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Artigo de Pesquisa

Genetics and evolutionary aspects of the Apertados Canyons Geosite, in the Seridó UNESCO Global Geopark, NE Brazil

Aspectos genéticos e evolutivos do Geossítio Cânions dos Apertados, no Seridó Geoparque Mundial da UNESCO, NE do Brasil

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Abstract: This paper reports and analyze the transverse drainage process responsible for the sculpting of the Apertados Canyon (Seridó UNESCO Global Geopark), located in the northern portion of the Umburanas Mountain Range, in Northeastern Brazil. Morphological and lithostructural evidence of superimposition was obtained through remote sensing (e.g., extraction of structural lineaments, drainage network, slope) and field work. Remnants of an agradational paleosurface were observed in the Picuí River basin area; the presence of other transverse drainages (water gaps) cutting the same topographic barrier; and orthogonal inflections of river courses. This evidence allowed us to deduce that the superimposition drainage mechanism was responsible for the formation of the Cânion dos Apertados. This mechanism was influenced by changes in regional base level, climatic oscillations and tectonic reactivations, observed from the Middle Miocene onwards, resulting from W-E and NW-SE compressive efforts, along the deformation structures.

Keywords: Topographic barrier; Transverse drainage; Rocky gap; Picuí River; Superimposition.

Resumo: Este trabalho analisa o processo de drenagem transversal responsável pela esculturação dos Cânions dos Apertados, localizado na porção setentrional da Serra das Umburanas, no Nordeste do Brasil. As evidências morfológicas e litoestruturais de superimposição foram obtidas por meio de sensoriamento remoto (e.g., extração de lineamentos estruturais, rede de drenagem, declividade) e trabalhos de campo. Observou-se, na área da bacia hidrográfica do rio Picuí, remanescentes de uma paleosuperfície agradacional; presença de outras drenagens transversais (*water gaps*) seccionando a mesma barreira topográfica; e inflexões ortogonais de cursos fluviais. Essas evidências permitiram deduzir que o mecanismo de superimposição de drenagem foi responsável pela Formação dos Cânions dos Apertados. Esse mecanismo foi influenciado por mudança do nível de base regional, oscilações climáticas e reativações tectônicas, verificadas a partir do Mioceno Médio, resultantes de esforços compressivos W-E e NW-SE, ao longo das estruturas de deformação.

Palavras-chave: Barreira topográfica; Drenagem transversal; Garganta rochosa; Rio Picuí; Superimposição.

1. Introduction

Transverse drainages (e.g., antecedent, superimposed) (Stoker; Mather, 2003; Douglass; Schmeeckleb, 2007; Douglass et al., 2009), which are discordant with the regional lithostructural fabric, occur throughout the northern portion of the Borborema Geological Province (PGB), showing, over time, considerable influence on the shaping of the relief and the organization of the regional hydrographic network (Peulvast; Claudino-Sales, 2004; Peulvast; Bétard, 2015; Maia; Bezerra, 2019; Corrêa et al., 2019).

Drainage superimposition is the most widely reported process of fluvial rearrangement in fluvial geomorphology (Douglass; Schmeeckleb, 2007; Douglass et al., 2009; Larson et al., 2017), involving the exhumation of more resistant underlying geological substrate (Summerfield, 1991; Holbrook; Schumm, 1999; Twidale, 2004; Bordal, 2014), which will form topographic highs (e.g., residual ridges). The vertical advancement of incision through these highs creates transverse valleys, which are generally perpendicular to the regional lithostructural trend (Douglass; Schmeeckle, 2007; Hilgendorf et al., 2020), through canyons or epigenetic water gaps (Thompson, 1939).

Frequently developed during or after a period of tectonic activity (Douglass et al., 2009), transverse drainages and the morphogenetic mechanisms responsible for their development (e.g., differential uplift, base-level lowering, climatic oscillations) have been discussed in geomorphological literature since the 19th century (Gilbert, 1877; Dutton, 1882; Davis, 1889; Powell, 1895; Lane, 1899; Johnson, 1931; Meyerhoff; Olmstead, 1934, 1936; Oberlander, 1965; Mckee et al., 1967; Clark, 1989; Lee, 2013; Whipple et al., 2017; Rodrigues; Salgado; Maia, 2022).

Within the context of the Borborema Geological Province (PGB), epigenetic processes through the mechanisms of antecedence and superimposition have been little discussed in the geomorphological evolution models proposed for the region (Ab’sáber, 1969; Andrade; Lins, 1965; Mabesoone; Castro, 1975; Peulvast; Claudino-Sales, 2004, 2006; Maia; Bezerra, 2014).

In the northern portion of the PGB, specifically in the eastern sector of the Rio Piranhas-Seridó Domain (DRPS) (Nascimento; Medeiros; Galindo, 2015), river channels, such as the Seridó, Carnaúba, and Picuí rivers (Figure 1), descending from the western slopes of the Borborema Plateau, section quartzitic residual ridges with a preferential NNE-SSW orientation. These aligned and discontinuous ridges form epigenetic canyons and gorges, known as transverse valleys (Stokes; Mather, 2003; Douglas et al., 2009; Becerril; Heydt; Durán, 2010; Larson et al., 2017). A striking example is the Cânions dos Apertados, whose uniqueness justifies its designation as a Geosite of the Seridó UNESCO Global Geopark (Nascimento et al., 2021).

Given the above, the present research analyzes the genesis and evolution of the Cânions dos Apertados, which are developed in quartzites of the Equador Formation, an Ediacaran unit of the Seridó Group (Van Schmus et al., 2003; Cabral Neto et al., 2018). The analyses were based on (neo)tectonic and lithostructural controls and on Cenozoic climatic oscillations, referring to fluctuations in the degree of aridity, which together enhanced the incisive power of the fluvial systems in the study area.

2. Study Area

The Cânions dos Apertados Geosite (GCA), part of the Seridó UNESCO Global Geopark, is located in the northern portion of the Serra das Umburanas, near the western slopes of the Borborema Plateau, at geographical coordinates 6°20'31''S and 36°30'07''W (Figure 1). This geosite is a geomorphological feature carved into quartzites of the Equador Formation (Seridó Group), which are flanked by micaschists of the Seridó Formation. Both formations overlie paragneisses of the Jucurutu Formation (Medeiros et al., 2012) and are partially covered by laterized sandstones of the Serra dos Martins Formation (FSM) (Cabral Neto et al., 2018). The quartzites are highly fractured, sometimes with quartz exudates and intruded by pegmatite dikes of various sizes (Medeiros et al., 2021).

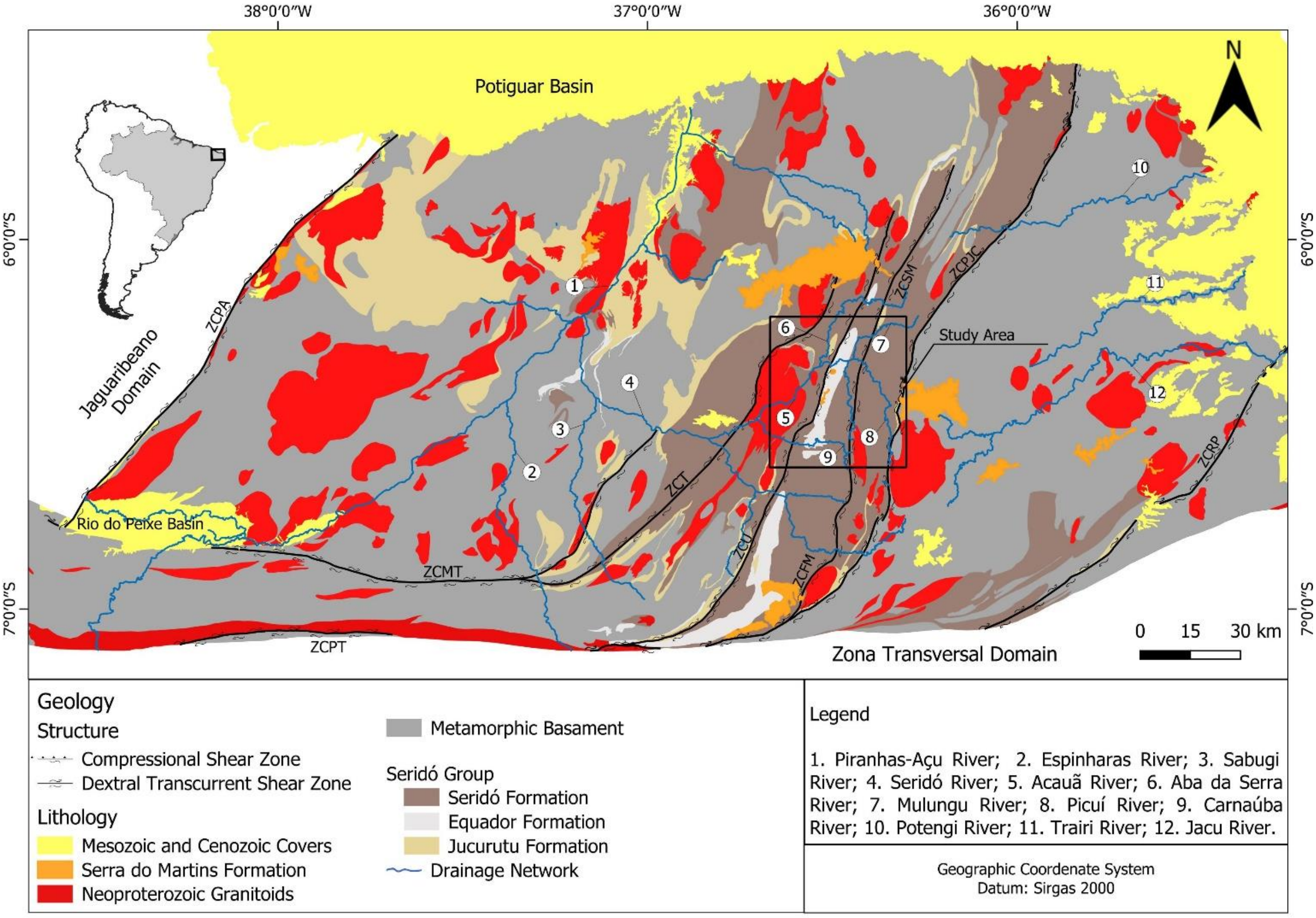


Figure 1. Simplified geological framework of the Rio Piranhas-Seridó and São José do Campestre domains, in the NE portion of the northern PGB, and the location of the study area and surroundings. Source: Prepared by the authors (2025), based on Medeiros et al. (2012); Nascimento, Medeiros, and Galindo (2015); Cabral Neto et al. (2018); and Dantas, Medeiros, and Cavalcanti (2021). Legend: ZC: Shear Zone; ZCPT: Patos; ZCMT: Malta; ZCPA: Portalegre; ZCRP: Remígio Pocinhos; ZCT; Totoró; ZCU: Umburana; ZCFM: Frei Martinho; ZCSM: Santa Mônica; ZCPJC: Picuí João Câmara.

The quartzites of the Equador Formation are mineralogically composed of quartz (85%), muscovite (15%), black tourmaline, and traces of opaque minerals (iron oxide), as well as plagioclase and sillimanite (Cavalcanti Neto, 2008). These are associated with the terrigenous fraction of a shallow intracontinental rift marine environment (Jardim de Sá, 1994; Caby et al., 1995), where progressive crustal extension and thinning resulted in the deepening of a small oceanic basin (the Seridó Basin) (Nascimento, 2002; Padilha et al., 2021). The resulting sedimentary succession (Seridó Group) was compressed and metamorphosed (transpressive deformation) during the Brasiliano Cycle (Archanjo et al., 2013; Hollanda et al., 2015). According to Van Schmus et al. (2003), the Seridó Basin may have originated in a short tectonic cycle of extension and compression between 700 Ma and 600 Ma.

The Serra das Umburanas (a regional antiform) (Cavalcanti Neto, 2008; Medeiros et al., 2017), with an area of approximately 141 km², is a slightly elongated residual relief, with a preferential NNE-SSW direction, conditioned by the ZCU and ZCFM. It has altimetric elevations between 450 and 690 meters (Figure 1; Figure 2).

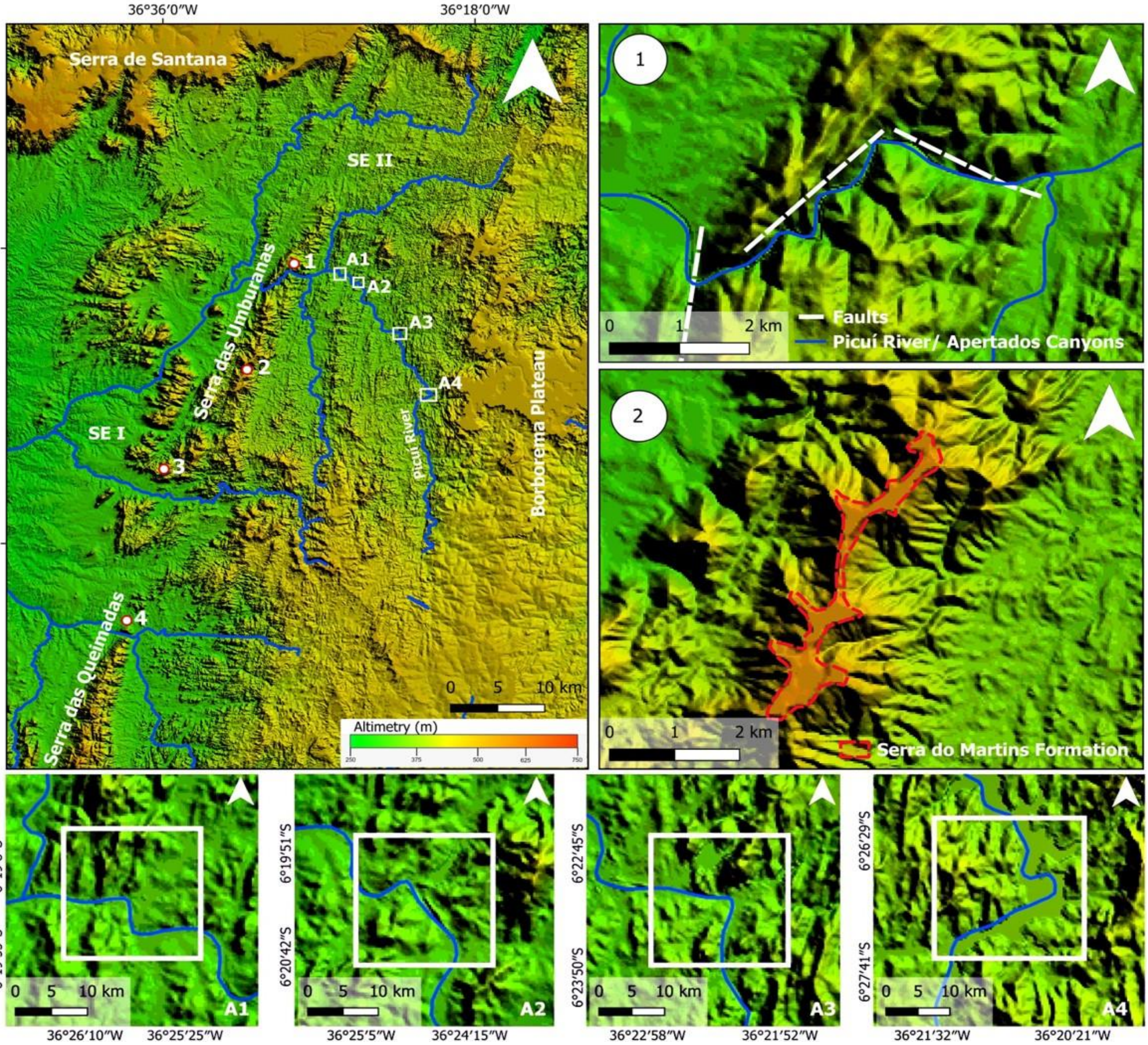


Figure 2. Hypsometry, relief units, and drainage anomalies in the Picuí River channel. Source: Prepared by the authors (2025), based on NASADEM image editing. Legend: SEI and SEII: Erosional Surfaces; 1: Cânions dos Apertados; 2: Laterized sandstone capping (Serra do Martins Formation-FSM); 3. Carnaúba dos Dantas water gap; 4. Parelhas water gap (Boqueirão de Parelhas); A1 to A4: Orthogonal inflections in the Picuí River channel.

From a geomorphological perspective, the Serra das Umburanas is located on the erosional surface of the Sertões do Piranhas (Diniz et al., 2022), where Cenozoic denudation processes, concordant with ductile and brittle deformation structures, led to the progressive lowering of the metamorphic basement, revealing a diverse display of granitic and quartzitic forms, such as massifs, inselbergs, rock pavements (lajedos), and residual ridges.

The climate of the study area is semi-arid, with annual average rainfall between 400 and 500 mm (Jesus; Mattos, 2013; Diniz; Pereira, 2015) and an annual potential evapotranspiration of about 2,200 mm (Jesus; Mattos, 2013). The short rainy season is typically evident in the first four months of the year (Neves et al., 2010), between late summer and mid-autumn, with the wettest quarter from February to April, followed by a dry season that can extend for more than eight months (Diniz; Pereira, 2015).

The main atmospheric system responsible for the region's rainy season is the Intertropical Convergence Zone (ITCZ) (Ferreira; Mello, 2005). Its expressiveness is associated with El Niño events, which favor a reduction in precipitation, and La Niña, which provides periods with positive precipitation anomalies (Rodrigues et al., 2017). Temperatures fluctuate between a minimum of 18°C, an average of 27.5°C, and a maximum of 33°C (Mascarenhas et al., 2005). The drainage network consists of small, ephemeral, and intermittent watercourses that flow into the Picuí River, which in turn is part of the Piranhas-Açu river basin.

In the region, there is a predominance of Chromic Luvisols, Litholic and Regolithic Neosols, and it is also possible to identify associated Yellow Latosols and/or Petric Plinthosols, primarily in areas with sedimentary rocks (Santos et al., 2023; Silva et al., 2024). In the study area, traditional methods of managing and exploiting the Caatinga, combined with the climatic conditions inherent to this biome, are significantly contributing to increased environmental degradation. Human uses, related to the expansion of pastures, suppression of native vegetation, mineral exploration of clay, and rudimentary subsistence farming techniques, can potentiate soil degradation, compromise the quality and quantity of water resources, and reduce biodiversity and the quality of life for the population.

3. Materials and Methods

The method employed involved an extensive specialized bibliographic review on transverse drainage, cartographic surveys, field expeditions, and the acquisition of images with a camera and an unmanned aerial vehicle (UAV), a Mavic 2 Pro model, equipped with a 4K 35 mm camera. The field expeditions aimed to identify, record, and analyze the morphological and geological evidence that proves the development of transverse drainage by the superimposition mechanism. At the same time, the goal was to understand the role of the Picuí River's vertical incision associated with the lithostructural characteristics of the quartzites that support the Serra das Umburanas.

Geological information obtained from the geological and lithium mineral resources map of the Borborema Pegmatite Province, at a 1:250,000 scale (Cabral Neto et al., 2018), and the geological map of the state of Rio Grande do Norte, at a 1:500,000 scale (Dantas; Medeiros; Cavalcante, 2021), was combined with data on changes in the intraplate stress field (Cremonini; Karner, 1995; Assumpção et al., 2016; Bezerra et al., 2020; Oliveira et al., 2023). This was supplemented by information on crustal thickening (magmatic underplating), related to the "Macau Magmatism" thermotectonic event (Werneck; Magini; Salgueiro, 2018; Oliveira; Medeiros, 2012), and oscillations in the degree of aridity observed in the Upper Pleistocene and Middle Holocene (Wang et al., 2004; Zhang et al., 2017; Behling et al., 2000; Fadina et al., 2019; Souza et al., 2023). This data, along with the bibliography related to the role of fluviais systems in the evolution of the geomorphological landscape, supported the analysis of the superimposition process in the study area and the consequent sculpting of the Cânions dos Apertados.

The S07W037 scene from the Forest And Buildings Removed Copernicus DEM (FABDEM) V1-2 model with a spatial resolution of ~30 m (Neal; Hawker, 2023) was used to extract topographic attributes (altimetry and slope). This allowed for the analysis of morphological variations, which were examined in conjunction with lithostructural data to produce geological and slope cartographic products. Next, the drainage network and structural lineaments were extracted from the FABDEM. The drainage network was obtained using QGIS 3.36.0-Maidenhead software (QGIS Association), with a threshold of 1,000 pixels and the Strahler (1952) fluvial hierarchy.

The rose diagram, which shows the directional frequency of the azimuths of the drainage network and lineaments, was created using the AzimuthFinder tool (Queiroz et al., 2015) and scripts in RStudio-2023.12.1-402 (RStudio Team, 2020). It is important to note that first- and second-order rivers have only lithological control and do not align with the regional context. Therefore, the drainage roses were created using third-order and higher rivers, which allowed for a better understanding of the drainage network in line with the geological and topographic characteristics of the study area.

The asymmetry factor (AF) (Hare; Gardner, 1985), which aims to identify the occurrence of tilting due to possible tectonic causes in a hydrographic basin, was obtained by calculating the ratio between the area of the right bank of a basin and its total area (El Hamdouni et al., 2008; Cherem et al., 2020; Oliveira et al., 2023). The AF is defined by the following equation: $FA = 100(Ar/At)$, where Ar is the area corresponding to the right bank of the basin and At is the total area of the basin (Hare; Gardner, 1985).

The geological-topographical profile and the block diagrams, which supported the geomorphological interpretation of the study area and the drainage superposition process, were created using CorelDRAW Graphics Suite (Windows).

4. Results

4.1. The (neo)tectonic and lithostructural control of relief and drainage

The Serra das Umburanas is situated along the Umburana and Frei Martinho shear zones, which influenced the direction of the discontinuity surfaces (e.g., faults, fractures, pegmatite dikes) and the denudation processes. The sectors with the highest fracturing density are located in the surrounding basement, consisting of micaschists from the Seridó Formation, outlining the erosional surfaces (SE I and SE II) (Figure 2), which are peripheral to the residual reliefs. In the case of granitoids and quartzites, despite the incidence of planes of weakness (Figure 3), the lithological resistance to erosion accounts for the topographic highs in the study area, indicating differential erosion controlled by lithostructural features.

The brittle deformation structures with E-W and NW-SE directions (Figure 3), although less prominent, cut through both the surrounding basement and the Serra das Umburanas. They are a significant conditioning factor for the superimposed valleys observed in the eastern portion of the DRPS (Figure 3). Specifically, in the municipality of Currais Novos-RN, the transverse flow of the Picuí River cuts through the Serra das Umburanas antiform in an E-W direction, carving a confined transverse valley approximately 7 km long and 40 m wide. The slopes on both banks have an inclination varying from 35º (eastern sector) to sub-vertical (western sector), with a vertical drop that can reach 110 m, known as the Cânions dos Apertados (Figure 3A and 3B).

The presence of orthogonal inflections in the Picuí River channel (Figure 2) reveals the progressive adaptation of the flow to the NW-SE and W-E geological structures, which diverge from the predominant N-S and NNE-SSW tectonic directions. This structural divergence is related to intraplate stresses, which have been predominantly W-E to NW-SE compressive since the Middle Miocene to the present day (Bezerra et al., 2020). These stresses are associated with the expansion of the mid-Atlantic seafloor (ridge push forces), compression in the Andean Chain

(Cremonini; Karner, 1995; Ferreira et al., 2008; Assumpção et al., 2016), and/or the E-W extensional stress field resulting from the intrusion of the Macau magmatism (Bezerra et al., 2007), represented in the study area by the Saco do Inferninho Plug (Figure 3) (Barros et al., 2021) and an array of basalt dikes arranged in a N-S oriented strip, about 350 km long by 60 km wide (Ngonge et al., 2016; Barros et al., 2021).

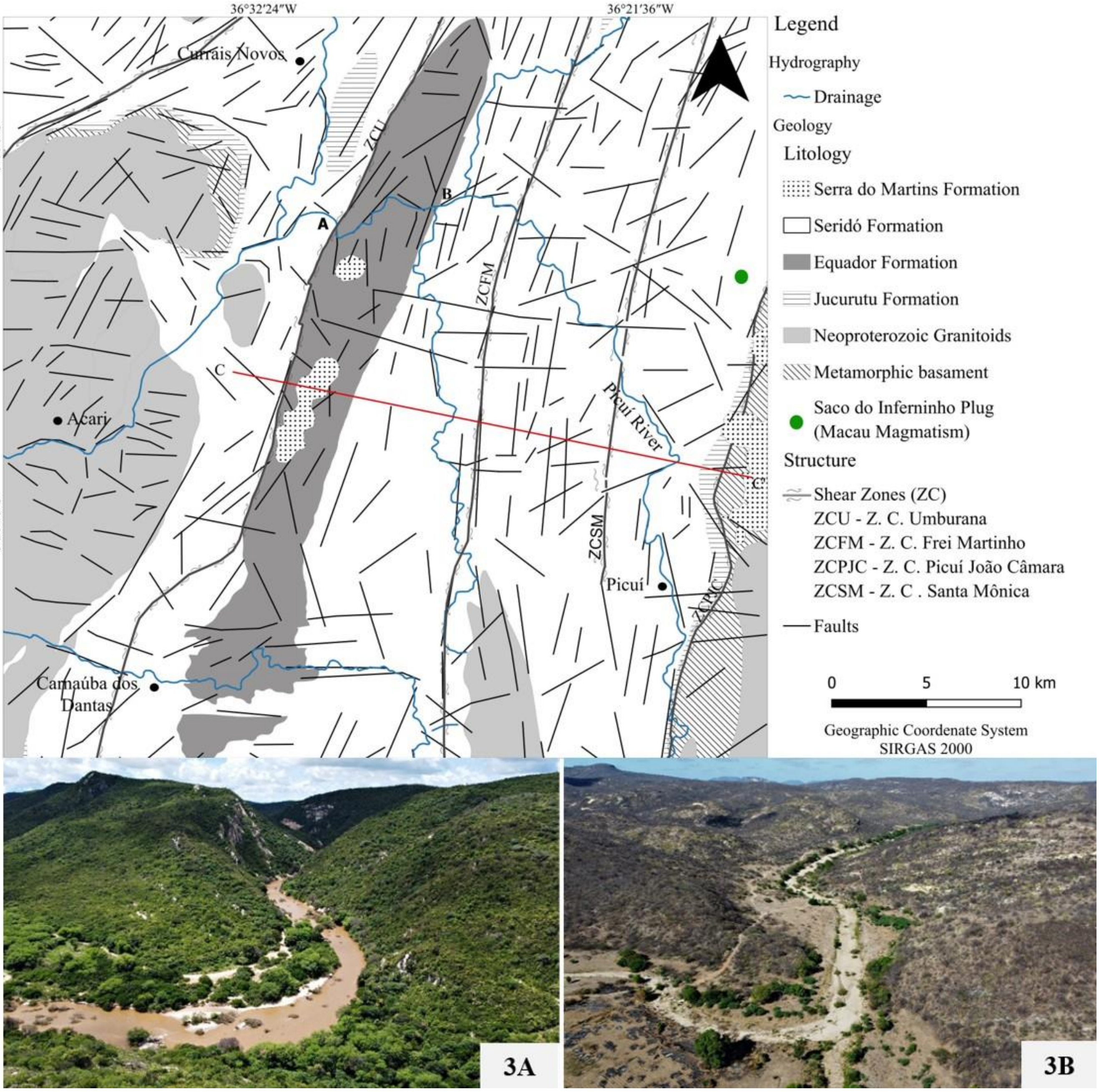


Figure 3. Distribution of ductile and brittle deformation structures in the study area, highlighting the close relationship between the Picuí River drainage and the brittle structures with an E-W direction. Source: Prepared by the authors (2025). Legend: (3A) Frontal view of the western portion of the Cânions dos Apertados; (3B) Start of the transverse incision of the Picuí River in the Serra das Umburanas antiform; (C-C') Red line - geological-topographical profile (Figure 4). Note the contrast in vegetation during the rainy (3A) and dry (3B) seasons.

Tectonic reactivations, which have occurred since the Middle Miocene (Bezerra et al., 2020; Oliveira et al., 2023) and resulted from W-E and NW-SE compressive forces (Cremonini; Karner, 1995; Bezerra; Vita-Finiz, 2000; Assumpção et al., 2016) along deformation structures, along with crustal thickening (magmatic underplating) associated with the "Macau Magmatism" thermotectonic event (Oliveira; Medeiros, 2012), with its main peak between 30-20 Ma (Werneck; Magini; Salgueiro, 2018; Bezerra et al., 2020), may have been the predominant factor in the alteration of the regional base level. This is suggested by the altimetric rejuvenation of the Borborema Plateau, which intensified the degree of vertical incision of the Picuí River drainage network and denudational activity in the study area.

The stepping between the erosional surfaces (SE I [250 to 350 m]; SE II [350 to 500 m]) and the summit surfaces of the Borborema Plateau, with or without a laterized sandstone capping (FSM) (Figure 4), reflects the density of brittle deformation structures, consistent with the resistance of the lithologies that make up the study area. This also shows the influence of compressive uplift processes since the Neogene on the current topographic distribution (Figure 4).

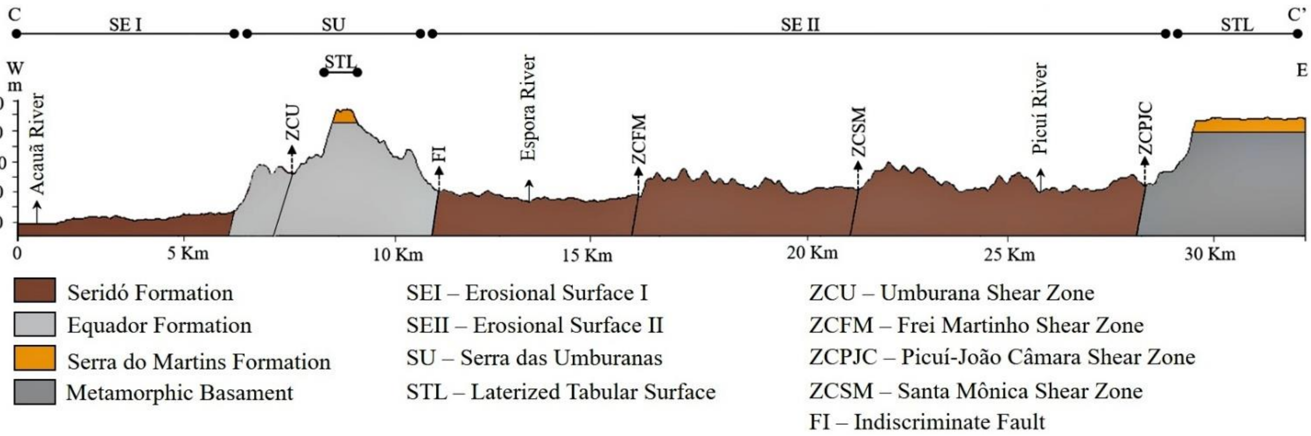
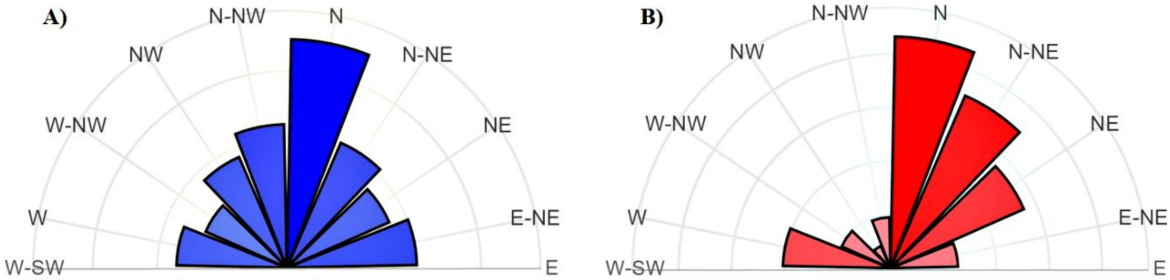


Figure 4. Geological-topographical profile, W-E direction, of the study area. Source: Prepared by the authors (2025), based on Costa et al. (2019). Legend: C – C′ identifies the profile location in Figure 3.

Therefore, the differential uplift of the Borborema Plateau and its immediate surroundings (SE II) could be the result of epeirogenic processes associated with Macau magmatism (Bezerra et al., 2007; Corrêa et al., 2010; Oliveira; Medeiros, 2012), as well as Cenozoic tectonic reactivations (Bezerra et al., 2020; Oliveira et al., 2023), or, more likely, a complex interaction between both mechanisms. These are fundamental for interpreting denudational cycles and the drainage superposition process of the Picuí River.

The lateral tilting of SEII, mainly associated with the brittle deformation structures with orientations varying from W-E, WNW-ESE, and NNW-SSE (Graph 1B), which cut across SEII, justifies the change in orientation of the Picuí River hydrographic basin drainage network (BHRP) (Figure 5). This network was directed to a confluence point on the eastern slope of the Serra das Umburanas, resulting in the carving of a confined and sometimes steep-sided valley, the Cânions dos Apertados. In this regard, Maia (2023) and Bagni et al. (2022) state that fracture trends condition the formation of structural valleys and canyons through the incision of the drainage network and the consequent widening of the plane of weakness (Martins et al., 2009).

Regarding the main channel of the Picuí River, as its course cuts through the Serra das Umburanas, it adapts to the brittle structures that control segments of the transverse valley with orthogonal inflections from W to NE and from NE to NW. Cunha et al. (2005) state that the vertical incision of the Tagus River, perpendicular to the orientation of the quartzitic ridge "Serra das Talhadas" in central Portugal (Vila Velha de Ródão), was enabled by fractures with NE-SW and SSW-NNE directions.



Orientation	Angle	Percentage (%)
N	0º-22.5º	20,34
N-NE	22.5º-45º	12,15
NE	45º-67.5º	10,09
E-NE	67.5º-90º	11,73
W-SW	245.5º-270º	4,20
W	270º-292.5º	9,96
W-NW	292.5º-315º	8,00
NW	315º-337.5º	10,76
N-NW	337.5º-360º	12,77
Total		**100**

Orientation	Angle	Percentage (%)
N	0º-22.5º	26,19
N-NE	22.5º-45º	21,29
NE	45º-67.5º	16,63
E-NE	67.5º-90º	7,71
W-SW	245.5º-270º	1,33
W	270º-292.5º	12,28
W-NW	292.5º-315º	6,12
NW	315º-337.5º	2,75
N-NW	337.5º-360º	5,7
Total		**100**

Graph 1. Rose diagrams of the preferred azimuth directions of the drainage network (A) and structural lineaments (B), extracted from the Picuí River Hydrographic Basin (BHRP). Source: Prepared by the authors (2025).

According to the drainage basin asymmetry factor (AF = 54.75), the BHRP has been or is still subject to tectonic tilting, with a gradual migration of the main channel to the left side, that is, toward the lower-lying portion of SEII (Figure 5).

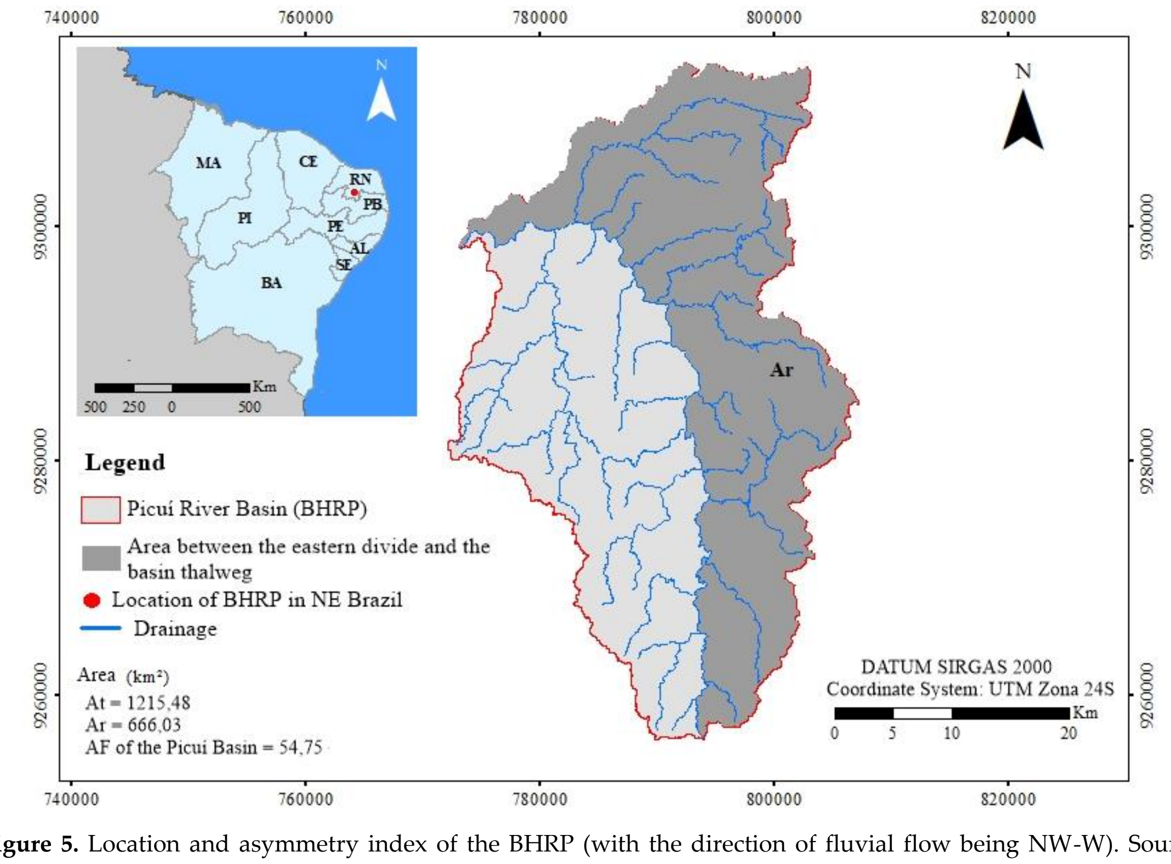


Figure 5. Location and asymmetry index of the BHRP (with the direction of fluvial flow being NW-W). Source: Prepared by the authors (2025). Legend: At (Total basin area); Ar (Area of the right side of the basin: when looking downstream); AF (Basin asymmetry factor).

Asymmetry factor (AF) values greater than 50 (AF=50: tectonic stability; 57≤AF<65: moderately tilted; AF<57: weakly tilted; AF≥65: strongly tilted) indicate tilting and migration of the river channel to the left side (El Hamdouni et al., 2008; Cherem et al., 2020; Oliveira et al., 2023). According to Alexander and Leeder (1987), lower rates of lateral tilting can cause slow migration of the fluvial channel due to preferential erosion of the subsided portion (Holbrook; Schumm, 1999).

4.2 *Paleoclimatic indicators, exhumation, and superimposition*

Preserved but disconnected remnants of an ancient lateritic capping are distributed over the Serra das Umburanas, giving it a tabular appearance in the higher altitude sectors, between elevations of 670 to 690 m (Figure 6). These tabular surfaces are important indicators of the progressive exhumation of the antiform, as well as the consequent process of relief inversion through differential erosion. This is because they correspond to an old depositional base level (depositional paleosurface) (Maia; Bétard; Bezerra, 2016), related to the aggradational systems of the FSM with an estimated age between the Oligocene (25 Ma) (Moraes Neto et al., 2009) and the Miocene (20 Ma) (Lima, 2008).

The exhumation of the Serra das Umburanas, considering the depositional age of the sediments associated with the FSM (25-20 Ma), the 40Ar/39Ar and (U-Th)/He ages obtained for the Mn and Fe oxides/hydroxides that cement the FSM fluvial sandstones (lateritic weathering), ranging from 17 to 13 Ma (Lima, 2008), and denudation rates of 15-22 m.Ma-1 (Morais Neto et al., 2012) and 10-24 m.Ma-1 (Brito et al., 2025) established for this sector of the PGB and the Pereiro Massif, respectively, likely began between the Middle/Upper Miocene, shortly after the epeirogenetic uplift of the Borborema Plateau (Corrêa et al., 2010; Bezerra et al., 2020; Oliveira et al., 2023).

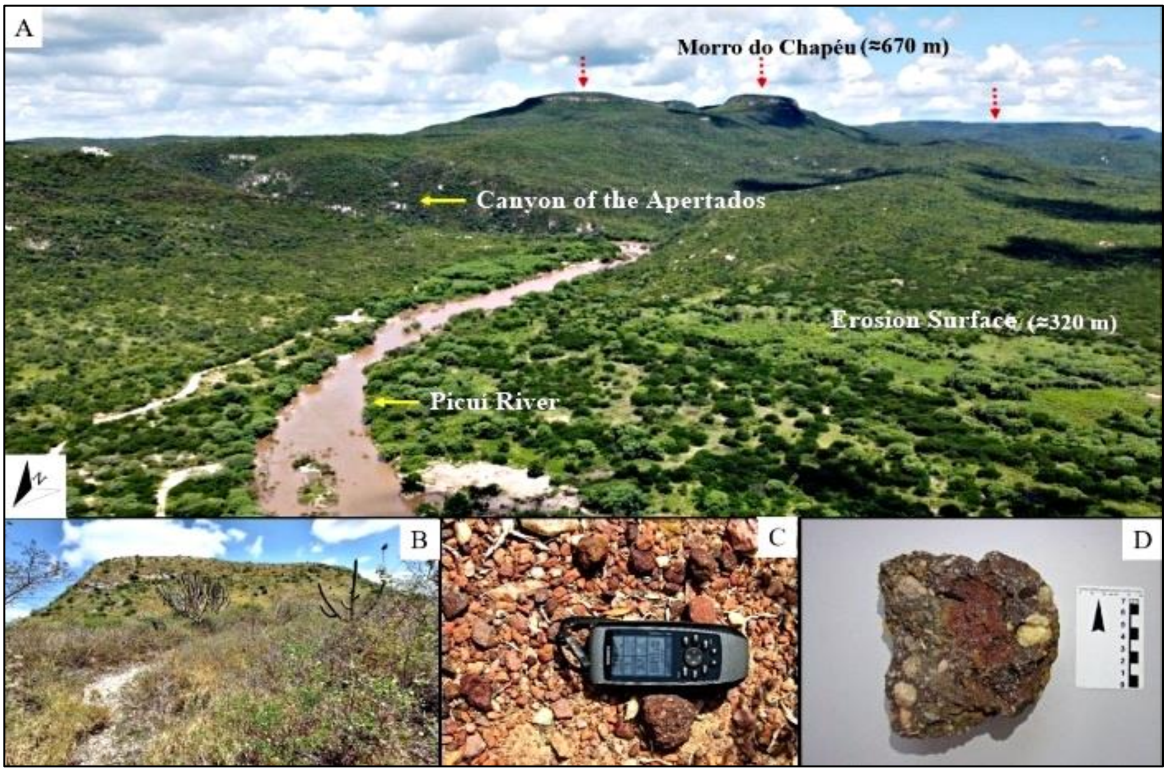


Figure 6. (A) Partial view of the summit surface of the Serra das Umburanas with tabular and disconnected remnants of a continuous ancient lateritic capping associated with the FSM (red arrows). (B) Eastern escarpment of Morro do Chapéu. (C and D) Sub-rounded fragments of iron oxides/hydroxides associated with the dismantling of the FSM (samples collected at Morro do Chapéu). Source: Authors' collection (2025).

Another relevant point to consider in the exhumation process of the Serra das Umburanas was the marked change caused by the progressive aridification of the climate, which began in the Miocene (Harris; Mix, 2002; Bétard, 2012; Peulvast; Bétard, 2015; Souza et al., 2023). This led to a phase of intense denudation that coincided with the age limits of the depositional sediments of the Barreiras Formation, between 22-17 Ma (Lima, 2008; Rossetti et al., 2013), exposing underlying lithologies, such as the quartzites of the Equador Formation and pegmatite dikes, through differential erosion. It also led to the dismantling of the laterized sandstone capping that covered the summit surface of the Serra das Umburanas and the Borborema Plateau.

Paleoclimatic studies from the Upper Pleistocene in the Brazilian Northeast also indicate abrupt climatic changes, with shifts in fluvial regimes and colluvium events, associated with periods of heavy rainfall and higher moisture concentration during millennial-scale events (e.g., Heinrich) (Wang et al., 2004; Zhang et al., 2017; Souza et al., 2023), between 60-24 ka (Behling et al., 2000; Fadina et al., 2019) and between 15.5-12.3 ka (Behling et al., 2000; Bouimetarhan et al., 2018), and in the period called the Climatic Optimum, between 7.5-4.5 ka (Corrêa, 2001; Mutzenberg, 2007; Missura, 2013).

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Thus, the change in the regional base level favored the exhumation of the Serra das Umburanas and mineralized pegmatite dikes (Cabral Neto et al., 2018), which were observed in SEII and were transversely sectioned by the Picuí River drainage network. This occurred due to the presence of brittle deformations that diverge from the orientation of the structural lineament trends of the DRPS (Graph 1B).

In the BHRP area (Figure 5), the western flank of the Borborema Plateau has surfaces with an average elevation of 650 m, approximately 310 m above the location where the superposition process occurred. This mismatch in the fluvial gradient of the BHRP, associated with the change in the direction of the Picuí River and some tributaries through orthogonal inflections (frequent in SEII), and the consequent confluence of the drainage system, enabled the accentuated fluvial incision into the Serra das Umburanas, which was subordinated to planes of weakness in the quartzites of the Equador Formation.

On the other hand, the presence of remnants of an ancient lateritic capping, associated with the FSM, on the summit surface of the Serra das Umburanas suggests that the beginning of the superposition process occurred after the dismantling of the depositional paleosurface and concurrently with the exhumation of the Serra das Umburanas, that is, between the Middle and Upper Miocene (Figure 7).

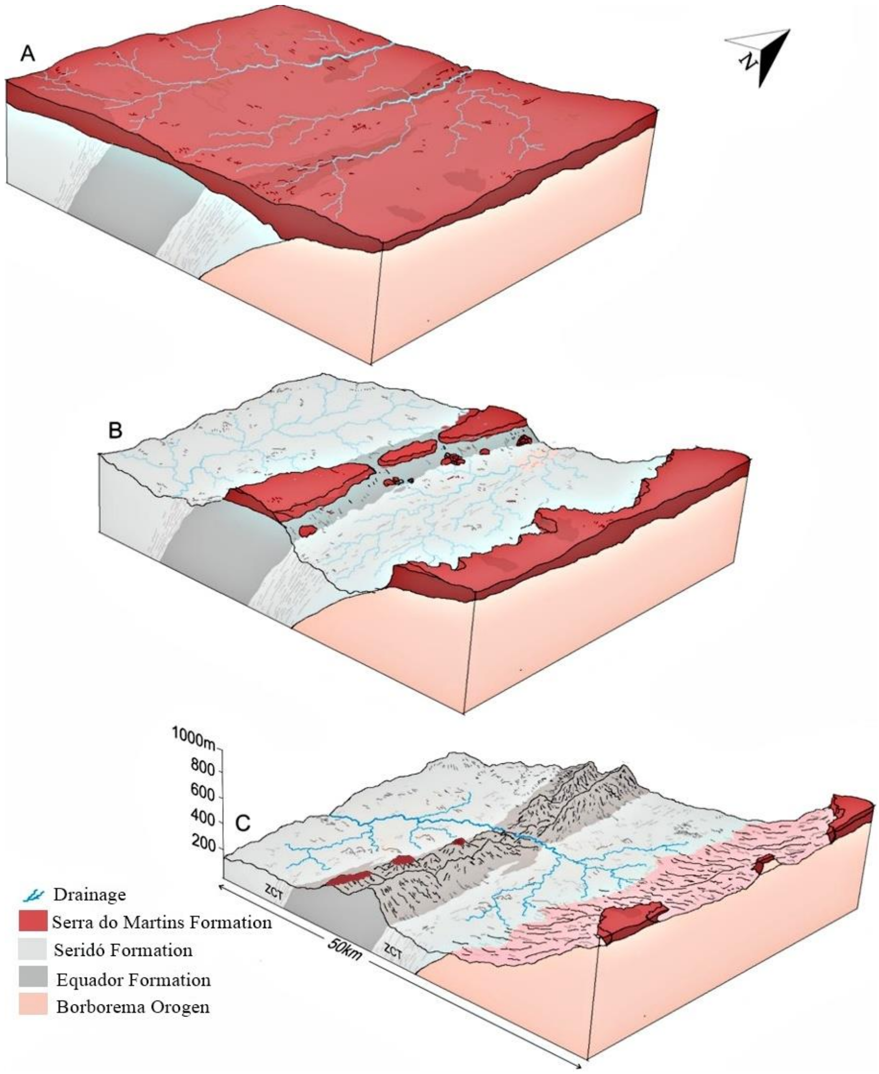

Figure 7. Synthesis of the transverse drainage evolutionary model by superimposition in the study area. (A) Represents the initial pre-exhumation stage. (B) Intermediate phase of erosion and retreat of the capping represented by the FSM. (C) Current stage, with the superimposition of the drainage that led to the formation of the Cânions dos Apertados. Source: Prepared by the authors (2025).

5. Discussion

5.1. Drainage analysis, genetic and evolutionary aspects of the Cânions dos Apertados

According to Twidale (2004) and Lee (2013), "trunk" channels—that is, higher-order channels—generally adapt to lithostructural weakness zones in the basement, following the course of structural valleys (Holbrook; Schumm, 1999). In the northern part of the PGB, rivers form incised valleys with a preferential NE-SW direction (Maia; Bezerra, 2011), indicating an adaptation to pre-existing geological structures (Rodrigues; Salgado; Maia, 2022). Regarding transverse drainages, which are discordant river patterns, Stokes and Mather (2003) and Douglass et al. (2009) state that river courses cut through geological structures such as faults and orogenic mountain belts, often forming gorges or canyons (Thompson, 1939; Oberlander, 1965; Clarck, 1989; Alvarez, 1999; Larson et al., 2017).

To understand the drainage superimposition process in a specific area, it is necessary to identify the mechanisms that conditioned its origin and development to improve the understanding of the fluvial system. For Stokes et al. (2008), the mechanisms of transverse drainage correspond to the fluvial incision response in the bedrock to an increased flow potential, controlled by the complex interaction between internal (geomorphic) or external (tectonic, eustatic, and climatic) variables, which significantly affect the fluvial system (Schumm, 1981).

Changes in the intraplate compressional regime from the Middle Miocene to the Holocene (Bezerra et al., 2020; Oliveira et al., 2023), characterized by W-E and NW-SE directed stresses (Cremonini; Karner, 1995; Bezerra; Vita-Finiz, 2000) and related to the drift stage of South American Plate movement (Ferreira et al., 2008; Assumpção et al., 2016), were responsible for directional anomalies in the northern portion of the PGB (Bezerra et al., 2011; Maia; Bezerra, 2019).

In the study area, the superimposition process indicates that the BHRP drainage network systematically evolved from a longitudinal dominance, where the fluvial channels likely followed the predominant directions of the discontinuity surfaces (N-S [26.19%], NNE-SSW [21.29%], and NE-SW [16.63%]) (Graph 1B), to a transverse dominance. This means the flow direction became perpendicular to the lithostructural control, with predominant drainage directions of NNW-SSE (12.77%), NW-SE (10.76%), and W-E (9.96%), followed by the WNW-ESE (8%) and WSW-ENE (4.2%) directions (Graph 1A).

The gradual migration of the Picuí River channel indicates that the lithology of the BHRP, as well as the topographic lineament trends (e.g., ridges and valleys) associated with the predominant N-S and NNE-SSW Brasiliano deformation planes, were not the dominant factors in the orientation of the BHRP drainage network. Instead, the tilting and slope of SEII, where classes of ≤ 8 and 8-20% predominate (Figure 8), as well as the interactions with brittle deformation structures in the W-E (12.28%), WNW-ESE (6.12%), NNW-SSE (5.7%) directions, and, secondarily, the NW-SE (2.75%) and WSW-ENE (1.33%) directions (Graph 1B), were the determining factors.

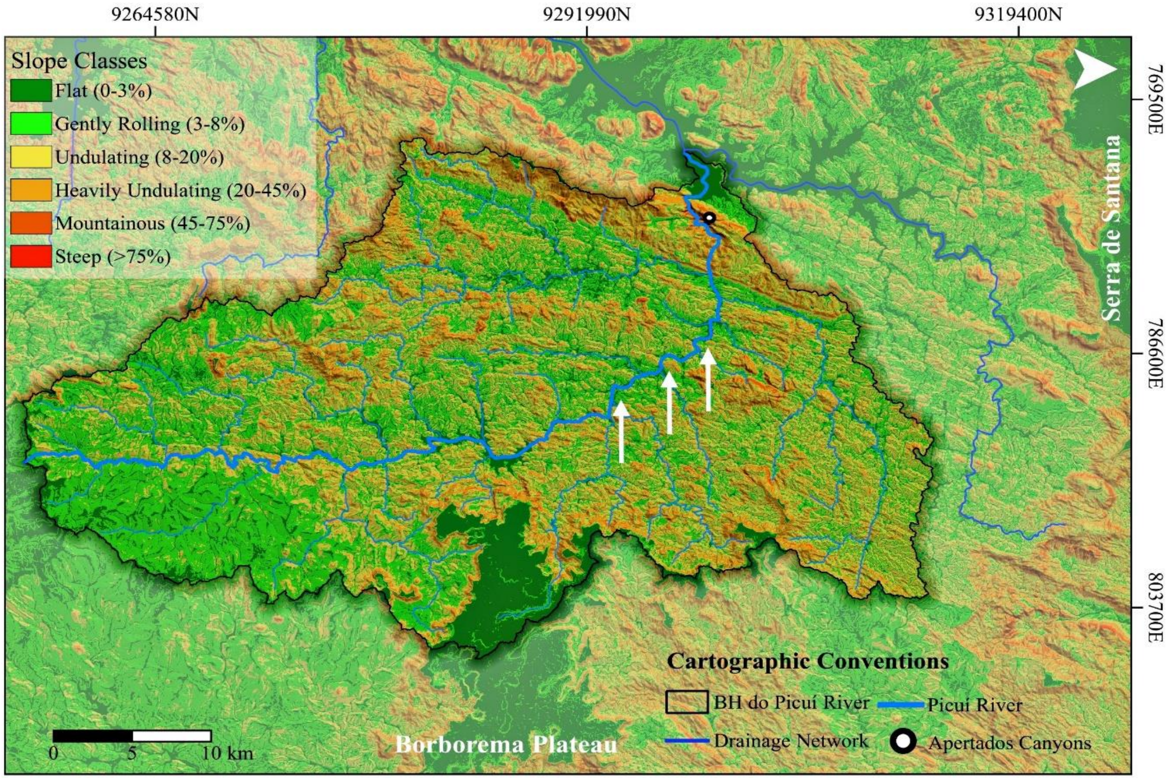

Figure 8. Slope Map of the BHRP. Source: Prepared by the authors (2025). Legend: The white arrows indicate the gradual change of the Picuí River's flow, which is perpendicular to the basin's lithostructural control.

The fault system resulting from Cenozoic compressive forces led to significant changes in the orientation of the BHRP's drainage network. The orthogonal inflections observed in the main channels of the BHRH are commonly associated with the influence of structural lineaments with orientations ranging from W-E to WNW-ESE (Graph 1A). According to Maia and Bezerra (2011), in addition to the paleoclimatic framework and basement configuration, current tectonics are of great importance in defining evolutionary models, especially fluvial ones, due to their adaptation to pre-existing lines of weakness such as faults and shear zones (Maia; Bezerra, 2019).

The sectors with slope classes of ≤ 3% and 3-8%, located on the Borborema Plateau in the upper course of the BHRP (southern portion) and the central-eastern portion (the highest sector of the BHRP - the "Picuí-Cuité Tabular Plateau"), are justified by the presence of laterized sandstones of the FSM, partially covering the summit surfaces, giving them a flat top, which is commonly associated with very porous soils, such as Yellow Latosols and Petric Plinthosols (Santos et al., 2023; Silva et al., 2024).

According to Whipple, Hancock, and Anderson (2000) and Peifer et al. (2022), several processes contribute to fluvial incision in bedrock rivers, the main ones being abrasion, plucking, corrosion, cavitation, and debris-flow scour. Among the processes that have contributed and continue to contribute to the fluvial incision of the Picuí River on the Serra das Umburanas, abrasion stands out. In the Cânions dos Apertados, abrasive wear is responsible for sculpting erosional features into the quartzite riverbed, such as potholes, flutes, and ripples (Figure 9).

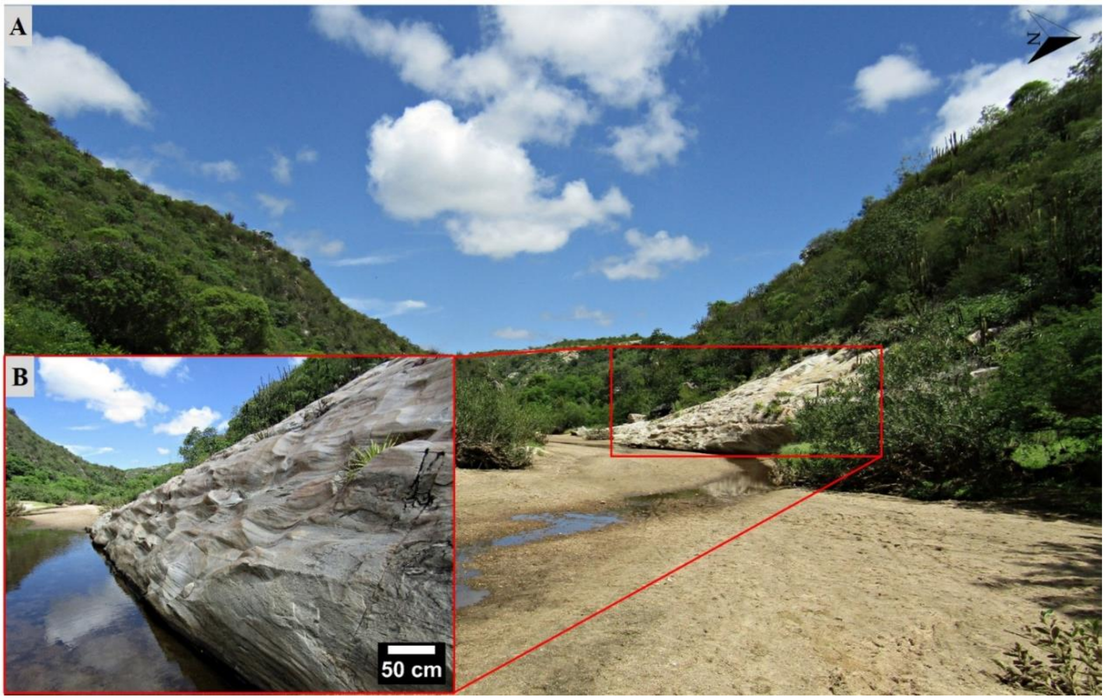

Figure 9. (A) Downstream view of a canyon wall in the Picuí River's thalweg (during a dry period), with the presence of centimeter-long ripples (B) carved by the energetic collisions between sediment grains and the exposed bedrock surface, attesting to vigorous erosion by suspended load. Source: Authors' collection (2025).

The presence of these erosional features, carved into the bedrock riverbed and the canyon walls, attests to vigorous erosion resulting from a combination of bedload and suspended load abrasion (Whipple; Dibiase; Crosby, 2013; Peifer et al., 2022; Dias et al., 2024). Furthermore, the steepness of the slopes of the Cânions dos Apertados also demonstrates the erosive capacity of the Picuí River.

The walls of the Cânions dos Apertados are also susceptible to gravitational mass movements along virtually their entire length. In the sections with the greatest amplitude (the central-western portion), these walls can easily reach 100 m in height, featuring sub-vertical inclinations and sub-horizontal and sub-vertical fracturing patterns (Figure 10). The sub-vertical fractures, which transversely intersect the sub-horizontal discontinuities, cause different segmentation patterns in the quartzites of the Equador Formation, thus conditioning the occurrence of rockfall-type gravitational movements.

At the base of the Cânions dos Apertados' walls, talus deposits with blocks of various sizes are found. These blocks have broken away and moved downward with the slope over geological time. In the Picuí River bed, it is also possible to observe quartzite blocks of different sizes, ranging from dm^3 to m^3, and irregular shapes, which are the result of gravitational movements (Figure 10).

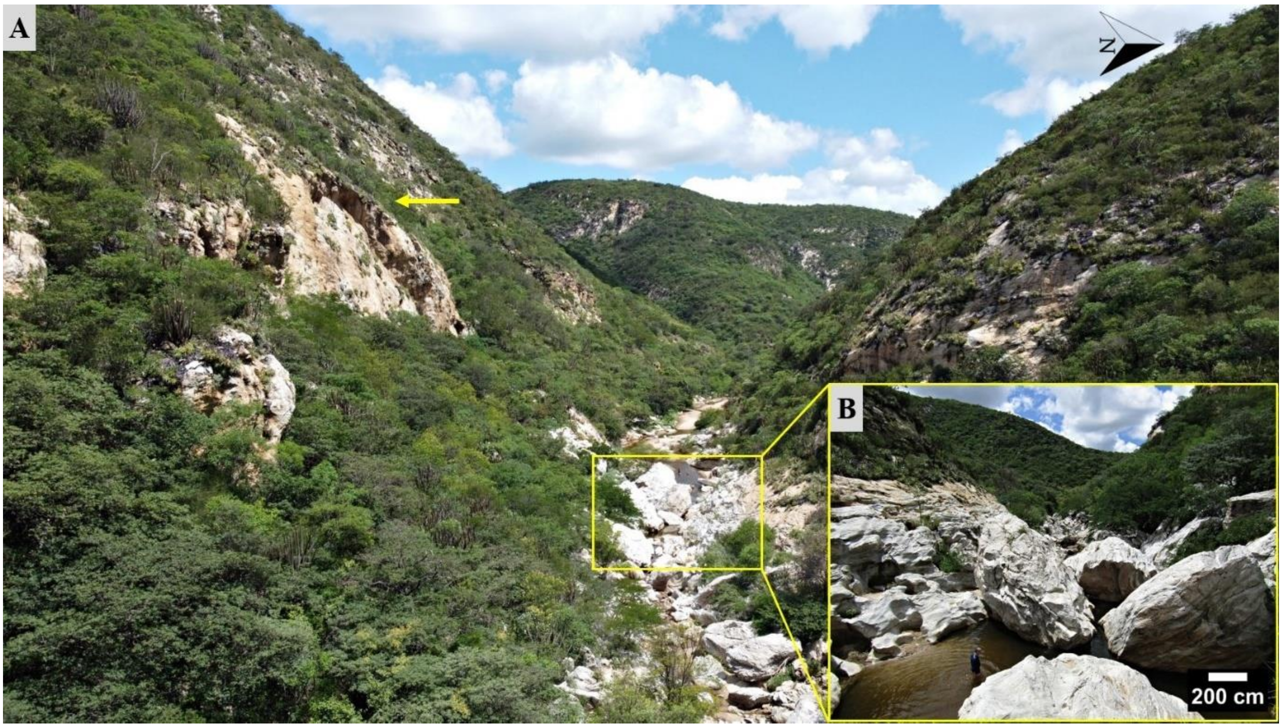

Figure 10. (A) Canyon wall with a mass movement scar (rockfall), caused by the detachment of a rock slab. (B) Large quartzite blocks deposited in the bed of the Picuí River, in the central-western sector of the Cânions dos Apertados. Source: Authors' collection (2025).

The identification of talus deposits at the base of the walls, as well as the presence of quartzite blocks in the Picuí River bed, especially in the central-western sector, suggests morphogenetic phases of escarpment retreat in the Cânions dos Apertados, associated with gravitational mass movements (Figure 10). The discontinuity surfaces in the Equador Formation quartzites (fractures, quartz and pegmatite veins and dikes) and the sub-vertical inclination of the escarpments have conditioned and continue to condition mass movements, but they do not compromise the maintenance of the escarpments themselves.

A central issue in the vertical evolution of the Cânions dos Apertados lies in the resistance of the Equador Formation quartzites, due to the difficult dissolution of silica (SiO_2), the main chemical compound present in quartz (Penteado, 1983; Hollocher, 2014). The quartzites that support the Serra das Umburanas are mineralogically composed of quartz (85%), muscovite (15%), black tourmaline, traces of iron oxide, plagioclase, and sillimanite (Cavalcanti Neto, 2008).

However, the impermeability of the quartzites, combined with the existence of discontinuity surfaces, facilitated the Picuí River's capacity for vertical incision. In other words, the brittle deformation structures guided and concentrated the water flow, both on the topographic surface and in the subsurface, giving it greater erosive power. In order to reach its base level and equalize it with the base level of SEI, the Picuí River deepened its valley into the Equador Formation, adapting to the brittle deformation structures that cut through the Serra das Umburanas, resulting in the erosion that created a sinuous canyon.

5. Conclusions

It is concluded that the Cânions dos Apertados are a case of transverse drainage that evolved from a complex combination of tectonic, lithological, and paleoclimatic factors, interpreted through the drainage superimposition model by correlating the following pieces of evidence:

- Identification of remnants of an aggradational paleosurface on top of the Serra das Umburanas, composed of partially laterized sandstones (FSM) with an inferred Oligo-Miocene age, deposited over the quartzites of the Equador Formation;
- The existence of other water gaps, such as the Boqueirão de Parelhas (Figure 2), on this same geological formation, considering that the Serra das Umburanas is a structural prolongation of the Serra das Queimadas;
- A change in the regional base level in response to the uplift of the Borborema Plateau due to Oligo-Miocene magmatism (Macau Magmatism) and, in solidarity, the SEII, which enhanced the vertical incision power of the Picuí River;
- The establishment of a dry climate from the Miocene onward, with the subsequent dismantling of the FSM sedimentary unit and the consequent exposure of the quartzites that now form the Serra das Umburanas;
- Differential erosion of the Precambrian basement, concomitant with the fragmentation of the FSM, which explains the topographic highs (e.g., Serra das Umburanas) related to the quartzites of the Equador Formation and the lowered planation surfaces associated with the micaschists of the Seridó Formation.

The formation age of the FSM depositional paleosurface, which partially covered both the SEII and the Borborema Plateau, and its subsequent dismantling, related to the progressive aridification of a previously humid climate that began in the Miocene, can be considered a marker for the vertical incision of the Picuí River into the Serra das Umburanas, according to the brittle deformation structures. Furthermore, the regional climatic oscillations observed in the Upper Pleistocene and Middle Holocene minimized the flow intermittency of the BHRP fluvial systems, resulting in greater water availability and thus justifying the Picuí River's increased erosive power.

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