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Geology and geomorphology as support for territorial and environmental management in Brazil

Geología y geomorfología como soporte para la gestión ambiental en Brasil

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João Cordeiro de Moura[a], Vanda de Claudino-Sales[b], Marcelo Martins de Moura-Fé[c]

[a] Filiación: Viçosa do Ceará Municipal Department of Education. Correo: juniormourag7@gmail.com. ORCID: https://orcid.org/0000-0002-4967-6074
[b] Filiación: Federal University of Pelotas. Correo: vcs@ufc.br. ORCID: https://orcid.org/0000-0002-9252-0729
[c] Filiación: Regional University of Cariri. Correo: marcelo.mourafe@urca.br.ORCID: https://orcid.org/0000-0002-0336-557X

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Brazilian Northeast, geology, geomorphology, Ibiapaba, natural components

ABSTRACT

The physical environment has been increasingly exploited due to the expansion of economic activities in the territories, which requires an increasingly intense use of natural resources. These activities sometimes disregard the characteristics of natural components, causing degradation. In the municipality of Viçosa do Ceará, in the northwestern region of Ceará, northeastern Brazil, geomorphological features and geological formations stand out as elements of the local physical environment that have a high geotouristic, scientific and scenic potential, among others, which, in some contexts, are exploited without proper understanding of their specificities, thus causing negative environmental impacts. With this in mind, this article aims to characterize and analyze the geological-geomorphological aspects of the municipality of Viçosa do Ceará as support for territorial and environmental management. The methodology used in this research, based in a systemic approach, was organized into three main stages: a survey of the theoretical framework, fieldwork and systematization of the characterization of the natural components using geoprocessing techniques. The study showed that the municipality of Viçosa do Ceará has a rich geological and geomorphological diversity, which requires land-use planning and environmental management policies that consider the potential and limitations of these components of the physical environment.

Palabras clave
Componentes naturales, geología, geomorfología, Ibiapaba, Nordeste de Brasil

RESUMEN

El medio físico ha sido cada vez más explotado debido a la expansión de las actividades económicas en los territorios, lo que requiere un uso cada vez más intenso de los recursos naturales. Estas actividades en ocasiones ignoran las características de los componentes naturales, provocando su degradación. En el municipio de Viçosa do Ceará, en la región noroccidental de Ceará, noreste de Brasil, se destacan rasgos geomorfológicos y formaciones geológicas como elementos del medio fisico local que tienen un alto potencial geoturístico, científico y paisajístico, entre otros, que, en algunos casos, contextos, son explotados sin una comprensión adecuada de sus especificidades, causando así impactos ambientales negativos. Teniendo esto en cuenta, este artículo tiene como objetivo caracterizar y analizar los aspectos geológico-geomorfológicos del municipio de Viçosa do Ceará como soporte para la gestión territorial y ambiental. La metodología utilizada en esta investigación, basada en un enfoque sistémico, se organizó en tres etapas principales: levantamiento del marco teórico, trabajo de campo y sistematización de la caracterización de los componentes naturales mediante técnicas de geoprocesamiento. El estudio demostró que el municipio de Viçosa do Ceará tiene una rica diversidad geológica y geomorfológica, lo que requiere políticas de ordenamiento territorial y gestión ambiental.

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Introduction

The physical environment has been increasingly exploited due to the intensification of economic activities in various territories, which demands an ever-growing use of natural resources. These activities sometimes disregard the environmental limitations of natural components, resulting in the degradation of the planet's abiotic and biotic resources. In this context, the importance of studies that characterize the natural components of the physical environment becomes evident, as it is necessary to conduct research that supports environmental and territorial planning—particularly research focused on the rational use of natural resources and land occupation (Teixeira et al., 2023).

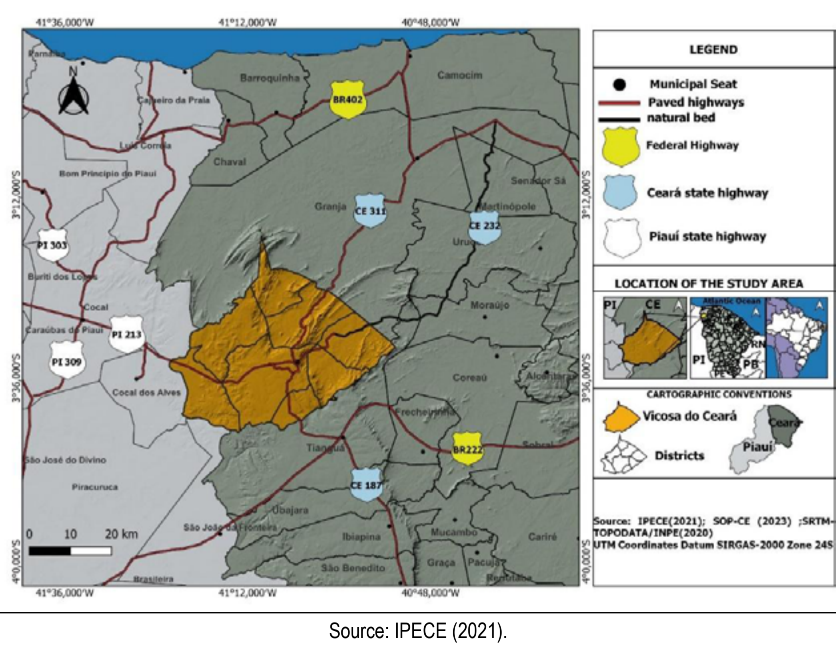
According to Amorim et al. (2021), the disorderly intensification of human activities, often carried out without proper understanding of the specificities of natural components, has compromised environmental balance and caused negative impacts on both nature and society. Therefore, for territorial management and environmental planning policies to genuinely reflect a sustainable approach and improve the population's quality of life, it is essential to thoroughly understand the natural environment and society's relationship with it (Diniz & Oliveira, 2015).

In the micro-region of Ibiapaba, located in the northwest of Ceará in Brazil's Northeast region, commercial agriculture exploits the favorable climatic conditions, and the deep, friable, and mechanized soils found on the flat tops of the Ibiapaba Plateau. Additionally, geodiversity is used as a resource for civil construction and tourism (Brandão & Freitas, 2014; Silva & Lima, 2020) As a result, the region has become a focal point for environmental studies that conduct detailed analyses of the physical environment's various natural components to promote the sustainable use of nature (Sousa & Ferreira, 2021).

In the municipality of Viçosa do Ceará, in particular, geomorphological features and geological formations stand out as elements of the physical environment and geodiversity with significant geotouristic, scientific, and scenic potential. However, in some contexts, these elements are exploited without adequate understanding of their specific characteristics, leading to negative environmental impacts on the municipal territory.

In this regard, this article aims to characterize and analyze the geological and geomorphological aspects of the municipality of Viçosa do Ceará to support territorial and environmental management in the region. To get there, the paper presents an overview of the study area, followed by the analysis and mapping of the main geological structures, as well as of the most important landforms. It also presents suggestions to the local government about how to do sustainable development, taking into account mapping and geoinformation.

Figure 1. Location map of the municipality of Viçosa do Ceará



Source: IPECE (2021).

Materials and Methods

The municipality of Viçosa do Ceará (Figure 1) has a population of 59,712 inhabitants, located in the micro-region of Ibiapaba and in the Intermediate Region of Sobral. The territory of the municipality comprises an area of 1,310.910 km², divided regionally into 8 districts: Viçosa do Ceará, General Tibúrcio, Juá dos Vieiras, Lambedouro, Manhoso, Padre Vieira, Passagem da Onça and Quatiguaba (IBGE, 2022).

The research presented in this article is grounded in a systemic perspective as its theoretical-methodological foundation. The systemic approach in geographic science seeks to interpret the complexity underlying the organization of spatial systems, considering the interactions among their components in a dynamic and non-linear manner. This perspective emphasizes the integration and interplay of the elements that constitute the whole, where phenomena manifest in space, interact, and contribute to either the stability or transformation of systems (Otto & Morais, 2019). In Physical Geography, the adoption of the systemic approach dates back to the 1950s, initially applied in hydrological and climatological studies. In Geomorphology, the systemic perspective has been employed since the 1960s (Chorley, 1962; Claudino-Sales, 2004).

The methods employed in this research were organized into three main stages: (1) a survey of the theoretical framework, (2) fieldwork, and (3) the systematization and characterization of the geological and geomorphological aspects of the study area using geoprocessing techniques. The bibliographic survey focused on identifying key authors relevant to the topic, including Claudino-Sales & Lira (2011), Maia & Bezerra (2014), Claudino-Sales (2016, 2018, 2020), Moura-Fé (2015), Pinéo et al. (2020) and Santos (2022).

During fieldwork, the general characteristics of the geological and geomorphological aspects (e.g., form and structure) were analyzed on-site, along with the collection of photographic records. In the geoprocessing stage, thematic maps of the natural components under analysis were created. For map preparation, QGIS 3.22.14 and Google Earth Pro software were utilized. To systematize the cartographic base, data were sourced from the following platforms:

- Raster data: Topodata (INPE)
- Planimetry: IBGE, COGERH, and IPECE
- Geological data: Pinéo et al. (2020)
- Geological maps: CPRM (Viçosa do Ceará Sheet AS.24-Y-C-V, Granja, Frecheirinha AS.24-Y-C-V)

Results and Discussion

The complex and diverse geology and geomorphology of the municipality of Viçosa do Ceará

The morphostructures underlying the relief forms that define the geomorphology of the municipality of Viçosa do Ceará originated from geological events associated with the formation of the Borborema Province, particularly the Middle Coreaú Domain, and the consolidation of the Parnaíba Basin. These processes occurred over a period spanning from the Neoproterozoic to the Paleozoic, representing a natural history of approximately 600 million years (Claudino-Sales, 2018; Claudino-Sales & Falcao-Sobrinho, 2024; Mayer & Lima, 2021, Santos, 2022).

In this context, several studies with diverse methodological approaches have been conducted in the fields of geology and geomorphology in northwest Ceará. Among the most foundational works, Ab'Sáber (1949) identified the existence of peripheral denudation zones in various regions bordering Brazil's large sedimentary basins. In his study, the author highlighted the Ibiapaba Plateau as one of the most characteristic examples of circumdenudation scarps, associated with the Meio Norte Basin (Parnaíba Basin). This topic was revisited by Costa et al. (2020), who provided detailed illustrations of the process.

Souza & Oliveira (2006) aimed to establish an integrated analysis of the geoenvironmental context and renewable natural resources of humid and sub-humid enclaves in northeastern Brazil. In their study, the authors characterize the geology of the Ibiapaba Plateau and define it as a morphological feature of a "cuesta." According to the authors, this classification is due to the presence of a very steep slope facing the state of Ceará, in contrast to the gentler, opposite slope descending towards the state of Piauí (the reverse side of the cuesta).

Claudino-Sales & Lira (2011) were the first to conduct more specific studies on the geology and geomorphology of northwest Ceará, including the municipality of Viçosa do Ceará. In their work titled *"Megageomorphology of the Northwest of the State of Ceará,"* the authors described the evolution of the relief in this region as a result of multiple tectonic events combined with climatic action.

Moura-Fé (2015) presents the geomorphological evolution of Ibiapaba plateau, analyzing its genesis and modeling processes. Taking into account the unique geodiversity of the region, the author presents conservation proposals based on the geoconservation of abiotic elements.

Claudino-Sales et al. (2020), following analytical techniques from structural geomorphology and megageomorphology, analyze the contact between the edge of the Parnaíba basin and the crystalline basement. In this study, the authors defined the existence of different contacts, which they defined as type 1 glint, where crystalline lithologies occur on the slope of the homoclinal relief and in the peripheral depression, type 2 glint, in which only the peripheral depression is maintained by lithologies of the peripheral depression. In the research, a "glintoid" type contact was also defined, where the peripheral depression is moved, exposing ridge-type reliefs composed of rocks from the Middle Coreaú Domain and a tabuliform segment on the surface (cuestiform in structure).

The morphostructural evolution of northern Ibiapaba plateau and adjacent areas (including the municipality of Viçosa do Ceará) was the subject of study by Santos (2022). To this end, the author used thermochronology using fission traces in apatites to demarcate the tectonic-denudational events from the Lower Cretaceous, which had an influence on the geomorphology of northwestern Ceará.

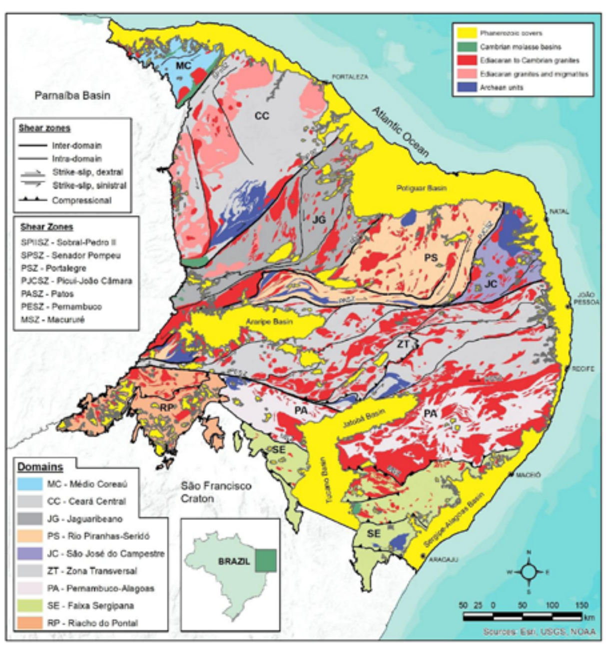
Sobrinho et al. (2024), in the work called "Geographic Expedition to the Ibiapaba Plateau", analyzed the Ibiapaba plateau with the aim of getting to know, revisiting and recording different academic perspectives on the Plateau. In this work, the step/level that characterizes the morphology of the city of Viçosa do Ceará is highlighted, whose genesis is related to the lithological characteristics of the Tianguá Formation.

Geological aspects of the Municipality of Viçosa do Ceará

The municipality of Viçosa do Ceará is inserted in the geological context of the Middle Coreaú Domain (MCD) and the Parnaíba Basin (PB) and is part of two structural provinces, the Borborema Province (BP) and the Parnaíba Province (PP) (e.g. Pinéo et al., 2020; Ribeiro & Santos, 2022).

The BP (Figure 2) is a large geological structure that occupies an area of approximately 450,000 km² located in the Northeast of Brazil. Of Neoproterozoic age, its tectonic evolution is complex, being related to Precambrian orogenic cycles, with extension and rupture during the Mesozoic, intraplate volcanism and uplift since the Cretaceous (Almeida et al., 2015; Nunes, 2018; Oliveira, 2008).This great geological-structural domain is bordered to the south by the São Francisco Craton, to the west by the Parnaíba Paleozoic Basin and to the north and east by the Coastal Basins. This province is characterized by extensive shear zones dating back to the Brazilian/Pan-African Cycle and is subdivided into five major tectonic domains: Middle Coreau, Central Ceará, Rio Grande do Norte, Transversal and South (Nunes, 2018; Oliveira, 2008).

Figure 2. Borborema Province and adjacent areas



Source: Santos et al. (2023).

The Middle Coreaú Domain (MCD), in turn, is bordered to the southeast by the Sobral-Pedro II Shear Zone and to the west by the Parnaíba sedimentary basin. The MCD presents an intense system of SW-NE shear zones, whose evolution took place in a compressive-transpressive regime related to the Brasiliano cycle, being composed of several lithologies with ages ranging from Siderian (2.5Ga) to Cambrian (485 Ma) (Araújo, 2014).

According to the geological mapping of Pinéo et al. (2020), the lithostratigraphic units of the Middle Coreaú Domain occurring in the municipality of Viçosa do Ceará are the Granja Complex (Sideriano -2.5 to 2.3 Ga), Martinópole Group (Cryogenian-720 to 635 Ma) and Sairi Creek Group (Cambrian-541 to 485 Ma).

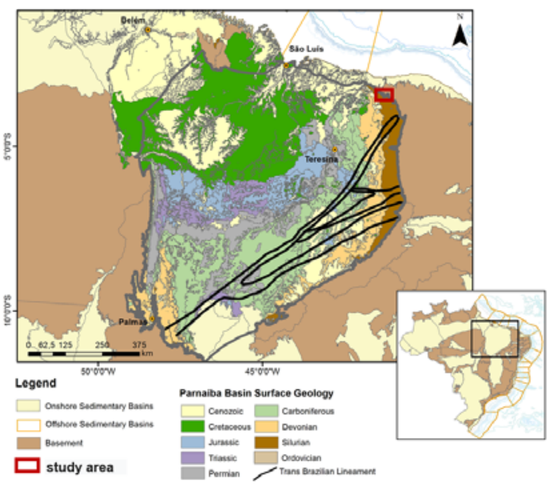
The lithologies of the Granja Complex that make up the Paleoproterozoic basement are made up of orthogneisses and orthomigmatites with tonalitic, trondhjemitic and granodioritic (TTG) compositions. There are aslo migmatitic paragneisses, amphibolites, calc-silicate lithologies, with the presence of orthorhombic and paraderived granulites, represented by mafic granulites, enderbitic gneisses and sillimanite-granade gneisses (kinzigites/kondalites) (Pinéo et al., 2020) occurring in the study area, especially in the Lambedouro and Manhoso districts in the geomorphological context of the peripheral depression.

The Martinópole Group (Supracrustal Sequence) is divided into four formations arranged from the base to the top: Goiabeira Formation, São Joaquim Formation, Covão Formation and Santa Terezinha Formation (Pinéo et al., 2020). Only the São Joaquim, Covão and Santa Terezinha formations are present in the municipality of Viçosa do Ceará. The São Joaquim Formation is made up of quartzite, metacalcareous and metavolcanic rocks. The Covão and Santa Terezinha Formations, on the other hand, are composed of a set of low-grade metamorphic carbonate-psammitic-pelitic rocks (Araújo, 2014), which occur on the structural ridges and in the peripheral depression.

In terms of genesis, the Martinópole Group's evolution is related to processes of sedimentation, deformation and metamorphism, restricted to the Neoproterozoic Era, with ages from 775-800 Ma. The Martinópole Basin begins with the formation of a rift, whose initial filling is characterized by volcanic rocks from the basal formation (Santos, 1999).

In turn, the Riacho Sairi Group is divided into three formations, arranged from bottom to top: Barra do Sairi Formation, Morada Nova Formation and Fazenda Fortaleza

Figure 3. Geological map of the Parnaíba Basin showing the location of the study area



Source: Modified from Abelha et al. (2018).

Formation (Pinéo et al., 2020). In the municipality of Viçosa do Ceará, only the Barra do Sairi Formation outcrops near the foot of the Ibiapaba, in the Passagem da Onça district. The Barra do Sairi Formation is a volcano-sedimentary sequence that was deposited before the sedimentation of the Paleozoic Parnaíba Basin. This formation is made up of polymict conglomerates, with the presence of quartzite pebbles, granitoids, gneisses and phyllites with a grey sandy-archaean matrix (Pinéo et al., 2020; Santos, 2022).

Regarding the Paleozoic Parnaíba Province (PP) (Almeida et al., 1977), this is a structural province that occupies a total area of 650,000 km². Considering its polycyclic evolution, Góes (1995) individualized the PP into four basins with distinct style, genesis and age characteristics, namely: the Grajaú Basin, the Alpercatas Amphiclase, the Espigão-Mestre Basin and the Parnaíba Basin (Chamani, 2015). The Parnaíba Basin (BP) has a complex evolution, distinguishing evolutionary stages from the Silurian to the Triassic, Jurassic and Cretaceous, as well as a stratigraphic and structural heritage, whose origin dates back to the end of the Brasiliano Orogenic Cycle (Lima, 2015).

In general terms, the techno-sedimentary evolution of the Parnaíba Basin is associated with magmatic pulses that occurred during the end of the Brasiliano Cycle, which led to the formation of grabens or rifts with N-NE axes (Góes et al., 1990 as cited in Lima, 2015). As a reflection of these magmatic pulses, a large Ordovician-Silurian depression was established, where fluvial and shallow marine sediments were deposited that gave rise to the sedimentary rocks of the Serra Grande Group (Cruz et al., 2019) in the thermal subsidence phase of the Basin, probably from materials originating from the collapse of the Neoproterozoic chain (Araújo, 2014).

The BP comprises the states of Piauí, Maranhão, part of the territory of Pará, Tocantins and the western portion of Ceará. The Parnaíba Basin has an asymmetrical surface geometry, of the intracratonic type, with its configuration controlled by the structural aspect of the crystalline basement (Lima, 2015).

In Viçosa do Ceará, the Parnaíba Basin occupies approximately 53% of the municipality's land area. The Basin in the study area is made up of sedimentary rocks of the Serra Grande Group that outcrop forming a glint-shaped relief. The rocks of this Group have an Ordovician-Silurian age and are made up of three formations: Ipú Formation (Basal Formation) Tianguá Formation (Intermediate Formation) and Jaicós Formation (Top Formation) (Pinéo & Palheta, 2021) (Figure 3).

In the study area, on the road to the district of Lambedouro, the thickness of the Serra Grande Group reaches 223 m; and on the road to Granja, still in Viçosa, the thickness reaches 156 meters over the rocks of the crystalline basement (Moura-Fé, 2015).

From a lithostratigraphic point of view, the Group is composed of differentiated sedimentary sequences, since the sedimentation of the basal layer is formed by fluvial deposits with a marine sedimentary overlay (Tianguá Formation), with the top formed by a layer deposited in a fluvial environment (Jaicós) denoting a complete transgressive-regressive cycle (Caputo & Lima, 1984; Cruz et al., 2019).

The Ipú Formation does not emerge in the municipality of Viçosa do Ceará. It is covered by the Tianguá Formation (Caputo & Lima, 1984), which is composed of fine sandstones, beige and yellow in color, with a well-selected matrix, interspersed with siltstones, claystones and shales, with wave marks and herringbone stratifications (Pinéo et al., 2020). The Jaicós Formation has an estimated maximum thickness of 400 meters, with concordant contact with the Tianguá Formation (Caputo & Lima, 1984). The Jaicós Formation is made up of conglomerates, conglomeratic sandstones, with tabular and fluted, plane-parallel and cross stratifications (Pinéo et al., 2020).

Regarding the genesis of the sediments, Sousa (2014) states that the Tianguá Formation was deposited in a shallow marine environment influenced by waves during the Venlokian (Homerian -430Ma.). The Jaicós Formation was deposited in a fluvial delta environment in a tidal context during the Ludlovian (Gorstian -427 Ma).

These two formations in the municipality of Viçosa do Ceará are notable for the presence of ichnofossils[1]. Sousa (2014) identified the presence of Cruziana ichnofacies in the Tianguá Formation and Skolithos ichnofacies in the Jaicós Formation. The finds were identified in sandstone layers that are exposed in a group of waterfalls on the Pirangi River, on the border with the state of Piauí.

The municipality of Viçosa do Ceará also has Cenozoic sedimentary cover, made up of unconsolidated sediments less than 23 Ma old (Pinéo & Palheta, 2021).

In the study area, these coverings make up the colluvial-eluvial deposits that correspond to the mantle of alteration of underlying rocks formed by deposits of varied sediments (Pinéo & Palheta, 2021), with occurrences along the peripheral depression. Still forming part of the Cenozoic Sedimentary Cover, it is possible to find Recent Thallus Deposits formed by angular rock fragments of varying sizes in gravelly, sandy and sandy-clay matrices, occurring at the foot of the Ibiapaba (Pinéo & Palheta, 2021) in the Lambedouro district. This geological framework is illustrated in the Figure 4.

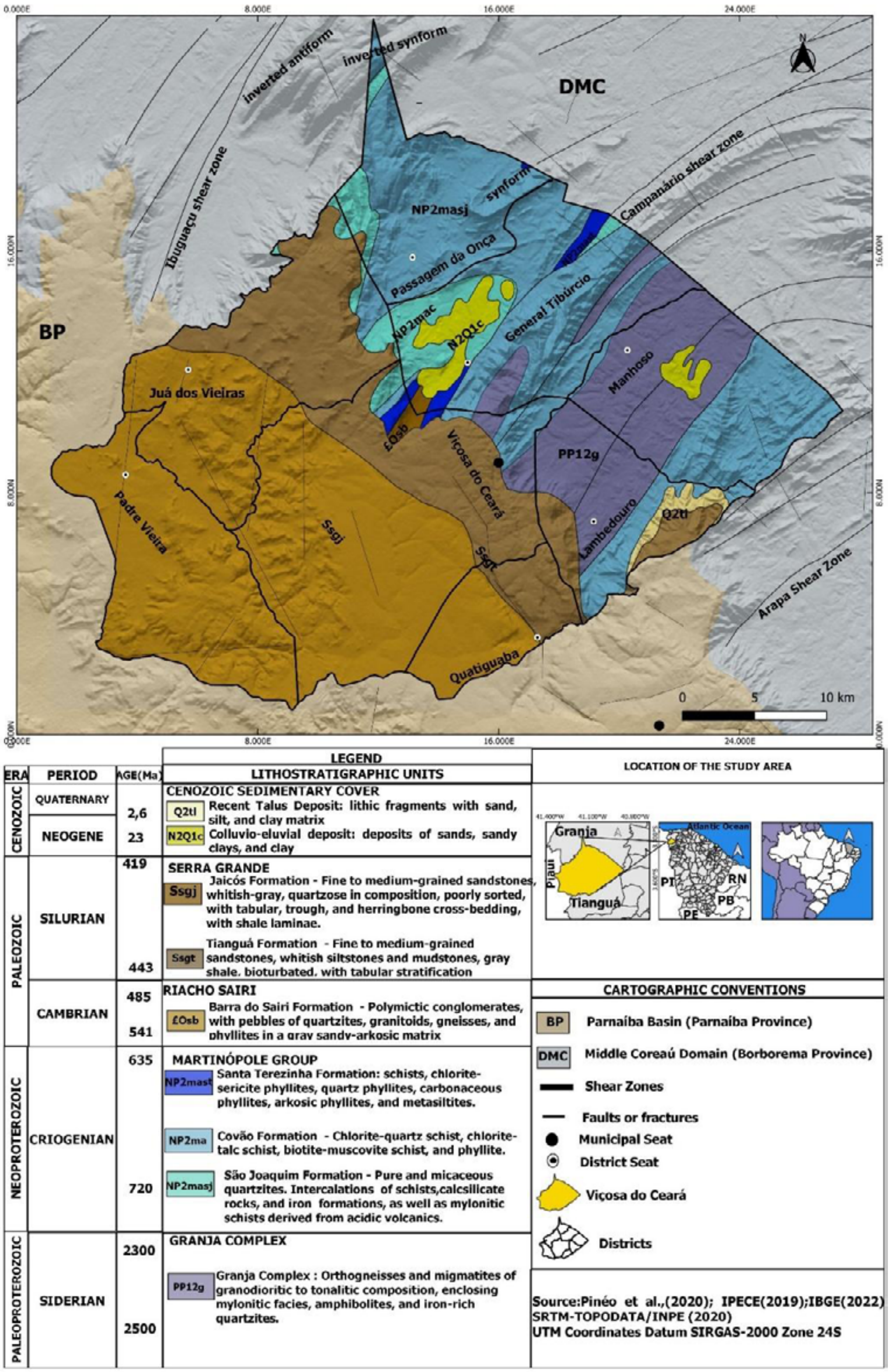
The geomorphology of the municipality of Viçosa do Ceará

From a geomorphological point of view, the main morphostructural conditioning factors of the local geomorphological landscape are related to:

- Atlantic Orogenesis (2.2 Ga), which originated part of the rocks of the Palaeoproterozoic basement, which forms the peripheral depression of the municipality (Claudino-Sales, 2016);
- Brasilian Orogeny (600 Ma), which defined the NW-SE and EW shear zones (Brito Neves, 1999; Pinéo et al., 2020);
- Splitting of Pangea in the lower Cretaceous (100Ma) that uplifted the regional surface of the study area (Santos et al., 2020).

[1] Icnofossils are the result of the activities of organisms that lived in past times and have been preserved in sediments and sedimentary rocks (Micheletti, 2017).

Figure 4. Geological map of the municipality of Viçosa do Ceará



It is clear that the morphostructural evolution of the municipality of Viçosa do Ceará originates from past geological events, with the most significant implications for the current geomorphological landscape linked to the Brazilian Orogenesis and the breakup of Gondwana during the Cretaceous period. These events are reflected in the geomorphology of the study area through uplift processes and ductile and brittle lineaments, which have shaped the relief and influenced Cenozoic differential erosion (Claudino-Sales, 2016; Santos, 2022).

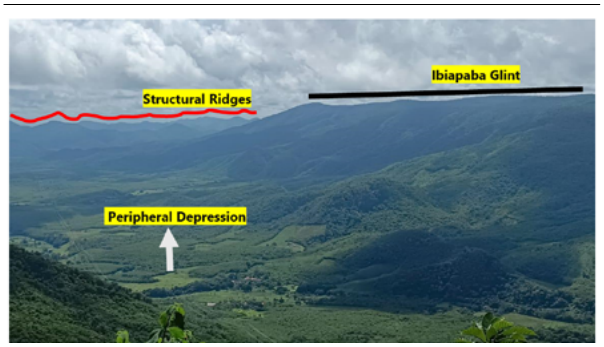
In this evolutionary context, the municipality of Viçosa do Ceará has five features that stand out most in the landscape: the Ibiapaba glint, plateaus and reverse hills, peripheral depression, structural ridges and river plains (Figure 7).

According to Meira (2020), the Vocabulaire de la Géomorphologie defines glint as a term of Swedish origin that reflects the "plateau edge defined by a sedimentary cover of aclinal structure resting directly on a flattened support" (CILF, 1979, p. 94; Meira, 2020, p. 84).

About the Ibiapaba glint, during the continental division of Pangea in the Mesozoic, there was rifting of certain portions of the northeastern terrains, with the lateral terrains to the rifts rising in the form of rift shoulders (Claudino-Sales, 2002). This episode affected sedimentary and crystalline lithologies, forming compact blocks of uplifted rocks (Claudino-Sales, 2002; Claudino-Sales & Lira, 2011). In this geological context, the north-eastern edge of the Paleozoic Parnaíba Basin was uplifted, providing the relief inversion that gave rise to the Ibiapaba Plateau (Claudino-Sales, 2002; Moura-Fé, 2015).

As Santos (2022) explains, in the Mesozoic, the tectonic reactivation of the Café-Ipueiras Fault and the Transbrasilian Lineament possibly uplifted the structures of the Middle Coreaú Domain, which were intruded into the Parnaíba Sedimentary Basin. Still, according to the author, "The rise in the relief exposed the sandstone escarpments to the resumption of erosion, due to the installation of a new regional base level, responsible for the exhumation of structural blocks opposite the cornice" (Santos, 2022, p. 184).

Figure 5. Geomorphological features making up the landscape of the municipality of Viçosa do Ceará. Record taken from a viewpoint located at the Jaguaribe site

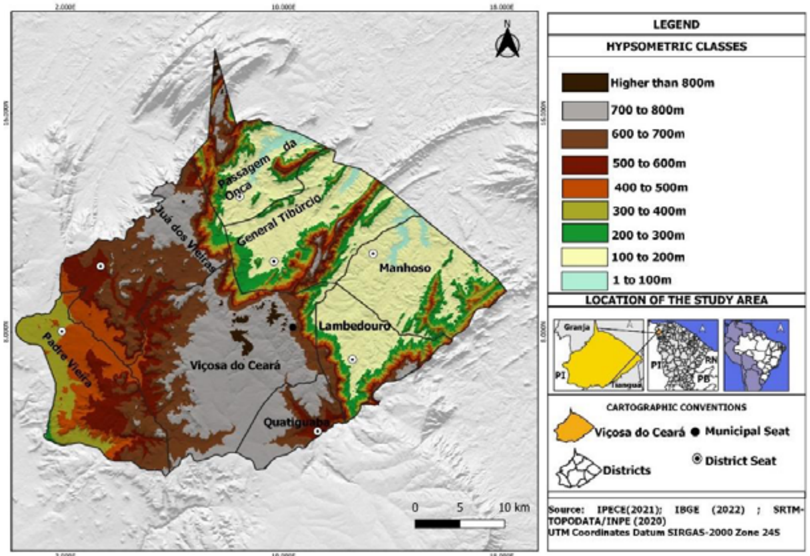


According to Costa et al. (2020), erosion of the eastern edge of the Ibiapaba plateau occurs differently depending on the lithology present on the escarpment. From the base to intermediate sectors of the escarpment, there are crystalline rocks (at altitudes of 200 to 700m), in which sector erosion promotes the retreat of the edge. At the top, between 700 and 900 meters, erosion is caused by the collapse of sandstone blocks from the Parnaíba Basin. In this evolutionary context, the peripheral depression was developed from the retreat of the Parnaíba basin by circumdenudation, forming a flattening surface on softer gneissic and migmatitic rocks (Cordeiro et al., 2021; Peulvast & Claudino-Sales, 2005; Santos, 2022), whose topography has a maximum altitude of 200 meters in the municipality of Viçosa do Ceará.

The favorable conditions for the retreat of the Parnaíba Basin possibly occurred 65 Ma ago (Cordeiro et al., 2021). This retreat led to the exhumation of Martinópole Group lithologies that were metamorphized during the Brasiliana Orogeny, which, subjected to climatic oscillations from the Paleogene onwards, and associated with differential erosion and tectonic reactivations, produced positive relief features resulting from the exposure of quartzites (Cordeiro et al., 2021; Santos, 2022). It forms the structural ridges present in the municipality of Viçosa do Ceará (Figures 5, Figure 6).

Based on Santos (2022), the ductile structures guide the festoons in contact with rocks that are more resistant to erosion, through the quartzite ridges of the São Joaquim Formation, which preserve the paleo-levels of the front. Santos (2020) attests that, in these festoons, remount erosion abruptly dissects the escarpment, according to the control of the NW-SE and NE-SW brittle lineaments. In the sector where the escarpment comes into contact with the lithologies of the Granja Complex and the Covão Formation, the notching of the anaclinal drainage promotes the opening of recesses in weaker areas of the front due to the presence of NE-SW and E-W brittle structures, that have a predisposition to linear incision This evolutionary dynamic resulted in the formation of the two erosional amphitheaters in the study area, which

Figure 6. Hypsometry map of the municipality of Viçosa do Ceará



include the districts of Lambedouro, Manhoso, General Tibúrcio and Passam da Onça.

In relation to the River Plains, these "are the recent forms of relief that result from the accumulation of Quaternary sediments by fluvial action in the lower areas" (Santos, 2022, p. 210). In the study area, the plains of the Itacolomi and Ubatuba rivers are organized according to the structural control of the shear zones of the Middle Coreaú Domain. The plains of the Pirangi and Gameleira rivers, on the other hand, follow the topographic gradient conditioned by the dip of the sedimentary layers of the Serra Grande Group towards the state of Piauí.

At the top of the Ibiapaba glint, the plains that are embedded between the lithologies of the Serra Grande Group are narrow, whose water regime is conditioned by the rainy season, while the plains located at the foot of the Ibiapaba plateau tend to widen, in a geomorphological context where less resistant rocks predominate (Moura-Fé, 2015).

In this sense, it can be seen that the lithologies of the Granja Complex are more fragile in relation to the fluvial rifting of the Itacolomi River, forming a more spaced valley, while the lithologies of the São Joaquim Formation are more resistant to fluvial carving, forming overlapping valleys in some sectors of the peripheral depression.

At the top of the Ibiapaba plateau, the glint has altitudes of over 700 meters. This feature covers the city and three districts (Quatiguaba, Juá dos Vieiras and Padre Vieira),

Figure 7. Hills and plateaus embedded in the reverse of the Ibiapaba. CE 232 in the area of Assemim, Viçosa do Ceará (CE)

occupying an area of approximately 55% of the municipal territory. The peripheral depression covers the districts of Lambedouro, Manhoso, Passagem da Onça and General Tibúrcio, occupying approximately 30% of the municipality's territory.

The peripheral depression is characterized by being "a depressed area that appears in the contact zone between sedimentary terrains and the crystalline basement" (Guerra & Guerra, 2008, p. 193). The feature in the study area is dissected by humps and hills, with a maximum altitude of 200 meters, extending towards the coast at a straight-line distance of around 75 km (Claudino-Sales & Lira, 2011). Approximately 15km from the front of the glint, the back side of the Ibiapaba is characterized by the presence of elevated topography, mainly made up of sandstones from the Jaicós Formation (Serra Grande Group). In this sector, these features are dissected by rivers with higher flows, such as the Pirangi and Gameleira rivers.

These elevated features appear as plateaus and hills (Figure 7), whose altitude in some sectors reaches heights of over 600 meters. According to Santos (2022), these elevated topographies preserve the Paleozoic surface, which covered the northwest of Ceará until the Lower Cretaceous.

According to Moura-Fé (2015) in this sector, the reverse is controlled by the background architecture of the Paleozoic Parnaíba Basin. The lithological characteristics and the weathering-erosion processes deepen the pre-existing tectonic and lithological conditions, especially about the development of river valleys of different sizes and profiles that are fundamental to the process of scaling the relief in the reverse of the Ibiapaba plateau.

The structural ridges in the study area are made up by the Serra de São Vicente and Serra do Gado "Brabo", located in the district of Manhoso. They are also present in the district of General Tibúrcio (Serra de São Joaquim) and Passagem da Onça (Serra de Ubatuba and Serra da Timbaúba). It is worth noting that the Serra de Ubatuba is the highest altitude area in the municipality of Viçosa do Ceará.

About the Serra da Timbaúba, this feature has a specificity in relation to the other mountain ranges, as it has both a hogback and a crest layout. This is related to the structural context of the area (Santos, 2022). Due to its quartzite composition, this mountain range has been exploited in its western portion (Fazenda Timbaúba de Cima) by mineral activities aimed at producing ornamental stone. The geomorphology of the area is presented in the Figure 8. The structural ridges occupy approximately 15% of the land area of the municipality of Viçosa do Ceará, presenting themselves as a set of asymmetrical mountain ranges with steep slopes. These features are supported by quartzite rocks of the São Joaquim Formation at an altitude of over 500m with a SW-NE orientation inherited from the ductile deformations of the Brasiliano Orogeny.

According to Santos (2022) these ridges are the result of the exhumation of the Neoproterozoic Supracrustal Sequences that were metamorphized to varying degrees during the Brasiliano Orogeny and sculpted by the process of differential erosion as part of the Meso Cenozoic enudation.

Figure 8. Geomorphological units in the municipality of Viçosa do Ceará

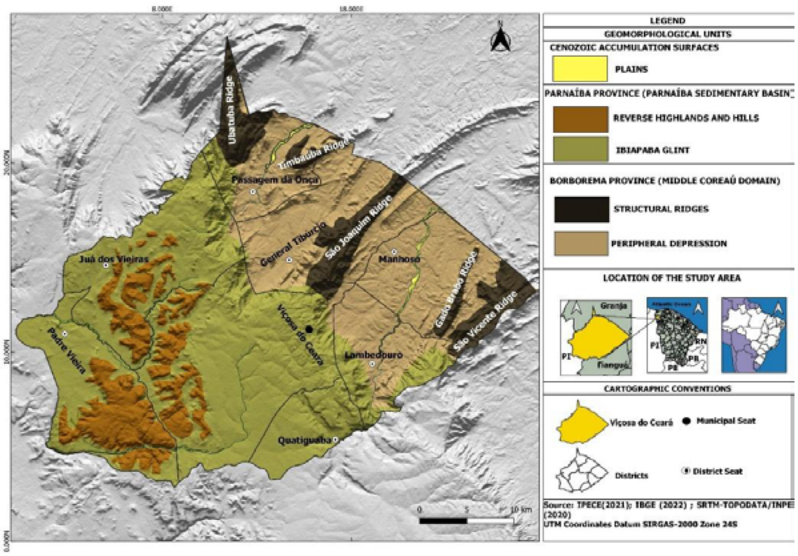


Table 1
Summary of the geological and geomorphological aspects of the municipality of Viçosa do Ceará

Structural province	Geological structure	Lithostratigraphic unit	Geomorphological Unit
Borborema Province	Middle Coreaú Domain	Granja Complex; Martinópole Group (Fm. São Joaquim, Fm. Covão and Fm. Santa Terezinha); Riacho Sairi Group (Fm. Barra do Sairi)	Peripheral Depression; Structural ridges; Itacolomi and Timonha river plains
Parnaíba Province	Parnaíba sedimentary basin	Serra Grande Group (Fm. Tianguá and Fm. Jaicós)	Glint of the Ibiapaba; Plateaus and Hills of the Reverse; Plains of the Pirangi and Gameleira rivers

The long natural history of the study area has made it possible to structure a set of natural attributes made up of a variety of rocks, soils, icnofossils, viewpoints, waterfalls and ruiniform reliefs which, together with the abiotic and historical aspects, give the municipality of Viçosa a unique space in Northeast Brazil.

Conclusions

As demonstrated, the natural diversity of the municipality of Viçosa do Ceará originates from geological events dating back to the Neoproterozoic, marked by the Brasiliano Orogeny. Significant changes occurred during the Paleozoic with the formation of the Parnaíba Sedimentary Basin and in the Mesozoic with the uplift of morphostructures during the Cretaceous. This ensemble was subsequently reworked by the systematic action of Cenozoic exogenetic forces, representing a natural history spanning approximately 600 million years.

From a geolocigal and geomorphological point of view, the main morphostructural conditioning factors of the local geomorphological landscape are related to the Atlantic Orogenesis (2.2 Ga), which originated part of the rocks of the Palaeoproterozoic basement, which forms the peripheral depression of the municipality. It was followed by the Brasiliano Orogeny (600 Ma), which defined the NW-SE and EW shear zones. Finally, the splitting of Pangea in the lower Cretaceous (100Ma) uplifted the regional surface of the study area.

In this evolutionary context, it resulted, in the municipality of Viçosa do Ceará, five geofeatures that stand out most in the landscape: the Ibiapaba glint, plateaus and reverse hills, peripheral depression, structural ridges and river plains (Figure 8).

As shown above, the complex and diverse geology of Viçosa do Ceará has conditioned the dynamic evolution of the relief (Table 1) which, in turn, has determined the constitution of a rich geomorphological diversity in the study area. The table presents a summary of the principal aspects of Viçosa do Ceara's landscape, mainly in terms of geology and geomorphology, showing in the first line the name of the geological structural province, followed by geological subdivisions as domain and lithostratigraphic units, finalizing with the main geofeatures of the area.

The regional evolutionary history has fostered a geodiversity with significant geotouristic, scientific, and scenic potential. However, in some cases, this potential is exploited without a proper understanding of its specific characteristics, leading to negative environmental impacts.

By characterizing the natural elements of the study area, this research highlights that the municipality of Viçosa do Ceará possesses a rich geological and geomorphological diversity. This diversity necessitates land-use planning and environmental management policies that account for both the potential and limitations of these physical environment components as indicated by Medeiros & Gomes (2021).

In Viçosa do Ceará, the interaction between geological and geomorphological characteristics plays a critical role in environmental planning, in the terms analyzed by Freitas & Ferreira, 2021 Understanding the geological composition, including rocky formations and areas susceptible to erosion, is essential for evaluating risks associated with landslides and flooding. This knowledge can guide environmental planning efforts by enabling the zoning of vulnerable areas and the implementation of preventive measures, such as afforestation initiatives and building regulations designed to mitigate these risks as suggested.

Since geomorphology significantly influences drainage patterns and the availability of water resources, proper watershed mapping is crucial for effective water resource management, which in itself is essential for both agricultural and urban planning (Pinheiro & Oliveira, 2023). Furthermore, environmental policies can be designed to protect these water sources from pollution and overexploitation, ensuring sustainable access for the community. Additionally, the diverse geomorphological features—such as hills, valleys, and river systems—support varied habitats that sustain local biodiversity. Environmental planning can capitalize on these features to establish conservation areas, promoting biodiversity while enabling the sustainable use of natural resources.

The topography of Viçosa do Ceará plays a pivotal role in shaping urban development patterns. By utilizing GIS tools to integrate geological and geomorphological data, planners can make informed decisions regarding zoning laws, infrastructure development, and transportation planning. This integration promotes sustainable urban expansion by addressing critical factors such as slope stability and natural drainage systems.

Finally, as the impacts of climate change intensify, it is essential to consider how geological and geomorphological features can enhance resilience. For instance, preserving natural landforms can help mitigate flood risks, while responsible land use practices can prevent soil degradation and maintain vital ecosystem services.

In summary, the geological and geomorphological characteristics of Viçosa do Ceará are fundamental to effective environmental planning. By incorporating this knowledge into planning processes, the municipality can promote sustainable development that harmonizes economic growth with environmental conservation and risk management.

Conflict of interest

The authors have no conflicts of interest to declare.

Declaration of authorship

Joao Cordeiro de Moura: Conceptualization, Investigation, Methodology, Data curation, Formal analysis, Writing-original draft, Visualization.
Vanda Claudino-Sales: Conceptualization, Investigation, Methodology, Formal analysis, Supervision, Writing-review & editing, Visualization.
Marcelo Martins Moura-Fé: Conceptualization, Investigation, Supervision, Writing-original draft, Writing-review & editing.

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