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GEOLOGICAL AND GEOMORPHOLOGICAL CHARACTERIZATION OF THE MUNICIPALITY OF TEJUÇUOCA, CEARÁ

CARACTERIZAÇÃO GEOLÓGICA E GEOMORFOLÓGICA DO MUNICÍPIO DE TEJUÇUOCA, CEARÁ

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Abstract: The municipality of Tejuçuoca, located in the northern region of the state of Ceará, northeastern Brazil, exhibits a diverse range of landforms associated with the geological framework of the Borborema Province, particularly the residual massifs of the Catirina, Caboretinga, Barra, and Vertentes ranges. Although the area is primarily recognized for the occurrence of karst landforms developed in carbonate rocks, other geomorphological compartments within the municipality remain insufficiently investigated from both geological and geomorphological perspectives. In this context, the aim of this study was to provide an integrated geological and geomorphological characterization of the municipality of Tejuçuoca, Ceará, in order to understand the relationship between the geological substrate and the evolution of the identified landforms. The adopted methodology followed a qualitative and descriptive approach, structured into four stages: literature review, data collection and selection, fieldwork, and cartographic production. The results revealed the occurrence of distinct geomorphological compartments, including the Preserved Sertaneja Surface, Fluvial Plain, Crystalline Residual Massifs, ridges, inselbergs, spurs, and karst landforms. The diversity of these landforms is associated with the municipality's lithological heterogeneity, which comprises crystalline and carbonate rocks that have been subjected to tectonic activity, weathering, erosion, and chemical dissolution throughout geological time.

Keywords: Geomorphologic Cartography; Environmental Planning; karst reliefs.

Resumo: O município de Tejuçuoca, localizado na região norte do estado do Ceará, apresenta uma diversidade de formas de relevo associadas ao contexto geológico da Província Borborema, destacando-se os maciços residuais das serras da Catirina, Caboretinga, Barra e Vertentes. Embora a área seja reconhecida principalmente pela ocorrência de feições cársticas desenvolvidas em rochas carbonáticas, outros compartimentos geomorfológicos presentes no município ainda apresentam lacunas quanto à sua caracterização geológica e geomorfológica. Nesse contexto, o objetivo desta pesquisa consiste em realizar uma caracterização integrada dos aspectos geológicos e geomorfológicos do município de Tejuçuoca, Ceará, buscando compreender a relação entre o substrato rochoso e a evolução das formas de relevo identificadas. A metodologia adotada possui abordagem qualitativa e caráter descritivo, estruturada em quatro etapas: revisão bibliográfica, coleta e seleção de dados, trabalho de campo e produção cartográfica. Os resultados evidenciaram a presença de diferentes compartimentos geomorfológicos, representados pela Superfície Sertaneja Conservada, Planície Fluvial, Maciços Residuais Cristalinos, cristas, *inselbergs*, esporões e relevos cársticos. A diversidade das formas identificadas está associada à heterogeneidade litológica do município, composta por rochas cristalinas e carbonáticas submetidas a processos tectônicos, intempéricos, erosivos e de dissolução química ao longo do tempo geológico.

Palavras-chave: Cartografia Geomorfológica; Ordenamento Ambiental; Relevos Cársticos.

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1. Introduction

The typologies of landforms provide evidence of the geomorphological evolution and landscape transformations that have occurred over time, reflecting the dynamics of the natural processes responsible for shaping the Earth's surface. As one of the principal components of the physical environment, relief represents the spatial expression of the Earth's surface and encompasses the diverse configurations of the geomorphological landscape (CHRISTOFOLETTI, 1980). Although relief is an abstract concept from a theoretical standpoint, it is manifested through local and regional variations in the Earth's surface resulting from the interaction among geological, climatic, and geomorphological factors (ROSS, 2023).

Despite its conceptual abstraction, relief constitutes the physical framework supporting human activities and exhibits a wide diversity of landforms, geomorphological features, morphologies, and geological structures (FALCÃO SOBRINHO, 2006). Its evolution results from the dynamic interaction among the components of the natural environment through the continuous exchange of energy and matter. These processes govern landscape evolution and the genesis of landforms, forming the basis of the natural history of geomorphological development (ROSS, 2023).

This geomorphological dynamism arises from the integrated action of endogenous and exogenous processes. Endogenous processes originate within the Earth's interior and include tectonism, seismic activity, volcanism, and intrusive magmatism. In contrast, exogenous processes operate at the Earth's surface, promoting physical, chemical, and biological weathering, as well as erosion, which are responsible for the continuous sculpting and reshaping of the landscape (BASTOS *et al*., 2019; FLORENZANO, 2008).

The combined action of endogenous and exogenous processes has resulted in the development of distinct geomorphological units. In the state of Ceará, the Geological Survey of Brazil (CPRM) recognizes the following geomorphological domains: the Ceará Coastal Plain, the Jaguaribe and Acaraú River Alluvial Plains, the Coastal Tablelands, the Apodi Plateau, the Araripe Plateau, the Ibiapaba Plateau, Sertaneja Depression I, Sertaneja Depression II, Depressions within the Sertaneja Surface, and the Crystalline Residual Massifs (CPRM, 2014). The latter are further subdivided into humid and dry mountain ranges, reflecting distinct morphostructural characteristics controlled by geological conditions, climatic factors, and long-term geomorphological evolution.

Exceptional karst landforms associated with carbonate rocks occur within several of these geomorphological units. These landscapes are found in the Apodi Plateau, in eastern Ceará along the border with the state of Rio Grande do Norte; in the Araripe Plateau, in southern Ceará, within the Cariri region; and in the Ibiapaba Plateau, in northwestern Ceará along the border with the state of Piauí. In addition to these areas, karst features also occur within sectors of the Sertaneja Surface, particularly in the municipalities of Madalena and Tejuçuoca, where carbonate rock outcrops have controlled the development of these distinctive landforms.

The occurrence of these karst features contrasts with the present-day semiarid climate of Ceará and constitutes important evidence of paleoclimatic conditions that differed substantially from those observed today. In 2025, part of this geological heritage was officially protected through the establishment of Conservation Units under the framework of the Brazilian National System of Nature Conservation Units (Sistema Nacional de Unidades de Conservação da Natureza – SNUC). Among these protected areas, the Furna dos Ossos Natural Monument, located in the municipality of Tejuçuoca, was selected as the study area. Accordingly, this study investigates the geological and geomorphological characteristics of the area to understand how the geological substrate has controlled the evolution and geomorphological compartmentalization of the local landscape.

Although previous studies have investigated the geomorphology of the municipality of Tejuçuoca, they have focused predominantly on karst landforms developed in carbonate rocks. However, the municipality also contains landforms associated with non-carbonate lithologies that are of considerable scientific interest but remain poorly investigated. Therefore, this study aims to characterize the geological and geomorphological framework of the municipality of Tejuçuoca, Ceará, thereby improving the understanding of the relationship between the geological substrate and the spatial distribution of geomorphological units.

This study also contributes to advancing the knowledge of the geodiversity and geomorphology of the municipality of Tejuçuoca by providing a scientific basis for identifying areas with conservation potential. The results may support the recognition of sites that meet the criteria established by the Brazilian National System of Nature Conservation Units (SNUC), thereby contributing to future initiatives for the protection of natural heritage. Furthermore, the findings may provide valuable support for geomorphological planning, environmental vulnerability and fragility assessments, land-use zoning and territorial planning, as well as the development of strategies for sustainable land management and the conservation of natural environments.

1.1 Study Area

The municipality of Tejuçuoca is located in the Northern Mesoregion of the state of Ceará, northeastern Brazil, approximately 148.5 km from Fortaleza, the state capital. It covers an area of 758.706 km² and is administratively divided into two districts: Tejuçuoca and Caxitoré. The municipality is bordered by Itapajé to the north, Canindé to the south, Apuiarés and General Sampaio to the east, and Irauçuba to the west (Figure 1).

From a cartographic perspective, the municipality is located within the SA.24 – Fortaleza and SB.24 – Jaguaribe map sheets, according to the classification adopted by the Geological Survey of Brazil (CPRM, 1981). It is also covered by the following map sheets produced by the Superintendence for the Development of the Northeast (SUDENE): Irauçuba (SA.24-Y-D-V), São Luís do Curu (SA.24-Y-D-VI), and Taperuaba (SB.24-V-B-II) (SUDENE, 2018).

According to the Brazilian Institute of Geography and Statistics (IBGE, 2022), the municipality has a population of 17,154 inhabitants. Access to the study area is primarily provided by the BR-222 federal highway.

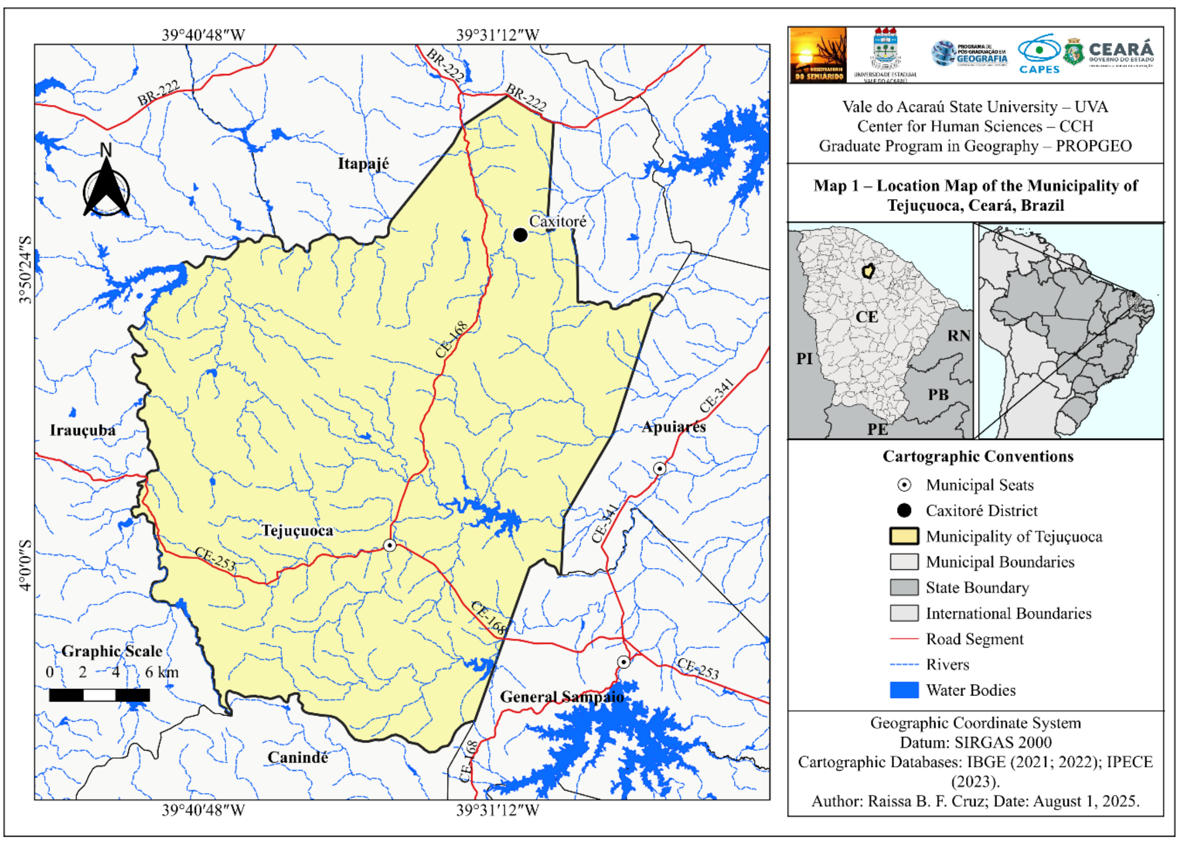

Figure 1. Location map of the municipality of Tejuçuoca, Ceará State, Brazil.
Source: authors (2025).

2. Materials and Methods

This study adopted a qualitative and descriptive approach and was structured into four methodological stages: (i) literature review, (ii) data collection and selection, (iii) field survey, and (iv) cartographic production.

The first stage consisted of a comprehensive literature review focused on geomorphology and the theoretical and methodological foundations of landform analysis. Classical and contemporary studies by Christofoletti (1980), Florenzano (2008), and Ross (1992, 2023) were used as the primary theoretical framework. In addition, previous investigations addressing the geological, geomorphological, and environmental characteristics of the municipality of Tejuçuoca were consulted, particularly the studies conducted by Bastos, Cavalcante, and Silva (2016), Cavalcante *et al*. (2019), Cezário

(2019), and Mapurunga (2003). The literature survey included peer-reviewed scientific journals, institutional repositories, books, and digital databases, providing the theoretical basis for the interpretation of the data obtained during the subsequent stages of the research.

The second stage comprised the collection, organization, and selection of environmental, cartographic, and geospatial datasets used throughout the study. Environmental data were obtained from the Ceará State Superintendence for the Environment (SEMACE), whereas cartographic and territorial information was acquired from the Ceará Institute for Research and Economic Strategy (IPECE), the Brazilian Institute of Geography and Statistics (IBGE), and the Ceará Foundation for Meteorology and Water Resources (FUNCEME). Elevation data were derived from the Brazilian Geomorphometric Database (TOPODATA), which provides a 30-m spatial resolution Digital Elevation Model (DEM) used to generate terrain-derived products. Georeferenced satellite imagery available through Google Earth was also employed to support the spatial interpretation of the study area. Complementary geological, geomorphological, and speleological information was obtained from the Geological Survey of Brazil (SGB), the Geological Survey of Brazil (CPRM), the Superintendence for the Development of the Northeast (SUDENE), the Brazilian Speleological Society (SBE), and the National Center for Cave Research and Conservation (CECAV).

The third stage consisted of field surveys conducted to collect geomorphological information and validate the results obtained from the cartographic analyses and literature review. Field data were acquired using a Garmin eTrex 10 Global Positioning System (GPS) receiver, the Outdoor GPS Wikiloc navigation application (version 3.41.5), a DJI Mini 2 Unmanned Aerial Vehicle (UAV; approximately 249 g), and a Redmi Note 12 Pro smartphone. During the field campaigns, photographic records were acquired, geomorphological points of interest were surveyed, and the morphological characteristics of the landforms were documented. These observations provided essential information for landscape interpretation and validation of the cartographic products.

The fourth stage involved the preparation of the cartographic products within a Geographic Information System (GIS) environment using QGIS version 3.28.6. Data organization, processing, and spatial analyses were performed to produce the thematic maps used for the geological and geomorphological characterization of the study area.

The cartographic products were developed using vector and raster datasets obtained from the official databases previously described. Initially, the datasets were preprocessed through layer organization, reprojection to the adopted coordinate reference system, clipping to the municipal boundary of Tejuçuoca, and standardization of cartographic symbology. Terrain analysis was based on the Digital Elevation Model, allowing the generation of hypsometric, slope, and geomorphological compartmentalization maps.

The delineation of the geomorphological units was based on the integration of morphostructural and morphosculptural attributes of the landscape. The adopted criteria included elevation distribution, slope patterns, lithological characteristics, geological structures, landforms identified during the field surveys, and information obtained from the specialized literature. The geomorphological classification followed the taxonomic framework proposed by Ross (1992) and Souza (1988), considering the interaction between geological and geomorphological processes responsible for the present-day landscape configuration.

3. Results and Discussion

The study area is located within the northern sector of the Borborema Province, a geological province formed during the Neoproterozoic assembly of a complex orogenic system that extends into several orogenic belts of West Africa (SANTOS *et al*., 2014). This province constitutes a major segment of the South American Platform, whose geological evolution involved successive tectonothermal events, crustal accretion, and reworking processes that occurred from the Archean to the early Paleozoic (CPRM, 2018). These geological events controlled the structural organization of the regional basement, conditioning the distribution of lithological units and exerting a fundamental influence on the present-day geomorphological configuration of the municipality of Tejuçuoca.

Within the northern Borborema Province, crustal evolution is primarily associated with the Atlantica and Brasiliano orogenic cycles, which were responsible for the consolidation and reorganization of major geological domains during the Precambrian (BRITO NEVES, 1999). In this context, the study area corresponds to a basement inlier, characterized by the exposure of ancient crystalline rocks that preserve evidence of multiple episodes of crustal formation, deformation, and reworking. These geological processes involved successive episodes of continental amalgamation and fragmentation associated with the evolution of major crustal blocks during the assembly and breakup of the Atlantica, Rodinia, and Pannotia supercontinents (SARAIVA JÚNIOR, 2009).

The Brasiliano Orogeny represents one of the most significant tectonic events in the geological evolution of northeastern Brazil and played a fundamental role in the assembly of the Gondwana Supercontinent, corresponding to the southern sector of the former Pannotia and, subsequently, Pangaea supercontinents (BRITO NEVES, 1999). This continental amalgamation process, completed at approximately 515 Ma, produced intense deformation, regional metamorphism, and structural reorganization of the terranes that compose the Borborema Province (CABY *et al*., 1995). As a result, lithological units with contrasting structural characteristics and mechanical resistance were established, subsequently controlling the response of the landscape to exogenous geomorphological processes.

The interaction between the inherited geological framework and long-term weathering and erosional processes has controlled the regional geomorphological evolution. Differential lithological resistance favored the development of distinct geomorphological compartments, as more resistant rocks were preserved as topographically elevated areas, whereas less resistant lithologies were progressively lowered through denudational processes. Consequently, the present-day landforms observed in the municipality of Tejuçuoca reflect the combined influence of regional geological evolution and the geomorphological processes responsible for shaping the Earth's surface.

3.1 Geological Framework of Tejuçuoca

The municipality of Tejuçuoca exhibits considerable geological diversity (Figure 2), as documented by the Geological Survey of Brazil (SGB, 2020). The study area is situated within the Precambrian crystalline basement and comprises a wide range of lithological associations, including gneisses, schists, paragneisses, orthogneisses, quartzites, granodiorites, metagranitoids, migmatites, metacarbonate rocks (marbles), calcitic marbles, and calc-silicate rocks, ranging in age from the Paleoproterozoic to the Neoproterozoic. These lithological units represent ancient crustal terranes that experienced multiple tectonic and metamorphic events. Their lithological diversity directly controls differential resistance to weathering and erosion, thereby exerting a strong influence on the spatial distribution and development of the geomorphological units within the municipality.

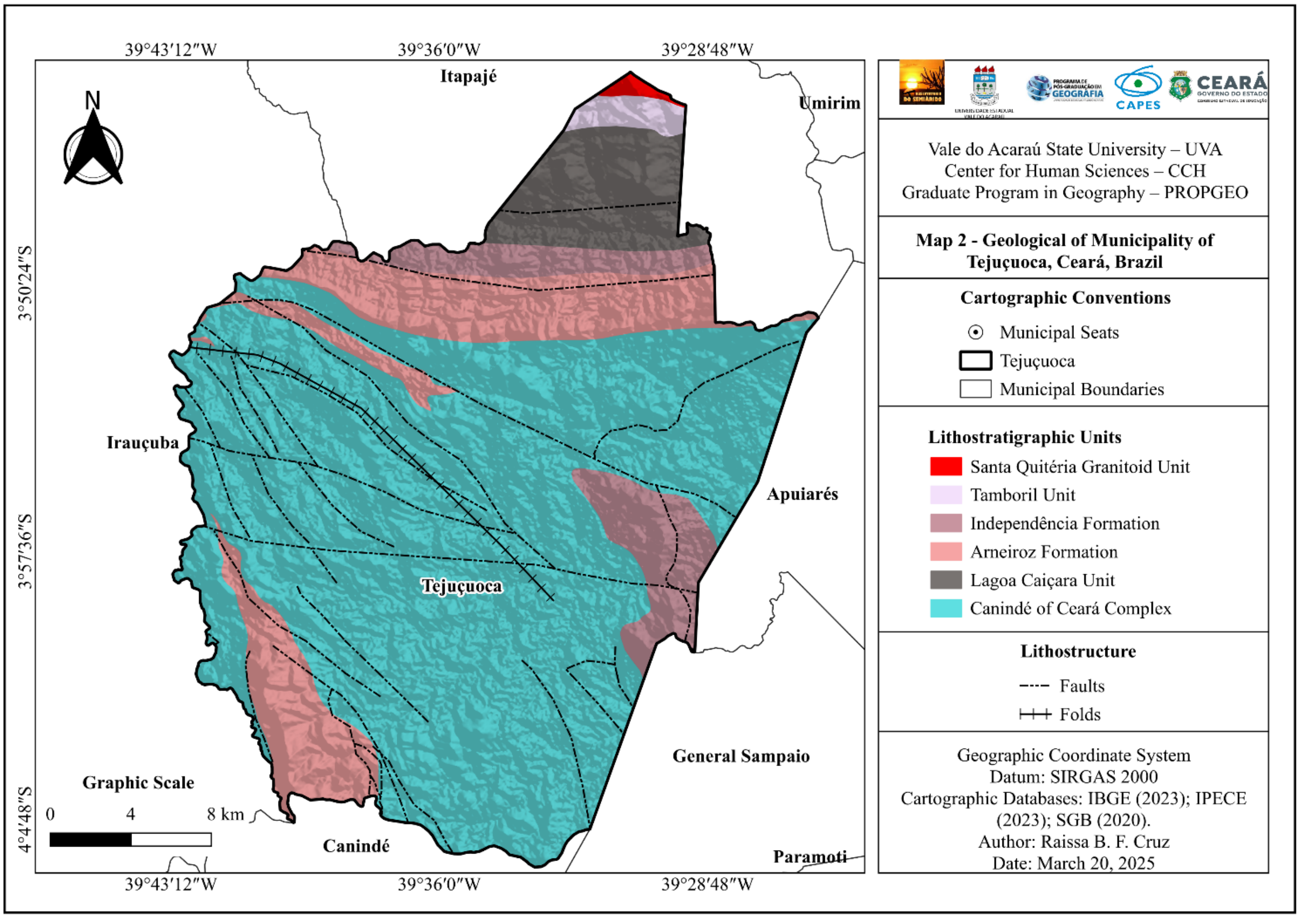

Figure 2. Geological map of the municipality of Tejuçuoca, Ceará State, Brazil.
Source: authors (2025).

The Santa Quitéria Granitoid Unit corresponds to a major magmatic body within the Tamboril–Santa Quitéria Complex, composed predominantly of granitoid rocks exhibiting different degrees of magmatic differentiation (CPRM, 2018). The occurrence of these lithotypes is associated with areas of greater structural resistance, favoring the preservation of elevated topographic sectors and contributing to the development of prominent geomorphological compartments, such as crystalline residual massifs and steep slopes. According to SAMPAIO (2017), this unit comprises less differentiated granitoids, represented by metadiorites, metamonzodiorites, metaquartz diorites, and metagranodiorites, as well as more evolved granitoids, including meta-alkali feldspar granites and metasienogranites.

The Tamboril Unit originated from partial melting processes affecting the rocks of the Lagoa Caiçara Unit between approximately 625 and 600 Ma, producing anatexites derived from the *in situ* partial melting of country rocks belonging to the Lagoa Caiçara and Santa Quitéria units, as well as metasedimentary rocks of the Ceará Complex (FRANCO, 2018). The occurrence of these lithologies exerts a strong influence on the structural configuration of the landscape, since differences in rock resistance control the intensity of weathering and differential erosion processes.

Another geological unit present in the study area is the Independência Formation, whose lithotypes are associated with low-relief surfaces, gently undulating terrains, and elevated ridges, particularly where resistant quartzite bodies crop out (CPRM, 2018). This unit, dated at approximately 772 Ma, consists predominantly of metasedimentary rocks, including biotite-, muscovite-, garnet-, kyanite-, and sillimanite-bearing schistose gneisses, together with intercalations of amphibolites, quartzites, and calcitic and dolomitic marbles (CPRM, 2021). The lithological diversity of this formation contributes to marked geomorphological contrasts, whereby more resistant rocks preserve elevated landforms, whereas less resistant materials favor the development of lower-relief sectors.

The Arneiroz Formation represents another geological unit within the municipality of Tejuçuoca and is composed predominantly of quartzites and mica schists, with subordinate occurrences of calc-silicate rocks, two-mica gneisses, and migmatitic gneissic domains (MOREIRA; SILVA, 2017). These lithologies contribute to the structural diversity of the local geological framework, as quartzites exhibit high resistance to weathering and erosion, favoring the preservation of elevated terrains and rugged topography.

The Ceará Canindé Complex constitutes the predominant geological unit in the municipality of Tejuçuoca and is regarded as one of the principal Paleoproterozoic crustal segments of the Borborema Province (CPRM, 2018). This complex comprises several lithological associations, among which the Paraderived Migmatites (PRcn1) and Orthogneisses (PRcn2) are the most representative. The Paraderived Migmatites are related to anatectic processes involving the partial melting of pre-existing rocks, predominantly metasedimentary protoliths, resulting in heterogeneous lithological assemblages characterized by varying degrees of deformation and mineral recrystallization.

The Orthogneisses (PRcn2) occur mainly as extensive rock pavements and slightly weathered rock outcrops in the northwestern portion of the municipality (CPRM, 2018). These rocks exhibit high mechanical strength, favoring the preservation of rocky outcrops and contributing to the development of landforms controlled by differential erosion. Consequently, the spatial distribution of the lithological units of the Ceará Canindé Complex exerts a direct influence on the geomorphological organization of Tejuçuoca, controlling the occurrence of compartments with distinct elevation, slope, and landscape dissection patterns.

3.2 Geomorphological Framework of Tejuçuoca

The geomorphological framework of the municipality of Tejuçuoca comprises several landscape units, including the Preserved Sertaneja Surface, Crystalline Residual Massifs, Ridges, Inselbergs, and the Fluvial Plain. Among these units, the Preserved Sertaneja Surface is the most extensive, occupying approximately 74.2% of the municipal territory.

This geomorphological unit is associated with the Sertaneja Depression, which represents the regional geomorphological surface developed through long-term denudational processes acting upon the crystalline basement (CAVALCANTE; BASTOS, 2016). In Tejuçuoca, it is characterized by predominantly flat to gently undulating relief interrupted by residual landforms, including crystalline massifs, ridges, and inselbergs, which are sustained by lithologies exhibiting greater resistance to weathering and erosion (TEIXEIRA, 2018).

As illustrated in Figure 3, the spatial distribution of these landforms highlights the strong influence of the geological framework on the geomorphological organization of the municipality. Areas underlain by relatively less resistant rocks underwent progressive denudation, whereas sectors supported by more resistant lithologies remained preserved, giving rise to residual landforms that stand out prominently within the landscape.

The Preserved Sertaneja Surface represents a geomorphologically stable compartment dominated by long-term dissection processes resulting from prolonged weathering and erosion of the crystalline basement. The evolution of these surfaces is closely associated with pediplanation processes typical of semiarid environments, which have produced extensive planation surfaces characterized by widespread exposure of crystalline rocks (PAISANI; PONTELLI; ANDRES, 2008; AB'SÁBER, 1969). Within this regional context, the Preserved Sertaneja Surface plays an important geomorphological role by connecting elevated terrains with adjacent lower-relief compartments while also contributing to sediment transport and depositional processes (DORANTI; FRANCO-MAGALHÃES, 2011).

Figure 3. Gently undulating planation surface.
*Source**:** authors (2025).*

Within the study area, the Preserved Sertaneja Surface is characterized predominantly by elevations below 200 m, forming a topographically subdued compartment compared with the higher terrains represented by the crystalline residual massifs and other isolated landforms within the municipality. As shown in Figure 4, the municipality exhibits an altitudinal range of approximately 700 m, highlighting pronounced topographic contrasts associated with the differentiation of its geomorphological compartments.

This geomorphological configuration reflects the interaction between the inherited structural framework of the Borborema Province and the prolonged action of denudational processes. Tectonic events associated with the Brasiliano Orogeny produced intense deformation, regional metamorphism, and structural reorganization of the crust, contributing to the differentiation of the lithological units (BRITO NEVES, 1999). Subsequently, exogenous processes promoted differential denudation, resulting in the progressive lowering of less resistant terrains while preserving areas underlain by more resistant lithologies.

Within this context, the Crystalline Residual Massifs constitute prominent geomorphological features that interrupt the continuity of the regional planation surfaces. In Tejuçuoca, these landforms are dispersed across the Preserved Sertaneja Surface and occupy approximately 16.1% of the municipal territory. They occur both as groups of residual ridges supported by resistant quartzites and mica schists and as isolated residual hills represented by inselbergs (TEIXEIRA, 2018).

The preservation of these elevated landforms is primarily controlled by the differential resistance of the lithologies composing the geological substrate. While the surrounding areas were progressively lowered by long-term denudational processes, the more resistant rocks remained as erosional remnants recording the geomorphological evolution of the region. Consequently, the crystalline residual massifs clearly demonstrate the fundamental role of geological structure in controlling the geomorphological compartmentalization of the municipality of Tejuçuoca.

In addition to the crystalline residual massifs, mountainous terrains are also present, characterized by highly dissected landscapes with steep slopes developed on contrasting lithological assemblages and expressed as ridges, summit crests, and escarpments (IBGE, 2019). These landforms represent the highest-energy sectors of the landscape, where the present-day topography reflects the combined influence of lithological resistance, geological structures, and the long-term action of geomorphological processes.

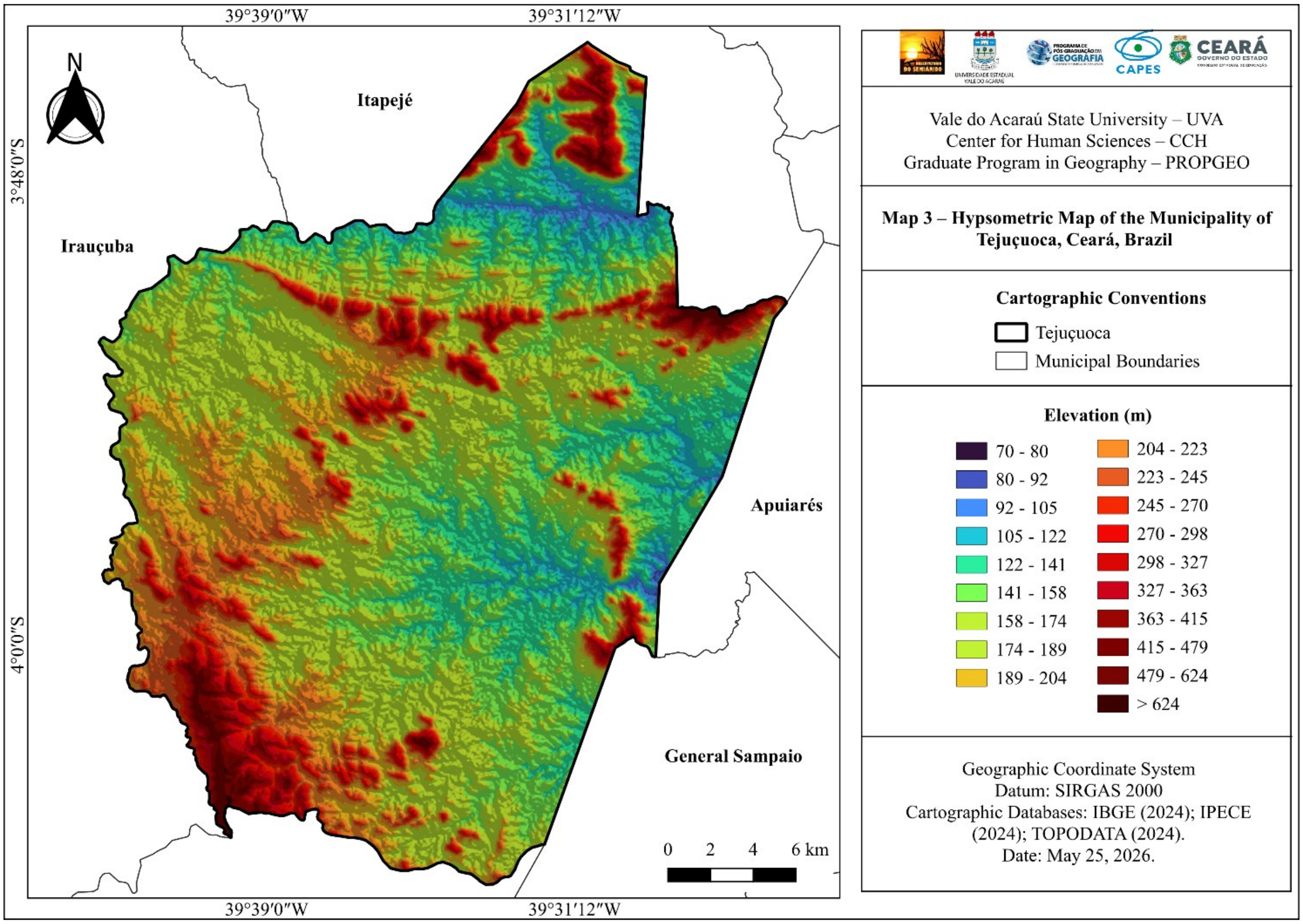

Figure 4. Hypsometric map of the municipality of Tejuçuoca, Ceará State, Brazil.
Source: Authors (2026).

The most prominent crystalline residual massifs in the municipality of Tejuçuoca are represented by the Catirina, Caboretinga, Vertentes, and Barra mountain massifs, which form elevated geomorphological compartments within the Preserved Sertaneja Surface. Among these, the Catirina Massif, located in the southwestern portion of the municipality, stands out with elevations reaching approximately 600 m. This massif hosts the principal karst landforms identified in the study area.

The Catirina Massif constitutes a residual landform developed within the crystalline basement of the Borborema Province and is characterized by the occurrence of metamorphosed carbonate rocks, particularly metacarbonate rocks (marbles), whose lithological composition has favored the development of solutional processes. These lithological conditions promoted the formation of both exokarst and endokarst features, including surface solution landforms, subterranean cavities, and microkarst features associated with karst landscape evolution.

This geomorphological compartment encompasses the Furna dos Ossos Natural Monument, a protected area established by Decree No. 37,015 of December 16, 2025. The conservation unit covers approximately 60.37 ha and has a perimeter of 3.93 km. It is recognized for its outstanding geomorphological significance due to the concentration of karst landforms developed in carbonate rocks embedded within a crystalline residual landscape.

The occurrence of these karst landforms under the present-day semiarid climatic conditions represents an important paleoclimatic indicator, as contemporary hydroclimatic conditions are insufficient to explain the intensity of the karstification processes observed in the area. Consequently, the karst features of Tejuçuoca are interpreted as inherited landforms developed during wetter climatic phases of the Quaternary, when increased water availability and humidity enhanced the chemical dissolution of carbonate rocks (AULER *et al*., 2005; BIGARELLA *et al*., 2009).

In addition to the landforms produced by chemical dissolution, the Catirina Massif contains small inselbergs and ruiniform landforms generated through the combined effects of weathering and differential erosion. These processes acted unevenly in response to variations in lithological resistance, leading to the preservation of more resistant rock masses surrounded by progressively denuded surfaces. As illustrated in Figure 5, the massif exhibits well-developed ruiniform landforms and microforms occurring both on exposed rock surfaces and within subterranean cavities, highlighting the interaction among geological structure, erosional processes, and chemical dissolution in shaping the local karst landscape.

Figure 5. Panoramic view of the crystalline residual massif.
Source: Authors (2026).

During field surveys conducted in the Catirina Massif, seven natural underground cavities—locally referred to as caves, grottos, or *furnas*—were identified. These features represent key elements of the local geomorphological heritage, as they preserve evidence of dissolution processes, mineral deposition, and paleoenvironmental evolution (MONTEIRO, 2014).

A variety of speleothems was identified within the cavities, including stalactites, stalagmites, columns, draperies, coralloids, skylights, rimstone dams, and other secondary mineral deposits. These features constitute the endokarst, defined as the network of underground conduits and mineral deposits developed within carbonate rocks (PILÓ, 2000).

As shown in Figure 6, the cavities exhibit varying dimensions and stages of development, comprising chambers with distinct ceiling heights and spatial configurations. Among them, Furna do Sino Cave is particularly noteworthy for its pronounced vertical development, reaching an estimated height of 7–10 m, reflecting the prolonged action of chemical dissolution within the carbonate rocks of the Catirina Massif.

The formation of these karst features is primarily controlled by the carbonation process, in which CO_2-enriched water promotes the dissolution of calcium carbonate. Initially, carbonic acid is formed through the following reaction:

$$CO_2 + H_2O \rightarrow H_2CO_3$$

Subsequently, carbonic acid reacts with the calcium carbonate present in the carbonate rocks according to the following reaction:

$$CaCO_3 + H_2CO_3 \rightarrow Ca^{2+} + 2HCO_3^-$$

This process promotes the development of fractures, subsurface conduits, and cavities, subsequently leading to the precipitation of dissolved minerals that give rise to the speleothems observed in the Furna dos Ossos cave system (AULER & ZOGBI, 2005; MONTEIRO, 2014).

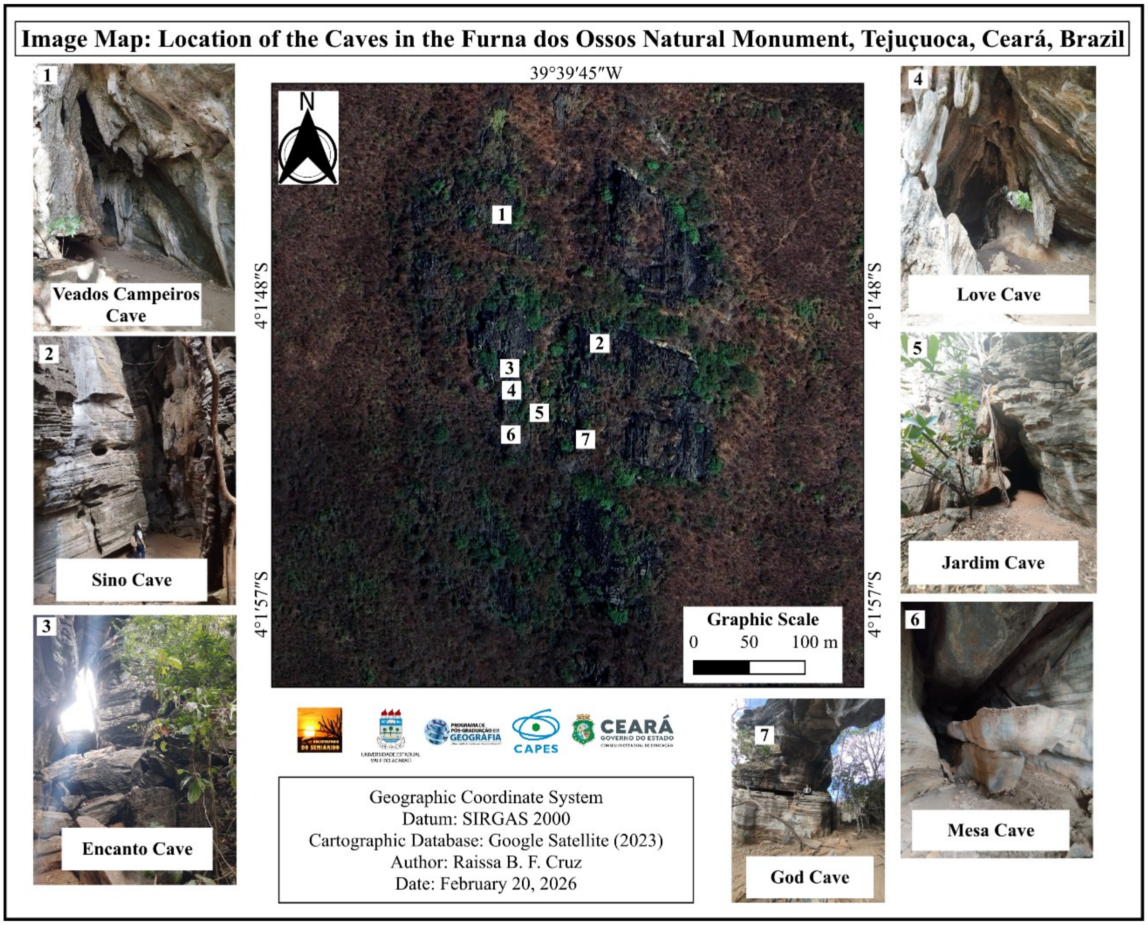

Figure 6. Location map of the caves within the Furna dos Ossos Natural Monument, Tejuçuoca, Ceará, Brazil. Source: Authors (2026).

Among the speleothems identified in Furna dos Ossos Cave, stalactites and stalagmites are the most prominent (Figure 7). Their formation is associated with the precipitation of carbonate minerals within the cave environment. Stalactites develop from the dripping of calcium bicarbonate-rich solutions that percolate through fractures and fissures in the cave ceiling. During this process, carbon dioxide is released, promoting the precipitation of calcium carbonate and the progressive downward growth of these speleothems.

Stalagmites, in turn, form through the deposition of carbonate minerals transported by water droplets reaching the cave floor. Partial evaporation of the water and the release of CO_2 promote calcite crystallisation, giving rise to structures that grow vertically upward from the cave floor. As these processes continue, the simultaneous growth of stalactites and stalagmites may eventually result in their coalescence, forming speleothems known as columns (TORTELLI, 2009).

Coralloids were also identified throughout the Furna dos Ossos Natural Monument. These speleothems result from the precipitation of carbonate minerals associated with the circulation of aqueous solutions within the caves and may develop through dripping, seepage, or the splashing of fine water droplets onto rock surfaces. Curtains constitute another type of speleothem observed in the study area, developing mainly along inclined sections of the cave ceiling. Their growth results from the successive deposition of minerals transported by thin water films flowing over these surfaces, producing laminar structures that may range from a few centimetres to several metres in length.

In addition to these mineral deposits, travertine rimstone dams were identified and are associated with the continuous circulation of water within the caves. According to ICMBio (2019), these structures are formed by the precipitation of calcium carbonate resulting from CO_2 degassing at the water surface, producing small mineral deposits that remain partially supported by surface tension.

Several exokarst landforms were identified in the surface sector of the cave system, including folded marble (metacarbonate) outcrops, fractured surfaces, karren, alveoli, and ruiniform features, as well as morphologies exhibiting patterns interpreted as pareidolia. These landforms reflect the combined influence of geological structure, chemical weathering, and surface erosion on the evolution of the local karst landscape (PILÓ, 2000).

The observed exokarst features, particularly the ruiniform morphologies, are associated with the differential weathering of carbonate rocks, whereby lithological domains with distinct resistance respond differently to weathering processes. Furthermore, the folds identified in the marbles record the tectonic evolution of the Borborema Province and are related to ancient crustal deformation events responsible for the structural framework of the regional geological basement. According to the structural classification proposed by CPRM (2014), these structures exhibit different degrees of deformation, ranging from weakly to moderately folded and locally to intensely folded. This structural pattern is characteristic of sedimentary, volcano-sedimentary, and granitoid–gneissic migmatitic terranes affected by multiple tectonic events during the geological evolution of the Borborema Province.

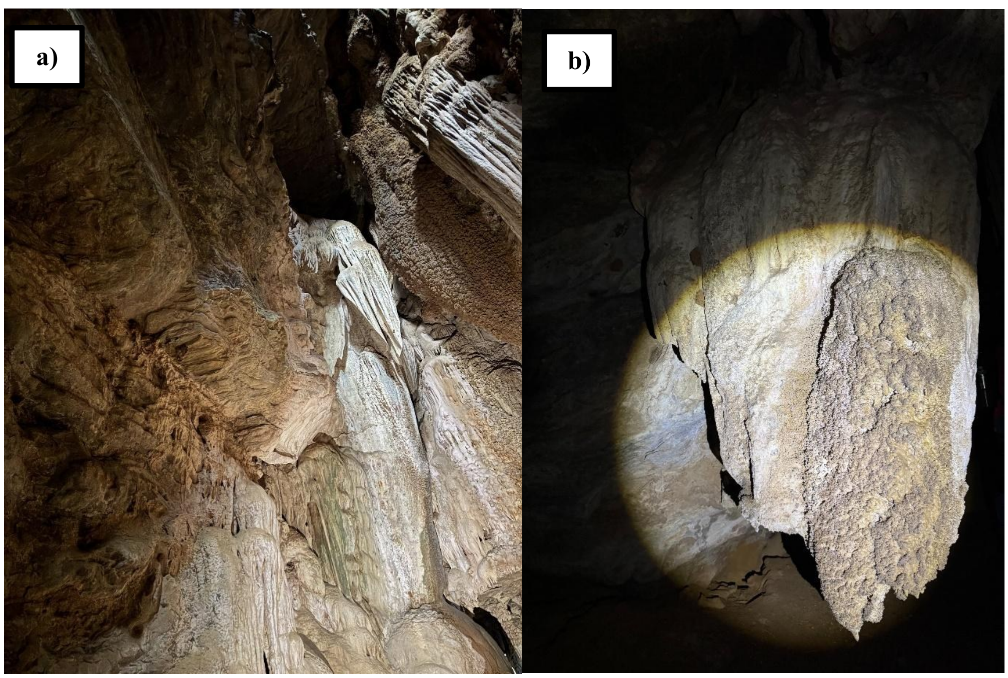

Figure 7 – Speleothems: (a) ceiling of Sino Cave; (b) stalactite covered with coralloids.
Source: Authors (2026).

In addition, fractures in the marble were observed, recording ancient tectonic stresses associated with the geological evolution of the Borborema Province (ROCHA *et al*., 2018). These structures constitute important controlling factors in the evolution of the karst landscape, as rock discontinuities facilitate groundwater circulation and enhance the chemical dissolution of carbonate minerals.

Sub-horizontal planar structures were also identified in the marble and may be related to ancient bedding planes preserved during the metamorphic and deformational processes that occurred throughout the regional geological history. These structures influence the internal architecture of the rock and may act as preferential pathways for the development of dissolution features.

The karren shown in Figure 8 correspond to small-scale surface landforms developed by the chemical dissolution of carbonate rocks. According to Moura (2017), these features are characterised by grooves, channels, and small cavities formed by the action of slightly acidic water on exposed rock surfaces and near-surface areas, providing evidence of karstification processes in the Catirina Range.

Figure 8 – Types of karren.
Source: Authors (2026).

A remarkable occurrence of alveoli was also observed on the steep rock faces of the massif, displaying a predominantly horizontal arrangement. The origin of these features remains a matter of debate in the geomorphological literature, as they may result from different surface processes, including chemical dissolution, differential weathering, and the action of water on vertical or inclined rock surfaces (ROCHA *et al*., 2018). According to Guerra (2008), alveoli are small cavities or perforations developed on rock walls and may represent the initial stages in the evolution of larger weathering forms, such as tafoni, depending on the prevailing structural and environmental conditions.

With regard to the Caboretinga Range, other prominent residual landforms occurring in the municipality of Tejuçuoca are represented by inselbergs (Figure 9). These landforms consist of isolated hills rising above the surrounding low-relief surfaces and are associated with the greater resistance of their constituent lithologies to weathering and differential erosion. In addition to their wide variation in size and morphology, the inselbergs exhibit several associated geomorphological features, including rock pavements, solution pans, tafoni, runnels, and boulders, which have developed through the prolonged action of weathering and erosional processes on the rocky substrate (OLÍMPIO *et al*., 2021).

Figure 9 – Caboretinga Range, Tejuçuoca, Ceará, Brazil.
Source: Authors (2025).

The Caboretinga Range is located in the southeastern sector of the municipality of Tejuçuoca and constitutes an isolated residual landform within the geological framework of the Canindé do Ceará Complex. This geological unit is composed of Paleoproterozoic rocks, dated at approximately 1.8–1.6 Ga, with migmatitic paragneiss representing the dominant lithology in the study area.

The relatively high resistance of these lithologies has favoured the preservation of this elevated landform amidst the surrounding low-relief surfaces of the Sertaneja Depression. However, the prolonged action of weathering processes has promoted the development of several microlandforms associated with the differential weathering of the rock, among which a natural tafoni cavity is particularly noteworthy.

Tafoni are cavities developed on exposed rock surfaces through the combined action of physical and chemical weathering, which promote mineral alteration, granular disintegration, and the progressive removal of less resistant materials. Although tafoni are most commonly associated with granitic rocks, they may also develop in other lithologies, including sandstones, limestones, and metamorphic rocks, depending on the prevailing structural and environmental conditions.

Near the tafoni, in the upper sector of the range, a talus deposit was identified, formed by the accumulation of rock fragments derived from weathering and the gravitational downslope movement of materials along the hillside. These deposits provide evidence of the present-day geomorphological dynamics and reflect the combined influence of weathering processes and mass movements on slope evolution (CAVALCANTE *et al*., 2018).

Alveoli, also referred to as honeycomb weathering structures, were identified inside the cavity. These features are characterised by small cavities developed on the rock surface and are associated with differential weathering controlled by the mineralogical and structural characteristics of the migmatitic paragneiss. Owing to the penetration of natural light into the cavity, it contains a photic zone. The identified alveoli range in size from a few centimetres to several metres, as shown in Figure 10.

Figure 10 – Interior of the tafoni in the Caboretinga Range, Tejuçuoca, Ceará, Brazil.
Source: Authors (2025).

The Barra Range, locally known as Pedra do Oratório, is located in the northern sector of the municipality of Tejuçuoca and constitutes an important crystalline residual landform (Figure 11). This geomorphological unit is predominantly composed of granodioritic orthogneisses associated with the geological framework of the Borborema Province, with ages ranging from the Late Mesoproterozoic to the Early Neoproterozoic.

The highest point of the massif corresponds to a residual ridge reaching approximately 500 m above sea level. Its geomorphological configuration is controlled by the differential resistance of the underlying lithologies, which has favoured the preservation of a prominent rock mass rising above the adjacent low-relief surfaces.

Figure 11 – Barra Range (Pedra do Oratório), Tejuçuoca, Ceará, Brazil.
Source: Authors (2025).

A tafoni cavity was identified on the mid-slope of the Barra Range (Figure 12), where it developed through the prolonged action of differential weathering affecting the granodioritic orthogneiss. The presence of fractures and structural discontinuities facilitated water infiltration and the progressive alteration of minerals, promoting the removal of less resistant material and the formation of cavities on the rock surface.

Figure 12 – Interior of the Pedra do Oratório tafoni cavity, Barra Range, Tejuçuoca, Ceará, Brazil.
Source: Authors (2025).

Several alveoli, also referred to as honeycomb weathering forms, were observed inside the tafoni cavity. These features are characterised by small cavities distributed along the inner walls of the rock. The area contains a photic zone due to the direct incidence of natural light within the cavity, allowing the observation of microforms associated with surface alteration processes.

According to Guerra (2008), rock surfaces with a high concentration of these cavities may be classified as cavernous surfaces, particularly when they exhibit numerous perforations developed on vertical or inclined walls. These features result from the combined action of weathering and erosional processes, controlled by the mineralogical, structural, and environmental characteristics of the rocky substrate.

The residual massif known as the Vertentes Range (Figure 13) is located within the Northern Sertaneja Depression, in the northwestern sector of the municipality of Tejuçuoca. This geomorphological unit reaches an approximate elevation of 630 m and corresponds to an elongated relief alignment extending for approximately 29.5 km, standing out as an important residual feature in the municipal landscape.

Figure 13 – Panoramic view of the residual landform of the Vertentes Range, Tejuçuoca, Ceará, Brazil.
Source: Authors (2026).

As shown in Figure 14, the Vertentes Range exhibits different morphological patterns in its summits and slopes, including sharp summits (Ta), concave summits (Tc), and flat-topped summits (Tt), as well as concave slopes (Vc), sharp slopes (Va), and straight slopes (Vr). This morphological diversity reflects different degrees of landscape dissection and the differential action of geomorphological processes on the rocky substrate.

The current configuration of this massif is associated with the prolonged evolution of the regional landscape, characterised by the action of weathering, erosion, and the removal of surface materials. The alternation between wetter climatic conditions and periods of increased aridity throughout geological time contributed to the development of planation surfaces and the preservation of elevated residual landforms associated with pediplanation processes characteristic of semi-arid environments (SANTOS; BACCARO, 2004).

The Vertentes Range also has significant environmental conservation relevance, partially encompassing the municipality of Itapajé, where the Mãe da Lua Private Natural Heritage Reserve (RPPN) is located. This protected area contributes to the preservation of natural environments associated with the massif, highlighting the importance of these geomorphological compartments for maintaining biodiversity and conserving the regional landscape (CEZÁRIO, 2019).

In addition to the large residual massifs, the municipality contains other smaller-scale landforms, such as hills, hillocks, and narrow ridges. Hills correspond to elevations generally ranging from 100 to 200 m in relative relief amplitude, with rounded summits; hillocks exhibit smaller amplitudes, approximately between 20 and 60 m, and steep slopes; whereas narrow ridges correspond to elongated and isolated elevations within the landscape (FLORENZANO, 2008). These landforms represent different stages of geomorphological evolution controlled by rock resistance and the action of erosional processes.

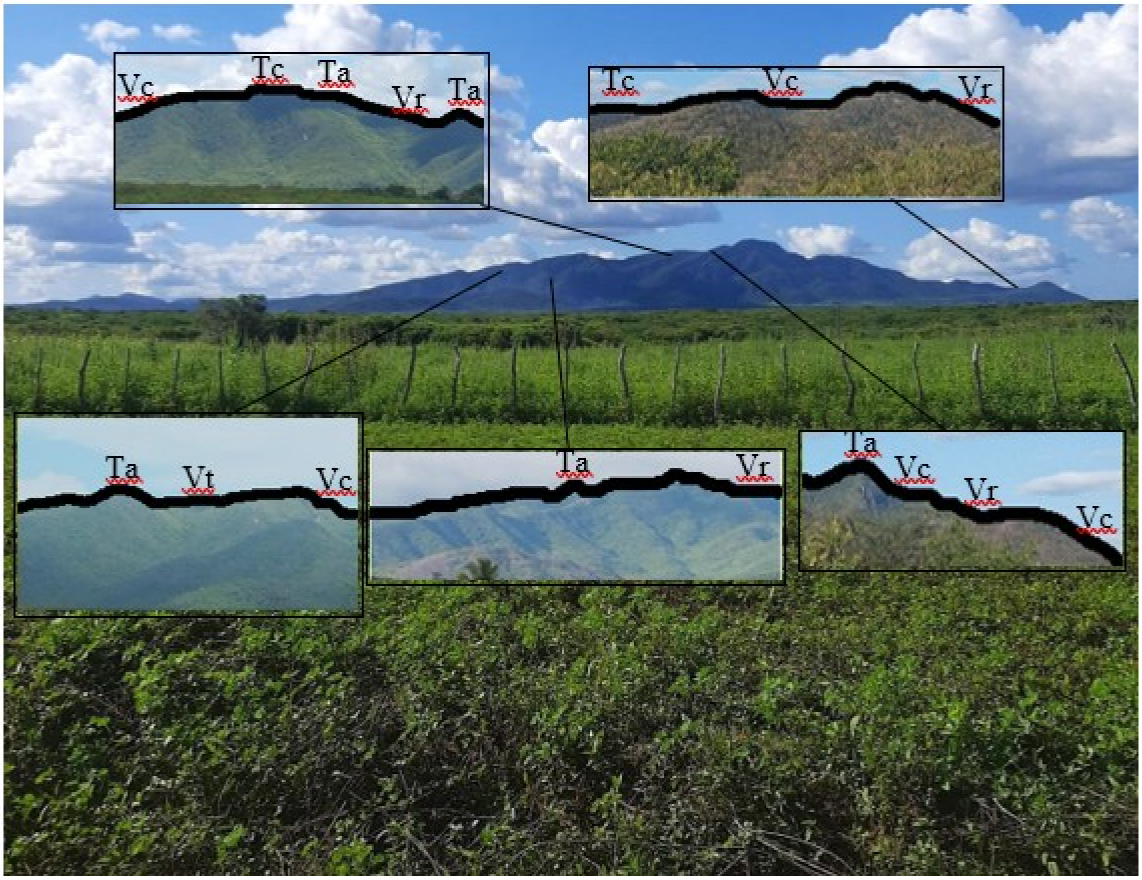

Figure 14 – Residual ridge of the Vertentes Range, Tejuçuoca, Ceará, Brazil.
Source: Authors (2026).

The municipality of Tejuçuoca is characterised by a significant predominance of metamorphic rocks associated with the tectono-metamorphic events that shaped the geological evolution of the Borborema Province. During the Brasiliano Orogeny, intense processes of crustal deformation, metamorphism, and magmatism occurred, related to the amalgamation of the Gondwana supercontinent and promoting the structural reorganisation of the Precambrian terrains that compose the region.

These processes were responsible for the development of structures such as faults, fractures, and folds, which are currently preserved in the municipal geological substrate. In the Catirina Range, these structures are evidenced by the occurrence of intense folding and fractures in marble, demonstrating the influence of ancient tectonic stresses on the geological and geomorphological configuration of the area. According to Rocha *et al*. (2018), the multidirectional folds observed in the Borborema Province record different phases of crustal deformation associated with its geological evolution.

The presence of these structures directly influences landscape evolution, as fractures and deformation zones may control groundwater circulation, weathering processes, and the development of specific geomorphological features. Therefore, the current organisation of the landforms in Tejuçuoca represents the result of the interaction between geological structure, lithological resistance, and the action of exogenous processes throughout geological time.

Another geomorphological unit identified in the municipality corresponds to the fluvial plain of the Caxitoré River sub-basin, shown in Figure 15. This unit encompasses sectors of the municipalities of Irauçuba, Itapajé, Pentecoste, Umirim, and Tejuçuoca, covering an area of approximately 1,290 km². It is located on the left bank of the middle course of the Curu River watershed (IBGE, 2020).

The fluvial plain corresponds to a geomorphological compartment associated with sediment deposition processes driven by river dynamics, characterised by areas of low slope and a greater influence of accumulation processes. In the municipality of Tejuçuoca, the Caxitoré and Tejuçuoca rivers are particularly important, providing water input mainly during the rainy season and contributing to the hydrological and depositional dynamics of the fluvial landscape (CEZÁRIO, 2019).

Figure 15 – Caxitoré River, Tejuçuoca, Ceará, Brazil.
Source: Authors (2026).

The occurrence of this geomorphological unit is associated with the erosional, transport, and depositional dynamics promoted by the Caxitoré River, an important tributary of the Curu River. The fluvial plain corresponds to a relatively flat relief area developed over time through the continuous action of flooding, sediment transport, and accumulation processes during high-flow events.

Associated with the transitional zones between elevated relief sectors and lower surfaces, spur landforms were identified. According to Guerra (2008), this term is used in topography to describe the terminal portion of a ridge line or an elongated projection along a slope that does not maintain a continuous slope gradient. These features correspond to elongated relief projections, generally with triangular geometry, extending from mountain ranges and residual massifs towards lower landscape sectors.

Along the channel of the Caxitoré River within the territory of Tejuçuoca, the predominance of a dendritic drainage pattern was identified (CEZÁRIO, 2019). This pattern is characterised by the branched distribution of streams and generally occurs in areas where structural control exerts limited influence on the drainage network (PENTEADO, 1980). However, sectors exhibiting a rectangular drainage pattern were also identified, associated with the influence of geological structures such as faults and fractures present in the rocky substrate (CEZÁRIO, 2019). This variation highlights the influence of regional geological structures on the organisation of the drainage network.

In addition to the current fluvial dynamics, landforms related to sediment transport and deposition processes were identified, including colluvial deposits and fluvial terraces. Colluvial deposits correspond to the accumulation of sediments transported by gravitational processes along slopes and are commonly found at the base of steeper reliefs, being associated with talus deposits composed of rock fragments and unconsolidated materials. Fluvial terraces, in turn, represent former floodplains abandoned as a result of the progressive incision of river channels, recording different stages of fluvial system evolution.

Therefore, Figure 16 presents the distribution of the main morphological units identified in the municipality of Tejuçuoca, highlighting the geomorphological diversity resulting from the interaction between geological structure, erosional processes, fluvial dynamics, and landscape evolution throughout geological time.

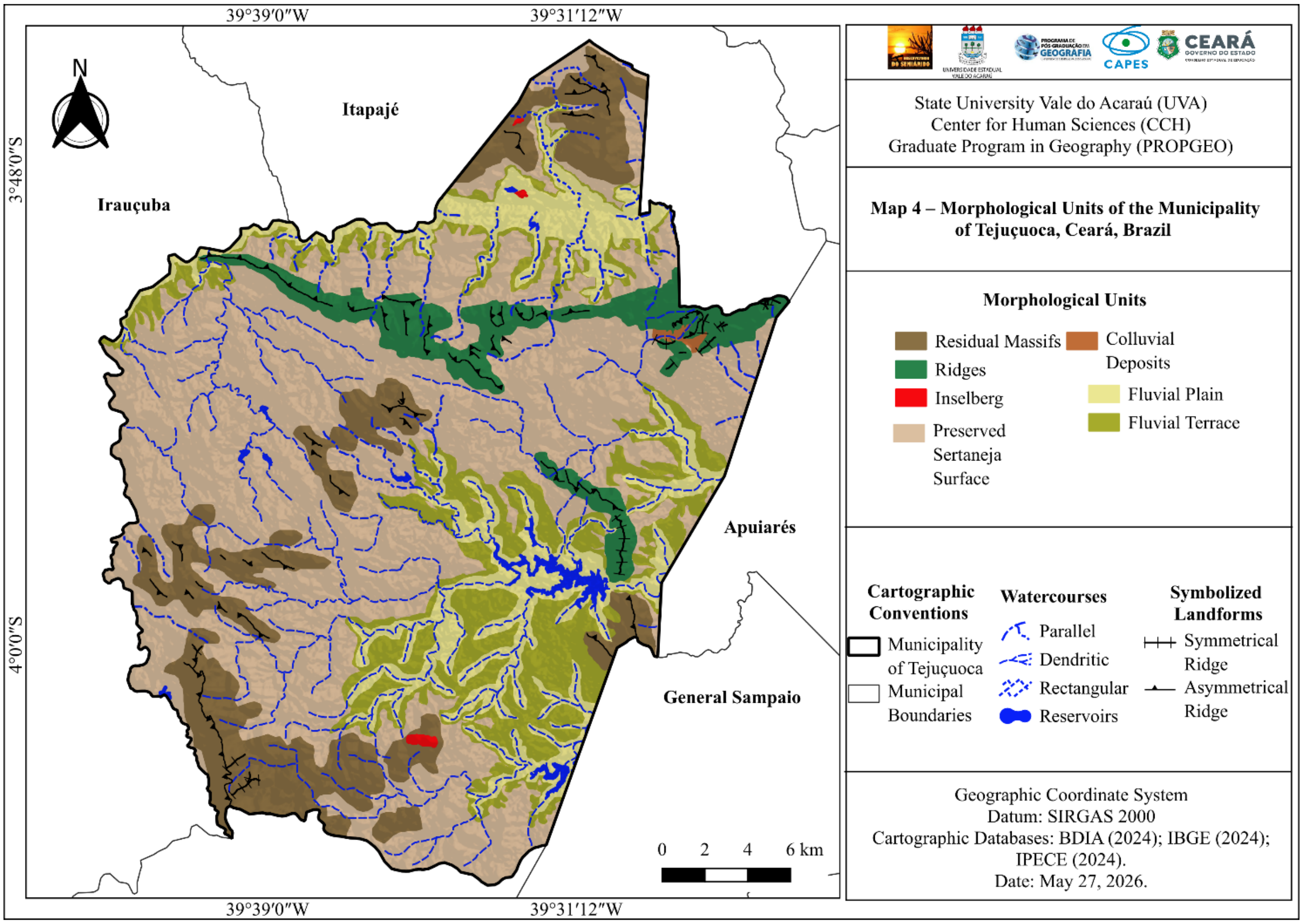

Figure 16 – Morphological units of the municipality of Tejuçuoca, Ceará, Brazil.
Source: Authors (2026).

4. Final Considerations

This study revealed the significant geological and geomorphological diversity present in the municipality of Tejuçuoca, highlighting the influence of geological structure and geomorphological processes on the current configuration of the landscape. The integrated analysis allowed the identification of different relief compartments, mainly associated with the Conserved Sertaneja Surface and the Fluvial Plain, as well as residual landforms and specific features, including crystalline massifs, mountain ranges, ridges, spurs, hills, hillocks, inselbergs, and karst landforms.

The results demonstrated that the geomorphological evolution of the municipality is directly related to the lithological diversity of the rocky substrate, characterised by the occurrence of Precambrian crystalline units subjected to tectonic, metamorphic, erosional, and weathering processes throughout geological time. This interaction controlled the preservation of residual landforms amidst surrounding low-relief surfaces and favoured the development of karst features and microforms associated with the different lithologies identified.

The characterisation presented herein contributes to expanding knowledge of the geodiversity of Tejuçuoca, particularly regarding landforms associated with crystalline residual massifs and karst occurrences within the semi-arid context of Ceará. Therefore, this study provides an initial framework for future investigations focused on geomorphological evolution, natural heritage conservation, environmental planning, and the development of strategies for protecting areas of significant geoscientific interest.

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