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Review Article

Lithostructural control of the relief in the eastern sector of the Parnaíba sedimentary basin (Ibiapaba Plateau), Northeast Brazil

Controle litoestrutural do relevo da borda oriental da bacia sedimentar do Parnaíba (Planalto da Ibiapaba), Nordeste do Brasil

Frederico de Holanda Bastos[1], Lionel Siame[2], Danielle Lopes de Sousa Lima[3], Abner Monteiro Nunes Cordeiro[4]

[1] State University of Ceará, Graduate Program in Geography, Fortaleza, Ceará, Brazil. Productivity Fellow 2 (CNPq). fred.holanda@uece.br
ORCID: https://orcid.org/0000-0002-4330-7198

[2] Aix-Marseille University, Center for Research and Teaching in Environmental Geosciences, Aix-En-Provence, France. siame@cerege.fr.
ORCID: https://orcid.org/0000-0002-4288-9528

[3] State University of Ceará, Graduate Program in Geography, Fortaleza, Ceará, Brazil. danielle.llopes@hotmail.com.
ORCID: https://orcid.org/0000-0002-9729-9939

[4] Federal University of Rio Grande do Norte, Department of Geography, Center for Higher Education of Seridó, Caicó, Brazil. abner.cordeiro@ufrn.br
ORCID: https://orcid.org/0000-0002-4867-7083

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Abstract: Cartographic updates of the geological area between the Parnaíba and Borborema Provinces made it possible to provide details in the interpretation of the lithostructural control of the Ibiapaba Plateau and surroundings. The article aims to interpret regional morphostructural aspects based on bibliographic review, fieldwork and GIS interpretations. The area is characterized by an asymmetrical plateau with a continuous glint-type escarpment (≈800 m), supported by Paleozoic sandstones overlying the Precambrian basement. In the surroundings, flat surfaces predominate (≈200m), whose morphologies vary according to the lithologies. From a structural point of view, the Transbrasilian Lineament (LT) constitutes the main regional tectonic divide, influencing the behavior of the escarpment and the reverse. In lithological terms, the sandstones and conglomerates of the Serra Grande Group stand out, responsible for maintaining the top of the plateau, the Cabeças Formation and lateritic coverings, which support small tabular plateaus within the sedimentary basin, in addition to the granitoids, quartzites and orthogneisses that support residual reliefs in the basement. Considering a regional geomorphological evolution associated with Cretaceous uplifts of rift and post-rift phases, the detailing of lithostructural aspects is fundamental to explain the relationship of differential erosion in the current regional morphology.

Keywords: Monoclinal structures; Glint; Borborema Province; Brazilian semi-arid.

Resumo: Atualizações cartográficas da geológica da área entre as Províncias Parnaíba e Borborema viabilizaram detalhamentos na interpretação do controle litoestrutural do Planalto da Ibiapaba e entorno. O artigo tem o objetivo de interpretar os aspectos morfoestruturais regionais a partir de revisão bibliográfica, trabalhos de campo e interpretações de SIG. A área é caracterizada por um planalto dissimétrico com um escarpamento contínuo (≈800 m) do tipo glint, sustentado por arenitos paleozoicos sobrepostos ao embasamento pré-cambriano. No entorno predominam superfícies de aplainamento

(≈200m), cujas morfologias variam de acordo com as litologias. Do ponto de vista estrutural o Lineamento Transbrasiliano (LT) constitui o principal divisor tectônico regional, influenciando o comportamento do escarpamento e do reverso. Em termos litológicos destacam-se os arenitos e conglomerados do Grupo Serra Grande, responsável pela manutenção do topo do planalto, a Formação Cabeças e recobrimentos lateríticos, que sustentam pequenos planaltos tabulares no âmbito da bacia, além dos granitoides, quartzitos e ortognaisses que sustentam relevos residuais no embasamento. Considerando uma evolução geomorfológica regional associada a soerguimentos cretáceos de fase rift e pós-ritf, o detalhamento dos aspectos litoestruturais é fundamental para se explicar a relação da erosão diferencial na atual morfologia regional.

Palavras-chave: Estruturas monoclinais; Glint; Província Borborema; Semiárido brasileiro.

1. Introduction

The Parnaíba Basin, also known as the Middle-North or Maranhão Basin, is a vast Paleozoic syneclise (MILANI; ZÁLAN, 1999) developed over a complex sector of Western Gondwana (CASTRO et al., 2016), formed by subsidence (ALMEIDA et al., 1981; BRITO NEVES et al., 1984). Its current total area is approximately 600,000 km² (VAZ et al., 2007; GÓES; FEIJÓ, 1994), covering parts of the states of Maranhão, Piauí, Tocantins, Pará, Ceará, and Bahia.

The eastern sector of the Parnaíba Basin is characterized by the contact of monocline structures (DANNI, 1972) unconformably superimposed on the Proterozoic basement of the western sector of the Borborema Province. This morphostructural behavior results in one of the most important geomorphological compartments of northern northeastern Brazil, known as the Ibiapaba Plateau, Serra Grande, Ibiapaba Cuesta (AB`SÁBER, 1969; SOUZA, 1988), or Ibiapaba Glint (CLAUDINO SALES et al., 2020), encompassing parts of the states of Ceará and Piauí (Figure 1).

The Ibiapaba Plateau constitutes a watershed dividing basins that drain into different morphostructural contexts (Borborema and Parnaíba Provinces). In the sedimentary basin, the drainage network is part of the Parnaíba River Basin, while in the basement, the Timonha, Coreaú, Acaraú, Poti, and Jaguaribe Basins drain, with the Poti Basin being a sub-basin of the Parnaíba, converging through one of the most significant fluvial superimpositions in northeastern Brazil, known as the Poti Canyon.

From a structural perspective, this relief represents the eastern boundary of the Parnaíba sedimentary basin, whose morphology constitutes one of the most characteristic alignments of circumnudational escarpments (AB`SÁBER, 1949), representing the most notable eversive area in northeastern Brazil and one of the largest in the country (AB`SÁBER, 1969; SOUZA, 2000). While the modern planation surfaces (Neogene sertaneja surfaces) are located at approximate elevations of 200 meters, the contact between the pre-Silurian planation surface and the basal formation of the Parnaíba Basin (Serra Grande Group) is found at elevations that can reach 600 meters, at the base of the sandstone cornice.

In regional terms, this area is located on a transform margin, whose regional morphogenesis is associated with uplifts during the rift and post-rift phases (Jurassic-Cretaceous), coinciding with the reactivation of the Atlantic opening (PEULVAST; CLAUDINO SALES, 2004), and drift (Cenozoic), related to neotectonic events (SAAD; TORQUATO, 1992), flexural uplifts (PEULVAST; CLAUDINO SALES, 2004), and volcanism (ALMEIDA et al., 1988). On the other hand, the Cenozoic denudational cycles, especially the dry climates from the Neogene onwards (HARRIS; MIX, 2002), interspersed with wet periods (WANG et al., 2004), were responsible for shaping the current morphology.

The lithostructural organization of northern northeastern Brazil, characterized by NE and E-oriented Brasiliano shear zones, and a complex mosaic of crystalline and sedimentary lithologies with different geomorphological properties (BASTOS; CORDEIRO, 2021), influenced the erosive processes and, consequently, the current geomorphological context (PEULVAST; CLAUDINO SALES, 2004; MAIA; BEZERRA, 2014). However, even with recent advances in geomorphological interpretations of the Ibiapaba Plateau (CLAUDINO SALES et al., 2020; MOURA FÉ, 2015; RODRIGUEZ TRIBALDOS, 2017; SANTOS, 2022), detailed studies on the lithostructural controls on its morphology can greatly contribute to regional geomorphological analysis.

The official geological cartography of the study area has provided greater lithological details in mapping projects at a scale of 1:100,000 since 2011 (CPRM, 2011; 2013; 2014, and 2015), with georeferenced vector files organized and made available in the latest version of the Geological Map of Ceará (CPRM, 2020).

Given this, and based on recent geological data, this work aims to analyze the lithostructural conditioning of the Ibiapaba Plateau's relief and its surroundings, focusing on the lithological control of the Paleozoic basin layers and the Precambrian basement rocks on the regional morphology, as well as the morphological control of structural deformations.

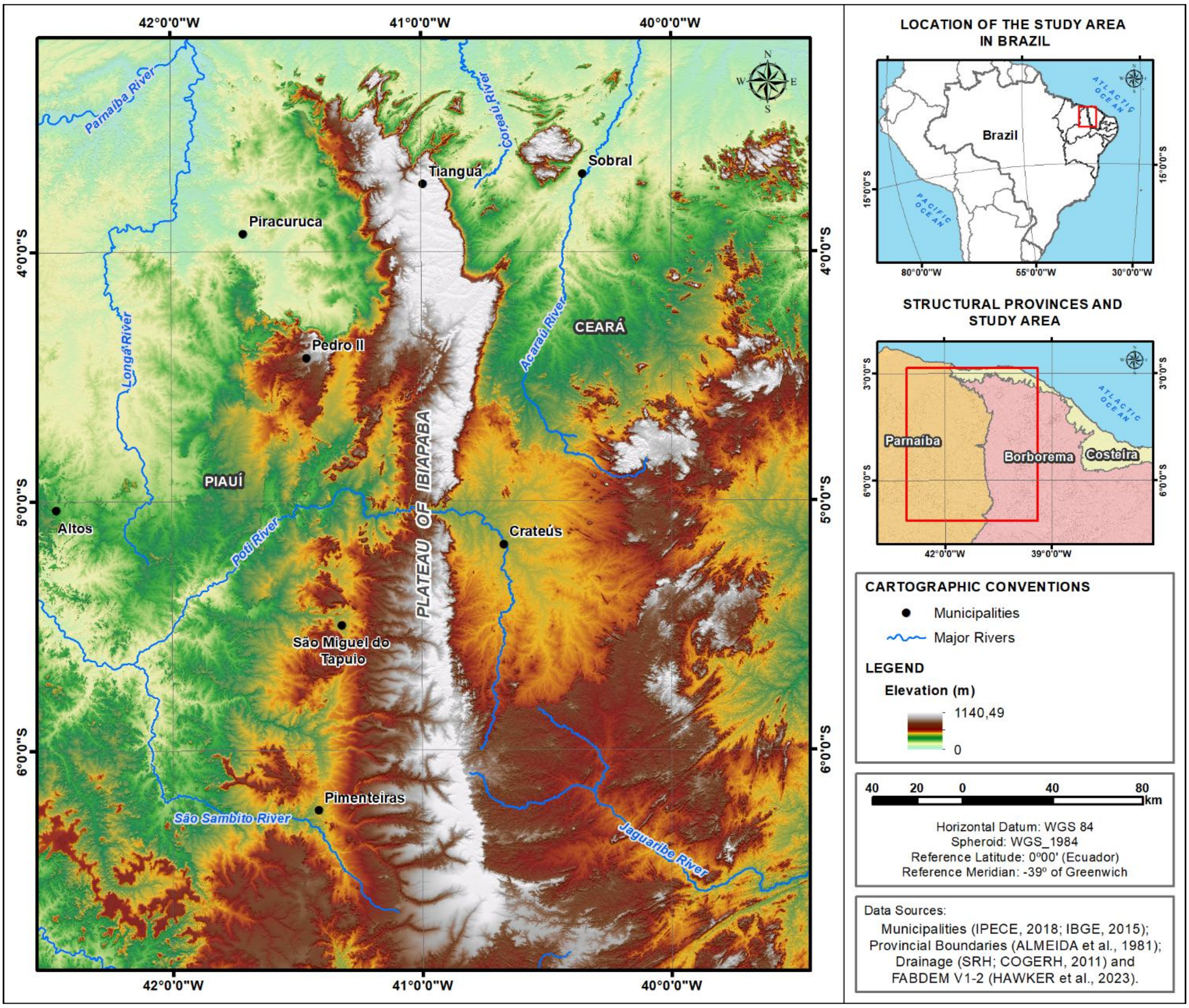

Figure 1. Location of the Ibiapaba Plateau.

2. Lithostructural Characterization of the Study Area

The study area is located on the eastern edge of the Parnaíba sedimentary basin, at the boundary between the Parnaíba and Borborema Provinces (Figure 1). This basin lies on a Proterozoic-Lower Paleozoic basement, comprising at least three large crustal blocks, representing syn-Brasiliano cratons and faulted Brasiliano orogenic belts (DALY et al., 2018; SILVA et al., 2003).

The depositional sequences of the Parnaíba Basin have a polycyclic origin, derived from events of subsidence of the platform surface below the regional base level, followed by its uplift (CACAMA, 2015). The current area of the basin includes five tectono-sedimentary sequences separated by regional unconformities (CASTRO et al., 2016; GÓES; FEIJÓ, 1994), divided into the Serra Grande Group (Silurian), with the Ipu, Tianguá, and Jaicós Formations (CRUZ, et al. 2019); the Canindé Group (Devonian), with the Pimenteiras, Cabeças, Longá, and Poti Formations; the Balsas Group (Carboniferous-Triassic) and Mearim Group (Jurassic); in addition to volcanic rocks of the Sardinha Formation (Jurassic), occurring as dikes and sills (FERRAZ et al., 2017) (Figure 2). The depositional unconformities, very common in this basin, are related to long-term variations in subsidence trends (RODRIGUEZ TRIBALDOS, 2017).

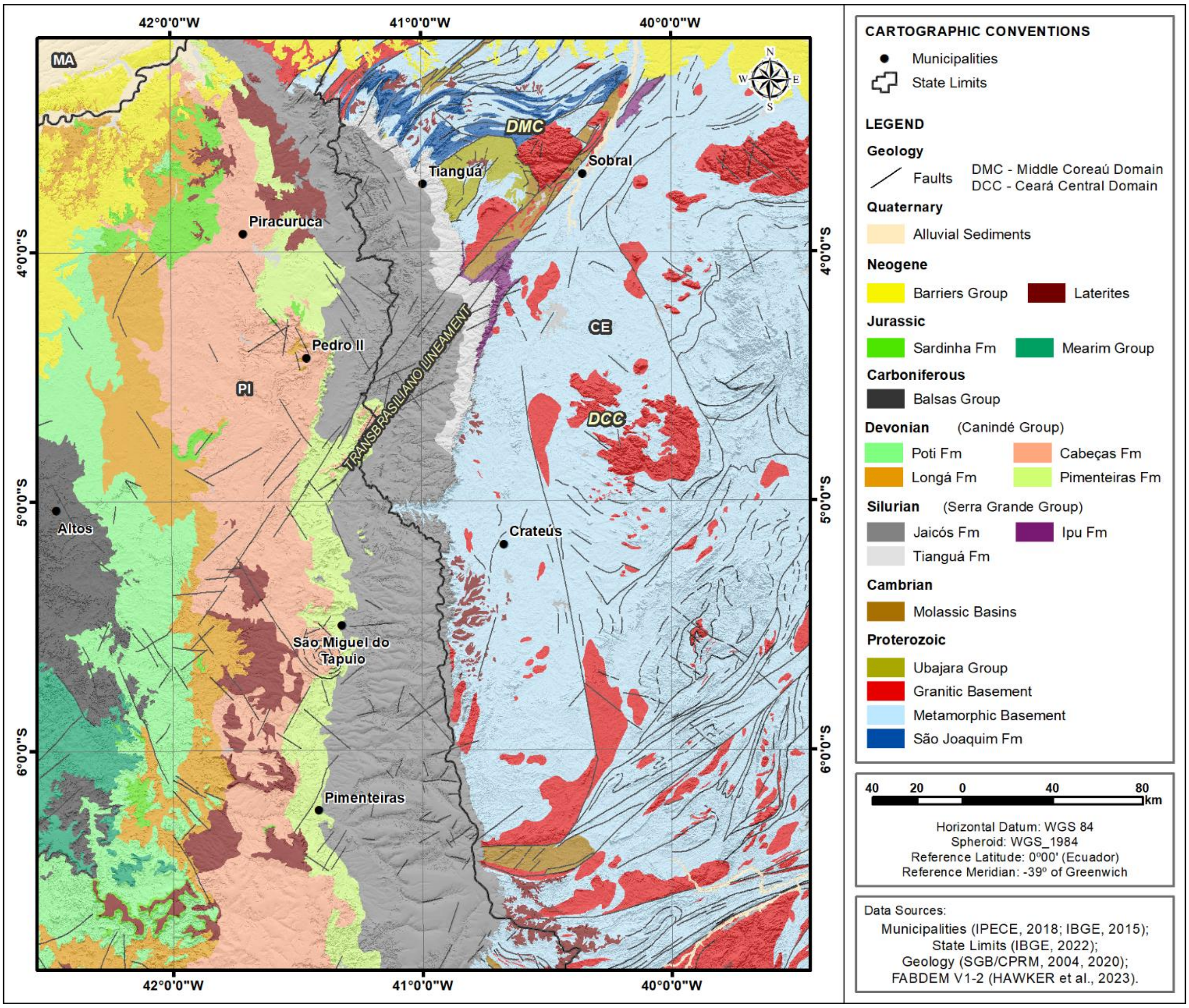

Figure 2. Geology of the Ibiapaba Plateau and Surrounding Areas. Source: CPRM, 2020; CPRM, 2006.

In the eastern part of the study area, there are planation surfaces developed over Proterozoic lithologies in the northwest sector of the Borborema Province, represented by the Médio Coreaú (DMC) and Central Ceará (DCC) Domains (ANGELIM et al., 2003) (Figure 2). The Proterozoic basement of the DMC was deformed and metamorphosed during the Brasiliano Orogeny (Neoproterozoic), characterized by a sequence of grabens and horsts (Martinópolis and Jaibaras grabens and Tucunduba and Granja horsts), separated by NE-oriented shear zones (SANTOS et al., 2008), the most prominent being the Transbrasiliano Lineament (TL) (COSTA et al., 1979), regionally known as the Sobral-Pedro II Fault (ANGELIM et al., 2003).

The TL represents a continental-scale structural discontinuity, approximately 4,000 km long, trending NE, extending from the continental shelf of Ceará to the northern limit of Patagonian terrains (BRITO NEVES; FUCK, 2014). In the context of the study area, the TL divides the tectonic compartments DMC and DCC, whose tectonic evolution helps explain the current morphological behavior of the Ibiapaba Plateau, as will be addressed later.

From a lithological perspective, the Neogene lateritic coverages (ANGELIM et al., 2003) are also noteworthy, with spatial distribution that holds both morphological and paleoclimatic significance, occurring sporadically over both basement rocks and sedimentary lithologies.

The sediments of the Barreiras Group stand out as the primary Cenozoic deposits, located in the northernmost section of the spatial area analyzed, representing a correlative deposit of the Neogene planation surfaces. In the study area, the Barreiras Group is composed of the Barreiras Formation (undivided) and the Camocim Formation, the latter representing an extensive gravel deposit in the pre-coastal zone of the DMC (PINÉO et al., 2018). Quaternary sediments are represented by alluvial and colluvial deposits, which have limited spatial distribution in the mapping presented in Figure 2.

3. Materials and Methods

The research began with a bibliographic and cartographic review of the morphostructural context of the contact zone between the Parnaíba and Borborema Provinces. Subsequently, fieldwork was conducted between 2020 and 2022 in various spatial sections throughout the study area, aiming to analyze the morphological behavior of different lithological contexts and to capture photographic records using cameras and drones.

Geoprocessing techniques allowed for correlating morphological variations with the lithostructural aspects available in updated geological maps from CPRM at a 1:100,000 scale (CPRM, 2011; 2013; 2014, and 2015). Additionally, geological bases at a 1:1,000,000 scale from the SA:24, SA:23, SB:23, and SB:24 sheets (CPRM, 2004) were used, along with geological maps of Ceará at a 1:500,000 scale (CPRM, 2020) and Piauí at a 1:1,000,000 scale (CPRM, 2006).

For morphological interpretation, images from FABDEM (Forest and Buildings removed Copernicus DEM V1-2) were utilized, which constitutes a digital process for removing forests and buildings/infrastructure from the global COPERNICUS DEM, with a spatial resolution of 30 meters, enabling greater topographical detail (HAWKER et al., 2022). From this base, three-dimensional elevation models were generated using QGis software version 3.22 (QGIS TEAM, 2023).

Next, topographic attributes such as elevation and slope were extracted from FABDEM, allowing for the analysis of topographic profiles and morphological variations. This information was analyzed together with lithological data, resulting in cartographic products of geology and regional compartments.

Structural lineaments were obtained through the lineament extraction tool in PCI Geomatics 2020 software and underwent correction and validation through the interpretation of satellite images and products from FABDEM-V1-2. The drainage network was extracted from the DEM in Matlab R2023b software, using a threshold of 30,000 pixels and determining the fluvial hierarchy according to Strahler (1952). From this data, lineament density and drainage maps were obtained using the line density tool in ArcMap software.

Subsequently, for generating rose diagrams, the AzimuthFinder tool (QUEIROZ et al., 2014), incorporated into ArcMap software, was used to obtain azimuthal data, which were loaded into OpenStereo software (GROHMANN; CAMPANHA; SOARES JUNIOR, 2011) at intervals of 10° (ten degrees). The rose diagrams were based on the directional frequency of the azimuths of the structural lineaments and the drainage network.

In order to analyze the regional morphostratigraphic context, particularly regarding the formation of planation surfaces, the low relief surface technique (WHIPPLE et al., 2017) was applied, starting with the extraction of slope percentages, which were reclassified into two classes: 0–8% (flat to gently undulating relief) and >8% (undulating to steep relief) (EMBRAPA, 2018). Subsequently, the raster with elevation values was reclassified, generating a new matrix file with elevation classes in 100 m intervals.

Based on the reclassified slope and elevation files, through matrix algebra, the elevation raster was subdivided according to the two slope classes initially generated. From the matrix algebra product, the elevation classes with slopes >8% were excluded, leaving only the tops and valleys (surfaces with 0–8% slope). These were differentiated using the topographic position index (TPI) attribute, proposed by Weiss (2001). This step aimed to generate and exclude the file of valleys, which are inclined depressions in the terrain surface (HUGGETT, 2007), primarily serving to interpret the extent of the evolution of planation, tabular, and/or structural surfaces on a regional scale.

Finally, a file was obtained consisting of surfaces located at the top of the relief with slopes less than 8%, divided into 100 m elevation classes, with low relief surfaces occurring at different altitudes, forming a fundamental base for morphostratigraphic interpretation.

4. Results

4.1. General aspects of the regional morphology of the Ibiapaba Plateau and adjacent areas

On a regional scale, the relief of the study area can be compartmentalized into planation surfaces in the basement (sertaneja surface) dotted with massifs, inselbergs, and ridges; the main escarpment (Ibiapaba glint); structural reverse supported by the Serra Grande Group; and a monoclinal depression that constitutes planation surfaces in the sedimentary basin, with some tabular plateaus (mesas) (Figure 3).

The most important lithological unit of the Ibiapaba Plateau is the Serra Grande Group (Silurian), whose siliciclastic nature (BATISTA et al., 2020) is responsible for maintaining a continuous escarpment marked by the discordant contact between the sandstones and conglomerates of this group and the Precambrian basement, on which the ancient pre-Silurian planation surface was formed. Escarpments supported by layers of resistant sedimentary rocks, discordantly superimposed on the planed basement, can be designated as glints (PECH, 2005; FOUCAULT; RAOULT, 2010; CILF, 1979), and the designation of the Ibiapaba glint has been adopted in recent works on the regional geomorphology of this area (PEULVAST; CLAUDINO SALES, 2004; PEULVAST et al., 2008; CLAUDINO SALES et al., 2020).

The Serra Grande Group consists of the Ipu, Tianguá, and Jaicós Formations, from the oldest to the most recent, which are responsible for maintaining cornices in different sectors of the escarpment. This escarpment extends for more than 400 km, along nearly the entire western sector of Ceará, being interrupted only by the percée (canyon) formed by the consequent drainage of the Poti River.

It is worth noting that, besides the mentioned escarpment, the eastern sector of the plateau is also constituted by dissected crystalline pediments, with altitudes ranging from 200 to 600 m. These "ramps" separate the glint from the Neogene planation surfaces (Figure 6).

The circumdenudational processes that carved the Ibiapaba escarpment formed an abrupt topographical staircase that separates sertaneja surfaces, with elevations ranging from 200 to 500 m, from a sedimentary plateau that reaches elevations ranging from 700 to 900 m. In the morphostratigraphic interpretation by Peulvast and Claudino Sales (2004), the summit part of this plateau was designated as a dissected structural surface of uncertain age, inferred as pre-rift.

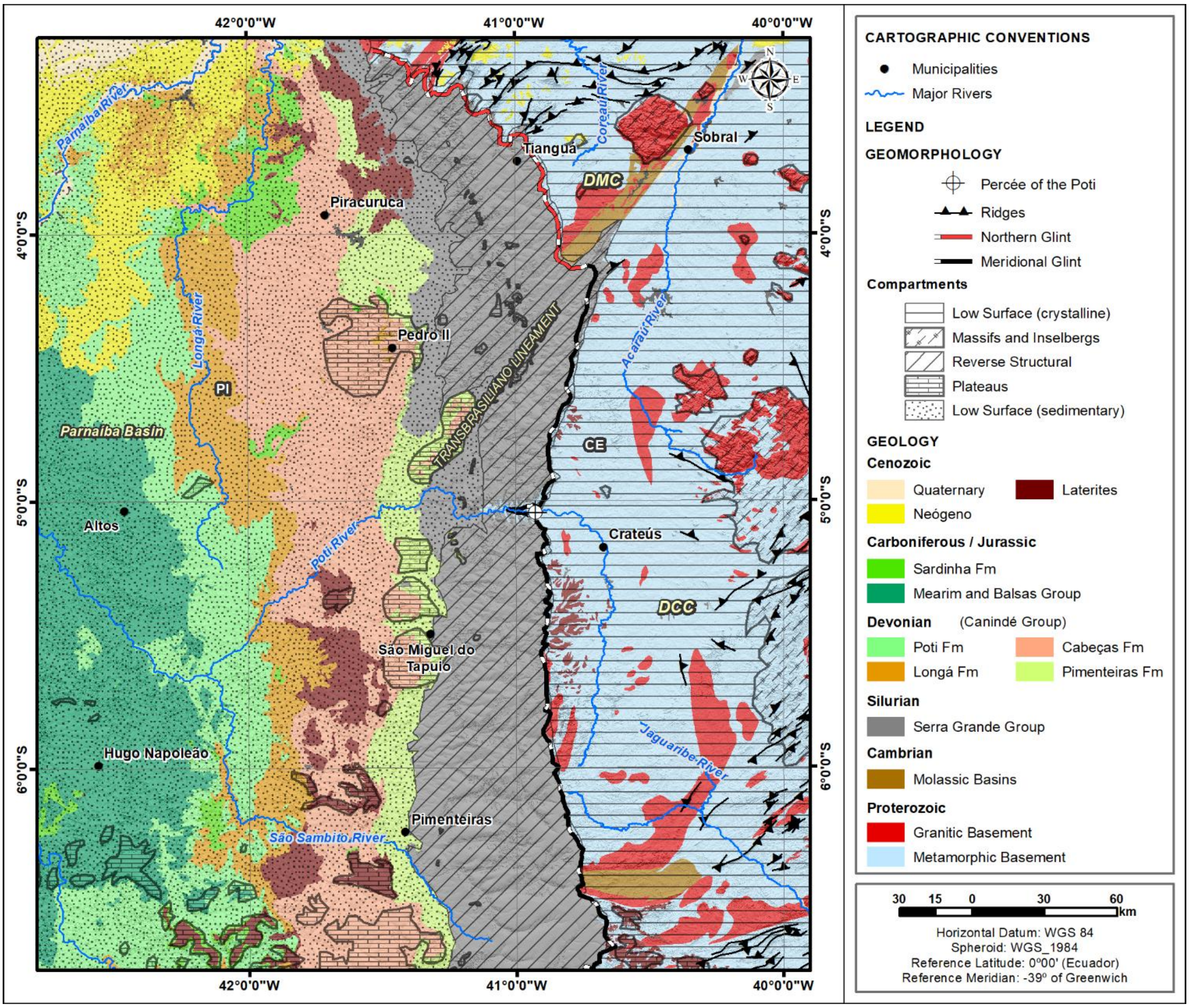

Figure 3. Morphostructural compartmentalization of the Ibiapaba Plateau and surrounding areas.

It is important to note that evidence of sedimentary rocks from the basin along the surrounding sertaneja surfaces is quite limited, with a notable example being an elongated NE-oriented ridge located in Santana do Acaraú/CE, composed of rocks from the Ipu Formation preserved in the Jaibaras Graben (Figure 2).

In the broader context of the Ibiapaba Plateau, the Transbrasiliano Lineament (TL) stands out as the main tectonic divider in the area (SCHOBBENHAUS et al., 1975), separating the Central Ceará Domain (CCD) and the Middle Coreaú Domain (MCD), and influencing significant morphological aspects of the plateau. The TL marks the main inflection point in the escarpment's orientation, which runs predominantly N-S in the southern sector of the TL, and NW-SE in the northern sector of the TL (Figure 3). In addition to the escarpment, the TL also affects the reverse structure, which will be discussed later.

Analyzing the structural lineaments of the study area, a predominant NE orientation is observed, particularly within the Borborema Province. This structural framework plays a crucial role in the organization of the drainage network, which shows a preferential N-NE orientation (Figure 4). The spatial distribution of drainage patterns also indicates lithostructural control, with dendritic patterns prevailing in the basement and parallel patterns following the monocline structures of the Parnaíba Basin. Additionally, the density of the drainage network is higher in the basement due to its low permoporosity.

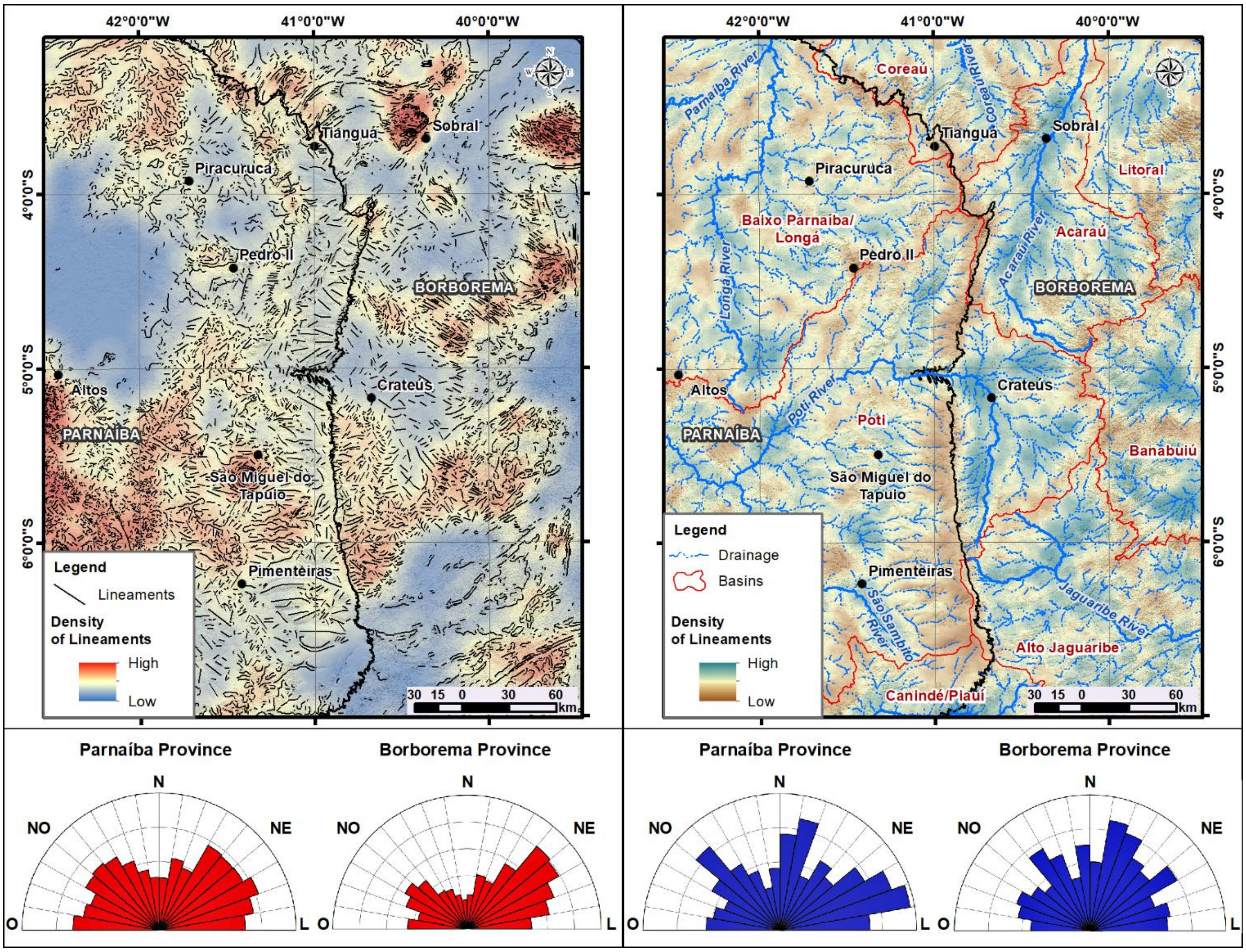

Figure 4. Structural lineaments and drainage network organization in the Ibiapaba Plateau and surrounding areas.

Applying the "low relief surface" topographic tool to the study area (Figure 5), the evolutionary behavior of the lowered planation surfaces in the study area becomes evident. Surfaces below 300 m (low sertaneja surfaces and monoclinal depression) develop over diverse lithologies and expanding over both the basement and the lithologies of the sedimentary basin. However, their spatial expansion is much more pronounced over the sedimentary lithologies of the Balsas and Mearim groups.

Intermediate planation surfaces (500/600 m) are concentrated in the southern part of the study area, representing lateritic surfaces and higher sertaneja surfaces. The highest flat surfaces (>700 m) are located at the top of the Ibiapaba Plateau, forming structural surfaces related to the Serra Grande Group (Jaicós Formation). No planation surfaces were identified at the top of crystalline plateaus due to the dissection of the relief in these areas.

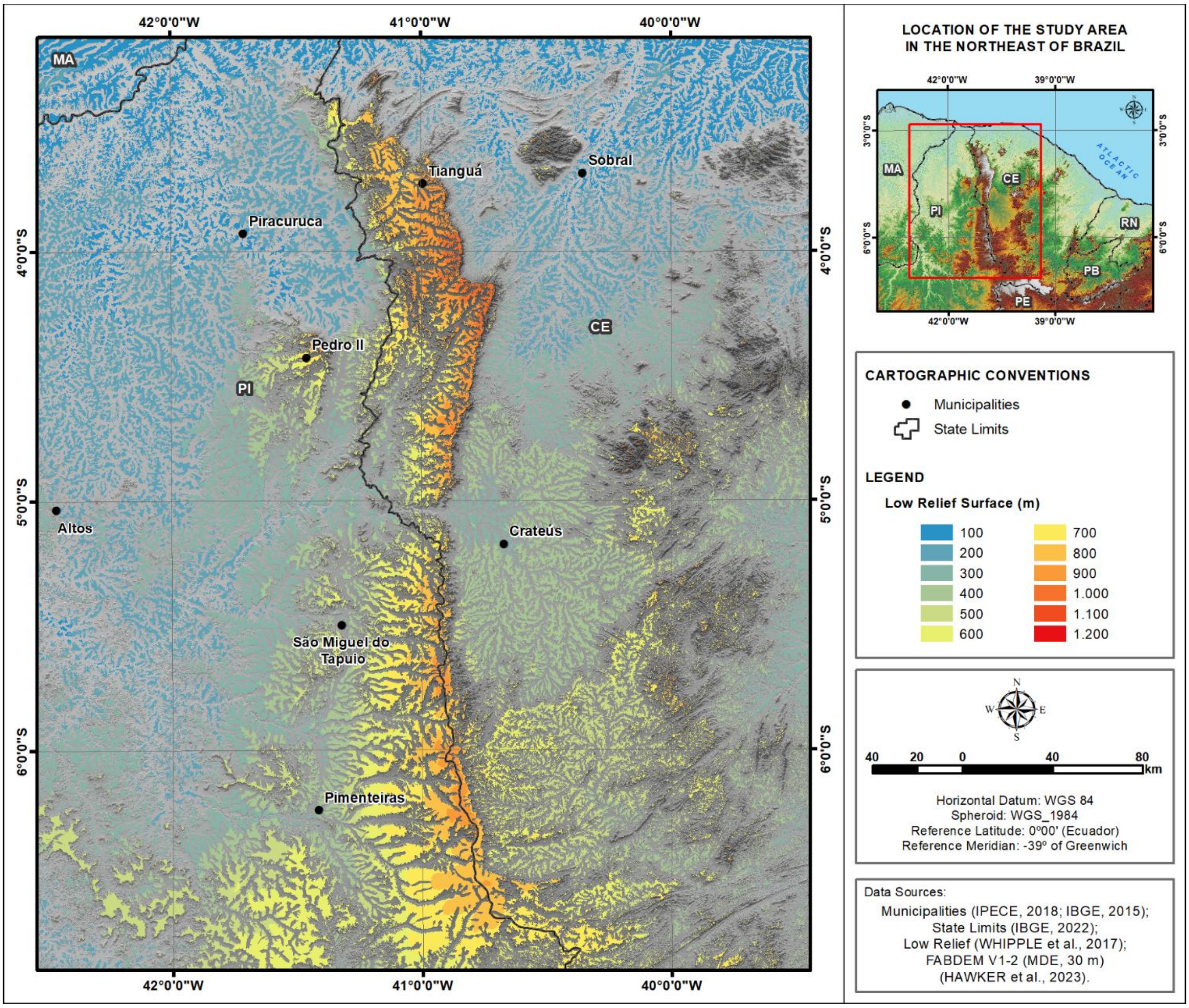

Figure 5. Identification of flat surfaces using the "Low Relief Surface" tool in the Ibiapaba Plateau and surrounding areas.

4.1.1. Escarpment characteristics

The Ipu Formation (Silurian) forms the basal layer of the Parnaíba Basin, composed of conglomerates and sandstones of glacial and fluvial origin, with thicknesses reaching up to 350 meters (VAZ et al., 2007; CAPUTO; LIMA, 1984; CRUZ et al., 2019). This formation is responsible for maintaining the largest cornices of the Ibiapaba Glint (over 350 meters) (Profile E – E′ in Figure 10), which are mainly located between the TL and the Poti River percée. The escarpments in this area generally begin at elevations ≈ 300 meters and can reach ≈ 700 meters.

The Tianguá Formation lies conformably above the Ipu Formation and consists of sandstones, with subsurface thicknesses of up to 270 meters (CAPUTO; LIMA, 1984). The escarpments associated with this layer are found in the northern sector of the Ibiapaba Plateau, starting from the TL, forming cornices with thicknesses ranging from ≈100 to 200 meters. The northern slopes of Ibiapaba exhibit the greatest representation of basement lithologies, reaching elevations of ≈ 600 meters, forming dissected ramps in crests developed between first-order parallel drainage systems (Figure 6 and profile B – B′ in Figure 10).

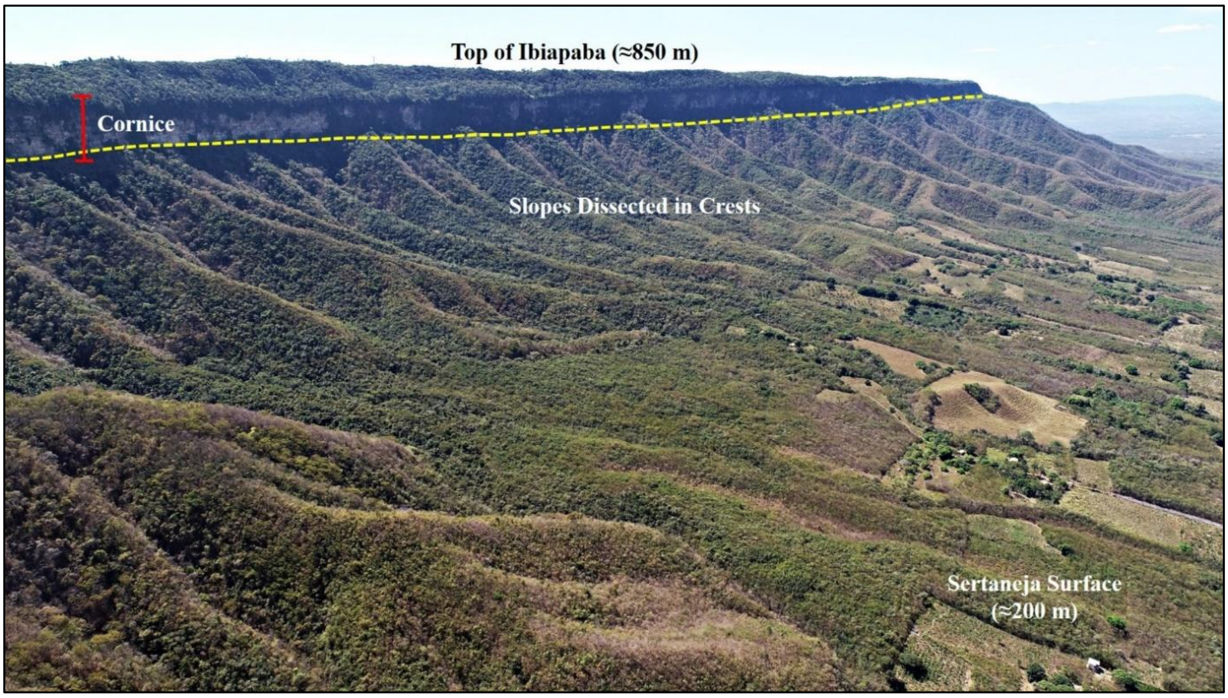

Figure 6. Escarpment sustained by the sandstones of the Tianguá Formation, discordantly overlying the basement sculpted in dissected ramps in crests (Tianguá/CE). (The yellow dotted line indicates the contact between the crystalline basement and the sedimentary lithologies of the Serra Grande Group). Source: authors' collection (2021).

The Jaicós Formation consists of sandstones and conglomerates conformably overlying the Tianguá Formation, with a maximum estimated subsurface thickness of 400 meters (VAZ et al., 2007; CAPUTO; LIMA, 1984). This formation is responsible for maintaining cornices located south of the Poti River percée (Figure 7), supporting the thinnest escarpments of the Ibiapaba Glint, with the top reaching elevations of approximately 700 meters (Profile I – I′ in Figure 10), as well as supporting the majority of the tabular structural reverse of the plateau.

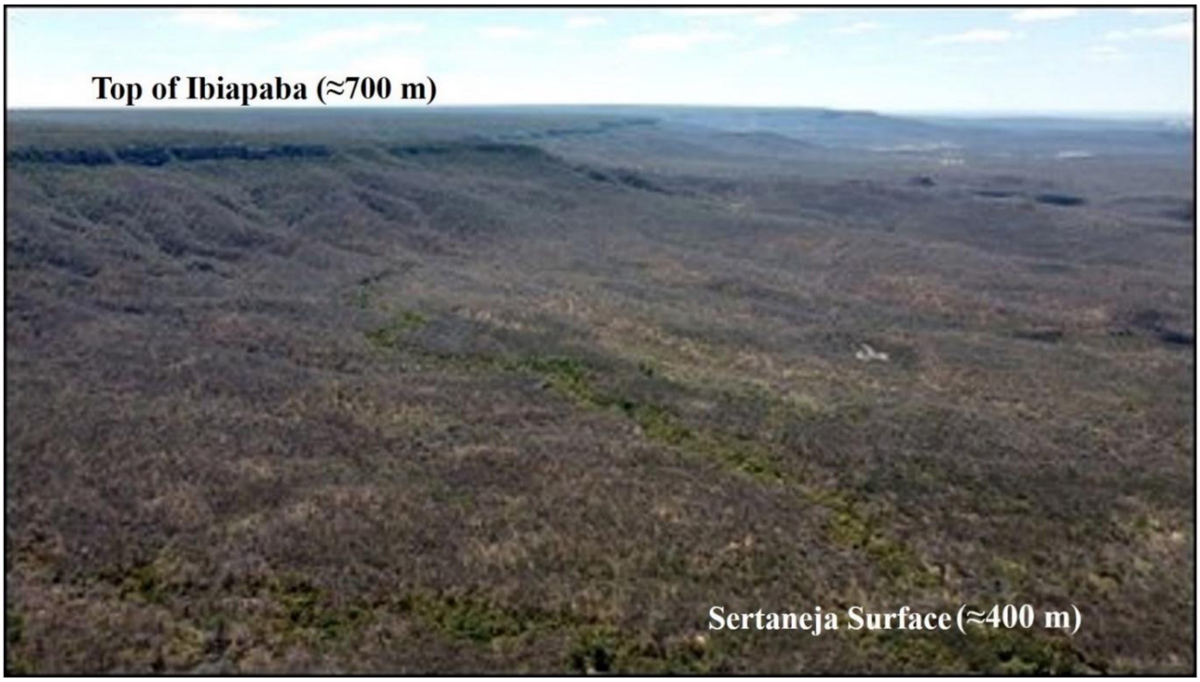

Figure 7. Southern sectors of the Ibiapaba Glint supported by the sandstones of the Jaicós Formation (Parambu/CE). Source: authors' collection (2021).

It is important to note that the lithological contacts between the formations of the Serra Grande Group do not exhibit significant evidence of topographic breaks. An exception is identified in the municipality of Ipu (CE), where there is a noticeable topographic step between the Ipu and Tianguá formations (Figure 8), justifying a glint-type escarpment between the crystalline basement and the Ipu Formation, and a cuesta-type escarpment between the Ipu and Tianguá formations.

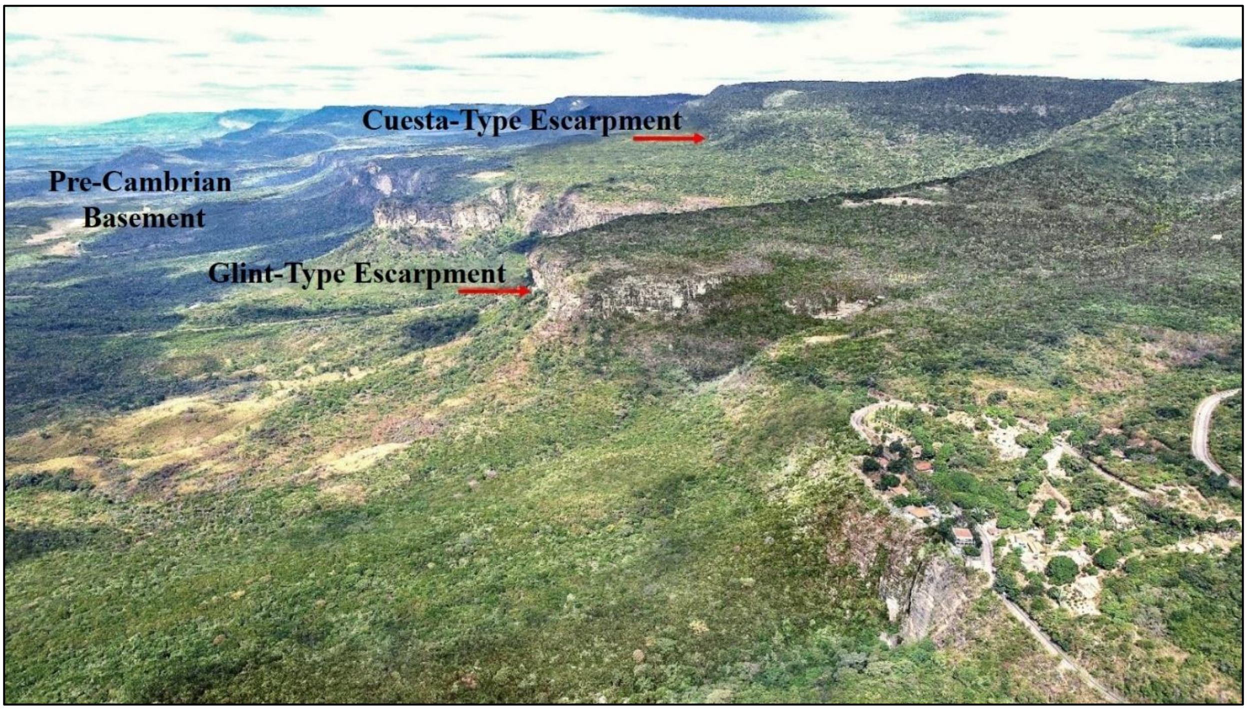

Figure 8. Formation of a glint-type escarpment between the crystalline basement and the Ipu Formation, and a cuesta-type escarpment between the Ipu and Tianguá Formations around the city of Ipu/CE. Source: authors' collection (2022).

Another similar topographic break, though without the formation of distinct escarpments, occurs in the immediate reverse slopes of the glint near the town of Tianguá and in the area around the town of Viçosa do Ceará. In this case, the topographic break is associated with the contact between the Tianguá (≈700/750 m) and Jaicós (≈800/850 m) Formations (CPRM, 2020). On the lower surface, formed over the Tianguá Formation, a obsequent drainage network has developed (anaclinal rivers), whose denudation in this sector has formed ruiniform features (pinnacles), supported by weathered and friable coarse sandstones, as exemplified by the area locally known as "Castelo de Pedras".

Another important aspect to consider regarding the morphological behavior of the Ibiapaba Glint refers to the variation in lithologies of the basement underlying the Serra Grande Group, as well as the intensity of the uplift that these structures have undergone.

Thus, in the northern sector of the glint, the exhumation of quartzites from the São Joaquim Formation stands out (Figure 2 and Profile A – A' in Figure 10), preserving sigmoidal ridges reaching elevations of up to 600 meters, which were exhumed after the denudation of the Serra Grande Group and exposed in topographic relief by differential erosion compared to the other Precambrian lithologies of the surrounding sertaneja surface. These ridges, called the Ubatuba, São Joaquim, and Umari mountains, form watershed divides for small sub-basins and are responsible for the formation of erosive amphitheaters (Figure 3).

This northern sector of the basement constitutes the DMC, whose NE-trending deformations formed graben and horst sequences that are closely related to the erosive irregularities of the escarpment, contributing to the formation of these amphitheaters (BELARMINO; BASTOS, 2021). In addition to the aforementioned quartzites, this sector of the basement is composed of gneiss-migmatite complexes from the Martinópole Group and the Granja Complex (CAVALCANTE et al., 2003), forming lowered sertaneja surfaces.

From the municipality of Tianguá (CE) southwards, the base of the escarpment is composed of lithologies from the Ubajara Group (Neoproterozoic) (Profile C – C′ in Figure 10), whose Trapiá, Caiçaras, and Coreaú Formations, made up of fine-grained metasedimentary lithologies, constitute planation surfaces. However, the Frecheirinha Formation, composed of metacalcareous rocks, plays a significant role in the escarpment's morphology, sustaining a karst system (Figure 9), with pinnacle and lapiez outcrops, as well as the most complex and extensive endokarst system in Ceará, with the main example being the Ubajara Cave.

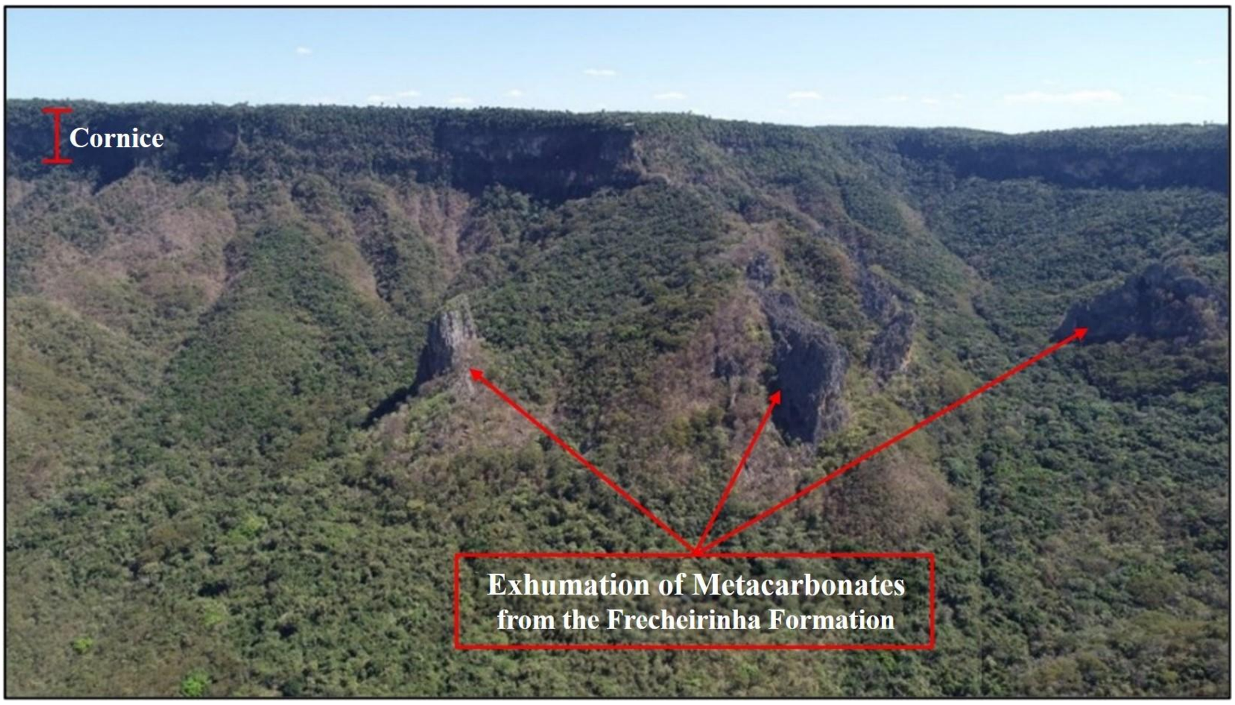

Figure 9. Morphology of the escarpment between the Tianguá formation (Silurian) and the metacarbonates of the Frecheirinha Formation (Neoproterozoic), with the development of a karst system in the Ubajara National Park Area/CE. Source: authors' collection (2022).

The Brasiliano deformations associated with the TL were filled into a molassic basin (Cambro-Ordovician) called the Jaibaras Graben (COSTA et al., 1979). This sector is responsible for the largest inflection of the Ibiapaba escarpment, where a "promontory" is observed, formed by the Tianguá and Ipu Formations, trending NE (Figure 2). Following the direction of the graben, a low ridge (≈200m) is sustained by conglomerates of the Aprazível Formation (Ordovician), which belongs to the Jaibaras Group.

South of the TL, the basement lithologies are mainly represented by the metamorphic rocks of the Canindé Unit of Ceará (paragneisses) and Tamboril (gneisses), with the main exception being the sedimentary lithologies of the small Cococi molassic basin (Cambro-Ordovician) (CAVALCANTE et al., 2003). In this extensive sector of Ibiapaba, no significant variations in the escarpment are noted due to the influence of basement lithologies, except for a small area near the municipality of Quiterianópolis (CE), where the Santa Quitéria granitoids and the quartzites of the Bonsucesso Formation, both Neoproterozoic, sustain a high topographic level (≈700 m), situated between the sandstone cornice (≈800 m) and the sertaneja surface (≈400 m). This sector provides the best evidence of the exhumation of the pre-Silurian surface in basement rocks in the analyzed area, located about 300 m above the Neogene sertaneja surface.

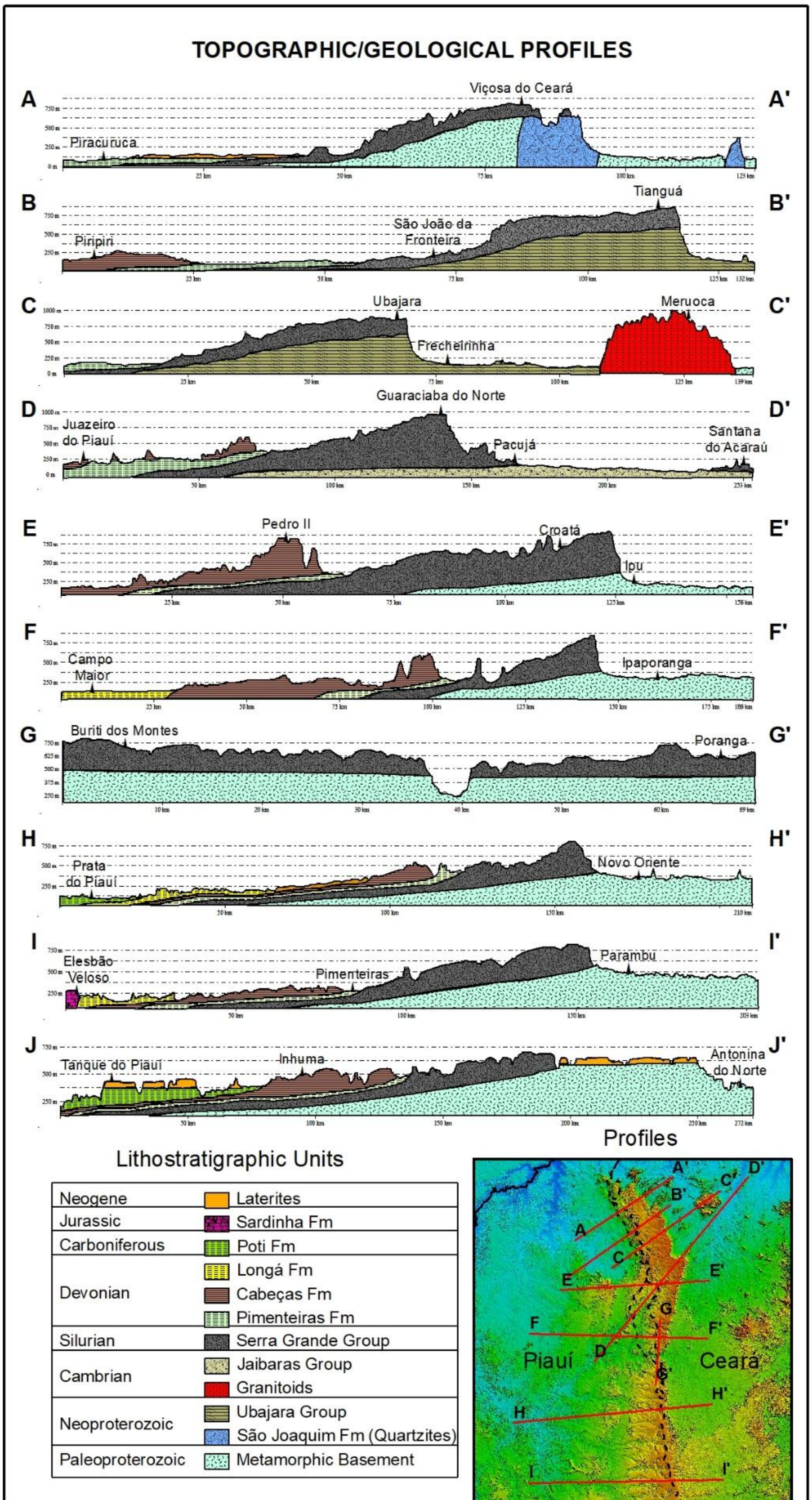

Figure 10. Topographic and geological profiles of the Ibiapaba Plateau and surrounding areas.

An important feature of the Ibiapaba escarpment is that, from south of the Poti River percée, there is a progressive reduction in the altimetric difference between the top of the sandstone cornices and the surrounding basement surface. This is due to the fact that the sertaneja surfaces in this sector are at higher elevations (above 400 m). These surfaces were designated by Souza (2000) as the old sertaneja surface, preserved about 200-300 m above the new sertaneja surface (<200 m), the latter being prominently present in the northern sectors of the analyzed basement area (Figures 3 and 4).

As previously described, the only discontinuity in the Ibiapaba escarpment is due to the Poti percée (Figure 3 and Profile G – G' of Figure 10), which, within the main escarpment, appears as an open valley, gradually narrowing and fitting into the reverse and monoclinal depression. Its valley becomes deeply entrenched when it begins to drain over the Pimenteiras Formation.

At the southernmost end of the glint, the base of the escarpment is sustained by Neogene-age lateritic coverings (ANGELIM et al., 2003). These laterites are autochthonous (CORDEIRO, BASTOS, MAIA, 2018) and are situated at elevations of ≈700m, which characterizes this sector as the least represented part of the escarpment, which reaches ≈750m (Profile J – J' of Figure 10). These lateritic surfaces are inferred to be preservation sectors of pre-Cenomanian surfaces (PEULVAST; BÉTARD, 2015).

The morphological behavior of the Ibiapaba plateau, along its northern and southern sectors, can be observed in the topographic and geological profiles of Figure 10.

4.1.2. Morphology of the structural reverse

In general, the structural reverse of the Ibiapaba Plateau exhibits distinct morphological behaviors between the northern sector (north of the TL) and the southern sector (south of the TL). The northern sector, located over the DMC, was likely subjected to more significant uplifts than the southern sector. However, no topographic ruptures are evident between these two areas due to a possible strike-slip movement (CLAUDINO SALES et al., 2020).

In the northern sector, the reverse forms a preserved plateau about 30 km wide and 60 km long, trending NW, and is gently dissected by the consequent drainage of the upper course of the Longá River basin, forming tabular interfluves (SOUZA, 1988). This structural plateau is sustained by the sandstones and conglomerates of the Jaicós Formation and maintains altimetric elevations between ≈900 and ≈750 m, with a gentle westward slope.

In the western part of this plateau, over the Jaicós Formation, at elevations of ≈750 m, lateritic coverings are responsible for the preservation of isolated mesas, slightly elevated above the surrounding surface (Figures 3 and 11). These tabular landforms were designated by Souza (2000) as possible remnants of the Pimenteiras Formation or other overlying formations of the Parnaíba Basin. It is worth noting that these lateritic coverings are not identified in official geological maps due to the scale of mapping. Regardless of the origin of the lateritized material, its geomorphological importance is unquestionable, both in preserving the plateaus and in protecting this plateau against the upwelling erosive action in a W direction derived from the tributaries of the Longá River sub-basin, a tributary of the Parnaíba River.

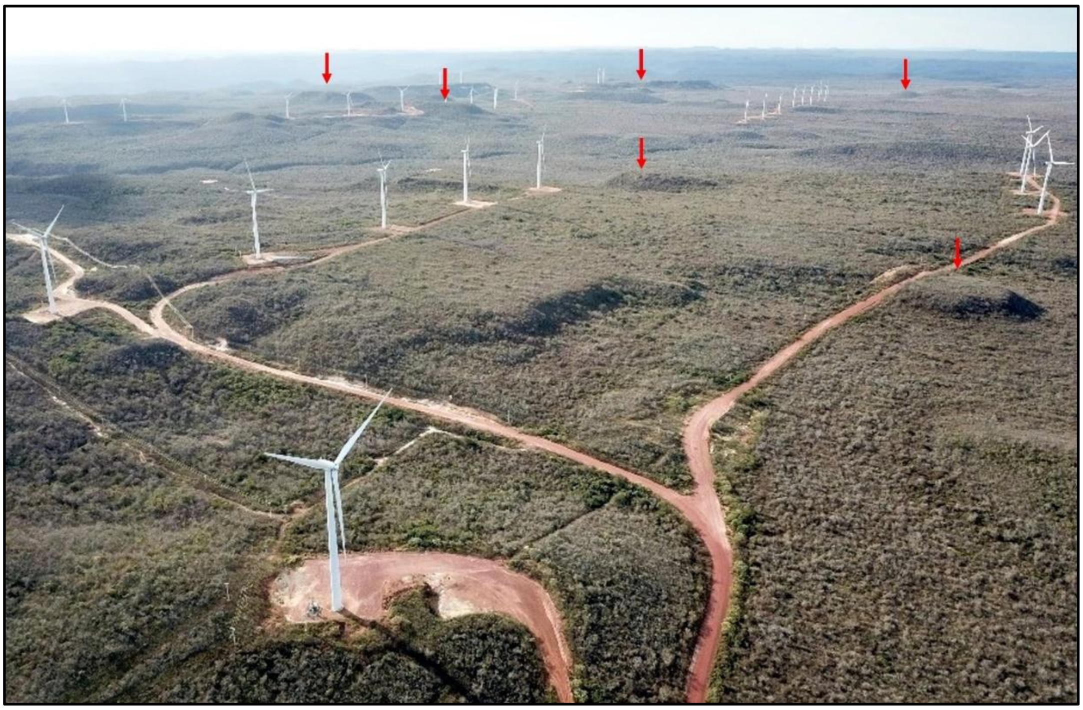

Figure 11. Lateritic mesas located in the western sector of the northern reverse of Ibiapaba (red arrow). Source: authors' collection (2022).

Also in the northern sector of Ibiapaba, moving westward, between the contacts of the Jaicós and Pimenteiras Formations, there is a topographic rupture with significant dissection of the consequent drainage due to the gradient, forming entrenched valleys (Figure 12). This rupture represents the division between the reverse plateau (≈750 m) and the erosion surface of the basin (monoclinal depression) (≈150 m). This compartmentalization is related to differential erosion at the lithological contact between resistant lithologies (sandstones and conglomerates of the Jaicós Formation and lateritic coverings) and fragile ones (shales and siltstones of the Pimenteiras Formation).

Figure 12. Fluvial dissection of the consequent drainage in the northern sector of the Ibiapaba reverse. Source: authors' collection (2022).

In the southern sector of the Ibiapaba reverse, the topography shows a steeper slope, justifying greater dissection by the consequent rivers and the absence of a preserved plateau (Figures 1 and 4, and profiles D – D′, E – E′, and F – F′ in Figure 10). The morphological behavior of these consequent channels suggests strong erosive action on the side of the Parnaíba River basin, compared to the basins draining the basement, indicating possible trends for future river captures (Figure 1).

In addition to the morphology of the Ibiapaba escarpment, the TL also influences the morphology of the reverse. A clear structural control is observed in the organization of the consequent drainage network developed over the TL, with dissection trending SW coinciding with the TL. Furthermore, the change in morphological behavior between the sectors situated north and south of the TL is certainly related to the respective uplift of the tectonic compartments DMC and DCC.

4.2. Adjacent Planation Surfaces

In the surroundings of the Ibiapaba Plateau, there are planation surfaces formed in different morphostructural contexts. One surface is sculpted over pre-Cambrian basement rocks (sertaneja surface) on the eastern side, and another is formed in the monoclinal depression of the Parnaíba Basin, over sedimentary rocks (Figure 3). In the northern sectors, closer to the coast, these surfaces have elevations ranging from 100 to 200 m, with greater representation within the sedimentary basin, indicating more significant denudational action in this area (Figure 4). In the southern sectors, these surfaces exhibit gradually higher elevations (≈500 m).

In the Sertaneja surfaces, Paleoproterozoic metamorphic rocks predominate, whose geomorphological properties, such as plasticity, discontinuity planes, mineralogical heterogeneity and structural deformations throughout their structural evolution, justify their limited resistance to erosion processes, forming planation surfaces that are clearly separated into two topographic levels, described by Souza (1988) as new Sertaneja surface (lower – ≈100 to ≈200 m) and old Sertaneja surface (higher – ≈400 to ≈500 m). The lower sertaneja surfaces are located in the northern watersheds (Acaraú, Coreaú, and Timonha), while the higher surfaces are found in the upper Jaguaribe watershed. The Poti sub-basin has intermediate elevations between the two surfaces (≈300 m), indicating a possible recent river capture, possibly related to increased regional denudational action in the Parnaíba Basin area.

The altimetric variations between the low and high sertaneja surfaces can be explained by the relationship between the competence of neogenic regressive denudational action and regional lithological diversity, justifying differential erosion. Thus, lower surfaces are found in the pre-coastal sectors, while higher ones are located inland, separated by residual landforms (granitoid, quartzitic, and orthogneissic) that act as barriers to regressive erosion.

Scattered throughout the sertanejas surfaces are residual landforms of varied dimensions, morphologies, and altitudes (massifs, crests, inselbergs, and inselguebirgs), formed by differential erosion and supported by granitoids, orthogneisses, quartzites, and lateritic duricrusts, as seen in the Meruoca, Carnutim, Penanduba, São Joaquim, Ubatuba, and Pedra Branca mountain ranges (Figure 3).

In the western sector of the study area, there are planation surfaces (monoclinal depression) developed over the lithologies of the Canindé (Devonian), Balsas (Carboniferous), and Mearin (Jurassic) Groups, primarily composed of fragile sedimentary rocks with fine grain sizes (siltstones, shales, and very fine sandstones). Thus, a vast low planation surface (<200 m) is formed, extending much further south (about 350 km from the coast) than the behavior observed in the sertaneja surface of the crystalline basement, where such low surfaces reach a maximum distance of 180 km from the coast (Figure 4).

The monoclinal depression in the study area is characterized by flat topographies with no significant morphological variations. However, specifically in the Canindé Group, the difference in resistance between the Cabeças Formation and the others (Pimenteiras, Longá, and Poti Formations) stands out. In this case, residual landforms are maintained, such as small sedimentary plateaus, buttes, and various ruiniform features (pinnacles), sometimes densely packed and closely spaced in "rock cities" (MIGOŃ et al., 2017), as can be observed in the Sete Cidades National Park (Piracuruca/PI), which has one of the most beautiful ruiniform landscapes in the country (AB'SÁBER, 1977), being described as a fine example of karst developed in sandstone (MIGOŃ, 2021).

The Pimenteiras Formation also plays an important regional morphological role by being situated between two more resistant layers (Cabeças and Jaicós Formations). At its contact with the Jaicós Formation (Serra Grande Group), it represents the morphological transition between the Ibiapaba reverse and the monoclinal depression. On the other hand, at its contact with the Cabeças Formation, topographical ruptures exhibiting cuestas behavior are evident, influencing the configuration of the drainage network and the formation of escarpments, such as the Matões mountain range in Pedro II (PI) (Figure 10 – Profile E-E').

The higher sectors of the monoclinal depression are due to the greater resistance of the sandstones of the Cabeças Formation and the Cenozoic lateritic covers that support altitudes between ≈350 and ≈500 m, which can be designated as structural surfaces. The exception relates to the Pedro II sector, where altitudes exceed 700 m, forming a small sedimentary plateau. In the case of Pedro II, besides the presence of the Cabeças Formation, the structural control in the TL is noteworthy, with evident uplift in the northern sector of the TL. In addition to the examples mentioned, one of the elevated sectors of this area refers to the circular structure of São Miguel do Tapuio, described as a landform resulting from an asteroid impact, with recrystallization of metaarenites (MARTINS et al., 2016).

The altimetric difference between the marginal surfaces of the Ibiapaba Plateau clearly indicates a much more aggressive erosive action on the side of the sedimentary basin (west), supporting the hypothesis that the watersheds in this sector are capturing the surrounding basins.

5. Discussion

The evolution of the Ibiapaba Plateau has been designated as post-Cretaceous, associated with positive epeirogenies (AB'SÁBER, 1949). Peulvast and Claudino Sales (2004) and Claudino Sales et al. (2020) indicate phases of uplift in the Ibiapaba sector related to intracontinental rifts (Cenomanian) and the opening of the transform margin (Albian), where compression pulses along the equatorial margin reactivated the transcurrent movement along the TL (SZATIMARI et al., 1987). From this point, denudational actions began to dominate regional morphogenesis at rates inferred to be about 10 m/Ma (PEULVAST et al., 2008), whose evolution, marked by the transition between biostatic and resistatic phases, allows adaptations to etchplanation models (MOURA FÉ, 2015).

These low inferred rates of Cenozoic denudation for northeastern Brazil can be justified by factors such as the low uplift of Albian marine layers (Araripe and Apodi basins), the lithological resistance of basement rocks (granites, quartzites, and orthogneisses) and sedimentary rocks (sandstones and limestones), explaining the widespread preservation of residual topography and elevated surfaces above the sertanejas surfaces (PEULVAST; BÉTARD, 2021). This denudational behavior was fundamental in the evolution of escarpments, as is the case with the Ibiapaba Plateau.

The identification of detrital cones over dissected pediments below and elevated scarps, as well as the presence of stony terraces in the middle and lower river courses, reflect resistatic periods favorable to the ablation of deep regoliths, suggesting a morphogenetic phase of generalized topographic lowering (downwearing), albeit moderate, with local phenomena of retreat (backwearing) (PEULVAST; CLAUDINO SALES; BÉTARD, 2008). In the specific case of Ibiapaba, mappings of coluvial deposits located immediately at the base of the escarpment are limited, indicating a restricted Quaternary evolution by backwearing. However, the significant deposition of gravel from the Camocim Formation (PINÉO et al., 2018), located in the coastal sector of the DMC, indicates a resistatic phase likely associated with the intensification of aridity in the Miocene (HARRIS; MIX, 2002).

Uplifts inferred by thermochronological methods (AFT) indicate a cooling event between the Late Jurassic and Late Cretaceous, related to uplifts during the rift and post-rift phases, and another between the Eocene and Miocene, related to flexural uplifts (SANTOS, 2022). These geochronological data corroborate the regional morphogenetic interpretation of Peulvast and Claudino Sales (2004).

The inclination of flexural movements in the tectonic compartments separated by the TL reflects the morphological behavior of the Ibiapaba Plateau and the surrounding lowered surfaces. After the opening of the Atlantic Ocean, during the post-rift and drift phases, the DCC and DMC underwent flexural uplift (PEULVAST; CLAUDINO SALES, 2004), with distinct axes, contributing to the current morphological behavior of the Ibiapaba Plateau.

These flexural axes help explain the behavior of the glint in the DMC and DCC. A more pronounced flexural angle is noted in the DMC, which justifies the preferential direction of the escarpment retreating southwest in the northern sector of the glint, while the escarpments of the DCC retreat westward in the southern sector (Figure 13). This flexural behavior, along with the presence of lateritic covers, contributes to justifying the greater preservation of elevated sectors of the reverse over the DMC, with a preserved plateau reaching widths of up to 30 km in the east-west direction, featuring elevated flat surfaces with slopes < 5º. South of the TL, the structural reverse is dissected by the consequent drainage network, without the preservation of extensive plateaus as observed above the TL.

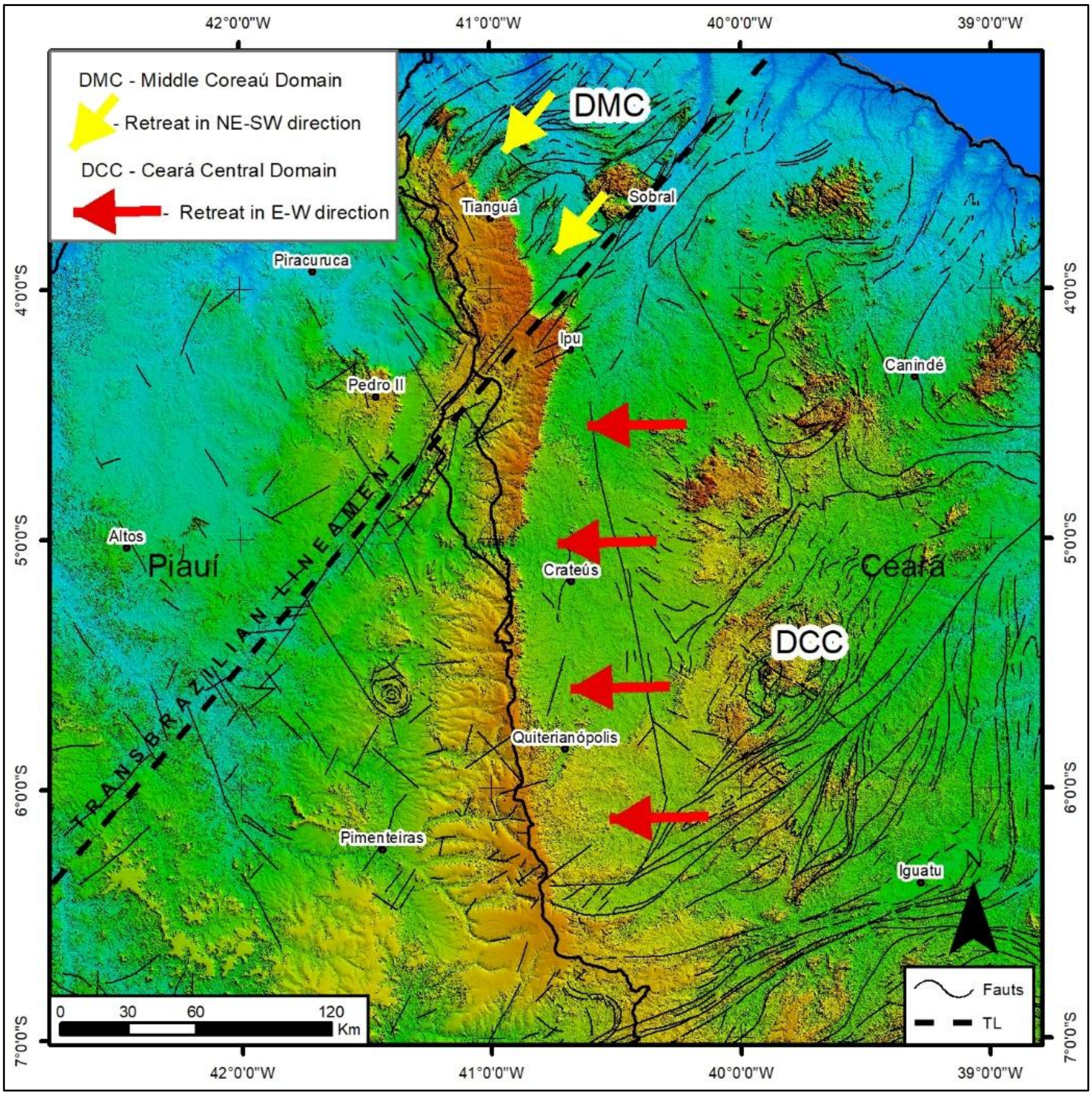

Figure 13. Structural reflections in the behavior of the glint escarpment and the reverse of the Ibiapaba Plateau.

The influence of this flexural behavior can also be perceived in the morphology of the monocline depression. To the north of the TL, higher sectors are observed, particularly the Serra dos Matões, where the municipal seat of Pedro II (PI) is located, with altitudes above 700 m. Moreover, the TL also controls the organization of the drainage network, forming the watershed between the Poti sub-basin (to the south) and the Longá sub-basin (to the north) (Figure 4).

The Cretaceous reactivations of the TL produced deformations in the Jaibaras Graben (CLAUDINO SALES; PEULVAST, 2007), which were responsible for maintaining the only record of the Serra Grande Group (Ipu Formation) outside the context of the Ibiapaba Plateau. This record occurs in the surroundings of the city of Santana do Acaraú/CE, located about 65 km from the current escarpment of Ibiapaba (Figure 2 and Profile D – D' in Figure 10). It is noteworthy that this reactivation is also related to the exhumation of the Ipu Formation around the city of Ipu/CE, justifying an extension of the escarpment, similar to a large "promontory" that extends to the city of Pacujá/CE, whose NE-directed ruptile structural deformations of the Ipu Formation conditioned the development of endokarst features in sandstone (CAVALCANTE; BASTOS; CORDEIRO, 2022).

In addition to the structural control of the TL, the tectonic organization of the DMC also influences the behavior of the northern escarpment of Ibiapaba, which can be observed through the erosional reentrances related to the organization of consequent drainages associated with the contacts between the Martinópole and Jaibaras grabens and the Granja and Tucunduba horsts (BELARMINO; BASTOS, 2021).

The behavior of landforms in sedimentary basins depends on factors such as the diversity of layers, the types of contacts (concordant, inclined, or discordant), and the intensity of uplift to which the basin has been subjected (PENTEADO, 1983). In the study area, the most important lithologies in terms of differential erosion within the context of the sedimentary basin are the sandstones and conglomerates of the Serra Grande Group and the sandstones of the Cabeças Formation, which are responsible for the maintenance of escarpments and plateaus.

The Cabeças Formation is a Devonian sedimentary package predominantly composed of medium to coarse-grained sandstones, with thin intercalations of siltstones and shales (VAZ et al., 2007). Lima and Augustin (2010) assert that although the Cabeças Formation is composed of sandstones, it features ferruginous crusts that enhance its resistance to denudational processes, maintaining it as another elevated structural level compared to the outcropping rocks of the Pimenteiras Formation, with predominantly straight slopes.

The evolution of escarpments in sedimentary rocks involves differential weathering among the exposed lithologies, whose most important characteristics are mineralogical composition, porosity, and the presence of discontinuities (DUSZYŃSKI et al., 2019). Thus, in the evolution of the Ibiapaba glint, the siliceous matrix and cement of the sandstones and conglomerates of the Serra Grande Group are much more resistant to weathering than the adjacent basement. The structural discontinuities in the Serra Grande sandstones (stratification and fracturing) condition mass movements; however, they do not compromise the maintenance of the escarpment.

A central issue regarding the evolution of the Ibiapaba escarpment lies in the restricted occurrence of talus deposits, indicating a dissociated evolution from complex systems of gravitational mass movements. Thus, non-catastrophic evolutionary models with retreat of the lower slope (DUSZYŃSKI et al., 2019) seem more appropriate to describe the evolution of the Ibiapaba escarpment, considering the lower resistance of the metamorphic basement compared to the lithologies of the Serra Grande Group.

In sedimentary rocks, larger grain size tends to increase resistance, contrary to what is observed in crystalline rocks (PENTEADO, 1983; BASTOS; CORDEIRO, 2021), and this is very clearly reflected in the study area, where the finer lithologies (siltstones, shales, and fine sandstones) of the Canindé, Balsas, and Mearim Groups constitute vast planation surfaces (monoclinal depression), while the coarse sandstones and conglomerates (Serra Grande Group and Cabeças Formation) support the plateaus.

Sandstones tend to exhibit greater resistance under dry climatic conditions (HUGGET, 2007), and siliceous cementation generally develops a low-density drainage network and rugged topographies, as is the case under analysis. Among the important geomorphological properties of these rocks are cementation, jointing, sedimentary layering, and permeability (CHORLEY et al., 1984).

The inclination of the sedimentary layers constitutes another important element in the behavior of the escarpment. Horizontal structures with layers of different resistances, such as in the case of the Araripe Plateau (southern Ceará), promote intense gravitational evolution with large erosive amphitheaters, while the monoclinal behavior of Ibiapaba inhibits this retreat (PEULVAST; VANNEY, 2001), justifying smaller amphitheaters, even with the lithological variety of the underlying basement observed in the area under analysis.

The morphological behavior related to the lithologies of the basement at the base of the glint can be observed in the profiles shown in Figure 10. Generally, the more fragile metamorphic basement (Canindé Group of Ceará) tends to form ramps with gentle profiles, while more resistant lithologies, such as the quartzites of the São Joaquim Formation and the metacalcareous rocks of the Frecheirinha Formation, justify steeper slopes. However, it is worth noting that this morphological behavior is also related to the altimetric difference between the base of the sandstone escarpment and the average elevations of the surrounding sertaneja surface. In this perspective, the greatest amplitudes are found in the northern sectors, while the smallest are in the southern sectors of the glint.

In terms of erosive resistance, lateritic coverings have significant relevance in the morphological context under analysis, supporting small tabular plateaus (mesas) in the summital sectors of Ibiapaba, on the sertaneja surface (Figure 15), and in the monoclinal depression. Lateritic crusts (duricrusts) form in hot and humid tropical contexts, serving as good paleoclimatic indicators (TARDY; ROQUIM, 1998) that, in the context of the study area, likely formed in the Paleogene (Eocene/Oligocene) (PEULVAST; BÉTARD, 2015), and were later fragmented by erosive actions in drier climates after the Miocene (CORDEIRO; BASTOS; MAIA, 2018).

Figure 14. Lateritic mesas (700 m) situated on the sertaneja surfaces in the municipality of Aiuaba/CE. Source: authors' collection (2022).

Within the sertaneja surfaces, geomorphological properties such as mass, solubility, plasticity, heterogeneity, and grain size (PENTEADO, 1983; BASTOS; CORDEIRO, 2021) are fundamental for explaining the maintenance of elevated topographies due to differential erosion in granites, quartzites, and orthogneisses.

An important geomorphological problem in this region lies in the evolutionary interpretation of the river Poti's fluvial superimposition. Morphostructural analyses and morphostratigraphic interpretations by Peulvast et al. (2008) suggest a superimposition by antecedence, where the course of the Poti River to the west has remained since the uplift during the post-rift phase (Albiano-Turoniano). However, interpretations based on morphometric analyses indicate recent fluvial capture (Neogene-Quaternary) developed in a sandy karst environment (RODRIGUES et al., 2024). This work does not aim to address the origin of this superimposition; however, there is undeniable evidence of greater denudational action on the side of the sedimentary basin, which can be explained by both the tender behavior of the fine sedimentary lithologies (Balsas and Mearim Groups) and the tectonic reflections of the uplifts of the DCC and DMC.

6. Final Considerations

The study of pre-Silurian surfaces in marginal sectors of Paleozoic basins requires regional interpretations that help to understand the geomorphological context more broadly, similar to other interpretations in Phanerozoic basins like that of Paraná (AB'SÁBER; BIGARELLA, 1961).

This work presents a general description of the lithostructural controls in the relief configuration at the eastern limit of the Parnaíba basin (Planalto da Ibiapaba and surroundings), which is a fundamental approach to understanding regional geomorphological compartmentalization as well as its morphostratigraphic context. Thus, it is important to highlight that analyzing morphological diversity at medium or micro scale is not the object of this work.

The results presented were generated from morphological and lithostructural interpretations based on literature review and the use of GIS tools; however, some hypotheses raised about trends in regional geomorphological evolution require specific studies capable of confirming or refuting such interpretations. In this perspective, the use of geochronological methods becomes fundamental, such as analyzing denudation rates based on the production of cosmogenic nuclides, dating sedimentary deposits through optically stimulated luminescence, in addition to applying specific morphometric studies in watersheds using GIS.

The interpretation of the geomorphological evolution of the Planalto da Ibiapaba is also of fundamental relevance for studies in other areas of natural sciences, such as biogeography/ecology, as it is an important ecological transition area between regional phytogeographic units (AB'SÁBER, 1981) (Caatinga, Amazon, and Cerrado), thus contributing to paleoecological interpretations.

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References

1. AB`SÁBER, A. N. Regiões de circundenudação pós-cretácea no Planalto Brasileiro. **Boletim Paulista de Geografia**, v. 1, p. 1-21, 1949.
2. AB'SÁBER, A. N. Participação das superfícies aplainadas nas paisagens do Nordeste brasileiro. **Geomorfologia**, v. 19, p. 1-38, 1969.
3. AB'SÁBER, A. N. Potencialidades paisagísticas brasileiras. In: **Recursos Naturais, Meio Ambiente e Poluição**: contribuição de um ciclo de debates. Rio de Janeiro: FIBGE/SUPREN, 1977. p. 19-38.
4. AB'SÁBER, A. N. **Domínios morfoclimáticos atuais e quaternários na região do Cerrado**. São José do Rio Preto: Craton & Intracraton, 1981. p. 1-37.
5. AB`SÁBER, A. N.; BIGARELLA, J. J. Superfícies aplainadas do primeiro planalto do Paraná. **Boletim Paranaense de Geografia**, Curitiba, n. 4-5, p. 116-125, 1961.
6. ALMEIDA, F. F. M.; CARNEIRO, C. D. R.; MACHADO JÚNIOR, D. L.; DEHIRA, L. K. Magmatismo pós-Paleozoico no Nordeste Oriental do Brasil. **Revista Brasileira de Geociências**, v. 18, n. 4, p. 451-462, 1988.
7. ALMEIDA, F. F. M.; HASUI, Y.; BRITO NEVES, B. B.; FUCK, R. A. Brazilian structural provinces: an introduction. **Earth-Science Reviews**, v. 17, n. 1-2, p. 1-29, 1981. DOI. 10.1016/0012-8252(81)90003-9.
8. ANGELIM, L. A. A.; VASCONCELOS, A. M.; GOMES, I. P.; SANTOS, E. J. Geotectônica do Escudo Atlântico: Província Borborema. In: BIZZI, L. A.; SCHOBBENHAUS, C.; VIDOTTI, R. M.; GONÇALVES, J. H. (Ed.). **Geologia, tectônica e recursos minerais do Brasil**: textos, mapas and SIG. Brasília: SGB, 2003. p. 264-281.
9. BASTOS, F. H.; CORDEIRO, A. M. N. Propriedades geomorfológicas das rochas e suas repercussões no relevo do nordeste setentrional do Brasil. **Revista William Morris Davis**, v. 2, n.1, p. 1-33, 2021. DOI: 10.48025/ISSN2675-6900.v2n1.2021.135.
10. BATISTA, Z. V.; VIANA, M. S. S.; BARROSO, F. R. G.; AGOSTINHO, S. M. O.; LIMA FILHO, M. F. Petrografia e Diagênese dos Arenitos Fossilíferos e Conglomerados Basais da Formação Ipu, no Noroeste do Ceará. **Revista de Geologia**/UFC, v. 33, n 1, p. 7 – 27, 2020.
11. BELARMINO, Y. S.; BASTOS, F. H. Análise morfoestrutural e aplicação do Índice Declividade Extensão (RDE) na bacia hidrográfica do rio Ubatuba, divisa CE/PI, Nordeste do Brasil. **Revista Brasileira de Geomorfologia**, v. 22, n. 2, p. 441-462, 2021. DOI: 10.20502/rbg.v22i2.1974
12. BRITO NEVES, B. B.; FUCK, R. A.; CORDANI, U. G.; THOMAZ-FILHO, A. Influence of basement structures on the evolution of the major sedimentar basins of Brazil: a case of tectonic heritage. **Journal of Geodynamics**, v. 1, p. 495-510, 1984. DOI. 10.1016/0264-3707(84)90021-8.
13. BRITO NEVES, B. B.; FUCK, R. A. 2014. The basement of South American Platform: half Gondwana + half Laurentia. **Precambrian Research**, 244:75-86. DOI. 10.1016/j.precamres.2013.09.020.

14. CACAMA, M. S. J. B. **Assinatura estrutural e geofísica da porção Norte (fronteira Ceará-Piauí) do Lineamento Transbrasiliano: reativação na Bacia do Parnaíba**. Dissertação (Mestrado em Geodinâmica e Geofísica) - Centro de Ciências Exatas e da Terra, Universidade Federal do Rio Grande do Norte, Natal. 2015. 92p.
15. CAPUTO, M. V.; LIMA, E. C. Estratigrafia, idade e correlação do Grupo Serra Grande - Bacia do Parnaíba. In: XXXIII Congresso Brasileiro de Geologia, 33, 1984, Rio de Janeiro. **Anais...** Rio de Janeiro, 1984.
16. CASTRO, L. C.; BEZERRA, F. H.; FUCK, R. A.; VIDOTTI, R. M. Geophysical evidence of pre-sag rifting and post-rifting fault reactivation in the Parnaíba basin, Brazil. **Solid Earth**, v. 7, p. 529-548, 2016. DOI. 10.5194/se-7-529-2016.
17. CAVALCANTE, J. C.; VASCONCELOS, A. M.; MEDEIROS, M. F.; PAIVA, I. P.; GOMES, F. E. M.; CAVALCANTE, S. N.; CAVALCANTE, J. E.; MELO, A. C. R.; DUARTE NETO, V. C.; BENEVIDES, H. C. **Mapa geológico do estado do Ceará**. Fortaleza: CPRM, 2003. Escala 1:500.000.
18. CAVALCANTE; D. R.; BASTOS, F. H.; CORDEIRO, A. M. N. Elementos para Geoconservação do Patrimônio Espeleológico do município de Pacujá, Ceará, Nordeste do Brasil. **Elisée**, Rev. Geo. UEG, v.11, n.1, e111221, 2022.
19. CILF. Conseil International de la Langue Française, Paris (FRA). **Vocabulaire de la geomorphologie**. Paris: Ed Hachette, 1979. 218p.
20. CHORLEY, R. J.; STANLEY, A.; SCHUMM, D.; SUGDEN, E. **Geomorphology**. Methuen & Co. Cambridge University Press, 1984. 608p.
21. CLAUDINO SALES, V.; PEULVAST, J. P. Evolução morfoestrutural do relevo da margem continental do Estado do Ceará, Nordeste do Brasil. **Caminhos de Geografia**, v.7, n. 2, p. 7-21, 2007. DOI. 10.14393/RCG82015469.
22. CLAUDINO SALES, V.; LIMA, E. C.; DINIZ, S. F.; CUNHA, F. S. S. Megageomorfologia do Planalto da Ibiapaba, Estado do Ceará: Uma Introdução. **William Morris Davis**: Revista de Geomorfologia, v. 1, n. 1, p. 186-209, 2020.
23. CORDEIRO, A. M. N.; BASTOS, F. H.; MAIA, R. P. Formações concrecionárias e aspectos genéticos e evolutivos do maciço do Quincuncá, Província Borborema, Nordeste do Brasil. **Revista Brasileira de Geomorfologia**, v.19, n.2, p. 359-372, 2018. DOI. 10.20502/rbg.v19i2.1330.
24. COSTA, M. J.; FRANÇA, J. B.; LINS, C. A. C.; BACCHIEGGA, I. F.; HABEKOST, C. R.; CRUZ, W. B. **Geologia da Bacia Jaibaras: Ceará Piauí e Maranhão**. Projeto Jaibaras. Ministério das Minas e Energia (MME)/Departamento Nacional da Produção Mineral. Brasília: (DNPM), 1979.
25. CPRM. Serviço Geológico do Brasil. **Carta Geológica do Brasil ao Milionésimo: Fortaleza: folha SA.24**. Escala 1:1.000.000. Programa Geologia do Brasil. Brasília: CPRM, 2004.
26. CPRM. Serviço Geológico do Brasil. **Mapa Geológico do Estado do Piauí**. Escala 1:1.000.000, Piauí. CPRM, 2006.
27. CPRM. Serviço Geológico do Brasil. **Mapa Geológico – Folha Crateús (SB.24-V.C-III)**. Escala 1:100.000, Ceará. CPRM, 2011.
28. CPRM. Serviço Geológico do Brasil. **Mapa Geológico – Folha Fronteiras (SB.24-Y.C-III)**. Escala 1:100.000, Ceará. CPRM, 2013.
29. CPRM. Serviço Geológico do Brasil. **Mapa Geológico – Folha Ipueiras (SB.24-V.A-VI)**. Escala 1:100.000, Ceará. CPRM, 2013.
30. CPRM. Serviço Geológico do Brasil. **Mapa Geológico – Folha Frecheirinha (SA.24-Y-C-IV)**. Escala 1:100.000, Ceará. CPRM, 2014.
31. CPRM. Serviço Geológico do Brasil. **Mapa Geológico – Folha Ipu (SB.24-V.A-III)**. Escala 1:100.000, Ceará. CPRM, 2015.
32. CPRM. Serviço Geológico do Brasil. **Mapa Geológico do Estado do Ceará**. Escala 1:500.000, Ceará. CPRM, 2020.
33. CRUZ, E. M. A.; CÓRDOBA, V. C.; SOUSA, D. C. Análise estratigráfica da sequência siluriana da bacia do Parnaíba, Nordeste do Brasil. **Revista de Geociências**, v. 38, n. 1, p. 33-49, 2019. DOI. 10.5016/geociencias.v38i1.12473.
34. DALY, M. C.; FUCK, R. A.; JULIÀ, J.; MACDONALD, D. I. M.; WATTS, A. B. (Ed.). **Cratonic Basin Formation: a case Study of the Parnaíba Basin of Brazil**. London: Geological Society, 2018. 472p. DOI. https://doi.org/10.1144/SP472.20.
35. DANNI, J. C. M. Geologia da porção sul do Grupo Jaibaras - Ceará. **Revista Brasileira de Geociências**, v. 2, n. 2, p. 85-97, 1972.
36. DUSZYŃSKI, F.; MIGOŃ, P.; STRZELECKI, M. C. Escarpment retreat in sedimentary tablelands and cuesta landscapes–Landforms, mechanisms and patterns. **Earth-Science Reviews**. 196. 2019. DOI: 10.1016/j.earscirev.2019.102890.
37. EMBRAPA. Empresa Brasileira de Pesquisas Agropecuárias. **Sistema brasileiro de classificação de solos**. 5ª Ed. Brasília: Embrapa, 2018. 356p.
38. FERRAZ, N. C.; CÓRDOBA, V. C.; SOUSA, D. C. Análise estratigráfica da sequência Mesodevoniana-Eocarbonífera da bacia do Parnaíba, Nordeste do Brasil. **Geociências**, v. 36, n. 1, p. 154-172, 2017. DOI. 10.5016/geociencias.v36i1.12302.
39. FOUCAULT, A.; RAOULT, J-F. **Dicctionaire de Géologie**. 7ª Ed. Paris: Dunod, 2010.
40. GERRARD, A. J. **Rocks and Landforms**. London: Unwin Hyman, 1988. 319p.
41. GÓES, A. M. O; FEIJÓ, F. J. Bacia do Parnaíba. **Boletim de Geociências da PETROBRÁS**, v. 8, p. 57-67, 1994.

42. GROHMANN, C. H.; CAMPANHA, G. A. da C.; SOARES JÚNIOR, A. OpenStereo: um programa Livre e multiplataforma para análise de dados estruturais. *In:* SIMPÓSIO NACIONAL DE ESTUDOS TECTÔNICOS, 13.; INTERNATIONAL SYMPOSIUM ON TECTONICS, 7., 2011, Campinas. **Anais...** São Paulo: Tec Art Editora, 2011. p. 24-26.
43. HARRIS S. E.; MIX A. C. Climate and tectonic influences on continental erosion of tropical South America, 0-13 Ma. **Geology**, v. 30, n. 5, p. 447-450, 2002. DOI. 10.1130/0091-7613(2002)030<0447:CATIOC>2.0.CO;2.
44. HAWKER, L.; UHE, P.; PAULO, L.; SOSA, J.; SAVAGE, J.; SAMPSON, C.; NEAL, J. **A 30 m global map of elevation with forests and buildings removed**. Environmental Research, Lett. 17, 2022. DOI: 10.1088/1748-9326/ac4d4f.
45. HUGGETT, R. J. **Fundamentals of Geomorphology**. 2ª Ed. Londres: Taylor and Francis, 2007. 458p.
46. LIMA, m. I. M.; AUGUSTIN, C. O relevo do espaço piauiense: aspectos de sua estrutura e evolução. In: VIII Simpósio Brasileiro de Geomorfologia, 8, 2010, Recife. **Anais...** Recife, 2010. 16p.
47. MAIA, R. P.; BEZERRA, F. H. R. Condicionamento estrutural do relevo no Nordeste setentrional brasileiro. **Mercator**, v.13, n.1, p. 127-141, 2014. DOI. 10.4215/RM0000.0000.0000.
48. MARTINS, J. A.; CASTELO BRANCO, R. M. G.; CASTRO, N. A.; PEULVAST, J. P. LIMA JÚNIOR, S. B. Morphological analysis of the São Miguel do Tapuio circular structure, Piauí - Brazil. **Revista Brasileira de Geomorfologia**, v. 17, n. 4, p.763-781, 2016. DOI. 10.20502/rbg.v17i4.703.
49. MIGOŃ, P.; DUSZYŃSKI, F., GOUDIE. A. Rock cities and ruiniform relief: Forms—processes— terminology. **Earth-Science Reviews**. 171: 78–104. 2017. DOI. 10.1016/j.earscirev.2017.05.012.
50. MIGOŃ, P. Sandstone geomorphology – Recent advances. **Geomorphology**. 373. 2021. DOI: 10.1016/j.geomorph.2020.107484.
51. MILANI, E. J.; ZALÁN, P. V. An Outline of the geology and petroleum systems of the Paleozoic interior basins of South America. **Episodes**, v. 22, n. 3, p. 199- 205, 1999. DOI. 10.18814/epiiugs/1999/v22i3/007.
52. MOURA FÉ, M. M. **Evolução Geomorfológica da Ibiapaba Setentrional, Ceará: gênese, modelagem e conservação**. Tese (Doutorado em Geografia) - Programa de Pós-Graduação em Geografia, Universidade Federal do Ceará, Fortaleza. 2015. 309p.
53. PECH, P. **Géomorphologie structurale. Synthèse**. Paris: Ed. Armand Colin, 2005. 95p.
54. PENTEADO, M. M. **Fundamentos de geomorfologia**. 3. ed. Rio de Janeiro: IBGE, 1983. 186p.
55. PEULVAST, J-P; CLAUDINO SALES, V. Stepped surfaces and paleolandforms in the northern Brazilian "Nordeste": constraints on models of morphotectonic evolution. **Geomorphology**, v. 62, n. 1-2, p. 89-122, 2004. DOI: 10.1016/j.geomorph.2004.02.006.
56. PEULVAST, J. P.; CLAUDINO SALES, V.; BÉTARD, F. Morphologie des escarpements et des piémonts sur la marge passive équatoriale du "Nordeste" brésilien: évolution du Néogène à l'Actuel et ses facteurs. In: **Bulletin de l'Association de géographes français**. Paraglaciaire et changements climatiques, 2008. p. 226-236. DOI. 10.3406/bagf.2008.2617.
57. PEULVAST, J-P.; CLAUDINO SALES, V.; BÉTARD, F.; GUNNELL, Y. Low post-Cenomanian denudation depths across the Brazilian Northeast: implications for long-term landscape Evolution at a transform continental margin. **Global and Planetary Change**, v. 62, p. 39-60, 2008. DOI: 10.1016/j.gloplacha.2007.11.005.
58. PEULVAST, J. P.; BÉTARD, F. **Landforms and Landscape Evolution of the Equatorial Margin of Northeast Brazil**. Springer Earth System Sciences, 182p, 2015. DOI 10.1007/978-3-319-18203-2_1.
59. PEULVAST, J-P.; BÉTARD, F. Morphostratigraphic constraints and low temperature thermochronology: lessons from a review of recente geological and geomorphological studies in northeast Brazil. **Journal of South American Earth Sciences**, 2021. DOI. 10.1016/j.jsames.2021.103464
60. PEULVAST, J. P.; VANNEY, J.R. **Géomorphologie structurale (Terre, corps planétaires solides)**. v. 1. Paris: Relief et structure. Gordon & Breach (Paris) and BRGM (Orléans), 2001. 505p.
61. PINÉO, T. R. G.; LIMA, A. F.; MARTINS, M. D; BESSA, M. D. M. R. Projeto ARIM Noroeste do Ceará. Mapa Geológico Geofísico de Chaval**. Folha SA.24-Y-C-II**. Escala 1:100.00. Fortaleza: SGB/CPRM, 2018.
62. QGIS TEAM, Q. D. **QGIS Geographic Information System**: Free Software Foundation. 2015. Disponível em: https://www.qgis.org/pt_BR/site/forusers/download>. Acesso em: 28/04/2023.
63. QUEIROZ, G. L.; SALAMUNI, E.; NASCIMENTO, E. R. AzimuthFinder: ferramenta para a extração de dados e apoio na análise estrutural. **Geologia USP**, Série Científica, São Paulo, v. 14, n. 1, p. 69-80, 2014. DOI: 10.5327/Z1519-87X201400010005
64. RODRIGUES, W. F.; MAIA, R. P.; SILVA, H. V. M.; SALGADO, A. A. R. Subterranean river captures in siliciclastic rocks in a semiarid climate: the case of the Poti River Canyon, Brazilian Northeast. **Revista Brasileira de Geomorfologia**, *25*(2), 2024. DOI: 10.20502/rbgeomorfologia.v25i2.2446.
65. RODRIGUEZ TRIBALDOS, V. **Epeirogeny of South America and Evolution of Parnaíba Basin, Northeast Brazil**. Tese. University of Cambridge, Downing College, 2017.

66. SAADI, A.; TORQUATO, J. R. Contribuição à Neotectônica do Estado do Ceará. **Revista de Geologia**, n. 5, p. 5-38. 1992.
67. SANTOS, T. J. S.; FETTER, A. H.; HACKSPACHER, P. C.; VAN SCHMUS, W. R.; NOGUEIRA NETO, J. A. Neoproterozoic tectonic and magmatic episodes in the NW sector of Borborema Province, NE Brazil, during assembley of Western Gondwana. **Journal of South American Earth Sciencs**, v. 25, p. 271-284, 2008. DOI: 10.1016/j.jsames.2007.05.006.
68. SANTOS, F. L. A. **Evolução morfoestrutural do Planalto da Ibiapaba (CE/PI) e Noroeste do Ceará, Brasil: interpretações a partir da termocronologia de baixa temperatura**. Tese (Doutorado em Geografia) - Programa de Pós-Graduação em Geografia, Universidade Federal do Ceará, Fortaleza. 2022. 274p.
69. SILVA, A. J. P.; LOPES, R. C.; VASCONCELOS, A. M.; BAHIA, R. B. C. Bacias Sedimentares Paleozoicas e Meso-Cenozoicas Interiores. In: BIZZI, L. A.; SCHOBBENHAUS, C.; VIDOTTI, R. M.; GONÇALVES, J. H. **Geologia, tectônica e recursos minerais do Brasil**. Brasília: CPRM, 2003.
70. SCHOBBENHAUS, C.; RIBEIRO, C. L.; OLIVA, L. A.; TAKANOHASHI, J. T.; LINDENMAYER, Z. G.; VASCONCELOS, J. B.; ORLANDI, V. Texto Explicativo. Folha Goiás SD.22. In: Schobbenhaus C. (Coord.). **Carta Geológica do Brasil Milionésimo**. Brasília: DNPM, 1975. 113p.
71. SOUZA, M. J. N. Contribuição ao estudo das unidades morfoestruturais do Estado do Ceará. **Revista de Geologia da UFC**, p. 73-91, 1988.
72. SOUZA, M. J. N. Bases Naturais e Esboço do Zoneamento Geoambiental do Estado do Ceará. In: LIMA, L. C., SOUZA, M. J. N., MORAES, J. O., **Compartimentação territorial e gestão regional do Ceará**. Fortaleza: FUNECE, 2000. 268p.
73. STRAHLER, A. N. Hypsometric (area-altitude) analysis of erosional topography. **Geological Society America Bulletin**, v. 63: 1117-1142, 1952. DOI: 10.1130/0016-7606(1952)63[1117:HAAOET]2.0.CO;2
74. SZATMARI, P.; FRANÇOLIN, J.B.L.; ZANOTTO, O.; WOLF, S. Evolução Tectônica da margem equatorial brasileira. **Revista Brasileira de Geociências**, v. 17, n. 2, p. 180-188, 1987.
75. TARDY, Y.; ROQUIN, C. **Dérive des continentes. Paléoclimats et altérations tropicales**. Orléans: Editions du BRGM, 1998. 473p.
76. VAZ, P. T.; REZENDE, N. G. A. M.; WANDERLEY FILHO, J. R.; TRAVASSOS, W. A. S. Bacia do Parnaíba. **Boletim de Geociências da Petrobrás**, v. 15, n. 2, p. 253-263, 2007.
77. WANG, X.; AULER, A. S.; EDWARDS, R. L.; CHENG, H.; CRISTALLI, P. S.; SMART, P. L.; RICHARDS, D. A.; SHEN, C. C. Wet periods in northeastern Brazil over the past 210 kyr linked to distant climate anomalies. **Nature**, v. 432, p. 740-743, 2004. DOI: 10.1038/nature03067.
78. WEISS, A. **Topographic position and landforms analysis**. In: Poster presentation, ESRI user conference, San Diego, CA. 2001.
79. WHIPPLE, K. X.; DIBIASE, R. A.; OUIMET, W. B.; FORTE, A. M. Preservation or piracy: Diagnosing low-relief, high-elevation surface formation mechanisms. **Geology**, v. 45, n. 1, p. 91-94, 2017. DOI: 10.1130/G38490.1.