https://rbgeomorfologia.org.br/
ISSN 2236-5664

Revista Brasileira de Geomorfologia

v. 25, nº 1 (2024)

http://dx.doi.org/10.20502/rbg.v25i1.2392

Research Article

Morphostructural aspects of the sandstone karst in Northeastern Brazil: Example from Serra da Capivara – PI

Aspectos morfoestruturais do carste em arenitos no NE brasileiro: Exemplo da Serra da Capivara – PI

Mickaelle Braga da Silva [1], Rubson Pinheiro Maia[2]

[1] Universidade Federal do Ceará, Departamento de Geografia, Fortaleza, Brasil.
E-mail: mickaellebragas@gmail.com
ORCID: https://orcid.org/0009-0001-4242-2135

[2] Universidade Federal do Ceará, Departamento de Geografia, Fortaleza, Brasil.
E-mail: rubsonpinheiro@yahoo.com.br
ORCID: https://orcid.org/0000-0002-1688-5187

Received: 25/04/2023; Accepted: 10/08/2023; Published: 30/01/2024

Abstract: This work analyses morphostructural aspects and their influence on the development of the karst relief of Serra da Capivara (State of Piauí, northeastern Brazil). For this purpose, structural data derived from lineament extraction, sedimentary bed geometry, karstification degree of the layer, and analysis of the karst morphology were performed. Structural lineament data showed a NE-SW orientation trend, coinciding with the orientation of the Transbrasiliano Lineament. The reactivation of the brittle structures can be related to the orientation, scarp retreat, direction, and incision of the main valleys. From the analysis of the fracture array (NE-SW) and bedding planes, we suggest that the fracture connectivity of these structures resulted in conduit formation, which evolved to form subterranean galleries. Thus, the expansion of the karst system led to the formation of valleys, which are situated in higher deformed zones, such as fold hinges. These valleys currently constitute the most advanced stage of karstification, with the development of the tributary drainages as the most recent stage. The structural directions show a NE-SW trend, represented by larger valleys, and subordinated to this, an NW-SE trend, where headwaters of low-order channels are located.

Keywords: Morphostructural analysis; Karst relief; Geomorphological evolution; Serra da Capivara

Resumo: O presente trabalho analisa os aspectos morfoestruturais e sua influência no desenvolvimento do relevo cárstico da Serra da Capivara (Piauí, NE do Brasil). Para tanto, foram utilizados dados estruturais provenientes de extração de lineamentos, geometria das camadas estratigráficas, grau de carstificação da camada e análise da morfologia cárstica. Os dados de lineamentos estruturais da área evidenciaram uma tendência de orientação principal NE-SW, mesma direção do Lineamento Transbrasiliano. A reativação das estruturas frágeis pode estar relacionada à orientação, ao recuo das vertentes, à direção e ao encaixe dos vales principais. A partir da análise do arranjo de fraturas (NW-SE) e dos planos de acamamento, sugere-se que a conectividade dessas estruturas resultou na formação de condutos, os quais evoluíram para galerias subterrâneas. Assim, a expansão do sistema cárstico levou a formação dos vales, os quais estão situados em zonas mais deformadas, como charneiras de dobras. Esses vales atualmente compõem a fase mais avançada da carstificação, tendo o desenvolvimento da rede de tributários como o estágio mais recente. As direções estruturais mostram uma tendencia NE-SW, representada pelos vales mais largos, e subordinada a esta, NW-SE, onde se situam as cabeceiras dos canais de ordem inferior.
Palavras-chave: Análise morfoestrutural; Relevo cárstico; Evolução geomorfológica; Serra da Capivara

1. Introduction

Karstification processes are not restricted to carbonate rocks, so that is possible to identify typical features of this system in terrains built of siliciclastic rocks, such as sandstones (HARDT, RODER e PINTO, 2010; YOUNG, 2010). This widened the possibilities of interpretation of geomorphological landscapes in a number of geological settings, further reinforcing the karst as a significant component in the explanation of landscapes.

In Brazil, works on karst relief have instigated important findings, such as studies on the abysses of Serra do Caraça (quartzite, MG), almost 500 m deep and more than 3.000 m in length, and the Guy-Collet Abyss (Serra do Acará, AM), the deepest of the world built in quartzites, with a depth of 670 m (EPIS, 2007; HARDT, RODET e PINTO, 2010). Near the city of Ouro Petro, MG, smaller cavities were studied in the Serra do Itacolomi (WIEGAND et. al., 2004). Still in the brazilian scientific scenario, we highlight the works of Wernick, Pastore and Pires Neto (1973); Troppmair and Tavares (1984); Martins (1985); Karmann (1986); Veríssimo and Spoladore (1994); Corrêa Neto and Batista Filho (1997); Corrêa Neto (2000); Monteiro e Ribeiro (2001); Hardt (2003); Auler (2004); Silva (2004); Spoladore (2006); Willems *et al.* (2004, 2008); Uagoda, Avelar and Coelho Netto (2006); Hardt and Pinto (2008); Hardt (2009); Morais (2009); Rodet *et al.* (2009), and Hardt *et al*. (2009).

Concerning the works that emphasized and analyzed sandstone karst landscapes in the brazilian and northeastern context, we point out the studies in the following places: Chapada dos Guimarães and Parecis (MT) (HARDT, 2011); Vila Velha (PR) (SALLUM FILHO e KARMANN, 2007; PONTES et al 2020); Palmas, Dianópolis and Palmeirópolis (TO) (MORAIS, 2009; MORAIS e SOUZA, 2009); Catimbau (PE) (FERREIRA *et al.*, 2017); Chapada Diamantina (BA) (PEREIRA, 1998); Serra das Confusões, Serra da Capivara and Sete Cidades (PI) (BARBOSA e FURRIER, 2012; CHARBER e COURBON, 1997; SANTOS, 2001; DELLA FAVERA, 2002; MUTZENBERG et. al., 2015).

In order to contribute to the understanding of the formation of the sandstone karst system in the brazilian Northeastern context, this research presents a morphostructural analysis concerning the development of the karst relief in Serra da Capivara (Piauí, Brazil). From this perspective, the research aims to comprehend the structural context in which the origin and evolution of the analyzed relief occurred, and the lithostructural and tectonic influence in the area. For this purpose, morphostructural data were collected and their repercussions in the drainage network incision and the current relief configuration were investigated.

2. Location and hydroclimatic characterization of the study area

The study area (representative geomorphological features) is located in the municipality of Coronel José Dias (Piauí, Brazil), bordered in the west by the municipality of São Raimundo Nonato (PI), comprising a polygon of 89 km² in the southeast of the State of Piauí. The area is inserted in the Serra da Capivara National Park (PARNA), where it can be found the geological landmark "Arco do Triunfo da Pedra Furada", a feature with a high tourist appeal (Figure 1). The features are underlain by sandstones and conglomerates of the Serra Grande Grup (Ipu Unity) and are bounded to the north by sandstones, shales, and siltites of the Pimenteiras Unit (Canindé Group), and to the south by the Barra Bonita Formation (Unity 1) composed of metalimestones, with subordinated intercalations of silt-argillaceous and arenaceous metasediments (PFALTZGRAFF, TORRES e BRANDÃO, 2010).

The climate is semiarid, with irregular precipitations, an annual average of 650 mm, and annual potential evapotranspiration in the order of 1400 mm. The humid season is evident in the first four months of the year, while the dry season can last for over eight months (BARROS et. al., 2012). The rainfall occurrence is related to the northeastern climate context influenced by the Intertropical Convergence Zone (ITCZ), as well as associated mechanisms, including Cold fronts, Upper-Tropospheric Cyclonic Vortex (UTCV), and easterly waves (NIMER, 1989). The temperatures oscillate between a minimum of 12 °C, averages of 25 °C, and a maximum of 35 °C (BARROS et. al., 2012).

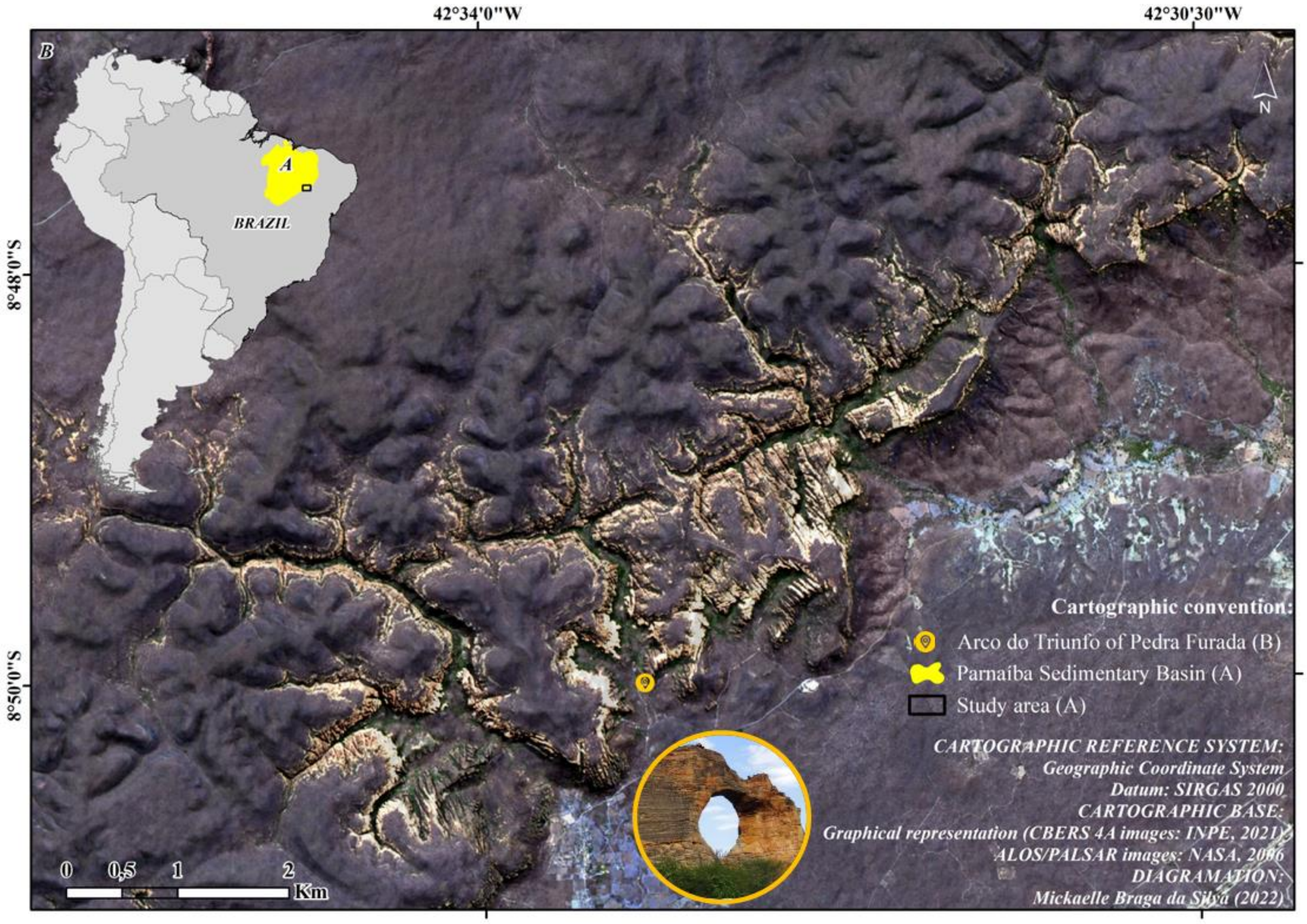

Figure 1. Location of the study area (B). Position of the area in the context of the Parnaíba Sedimentary Basin, and in South America (A).

3. Materials and Methods

The bibliographic survey supporting the discussion of this research was combined with cartographic surveys, in order to identify the representations (charts, maps, images) of the area, as well as the collection of remote sensing products, which were essential to carry out the mapping of the geomorphological features. Initially, fieldwork was necessary for the general recognition of the area, and to make photographic records of the landscape. Moreover, the application of geoprocessing techniques helped the extraction, characterization, and spatialization of the drainage network and relief lineaments.

Among the remote sensing products available for the study area, MDE ALOS/PALSAR data with a spatial resolution of 12.5 meters were utilized, which are gratuitously available by the Laboratory of Remote Sensing of the University of Alaska Fairbanks at the following address: https://vertex.daac.asf.alaska.edu/. In addition, the analyses were supported by satellite images of 2m-resolution, freely available by Google Satellite (Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN and GIS User Community) and aerial photographs acquired with drone. The softwares utilized were ArcGis (version 10.4), Global Mapper (version 18), PCI Geomatic and OpenStereo.

The cartographic representations and the remote sensing products allowed for the elaboration of thematic maps and tridimensional models, and for the extraction and vectorization of geomorphological features in the study area. Automatic extraction of the drainage network was executed in GIS environment, by using the tool TauDEM (Terrain Analysis Using Digital Elevation Models) enabled by the ArcGis software; this was combined with visual interpretation for further detailing of these features.

The lineament extraction was executed automatically combined with manual interpretation. This process was enabled by the software PCI Geomatic in the Focus module, using the LINE algorithm (Tools > Algorithm Librarian > LINE: Lineament Extraction). Therefore, linear features on the MDE ALOS/PALSAR were converted into vectorial segments based on global parameters, in which the values were modified from the visual interpretation of the 2m-resolution satellite image.

As a means to spatialize the lineament data concerning the fracturing features, a density map was elaborated. Similar to the drainage network data, statistics and rose diagram generation were used for presenting the trend direction and frequency of relief lineaments.

4. Geological and Geomorphological regional context

The study area is located at the junction of three provinces of the South American Platform: Borborema, São Francisco and Parnaíba. The two first are mostly composed of Precambrian rocks forming the basement of the latter, composed of sedimentary rocks (ALMEIDA, 1967; ALMEIDA et. al., 1981).

In terms of genesis, the region comprises the portion of the Parnaíba Basin that is a border of an intracratonic sedimentary basin (BPar). This area locally exhibits the shape of *cuesta* (homocline structure), where the layers were deposited during a stage of stabilization of the South American Platform (ALMEIDA e CARNEIRO, 2004), and corresponds to the margins of the Brasiliano Belt, which was eroded and underwent tectonic collapse. In its place, a syneclise basin was installed, having its origin related to the arrangement of intracratonic rifts resulting from the breakup of Panotia in Early Paleozoic, and which were later aborted (CASTRO *et al.,* 2016). In this context, the sedimentation of the Parnaíba Basin occurred during the rift phase related to the formation of the Cambro-Ordovician rifts of Jaibaras, Juguarapi, Cococi/Rio Jucá, São Julião, and São Raimundo Nonato (BRITO NEVES, 1998).

Associated with the inheritance of the Brasiliano shear zones, the tectonic evolution of the southeast border of the Parnaíba Basin occurred over at least three deformational events. The first, which occurred during Ediacaran-Cambrian, can be recognized only in the crystalline Precambrian basement and is related to a late-stage, retrometamorphic and plastic-brittle stage of the Brasiliano mylonite zones. The signature of this event includes NE-SW -strike transcurrent dextral shear zones and quartz veins filling distension joints E-W. The second event corresponds to a new stage of transcurrent dextral movement of the NE-SW structures, accompanied by normal faults and distension joints with orientations WNW to E-W, affecting, in this case, the Siluro-Devonian units. Finally, the third deformational cycle is characterized by normal faults, basic dikes (correlated to the Eocretacic Sardinha Suite), siliceous veins, and ridges of silicified sandstones, all striking NE-SW. This last phase results from a NE-SW distension, analogous to that recognized further to east, in the Interior Basins of Northeastern Brazil, related to the South Atlantic rifting (LIMA e SÁ, 2017).

Concerning the sedimentary lithostructural sedimentary units of the BPar present in the Serra da Capivara National Park (BARROS, *et. al.,* 2012; PFALTZGRAFF, TORRES e BRANDÃO, 2010) (Figure 2), the Cenozoic lateritic deposits (colluvial-eluvial) appear as the level of higher altitude and present a low degree of dissection, slightly inclined and following the plunge of the layers towards the center of the basin (preserved summit). The sandstones of the Cabeças Formation (Devonian) occur as slopes with a summit capped by the lateritic deposits (dissected top). On the other side, the sandstones, shales, and siltites of the Pimenteiras Formation (Devonian) compose the lower topographic sector between the Cabeças Formation and Serra Grande Group (sandstones and conglomerates of Silurian time), and display a distinct shape, acting as an intermediate surface between the two areas with a high degree of dissection (moderate summit); among these areas, the Serra Grande Group presents lower altitudes, but with a higher degree of relief dissection (very dissected summit) (MUTZENBERG et. al., 2015).

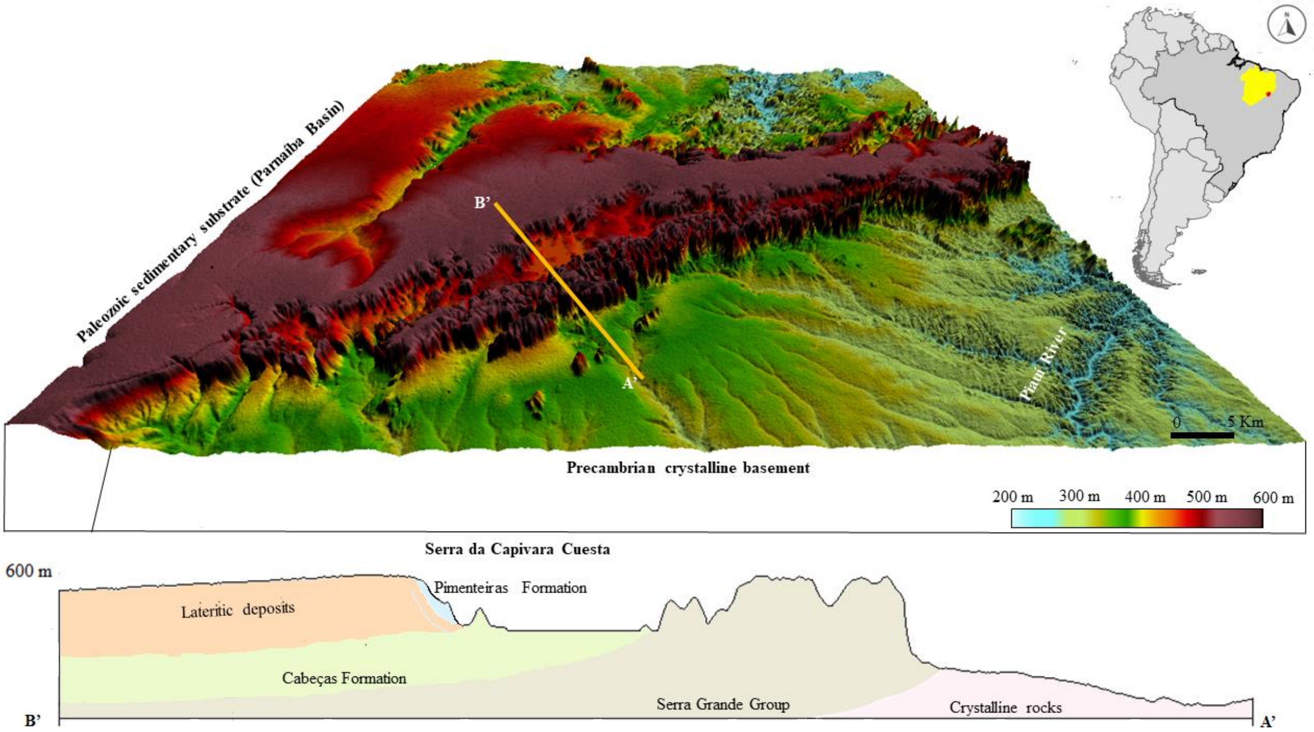

Figure 2. Block diagram and profile illustrating the topography of the Serra da Capivara National Park and adjacencies as well as the geomorphological behavior along the main lithostructural sedimentary units (Serra da Capivara Cuesta) and crystalline rocks (Sertaneja Surface).

As a result, the landforms of the area and its surroundings (Figure 3) are primarily related to the formations that constitute the BPar, being limited to the north by plateaus and to the south by flattened surfaces. In the topographic surface, the landforms appear as structural levels formed by valleys and eroded scarps, exhibiting a diversity of features, such as water gaps, canyons, plains, pinnacles, plateaus, besides rock shelters and caves (BARROS et. al., 2012).

Figure 3. Hillslopes underlain by sandstones of the Serra Grande Group with large, individualized blocks giving origin to residual features in the Serra da Capivara National Park.

5. Results

The results to be presented and analyzed reveal the lithostructural and tectonic influence in the area, demonstrating the behavior and the relationship between drainage and lineaments in the present morphological configuration.

5.1 Structural lineaments

The lineament data extracted in the area are presented in two representations, one in which relief lineaments were mapped, and the other in which a more detailed identification and mapping of fractures was carried out.

5.1.1 Relief lineaments

Concerning the relief lineaments mapped from the DEM, the linear features traced were those with surface repercussions – ridges, valleys, and scarp lines. According to the mapped features in Figure 4 and represented in Figure 5, the relief lineaments in the area display a primary NE-SW orientation trend, followed by an E-W trend.

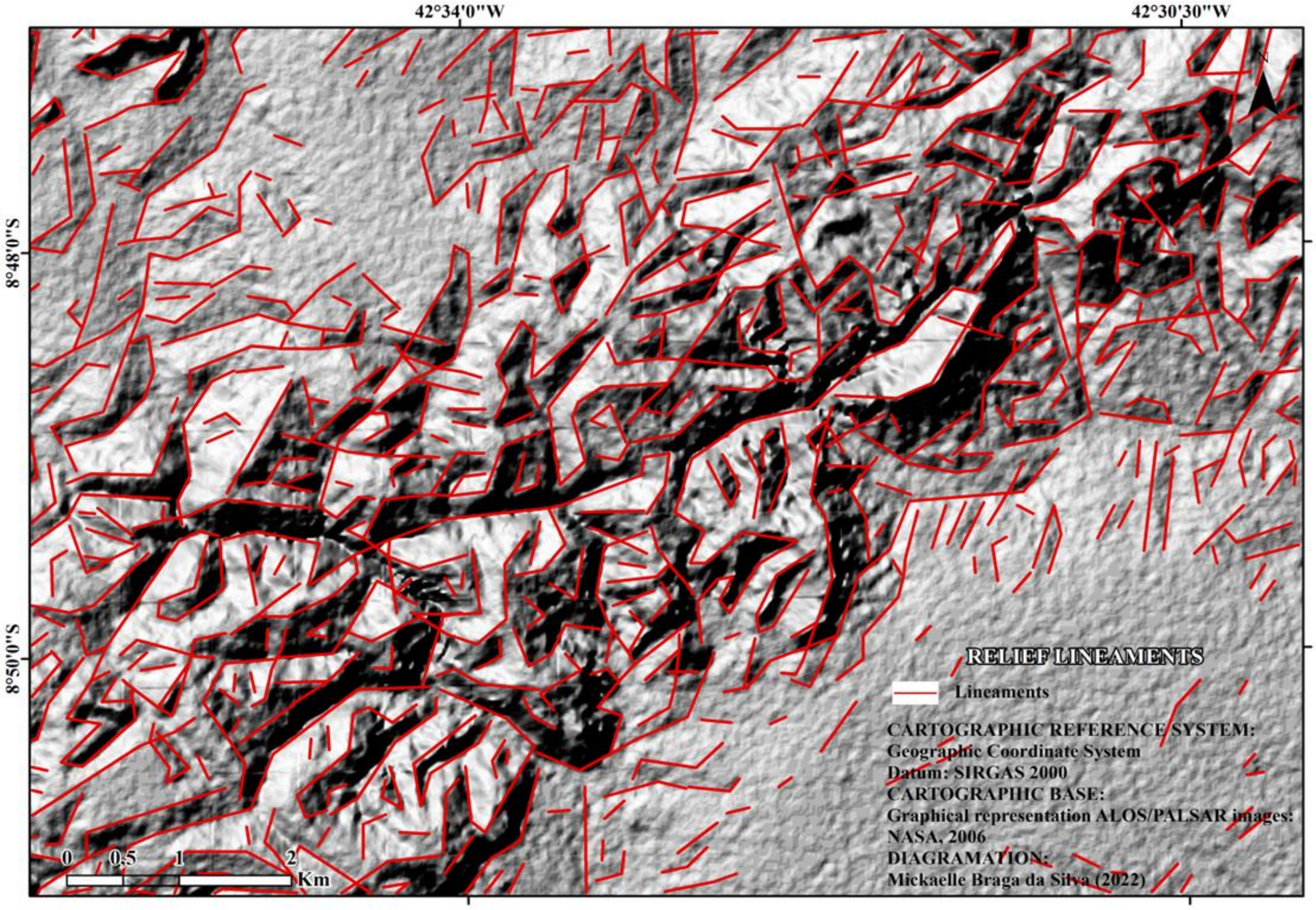

Figure 2. Map of relief lineaments extracted automatically in PCI Geomatic software.

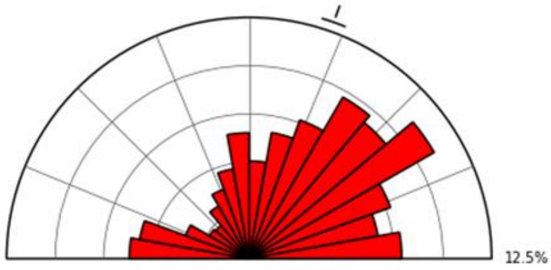

Figure 3. Rose diagram illustrating the Absolute Frequency of the relief lineaments mapped in the study area.

5.1.2 Fractures

The typical features of fracturing were extracted from high-resolution (2 m) satellite images, allowing the identification of fracture sets marked in the relief through vertical valley incisions (Figure 06). It was observed that in the upper outcropping facies of the Ipu Formation, the fractures are enlarged, whereas the idle and basal outcropping facies exhibit a more brittle behavior.

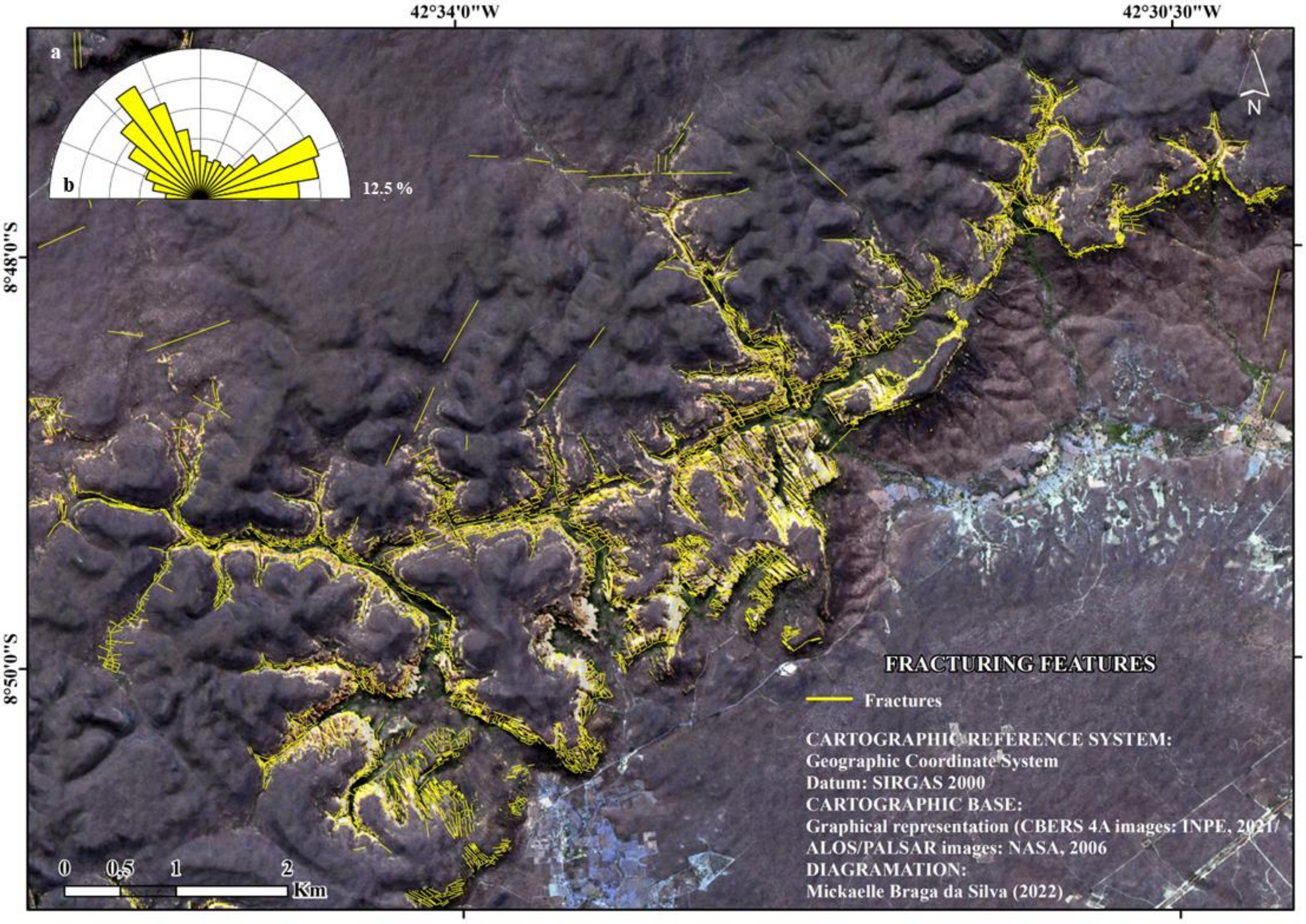

Figure 4. Structural lineaments: Fractures (a). Rose diagram according to the absolute frequency of the mapped fracturing features (b).

Regarding the direction of these features, it is possible to identify four main azimuthal intervals with features trending NW, W, NE, and N which appear on the surface forming a set of vertical and horizontal fractures (Figure 6).

The vertical fractures form two arrays with features perpendicular to each other associated with a third array composed of horizontal fractures, developed along the bedding planes. This arrangement allows us to infer, for vertical fractures, a classification of orthogonal pattern that, in association with the vertical set, provides a configuration on the surface of separated cubic sandstone blocks, and sectors with line scarps delimited and/ or disconnected in their extension by right angle contours.

The mapped fracturing features occur at the summit of the Serra da Capivara cuesta hillslopes and in isolated compartments at altitudes up to 590 m. A particular emphasis should be given to the clustering of features bordering the clefts formed by a narrow and extensive strip of sandstones and conglomerates of the Serra Grande Group (Figure 7).

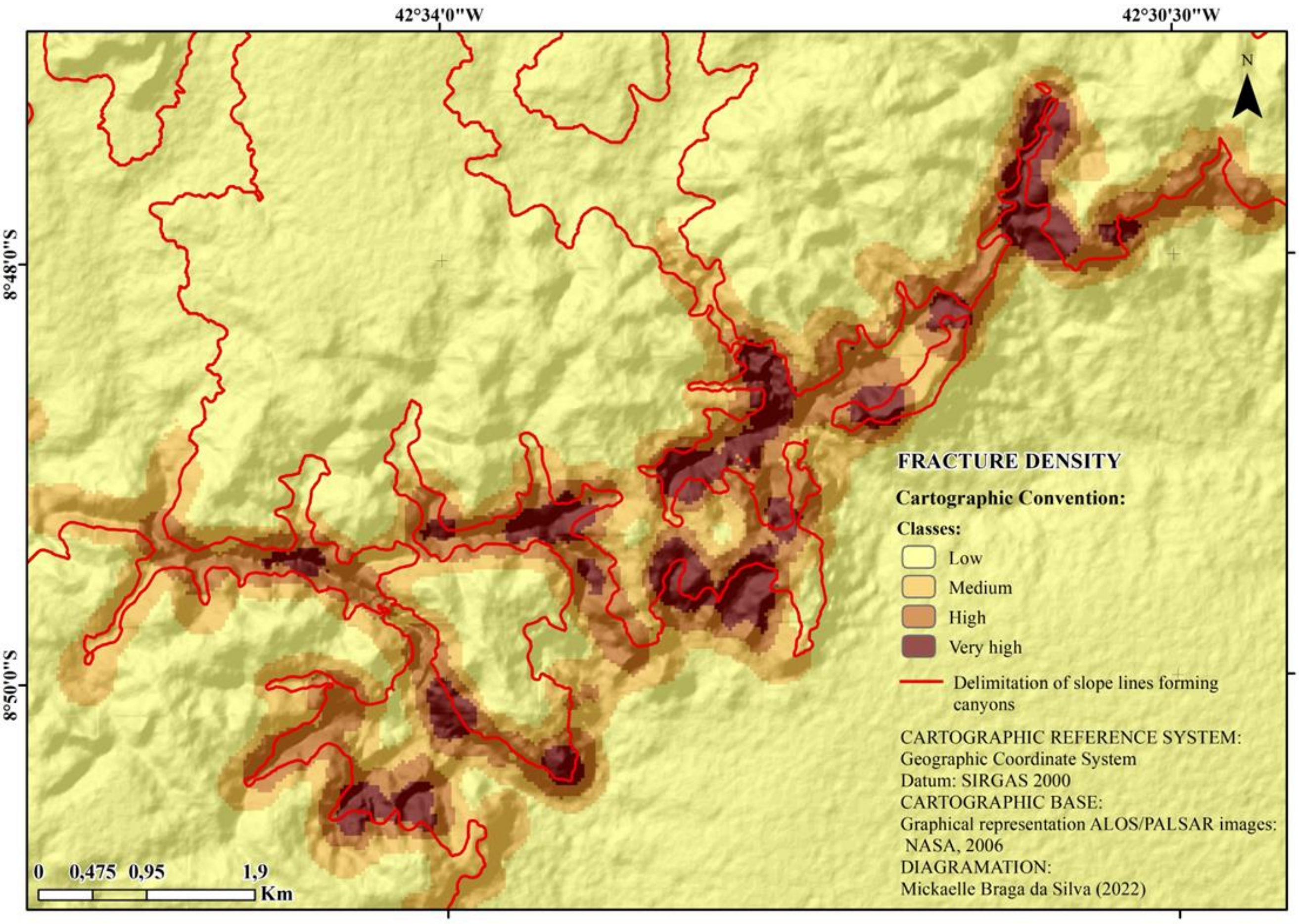

Figure 5. Density of the mapped fracturing features.

5.2. Drainage system

The delimitation of the study area comprises a regional transitional context of interface between Precambrian crystalline rocks and the Paleozoic sedimentary rocks, where the Serra da Capivara Cuesta behaves as a water divider trending NE-SW. Given this context, the hydrological framework also responds to this change through the configuration of its channel and drainage patterns, presenting rectilinear channels forming trellis to rectangular patterns.

In the Sertaneja Surface (low erosional surface), it is possible to find the headwaters of the high course of Piauí River, which flows towards the Parnaíba River as it advances to the east with a dendritic drainage pattern, irregular channels arranged in all directions. Insofar as the drainage advances towards the cuesta, the channels begin to assume, from the front to the back, a parallel drainage pattern, in which the streams are arranged virtually perpendicular to each other.

In the scale of analysis more directed to the defined polygon in the study area, it is possible to identify a drainage that stands outs, as it exhibits a drainage pattern that is not expected considering the geological context in which it occurs; Between the Sertaneja Surface and the cuesta, in a sector underlain by sandstones of the Serra Grande Group, there is a rectangular drainage, in which the main and secondary channels display curves at a right angle along their course and in the confluence of the channels. This arrangement is a consequence of the ramification of two main channels with tributaries of 5^{th} and 1^{st} order, draining the canyon into two portions: NW-SE and E-W (Figure 8).

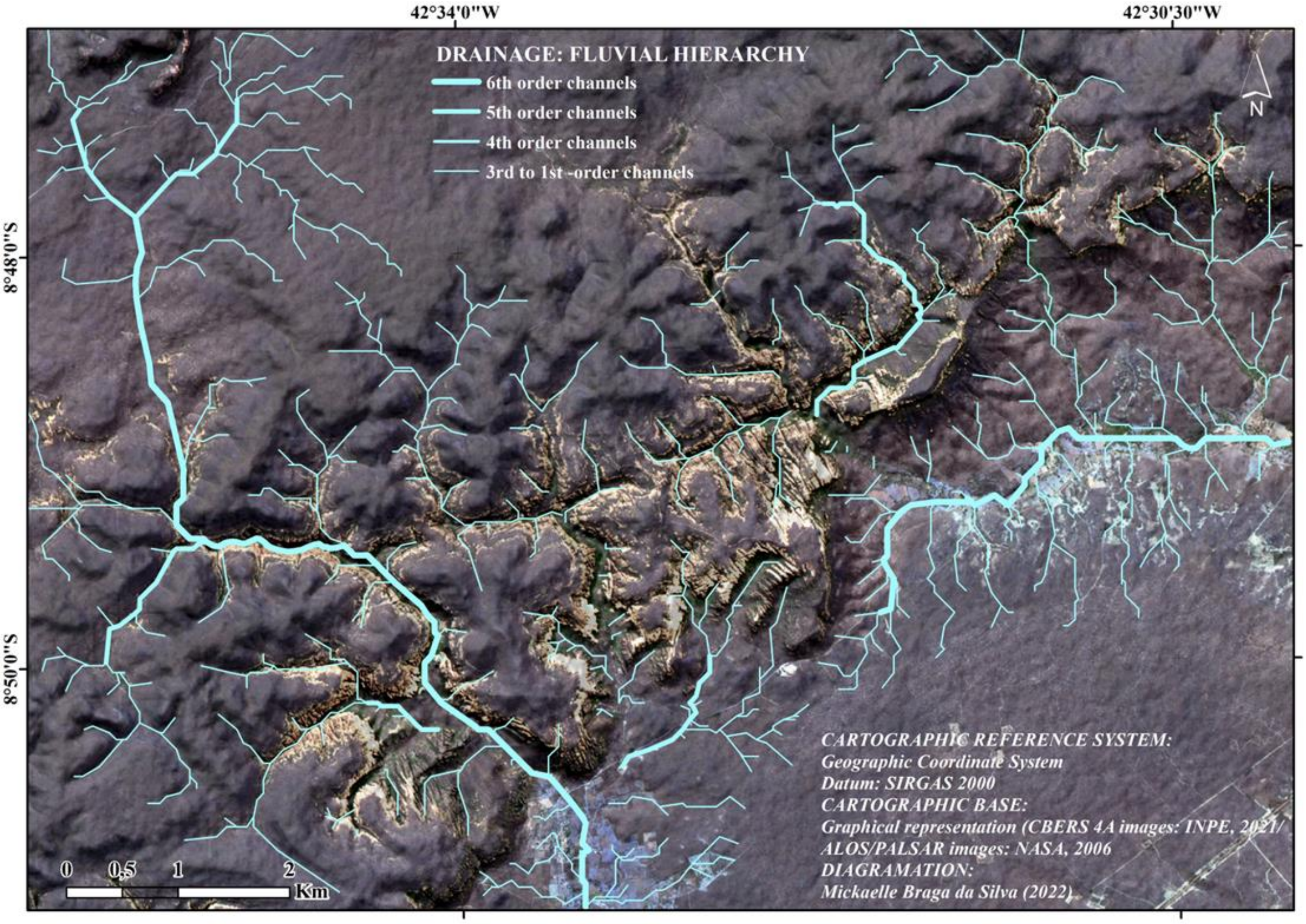

Figure 8. Local drainage network.

The area encompasses several headwaters, which advance from the border of the Parnaíba Sedimentary Basin to its center, meeting the water divider. The Serra da Capivara Cuesta demarcates the analyzed sector by dissected steep slopes (> 45°), providing the sector a strong declivity (in comparison with values proposed by LEPSCH, 1991).

In respect of the spatialization of the mapped channels' direction, the main channels (6th and 3rd order) exhibit a tendency of flow that obeys the effect of the semicircular border of the BPar and the path towards the channel of the Parnaíba River. Conversely, the lower order channels (Figure 9) are marked by the predominance of the NW-SE trending direction, but we also highlight the channels trending N-S and E-W.

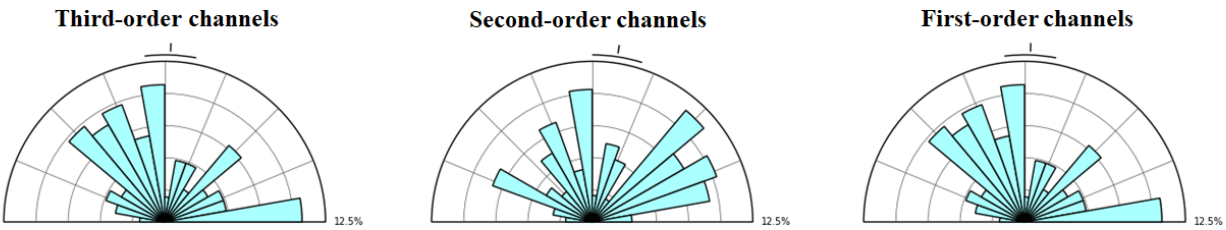

Figure 6. Rose diagrams according to the absolute frequency of the lower order fluvial channels.

5.3. Local geomorphology

The study area is located at the base of the backslope of the Serra da Capivara Cuesta, where escarpments up to 590 m separate this area from the adjacent sector underlain by crystalline rocks, exhibiting a topographic range of up to 240 m. The area is topographically divided by altitudes that correspond to the Sertaneja Surface, surrounding the base of the cliffs, which in turn, form valley scarps that present altitudes varying from 420 to 500 m at the base; at the top of these cliffs and of the front slope of the cuesta, the altitude range is from 500 m to 540

m. At the summit of the cuesta and at the top of isolated compartments (buttes) altitudes reach up to 590 m (Figure 10).

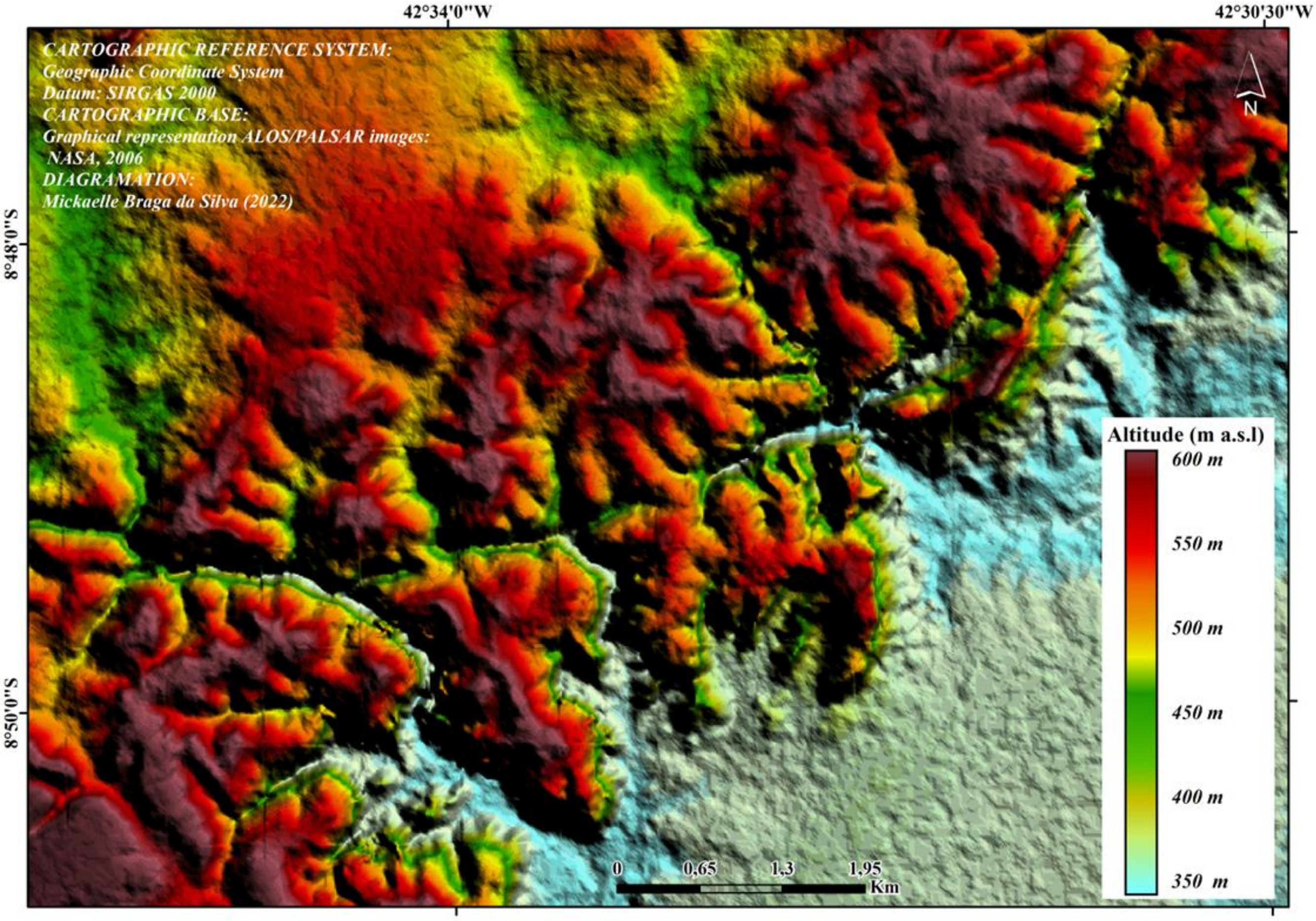

Figure 7. Altimetric representation of the study area.

The analyzed surfaces correspond to connected clefts surrounding the hillslopes of the cuesta and forming sectors with notable surface karst relief. It is possible to observe characteristics that distinguish them from other sedimentary sectors in the adjacencies, such as their steep rectilinear slopes with features bounded by acute to right angles (Figure 11).

Figure 8. View from the Museu da Natureza (Museum of Nature), where the steep slopes are built of sandstones and conglomerates (location: Coronel José Dias, PI).

The hillslopes host morphologies with characteristics of narrow and widened valleys (Figure 12a), as well as features that result from separation from the main slope, shaping towers and pinnacles (Figure 12b). It is still possible to identify waterfalls (Figure 12c) and shelters that evolve from the horizontal detachment of sandstone boulders (Figure 12d).

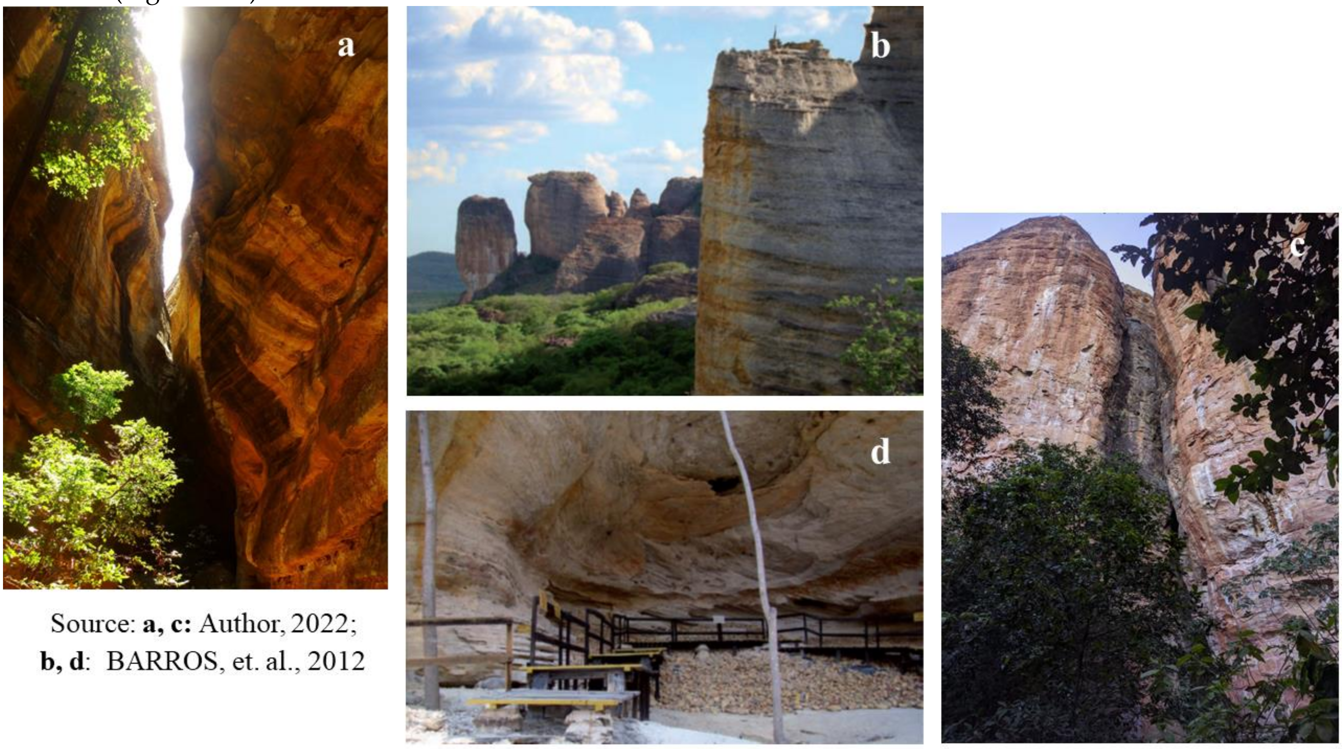

Figure 9. Geomorphological features typical of the study area. (a) Toca do Inferno site; (b) Toca do Sitio do Meio site; (c) Boqueirão da Pedra Furada site; (d) Toca da entrada do Pajeú site.

The area is also distinguished by the presence of arches shaped along parallel ridges, oriented NW-SE (Figure 13c), especially the geological landmark "Arco do Triunfo da Pedra Furada", at 400 m of altitude. These morphologies occur as circular features that may have their circumference still preserved (Figure 13a) or discontinued by collapse of its upper part (Figure 13d). In addition, we observed circular cavities behind the geological monument that did not cut through the structure (Figure 13b).

Figure 10. Geological landmark "Arco do Triunfo da Pedra Furada" (Serra da Capivara National Park) (a) aligned along sandstone ridges (c). Sectors along the monument that did not cut through the slope (b), and feature that transposed the structure, but displays a discontinued form due to the collapse of its upper portion (d).

6. Discussion

The selection of the study area to contextualize karstification processes in sandstones of Northeastern Brazil demonstrated that the morphostructural aspects are indispensable in understanding the formation and development of this system in a lithological context different from those reported in previous works, as it extrapolates the interpretation that karst environment is associated to carbonate lithologies (MIKULÁŠ, 2007; ADAMOVIČ, MIKULÁŠ and CÍLEK, 2010; URBAN and GÓRNIK, 2017; WRAY and SAURO, 2017).

With respect to the elements that govern the geomorphological evolution of these areas, it is worthwhile to note that tectonic events and geological structures associated with them exert a significant role in the geomorphological interpretation; moreover, its structural characteristic is increasingly present in the interpretations once it allows correlating landforms to tectonic and structural processes (PEULVAST and VANNEY, 2002). Therefore, the karst system in sandstones of the Serra da Capivara can be understood from the tectonic, structural, and climatic controlling factors.

6.1. Regional tectonic and climatic controlling factors

In the context of the morphotectonic evolution of the relief in Northeastern Brazil, the Gondwana breakup (Lower Cretaceous) is a key controlling factor of the current geomorphology of the Serra da Capivara; this event triggered the reactivation and brittle deformation along Precambrian structures, as well as regional uplift of formerly depressed areas, which would be better placed in the Late Cretaceous from the geochronological point of view and followed by the role of erosion (MATOS, 1992; CLAUDINO-SALES and PEULVAST, 2007). It is worth emphasizing the importance of the effect of the Transbrasiliano Lineament in the context of the BPar (CORDANI *et al.,* 2013a e b; BRITO NEVES and FUCK, 2014; GANADE DE ARAUJO *et al.,* 2014; CAXITO *et al*., 2020 e 2021), influencing the crystalline basement over which the sedimentation occurred through tectonic reactivations, mostly cretaceous; we highlight the repercussions in the bordering depositional layer that corresponds to the Serra Grande Group (LIMA and JARDIM DE SÁ, 2017; PORTO, *et al*., 2022). This dynamism suggests that landforms correlated to fault scarp and associated fractures, interrupted by sequences of grabens, demonstrate the role played by the regional brittle tectonics with local repercussions (PARENTE *et al*., 2004; MORAIS NETO *et al*., 2013; FREITAS, 2014; LIMA, 2015).

The deformational tectonic event that affected the Paleozoic sequence correspondent to the Serra Grande Group comprises normal and oblique faults and extensional joints trending NE-SW. This phase corresponds to a strain field with a main distension axis NE-SW and vertical shortening (CACAMA *et al*., 2015; SANTOS *et al*., 2018). In the surrounding areas, this event is accompanied by the emplacement of basic dikes (Sardinha Suite) of probably cretaceous age (VAZ *et al.,* 2007) and by the formation of siliceous veins associated with this magmatism. The cretaceous distension, NW-SE-striking, with expression in the east/southeast border of the BPar (LIMA, 2015), is characteristic of the other Inner Basins of Northeastern Brazil, reinforcing the compatibility with the rifting that originated the South Atlantic (LIMA e JARDIM DE SÁ, 2017).

The action of erosive processes promoted scarp retreat, which is controlled mainly by fault lines oriented at NE-SW and E-W (inherited fault scarp) (VASCONCELOS et al; 2004) and secondarily by headward erosion, promoted by the obsequent drainage (MUTZENBERG *et al.,* 2015). Behling *et al*. (2000), analyzing cores collected in the continental platform of the Northeast of Brazil, observed the occurrence of drastic climatic events at the end of the Pleistocene and beginning of the Holocene, with strong precipitations in the region, which permitted a high concentration of water to reach the sandstones sector in subsurface, enabling chemical weathering processes along lines of weakness and the slow and gradual development of typical weathering features. With the resumption of dryer climates, the erosion process was resumed more efficiently (UTIDA *et al.,* 2020).

6.2. *The role of fracturing features as a structural controlling factor in the formation process of the karst system in sandstones of the study area*

In the light of the tectonic and climatic context presented, we can attribute the formation of the sandstone karst relief under analysis to the assemblage of processes related to the silica dissolution and mechanical remobilization of the altered grains, associated simultaneously with the hydrological demand and to the high hydraulic gradient. Overall, this process of chemical disaggregation of the grains by cement dissolution is named "arenization" (first process) (MARTINI, 1979; 1984). Generally, this dynamic occurs in rather small amounts, until the cohesion decreases exponentially, which allows mechanical remobilization. Once remobilized, the material displays small channels that characterize a drainage network via piping (JENNINGS, 1985). Thus, the mechanical remobilization of the altered grains results in conduit formation, which may evolve into forming subterranean galleries MARTINI, 1979; GALÁN, 1991).

The impact of structural features such as faults and fractures in fluid flow (water and weathered material) in the formation of a karst system in sandstones is imperative (RAWLING *et al*., 2001; SCHULTZ and FOSSEN, 2008; BENSE *et al*., 2013; PARDO-IGÚZQUIZA *et al*., 2018). Furthermore, the condition that these structures function as conduits (JOLLEY et al., 2007; DIMMEN et al., 2017) reinforces that it is not enough for water to reach the system by primary infiltration, but that it also circulates between the conduits besides circulating intergranularly in the rock pores; therefore, the presence of structural controlling factors are necessary. For such reasons, structures such as bedding planes and fractures significantly act influenced the morphology of the area by providing a secondary permeability (DIMMEN *et al*., 2017; BAGNI *et al.,* 2022), through which the water circulation was eased, enhancing intergranular dissolution processes.

Based on the arrangement formed by the mapped fractures in the area is also possible to infer conditions to explain why the area under analysis is significantly more exposed than the adjacent areas and exhibits a unique landscape setting. Generally, the fracture patterns tend to be more regular in sandstones, where frequently orthogonal systems are found, subjected to extensions along two perpendicular directions (LI and JI, 2021), consisting of two vertical/nearly vertical sets perpendicular to each other, typically associated to a third horizontal set, developed along the bedding planes (MIGÓN, DUSZYŃSKI and GOUDIE, 2017; MIGÓN, 2021; MIGÓN and DUSZYŃSKI, 2022).

Besides evidencing the role of these discontinuities in the formation of the karst system in the area, it is possible to suggest that the arrays, formed by the vertical and horizontal axis of fracturing and of bedding planes, behave as a condition of fracture connectivity (ROTEVATN and BASTESEN, 2014; RABELO *et al.*, 2020). At the surface, this condition is marked by the clefts' layout, forming rectilinear valleys connected with expressive angularity; by the continuous separation of blocks along the slopes, originating pinnacles and buttes, and by the expressiveness of landmarks such as "Pedra Furada", in which cavities along the ridges and their configuration suggest that they were formerly connected paleoconduits.

6.3. Analysis of relief lineaments, drainage network and associated features

In general terms, the density and direction of structural lineaments are aspects that evidence in which way valleys, slopes and ridges may be correlated with the orientation of tectonic structures. In the northern NE of Brazil, the influence of the Brasiliano events in the Borborema Province is widely recognized, mostly regarding the generation of important shear zones and ductile/brittle features, which were reactivated over geological time. In this context, it is possible to correlate the repercussion of the Transbrasiliano lineament and of the Senador Pompeu Shear Zone with the NE-SW-trending features, and the influence of Patos and Pernambuco lineaments in controlling the presence of E-W features (BEZERRA and VITA-FINZI, 2000; MABESSONE, 2002; CHAMANI, 2011; CASTRO *et. al.*, 2012).

Since the drainage network is a very sensitive element to crustal alterations, it also constitutes a significant variable in the geomorphological landscapes, as it reflects crustal dynamics along its evolution (SCHUMM, DUMONT e HOLBROOK, 2000). Its expressiveness in the study area is particularly noted, at the surface, by the transition of drainage patterns (dendritic-rectangular-parallel), indicating lithological and structural controls. The latter, in turn, is revealed in the linear features, especially fracturing arrangements at the summit of steep slopes, dissected in the form of valleys with the incision of the drainage network. Moreover, the occurrence of significant relief ruptures (knickpoints) along the clefts suggests a structural control in the area (ETCHEBEHERE, 2000; ACKLAS JR. and ETCHEBEHERE, 2003; ETCHEBEHERE *et al.*, 2004; SALAMUNI *et al.*, 2004; GUEDES *et al.*, 2006).

The evidence that the drainage network is concentrated in the more intensely fractured area exhibiting a different drainage pattern (rectangular) from the adjacent areas, allows us to consider that the exuberant forms usually termed watergaps and canyons do not apply to the analyzed setting as they do not result from fluvial action forming the features by drainage superimposition, a common occurrence, for example, along the fluvial channels of the Jaguaribe River, in Ceará (SAADI e TORQUATO, 1992; BARRETO, 2015; COSTA, *et. al.*, 2020). In this case, it consists of a drainage system formed from the adjustment of the channels to the fractured structures, enabling the adaptation of the rivers to the valleys (SILVA e MAIA, 2017). This structural control on the drainage can be identified when analyzing the track of one of the most important rivers in the region, the Piauí River, whose path is arranged in the same direction as the regional fault lines (NE-SW). In addition, it can be noted that the fracturing lines with NW-SE trend act as subordinate structural elements guiding the distribution of the secondary channels in the area (Figure 14) (MUTZENBERG *et al.*, 2015).

Figure 11. Clefts formed by connected valleys oriented according to the arrangement of fracturing features in Serra da Capivara.

6.4. Evolutionary proposal for the karst relief in sandstones in Serra da Capivara

Shaped in a basin edge, the karst relief of Serra da Capivara that is currently on surface, can be understood, concerning their evolutionary stages, from cretaceous tectonic events followed by Cenozoic denudational and erosive processes, which may be explained, based on the presented discussions, in three main stages.

The first stage (Figure 15a) corresponds to the effect of the cretaceous reactivation of the Precambrian ductile and brittle deformation zones on the Paleozoic sedimentary terrains of the BPar. The deformations associated with the Transbrasiliano Lineament were followed by the uplift of the crystalline basement and sedimentary layers, which until then formed depressed areas (Zone of maximum deformation).

As the erosive processes advanced from the edge towards the interior of the BPar, the retreat of fault lines delimited a scarp shaped in the sandstones of the Serra Grande Group. With the progressive slope retreat (karstification zone), given the advance of the drainage network in the direction of the basin edge, denudational processes in the fractured sector are evident on the surface, as they control a dissection guided by lines of weakness (second stage) (Figure 15b).

With regards to structural control, the dissection of the relief in ridges, main valleys, and scarps conforms to the orientation of the primary deformation with regional repercussions (NE-SW and E-W). Along the secondary deformations, especially the mapped fracture arrays of NW-SE trend, is evident, along the hillslopes, the presence of shorter and narrower valleys, which are connected to the main valleys, the isolation of fractured block and shaping of residual (ruiniform) relief, such as pinnacles, towers, buttes and associated rockfall (third stage) (Figure 15c).

In a more advanced stage, we highlight in the area the landmark “Arco do Triunfo da Pedra Furada” (Figures 12 and 15c), which constitutes part of a former karst currently exhumed. The homonymous cavity (arche) cuts through a residual ridge perpendicular to the main fracturing direction. The apparent dipping of the layers in this site is perpendicular to the valley with a descending angle, which indicates folding. Thus, this sector is likely situated in gentle fold hinges concentrating fracture corridors that generate high-permeability zones and contributed to karstification processes (BAGNI *et al*., 2020; LA BRUNNA *et al*., 2021).

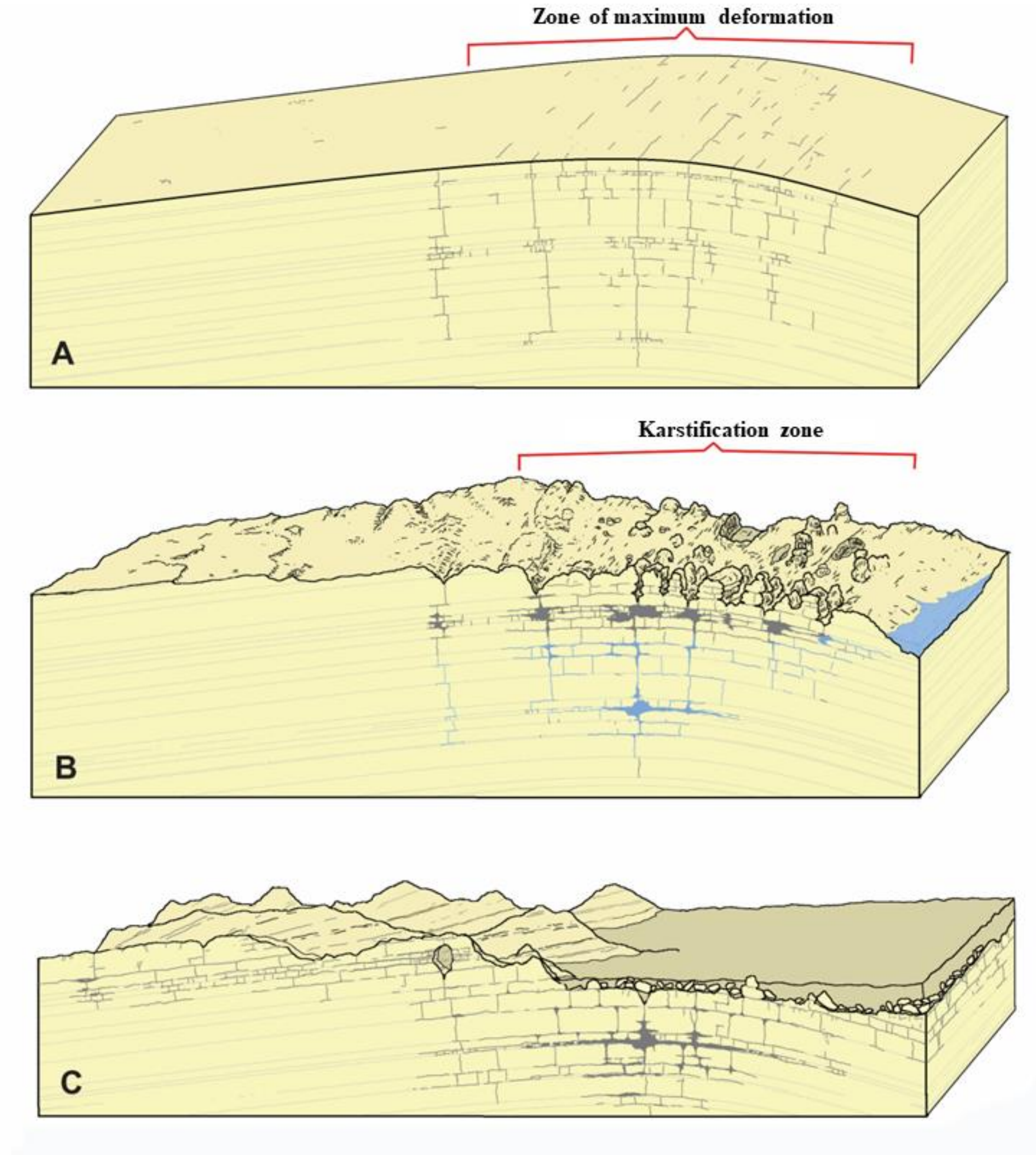

Figure 15. Evolutionary model of the karst relief in sandstones in Serra da Capivara. (A) First phase, demarcated by a zone of maximum deformation; (B) Second stage defined by the karstification zone formed along the deformations; (C) Third and present situation, guided by erosive events.

7. Final considerations

The data presented in this work show that the preferential tendency of valley widening according to the channel order (NE-SW for 3rd and 4th order and NW-SE for 1st and 2nd order) revel a structural control on the relief associated with the post-depositional phase of the Parníba Basin. Moreover, we observed that, besides the structural directions, dip angles observed in the Pedra Furada site suggest an anticlinal deformation. This type of deformation concentrates, in the hinge line, sets of fractures resulting from local distension. This structural context enhances localized karstification, since it increases secondary porosity of the rock due to the degree of fracturing. When interconnected, the fracture planes enable the development of zones of hydraulic flow, which guide the formation of karst relief according to the structural directions, being 30 % in the NE-SW and 31% in the NW-SE direction. Such structural control is expressed in the current morphology in the form of wined valleys connected by perpendicular galleries that feed the river channels.

Author Contribution: The authors Mickaelle Braga da Silva and Rubson Pinheiro Maia inform that they contributed to the present article as follows: Conceptualization; methodology; writing and validation. All authors read and agreed with the published version of the manuscript.

Funding information: This research received financial support from CAPES and the Post-Graduation Program in Geography of the Federal University of Ceará.

Acknowledgments: The authors are grateful to the cited funding agencies for the financial support of the research, as well as to their respective affiliated institutions.

Conflict of Interest: The authors have no conflicts of interest to declare.

References

1. ACKLAS JR.; R. ETCHEBEHERE, M. L. C. Análise de perfis longitudinais de drenagens do município de Guarulhos para detecção de deformações neotectônicas. **Revista UNG Geociências**, Guarulhos, v. 8, n. 6, p. 64-78, 2003.
2. ADAMOVIČ, J., MIKULÁŠ, R., CÍLEK, V. **Atlas pískovcových skalnych měst České a Slovenské republiky: Geologie a geomorfologie** [Atlas of Sandstone Rock Cities of the Czech and Slovak Republic: Geology and Geomorphology]. Academia, Praha, p. 460. 2010.
3. ALMEIDA, F. F. M. Origem e evolução da Plataforma brasileira. **Boletim DNPM**. Divisão de Geologia e Mineralogia, Rio de Janeiro, v. 241, p. 5-36, 1967.
4. ALMEIDA, F. F. M.; CARNEIRO, C. D. R. Inundações marinhas fanerozóicas no Brasil e recursos minerais associados. In: MANTESSO-NETO, V.; BARTORELLI, A.; CARNEIRO, C. D. R.; BRITO-NEVES, B. B. (Org.). **Geologia do continente sul-americano: evolução da obra de Fernando Flávio Marques de Almeida**. São Paulo: Beca, p.43-58, 2004.
5. ALMEIDA, F. F. M.; HASUI, Y.; BRITO-NEVES, B. B.; FUCK, R. A. Brazilian Structural provinces: an introduction. **Earth Science Reviews**, v. 17: p.1-29, 1981. DOI: 10.1016/0012-8252(81)90003-9
6. ANDREYCHOUK, V.; TRAVASSOS, L. E. P.; BARBOSA, E. P. As cavernas como objetos do turismo religioso em diferentes crenças religiosas: alguns exemplos mundiais. **O Carste**, v. 22, n. 2, p.48-64, 2010.
7. AULER, A. S. Quartzite Caves of South America. In: GUNN, J. **Encyclopedia of Caves and Karst Science.** New York, London: Taylor and Francis Group. p. 611-613, 2004.BAGNI, F.L., BEZERRA, F.H., BALSAMO, F., MAIA, R.P., DALL'AGLIO, M. Karst dissolution along fracture corridors in an anticline hinge, Jandaíra Formation, Brazil: implications for reservoir quality. **Mar. Petrol. Geol**. 115, 104249m 2020; DOI: 10.1016/j.marpetgeo.2020.104249.
8. BAGNI, F.L. ERTHAL, M. M.; TONIETTO, S. N.; MAIA, R. P.; BEZERRA, F. H. R.; BALSAMO, F.; CÓRDOBA, V. C.; DE SOUZA, F.G., BROD, J.A., FERNANDES, C.P., FONSECA, J.P.T. Karstified layers and caves formed by superposed epigenic dissolution along subaerial unconformities in carbonate rocks - Impact on reservoir-scale permeability. **Marine and Petroleum Geology**, v. 139, p. 1-23, 2022. DOI: 10.1016/j.marpetgeo.2022.105523.
9. BARRETO, L. L. **Suscetibilidade ao processo de desertificação no núcleo dos Sertões dos Inhamuns: o caso da sub-bacia do riacho do Urubu –Mucuim – Arneiroz – Ce.** Dissertação (Mestrado). Universidade Federal do Ceará, Fortaleza, 2015.
10. BARBOSA, M. E. F; FURIER, M. SISTEMAS DE DIACLASES E INFLUÊNCIA TECTÔNICA DA BORDA SUDESTE DA BACIA SEDIMENTAR DO PARNAÍBA: PARQUE NACIONAL SERRA DA CAPIVARA, BRASIL. **Revista do Departamento de Geografia** – USP, v. 23, p. 250-266, 2012.
11. BARROS, J. S.; FERREIRA, R. V.; PEDREIRA, A. J; GUIDON, N. **Geoparque Serra da Capivara (PI):** proposta. Rio de Janeiro: CPRM, p. 50, 2012.
12. BEHLING, H; ARZ, H. W; PÄTZOLD, J; WEFER, G. Late Quaternary vegetational and climate dynamics in northeastern Brazil, inferences from marine core eoB 3104-1**. Quaternary Science Reviews**, v. 19, p. 981-994, 2000. DOI: 10.1016/S0277-3791(99)00046-3.
13. BENSE, V.F; GLEESON, T; LOVELESS, S.E; BOUR, O; SCIBEK, J. Fault zone hydrogeology. **Earth-Science Rev**., v.127, p. 171–192, 2013. DOI: 10.1016/j.earscirev.2013.09.008.

14. BEZERRA, F H R; VITA-FINZI, C. How active is a passive margin? Paleoseismicity in Northastern Brasil. **Geology, Boulder**, v.28, p. 591-594, 2000.
15. BRITO NEVES, B. B. The Cambro-ordovician of the Borborema Pronvince. São Paulo, USP, **Boletim IG**, Série Científica, v. 29, p. 175-193, 1988.
16. BRITO NEVES, B. B; FUCK, R. A. The basement of the South American platform: Half Laurentian (N-NW)+half Gondwanan (E-SE) domains. **Precambrian Res**., v. 244, p. 75-86, 2014. DOI: 10.1016/j.precamres.2013.09.020.
17. CACAMA, M. S. J. B., JARDIM DE SÁ, E. F., ALVES DA SILVA, F. C., LIRA LINS, F. A. P. Assinatura estrutural e geofísica da Porção Norte (fronteira Ceará-Piauí) do Lineamento Transbrasiliano: reativação na Bacia do Parnaíba **Revista do Instituto de Geociências - USP**, v. 15, n. 3-4, p. 67-81, 2015. DOI: 10.11606/issn.2316-9095.v15i3-4p67-81
18. CASTRO, D. L., BEZERRA, F. H. R., FUCK, R.A. Influence of Neoproterozoic tectonic fabric on the origin of the Potiguar Basin, northeastern Brazil and its links with West Africa based on gravity and magnetic data. **Journal of Geodynamics**, v.54, p. 29-42, 2012. DOI: 10.1016/j.jog.2011.09.002.
19. CASTRO, D. L; 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
20. CAXITO, F.A; BASTO, C.F; SANTOS, L.C.M.D.L; DANTAS, E.L; MEDEIROS, V.C.D; DIAS, T.G; BARROTE, V; HAGEMANN, S; ALKMIM, A.R; LANA, C. Neoproterozoic magmatic arc volcanism in the Borborema Province, NE Brazil: possible flare-ups and lulls and implications for western Gondwana assembly. **Gondwana Res**. v. 92, p. 1–25, 2021. DOI: 10.1016/j.gr.2020.11.015.
21. CAXITO, F.D.A; SANTOS, L.C.M.D.L; GANADE, C.E; BENDAOUD, A; FETTOUS, E. H; BOUYO, M. H. Toward an integrated model of geological evolution for NE Brazil-NW Africa: The Borborema Province and its connections to the Trans-Saharan (Benino Nigerian and Tuareg shields) and Central African orogens. Brazilian J. Geol. v. 50 (2). 2020. DOI: 10.1590/2317-4889202020190122.
22. CHABERT, C; COURBON, P. **Atlas des Cavités non Calcaires du Monde**. Union Internationale de Spéléologie, 1997.
23. CHAMANI, M. A. C. **Tectônica intraplaca e deformação sinsedimentar induzida por abalos sísmicos: o lineamento transbrasiliano e estruturas relacionadas na província Parnaíba, Brasil**. Master thesis, Universidade de São Paulo, 2011.
24. 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, p.1-21, 2007.
25. CORDANI, U. G; BRITO NEVES, B. B; TOMAZ FILHO, A. Estudo preliminar de integração do Pré-Cambriano com os eventos tectônicos das bacias sedimentares brasileiras (Atualização), **Bol. Geociencias da Petrobras**, v. 17, n. 1, p. 205-219, 2008.
26. CORDANI, U. G; PIMENTEL, M. M; ARAÚJO, C. E. G; FUCK, R. A. The significance of the Transbrasiliano-Kandi tectonic corridor for the amalgamation of West Gondwana. **Brazilian J. Geol**., v. 43, n. 3, p. 583-597, 2013a. DOI: 10.5327/Z2317-48892013000300012.
27. CORDANI, U. G; PIMENTEL, M. M; GANDADE DE ARAUJO, C. E; BASEI, M. A. S; FUCK, R. A; GIRARDI, V. A. V. R. Was there an ediacaran clymene ocean in central south America? **American journal of science,** v. 313, p. 517–539, 2013b. DOI 10.2475/06.2013.01.
28. CORREA NETO, A. V. Speleogenesis in Quartzites from Southeastern Minas Gerais, Brazil. In KLIMCHOUK, B. A.; FORD, D. C.; PALMER, A. N.; DREYBRODT, W. (ed.) Speleogenesis - Evolution of Karst Aquifers. Huntsville (USA). **National Speleological Society**, p. 452 – 457. 2000.
29. CORREA NETO, A. V.; BAPTISTA FILHO, J. Espeleogênese em quartzitos da Serra de Ibitipoca, sudeste de Minas Gerais. **Anuário do Instituto de Geociências**,v. 20,p. 75-87. 1997.
30. COSTA, L. R. F; MAIA, R. P.; BARRETO, L. L.; CLAUDINO, S. V. C. de. GEOMORFOLOGIA DO NORDESTE SETENTRIONAL BRASILEIRO: UMA PROPOSTA DE CLASSIFICAÇÃO. **Revista Brasileira de Geomorfologia**, [S. l.], v. 21, n. 1, 2020. DOI: 10.20502/rbg.v21i1.1447.
31. DELLA FÁVERA, J. C. Parque Nacional de Sete Cidades, PI - Magnífico monumento natural. In: SCHOBBENHAUS, C.; CAMPOS, D.A.; QUEIROZ, E.T.; WINGE, M.; BERBERT-BORN, M.L.C. (Edits.) **Sítios Geológicos e Paleontológicos do Brasil.** 1. ed. Brasilia: DNPM/CPRM - Comissão Brasileira de Sítios Geológicos e Paleobiológicos (SIGEP), 2002.
32. DIMMEN, V; ROTEVATN, A; PEACOCK, D.C.P; NIXON, C.W; NÆRLAND, K.. Quantifying structural controls on fluid flow: Insights from carbonate-hosted fault damage zones on the Maltese Islands. **J. Struct. Geol.** v. 101, p. 43–57. DOI: 10.1016/j.
33. EPIS, L. **Expedição Amazonas**. Campinas: Informativo SBE, v. 92, p. 30-36, 2007.

34. ETCHEBEHERE, M. L. C. **Terraços neo-quaternários no vale do rio do Peixe, planalto ocidental paulista: Implicações estratigráficas e tectônicas**. Tese (Doutorado em Geociências) - Instituto de Geociências e Ciências Exatas, Universidade Estadual Paulista Júlio de Mesquita Filho, Rio Claro, 2000.
35. ETCHEBEHERE, M. L. C.; SAAD, A. R.; PERINOTTO, J. A. J.; FULFARO, V. J. Aplicação do Índice "Relação Declividade-Extensão - RDE" na Bacia do Rio do Peixe (SP) para detecção de deformações neotectônicas. **Revista do Instituto de Geociências - USP** - Série Científica, São Paulo, v. 4, n. 2, p. 43-56, 2004.
36. FERREIRA, R. V; SILVA, C. R. M; ACCIOLY, A. C; SANTOS, C. A; MORAIS, D. M. F. **GEOPARQUE CATIMBAU PEDRA FURADA – PE: Proposta**. Recife: CPRM, 2017.
37. FREITAS, M. S. **Carta Geológica de Parnaguá. Folha SC.23-Z-A-I. Escala 1:100.000.** Teresina: Serviço Geológico do Brasil/CPRM, 2014.
38. GALÁN, C. **Disolución y Génesis del karst en rocas carbonáticas y rocas slíceas: un estúdio comparado**. Munibe. v. 43, p.43-72, 1991.
39. GANADE DE ARAUJO, C.E; RUBATTO, D; HERMANN, J; CORDANI, U.G; CABY, R; BASEI, M.A.S. Ediacaran 2,500-km-long synchronous deep continental subduction in the West Gondwana Orogen. **Nat. Commun.** 5 (1), 2014. DOI: https://doi.org/10.1038/ncomms6198.
40. GUEDES, I. C.; SANTONI, G. C.; ETCHEBEHERE, M. L. C.; STEVAUX, J. C.; MORALES, N.; SAAD, A. R. Análise de perfis longitudinais de drenagens da bacia do rio Santo Anastácio (SP) para detecção de possíveis deformações neotectônicas. **Revista UNG Geociências**, Guarulhos, v. 5, n. 1, p. 75-102, 2006.
41. HARDT, R. Caracterização morfológica das cavernas Aroê-Jari, Lago Azul e Kiogo-Brado – MT. **XXX Congresso Brasileiro de Espeleologia (Anais em CD Rom).** Sociedade Brasileira de Espeleologia, p. 95-100, 2009.
42. HARDT, R. **Da Carstificação em Arenitos. Aproximação com o Suporte de Geotectonologias.** Tese (Doutorado em Geografia e Docteur em Géologie). Rio Claro: Universidade Estadual Paulista. Université de Rouen. 2011.
43. HARDT, R. **Formas Cársticas em Arenito.** Monografia de Especialização. UNESP, p. 47. 2003.
44. HARDT, R.; PINTO, S. A. F. Carste Em Rochas Não Carbonáticas. **VIII Sinageo (Anais CD-Rom),** p. 11, 2008.
45. HARDT, R.; RODET, J.; PINTO, S. A. F. Karst evolution in sandstone: The Chapada dos Guimarães site, Brazil. In. 16th International Congress of Speleology. Proceedings of the 16th International Congress of Speleology, Brno (Czech Republic), **USF Libraries**, v. 1, p. 254-267, 2013.
46. HARDT, R., RODET, J., PINTO, S. A. F. 2010. O Carste. Produto de uma evolução ou processo? Evolução de um conceito. **Revista de Geografia (Recife**). V. Espec, p. 100 – 111, 2010.
47. HARDT, R.; RODET, J.; WILLEMS, L.; PINTO, S. A. F. Exemplos Brasileiros de Carste em Arenito: Chapada dos Guimarães (MT) e Serra de Itaqueri (SP). **Espeleo-Tema** (20) 1/2 p. 7-23. 2009.
48. JENNINGS, J. N. **Karst Geomorphology**. Oxford: Basil Blackwell. 1985.
49. JOLLEY, S.J; BARR, D; WALSH, J.J; KNIPE, R.J. Structurally complex reservoirs: an introduction. Geol. Soc. London. **Spec. Publ**. v. 292, p, 1–24, 2007. DOI: https://doi.org/10.1144/SP292.1.
50. KARMANN, I. Caracterização geral e aspectos genéticos da gruta arenítica "Refúgio do Maroaga", AM-02. **Espeleo-Tema**, v. 15: p. 9-18. 1986.
51. KLIMCHOUK, A. B; FORD, D. C. Lithologic and structural controls of dissolutional cave development. Speleogenes. Evol. **Karst Aquifers** , p. 54–64, 2000.
52. LA BRUNA, V; BEZERRA, F.H.R.; SOUZA, V.H.P. ; MAIA, R.P; AULER, A.S; ARAUJO, R.E.B.; CAZARIN, C. L; RODRIGUES, M.A.F; VIEIRA, LUCIETH C. ; SOUSA, M. O.L. High-permeability zones in folded and faulted silicified carbonate rocks – Implications for karstified carbonate reservoirs. Ournals. **Marine and petroleum geology**, Vol.128, p.105046, 2021. DOI: 10.1016/j.jog.2011.09.002.
53. LEPSCH, I.F. (Coord.) **Manual para levantamento utilitário do meio físico e classificação de terras no sistema de capacidade de uso**. 2ª ed. Campinas: SBCS, p. 175, 1991.
54. LI, L., JI, S. A new interpretation for formation of orthogonal joints in quartz sandstone. **Journal of Rock Mechanics and Geotechnical Engine**ering, v. 13, p. 289–299, 2021. DOI : https://doi.org/10.1016/j.jrmge.2020.08.003.
55. LIMA, T. P. C. Expressão Geofísica-Estrutural do Lineamento Transbrasiliano na Porção Central da Bacia do Parnaíba (Maranhão-Piauí). Dissertação (Mestrado). Natal: Centro de Ciências Exatas e da Terra – UFRN, 2015.
56. LIMA, F. G. F; JARDIM DE SÁ, E. F**.** Controle estrutural da borda sudeste da Bacia do Parnaíba, Nordeste do Brasil: relação com eventos geodinâmicos no Gondwana**. Revista do Instituto de Geociências – USP,** v. 17, n. 3, p. 21,2017**.** DOI: 10.11606/issn.2316-9095.v17-125909**.**
57. MABESSONE, J. M. Historia da Província Borborema NE do Brasil. **Revista de Geologia**, v.15, Recife, p.119-129, 2002.

58. MARTINI, J. Karst in the Black Reef Quartzite near Kaapsehoop, Transvaal. **Ann. Geol. Surv. South Africa**, v. 13, p. 115-128, 1979.
59. MARTINI, J. Rate of Quartz Dissolution and Weathering of Quartzite. **The Boletin of the South Africa**: Speleological Association. v. 25. 1984.
60. MARTINI, S. B. M. P. **Levantamento dos Recursos Naturais do Distrito Espeleológico Arenítico de Altinópolis-SP.** Monografia de Especialização. Rio Claro: UNESP. p. 94, 1985.
61. MATOS, R. M. D. The Northeast Brazilian Rift System. **Tectonics,** v.11, p. 766-791, 1992.
62. MIGON, P. Sandstone geomorphology – recent advances. **Geomorphology**, v. 373, 2021. DOI: 10.1016/j.geomorph.2020.107484.
63. MIGÓN, P; DUSZÝNSKI, F. Landscapes and landforms in coarse clastic sedimentary tablelands – Is there a unifying theme? **Catena**, v. 218, 2022. DOI: 10.1016/j.catena.2022.106545.
64. MIGÓN, P; DUSZÝNSKI, F., GOUDIE, A. Rock cities and ruiniform relief: Forms – processes – terminology. **Earth-Science Reviews**, v. 171, p. 78–104, 2017. DOI : 10.1016/j.earscirev.2017.05.012.
65. MIKULÁŠ, R. Microforms of the sandstone relief. In: HÄRTEL, H., CÍLEK, V., HERBEN, T., JACKSON, A., WILLIAMS, R. (Eds**.), Sandstone Landscapes**. Academia, Prague, p. 66–75, 2007.
66. MONTEIRO, R. C.; RIBEIRO, L. F. B. Espeleogênese de Cavernas Areníticas: algumas considerações aplicadas à Província Espeleológica da Serra de Itaqueri, Estado de São Paulo**, Espeleologia**. p. 09-116, 2001.
67. MORAIS, F. Contexto geológico das cavernas em arenito do Estado do Tocantins**. XXX Congresso Brasileiro de Espeleologia (Anais em CD Rom).** Sociedade Brasileira de Espeleologia. p. 139-144. 2009.
68. MORAIS, F; SOUZA, L. B. Cavernas em arenitos na porção setentrional da Serra do Lajedo, Estado do Tocantins, Brasil. **Revista de Biologia e Ciências da Terra**. v.9, ed. 2, p. 1-13, 2009.
69. MORAIS NETO, J. M., TRODSTORF JR., I., SANTOS, S. F., VASCONCELOS, C. S., MENEZES, J. R. C., RIBAS, M. P., IWATA, S. A. Expressão sísmica das reativações tectônicas do Lineamento Transbrasiliano na Bacia do Parnaíba. XIV Simpósio Nacional de Estudos Tectônicos / VIII International Symposium on Tectonics, **Anais...** CD-ROM. Chapada dos Guimarães: SBG, 2013.
70. NIMER, E. **Climatologia do Brasil**, Rio de Janeiro: Instituto Brasileiro de Geografia e Estatística, 1989.
71. MUTZENBERG, D.; BARROS, C. A. C.; AZEVEDO, T. B.; CISNEIROS, D. Serra da Capivara National Park: Ruiniform Landscapes on Parnaíba Cuesta. In: VIEIRA, B.C., SALGADO, A.A.R., SANTOS, L.J.C. (Eds.), **Landscapes and Landforms of Brazil**. Springer, Dordrecht, p. 253–263, 2015.
72. PARDO-IGÚZQUIZA, E., DOWD, P.A., RUIZ-CONSTÁN, A., MARTOS-ROSILLO, S., LUQUE-ESPINAR, J.A., RODRÍGUEZ-GALIANO, V., PEDRERA, A. Epikarst mapping by remote sensing. **Caten,** v. 165, p. 1–11, 2018. 10.1016/j.catena.2018.01.026.
73. PARENTE, C. V., SILVA FILHO, W. F., ALMEIDA, A. R. Bacias do Estágio de Transição do Domínio Setentrional da Província Borborema. In: MANTESSO NETO, V; BARTORELLI, A; CARNEIRO, C. D. R; BRITO-NEVES; B. B. (Eds.). **Geologia do Continente Sul-Americano: Evolução da Obra de Fernando Flávio Marques de Almeida**. São Paulo: BECA, v. 1, p525-536, 2004.
74. PEREIRA, R.G.F.A. **Caracterização geomorfológica e geoespeleológica do Carste da Bacia do Rio Una, Borda Leste da Chapada Diamantina.** Dissertação de Mestrado. Instituto de Geociências, São Paulo, 1998.
75. PEULVAST, J. P; VANNEY, J. **Géomorphologie structurale : terre, corps planétaires solides ;Tome 1 : Relief et structure.** Co-édition Gordon and Breach Science Publishers,Paris, Édi t ions du BRGM, Or léans, et Société géologique de France, Paris, 2002.
76. PFALTZGRAFF, P. G. S; TORRES, F. R.M; BRANDÃO, R. L. **Geodiversidade do estado do Piauí.** Programa Geologia do Brasil. Levantamento da Geodiversidade. Recife: CPRM, p. 260, 2010.
77. PISANI, L; ANTONELLINI, M; DEWAELE, J. Structural control on epigenic gypsumcaves: evidences from Messinian evaporites (Northern Apennines, Italy**). Geomorphology**, v. 332, p. 170–186, 2019. DOI: 10.1016/j.geomorph.2019.02.016.
78. PONTES, H.S.; FERNANDES, L. A.; DE MELO, M. S.; GUIMARÃES, G. B.; MASSUQUETO, L. L. Speleothems in quartz-sandstone caves of Ponta Grossa municipality, Campos Gerais Region, Paraná state, southern Brazil. **International Journal of Speleology**, v. 49 p.119-136, 2020. DOI: 10.5038/1827-806X.49.2.2313.
79. PORTO, A; CARVALHO, C; LIMA, C; HEILBRON, M; CAXITO, F; LA TERRA, E; FONTES, S. L. The Neoproterozoic basement of the Parnaíba Basin (NE Brazil) from combined geophysical-geological analysis: A missing piece of the western Gondwana puzzle. **Precambrian Research**, v. 379, 2022. DOI: 10.1016/j.precamres.2022.106784.

80. RABELO, J; MAIA, R. P; BEZERRA, H. R ; SILVA, C. C. N. Karstification andfluidflow in carbonate units controlled by propagationand linkage of mesoscale fractures, Jandaíra Formation, Brazil. **Geomorphology**, v. 357, p. 1-17, 2020. DOI: 10.1016/j.geomorph.2020.107090.
81. RODET, M. J.; RODET, J.; WILLEMS, L.; POUCLET, A.; NASCIMENTO, S. **Geoarqueologia do Parque Estadual do Rio Preto - Minas Gerais, Brasil.** Editions du CNEK. Saint-Martin-aux-Buneaux, França. 57 p. 2009.
82. ROTEVATN, A; BASTESEN, E. Fault linkage and damage zone architecture in tight carbonate rocks in the Suez Rift (Egypt): implications for permeability structure along segmented normal faults. **Geol. Soc. of London. Spec. Publ**. v.374, p. 79–95, 2014. DOI: 10.1144/SP374.12.
83. SAADI, A.; TORQUATO, J.R. Contribuição à Neotectônica do Estado do Ceará. **Revista Geologia UFC**, v. 5, p. 1-38, 1992.
84. SCHULTZ, R.A; FOSSEN, H. Terminology for structural discontinuities. **Am. Assoc. Pet. Geol. Bull**., v. 92, p. 853–867, 2008. DOI: 10.1306/02200807065.
85. SALAMUNI, E.; EBERT H. D.; HASUI Y. Morfotectônica da Bacia Sedimentar de Curitiba. **Revista Brasileira de Geociências**, v. 34, p 469-478, 2004.
86. SALLUM FILHO, W; KARMANN, I. Dolinas em arenitos da Bacia Paraná: Evidências de carste em Jardim (MS) e Ponta Grossa (PR). **Revista Brasileira de Geociências**, v. 37, ed. 3, p. 551-564, 2007.
87. SANTOS, J. C. **Quadro geomorfológico do Parque Nacional de Sete Cidades-PI.** (Dissertação de mestrado em Geografia). Florianópolis: 2001.
88. SANTOS, C. H. O. S; JARDIM DE SÁ, E. F; SILVA, F. C. A; ANTUNES, A. F. Reativações pós-silurianas do Lineamento Transbrasiliano na porção sul da Bacia do Parnaíba. **Revista do Instituto de Geociências – USP**, v. 18, n. 2, p. 7-86, 2018. DOI: 10.11606/issn.2316-9095.v18-134712.
89. SCHUM, S. A.; DUMONT, J. F.; HOLBROOK, J. M. **Active Tectonics and Alluvial Rivers**. Cambridge University Press, Cambridge, p.401, 2000.
90. SILVA, M. B; MAIA, R. P. Caracterização morfoestrutural do alto curso da bacia hidrográfica do rio Jaguaribe, Ceará-Brasil. **Revista Brasileira de Geomorfologia**, v. 18, p. 637-655, 2017. DOI: 10.20502/rbg.v18i3.1083.
91. SILVA, S. M. **Carstificação em Rochas Siliciclásticas:** Estudo de caso na Serra do Ibitipoca, Minas Gerais (Dissertação). Belo Horizonte: UFMG, 143 p. 2004.
92. SPOLADORE, A. **A geologia e a geoespeleologia como instrumentos de planejamento para o desenvolvimento do turismo – O caso de São Jerônimo da Serra / PR**. Tese (Doutorado em Geologia) Universidade Estadual Paulista, Rio Claro, p. 304, 2006.
93. TROPPMAIR, H.; TAVARES, A. C. Observações Geomorfológicas e Biogeográficas na região Espeleológica de Altinópolis. **Boletim de Geografia Teorética**, 15, (29-30), p. 329-336. 1985.
94. UAGODA, R.; AVELAR, A. S.; COELHO NETTO, A. L. Depressões Fechadas em Relevo Cárstico-Quartzítico, Bacia do Ribeirão Santana, Médio Vale do Rio Paraíba do Sul. **Anuário do Instituto de Geociências**. 29 – 2, p. 87-100. 2006.
95. URBAN, J., GÓRNIK, M. Some aspects of lithological and exogenic control of sandstone morphology, the Świętokrzyskie (Holy Cross) Mts. case study, Poland. **Geomorphology,** v. 295, p. 773–789, 2017. DOI: 10.1016/j.geomorph.2017.08.010.
96. UTIDA, G; CRUZ, F. W; SANTOS, R. V; SAWAKUCHI, A. O; WANG, H; PESSENDA, L. C ; NOVELLO, V. F; VUILLE, M; STRAUSS , A. M; BORELLA, A. N; STRÍKIS, N. M; GUEDES, C. F; ANDRADE, F. R. D; ZHANG, H; CHENG, H; EDWARDS, R. L. Climate changes in Northeastern Brazil from deglacial to Meghalayan periods and related environmental impacts. Qu**aternary Science Reviews**, p. 250, 2020. DOI: https://doi.org/10.1016/j.quascirev.2020.106655.
97. VAZ, P. T; RESENDE, N. G. A. M; WANDERLEY FILHO, J. R; TRAVASSOS, W. A. S. Bacia do Parnaíba. **Boletim de Geociências Petrobras**, Rio de Janeiro, v. 15, n. 2, p. 253-263, 2007.
98. VASCONCELOS, A. M., KOSIN, M., SOUZA, J. D. DE, VALENTE, C. R., NEVES, J. P., HEINECK, C. A., LACERDA FILHO, J. V., TEIXEIRA, L. R., BORGES, V. P., BENTO, R. V., GUIMARÃES, J. T., NEVES, J. P., OLIVEIRA, I. W. B., GOMES, I. P., MALOUF, R. F., CARVALHO, L. M. DE, ABREU FILHO, W. Folha SC.23 - Rio São Francisco. In: C. SCHOBBENHAUS, J. H. GONÇALVES, J. O. S. SANTOS, M. B. ABRAM, R. LEÃO NETO, G. M. M. MATOS, R. M. VIDOTTI, M. A. B. RAMOS, J. D. A. DE JESUS (Eds.). **Carta Geológica do Brasil ao Milionésimo, SIG.** Programa Geologia do Brasil. Brasília: CPRM, 2004.
99. VERÍSSIMO, C. U. V.; SPOLADORE, A. Gruta do Fazendão (SP-170): Considerações geológicas e genéticas. **Espeleo-Tema**, v. 17 p. 7-17. 1994.
100. WERNICK, E.; PASTORE, E. L.; PIRES NETO, A. Cavernas em arenito. **Notícia Geomorfológica**, v.13: p. 55-67. 1973.
101. WIEGAND, J.; FEY, M.; HAUS, N.; KARMANN, I. Investigações Geoquímicas e Hidroquímicas da gênese de carste em arenitos e quartzitos da Chapada Diamantina e Quadrilátero Ferrífero (Brasil). **Z. Dt. geol. Ges**, v. 155, p. 61-90, 2004.

102. WILLEMS, L.; RODET, J.; POUCLET, A.; MELO, S; RODET, M; COMPÈRE, P; HATERT, F.; AULER, A. S. Karst in sandstones and quartzites of Minas Gerais, Brazil**. Cadernos Lab. Xeolóxico de Laxe.** v. 33. p. 127 – 138, 2008.
103. WILLEMS, L.; RODET, J.; POUCLET, A.; RODET, M. J.; HARTERT, F. COMPÈRE, P.; AULER, A. S.. Carste em Quartzito da Região de Diamantina: Gruta do Salitre e Parque Estadual do Rio Preto, Minas Gerais. **I Encontro Brasileiro de Estudos do Carste.** Caderno de Resumos. Belo Horizonte, 2004.
104. WRAY, R. A. L; SAURO, F. An updated global review of solutional weathering processes and forms in quartzsandstones and quartzites**. Earth-Science Reviews**, v, 171, 2017. DOI: 10.1016/j.earscirev.2017.06.008.
105. YOUNG, R. W. Bungle Bungle: Tower Karst in Sandstone. In: MIGOŃ, P. **Geomorphological Landscapes of the World**. Springer-Verlag, p. 333-340, 2010.