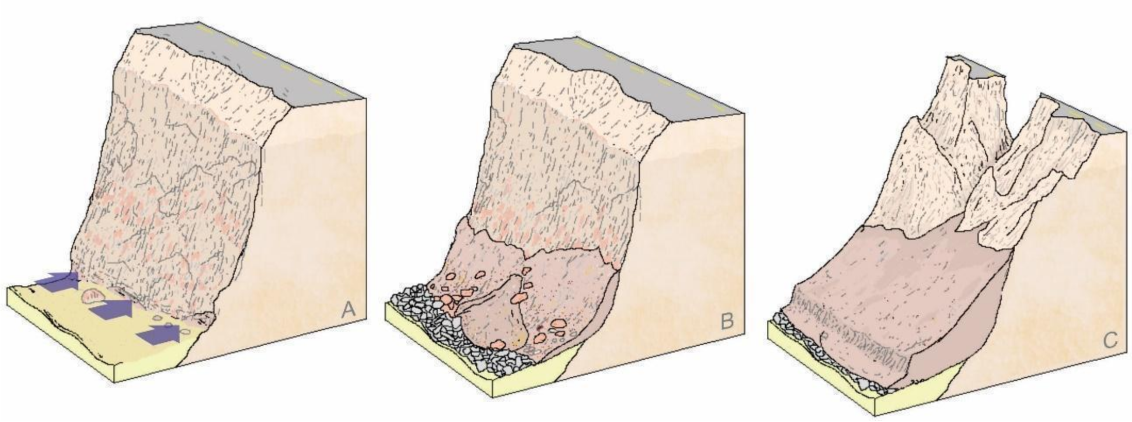

Figure 08. Conceptual Block Diagram – Predictive Geomorphological Evolution Model for the Cabo Branco Cliff – João Pessoa – Paraíba. A – The impact of waves directly on the base of the cliff removes the talus deposits and creates the primary geomorphological mechanism controlling the angularity of the escarpment. B – The installation of the erosion control structure at the base of the cliff does not directly protect the cliff from erosion but rather the talus deposits at its base. Although its effectiveness in controlling erosion may not be immediately apparent, its long-term installation will reduce the rate of escarpment retreat. C – The erosion control structure will allow for the preservation of talus deposits at the base of the cliff. This will lead to a change in the mode of cliff retreat, which will evolve more slowly and gradually through rilling, with the formation of labyrinthine grooves.

In light of the foregoing, it is recommended as a safety measure to establish guidelines for visitors, advising them not to approach the cliff. The current instability of the cliff creates a high-risk situation, as the erosion scars and resulting deposits partially cover the erosion control structure (Enlarged Detail B in Figure 06), illustrating the extent of block falls.

5. Conclusion

Active cliffs tend to exhibit variation in the size of collapsed blocks and the volume of material produced due to factors such as the characteristics of the stratigraphic stacking, joint sets in the escarpment, the width and topography of the beach zone, and the undermining energy at the base. The Cabo Branco cliff in João Pessoa – PB is subject to predominantly gravitational block collapse and tilting erosion processes. The erosion control structure composed of granite blocks at its base, although it does not show immediate practical effects in reducing cliff erosion, has the potential, in the long term, to slow the rate of erosion. This is due to the reduction in stress caused by the direct wave abrasion at the cliff base, subjecting the escarpment to a more rainfall-driven erosion process. In this way, the shift from rockfall to gullying will mark the geomorphological effectiveness of the erosion control structure in reducing the erosion rate. This is expected to result in a more concave and stable escarpment profile. However, it is important to emphasize that the reduction in instability and the change in profile do not signify the cessation of the cliff's erosional process. Even "dead" cliffs, and therefore inactive ones, undergo karstification and erosion, although at a slower pace compared to active cliffs, particularly in narrow beach zones such as Cabo Branco in Paraíba.

Authors Contributions: R.P. Maia: Conceptualization, Methodology, Validation, Formal analysis, Data curation, Writing – original draft, Writing – review and editing, Visualization, Supervision, Project administration, Funding acquisition. A.S.V. Souza: Methodology, Validation, Formal analysis, Resources, Writing – original draft, Writing – review and editing. A.B.F. Andrade: Validation, Formal analysis, Writing – original draft, Writing – review and editing, Visualization. All authors have read and agreed to the published version of the manuscript.

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Conflict of Interest: The authors declare no conflict of interest.

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