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Research Article

Erosion Surface and Pre-Cretaceous Inselbergs of the Western Margin of the Potiguar Basin – Northeastern Brazil

Superfície de erosão e Inselbergs pré-Cretáceos da borda da Bacia Potiguar – nordeste do Brasil.

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Abstract: The exhumation of inselbergs in the Potiguar Basin has revealed morphologies previously buried by Cretaceous sedimentation. These constitute granitic inselbergs formerly underlying the sedimentary rocks of the Apodi Group (Açu and Jandaíra Formations). This article aims to understand whether exhumed inselbergs in the western margin of the Potiguar Basin may serve as markers for the pre-Cretaceous geomorphological evolution in the studied area. Hypotheses were tested based on morphometric data combined with field collections for landscape interpretation. The results indicate that in the Cenozoic era, erosion of the western margin of the Potiguar Basin was intensified by the formation of the Jaguaribe River, which carved the valley and gave rise to the escarpment. With the migration of the main channel to the east, the escarpment underwent lateral retreat, revealing inselbergs, which are now situated within the valley, some even within the riverbed of the Jaguaribe River. These inselbergs might constitute the oldest granitic reliefs on Earth with respect to the overall granitic morphology. Their recent exhumation exposes a pre-Cretaceous erosion surface currently buried by the alluvium of the Jaguaribe River. This surface, along with the inselbergs, has been preserved since the Jurassic, as during the Cretaceous, the opening of the Atlantic and continental rifting allowed the formation of the Potiguar Basin.

Keywords: Granite landscapes; Geomorphological Evolution; Jaguaribe River

Resumo: A circudenudação da Bacia Potiguar tem revelado morfologias até então soterradas pela sedimentação cretácea. Essas, constituem inselbergs graníticos que estiveram sob as rochas sedimentares do Grupo Apodi (Formação Açu e Jandaíra). O presente artigo tem como objetivo compreender se inselbergs exumados da borda oeste da Bacia Potiguar podem constituir marcos da evolução geomorfológica pré-cretácea na área estudada. Hipóteses elencadas foram testadas partindo de dados morfométricos atrelados a coletas de campo para interpretação da paisagem. Os resultados indicam que, no Cenozoico, a erosão da borda oeste da Bacia Potiguar foi intensificada pela formação do Rio Jaguaribe, que abriu o vale e originou o escarpamento. Com a migração do canal principal para leste, a escarpa foi retroagindo lateralmente e revelando inselbergs, que hoje, estão dispostos dentro do vale, sendo possível encontrar até dentro leito fluvial do Rio Jaguaribe. Esses inselbergs provavelmente compõem os relevos graníticos mais antigos da Terra, no que diz respeito ao conjunto da morfologia granítica, porquanto sua recente exumação revela uma superfície de erosão pré-cretácea, atualmente soterrada pelas aluviões do Rio Jaguaribe. Essa superfície, assim como os inselbergs, estiveram preservados desde o Jurássico, uma vez que no Cretáceo a abertura do atlântico e o rifteamento continental originaram a Bacia Potiguar.

Palavras-chave: Paisagens graníticas; Evolução geomorfológica; Rio Jaguaribe

1. Introduction

The landscape of the Northern northeast of Brazil exhibits a relief marked by tectonic events of continental magnitude with a genesis related to the Brasiliano Orogeny and opening of the Atlantic Ocean, resultant from the divergent and transcurrent processes. Given its characteristics and privileged position in South America (Ab'saber, 1998; Ross, 2016), the Borborema Province holds registers capable of reconstructing several geological periods, including Proterozoic terrains (Sá et al., 1992).

The geochronological context of the study area comprises the period of the Gondwana amalgamation between 650 Ma and 540 Ma during the Neoproterozoic (Brito Neves, 1999) responsible for the Brasiliano Orogeny and formation of a Himalayan-type Mountain chain in the Borborema Province, including terranes of the northern Northeast (Caby et al., 1995; Claudino-Sales, 2007; 2018). This landform formation was subsequently eroded linked to the cease of the tectonic activity during the platform formation until the Jurassic, followed by the reactivation on the account of the cretaceous rifting, and maintained by pulsatile events during the Cenozoic.

In theory, Claudino-Sales (2016) considers that the dominant landscapes of the Gondwana supercontinent, including the segment of the Borborema Province, were typified by planation surfaces, given the prolonged tectonic quiescence, during which is likely that no important episodes of relief reactivation occurred.

Thus, following the Brasiliano Orogeny, the Borborema Province was subjected to a long period of tectonic quiescence, which lasted until the Mesozoic (≅ 200 Ma BP), when processes responsible for the separation of the Gondwana continent between 200 and 180 Ma BP during the Jurassic (Matos, 2000), the opening of the Atlantic Ocean, the individualization of the South America and Africa continents, and the formation of the continental margin of the Brazilian Northeast started.

In this context, extensional stresses during the pre-rift phase give rise to the lineaments oriented in the NE-SW direction (Bezerra et al., 2001). The rift phase, specifically the Potiguar rift, allowed the marine transgression to the continent and, subsequently, the drift process occasioned the reorientation of the stresses of continental breakup, thus aborting rifts and generating 19 sedimentary basins, such as the Araripe and Apodi Basins, among other minor basins (Matos, 2000).

The main sedimentary basins underwent thermal subsidence, allowing for the deposition of the top formations between the Cenomanian and Campanian (100-83.6 Ma BP), represented by the Açu and Jandaíra Formation in the Potiguar Basin. The uplift promoted by the pre-Cretaceous epeirogenesis raised the former marine floor to the level of these tablelands, which were later removed by erosion during the Cenozoic (Dantas et al., 2008).

The Cretaceous tectonics that culminated with the opening of the continent is considered by many as one of the most important geological-geomorphological events in the Brazilian Northeast (Maia and Bezerra, 2014), Being the Cretaceous a significant temporal marker to unveil the morphogenesis of the south American relief (Roos, 2016). Following the end of the Cretaceous period, climate and sea level variations and the occurrence of the Holocene marine transgression and regression shaped the coastal landforms and fluvial valleys (Maia et al. 2010), being the final eustatic episodes to model the coastal relief of the region.

In view of this geochronological framework, multiple are the resultant morphologies in the landscape which instigate the application of geomorphological theories, aiming at reconstructing events and processes of global tectonics in the northern northeast.

Located in the brazilian semiarid, in the easternmost Ceará State, the study area is located in the extensive Rio Jaguaribe alluvial plain, whose lower course bounds the Apodi plateau escarpment, a Cretaceous sedimentary plateau of Potiguar Basin. Between the two sedimentary units, granitic outcrops displaying inselbergs compose and outstanding in the landscape, revealing a complex and dynamic relief evolution system (Peulvast; Claudino-Sales, 2004; Maia et al., 2010; Claudino-Sales, 2016).

This work aimed to discuss how these inselbergs evolved in the regional geomorpho-chronological context and their influence as an element of the present landscape; the main objective is thus to characterize and propose a model of geomorphological evolution for the given area.

The adopted methodology was based on geomorphological mapping and delineation of major stratigraphic correlation employing digital procedures in GIS (Geographic Information Systems), associated with theoretical interpretations of the evolution of the local relief. Topographic profiles were extracted from Digital Elevation models (DEM) and combined with illustrative 3D sketchs. Considering events of mega-geomorphological scale and microfeature origin resulting from intensive Quaternary processes and climate alternations, we aimed at characterizing the features derived from the relationship among the geomorphological units in the area.

2. Literature review

A review of planation surfaces, such as the formulations about endogenous and exogenous forces of Penck (1924), the pediplanation and base level theories of King (1953), the evolution of hillslopes from through pedogenesis and morphogenesis of Bigarella (1965), the Etchplanation of Budel (1982), among others, was made. Thus, in order to elaborate a proposal of geomorphological evolution, we adopted the comprehension of base level at various scales, differential erosion guided by lithological variation (Maia, 207), backwearing (Marent and Valadão, 2019), knickpoints, two-stage concept and etchplanation (Budel, 1982).

In agreement with Bigarella et al. (1965) and based on the plentiful documentation on the climatic variation that characterized mainly the Quaternary period, we considered the landforms, in their majority, as paleomorphologies that constitute remnants, frequently dissected and inherited from paleoclimates with a predominance of processes related to mechanical morphogenesis and sheet erosion. In this context, we consider the climate a fundamental factor in understanding relief evolution.

Salgado (2007) claims that the relief is polygenetic, in that all theories require complementing and specific comprehension when applied, i.e., the juxtaposition of theories is possible. Maia et al. (2018), in turn, point to the need to assess relief evolution from the macro-temporal scale, based on well-founded Geomorphological theories (Etchplanation and Pediplanation).

In this respect, granite geomorphology has been important for climate geomorphology since granite landscapes can provide significant information about relief evolution in this type of terrain.

Ross et al. (209) argue that the challenge to understand the morphogenesis and morpho-chronology of the South America relief resides in considering firstly the ancient tectonics and the consequent structural rearrangements, followed by denudational processes occurring for hundreds of millions of years over pre-Cambrian cratons and orogenic belts. Therefore, depending on the local lithology, the tectonic configuration, and the environmental history, the long-term etching process can transform a landscape, developing a diverse topography, from plains to mountainous relief (Migo, 2006).

It is worthwhile to point out that the resistance to endogenous and exogenous processes varies according to the material supporting the relief, enabling each lithology to respond differently to the same processes occurring in a certain area. Vitte (2005) maintains that it should be noted in the geomorphological analysis that the Etchplanation concept must be evaluated within a broader framework, i.e. the notion of a climatogenetic geomorphology and the polygenetic aspect of the relief evolution, in which the landforms are product of a cycle of Etchplanation-pediplanation.

Maia and Nascimento (2018) state that commonly this type of relief has its origin and evolution related to two stages: the first involving structurally controlled deep weathering, occurring by a progressive differential deepening of the weathering front, and the second associated with the stripping of the regolith by surface erosion, exposing the unaltered sectors of the weathering front, such as inselbergs.

However, in the specific case of the inselberg in Quixeré (NE Brazil), given their location, the processes of rifting, formation of the sedimentary basin, linear erosion processes, fluvial erosion and backwearing of the escarpment gained emphasis in the relief evolution. Thus, the action of mechanical and chemical weathering cannot be distinguished, as both play an important role in shaping diverse granite features, although in distinct moments of their morphogenetic evolution.

Considering the regional evolution and the prominence of these landforms in the landscape, exhibiting the serrated inselberg morphology facing the flat top of the Apodi Plateau, it is important to address the origin and evolution of these outcrops correlating the behavior of features with lithologies and morphometric parameters.

Several works are based on the topographic compartmentalization of the relief to delimitate morphologies and units, especially the mega-geomorphology studies and structural geomorphology which, frequently, carry out analysis and interpretation of Digital Elevation Models (DEM) such as Neves et al. (2003), Corrêa et al. (2010), Guadagnin and Trentin (2014), Maia and Bezerra (2014), Claudino-Sales (2016); Ross et al. (2019), among others.

3. Study area

The study area is constituted of two morphostructural units (Souza, 1988), namely the Apodi Plateau and the Jaguaribe River alluvial plain. The former is located in the southeastern escarpment of the sedimentary plateau, where the upper formations of the Potiguar Basin outcrop, formed in the rifted continental margin, denominated as Jandaíra (Turonian-Campanian 93.9 Ma BP) and Açu (113 – 100.5 Ma BP) Formations.

The Jandaíra Formation is composed of stratified limestone and silty-clay sediments, part of the domains of Mesozoic clastic-carbonate sedimentary sequences. In the Açu Formation, quartz-arenites and conglomerates predominate, with intercalations of silty-sandy or calciferous sediments, composing the domain of Mesozoic poorly to moderately consolidated sediments.

In the alluvial plain of Jaguaribe River, recent alluvial deposits composed of sand, gravel, silt and clay predominate; between the Apodi Plateau escarpment and the fluvial channel of Jaguaribe River, alkaline granites of the Itaporanga Intrusive Suite outcrop (CPRM, 2014). The fluvial channel in which granite feature outcrop is situated in the Lower Jaguaribe Sub-basin, precisely in the right channel of the Jaguaribe River, named Quixeré River (De Sousa Coelho; Andrade, 2020; Cavalcante et al., 2014). The main outcrop constitutes an inselberg, approximately 4-5 km long, with altitudes of ca. 130 m, undergoing a process of exhumation of Cretaceous age (Cenomanian), and are denominated as Quixeré Inselbergs, according to Peulvast and Claudino-Sales (2006) and Claudino-Sales (2016).

Based on Morais (2005), the depth of the alluvium reaches up to 30 m, while the outcropping formations of the Potiguar Basin are up to 80 m in the Jandaíra limestones and 80 m to 180 m in the Açu sandstone.

Regarding the evolution of the study area, Maia (2005) characterizes it as resulting from a complex interplay among tectonics, sedimentation, linear and alveolar processes; additionally, Peulvast and Claudino-Sales (2006) mention the occurrence of paleo-inselbergs, whose genesis is closely linked to the evolution of the Atlantic continental margin.

This erosive edge attests to a modern episode of backwearing, which exhumated a former planation surface, older than the overlying sedimentary rocks of Potiguar Basin, being, thus, of Cretaceous age, allegedly pre-Albian (Claudino-Sales; Peulvast, 2007; Peulvast et al., 2008, Miranda et al., 2012).

Analyzing the geodynamics of the Jagaribe system, Calacavante (1999) described the granite outcrops as projections in an area almost totally covered by Mesozoic-Cenozoic sediments, modeled with a p = 2.67 g/cm^3 likely corresponding to biotite, k-feldspar-rich granites, outcropping in the north and northwest of the city of Limoeiro do Norte (Quixeré granite) since the sedimentary bodies in this sector have low depths.

In the regional context of the granite landforms, this work takes the studies of Maia et al. (2015) and Maia and Nascimento (2018) as a basis, considering the potential for morphogenetic and geodiversity studies of these landscapes in the Brazilian Northeast.

In summary, Figure 1 shows information that characterize the study area, such as the location, geological-geomorphological context, and hypsometry.

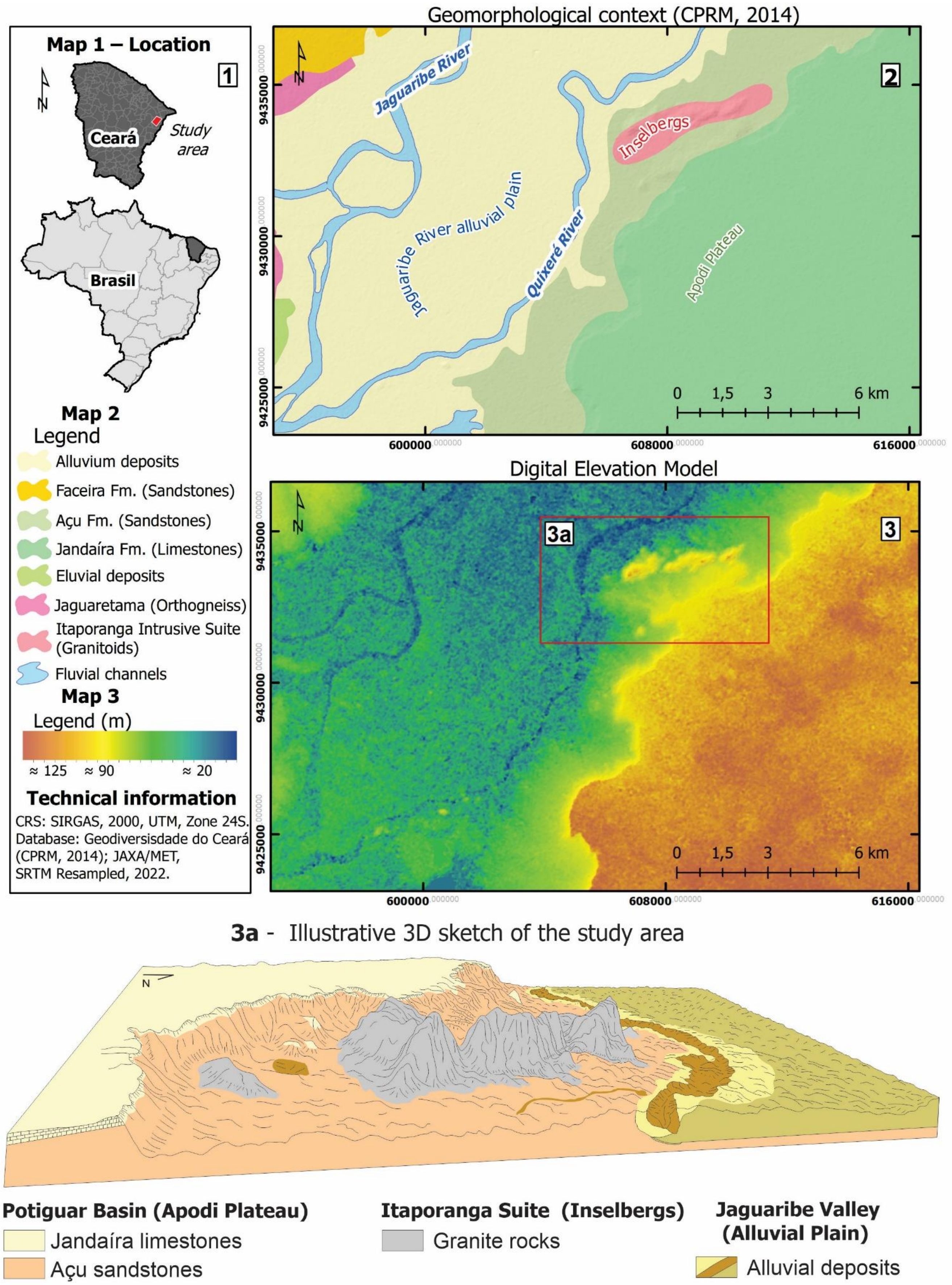

Figure 1. Characterization of the study area. A – Location map. 2 – Geomorphological context. 3 – Digital Elevation model. 3ª – 3D sketch of inselbergs and geomorphological features.

Inselbergs constitute erosion remnants that furnish important information about the geomorphological evolution of the areas in which they occur (Matmon et al., 3013). Given the resistance and capacity to accommodate compressive and extensional stresses, granite rocks outstand in supporting these landforms, although formed under diverse environmental conditions, being able to withstand several subsequent environmental changes.

Concerning the northern sector of the brazilian Northeast, the granitic landscapes stand out particularly as sectors of high touristic and scientific value, displaying clear evidence of the geomorphological history of the region. Saprolite landforms are commonly found in the countryside dominated by the crystalline basement (Maia et al., 2018; Maia; Nascimento, 2018).

Currently, the two-stage concept is the most widely accepted to explain the exhumation and development of these landforms in the regional context, which according to Twidale (2002) is due to the recognition that the factors governing the evolution of inselberg fields are related to processes occurring at the base of the regolith other than at the surface.

With that in mind, we point out that the structural basis for this work encompasses both mega-geomorphology and localized microfeatures in a given landform. Considering the geochronological events to investigate the landscape studied, different geomorphological subjects are addressed here, as this area constitutes a sector where, despite the small territorial extension, an alluvial plain, granite landforms, sedimentary basin with microfeatures and processes derived from each geomorphological unit occur. In the studied area, pre-Cambrian rocks outcrop among sedimentary deposits of the Potiguar Basin and Jaguaribe River Valley, where this interaction allows to consider the post-Cretaceous climatic variability in landscape interpretation, encompassing phases of pedogenesis and morphogenesis, culminating in processes of relief dissection.

It can be observed in the backwearing of the Apodi Plateau escarpment and in the deposition and erosion of fluvial channels over the plain part of the granite outcrops (view to the countryside), where the drainage flows over the crystalline basement and shallow soils. Figure 2 exhibits in the foreground the remaining granite landforms in the outcropping surface; we highlight also the escarpment of Apodi Plateau to the left (south) and the Jaguaribe River alluvial plain to the right in the background.

Figure 2. Elevated surface of the granite outcrop with rupicolous vegetation. In the background the Apodi Plateau and the Jaguaribe River alluvial plain.

4. Materials and methods

The following methodological steps were carried out in order to highlight the study area and its topographical features:

1) Conceptual and bibliographic revision, encompassing classical works and more recent publications concerning the subject and the selected study area, correlating information on the granite landforms and relief evolution.
2) Secondary data gathering and processing using Geographic Information System software, supporting the elaboration of products that allowed the landscape elements and were used as a reference for fieldwork expeditions.
3) Fieldwork surveys to collect primary data, validate previous GIS-obtained data, and interpret results.

Data gathering and processing using technologies is an essential part of geomorphological works since the organization of a database and digital processing are fundamental and allow an integrated analysis in environmental studies.

Re-sampled SRTM data (12, 5 m) were explored in the software Global Mapper, made available by ASF - ASF – Alaska Satellite Facility from the Japan Aerospace Exploration Agency (JAXA) Mission and submitted to the process "generator watershed", which enabled the extraction and classification of the drainage at the local scale, and "custom shader". This allowed us to extract and characterize the surface of the Digital Elevation Model, highlight diverse morphologies in the area, trace elevation profiles, and demarcate contour lines. These processes provided better visualization of features and, combined with the theoretical revision, permitted the analysis and mapping of the evolution of paleo-features (Figure 3).

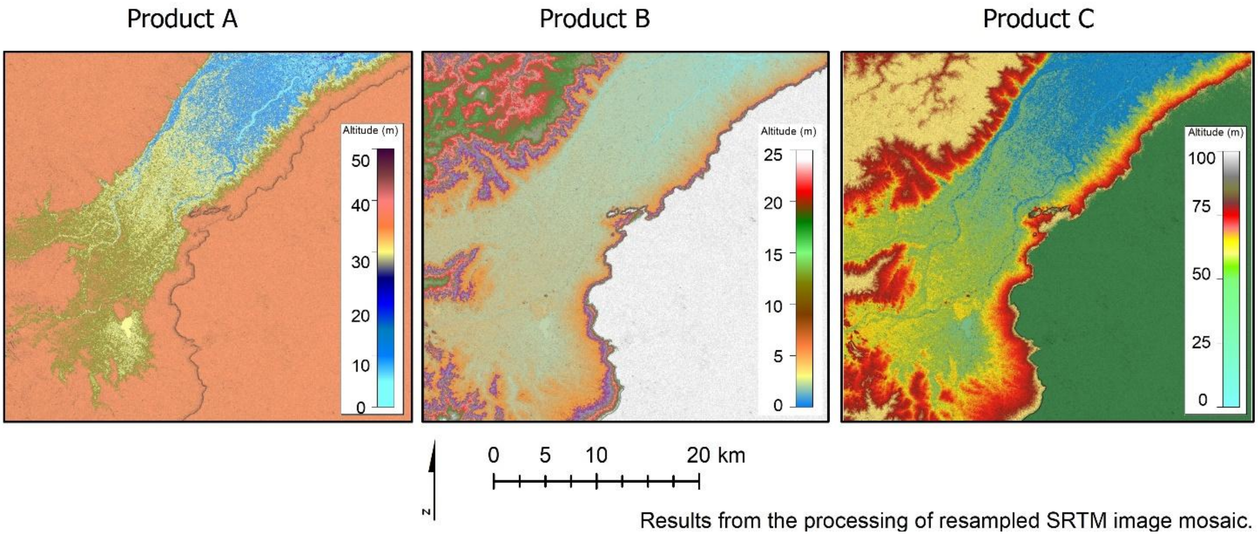

Figure 3. Products of the topographic compartmentalization stage, processed in the Global Mapper 17 software. Product A – emphasis on the plain features. Product B – Dissection of the Cretaceous surface of Potiguar Basin. C – General context of the study area.

With the results of the processing, the fieldwork aimed at verifying, identifying and crosschecking the morphological data evidenced after the manipulation of the Digital Elevation Model (DEM) with data of public domain available by the Brazilian Geological Survey (SBG), the Brazilian Institute of Geography and Statistics (IBGE), and the Institute of Research and Economic Strategy of Ceará (IPECE) for the geomorphological characterization. In the following step, the topographic survey had the objective of collecting defined points using Global Navigation Satellite System (GNSS) receptors operating in L1 and L2 bands with RTK correction, the validation of the results of processing, and the aerophotogrammetry survey using Unmanned aerial vehicle (UAV).

Given the diversity of geological and environmental features in the area, the fieldwork expeditions were also organized in steps that allowed the individualized analysis of the units, including surveys located in the Apodi Plateau, inselbergs and in the alluvial plain.

Finally, the products and results obtained were correlated and enabled the characterization of the geomorphological evolution of the study area, considering as main elements the Quixeré River (channel of the Jaguaribe River), the granite outcrops, and the western escarpment of the Apodi Plateau.

5. Results

Features related to processes of fluvial geomorphology, hillslope evolution, planation surfaces, and drainage patterns were identified, besides the granite features outstanding in the landscape, described in charts 1, 2, and 3 in Figure 4.

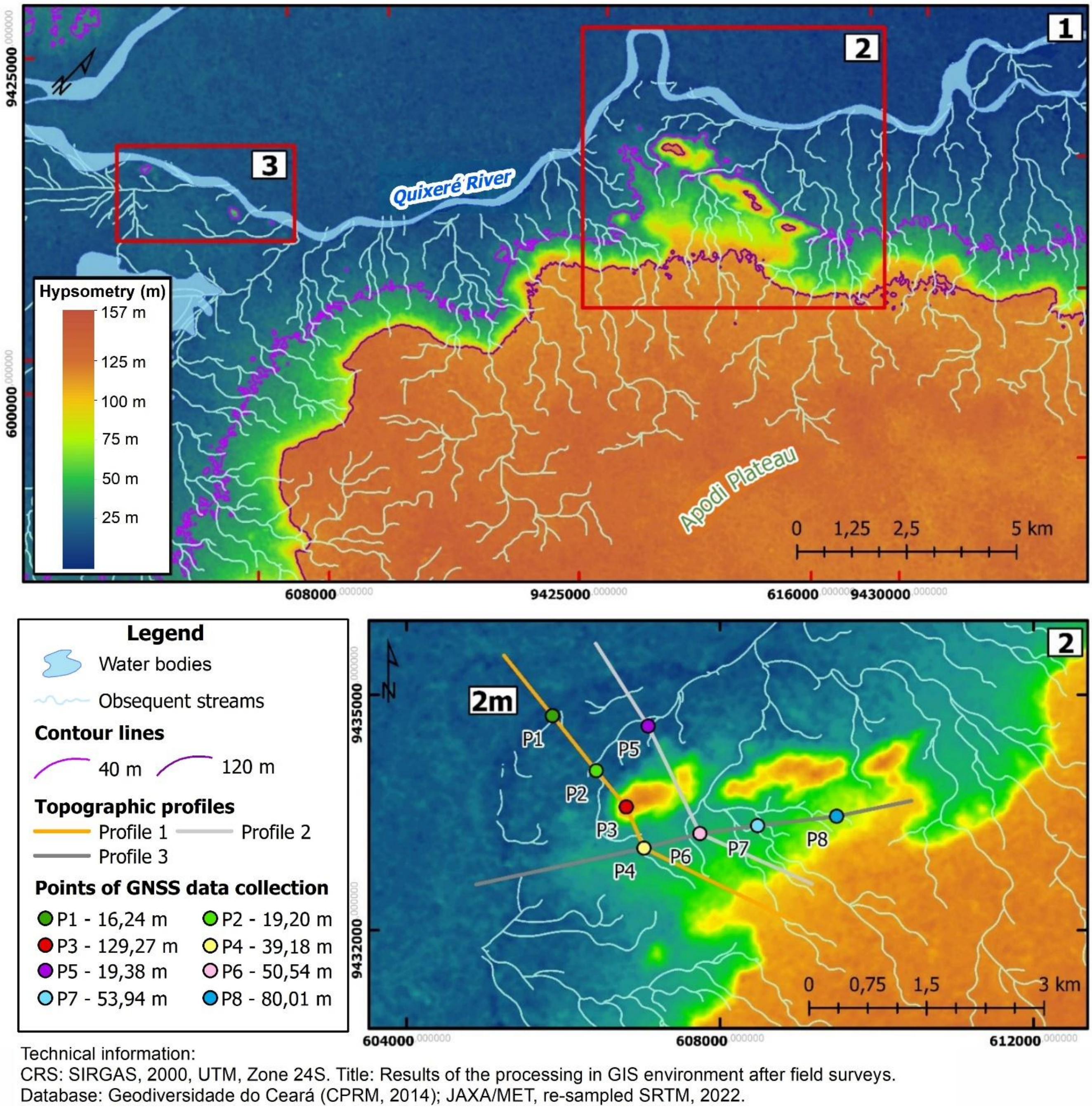

Figure 4. Identification of geomorphological features by DEM processing, obsequent drainage system, points of GNNS data collected in the field, and traces of topographic profiles. Chart 1 represents the overall context; Chart 2, the inselbergs and their correlation to the channel and the escarpment; Chart 3, the outcrops identified within the alluvial channel.

In chart 1, the main area of interaction among the morphologies, a granite outcrop in direct contact with the Apodi Plateau escarpment occurs, influencing the drainage of the current Quixeré River channel. In this sector, paleochannels, residual hills and granite macroforms such as inselbergs and slabs associated with saprolitization, as well as granite microforms including block chaos, boulders, polygonal cracking and split rock can be identified (Maia and Nascimento, 2018).

In chart 2, the drainage features stand out from the others. The presence of meandering paleodrainage (indicated in the 2m notation) provides fundamental answers for understanding the migration of the river channel and its relationship with the inselbergs; sandbanks, bars, and river islands are some of the features found in this area.

The inselbergs are located in the community of Sítio Saquinho, in the vicinity of the municipalities of Limoeiro do Norte and Quixeré, where the highest peak is popularly known as Pedra da Bandeira. In this sector, the outcrop categorically acts as an obstacle to the channel's migration since the drainage changes direction in a different flow from the preferred direction when approaching the base of the outcrops. This leads to a greater sediment accumulation upstream of the elevation, due to the drastic change in the local topography.

Given that these inselbergs reach elevations up to 13 0m, the effects on the landscape are more abrupt and expressive, considering that the channel does not superimpose onto the crystalline rocks. On the contrary, it migrates creating in its riverbed a large alluvial deposit in the vicinity of the granite landforms (2m in Figure 4).

The focus on these areas allows for better detailing of the features and visualization of the interactions in the fluvial dynamics with the lithologies and the geomorphological units with regard to the evolution of the area. The relationship between the inselbergs and the processes related to the Apodi Plateau and the river channel were delineated by tracing topographic profiles oriented by the points of data collection in the field (Figure 5).

Profile 1 (P1, P2, P3 AND P4) in Figure 5 shows the difference in the elevations of the preserved planation surface where the Açu Formation outcrops and the sediments carried from the plateau by the drainage accumulate, characterizing the escarpment. This difference is approximately 80 m in the area between the inselbergs and the Apodi Plateau, while in the area between the inselbergs and the river plain, the sandstones and the river channel are at 25 m. This topographic gradient (P4 and P2) is due to the accumulation of material transported by the obsequent streams that cannot reach the local base level due to the presence of the granite outcrops, which form a surface that preserves morphologies of the backwearing of Apodi Plateau with outcrops of the Açu sandstone at high levels. While these granite reliefs project as an obstacle to the migration of the channel to the east, they contribute to the accumulation of sediments derived from the lateral retreat of the escarpment in this sector.

In the P1m where the current alluvial channel and the alluvium sandbanks to P2, in the transition between fluvial terraces, granite outcrops and the occurrence of the Açu sandstone, it can be identified in the landscape riparian vegetation that results from the influence of the plain over the other landforms.

Profile 2, in turn, displays lower elevations in one of the inselbergs of the Quixeré outcrop, which is due to dissection along fractures. This profile attests to the denudation of the granite morphologies, posterior to the exhumation of the Cretaceous cover and consequent exposure to weathering processes responsible for the shaping of microforms in granite landforms.

The obsequent drainage system flowing from the escarpment towards the base level passing through the inselbergs, revealing the low areas between these landforms, which were formerly buried by Cretaceous sediments of the Potiguar Basin, therefore, forming the inselberg field.

According to Migon (2006), the fractures form in response to the stress applied over a rock mass and indicate that the material strength was insufficient to support the stress. In this sector, exfoliation fractures occur, through a slow and continuous process, generating instability and eventually leading to the detachment of rock slabs that collapse and form residual coarse deposits such as block chaos.

Additionally, this sector preserves the contact between the granite landforms and the remnants of the Apodi Plateau. The presence of higher elevations allows us to identify the occurrence of residual hills from the Apodi plateau, an uncommon landform in the southeast escarpment, due to intense erosive processes occurring in the alluvial plain of Jaguaribe River.

Profile 3 shows the preferred path of the obsequent stream. The drainage coming from the escarpment, although passing through the inselbergs, follows a gentler slope towards the plain, as observed in the topographic points. The surface runoff in this sector produces incisive streams over the outcrops of the Açu Formation, reflecting the steep slope represented in the elevation of points p4, p6, p7, and p8.

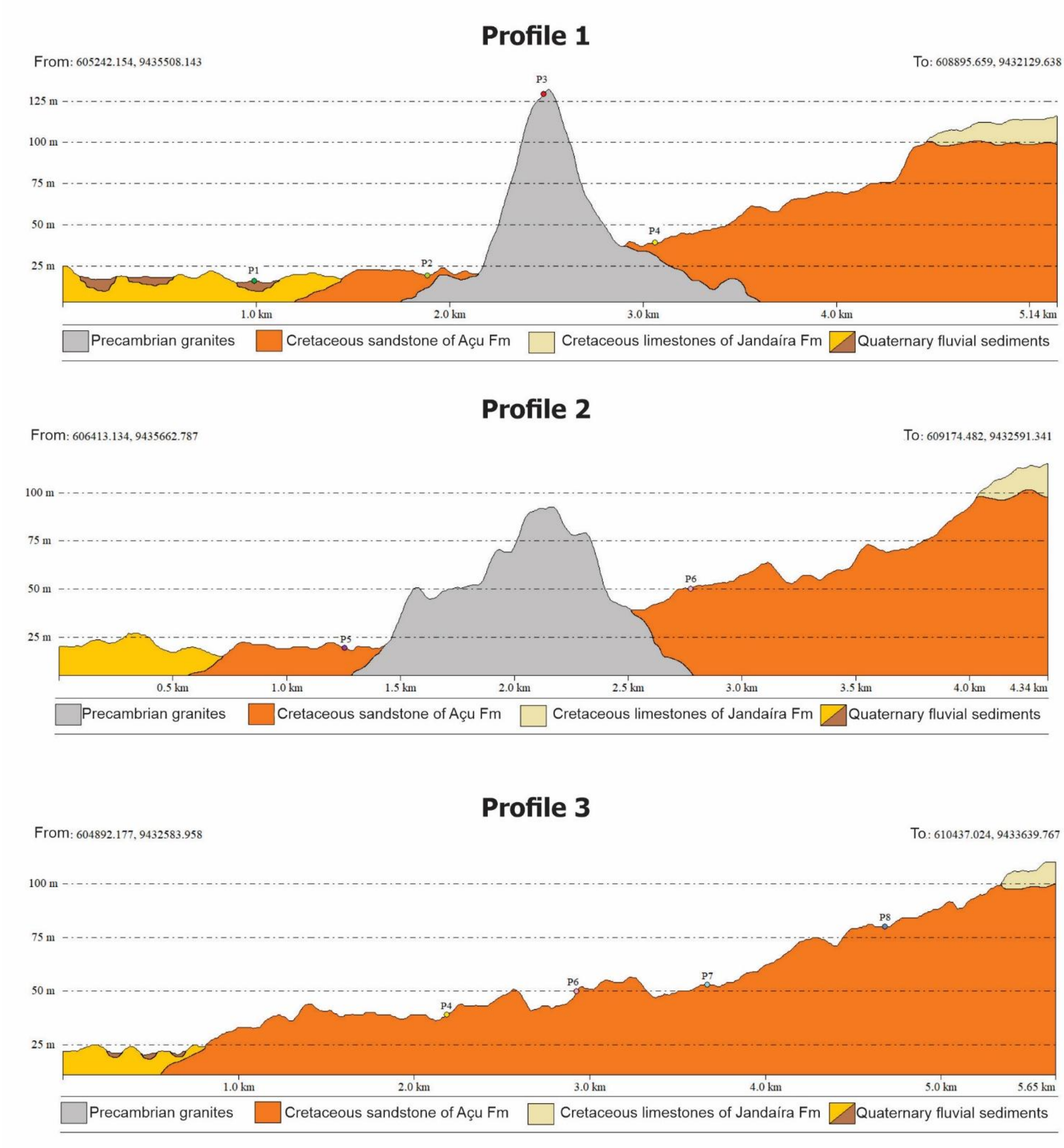

Figure 5. Topographic profiles obtained by processing in GIS environment with data collection points in the field.

The sector plain-inselbergs is characterized by the accumulation of fluvial sediments and riparian vegetation; in the other hillslope, in turn, the sector inselbergs-plateau is marked by an elevated sedimentary surface supported by cretaceous rocks with arboreal deciduous vegetation.

The inselbergs create prominent distinction in the landscape due to their elevations from the flattened surface. The are no features attesting to a paleodrainage between the granite landforms and the Apodi Plateau; however, the area displays signs of dissection processes on the Açu sandstones, as shown in Figure 6.

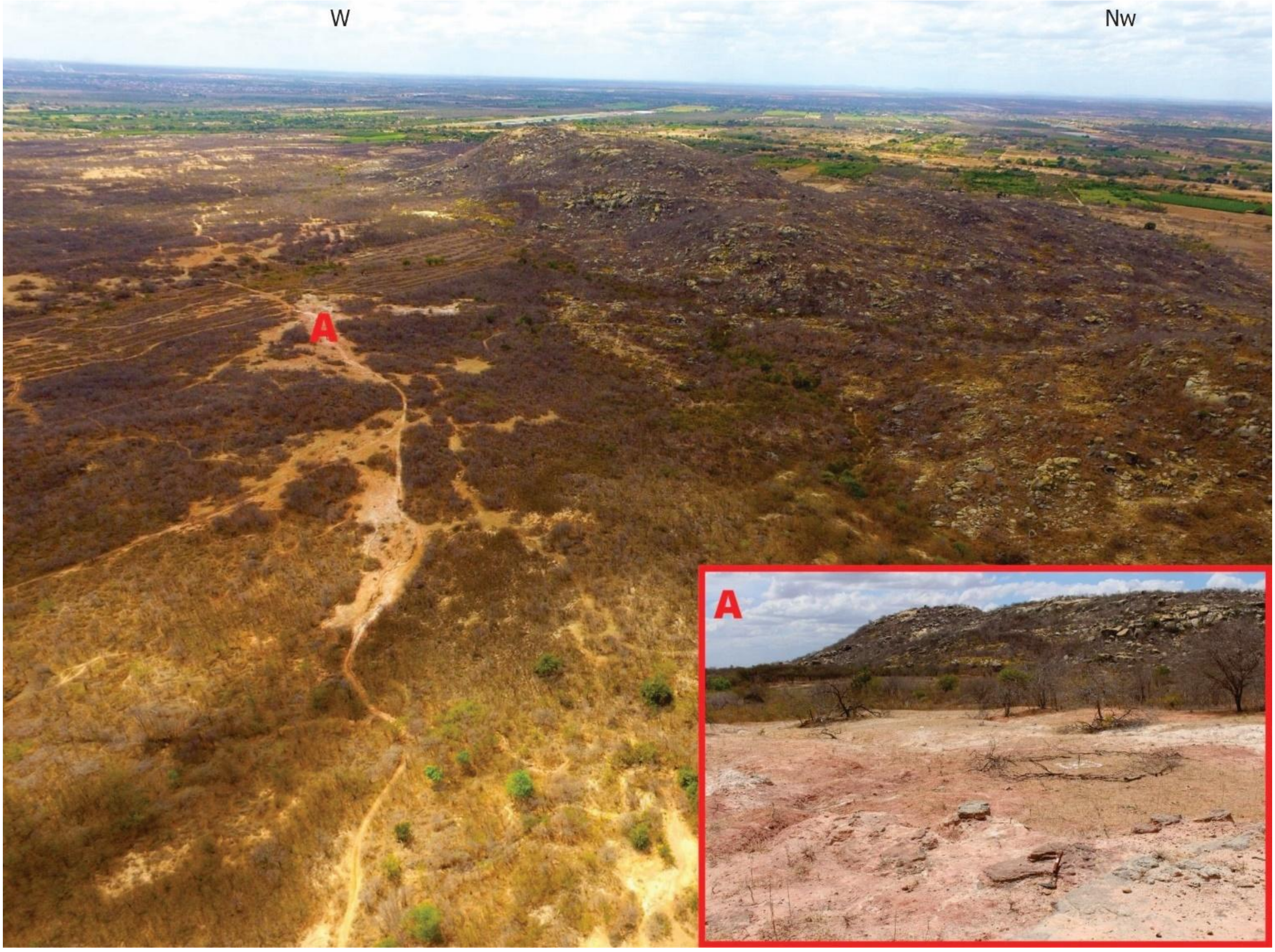

Figure 6. Granite outcrops (inselbergs) between the Apodi Plateau, typified by outcrops of the Açu sandstone and the alluvial plain. Chart A illustrates the sandstone outcrop on the opposite side of the alluvial plain.

Following the preceding stages and considering the information collected through bibliographical revision (Françolin; Szatmari, 1987; Brito Neves, 1999; Peulvast; Claudino-Sales, 2007; Maia, 2005, 2010), field survey, and DEM analysis, we propose a sequence of geomorphological evolution with an emphasis on geochronological, morphostructural, and morphogenetic evolution.

Starting in the Mesozoic, at the Triassic and Jurassic threshold (≅ 200 Ma BP), before the crustal stretching undergone by Gondwana, which would eventually lead to the opening of the Atlantic Ocean, the already exhumed granite outcrops were subjected to weathering processes, forming a pre-Cretaceous surface, responsible for the initial shaping of landforms, as represented in stage 1 in Figure 7.

In stage 2, due to the extensional forces acting during the Brazil/Africa break-up, the Jaguaribe structural framework was arranged, and the Potiguar rift opened. The invasion of the sea promoted sedimentary deposition upon the granitic landscape formerly exposed. Thereafter, the deposition of the sedimentary layers which filled the rift area and the formation of the Potiguar Basin began, preserving the granite landform underneath.

At the end of the Cretaceous, in the Maastrichtian ≅ 62 Ma AP, after the retreat of the sea, the Potiguar basin underwent thermal subsidence and consequently the edge warping, which resulted in the formation of the plateau. Additionally, during this period, a divergent tectonic quiescence began on the Atlantic margin of the South American plate and was followed by the incision of the drainage net along the Jaguaribe fault, as shown in stage 3 (Figure 7).

The weathering and erosion processes play a crucial role from this stage onwards. The alternations of wet and dry climates account for the widening of the valley, the lateral retreat of the escarpment and the new dissection of the granites. At this point, despite being covered by sedimentary layers, the granite landforms undergo subsurface weathering processes, which shape saprolitic forms. The Chapada do Apodi and the alluvial plain are the most affected sectors by erosion at this stage, given their sedimentary constitution and the friable nature of their lithological components. This process is estimated to have taken place from the Paleocene ≅ 66 Ma AP to the beginning of the Quaternary ≅ 2.5 Ma AP, represented by stage 4 (Figure 7).

Finally, the current landscape illustrated in stage 5 attests to Cenozoic climatic processes, during which the granite forms were once again exhumed, exposing the inselberg landforms; also, the alluvial plain widened due to the continuous migration of the channel and the Apodi plateau underwent hillslope weathering process, having its escarpment increasingly retracted towards the center of the Potiguar basin. The climatic processes, both weathering and erosion, are predominant in the landforms of the South American passive margin, without neglecting neotectonic factors.

Given the ongoing tectonic quiescence and climatic alternations, we, therefore, hypothesise that the current stage encompasses the backwearing of the Apodi Plateau and the related formation of an extensive planation surface. The resulting landforms are due to planation and relief dissection processes and are mainly distinguished by their lithological properties, although similar concerning their morphogenetic processes.

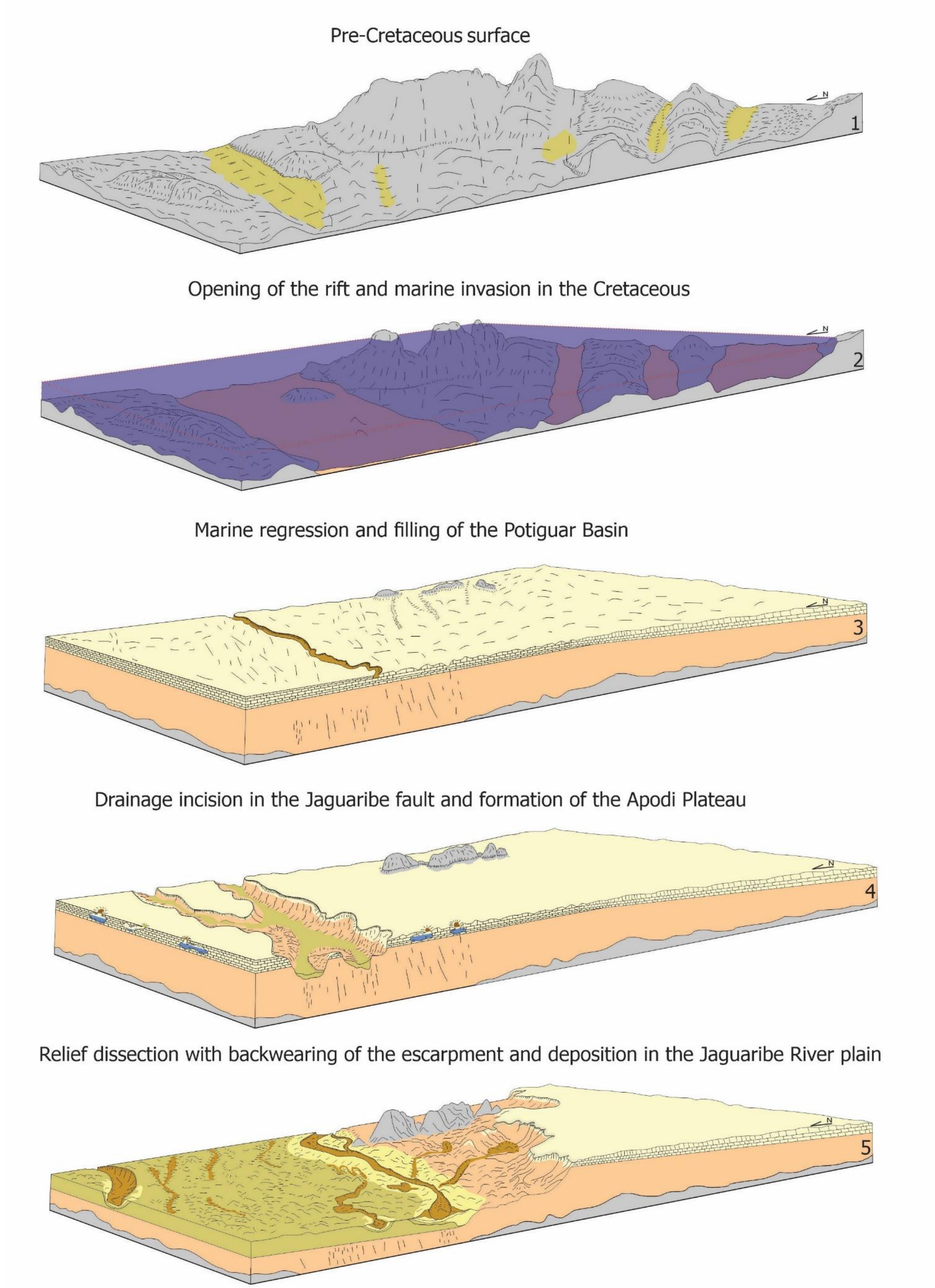

Figura 7. Sketches illustrating the proposed geomorphological evolution.

At the inselbergs summit, forms related to mechanical epigenetic weathering predominate and fractures are filled by regolith with ripaceous vegetation among the granitic microforms. Besides the evidence of cretaceous exhumation of inselbergs, granite landforms with grus deriving from weathering on their footslope and initial stages of spheroidal exfoliation occur. They both testify to the modern weathering processes acting upon the granite rocks.

Features related to the release of lithostatic pressure such as fracturing and spheroidal exfoliation are conspicuous in the inselbergs. Boulders of different forms and shapes occur on the footslopes and at the summits, attesting to the epigene character of granite features. Some boulders exhibit thin polygonal cracking at their surfaces, with a varied geometry of the polygons (Migon, 2006).

Figure 8 also shows granite microforms identified at the outcropping summit, where saprolite landforms including outcrops with regolith and boulders, tors, and polygonal cracking, among other features, occur.

Figure 8. Granite microforms on the Quixeré inselberg. Chart 1 shows tors upon the crystalline outcrop; Chart 2 shows exfoliation features, block chaos and bromeliads in the fractures; Chart 3 illustrates the occurrence of polygonal cracking; Chart 4 pictures granitic boulders resulting from the spheroidal exfoliation.

5.1. The granite landforms and the fluvial channel

The relationship between the granite forms and the river channel on the plain is a complex interaction of flows of matter and energy. This is in response to the eastward migration of the river channel, which, as it approaches the basal layers of the Apodi Plateau escarpment, encounters outcrops of the crystalline basement.

These outcrops were identified on the right channel margin (see item 3 of Figure 4) and characterized when morphologies different from the inselbergs occurred. Although the lithologies are similar, the shape of the outcrops allows for a distinction based on the ongoing processes and upbrings implications related to their location. Figure 9 shows an image chart of the outcrops of Morros, where granite features are in contact with the current Quixeré River channel.

The granite landforms of the Morros outcrop, located between Limoeiro do Norte and Tabuleiro do Norte municipalities, expose rocks in and around the river channel at elevations of around 70 m. They are relatively low compared to the Quixeré inselberg, which reaches 130 m. However, they are significant in the local context of the alluvial plain since they constitute a topographic high in the landscape.

The outcrops project as an obstacle to the actual course of the Quixeré River, causing energy loss in the hydraulic flow of the stream when it encounters the elevation formed by the outcrops; therefore, the river tends to accumulate sediments and widen the channel, which can lead to the formation of bars and river islands.

Downstream of the granite reliefs, the channel narrows after flowing around the topographical obstacles, then resuming a high-energy flow, with an 8 m deep thalweg. In these sectors, the crystalline rocks outcrop within and on the margins of the channel, as can be seen in charts A and B of Figure 9.

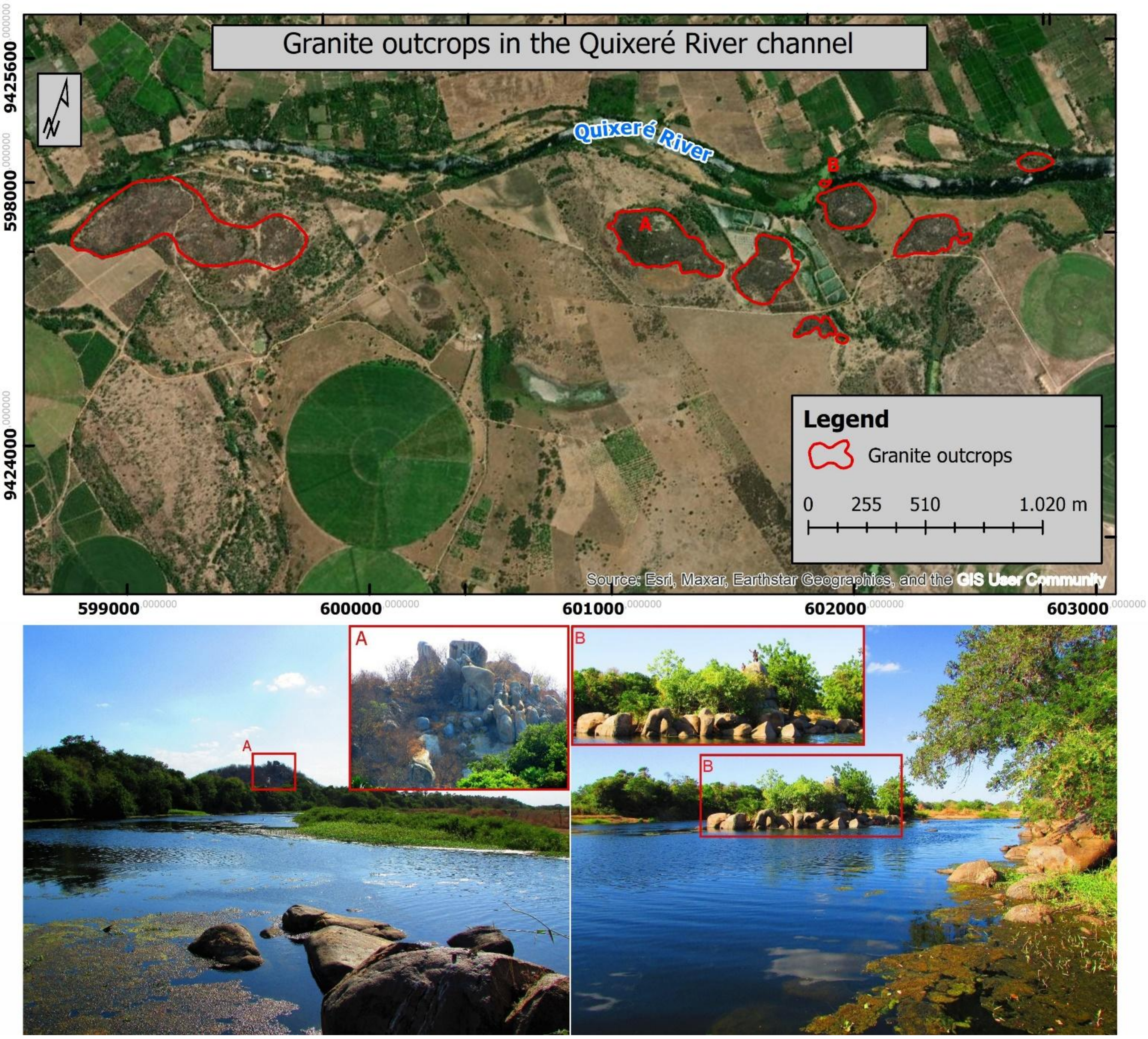

Figure 9. Morros outcrops, where granite landforms are in contact with the fluvial channels. Boulders, split rock (A), and tors occur.

At higher elevations, granite forms resulting from epigenetic processes, including tors, castle koppies and boulders with spheroidal exfoliation occur. Boulders and split rock act as divides in the lower elevation outcrops, affected by fluvial erosion without exposure of the regolith and with the Quaternary sediments of the alluvial plain. Knickpoints occur in the river course due to topographic breaks; they also appear where the rocks are more resistant to linear erosion, due to significant changes in the erosion process in an area, due to marked climatic changes (Bigarella, 1965).

6. Discussion

Based on the previous analyses, it can be interpreted that the referred granite landforms composed the landscape during the Cretaceous and are currently undergoing a second exhumation. The first must have occurred during the Paleozoic-Mesozoic (541-251 Ma BDP), ending in the initial stages of the crustal extension during Gondwana break-up, when structural faults favored the posterior exhumation.

From the opening to the rift abortion, which promoted the sea invasion during the Cretaceous, the crystalline basement outcrops were blanketed by the sediments that now form the Potiguar Basin. These sediments preserved the morphology of the exhumed granite inselbergs which, following the basin uplift and renewed escarpment erosion, were subjected to a second exhumation.

During this second stage, the superficial runoff and the lateral and linear processes reshaped and exhibited the granite landforms revealing inselbergs, which are objects of great potential for the analysis of the evolution of granite landscape due to their shapes, features, and the chronological events. They differ from most of the inselbergs in the Northeast of Brazil, inserted in a context of ancient and eroded surfaces, as the granite landforms in the lower course of Jaguaribe River still preserve features of a recent exhumation, over a recent surface,

It is important to note that the proposed methodology and processing present limitations due to the following aspects: a) The re-sampled SRTM images can present shortcomings when applied to the analysis of large scales, being more adequate for mapping and identifying micro-features in aerophotogrammetric surveys. b) The fluvial dynamics of the Jaguaribe River plain becomes complex due to the control of water flow and drainage by the weirs, thus limiting possible stages of channel migration. c) The lateral retreat of the escarpment can be better estimated with the advance of climatic data related to the dating of correlated deposits or planation surfaces, possibly allowing one to quantify the rates of weathering and erosion that acted since the formation of the Chapada do Apodi Plateau.

We also highlight the importance of reporting the occurrence of these morphologies in crystalline rocks outside the Sertaneja Surface (regional planation surface), where residual morphologies resulting from this evolution pattern are commonly found. In the region of the low course of Jaguaribe River, there are reports of granite forms near the edge of interior tablelands (Tapera district in the municipality of Russas). Also, in the municipality of Jaguaribara, on the border with Aracati, outcrops in contexts similar to those described in this work occur in quartzite rocks. In the city of Limoeiro do Norte, there are other examples of granite outcrops in contact with water bodies in the alluvial plain. Outside this region, it should be noted the occurrence of a singular outcrop, environmental context and morphogenesis, in the coastal municipality of Chaval in the westernmost Ceará State (Cordeiro et al., 2023). These examples of landforms in the Atlantic margin present processes of morphogenesis and formation with particularities that might render information to the geomorphological debate.

7. Conclusions

The data generated by this work allow us to conclude that inselbergs on the western edge of the Potiguar Basin are currently being exhumed by the basin's circumdenudation. Since the Upper Cretaceous, these inselbergs have been covered by sedimentary rocks of the Apodi Group (Jandaíra and Açu Formations). In this context, several indicators of neotectonic activity already published for the Jaguaribe River valley (Maia, 2005; Gomes Neto, 2007) attest to the effects of the migration of the main channel of the Jaguaribe River towards the east, leaving its deposits exclusively on the west side (Faceira Formation). This migration to the east led to the advance of the Jaguaribe River towards the Potiguar Basin, promoting its lateral retrogradation and thus revealing the underlying inselbergs. Therefore, inselbergs are currently outcropping within the channel of the Jaguaribe River and on its seasonal floodplain. These inselbergs testify to the existence of a former planation surface existing prior to the opening of the Cretaceous rifting that culminated in the opening of the basin and later in the formation of the Atlantic Ocean.

These inselbergs can provide important information about the geomorphological evolution of granitic areas, common in NE Brazil. This information includes the degree and tempo for the development of fracturing features and post-exhumation dissolution compared to other inselberg fields. It is therefore essential to incorporate the inselbergs of the Jaguaribe Valley into the study of granitic areas with high research and geoconservation potential.

Given the complexity of the genesis and the diversity of features, the discussions presented here provide a characterization to be incorporated in studies on the evolution of the landscapes in the South American Atlantic margin.

The data and information gathered here suggest that the inselbergs exhumed from the western edge of the Potiguar Basin are important markers of the pre-Cretaceous geomorphological evolution in the interaction between the Potiguar Basin and the Jaguaribe River plain, constituting a barrier to the erosion of part of the escarpment and playing a preponderant role in the evolution of the region, according to the evolution model presented.

Although the area has a limited spatial scale compared to the regional context, the theories and processes used can be applied to similar areas. The reports and information in this paper investigate other studies focused on landscape evolution in the Lower Jaguaribe, such as the dating of deposits at the footslope of the plateau or inselbergs, the investigation of natural cavities revealed from the process of lateral retreat, as well as the exploration of the geotourism potential with a focus on conservation and scientific valuation of the landforms herein addressed.

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