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Research Article

Lithostructural control in the development of potholes in the rocky bed of the Carnaúba River, Seridó UNESCO Global Geopark, NE Brazil

Controle litoestrutural no desenvolvimento de marmitas no leito rochoso do rio Carnaúba, Seridó Geoparque Mundial da UNESCO, NE do Brasil

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Abstract: Granitic forms resulting from turbulent flow, with hydraulic vortices, characterize the rocky bed of the lower course of the Carnaúba River, in a geosite of the Seridó Geopark, in the Seridó Oriental microregion, Northeast Brazil. These forms constitute a variety of types of potholes that individually represent various stages of evolution, in addition to reflecting the variation in the erosive potential of river flow throughout the Quaternary. From a bibliographical review, fieldwork (quantification and measurements of the potholes), high-resolution photogrammetry and morphostructural analysis of the generated cartographic products, it was possible to establish a correlation between the preferential orientation of the potholes and the direction of the planes of weakness, as well as the classification of potholes by morphometric parameters. In this work it was demonstrated that the efficiency of hydraulic vortices is associated with discontinuity structures and the mineralogical composition of granite facies, with abrasive erosion being responsible for sculpting potholes, with different dimensions and geometries. In the rocky bed of the Carnaúba River, the small potholes deepen and their diameter evolves into cylindrical shapes as the turbulent vertical flow increases, eventually becoming sigmoidal. The lateral potholes, located on the walls of the river channel, are deeper than they are wide, and represent a destructive phase of evolution.

Keywords: Corrosion; River erosion; Intermittent rivers; Brazilian semi-arid region.

Resumo: Formas graníticas resultantes do fluxo turbulento, com vórtices hidráulicos, caracterizam o leito rochoso do baixo curso do rio Carnaúba, em um geossítio do Geoparque Seridó, na microrregião do Seridó Oriental, NE do Brasil. Essas formas compreendem uma variedade de tipos de marmitas que representam, individualmente, vários estágios de evolução, além de refletir a variação do potencial erosivo do fluxo fluvial no decorrer do Quaternário. A partir de revisões bibliográficas, trabalhos de campo (quantificação e medições dos eixos das marmitas), fotogrametria de alta resolução e análise morfoestrutural dos produtos cartográficos gerados, foi possível estabelecer uma correlação entre a orientação preferencial das marmitas e a direção dos planos de fraqueza, assim como a classificação das marmitas por parâmetros morfométricos. Neste trabalho foi demonstrado que a eficiência dos vórtices hidráulicos está associada às estruturas de descontinuidades e à composição mineralógica das fácies graníticas, sendo o desgaste abrasivo responsável por esculpir marmitas, com dimensões e geometrias distintas. Foram identificadas, no leito rochoso do rio Carnaúba, marmitas incipientes que se aprofundam e aumentam de diâmetro gradualmente em formas cilíndricas à medida que o fluxo turbulento vertical aumenta, evoluindo, em seguida, para formas sigmoidais. As marmitas laterais, maiores em profundidade do que em largura, que representam uma fase destrutiva da evolução, foram observadas, somente, nas paredes do canal fluvial.

Palavras-chave: Corrosão; Erosão fluvial; Rios intermitentes; Semiárido brasileiro.

1. Introduction

Potholes are erosive forms associated with bedrock rivers, commonly found mainly in granite and sandstone outcrops (TWIDALE; ROMANÍ, 2005), but also occurring in basaltic (COTTON, 1963) and gneissic beds (ORTEGA-BECERRIL; GARROTE, 2023). These forms result from the combined action of hydraulic dynamics and fluvial incision processes over geological time scales (>103) (PEIFER et al., 2022), acting on rocky channels (HOWARD, 1994; LIMA, 2010), influenced by climatic variations during the Quaternary (BEHLING et al., 2000; MORAIS NTO et al., 2009; FONSÊCA, 2018).

In the geomorphological literature, many studies have analyzed the morphology and fluvial processes responsible for the genesis and evolution of potholes, specifically in granitic-gneissic outcrops and occasionally in sedimentary lithology, as exemplified by the works of Lorenc; Barco; Saavedra (1994), Richardson and Carling (2005), Ortega-Becerril et al. (2014), Pelletier et al. (2015), Dhali and Biswas (2017), Costa et al. (2021), and Ortega-Becerril and Garrote (2023).

These studies demonstrate the importance of the interaction between erosive systems (e.g., corrosion/potholing) and chemical weathering with the lithostructural characteristics of the bedrock (e.g., fractures, faults, dikes, veins, and mineralogical predisposition) for the pattern, genesis, and evolution of potholes in different lithologies (ORTEGA et al., 2014). Potholes can occur in isolation or clusters and, in some cases, contain poorly sorted sediments inside them (ORTEGA-BECERRIL; GARROTE, 2023).

However, these depressions with diverse geometries, common worldwide regardless of latitude, are still not completely understood (LIMA, 2010; DHALI; BISWAS, 2017). Research on erosive forms in riverbeds, such as potholes, is incipient, especially in Brazilian literature, even though they are recognized as common elements in various landscapes across the national territory (WALDHERR; ARAÚJO-JÚNIOR; RODRIGUES, 2017; LIMA et al., 2023).

In the Brazilian Northeast, few studies attest to the effects of the potholing process on the sculpting of potholes, whether with a structural emphasis, through the analysis of energetic collisions between the detrital sediments transported by fluvial waters and the surfaces of discontinuities (LIMA, 2010), or emphasizing the relationship between the efficiency of fluvial erosion on a geological time scale and the resistance of the bedrock substrate exposed on the surface, which may be directly associated with the type and mineralogical composition of the rocks exposed in the channel (COSTA et al., 2021).

From this perspective, the present work aims to demonstrate how lithostructural conditions can constitute the starting point for the potholing process in granitic fluvial channels. To this end, the Geosite Marmitas do Rio Carnaúba, located in the Seridó UNESCO Global Geopark, in the Northeast of Brazil, was selected as a sample area. In this geodiversity hotspot (NASCIMENTO et al., 2021), the bedrock of the Carnaúba River is subject to hydraulic erosion processes driven by aridity fluctuations observed throughout the Quaternary, the erosive gradient produced along the longitudinal profile, and the mineralogical and petrographic predisposition of the granitic basement.

2. Study area

The Seridó UNESCO Global Geopark, with an area of 2,802 km² (SILVA; NASCIMENTO; COSTA, 2022), showcases one of the most complete and beautiful geoheritages in the Brazilian Northeast, with landscapes reflecting the numerous natural processes to which the region has been subjected over geological time. The Seridó Geopark includes 21 geosites, distributed across 6 municipalities, located in the eastern portion of the Rio Piranhas-Seridó Domain (DRPS) (NASCIMENTO; MEDEIROS; GALINDO, 2015). Among these geodiversity hotspots, the Geosite Marmitas do Rio Carnaúba (GMRC) stands out, situated in a small rocky bed section of the Carnaúba River, near its confluence with the Acauã River, in the municipality of Acari-RN, in the microregion of Eastern Seridó, at the geographical coordinates 6°29′43″S and 36°41′32″W (Figure 1). Geologically, this geosite is set within the context of Ediacaran plutonic activity (ANGELIM et al., 2006), one of the most important geological units of the Borborema Province, occupying a small portion of the southwestern sector of the Acari Pluton.

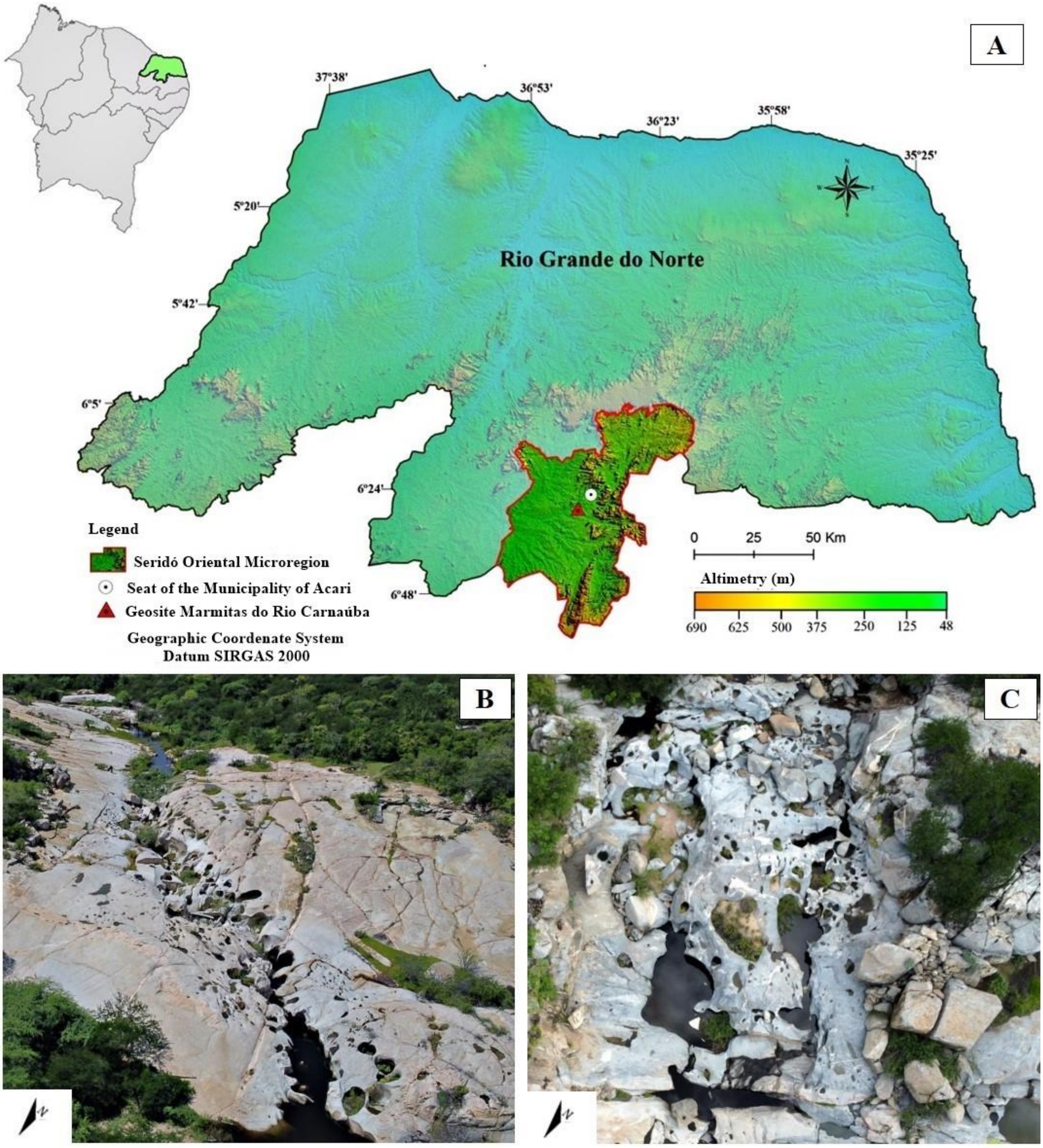

Figure 1. (A) Location of GMRC, Eastern Seridó Microregion, Rio Grande do Norte, NE Brazil; (B) Sector I of GMRC (Vale da Lua Potiguar); (C) Sector II of GMRC (Pedra da Caveira). Source: Created by the authors (2023).

The Borborema Province (BP) is one of the main geotectonic units in the Brazilian Northeast, subdivided by E-W trending shear zones (Pernambuco Shear Zone and Patos Shear Zone) into three domains: Southern, Transverse, and Northern (ANGELIM et al., 2006; ARCHANJO et al., 2013). In the latter, the Acari Pluton is found, occupying much of the eastern sector of the DRPS (NASCIMENTO; MEDEIROS; GALINDO, 2015), delineated by NE-SW trending shear zones (ANGELIM et al., 2006).

The Acari Pluton, outcropping in the homonymous municipality with ≈300km² (CAMPOS, 2016), is intrusive into the foliated orthogneisses and banded Paleoproterozoic gneisses (Caicó Complex) and the Neoproterozoic metasupracrustals (Seridó Group) that rest discordantly on the varied range of lithologies of the Caicó Complex (ARCHANJO et al., 2013).

The granites of the Acari Pluton are leucocratic to mesocratic with coarse to porphyritic granulation (megacrysts of feldspar up to 5cm) (CABRAL NETO et al., 2018). This granitic body, in the study area, is associated with fine to medium-grained diorites/gabbros of the São João do Sabugi Suite, and also presents intermediate facies of magmatic mixing (DANTAS et al., 2012; NASCIMENTO; MEDEIROS; GALINDO, 2015).

From a geomorphological perspective, the GMRC is located on the lowered erosional surface of the Sertões do Piranhas, where Cenozoic denudational processes have led to the progressive exhumation of the igneous basement, revealing a diverse display of granitic forms, such as massifs, inselbergs, and rock pavements. In this context, concerning the evolution of granitic reliefs, the Etchplanation Theory (BÜDEL, 1982) deserves mention, which states that the evolution of landforms derives from different paleoclimatic and structural situations, considering not only the current climatic dynamics but also the notion of polygenesis, relating to an etchplanation-pediplanation cycle (SALGADO, 2007).

The potholes that constitute this geodiversity hotspot were formed on the base of the "Cai Peixe" rock pavement (LCP), which has an elongated elliptical dome shape, resembling whalebacks, with an altitude of ≈260m.

This erosional surface is characterized by an average annual precipitation ranging from 460 to 670 mm/year, with summer-autumn rains, the rainiest quarter being from February to April (EMPARN, 2010). The denudational processes active in the study area are subject to the semi-arid climate (DINIZ; PEREIRA, 2015), with an average annual temperature of 27.5ºC, a maximum of 33ºC, and a minimum of 21ºC (MUTZENBERG, 2007; LUCENA, 2016; TAVEIRA, 2019), and approximately 2,455 hours of sunshine per year (BEZERRA JÚNIOR; SILVA, 2007), which explains the high rates of evapotranspiration, low soil moisture, and negative water balance throughout the year.

The predominant vegetation is hyperxerophilic deciduous shrub caatinga, with varying heights, featuring cacti (e.g., *Melocactus zehntneri* – Turk's cap cactus) and bromeliads (e.g., *Encholirium spectabile* – macambira). However, due to indiscriminate deforestation associated with temporary crops (corn and beans) and extensive livestock farming, the vegetation cover in this area has shown a reduction in both physiognomy and floristic composition, being replaced by herbaceous species.

2.1. General Aspects and Regional Morphogenesis

In the northern portion of the Borborema Province (PB), the uplifts associated with the rift and post-rift phases (Jurassic-Cretaceous) during the opening of the Atlantic (MATOS, 2000), and the drift related to tectonic inversion, active since the Paleogene, resulting from NW-SE and W-E compressive forces (CREMONINI; KARNER, 1995), as well as the flexural movements between the Eocene and Miocene (PEULVAST; CLAUDINO SALES, 2006) and intraplate basaltic magmatism (KNESEL et al., 2011) affected the fluvial erosive potential by disrupting the fluvial gradients of the river basins in northern Northeast Brazil.

This regional morphotectonic history was responsible for the current hydrographic organization, such as the Carnaúba River basin located west of the western slope of the Borborema Plateau (Figure 2), whose evolution, probably of post-Paleogene age, is associated with the dismantling of the lateritic cover of the Serra do Martins Formation (CORRÊA, 2001; LIMA; CORRÊA; FONSÊCA, 2016).

In addition to the uplifts, palynological and sedimentological evidence demonstrates that erosive processes were intensified from the Neogene to the mid-Holocene due to fluctuations in aridity, with short rehumidification intervals, related, for example, to Heinrich events (MORAIS NETO et al., 2009; WANG et al., 2004) and the period known as the climatic optimum (maximum humidification), which occurred between 7,500 and 4,500 years BP in Northeast Brazil (BEHLING et al., 2000; CORRÊA, 2001; MISSURA, 2013).

These climatic oscillations were responsible for the remobilization of thick regoliths, as well as for increasing the sediment transport capacity with a higher granulometric contribution, both in slope and fluvial environments

(LIMA; CORRÊA; FONSÊCA, 2016; FONSÊCA, 2018). Morais Neto et al. (2012) indicated erosion rates between 15-22m/Ma for the lowered erosional surfaces of the Borborema Province.

According to Mutzenberg (2007), the period understood as the Middle Holocene in the BHRC area had a more seasonal and regular rainfall regime (climatic optimum), associated with wetter paleoenvironmental conditions, with greater dynamics and fluvial flow, featuring alluvial and colluvial sediments present in the form of spatially disjointed fluvial terraces and mid-slope fans.

Therefore, the greater erosive potential of the Carnaúba River was associated with post-Paleogene uplifts, responsible for the rejuvenation of fluvial gradients, and the climatic oscillations observed between the Neogene and the Middle Holocene. The presence of orthogonal inflections in the Carnaúba River channel indicates the progressive adaptation of the flow to the brittle deformation structures oriented NW-SE and W-E, diverging from the predominant NE-SW tectonic direction. The post-Miocene tectonic reactivations (MAIA; BEZERRA, 2013; OLIVEIRA et al., 2023) resulted from W-E and NW-SE compressive forces along the ductile and brittle deformation structures, associated with the expansion of the Mid-Atlantic Ridge, the compression of the Andean Chain, and the "Macau Magmatism" thermotectonic event (BEZERRA; VITA-FINZI, 2000; ASSUMPÇÃO et al., 2016; BEZERRA et al., 2020).

During the Pleistocene/Holocene transition, there was a much wetter environment than the current one (CORRÊA, 2001; MISSURA, 2013), with higher precipitation and increased humidity due to the rapid warming of the planet. This warm, humid climate with possibly regular precipitation, observed regionally, lasted until the Middle Holocene (MUTZENBERG, 2007). However, it was only from the beginning of the Holocene that the influence of the Intertropical Convergence Zone (ITCZ) became more pronounced in the regions west of the Borborema Plateau (CORRÊA, 2001).

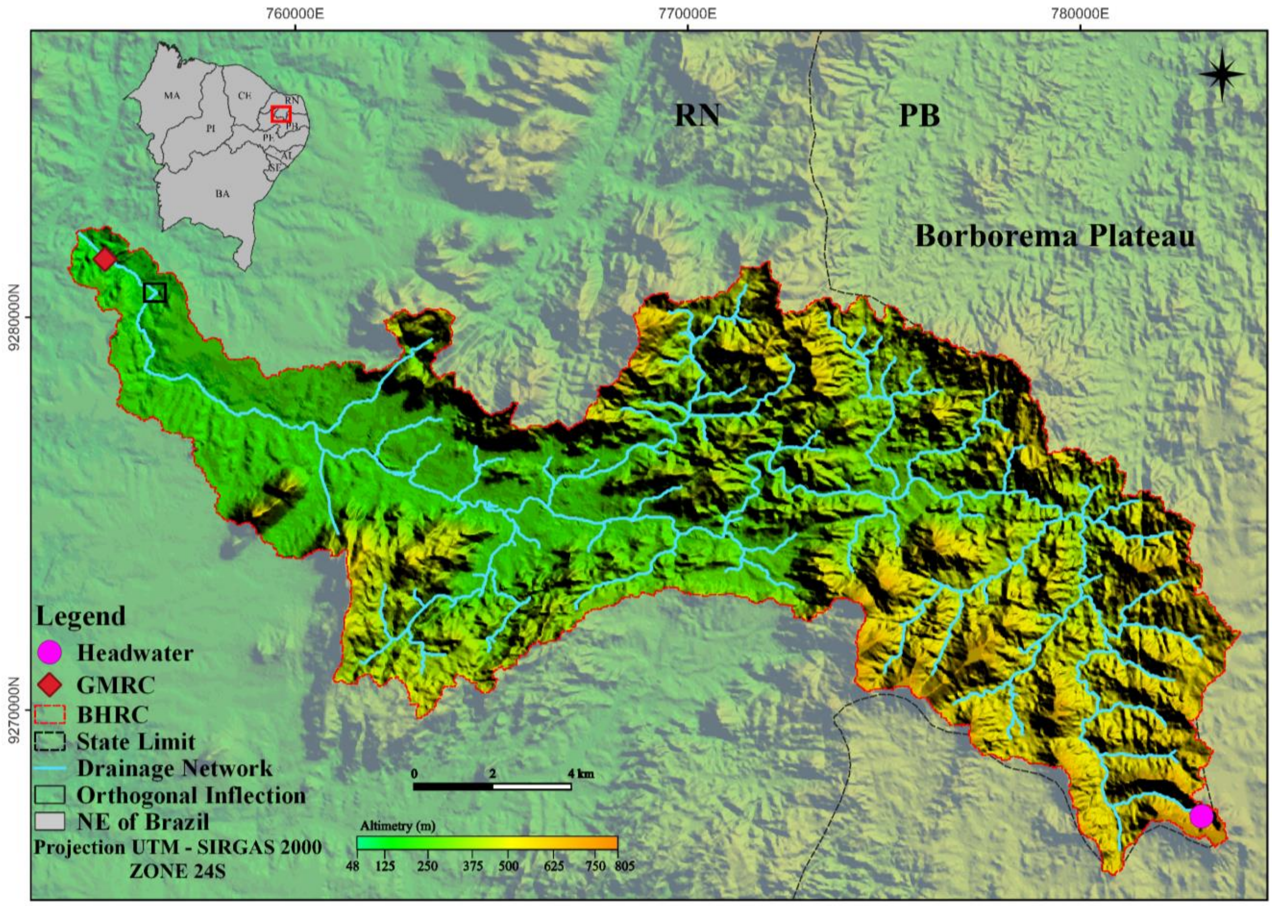

Figure 2. Delimitation and Altimetry of the Carnaúba River Basin (BHRC). Source: Created by the authors (2023), from SRTM image editing.

In other words, a certain climatic stability (rehumidification) seems to have characterized the BHRC, especially during the Holocene Climatic Optimum, where a more regular fluvial flow with greater capacity to transport detrital sediments was observed (MUTZENBERG, 2007). These conditions could have been necessary to trigger the pothole formation processes in the LCP. Besides factors related to Quaternary climatic influences, the existence of knickpoints and the consequent exposure of the Carnaúba River bedrock in the study area may be associated with movements of neotectonic origin.

3. Materials e Methods

The methodological approach of this study first involved an extensive literature review on erosive features in bedrock channels. GIS tools, utilizing images acquired by an unmanned aerial vehicle (UAV) model Mavic 2 Pro equipped with a 35 mm 4K camera, enabled the construction of an orthomosaic of aerial images. This orthomosaic supported the creation of a geospatial database with raster and vector files, facilitating the detailed extraction of discontinuity structures in the bedrock of the Carnaúba River, the description of the potholes' morphometric parameters, and the determination of the preferential direction of both the potholes and the planes of weakness.

The photogrammetric survey was conducted with 70% front and side overlap, processed in Agisoft PhotoScan (licensed to the Geomorphology Laboratory of the Federal University of Ceará). The vector files of the discontinuity structures, the rose diagrams, and the maps were created in a GIS environment using the open-source software QGIS version 3.22. The creation of block diagrams, demonstrating the relationship between structural discontinuities and the distribution of potholes, was done using CorelDRAW Graphics Suite (Windows).

Geological information was obtained from the Currais Novos sheet (SB.24-Z-B-II), at a scale of 1:100,000 (DANTAS et al., 2012), and the geological map of the Borborema Pegmatite Province, at a scale of 1:250,000 (CABRAL NETO et al., 2018), supplemented with macroscopic descriptions of rocks found in the GMRC area.

The macroscopic description, carried out in the Laboratory of Mineralogy and Petrology of the Department of Geology at the Federal University of Rio Grande do Norte, involved the use of a binocular stereo microscope, model Olympus SZ40, a pocketknife, and a magnet. This procedure involved identifying the minerals present, based on their different properties (e.g., color, cleavage, hardness). This led to the identification of felsic minerals (quartz and feldspars) in Sector II. The petrographic characterization of the five rock samples (two of the dominant granitic facies; one of the dioritic facies; one of the gneiss facies; and one of the leucomicrogranite dikes) related to the GMRC also involved the relationship between the different minerals, characterizing textural aspects such as the size and shape of the different grains. Finally, with the minerals identified, it was possible to classify the rocks based on the QAP diagram (STRECKEISEN, 1976).

The field identification of the 849 potholes involved the use of a Garmin 62s GPS, compass, metric tape, Canon R100 digital camera for photographic recording, and a notebook for recording morphometric variables (Length [L], Width [W], and Depth [D]).

The categorization of the potholes was based on the morphometric parameters established by Richardson and Carling (2005), into four groups: incipient, cylindrical, sigmoidal (coalescent), and lateral. The Cenozoic geological and paleoclimatic interpretations allowed correlating the potholes with the lithostructural context of the GMRC.

4. Results

4.1. Geological Context of the Marmitas do Rio Carnaúba Geosite

The granites that compose the LCP exhibit three distinct facies: i) Granitic facies characterized by leucocratic to mesocratic rocks (monzogranites), coarse to porphyritic-grained, inequigranular, Itaporanga-type, with biotite as the main mafic mineral (Figure 3A); ii) Granitic facies characterized by leucocratic rocks (syeno to monzogranites), equigranular, with fine to medium grain size (Figure 3B); iii) Dioritic facies (Figure 5B), mesocratic, inequigranular, occurring as oval or ellipsoidal mafic enclaves of centimeter to meter dimensions (Figure 3D), with fine to medium grain size, sometimes showing features of magma mingling with porphyritic granitoids.

Figure 3. Field features of the LCP Rocks. (A) Contact between porphyritic granite, Itaporanga-type, and fine to medium-grained granite associated with the Dona Inês Suite. (B) Equigranular leucomicrogranite dike cutting through coarse-grained granitic facies, with biotite as the main mafic mineral. (C) Xenolith of banded mesocratic gneiss with granolepidoblastic texture in porphyritic granite. (D) Mafic enclave (dioritic facies) in porphyritic granite. Source: Authors' collection (2023).

In addition to these units, the LCP is affected by Cambrian pegmatite dikes (homogeneous/heterogeneous leucogranites) with medium to coarse texture (Figure 4A); aplite dikes (equigranular leucomicrogranite) intruding granitic facies (Figure 3B) with very fine to fine phaneritic texture, and centimeter to decimeter dimensions, often associated with pegmatites (Figure 5A); quartz veins, with centimeter widths, as well as tension joints filled with quartz; and millimeter to centimeter veins of quartz/feldspar-rich material associated with oxides (e.g., magnetite, ilmenite) (Figure 4B), which are oxidized, creating ferruginous stains.

There are also occurrences of xenoliths and megaxenoliths of diorite (São João do Sabugi Suite) and banded and folded mesocratic gneisses (Figure 3C) with granolepidoblastic texture, primarily in the coarse to porphyritic-grained granitic facies associated with the Itaporanga Suite.

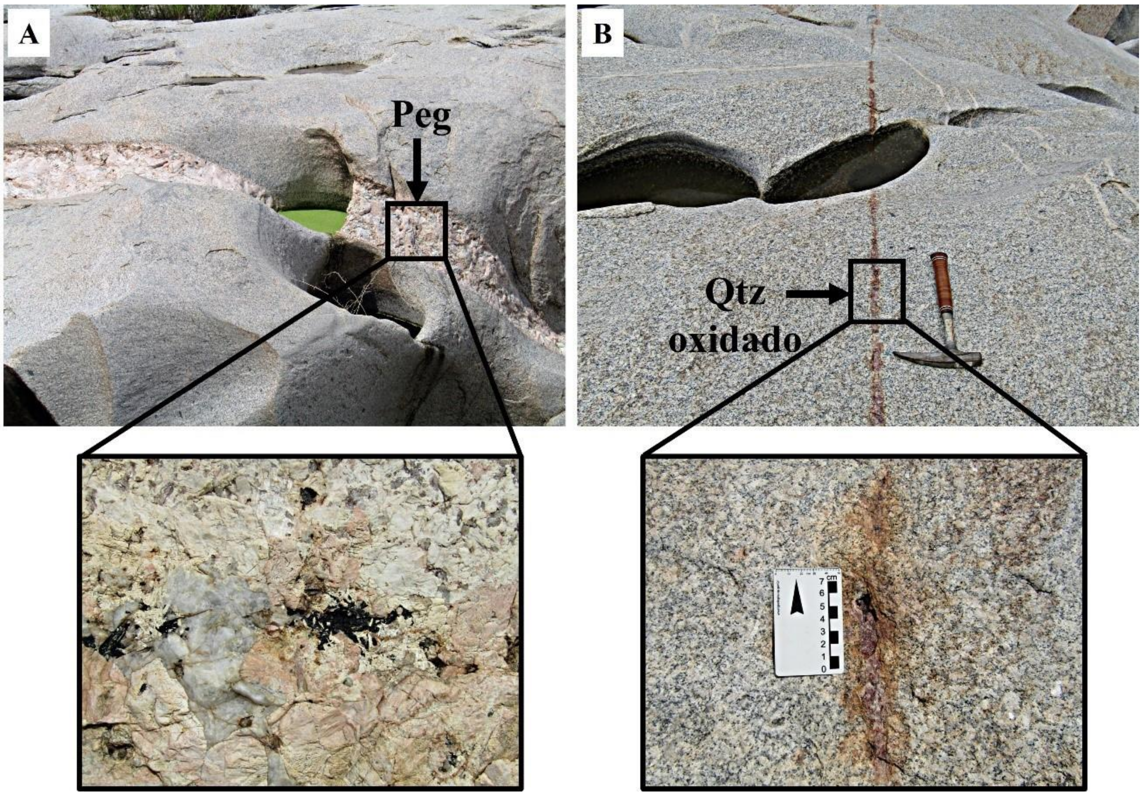

Figure 4. (A) Pegmatite dike (Peg) in fine to medium-grained granite. (B) Fine to medium-grained granite cut by a quartz vein with the presence of ferromagnesian minerals. Source: Authors' collection (2023).

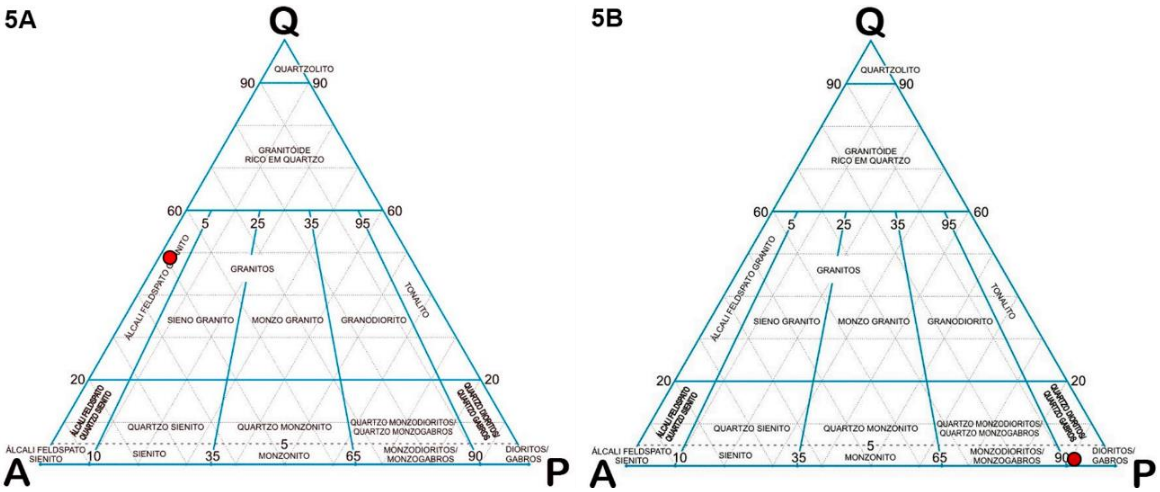

Figure 5. Streckeisen (1976) modal classification (Q-A-P) for aplite granites (5A) and dioritic rocks (5B). Source: Created by the authors (2023).

The occurrence of different lithological facies (e.g., granites, pegmatites, leucomicrogranite, diorites, gneisses) and structural discontinuities (e.g., fractures, fissures, veins, dikes) in the LCP denotes morphological features, mainly associated with abrasive wear, responsible for sculpting the paleomarmitas in the granitic facies, which can vary in size from a few centimeters to several meters in diameter.

4.2. Exhumation of the LCP and Origin of Bedrock Forms

The exhumation of the NE-SW oriented granitic dome during Cenozoic denudational cycles, associated with neotectonic movements, resulted in a slope break of approximately 11 meters in the gradient of the Carnaúba River channel. This knickpoint and the incision of the main channel (Figure 6), into NW-SE oriented brittle deformation structures that intersect the base of the LCP, facilitated the concentration of flow in this river section and, consequently, increased the potential energy of the flow, sediment transport competence and capacity, as well as bedrock wear due to the transported material.

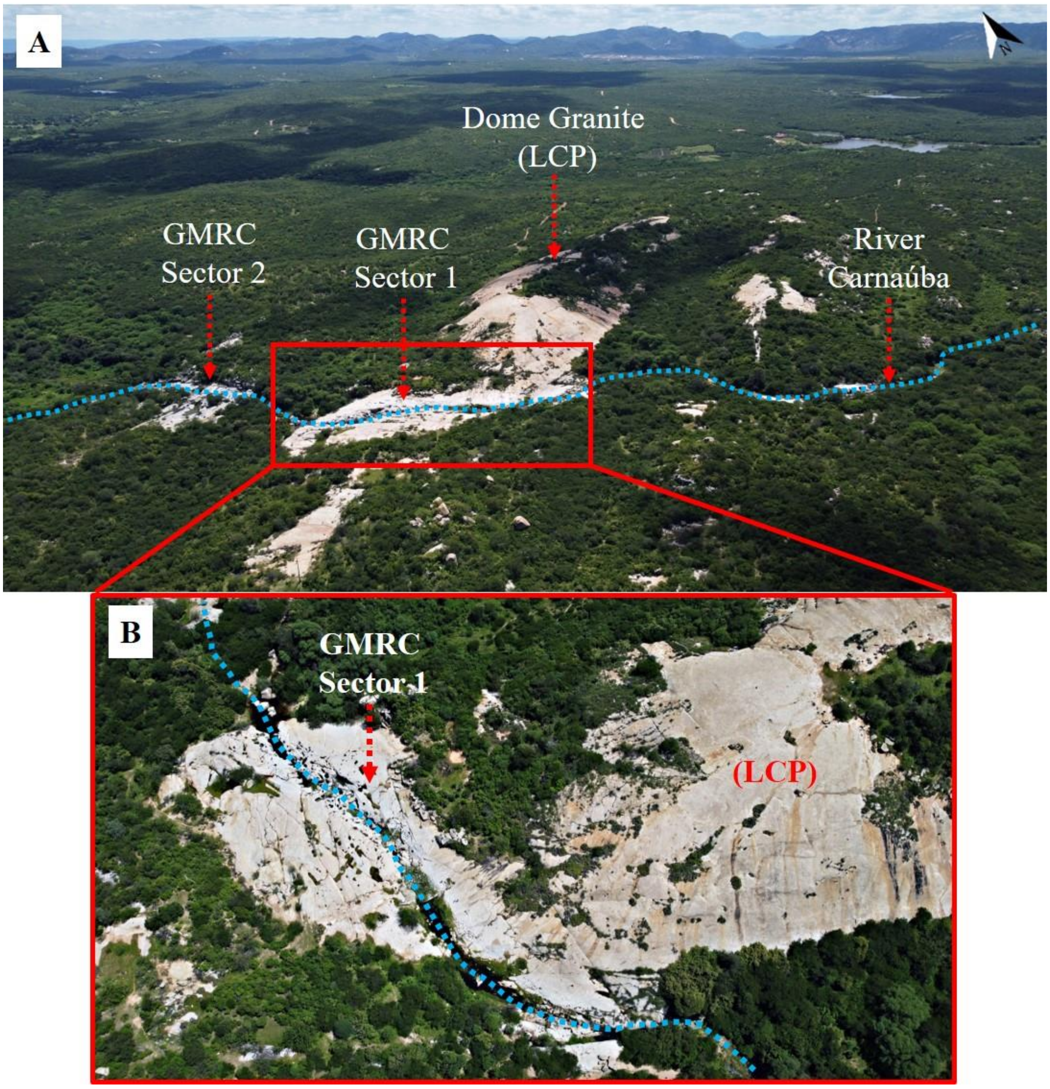

Figure 6. (A) Aerial image of the GMRC during the rainy season (Sector 1 – Vale da Lua Potiguar; Sector 2 – Pedra da Caveira) and the LCP. (B) Highlight of Sector 1, where the Carnaúba River intersects the base of the LCP controlled by discontinuity structures. Source: Authors' collection (2023).

The divergence between the direction of the channel and the granitic dome indicates the adaptation of the Carnaúba River in the study area, where it has a slope between 1.5° to 4.2° (Mutzenberg, 2007), to planes of weakness that significantly influence fluvial dissection. In this section of anomalous convexity in the longitudinal profile, the main channel of the Carnaúba River exhibits characteristics consistent with a context of transverse drainage evolution by superimposition and flow during a regular rainy season, sufficiently high to cause abrasive bedrock wear.

The abrasive wear (corrasion) caused by the energetic collisions between the detrital sediments, of varied composition and grain size (e.g., sand and pebbles), transported by the turbulent flow, with the Carnaúba River bedrock, created initial local depressions of increased static pressure. The pressure exerted by the swirling motion of the water flow (evorsion) on the stationary bedload deepened and enlarged the depressions, resulting in features known as marmitas or potholes, which vary in shape and size.

In the GMRC area, the propagation of potholes is facilitated by the mineralogical predisposition of the granitic facies, the distribution of structural discontinuities (e.g., fractures, veins, and dikes), and the presence of mesocratic gneiss xenoliths, diorite megaenclaves, and other mafic enclaves. The presence of NW-SE oriented brittle structures enhances the efficiency of fluvial erosion determined by the resistance of the granitic facies and the limitations associated with semi-arid morphogenesis.

The discontinuity surfaces, as well as xenoliths and enclaves, conditioned and continue to condition the selectivity of weathering and the efficiency of fluvial erosive processes (Figure 7), which have shaped and continue to shape the potholes in the Carnaúba River bedrock, albeit with less intensity due to the stabilization of the semi-arid landscape climate in the Upper Holocene (Behling et al., 2000; Corrêa, 2001; Mutzenberg, 2007), and consequently, the intermittence of fluvial flow. This current characteristic of the Carnaúba River basin provides long periods of low or no fluvial activity, alternating with short periods of high flow and energy runoff, due to extreme rainfall events, thus having the capacity to transport bedload, as well as to form potholes and to expand or destroy existing ones.

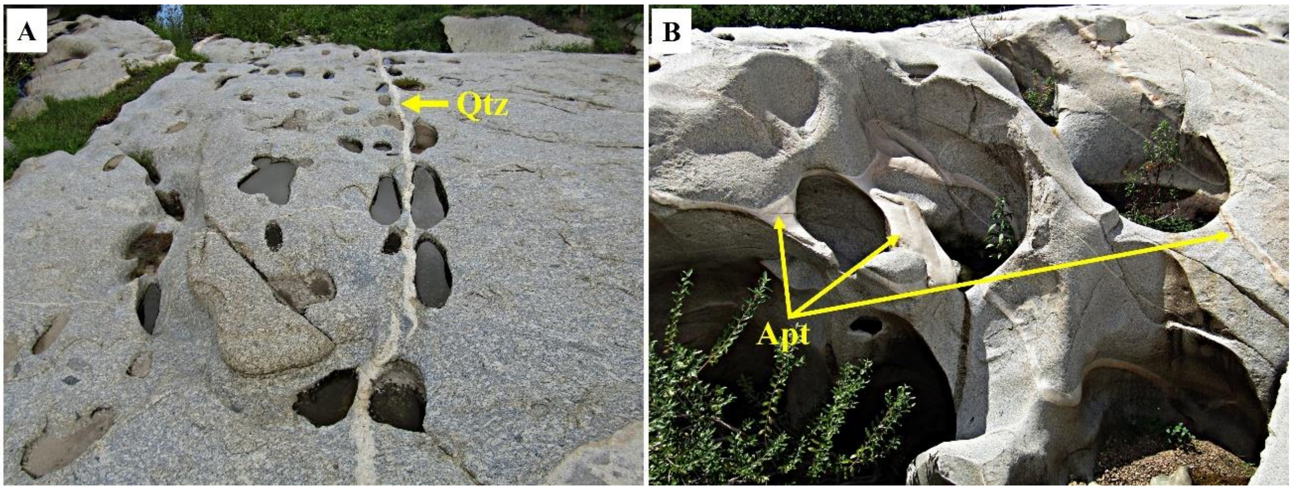

Figure 7. (A) Initial formation of potholes along discontinuity surfaces represented by the contact between a quartz vein (Qtz) and the host rock (inequigranular granite). (B) Potholes along the contact of aplite dikes (Apt) with equigranular granite. Source: Authors' collection (2023).

In Sector I of the GMRC, the corrasion and evorsion processes, given the higher resistance of the predominant leucocratic facies in this sector, had the following facilitating vectors for the formation and propagation of potholes: i) the incision of the main channel of the Carnaúba River along planes of weakness; ii) the high density of structural discontinuities intersecting the exposed rocks in the channel (Figure 8); iii) the contact between the granitic facies; and iv) the granular disaggregation of K-feldspar phenocrysts in the mesocratic facies, facilitated by the higher solubility of biotite compared to the other minerals analyzed.

The analysis of orientation patterns revealed a trend of NW-SE fracturing (Figure 8). This direction coincides with the major axis of development of most potholes, which vary in shape from sigmoidal to elliptical.

The incision of the main channel of the Carnaúba River along planes of weakness enhanced both the competence and capacity of fluvial transport. These characteristics of the Carnaúba River in the GMRC area can be observed through the caliber and quantity of sediments found both in the riverbed and within the potholes (Figure 9).

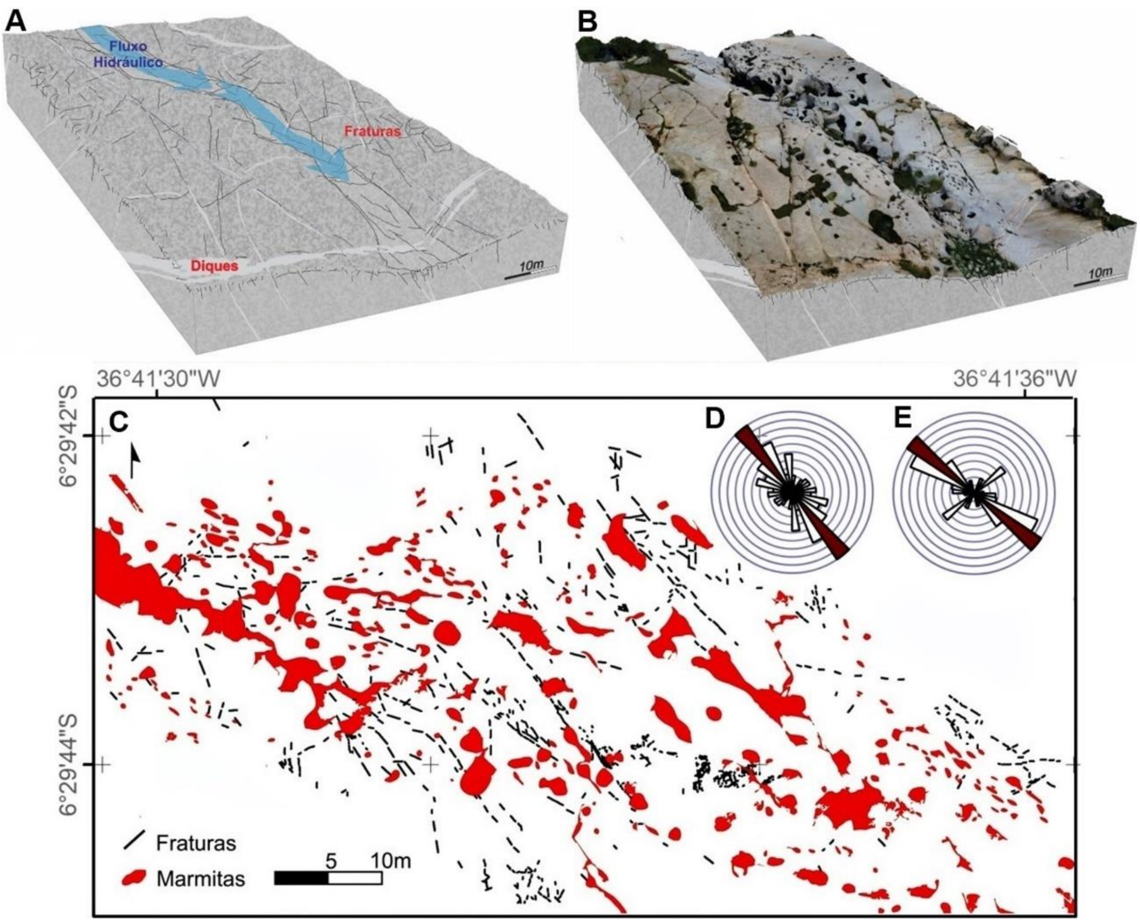

Figure 8. Sector I of GMRC. (A) Block diagram representing the fluvial flow of the Carnaúba River and the planes of weakness. (B) Orthomosaic showing the relationship between the planes of weakness and the distribution of potholes. (C) Rose diagrams of structures related to potholes, where "D" indicates the predominant direction of discontinuity planes and "E" indicates the main axis direction of the potholes. Source: Authors' collection (2023).

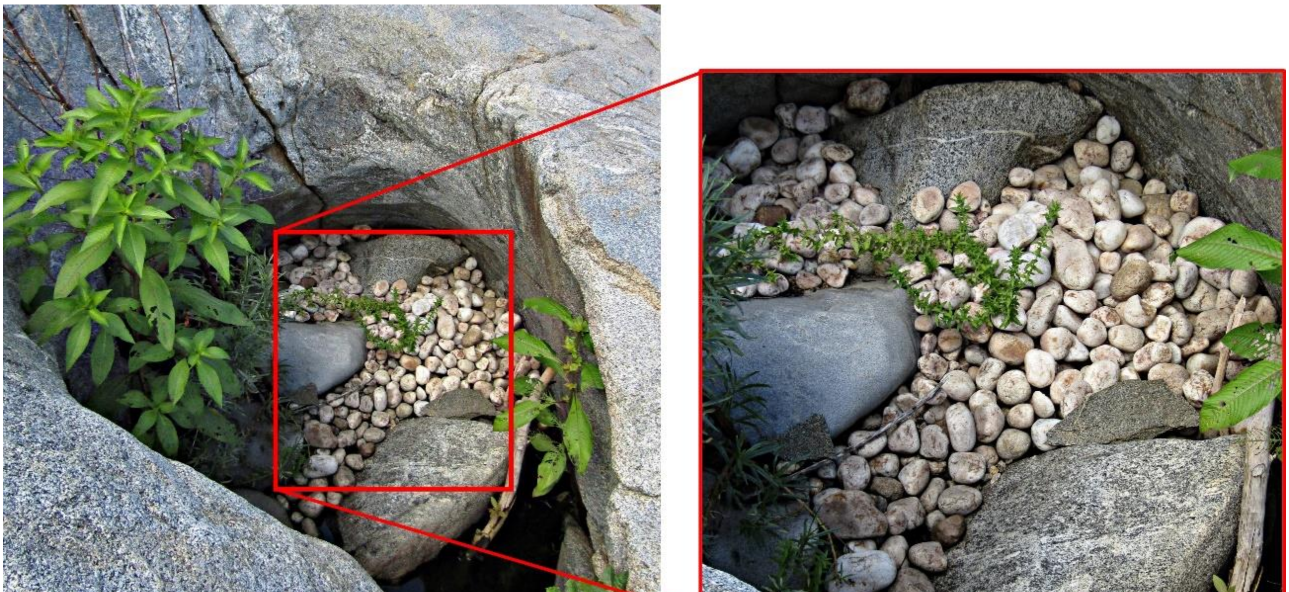

Figure 9. Caliber of abrasive load (quartz pebbles) transported by the Carnaúba River, filling the pothole. Source: Authors' collection (2023).

The abrupt orthogonal inflection of the main channel, from the NNE-SSW direction to WNW-SSE (Figure 2), and the occurrence of abandoned fluvial terraces (Mutzenberg, 2007), observed near GMRC, may be correlated with vertical neotectonic efforts, possibly altering the channel gradient by ≈11 m and thereby influencing fluvial erosion processes.

Mutzenberg (2007), analyzing the spatial distribution of the RDE (Relief Declivity Ratio) index in BHRC, stated that RDE values tend to increase along the basin, with the highest values near its mouth at the Acauã River, indicating a strong influence of neotectonic processes in the last kilometers of the basin, where the study area is located.

Chemical and physical weathering along discontinuity structures and in small cavities originated by the granular disaggregation of microcline megacrystals, as well as in mafic enclaves and xenoliths, contributed to weakening the granitic facies, thereby facilitating abrasive wear and vertical turbulent flow.

In Sector II of GMRC, there is a high incidence of well-developed potholes due to the following characteristics: i) a small slope break of ≈6 m, corresponding to a channel gradient change between the upstream section (Sector I of GMRC) and a downstream section; ii) predominance of two mesocratic granitic facies, one dioritic, and one porphyritic; and iii) significant occurrence of aplite dikes/veins of equigranular leucomicrogranite, fractures, and fissures.

The change in slope in the river channel, creating a knickpoint, determined the alteration in hydraulic gradient between the two sectors of the geosite, thereby enhancing the efficiency of corrasion and evorsion processes. The enrichment of granitic facies in mafic minerals (e.g., biotite), which increase their solubility, and the high density of aplite dikes/veins providing sectors of fragility, facilitated processes associated with the genesis and evolution of potholes. Meanwhile, brittle deformation structures, being preferential areas for physical-chemical weathering, induced processes of pothole coalescence.

4.3. Spatial Distribution and Morphological Classification of Potholes

In GMRC, a total of 849 potholes were counted, with 638 in Sector I (Vale da Lua Potiguar) and 211 in Sector II (Pedra da Caveira), ranging in length from 0.08 m to 24 m (average ≈0.87 m), width between 0.03 m to 11 m (average ≈0.48 m), and depth from 0.01 m to 3.7 m (average ≈0.23 m).

Of this total, only 45 potholes are partially filled with detrital sediments (sand and pebbles), with some of these located away from the main channel, indicating the competence and capacity of the Carnaúba River's fluvial flow, as well as a higher water flow level resulting from both a more humid paleoclimate and current episodes of torrential rains. Besides the Quaternary climatic influences, the presence of potholes away from the current bed of the Carnaúba River may possibly be associated with changes in the thalweg due to neotectonics, thereby justifying a higher concentration of incipient potholes on the right bank of the Carnaúba River, near the main channel.

Despite the variety of forms, and although each sector of GMRC presents specific lithostructural characteristics, such as mineralogical predisposition to chemical alterations, we categorized the GMRC potholes according to the morphometric parameters adopted by Richardson and Carling (2005) into four groups: incipient, cylindrical, sigmoidal (coalescent), and lateral.

Incipient or elliptical potholes are shallow and elongated cavities in the direction of flow (length [L] > width [W]), immature, located near the river channel, i.e., turbulent flow, representing the initial stage of formation, which is closely associated with hydraulic vortices, whose static pressure direction can vary between horizontal and vertical (Figure 10).

The evolution towards cylindrical form occurs gradually from deepening and widening, provided by increased vertical vorticity. According to Richardson and Carling (2005), at this stage of formation, potholes often cannot retain sediments due to their limited vertical dimensions.

Figure 10. Incipient potholes, in "footprint" shape, oriented longitudinally to the flow of the Carnaúba River. "C" indicates length and "L" width. Source: Authors' Collection (2023).

Most cylindrical (C ≅ L) or sub-cylindrical (C > L) potholes are also concentrated near the main channel, where the water flow occurs for longer periods and with vertical vorticity, capable of concentrating static energy and eroding the bedrock substrate. These negative features are relatively symmetrical (length ≅ width) (Figure 11); however, in some cases, they exhibit an elongated elliptical circular shape, where the ellipticity of the horizontal sections varies with cavity depth.

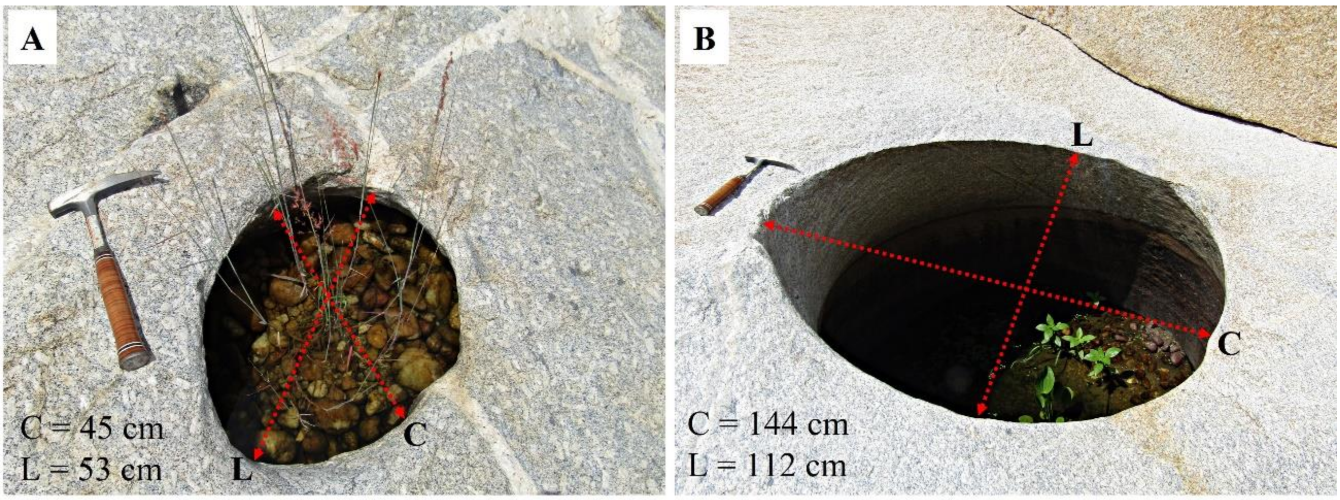

Figure 11. (A) Cylindrical-shaped pothole with relatively symmetrical dimensions. (B) Incipient pothole with an ellipsoidal appearance, where the length is much greater than the width. "C" indicates length and "L" indicates width. Source: Authors' Collection (2023).

These cavities correspond to the second stage of pothole evolution proposed by Lorenc, Barco, and Saavedra (1994), where the depth and diameter of the cavities remain approximately proportional. Richardson and Carling (2005) state that the nearly circular shape indicates early stages of pothole development, i.e., low maturity.

Their genesis is associated with the action of hydraulic vortex, which provides progressive abrasive wear by sand particles and pebbles that increase the size of the cavities. However, there comes a point where the flow energy is inadequate to lift detrital sediments (e.g., pebbles) into rotation, and consequently, abrasive wear becomes less effective at the top of the pothole (LORENC; BARCO; SAAVEDRA, 1994; SPRINGER; TOOTH; WOHL, 2006). Over time and with increased lateral vorticity, cylindrical shapes evolve into sigmoidal forms.

Due to their greater depth, which enables water accumulation during dry periods, as well as the density of discontinuity structures and the predominance of porphyritic and mesocratic granitic facies, we can affirm that the evolution of this pothole typology in GMRC has been heavily influenced by chemical weathering. Furthermore, the positioning of cylindrical potholes away from the river channel or "abandoned" suggests a recent decrease in the flow of the Carnaúba River.

Sigmoidal (compound) potholes represent the most advanced stage of evolution, corresponding to the coalescence phase, where the erosive vortex action on one of the pothole walls is conditioned by horizontal discontinuity structures, which facilitate the merging of cavities (Figure 12). During the coalescence phase, there is complete dissonance between the length and width of the cavity..

Figure 12. Coalescence of potholes induced by aplite veinlets of leucomicrogranite. Pothole outline (yellow dashed line), wall delimiting the potholes (red dashed line), white arrow (direction of secondary flow), and blue arrow (orientation of vertical vortex). Source: Authors' Collection (2023).

The result of pothole coalescence is a complex concave feature, generally with a vertical axis shorter than the horizontal axis, exhibiting, in some cases, relics of partition walls ranging from rounded and smooth to sharp, protruding vertical crests.

The genesis of these potholes is related to the resumption of erosive capacity of hydraulic vortices, which begin to widen the basal portion of the potholes laterally, making the diameter of the base progressively larger than the top, as the lower part of the pothole becomes more "bulbous" (LORENC; BARCO; SAAVEDRA, 1994). Therefore, their evolution is generally associated with an evolutionary stage of cylindrical potholes (ORTEGA-BECERRIL et al., 2014).

Richardson and Carling (2005) state that the connection of individual cavities and the consequent development of sigmoidal/compound forms occurs due to internal secondary sculpturing, which creates small-scale vortices at the base or walls of the pothole. The relationship between the morphology of these cavities and the presence of joints and fractures supports the idea of different stages of development (deepening and widening) occurring simultaneously (ÁLVAREZ-VÁZQUEZ; UÑA-ÁLVAREZ, 2017).

In GMRC, the direction of expansion of sigmoidal potholes is conditioned by the orientation of discontinuity surfaces. However, this direction can be altered, either by rotating to follow the orientation of a secondary weakness plane that intersects the initial path of coalescence, or because a dike or vein of higher resistance creates a barrier to fluvial erosion and/or weathering processes, causing the direction of abrasive wear of the cavities to shift towards more weakened lithologies.

This morphological typology occurs in both sectors of GMRC, but with greater frequency in Sector II (Pedra da Caveira), where metric-sized cavities are observed, likely due to the predominance of mesocratic facies. Larger cavities are found away from the river channel, while smaller ones are located near it. However, all are associated with discontinuity structures, regardless of their location relative to the Carnaúba River channel.

The positioning of large potholes away from the river channel suggests that the water flow level in the Carnaúba River was possibly higher in the Middle Holocene than at present, or that there was lateral migration of the river thalweg, thus justifying a higher concentration of incipient potholes on the right bank of the Carnaúba River, especially in Sector I of GMRC.

The presence of metric-sized potholes also suggests an "ancient" evolutionary stage, indicating erosive maturity. Conversely, the significant number of incipient and cylindrical potholes, representing immature forms, in both sectors of GMRC suggests more recent erosive wear on the bedrock, characterizing stages of youth.

Lateral potholes are slightly rounded features, deeper than wide, located on the sidewalls of the Carnaúba River channel and along the flanks of flow obstacles (rock blocks), representing a destructive phase with broken floors and walls and a certain degree of maturity (Figure 13). These cavities create small recesses in the channel walls and sections with strong turbulence upstream. In Sector I of GMRC, these potholes are closely related to some type of discontinuity structure, especially pegmatite or leucomicrogranite dikes, which facilitate both evorsion and plucking processes. The collapse of these features gradually modifies the width of the rocky channel.

Due to their broken structures, these cavities do not generate vorticity and, consequently, their dimensions (diameter and depth) remain stable (ORTEGA-BECERRIL; GARROTE, 2023). The high flow velocity along the channel-confined walls justifies the width and depth of the potholes, as well as their collapse.

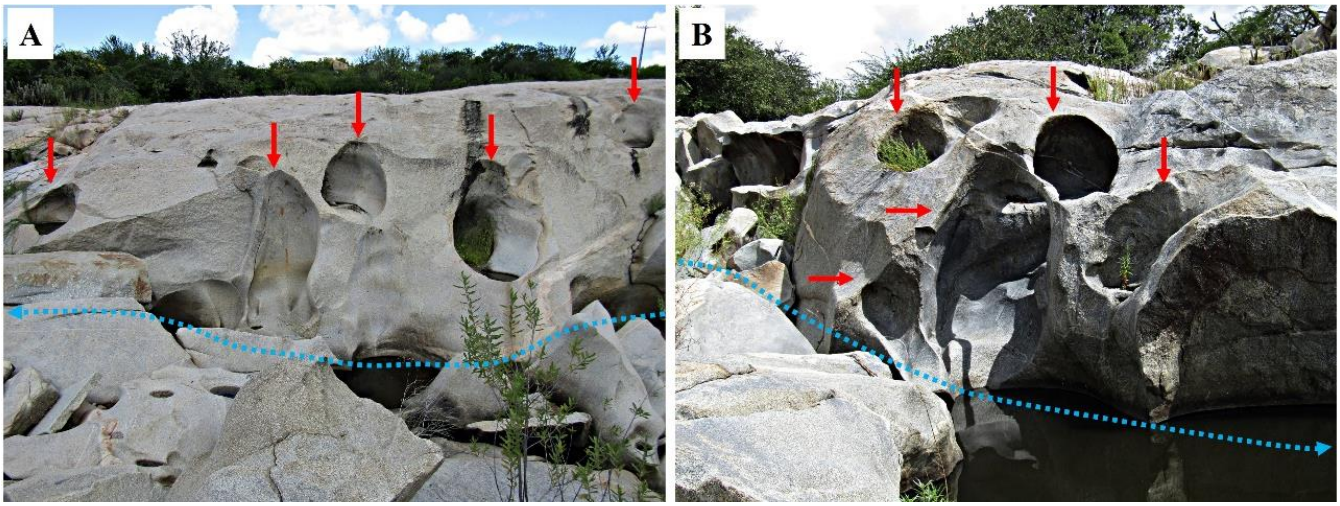

Figure 13. Asymmetric lateral cavities with vertical walls broken by vortices from the main flow of the Carnaúba River. (A) Sector I GMRC, known as Vale da Lua Potiguar. (B) Sector II - Pedra da Caveira. Red arrows indicate lateral potholes, and the blue dashed line represents the main channel of the Carnaúba River. Source: Authors' Collection (2023).

5. Discussion

In a generic sense, the genesis of potholes, regardless of the lithology of the bedrock, is associated with the process of evorsion (RICHARDSON; CARLING, 2005; SPRINGER; TOOTH; WOHL, 2006; PEIFER et al., 2022; ORTEGA-BECERRIL; GARROTE, 2023), as if it were a singular, independent process. However, the formation and development of these fluvial features are conditioned by the following factors: presence of structural discontinuities and knickpoints; mineralogical predisposition of the bedrock substrate; and concentration of mafic minerals arranged as enclaves (LORENC; BARCO; SAAVEDRA, 1994; SPRINGER; TOOTH; WOHL, 2006; YIN et al., 2016; COSTA et al., 2021).

Springer, Tooth, and Wohl (2006) state that high flow velocity and sediment grain size associated with irregularities of the bedrock are factors enabling the occurrence of potholes. However, it is important to note that in the absence of bedload sediment, the river flow alone lacks competence to carve out well-known erosive bed forms such as potholes, erosional flutes, and ripple marks (WIPPLE; HANCOCK; ANDERSON, 2000; YIN et al., 2016).

Detrital sediments are essential tools for evorsion (DHALI; BISWAS, 2017; ORTEGA-BECERRIL; GARROTE, 2023); however, if sediment input increases to a point where it exceeds the transport capacity of the river flow, causing the bedrock to be covered, abrasive wear will diminish because the covered bed will be shielded from energetic collisions between transported sediments and exposed rocks (PEIFER et al., 2022). Given that GMRC lies near a discrete knickpoint, which justifies a higher energetic gradient, the bed is entirely rocky, contributing to a higher density of potholes. However, both upstream and downstream of the study area, topographic smoothing results in lower energy and greater alluvial deposition, reducing pothole occurrence due to limited rocky substrates.

In these beds, lithostructural factors such as orientation of foliation planes, presence of dikes or enclaves, as well as the lithotype composition itself, must be considered for the formation of all bed morphology when sculpted directly on basement rocks.

In the study area, granitic facies exhibit a high density of discontinuity structures, exposing weakness planes to physical-chemical weathering processes, indirectly contributing to pothole formation. In both Sector I and Sector II of GMRC, potholes are preferably aligned parallel to faults, fractures, veins, and dikes, where microenvironments with higher moisture content are established. Initial weathering primarily occurs along weak planes, especially in zones where water can percolate or reside for extended periods (MAIA et al., 2022).

The different shapes and dimensions suggest, in some areas of the GMRC, that potholes are linked in an evolutionary sequence associated with weak planes and prolonged action of chemical weathering, primarily dissolution, especially in Sector II where there is a predominance of mesocratic facies intersected by aplite dikes/veins. The role played by mineralogical variation in the weathering process, according to Maia et al. (2022), should be highlighted, considering that the solubility of certain minerals can either promote chemical weathering (e.g., biotite) or limit its effectiveness (e.g., quartz).

Granitic rocks are composed of significant amounts of quartz crystals, which have low solubility, as well as feldspar and biotite, which are more soluble (PENTEADO, 1983). The mineral heterogeneity in granite is reflected in its chemical and textural characteristics, density, and pattern of fracturing, contributing to different morphological patterns (VIDAL ROMANÍ; TWIDALE, 2010).

The occurrence of potholes in one of the lower slope sectors of the BHRC, between 1.5° to 4.2° (MUTZENBERG, 2007), where the potential energy of water flow in most river channels is low, points to a typical example of local base level rejuvenation, possibly due to vertical neotectonic efforts (MUTZENBERG, 2007), which altered the longitudinal profile by approximately 11 m in the lower course. According to Dhali and Biswas (2017), potholes are predominantly found in the upper and middle courses of rocky-bedded drainage channels, where flow energy is maximal.

This change in local base level, associated with the incision of the main channel of the Carnaúba River into brittle deformation structures, concentrated flow and consequently increased competence and sediment transport capacity of detrital sediments.

Due to the current semiarid context, the Carnaúba River is typically intermittent, with surface flow during the rainy season from February to May. This current characteristic of the BHRC provides long periods of low or no fluvial activity, alternating with short periods of high-flow and high-energy discharge due to extreme rainfall events, thereby having competence for sediment transport in saltation, as well as for pothole formation and enlargement or destruction of previously developed cavities.

In arid and semiarid drylands, fluvial systems generally lack the competence to transport sediment in saltation (GOUDIE, 2013). However, during episodes of high intensity and energy, such as extreme rainfall events (POWELL, 2009), or during periods of increased water availability due to regular rainy seasons, such as in the Brazilian semiarid region, these channels effectively incise and transport sediment in saltation.

Hydrological parameters such as discharge, water velocity, seasonal variation of water, and energy of the river course play a fundamental role in the formation of new potholes, with seasonal variation in turbulent flow being the most important in this process (MILLER, 1991). Prolonged turbulent flows, according to Dhali and Biswas (2017), also create new potholes while enlarging and destroying old cavities, filling them with sediment.

The existence of continuous turbulent flows, associated with a higher water flow level than at present in the study area, likely during the Middle Holocene, a period when, according to Mutzenberg (2007), the BHRC had a more seasonal and regular precipitation regime, referred to as the Climatic Optimum (CORRÊA, 2001; MISSURA, 2013), can be evidenced by the presence of metric-sized sigmoidal potholes on the left bank of the Carnaúba River, away from the current main channel.

In addition to factors related to Quaternary climatic influences, the presence of potholes away from the current bed of the Carnaúba River may possibly be associated with changes in the thalweg due to neotectonics, thus justifying a higher concentration of incipient potholes on the right bank of the Carnaúba River, near the main channel.

6. Conclusions

This study reaffirms that abrasion is the key process necessary for the formation of potholes in rocky beds. However, the GMRC presents a wide range of factors that influence the genesis, evolution, and morphology of these features. Among these factors, the following stand out: i) alteration of the channel gradient; ii) incision of the main river channel into brittle deformation structures; iii) mineralogical composition of granitic rocks (predominance of mesocratic facies); iv) high density of structural discontinuities; v) concentration of mafic minerals arranged as enclaves; and vi) seasonal variability of river flow.

The constriction of the Carnaúba River channel enhanced the efficiency of fluvial erosion, dictated by the resistance of the bedrock, and generated sectors of increased static pressure in turbulent flows with bed load, which exploited the discontinuity structures, thereby triggering the formation of potholes.

Therefore, structural discontinuities influence the genesis, evolution, orientation, and morphology of potholes, specifically in resistant and non-directional rocky riverbeds such as granite. The orientation of weak planes relative to the direction of river flow and the presence of resistant veins and dikes promote bedrock abrasion and erosion. In the GMRC, the elongation orientation of potholes and discontinuity structures are highly correlated.

Contributions of the Authors: conception, DIAS, J. R. V., CORDEIRO, A. M. N.: methodology, DIAS, J. R. V., CORDEIRO, A. M. N., BASTOS, F. H.: software, DIAS, J. R. V., CORDEIRO, A. M. N., MAIA, R. P.: validation, CORDEIRO, A. M. N., BASTOS, F. H.: shape analysis, CORDEIRO, A. M. N., BASTOS, F. H., MAIA, R. P., NASCIMENTO, M. A. L.: investigation, DIAS, J. R. V., CORDEIRO, A. M. N., BASTOS, F. H.: data curation, DIAS, J. R. V., CORDEIRO, A. M. N.: writing – original draft preparation, DIAS, J. R. V., CORDEIRO, A. M. N.: writing – review and editing, BASTOS, F. H., MAIA, R. P., NASCIMENTO, M. A. L.: supervision, CORDEIRO, A. M. N. All authors have read and agreed to the published version of the manuscript.

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