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Geodiversity Inventory and Geomorphological Mapping as a Basis for Geotourism and Geoconservation in Salinópolis, Atlantic Coast of Pará, Eastern Amazon- Brazil

Inventário da Geodiversidade e Mapeamento Geomorfológico como Base para o Geoturismo e a Geoconservação em Salinópolis, Costa Atlântica do Pará, Amazônia Oriental – Brasil

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Abstract

This study investigates the geodiversity of the Salinópolis region, in the Atlantic Coast of Pará, through the development of detailed geomorphological and geomorphometric maps and the identification of geodiversity sites of scientific, educational, cultural, and touristic relevance using GEOSSIT. These tools are essential for supporting geoconservation actions and promoting geotourism, particularly through initiatives such as geotrails and other interpretive activities. By integrating theoretical and practical approaches, this work seeks to provide a solid foundation for decision-making in sustainable development policies and environmental management. The expected outcomes include increased awareness among public managers, educators, students, and local communities about the relevance of geodiversity, as well as the enhancement of regional governance through sustainable tourism practices embedded in geoconservation.

Keywords: Geodiversity; Geoturism; Atlantic coast of Pará; Coastal management.

Resumo

Este estudo investiga a geodiversidade da região de Salinópolis, na Costa Atlântica do Pará, por meio do desenvolvimento de mapas geomorfológicos e geomorfométricos detalhados e da identificação de geossítios de relevância científica, educativa, cultural e turística utilizando a metodologia GEOSSIT. Essas ferramentas são essenciais para promover o geoturismo e apoiar ações de geoconservação e, especialmente por meio de iniciativas como geotrilhas e outras atividades interpretativas. Ao integrar abordagens teóricas e práticas, este trabalho busca fornecer uma base sólida para a tomada de decisões em políticas de desenvolvimento sustentável e gestão ambiental na região. Os resultados esperados incluem o aumento da conscientização entre gestores públicos, educadores, estudantes e comunidades locais sobre a importância da geodiversidade, bem como o fortalecimento da governança regional por meio de práticas turísticas sustentáveis baseadas na geoconservação.

Palavras-chave: Geodiversidade; Geoturismo; Costa atlântica do Pará; Gerenciamento costeiro.

1. Introduction

Geodiversity refers to the wide range of geological and geomorphological features found on Earth, such as rock types, mineral compositions, landforms, surface water systems and other sites of geological interest that are significant for education and scientific research (Gray 2004). When these features are considered to have exceptional socio-economic and environmental values, it is assumed that society has benefits from the geodiversity referred as "geosystem services" (Gray 2011). Geodiversity provides a range of provisioning, regulating, support and cultural geosystem services to the human population. The Geosystem services have gained considerable attention, and it should be considered a crucial aspect of environmental management and conservation (Kubalíková & Coratza 2023).

Coastal geodiversity supports a wide range geoservices essential to human well-being, including: Regulating functions like protection against erosion and flooding; Provisioning services through the supply of food and water resources, and carbon storage; Supporting services, by sustaining soil formation, providing a physical platform for human activities,

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overall coastal resilience, and Cultural services that are also significant, encompassing historical values, geotourism and cultural identity like rock climbing and fossil collecting (Gray 2011, Lakshmi 2021). Finally, knowledge-based services allow for a better understanding of Earth's history, environmental monitoring, and scientific advancement through education and research. Recognizing and conserving these services is crucial for sustainable planning and for the appreciation of natural heritage (Gray 2011).

As these coastal geodiversity sites face increasing threats and the risk of irreversible transformations, particularly in the context of global climate change and rising sea levels (Luijendijk et al. 2018), it becomes necessary to recognize coastal geodiversity as a critical element in understanding and managing coastlines (Flemming & Hansom 2012). Effective management of coastal geodiversity areas demands an integrated approach that intertwines physical, biological, and cultural dimensions, aligning with a socio-environmental planning model that accounts for the complexity of coastal systems and the multiple, and sometimes conflicting, human activities associated with them (Leff 2009, Lins-de-Barros 2020).

In the context of these coastal geodiversity areas, geosites- are geographically delimited areas that concentrate geological formations and geomorphological features with a great scientific, aesthetic, ecological, tourist, cultural and educational value, and of interest to conservation (Brilha et al. 2018). Rocks, fossils, or even geomorphological features (geomorphosites) and archaeological sites can be among the characteristics of these sites and help tell the history of the Earth and their processes (Díaz-Martínez 2016). Many geosites can be tourist destinations and provide local and regional economic benefits, known as Geotourism (Pijet-Migoń & Migoń 2022).

Given that, geotourism also presents itself as an opportunity for the conservation of geodiversity that allows people visiting a particular destination to satisfy the needs or pleasurable motivations in geological-geomorphological environments (Brilha & Reynard 2018, Newsome & Dowling 2018). Considering the different contributions, especially in the last years (Brilha 2016, Gray 2004, Hose 2012), today there is no doubt that geotourism is part of a proposal for sustainable conservation and microeconomy that values the physical components and interpretation of landscape, diversity, and history.

Geotourism offers to the visitor a deepening understanding about the origins of the environment which it visits, as geological information being one of the founding elements for greater environmental knowledge. And so, this constitutes a rising segment of tourism, characterized by having geodiversity as the main attraction, and that through environmental interpretation activities, seeking to understand the geological-geomorphological phenomena operating in the visited place, as well as promoting scientific knowledge and sustainable involvement of the communities involved (Brilha & Reynard 2018). Following this text, some possibilities stand out.

Moreover, the relationship between geodiversity and geoconservation to natural and cultural values is multiples, as the introduction of certain conservation measures may require a good knowledge of the local context, including for example, the of indigenous societies intangible heritage (like sambaquis- shell middens). Recent studies have shown that tourism activities which promote a strong "sense of place" through engagement with the natural environment can encourage visitors to develop a sense of responsibility for conservation. In this context, the interpretation of Indigenous culture and traditional lifestyles has proven to be a powerful tool for raising awareness and respect for the historical, symbolic, and environmental value of landscapes, for example, shell mounds and archeological constructions could be considered as paleo sea-level indicators (Pirazzoli 1996). However, such initiatives must be carried out with cultural sensitivity and through collaborative planning involving local governments, tourism operators and traditional communities. In the case of the Atlantic coast of Pará, this perspective becomes particularly relevant, as the local population increasingly expresses the desire to learn about the region's pre-colonial history, exemplified by the presence of archaeological sites such as the sambaquis.

Although geotourism is still incipient on the Atlantic coast of Pará, in the north of Brazil, there is a growing number of travelers who enjoy visiting natural areas and consider the landscape and its geoforms part of the main attractions (Paca et al. 2013). In this conceptual scenario, the Amazon region, particularly the Atlantic coast of Pará, offers great geotourism potential due to the rich geodiversity present in its territory. This geodiversity encompasses not only lithological, geomorphological, pedological, and hydrological elements, but also the dynamic processes that shape the landscape and support ecosystem services. Among the highlights is the Pirabas Formation Marine Fossils Geosites located in the municipality of Pirabas, classified as a Geodiversity site with national relevance. This site presents a scientific value of 155, an educational value of 215 (National Relevance), and a touristic value of 180 (Regional/Local Relevance), with a low risk of degradation (180) (GEOSSIT 2025). It holds significant potential for both scientific research and educational outreach. Other notable geosites include areas related to archaeological remains, and sea level fluctuations, as well as locations of exceptional scenic beauty (Paca et al. 2013).

Geotourism on the Amazon has been addressed in several studies in recent years. Andrade & Carneiro, (2017) cataloged a digital base of studies with the theme: Geodiversity, geoconservation, geotourism and geopark in the State of Pará. In the insular estuarine sectors of Pará coastal region, Ferreira et al. (2019) analyzed the geological and geomorphological landscape in Mosqueiro Island, Bay of Guajará, with the influence of mesotidal amplitudes and huge Pará river, presenting a great geotourism potential of the island and highlighted the need for geoconservation of the abiotic means. In Cotijuba Island, also in the Guajará Bay, Andrade et al. (2021) analyzed geodiversity and elaborated public policy proposals regarding infrastructure and geotourism for the local development of the area. On Combu Island, De Lima et al. (2020) recognized it as a natural heritage, with environments favorable to ecological tourism and, at the same time, characterized as spaces of high vulnerability. However, in the Atlantic coast of Pará, Sepulvreda et al. (2022) quantitatively evaluated the geoheritage values of fossiliferous outcrops in Atalaia beach located in Salinópolis (Fig.1).

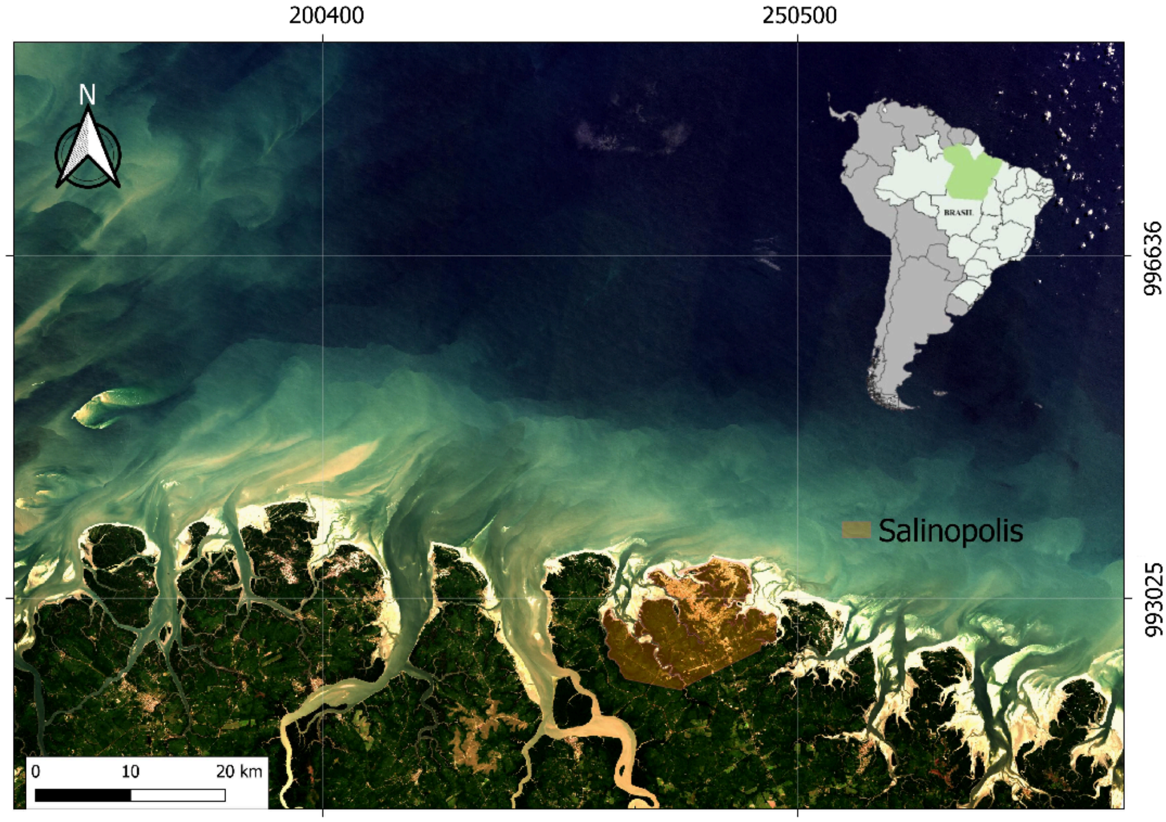

Figure 1: Location of the Salinópolis Coastal Zone on the Atlantic Amazon Coast, State of Pará, Brazil.

In this context, our study is focused on Cultural Heritage beaches of Salinópolis territory: (1) Maçarico Beach Cultural Heritage (Pará, law 9.663 of July 14, 2022); (2) Corvina Beach Cultural Heritage (Pará, law 9.684 of September 2, 2022); (4) Farol Velho Beach Cultural Heritage (May 2, 2022), and; (4) Atalaia Beach Cultural Heritage (Pará, law 9.684 of September 2, 2022) located in the Atlantic Coast of Pará (Fig. 2), which aims at the preservation, conservation and protection of Salinópolis beaches, where several geological-geomorphological research were carried out in the scope of beach morphodynamics (Ranieri & El-Robrini, 2020) and morphostratigraphy focusing on environmental and climatic changes during the Quaternary (Souza 2007).

The state conservation unit, Atalaia Natural Monument (MONA) was created to ensure the protection of scenic beauties, dunes, sandbanks, mangroves and lakes, as well as the preservation of resident and migratory species of flora and fauna; to protect representative areas of coastal ecosystems, especially under high anthropogenic pressure; contribute to planning tourism planning and to provide opportunities for environmental education for tourism and school purposes, especially aimed at local communities and users (Pará. 2018 -Decree no. 2077, of May 25, 2018). These localities have extraordinary and distinct coastal morphological characteristics and fossiliferous outcrops that preserve the paleoenvironmental history of the region.

This study aims, therefore, to develop a geological-geomorphological and archaeological inventory and characterize the geomorphological features to make a detailed map of the area. The goal is to draw attention to its value and assist in its conservation, through geotourism, as well as incorporate it sustainably into the geoheritage of the region.

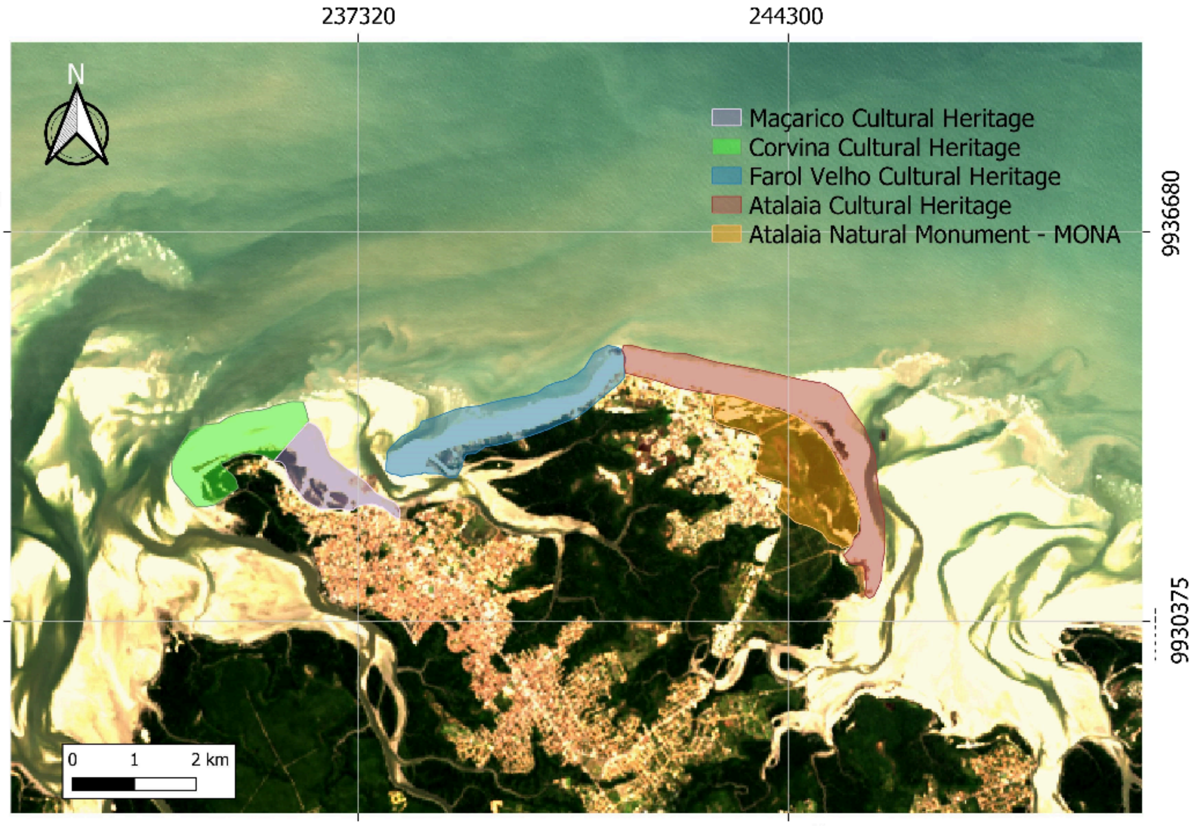

Figure 2: Cultural heritage sites and conservation units in the municipality of Salinópolis.

1.1 Geodiversity, Geotourism and Practices of Sustainability

According to Gordon (2018) and Hose (2016) geotourism is a form of tourism based on the geological and geomorphological interpretation of a site and should be understood as a contribution to the development of Earth sciences, beyond visual appreciation. Nascimento (2008) presented a triad Geodiversity- Geoconservation- Geotourism, where geodiversity represents the open archive of nature and keeps the information that allows us to reconstruct a history that goes back in time of hundred million years. Geoconservation, however, aims to protect some elements of geodiversity that have certainly values, whether of scientific, cultural, economic and geotouristic interest and can be considered as geological sites (geosites) or geoheritage (Brilha et al. 2018, Brilha & Reynard 2018).

Geoheritage can be considered as the set of geomorphological, paleontological, mineralogical elements, among other constituents of geodiversity. Thus, geosites represent irremovable testimonies of the geoheritage of a given region, which need to be protected and preserved and, therefore, should be a special target of the territorial planning policy and through measures of valorization and dissemination of geoheritage, through geoeducation and geotourism (Sepulvreda et al. 2022, Silva & Costa 2021) In this sense, geotourism is part of the so-called sustainable tourism, or alternative (non-traditional) tourism, and is registered in interpretation tourism (Dowling 2014, Sumanapala & Wolf 2022). Pijet-Migoń & Migoń (2022) explains that this form of tourism can reach two types of public: the specialized tourist and the ordinary visitor interested in understanding the landscapes he observes and travels/visits. For Pijet-Migoń & Migoń (2022) one of the main concerns of geoconservation is to make geoheritage accessible to the general public, resorting to the creation of public access strategies, among which geointerpretation stands out.

Geointerpretation is a process of communicating meanings and values inherent to a heritage, to an audience in an informal and recreational environment (Hose 2012). The implementation of interpretive trails has been the main form of geoheritage communication in Brazil, considered a successful strategy for environmental awareness (Mansur 2009). Such trails have been commonly employed to present the biota, or even in historical and architectural monuments (Mansur et al. 2012, Schmitt et al. 2021)

For Moreira (2012), there is a lack of interpretive resources for geotourists and courses for tour guides and the community that address geology and geomorphology in most Brazilian Nature Conservation Units. The author cites the importance of motivating projects related to the interpretation of geodiversity, although it is the main attraction for the interpretation of the environment, even so, aspects of biodiversity are favored.

Geotrails can become a driver of local development by establishing the importance of communicating natural and historical values using interpretive trails. It comprises a tool for the environmental interpretation of the landscape, aiming at the dissemination of geoheritage through the concept of geodiversity (Moreira 2008, 2012). It aims to strengthen the potential of geotourism in different regions, exploring an interdisciplinary approach to nature conservation. The project conceived the routes based on the evolution of the landscape and the description of the events that make up the local geodiversity, biodiversity, and the related scenario for anthropic interaction, aiming at building knowledge and environmental awareness in local communities (Cristiano 2018, Mansur, 2009).

The analysis of Rapanelli & Feger (2018) conducted an analysis and contextualization of the theoretical association existing between geodiversity and tourism and recommended an approach that brings together the conservation of the geodiversity heritage (geoconservation) and tourism (geotourism), as this combination has the potential to provide economic and social advantages to a particular region.

These authors cited above have presented various instances to establish that the objectives of the United Nations' Sustainable Development Goals (SDGs) in relation to geoconservation and geotourism can be attained only if the aspects and mechanisms of geodiversity are recognized at a global level. Additionally, geotourism aligns with sustainability practices, as it plays a significant role in the regional economy and contributes to local culture (Fleig & Valdati 2022).

This network of concepts discussed here shows the reference framework for an integrated and sustainable approach to the management of the geological-geomorphological environments emerging in each region so that their conservation is guaranteed.

1.2 Atlantic Pará Amazon Coast – Salinópolis

Salinópolis is a potential geosites and geomorphosites that receives thousands of visitors throughout the year, therefore, motivating them through geodiversity can be an educational and economic opportunity to arouse interest in safeguarding the natural legacy and the environment.

In addition, the geomorphological features described are essential for the balance of natural coastal dynamics. A series of not sustainable practices, such as the removal of dunes for the construction of summer houses, suppression of mangroves for the construction of infrastructure for tourists and permission for vehicle circulation, among many others, produce areas vulnerable to coastal erosion; this leads to a significant loss of beach resources, acceleration of erosion processes on the cliffs, changes in beach sediments and biodiversity and variability in coastal dynamics (Santos et al. 2023), as well as water quality and local garbage generation (Ribon et al., 2018). As well as cultural loss, where fishermen have gradually abandoned their ancestral fishing practices and turned to new forms of work associated with coastal tourism, such as caretaking for second homes, beachside commerce, or informal services during the high season (Adrião 2006).

These negative effects associated with the geomorphological framework have a direct impact on changes in biodiversity and on the loss of age of the paleontological heritage, especially when considering the regional context of the Salinópolis coastal zone (Sepulvreda et al. 2022).

The importance of this region can be emphasized since its geology and geomorphology preserve the paleoenvironmental and climatic record, particularly from the Cenozoic to the present. Thus, it is a key region for understanding the geo-biodynamic processes that have occurred during Earth's history. This contribution provides, therefore, valuable information about the geodiversity of the Atalaia Natural Monument and the areas of Cultural Heritage that will be vital for the development of a strategic plan that incorporates geodiversity as another main attraction in the scope of geotourism or scientific tourism.

This coastal plain constitutes a depositional system of semidiurnal macrotidal regime (6 m), Presents an AM climate type, according to the Köppen-Geiger classification system, it features a distinct wet season, accompanied by a brief dry season with at least one month with less than 60 mm of rainfall with annual precipitation around 2,800-3,100mm, classified as regions that do not have dry seasons (Alvares et al. 2013). The rainy season is concentrated between February and April and the dry season between July and September. The minimum variation ranges from 7.7 mm during the dry months to 631.7 mm in the rainy month. It is observed an annual maximum of 216 days of sunshine and a minimum of 200 days of sunshine (Rolim et al. 1991, Coutinho et al. 2018).

The climatic conditions of the Atlantic coast of Pará are regulated by the seasonal meridional shifts of the Intertropical Convergence Zone (ITCZ). During the boreal summer, the ITCZ is situated around 140 N, while in the boreal winter, it is positioned approximately 20 S, thereby exerting control over regional precipitation patterns (Nobre & Shukla 1996, Souza et al. 2000). Based on observations made by the National Institute of Meteorology (INMET), two distinct periods can be classified as the defining characteristics of rainfall in the region. These are the rainy season that extends from December to May (DJF/MAM) and the relatively rainless season, June to August and September to November (JJA/SON).

The Atlantic Coastal one of Pará comprises the mouth of the Amazon River to the mouth of the Gurupi River, which includes the Coast where the coastal plain of Salinópolis is inserted has a width of about 600 km. In this region, Franzinelli (1992) distinguished two primary geomorphological features in the coast: (1) emergence coast, represented by Marajo Island, with straight coastline, and (2) submersion coast, east of Marajo Bay to Gurupi Bay; the latter was subdivided into two sectors, first, from Marajo Bay to Pirabas Bay, where the bays cut through active cliffs, and the second, east of Pirabas Bay, where the coastal plateaus extend south like inactive cliffs (Souza Filho & El-Robrini 2000).

The geomorphology of this coastal plan was and still being influenced by neotectonics, geomorphic, climate extreme events and oceanographic processes. It is a coast characterized by presenting forms of flat topography and wider continental shelf, cutted by several recesses in the coastline formed by estuaries, configuring a coastline of "false rias" (El-Robrini et al 2018), drowned valleys developed over Neogene deposits, clastic and carbonate sediments of the Barreiras Group and Pirabas Formation, respectively. These Neogene deposits constitute the coastal plateaus that are continuous along the north coast at altitudes of about 50 to 60 m, progressively decreasing towards the sea, where they form inactive and active cliffs along the coast and estuarine margins (Souza-Filho et al. 2009).

It is located in the Cretaceous Bragança-Viseu coastal basin, where the distribution and thickness of Neogene and Quaternary deposits have been controlled by the geometry of the basin, its paleo-topography, and by recent tectonic movements (Rossetti 2006). Upper Cenozoic deposits exhibited in Bragança-Viseu Basin were individualized in three stratigraphic successions bounded by regional and sequence-designated discordances depositional A to C, similarly to the proposal for the Neogene deposits that occur along Brazil northern coast (Rossetti 2001, 2014).

A Sequence A, corresponding to the lithostratigraphic Pirabas Formation term and lower part of Barreiras Formation, is of Upper Oligocene age/ Early Miocene and includes terrigenous limestones, carbonaceous black shales and calciferous sandstones interdigitated with claystone and variegated sandstone. These warehouses are assigned to platform environments of the outer shelf, restricted platform/lagoon, and mangroves/plains of mud representative of a marine system progressive margin. Sequence B, old Middle Miocene, corresponds to the middle portion of the Barreiras Formation, and is made up of claystone and variegated sandstone deposited in environments that range from alluvial fans to transitional marine tidal dominated (tidal channel, tidal flat and mangrove), probably with characteristics estuarine. Sequence C, object of this study, includes indistinctly Pliocene and younger deposits referred to as Post-Barrier Sediments, whose reconstitution of the depositional environment is still imprecise, although it includes, at least in part, deposits formed by wind processes (Rossetti et al. 2013).

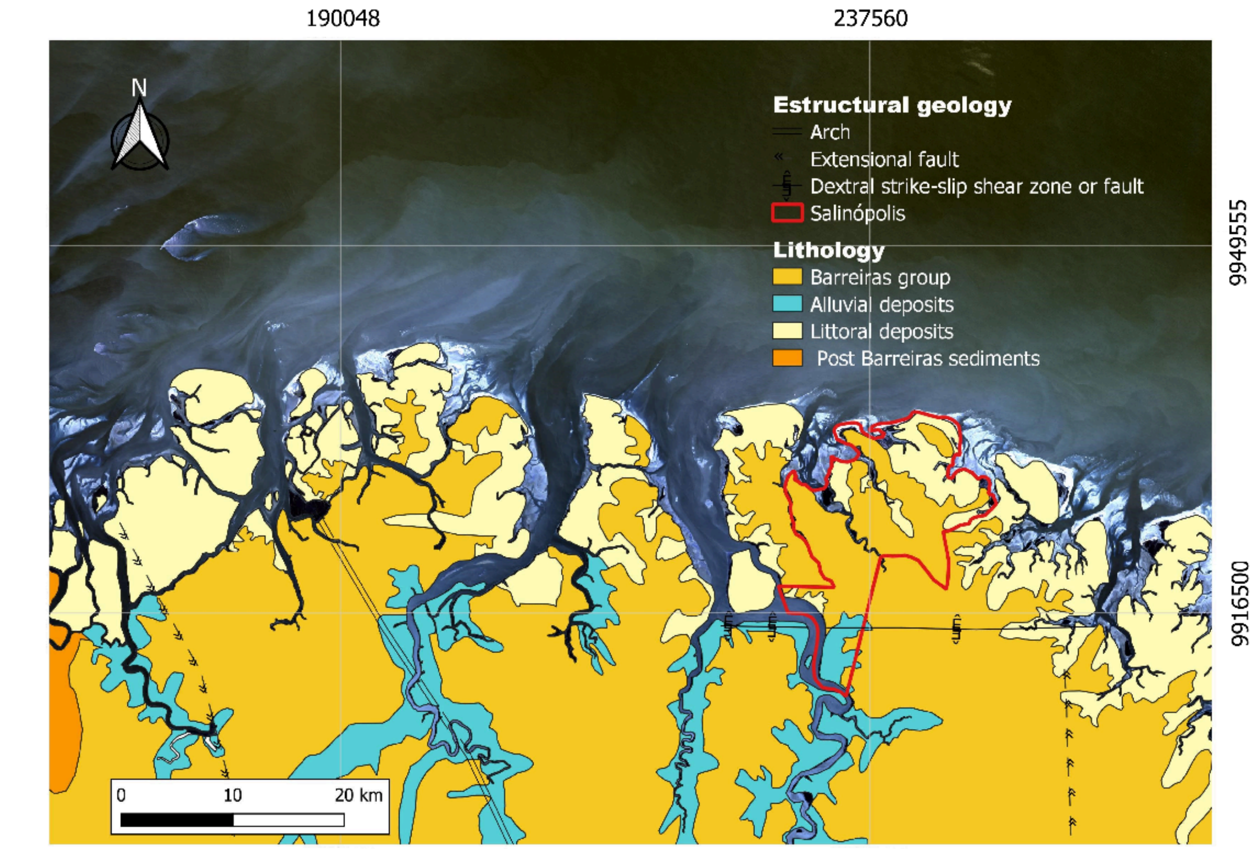

Figure 3: Geological map of the Atlantic Amazon Coast. Source: Geological Survey of Brazil (SGB/CPRM 2008)

The presence of cliffs makes evident Barreiras and Post-Barreiras Formation sediments at Maçarico Beach – Orla do Maçarico, in the west side of Arapepó tidal channel and at Atalaia Beach, in the east side of Arapepó tidal channel – Promontory. Rocky outcrops of the Pirabas Formation are found exposed at the Maçarico Beach and at the border between Atalaia and Farol Velho Beach. Along the coast, quaternary-aged sediments (Holocene deposits) predominate that make up the beaches, tidal plain and recent dune field (Souza 2007).

The Atalaia Beach is located between the Arapepó Channel and the Farol Velho Beach, along a stretch of ~4.2 km long sandy exposed coast, where the tide regime is classified as macrotidal (average amplitude of the tide of spring tide 4.7 m), with rocky cliffs carved in the sediments of the Barreiras Group, coastal dunes, and mangroves. The beach and intertidal face areas are relatively flat, with an average gradient of 1.7° (rough) in the rainy season and 0.8° (flatter) in the dry season (Ranieri & El-Robrini 2020). Atalaia is a high-energy beach, exposed both to waves formed by NE trade winds and swell waves coming from long distances from the Atlantic (Guerreiro et al. 2020).

The beach presents a configuration of double sandy bars of the intermediate morphodynamics stage (Transverse Sandy Bars and Rip Currents) with an internal bar and a growing external bar during the rainy season, and dissipative stage during dry period (Pereira & Pinto 2014, Ranieri & El-Robrini 2015). Ranieri & El-Robrini (2020) observed an increase in beach volume during the dry period, where the development of mobile front dunes occurs, and a decrease in beach volume during the rainy season, with the erosion of the dune escarpments, thus configuring large variations in the coastline and, consequently, in the width of the beach in this place. The accretion and retreat of the coastline at this location are highly seasonal and yet an increased trend was observed in Ponta da Sofia in the eastern sector of Atalaia beach and erosive to stable in the western beach sector due seasonality.

Maçarico Beach is located adjacent to the mouth of Arapepó Tidal Channel, a semi-exposed coast that has gentle slopes (<1°) and sliding waves (<0.5m), is covered with coarse to very fine sand (Ranieri & El-Robrini 2015) limited by the cliff (sediments of the Barreiras Group) to the east, and to the west by dunes, and mangrove, that make up the Beach-Barrier Ridges up to Corvina Beach. To the south is the urban complex of Orla do Maçarico.

2. Material and Methods

The identification and selection of geosites followed a multi-step methodological approach, including preliminary analysis of existing geological and geomorphological data, fieldwork, and application of the GEOSSIT assessment protocol.

Geologic map was obtained through the Geodiversity database from Survey of Brazil (SBG-CPRM 2008). Geomorphometric parameters map were manually digitalized using a geographic information system (QGIS) analyzing Landsat 9 image (USGS) and shaded images derived from digital elevation models (DEM) COPERNICUS 30 (https://panda.copernicus.eu/) performed with QGIS and PCRaster (https://github.com/pcraster/pcraster), Datum SIRGAS 2000 Zone 23S EPSG: 31983.

Fieldwork was conducted in two distinct stages during the dry season (September/2022) and rainy season (February/2023), focusing on pre-identified target areas based on previous studies, satellite imagery, and geomorphological mapping.

Recent satellite images from Landsat 9 (July/2023) were used to map the geomorphological features according to their characteristics and processes that formed them and field validation, was used to guide the selection of key landforms with potential geological interest, such as active cliffs, beach ridges, and fossiliferous outcrops. During field verification, new potential geosites were identified and incorporated into the inventory, especially those not previously documented in the literature. The selection criteria considered both scientific relevance and potential for public use (touristic or educational).

All geosites were subsequently evaluated using the GEOSSIT app developed by the Geological Survey of Brazil (SGB/CPRM), which quantifies scientific value (Ic), educational value (Id), touristic value (It), and degradation risk (R). GEOSSIT is an electronic platform, developed to systematize and support the inventory of the national geological heritage (Schobbenhaus et al. 2021). This tool is based on consolidated methodologies proposed by Brilha (2016) and García-Cortés & Urquí (2014) which offer a standardized and multidimensional approach for evaluating geological sites.

These values are quantified based on specific criteria, each assigned a different weight depending on its importance within each category. The weighted sum of these values results in a global index (Ig), calculated through a formula that integrates the contributions of each dimension along with the degradation risk (see Table 1).

In general, the evaluation criteria are based on aspects such as: (1) The demographics of the city or municipality where the site is located; (2) The degree of anthropization and urbanization of the surrounding area; (3) Be located within areas that intersect both cultural heritage zones and officially designated conservation units in the municipality; And, (4) most importantly, characteristics of geological significance, such as representativeness, integrity of the geological features, rarity, diversity, and the level of scientific knowledge available on the site.

Some criteria related to educational and touristic values are shared, such as accessibility and scenic beauty. However, they differ in terms of weighting: for example, scenic beauty may carry more weight in the touristic value, while accessibility may be more heavily weighted in the educational value, particularly when associated with didactic infrastructure and potential for use in teaching activities.

The maximum score that can be assigned to a geosites on the GEOSSIT platform is 400 points. However, if the scientific value is below 200 points, the site is not classified as a Geosites. Instead, it is designated as a Geodiversity Site, with local, regional, or national relevance, depending on the scores obtained in the other categories. This evaluation system allows for the ranking of sites according to their importance and vulnerability, establishing priorities for conservation, valorization and sustainable use, as well as guiding public policies focused on geological heritage (GEOSSIT 2025).

For Geotrails establishment, some criteria were established recommended by (Brilha, et al. 2018) for choosing the location as: Being part of a Natural and Cultural Heritage in Salinópolis; Have a potential for the practice of geotourism; Provide services and facilities to the tourist; Have a high representativeness as a didactic resource, aspects for learning in geology, geomorphology, environmental sciences, or at least, geoconservation, and Frequency of visitors, factor that indicates the possibility of reaching many people in relation to environmental education and selling the cultural content of geology.

Table 1 Criteria and scores used for the assessment of geosites using the GEOSSIT method.

Category	Score Obtained	Criterion Code & Description	Weight in Final Value (%)
Scientific Value	170	A1 – Representativeness	30%
		A2 – Type locality (Not applicable)	—
		A3 – Scientific knowledge	5%
		A4 – Integrity	15%
		A5 – Geological diversity	5%
		A6 – Rarity	15%
		A7 – Limitations to use	10%
Degradation Risk	305	B1 – Deterioration of geological elements	35%
		B2 – Proximity to degradation-causing areas or activities	20%
		B3 – Legal protection	20%
		B4 – Accessibility	15%
		B5 – Population density	10%
Didactic Value	300	C1 – Vulnerability	10%
		C2 – Accessibility	10%
		C3 – Limitations to use	5%
		C4 – Safety	10%
		C5 – Logistics	5%
		C6 – Population density	5%
		C7 – Association with other values	5%
		C8 – Scenic beauty	5%
		C9 – Uniqueness	5%
		C10 – Observation conditions	10%
		C11 – Didactic potential	20%
		C12 – Geological diversity	10%
Touristic Value	275	C1 – Vulnerability	10%
		C2 – Accessibility	10%
		C3 – Limitations to use	5%
		C4 – Safety	10%
		C5 – Logistics	5%
		C6 – Population density	5%
		C7 – Association with other values	5%
		C8 – Scenic beauty	15%
		C9 – Uniqueness	10%
		C10 – Observation conditions	5%
		C13 – Potential for dissemination	10%
		C14 – Economic level	5%
		C15 – Proximity to recreational areas	5%

Source: Sepulvreda et al., (2022).

3. Results

Geomorphometric parameters such as altitude, TWI and slope allowed us to approach this study from a new perspective, facilitating the visualization of morphologies through index measurements. The essential DEM data indicates the terrain altitude above the average level (MSL), where the coastal plateau has the highest elevations (37m), while the tidal plains are approximately 0 to -3m high (Fig.4A). The TWI map combines the local hydrological distribution area and slope and it is commonly used to quantify the topographic control of hydrological processes. These maps were used to visualize the lower (flatter) sub environments and recognize the flow movement that is connected to tidal channels and estuaries (Fig. 4B). Inclination refers to the difference between the vertical and horizontal distance of two points, it is expressed as an angle and represents the rate of change of elevation for each DEM cell.

Slope highest values (100) are for active and paleo cliffs (boundary between coastal plateau and other features, generally tidal plains and beaches); dunes and high trees of dense mangrove forest have medium to high values (4° to 21°), and the milder slopes (4° to 0°) are related to the abrasion platform, tidal plains, and beaches (Fig. 5A).

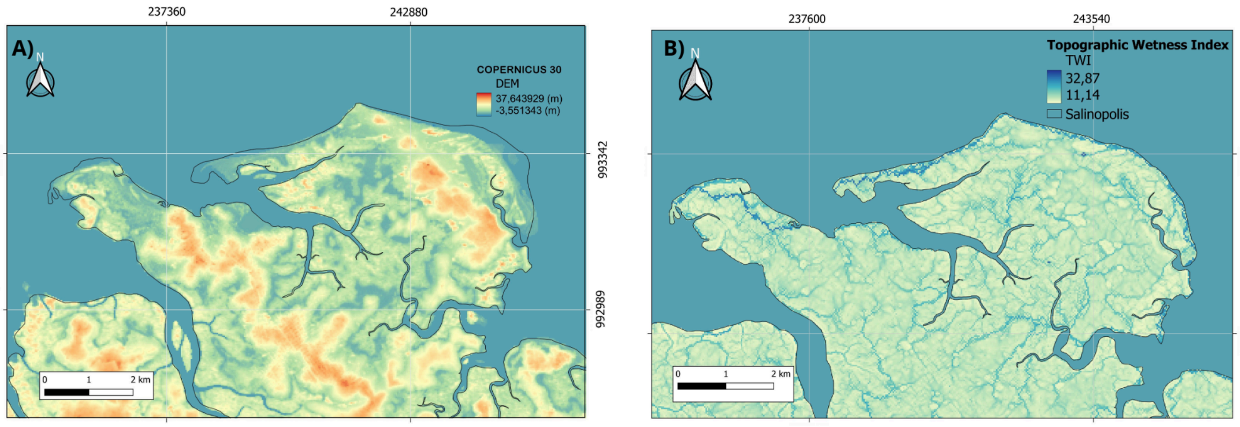

Figure 4 (A) Altitude map of the Salinópolis Coastal Zone, obtained from the Copernicus 30 m Digital Elevation Model (DEM). Higher altitudes are associated with the coastal plateau and cliffs (up to 46 m), while lower areas correspond to beaches, estuaries, and intertidal plains. (B) Slope map of the study area, highlighting geomorphic contrasts between steep coastal escarpments and gently sloping tidal flats and beaches. These geomorphometric parameters were used to classify landforms and support the delineation of geomorphic domains.

Field research validated the interpretation of the images, and the analyses carried out and allowed us to produce a detailed catalog of the landforms and to document and describe them in the 1:1 scale (Table 2).

Table 2: Percentage of each beach vulnerability degree along the coastline of Rio de Janeiro city between Leme and Macumba beaches.

Geodiversity	Area (Km^2)
Mudflat	4.5
Pirabas Formation	0.5
Coastal Plateau	40.1
Dune	5.1
Paleo-dune	10.1
Beach	12.3
Salina	0.18
Chenier	0.02
Lagoons	0.006
Mangroves	11.0
Supratidal flat	20.17
Sandbars	0.25

Geodiversity inventory was also based on the geomorphology, morphogenesis, Slope and Topographic Wetness Index map obtained for the study area allowed to classify the coastal reliefs that define the landscape. The interpretation of coastal environments was made possible by image analysis using visual interpretation techniques (Fig. 5B). In general, the territory of Salinópolis was subdivided into 5 geomorphic domains:

(1) Coastal Plateau characterized by cliffs, where the coastal plateau meets the coastline, located in Ponta do Cocal at Atalaia and Maçarico beach;
(2) Coastal Plain, which are subdivided by;
a) Tidal plain, characterized mainly by mangroves and supratidal muddy plain;
b) Estuarine plain, and,
c) Littoral plain, dominated by active dunes and palaeodunes, extensive beaches of macrotides and sandy bars and coastal lagoons.

According to the classification proposed by Souza Filho & El-Robrini (2013) and adapted by Teixeira & Bandeira (2020), the following relief patterns for Salinópolis coastal zone are characterized in:

- Palaeodune: the recent coastal cordons represent ancient dunes that are far from the current coastal processes, corresponding to the post-beach areas, being reworked by the equinoctial high tide and wind.
- Macrotidal beaches: occur bordering the mangroves and the active cliffs of the coastal boards. They are made up of sandy sediments, with low slope, being influenced by waves and tidal currents. During the low tide, they can expose stretch zones on the

order of hundreds of meters wide.

- Fluvial-marine plain or estuarine plains (mangroves): areas with low, almost horizontal terrain, consisting of muddy sediments, cut by tidal channels, and flooded daily by semi-diurnal macrotides.
- Apicuns or saline fields: These are flat areas, bordered by mangroves, floodable during the spring tide, present vegetation tolerant to saline conditions and during the boreal summer there is the accumulation of salt on the surface by capillarity.
- Tidal Mudflats: flat surfaces consisting of muddy deposits, rich in organic matter, which are positioned in front of mangroves, visible at low tide.
- Tidal Sandflats: these are flat areas consisting of quartz sands, in the form of sand banks, which can occur parallel to tidal currents, as spit and perpendicular on the banks of tidal channels and through the ebb tide deltas. They are exposed during the low tide.
- Fixed dune fields (Dunes with Vegetation): are undulating surfaces consisting of sandy bodies, with main orientation NE-SW, fixed by undergrowth or shrub vegetation. This wind environment surrounds the entire coastal zone through active and inactive dunes (due to the presence of vegetation). These geoforms have varying heights depending on the sector considered, in Atalaia beach they reach up to 20m and the maximum development occurs towards the Southwest.
- Mobile (Active) dune fields: these are elongated sandy bodies, deposited longitudinally to the shoreline, and have a preferred NE-SW direction, sometimes covered with undergrowth, but which are not able to fix them, in front of wind rework.

The mobile dunes cause the transport/transfer of sediments to the tidal plain by the action of continental winds. This effect causes the frontal dunes to grow and isolated dunes to develop around intertidal accretion, where the sea does not cover them during high tides. The elongated shape of the dune field and the orientation of the crests of individual dunes suggest that ENE is the dominant direction of wind mass transport. In Ponta da Sofia, in Atalaia beach, this fattening and accretion of the coastline was observed in 200 m in approximately 20 years (Guerreiro 2021).

In addition, there are barcanoid shapes that respond to a predominant wind direction and stellar dunes. Further inland, the dune fields gradually lose height until they become mounds of lower altitude, and the vegetation stabilizes their movements.

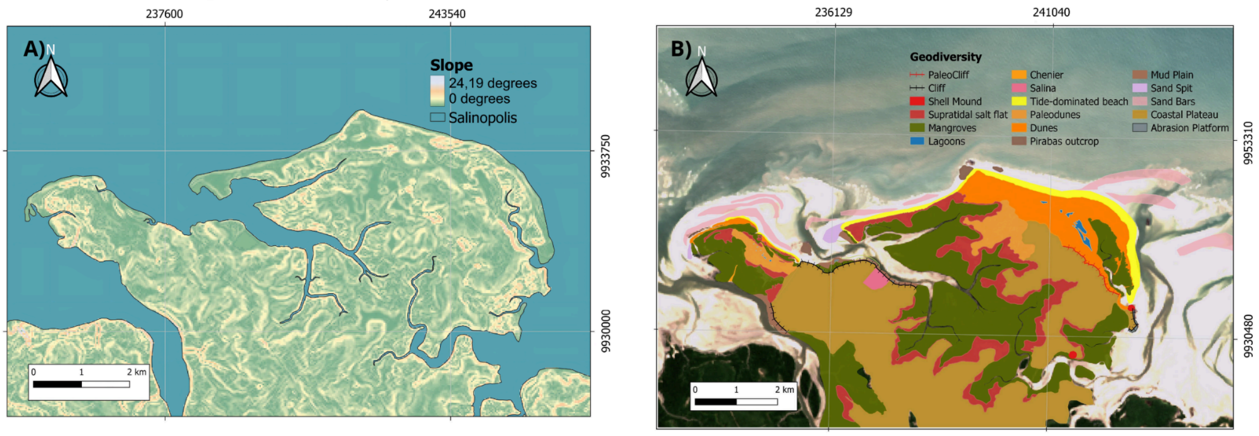

Figure 5: (A) Topographic Wetness Index (TWI) map, representing hydrological accumulation potential. Higher values indicate areas with greater moisture retention, such as mangroves and muddy tidal flats. (B) Geomorphological map of the Salinópolis Coastal Zone based on DEM analysis and field validation. The map delineates coastal plateaus, dune fields, estuarine plains, and beach ridges, which are key elements in the local geodiversity and geotourism potential.

3.1 Geodiversity Inventory

The selection of the elements comprising the geodiversity inventory in Salinópolis was primarily based on the geological and geomorphological configuration of the study area, grounded in evidence of the Cenozoic evolution (transgressive and regressive cycles) due to sea level change and tectonic in of Salinópolis in the Atlantic coast of Pará.

According to Souza, (2007), the evolution of this coastal zone is directly associated with relative sea level fluctuations that occurred during the Holocene. The Holocene transgression (~6,000 years B.P.) led to the erosion of the Coastal Plateau (Barreiras Group), forming cliffs and marine abrasion platforms, while drowning the Pleistocene Coastal Plain and depositing the basal transgressive sequence. Subsequently, a regressive phase or period of sea-level stability allowed for the development of muddy progradation zones, such as mangroves. Changes in sediment supply patterns and rapid sea-level oscillations favored the formation of ancient sandy ridges (Chenier), reflecting periods of higher wave energy and reduced fine sediment input. Currently, the region is undergoing a new transgressive phase, characterized by beaches, dunes, and sandy barriers advancing over the tidal plain. At the same time, estuarine systems are being infilled, and ebb-tidal deltas are developing at the mouths of estuarine bays and channels (Souza-Filho et al. 2009).

The Salinópolis lies on the Bragantina Platform, a tectonically stable and currently submerged structural unit (Costa et al. 1993). It is one of the most dynamic areas along the Pará coast, shaped by a humid tropical climate, macrotidal regime (>5 m), moderate winds (6.3 m/s), significant wave height (0.8 m), and strong tidal currents (1.4 m/s) (Pereira & Pinto 2014). These geodynamic conditions support the selection of landforms and features for the inventory, as they hold high representativeness and interpretive value within the context of Amazonian coastal geodiversity.

Table 3: Scientific (Ic), educational (Id), and touristic (It) values, along with degradation risk and classification level, assigned to geosites in the Salinópolis coastal region based on GEOSSIT methodology. Sites with scientific value scores above 200 are considered geoheritage sites, and those with national or international relevance are highlighted.

Geosite	Scientific Value (Ic)	Educational Value (Id)	Touristic Value (It)	Degradation Risk	Classification
Sambaqui and Cliffs (Ponta do Cocal)	330	300	245	Medium (250)	Geodiversity Site of International Relevance
Beach Ridge into Mangrove Area	340	325	270	High (315)	Geoheritage Site of International Relevance
Pirabas Outcrop Atalaia and Maçarico	340	335	280	High (315)	Geoheritage Site of International Relevance
Atalaia Dunes	60	295	270	Medium (270)	Geoheritage Site of National Relevance
Mud Plain (Mangroves and Muddy Tidal Plain)	165	290	270	Medium (250)	Geoheritage Site of National Relevance

Based on geomorphological and morphogenetic concepts, and following the classification proposed by Souza Filho & El-Robrini (2000) later adapted by Bandeira & Dantas (2016), and GOSSIT the coastal patterns identified in the Salinópolis region include sites of geological interest, which are organized into three categories:

The Coastal Plateau, which represents the continental limit of the coastal plain, as well as the basis on which the Holocene sediments of this plain are deposited, whose geological framework is integrated by the Barreiras Group and Post-Barreiras sediments, of Miocene-Pleistocene age. The main features of this unit along its boundary with the coastal plain are:

Ponta do Cocal (active cliffs), which is under a strong erosive hydrodynamic process during equinoctial tides allied with macrotidal high tides causes a continuous retreat of its edges in contact with the sea, leaving as traces of its presence, marine abrasion platforms, represents the internal limits of the coastal plains and position of the old coastline in the region, they are spectacular rugged vertical rock walls and are associated with the abrasion platform and the beach (Fig. 6). The cliffs are formed by layers of sedimentary rocks from the Barreiras Group and Post-Barreiras which provide excellent exposure from the evolution of the Neogene to the Quaternary. The lithology and age of the deposits define their general friable character, allowing a strong erosion at the foot of the cliffs. The escarpments surface extensively in an almost tabular scenario as continuous sea cliffs, with more than 8 km in the eastern sector of Beach do Maçarico, of 500m on the border between the beaches of Atalaia and Farol Velho and of 100m in Ponta do Cocal. Its heights are between 4 and 20m altitude, with an average thickness of 10m.

These cliffs offer a clear and accessible exposure of stratigraphic layers, showcasing active erosion processes and marine abrasion platforms. Due to their outstanding scientific and educational potential, they are considered highly valuable geosites. However, these features face ongoing threats from natural erosion and increasing urban development pressures.

Sambaqui are generally located in paleocliffs near estuaries and mangroves, highlighting the Atalaia Island. On the edges of the coastal plateau, there are several sambaquis (Ponta do Mangue and Cocal) in the limits of the studied area, which represent prehistoric traces of human presence, the margins of the coastal plain. These sambaquis are almost destroyed, due to their historical exploitation for the manufacture of lime and more recently by the indiscriminate construction of roads and/or access roads to the coastal zone (Fig. 7).

Sambaqui are a mound-shaped accumulation of shell valves and other materials, generating marks on the landscape. These marks that were left in the Amazonian landscape – shellmound archaeological sites, vary their occupations 6,000 and 3,000 A.P. (sambaquis present on the Amazon Estuaries) (Silveira & Schaan 2005).

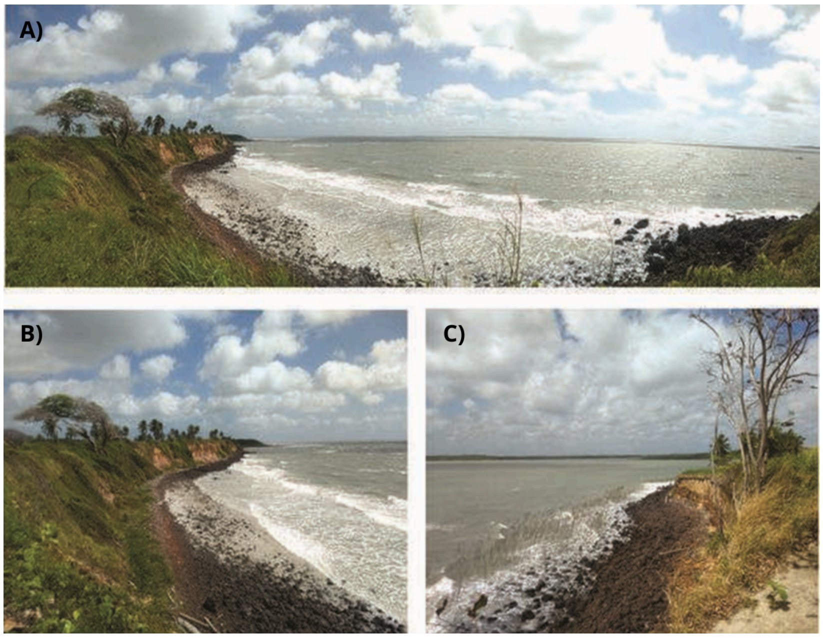

Figure 6: (A) Ponta do Cocal geosites showing active cliffs composed of friable sediments from the Barreiras and Post-Barreiras formations. These sea cliffs are under strong erosional pressure, forming marine abrasion platforms. (B) View of the cliff at Ponta do Cocal, showing the southeast face oriented toward and highlighting the Arapepó estuary (C) The northwest face oriented toward and highlighting Atalaia Beach. Detail of vertical sedimentary strata and the Abrasion Platform representing continuous retreat due to macrotidal and wave processes.

The presence of shells as building material in these middens, the presence of archaeological ceramics and faunal material that record human presence in generally high areas and close to the estuary characterize the geosites middens present on this coast. The geological period of occupation of this site dates to the middle Holocene. The ceramics associated with the coastal shell middens is known as Mina Tradition. Mina tradition was considered by (Lopes et al. 2018, Simões 1981) for settlements with the patterns of estuarine settlements, such as the presence of ceramics with similarities in their manufacture, exploitation of shells and mollusks for subsistence, among other social relations.

The Uruá phase is identified as one of the oldest of the Mina Tradition, which presents a likelihood based on hunting and collecting mollusks, in addition to having antiplastic made from ground shell. This phase is one of the earliest in the region for this type of settlement, and it is important to mention that it is one of the oldest in the Americas (Simões 1981).

They hold significant cultural and historical value and present strong potential for incorporation into educational programs and community-based geotourism initiatives. However, these sambaquis face threats from natural erosion, informal road construction, and past lime extraction activities.

2. Beach ridges represent different coastal dynamics; therefore, the evolution of the coastal environment and its curved shapes are convex towards the sea because of wave diffraction. Sediments are deposited because they are swept away from shallow water into a low-energy environment. In this context, the first division of mappable landforms linked to processes of erosion and coastal accumulation is simple to carry out.

Maçarico/Corvina Beach Ridge (Ancient Coastline) sites are sandy bodies, narrow and elongated, which occur isolated in relation to the coast, in the middle of the mangroves, also known as strandplains (Fig. 8). They are characterized by sandy bodies (ridge of beaches and/or dunes) on muddy deposits of mangroves, currently isolated from marine processes, indicating the progradation of the fluvial-marine plain and consequently of the coast over the ancient beach environment. At Beach do Maçarico, two main frontal dune crests were identified, aged 69 and 80 years, respectively, with an average progradation rate of 6 meters/year (Leite 2006).

Accordingly, this unit is determined by a sandy portion, covered by very thin dune deposits. Throughout the study area, but in its greatest extension located in Beach do Maçarico and Corvina, this unit has elongated shapes, parallel to the coastline, with widths ranging from 50 to 150 m and varying lengths. Covered by dune vegetation and backshore zone (restinga), reaching shrubby levels, this unit emerges interspersed with the fluvial- marine plains, through the vegetation of mangroves.

Figure 7: (A) Sambaqui site exposed on the eroded cliff, providing evidence of past sea level rise, as it is believed to represent the former top of the cliff. (B) Structures showing walls constructed with shell-based antiplastic materials (crushed shells). (C) Sambaqui site illustrating its vulnerability to sea level rise (D) and (E) Archaeological shell mound deposits containing ceramic fragments. (D, detail) (F) Ceramic artifacts recovered from the site constitute evidence of past human occupation and the cultural significance of the site within the Mina tradition.

Cohen et al. (2015) suggests that the displacement of mangrove forests to lower surfaces can be attributed to a fall in relative sea-level, which may have been caused by drier conditions and reduced rainfall during the Holocene period. However, they suggest that even small fluctuations in relative sea-level resulting from climatic changes at regional or global scales can have a significant impact on the mangrove area at present as El Niño Southern Oscillation (ENSO) events.

These features serve as important indicators of coastal progradation and environmental change, with notable vegetation succession occurring over time. They hold high educational and scientific value and offer strong potential for development into interpretive geotrails.

3. Erosive and accumulative landforms, such as dune escarpments, are characteristic of the base of dunes, and abrasion platforms are characteristic of cliffs, while forms of accumulation, such as sandy bars, beach ridges, and extensive sandy beaches and active and vegetated dunes characterize areas in accretion. These features are present throughout the Salinópolis Coastal Zone (Fig. 8).

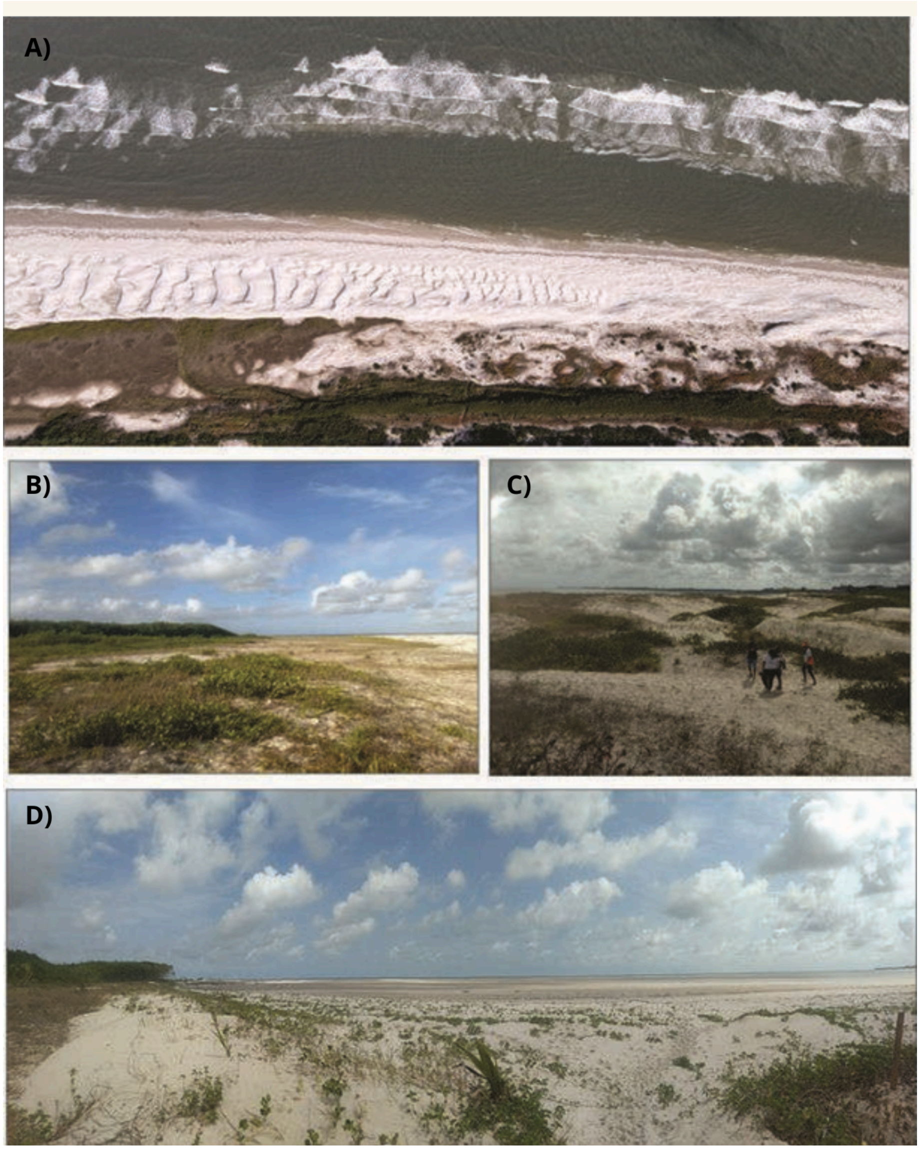

Figure 8: (A) Beach ridge system in the Maçarico–Corvina sector, representing ancient coastlines formed by wave diffraction and progradation processes. (B) Sandy ridges now embedded within mangrove forests, illustrating Holocene sea-level fluctuations and sedimentary dynamics; note the mangroves located behind the restinga vegetation. (C) Extensive high dune fields, composed of well-sorted quartz sand, shaped by persistent trade winds and reflecting the active eolian dynamics of the beach-dune system. (D) Frontal dune bordering the shoreline, with mangrove established in the more protected, landward sector, indicating interactions between eolian and beach–mangrove environments.

Palaeontological site (Pirabas Formation) - According to (Rossetti, 2001; Rossetti et al. 2013) the Oligocene to Miocene transitional deposits found in the Salinópolis region are the result of a transgressive-regressive cycle. Along the Amazon coast, the basin was filled with transgressive shallow-warm-water carbonate marine deposits due to global sea level rise in the Mid-Miocene and gradually gave way to regressive siliciclastic deposits. This change indicated a strong uplift of the basin edge caused by eustatic and tectonic activity during the Amazon River fan development, leading to the inhibition of carbonate deposits. After this predominantly transgressive and oscillatory depositional event, another regressive and siliciclastic sequence (Barreiras Group) dominated the sedimentation, and its typical Meso-Miocene sedimentary structures and palynological content suggest a certain contemporaneity and gradation between the Pirabas and Barreiras sequences. It could have marked the final stage of carbonate sedimentation in transitional zones of the Amazon coastline (Caputo et al 2006, Rossetti et al 2013).

The depositional model proposed by Góes et al. (1990) is comparable to previously proposed models, supported by evidence from storm waves on the continental shelf. Three major ecofacies have been described, the Capanema Ecofacies (lagoonal environment), the Baunilha Grande Ecofacies (open marine, lagoon, and mangrove forest environments) and the Castelo Ecofacies (continental and carbonate platform environments)) are organized in an interdigitated manner with cyclic sedimentation, indicating frequent fluctuations in sea level and an intensely jagged coastline.

Pirabas Formation is composed of gray limestones of variable composition, including coquinas, biohermites, micrites, dolomicrites, marls, and bioclasites, as well as calcarenites and black shales (Aguilera et al. 2019). These were deposited in a marine environment characterized by shallow and warm waters, and the lithofacies of the formation serve to define a particular ecosystem.

The Pirabas Outcrop at Beach do Maçarico is a fossiliferous limestone bioherm containing corals, algae, and echinoids, representing the only known Cenozoic reef system in Brazil. It provides a unique paleoenvironmental record from the Mid-Miocene, with high stratigraphic and taxonomic diversity, offering exceptional scientific and educational value. Despite its significance, it remains underutilized as a geotourism resource. Another important site, the Pirabas Outcrop at Atalaia Beach, features a rich fossil assemblage of vertebrates and invertebrates from shallow marine environments less than 50 meters deep. This outcrop holds significant potential for public education and scientific outreach but currently suffers from a lack of formal protection and restricted public access.

-Pirabas Formation Outcrop – Maçarico beach

Távora et al (2013) and Rossetti & Góes (2004) have interpreted the limestone outcropping at Maçarico beach as a biohermite (Fig. 9). This interpretation was based on the faciological pattern and biotic content, which is predominantly made up of hermatypic corals, coralline algae, and echinoids. Secondarily, it includes encrusting bryozoans and bivalves; all of which are typical of reefs. This description characterizes a depositional environment and a specific ecosystem, which is the only Cenozoic fossil reef recognized in Brazil so far (Souza 2010). It holds exceptional scientific and educational importance but remains underutilized as a geotourism resource (Fig. 9).

Figure 9: Fossiliferous outcrops of the Pirabas Formation at Maçarico Beach. (A) Outcrop located in the subtidal zone. (B) Aerial view showing the position of the outcrop across the intertidal and subtidal zones. (C) Limestone bioherm exposure containing corals, algae, and echinoids. (D) Fossiliferous outcrop in the supratidal zone, representing the only known Cenozoic reef system in Brazil. (E) Mollusk fossil with hematite and goethite (iron oxides) and quartz as an accessory phase.

-Pirabas Formation Outcrop – Atalaia beach

The Atalaia outcrop's fossil record displays a vast array of taxa, such as plants, calcareous algae, foraminifera, ostracods, sponges, bryozoans, molluscs, echinoderms, crustaceans, fish, and sea mammals that appear to have accumulated in a shallow tropical marine paleoenvironment. This environment ranges from the tidal zone to water depths of less than 50 meters on the inner continental shelf. According to (Silva & Costa 2021) this fossiliferous site is plausible to make a positive impact on educational and cultural initiatives for citizenship by means of community involvement, professional contributions, scholarly research, and governmental participation, however, it is undervalued, not being used to its potential (Fig. 10).

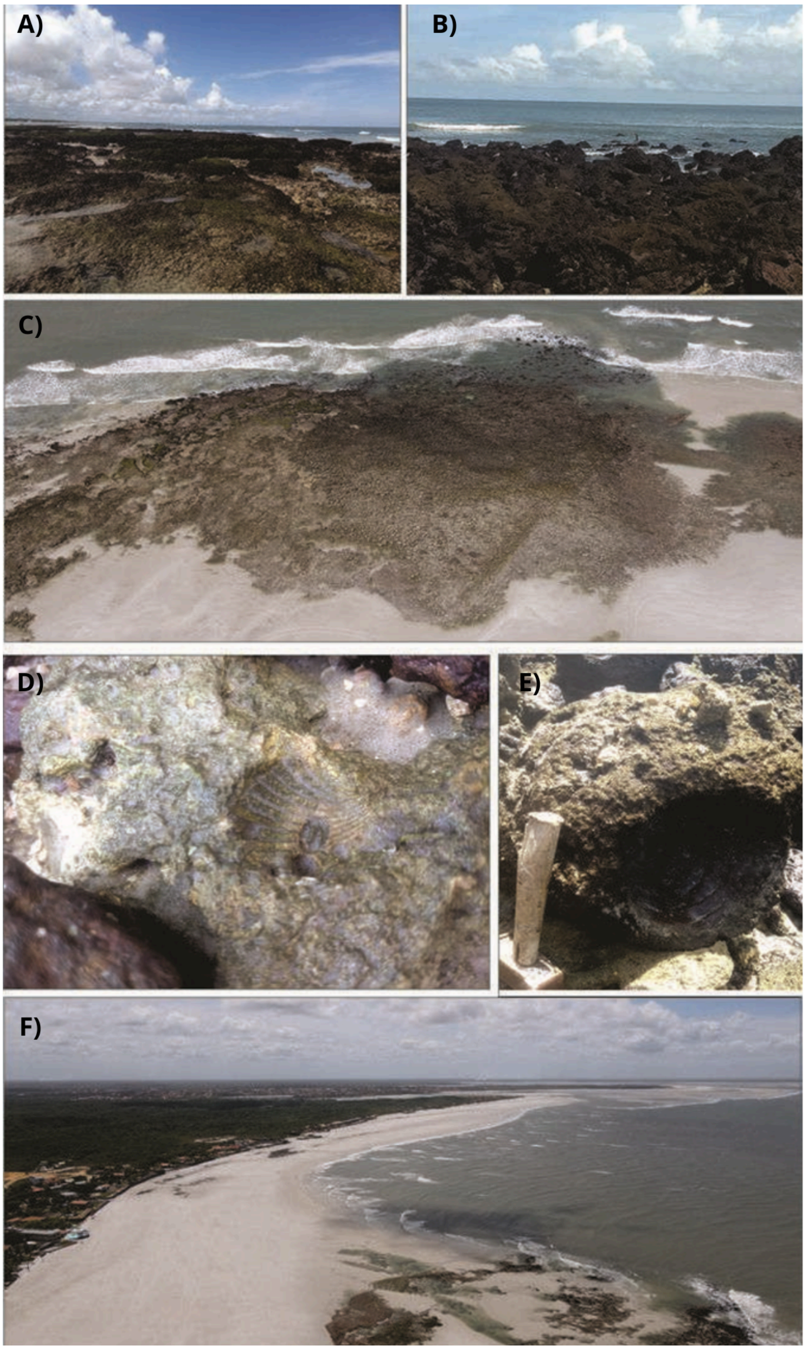

Figure 10: "Fossiliferous outcrop of the Pirabas Formation located in the subtidal zone of Farol Velho Beach (A). An aerial view shows the outcrop's position spanning the intertidal and subtidal zones (B). The limestone exposure contains well-preserved mollusks, and foraminifera (C, D), providing valuable paleoenvironmental evidence for a shallow-water marine system during the Miocene. A broader aerial perspective (F) highlights the precise location of the outcrop within the coastal setting, emphasizing its geomorphological and paleoenvironmental significance.

3.2 Geotrails establishment

TThe trails were developed according to the State Tourism Qualification Program (PEQTur, https://www.setur.pa.gov.br/peqturpa), which aims to provide knowledge about trails, training residents of the Salinópolis community and people who intend to act as drivers, enabling them to conduct visitors safely. Allied to this program, the originated Geotrails extension Project from Federal University of Pará in Salinópolis, assisted in environmental conservation practices, inducing local development based on the geoservices, natural resources, and social-cultural relationships. These geotrails act as an outdoor lab, where students of oceanography, coastal engineering and tourism learn about geodiversity with hands on (Fig. 11). Also, these geotrails used to be the main fisherman and surfers' access to the beach.

The main action of the project is to communicate the importance of geodiversity awareness by employing landscape interpretation panels (Fig. 12). For the project to be effective, wood pieces from the local shipyard were reused, improving sustainable commitment.

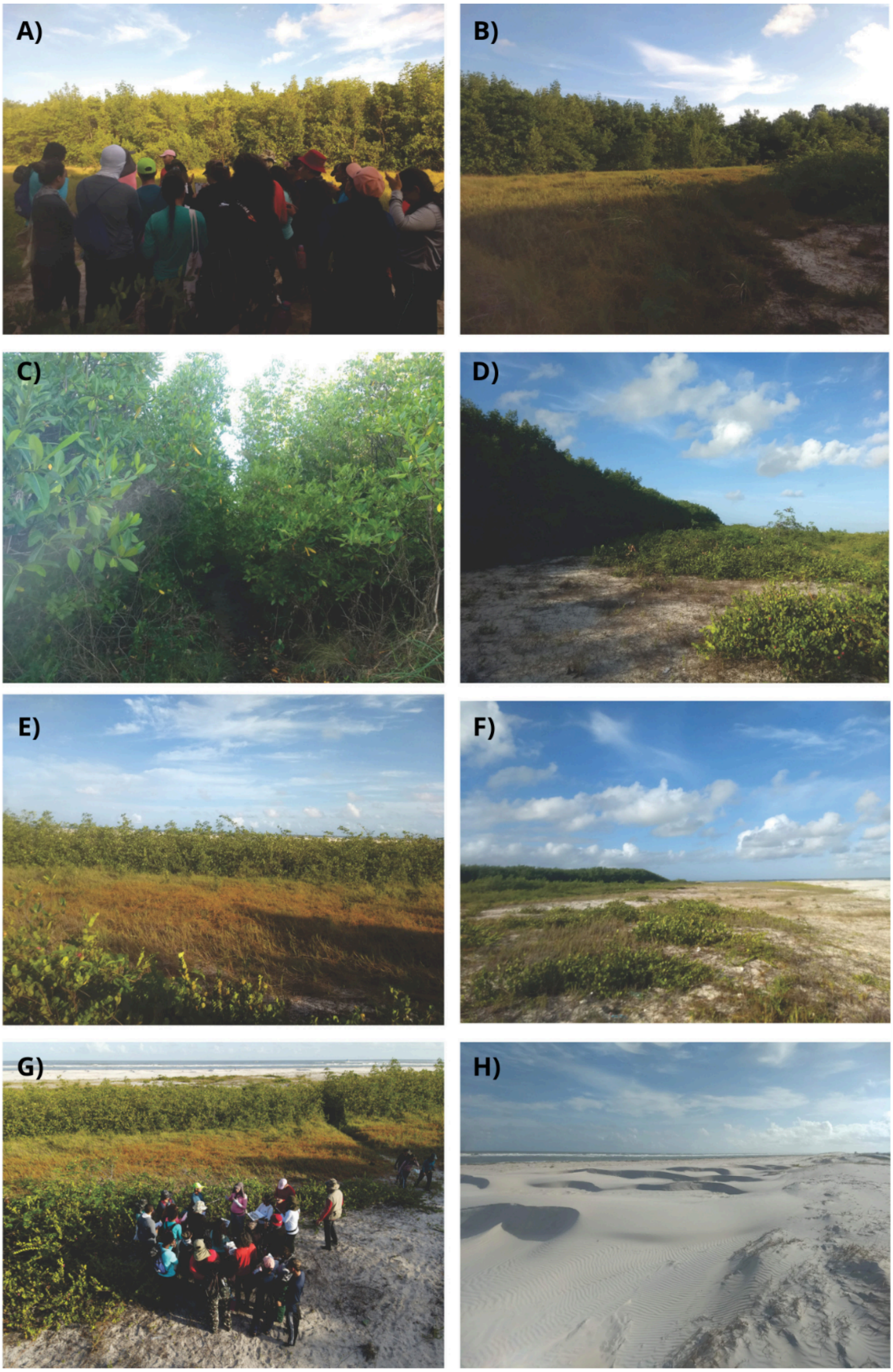

Figure 11: Geotrails on the beach ridge system at Corvinas Beach, serving as an educational resource to explore landscape evolution, sedimentary structures, and the relationship between geodiversity and coastal dynamics. (A) Oceanography students from the Federal University of Pará conducting fieldwork along the beach ridge trail. (B) Sandy beach ridge situated between mangrove areas. (C) Section of the mangrove trail. (D–F) Seaward sandy beach ridges; note the high mangrove trees behind the ridge and dune vegetation in the foreground. (E) Students on the outer beach ridge with the sea visible behind them. (F) Dunes developing in the supratidal zone of Corvinas Beach.

Figure 12: Interpretative panel on ecosystem services installed along the geotrails in Salinópolis. The signage explains geological and ecological processes, promoting environmental awareness and supporting geotourism and geoeducation in the region. (A) Mangrove creek. (B) Geosystem service provided by coastal dunes, such as protection against flooding. (C) Ecosystem service of mangroves as coastal protection and nursery for various marine species. (D) Section of the trail route. (E) Fruits along the trail, including Ajiru (Chrysobalanus icaco), typical of the Amazon coast. (F) 'Respect the beach' sign promoting conservation ethics.

5. Discussion

A primary concern of natural and cultural conservation has always been to protect critical features of natural resources, usually to protect indigenous, fauna and flora, fossils, and archaeological sites, however a broader view covers the characteristics of geology and landscape (UNESCO, 2002). Thus, State Conservation Units like Atalaia Natural Monument, and the Atalaia, Farol Velho, Maçarico and Corvina Beach Cultural Heritage, were created to preserve the species and diversity of the area. They acquired this status in 2022 for the purpose of protection and were extended to include the natural and cultural heritage of these sectors. Currently, there is no management plan for those areas which should be considered the growing presence of tourists, the use of scarce resources and the possible impact on marine resources such as cetaceans, turtles, mollusks, algae, fish, and birds, however, shows a growing interest of the state government in the area.

The results obtained in this study indicate that this coastal zone has a considerable geodiversity, such as landscapes, geomorphological features, and points of geological, fossiliferous, and archaeological interest, which have been mapped, catalogued, and described in detail in this contribution to highlight the importance of a geomorphological perspective for nature conservation and sustainable use of the region.

The detailed mapping of the landforms represents a basic tool for greater control and identification of characteristics in situ, allowing them to classify the coastal reliefs considering the processes of erosion and coastal accumulation. The geomorphometric parameters, distinguished different areas of the coastal zone and characterized them to obtain maps of altitude, topographic wetness index (TWI) and slope. The geomorphological mapping of Salinópolis plays a crucial role in identifying valuable landscape elements.

The geodiversity inventory, which classifies features according to geomorphology, contributes to the assessment of the region and is a useful tool for planning the essential steps in any geoconservation strategy and establishing management priorities (Brilha, 2016). In this context, this paper in the Salinópolis coastal zone, focused on geological-geomorphological data, represents the first step towards a proposal for the development of geotourism in this region.

The integration of geomorphological mapping with the GEOSSIT inventory enabled the identification of sites with high scientific, educational, and touristic potential. The GEOSSIT assessment carried out in the Salinópolis coastal zone revealed six geosites with diverse degrees of scientific, educational, and touristic value, as well as varying levels of vulnerability to degradation. Among these, three stand out for their exceptional scientific relevance: the Pirabas Formation outcrops, the Sambaqui and cliff complex, and the beach ridge embedded in mangrove systems — each scoring $Ic \geq 330$, well above the threshold ($Ic > 200$) typically used to classify sites as geoheritage of exceptional scientific value. However, in this study, these high value geosites were classified as geodiversity sites of national and international relevance, as part of an integrated approach that acknowledges not only their scientific importance but also their cultural and educational significance within the broader landscape.

The Pirabas Formation outcrops are recognized in national conservation strategies due to their fossil richness. As highlighted by Sepúlveda et al. (2022), fossiliferous sites like these are considered part of Brazil's geoheritage and are included in formal conservation policies. These sites are critical not only for preserving geological and paleontological records but also for reconstructing environmental and human histories. Their high scores in educational and touristic potential further emphasize their importance for geoconservation and the development of sustainable geotourism. However, they are also under medium to high risk of degradation, highlighting the need for urgent protective measures.

In contrast, other inventoried areas such as the Atalaia Dunes and the Mud Plain (including mangroves and tidal flats) did not reach the scientific value threshold to be classified as geoheritage sites but were still recognized as geodiversity sites of national relevance due to their high educational and touristic values. Although not outstanding from a purely scientific perspective, these sites play a vital role in public engagement, formal education, and the cultural and environmental identity of local communities.

The results underscore that the geodiversity of Salinópolis is not only a natural resource but also a strategic asset for regional sustainable development. The absence of management plans for some of the protected areas limits efforts to address increasing anthropogenic pressures, including urban expansion (Rosa et al. 2021), vehicle traffic over fragile landforms (Santos et al. 2022), dune and mangrove deforestation (Romero et al. 2025), acceleration of erosion processes on the cliffs and changes in beach sediments and variability in coastal dynamics (Ranieri 2014), as well as water quality and local garbage generation (Pinheiro 2019). These pressures directly impact sediment dynamics, biodiversity, and the preservation of fossil and archaeological records, ultimately threatening the integrity of the region's geoheritage.

Following the proposals of Brilha (2016) and Sepúlveda et al. (2022), this study suggests geoconservation strategies that integrate the values of geodiversity into broader environmental and cultural conservation initiatives. The classification and quantification of geosites and geomorphosites offer technical support for prioritizing protection, promoting environmental education, and enhancing local geotourism potential. The integration of geoscience and community-based tourism may foster territorial belonging, generate income, and strengthen the cultural identity of traditional populations.

This contribution provides, therefore, valuable information about the geodiversity of the Atalaia Natural Monument and the areas of Cultural Heritage that will be vital for the development of a strategic plan that incorporates geodiversity as another main attraction in the scope of geotourism or scientific tourism.

6. Conclusions

Salinópolis is a unique place where the geological history (mainly Cenozoic) recorded over millions, hundreds of thousands, and thousands of years up to the present, is visible in the landforms, stratigraphic sections, and spectacular landscapes. The area also offers a rich biodiversity, paleontological-archaeological heritage, and a diverse ecological system.

The detailed geomorphological map and the geodiversity inventory, developed using Geological

Survey of Brazil (CPRM) database and GEOSSIT methodology, identified and characterized geodiversity elements with high scientific, educational, and touristic value, including fossiliferous outcrops, beach ridges, and coastal landforms associated with dynamic sedimentary processes. These products can serve as a foundation for monitoring and quantifying aspects of erosion, hydrological flow and land use in the area, leading to improved conservation of the geodiversity sites. In the Atlantic coast of Pará.

Based on these results, it is possible to propose actions that support sustainable development and improve the management of protected areas, such as the creation of a geological-geomorphological guide and a relief inventory highlighting key landforms and their contribution to regional geodiversity. The systematic assessment also supports the integration of geodiversity into public policy and territorial planning, enhancing local identity and fostering community engagement in heritage conservation.

This approach enables the local community to better understand and value the geodiversity of the region, as well as its connections to biological, paleontological, and archaeological conservation and natural equilibrium.

The landscapes and geodiversity sites of the Conservation Unit and Cultural Heritage of Salinópolis present significant educational and touristic potential. These geodiversity sites should be recognized and incorporated into the ongoing proposal for a multipurpose reserve through the implementation of a geotourism circuit.

A more detailed quantification of geodiversity aspects is essential to ensure effective conservation of this heritage. Such initiatives can promote sustainability by fostering an activity that protects the environment, generates low impact, enables the development of geoservices, and encourages the construction of a new perspective that stimulates the appropriation and reappropriation of space by residents and visitors.

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Credit author statement

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