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Classification of granitic relief in the territory of the Sertão Monumental Geopark Project, Brazil

Clasificación del relieve granítico del territorio del Proyecto Geoparque Sertão Monumental, Brasil

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Abstract

The granitic relief is notable in the Brazilian northeastern landscape due to its resistance to geomorphological processes. In the territory of the Sertão Monumental Geopark Project, which covers the Ceará municipalities of Quixadá and Quixeramobim, there is a significant occurrence of the granitic features, with different shapes and sizes showing subsurface and surface processes. The Etchplanation Theory and morphodynamic studies enabled the analysis of the development of these forms, which was conducted through a literature review, fieldwork and photographic records. The features were classified into macroforms and microforms, taking into account their characteristics and origin. Macroforms are extensive plutonic bodies that stand out in areas of planation relief, exhibiting diverse morphogenetic characteristics, with varying sizes, including inselgebirg, inselberg, flagstones and vertical outcrops. The microforms were subdivided into features associated with weathering, saprolitization and fracturing, and include tafoni, "honeycomb", karren, gnammas and flared slopes. This classification and hierarchization contributes to future research and further study on the subject of granitic relief.

Keywords: Geomorphological Taxonomy; Etchplanation; Granitic features; Inselberg; Geopark; Brazilian Northeast.

Resumen

El relieve granítico se destaca en el paisaje del nordeste brasileño por su resistencia a los procesos geomorfológicos. En el territorio del Proyecto Geoparque Sertão Monumental, que abarca los municipios cearenses de Quixadá y Quixeramobim, hay una presencia significativa de rasgos graníticos, con diferentes formas y tamaños que muestran procesos subsuperficiales y superficiales. La Teoría del Grabado y los estudios morfodinámicos permitieron analizar el desarrollo de estas formas, lo cual se realizó mediante revisión de literatura, trabajo de campo y registros fotográficos. Los rasgos se clasificaron en macroformas y microformas, teniendo en cuenta sus características y origen. Las macroformas incluyen inselgebirg, inselberg, losas y afloramientos verticales. Las microformas se subdividieron en características asociadas con la meteorización, la saprolitización y la fractura. Esta clasificación y jerarquización contribuye a futuras investigaciones y estudios sobre el tema del relieve granítico.

Palabras clave: taxonomía geomorfológica; etchplanación; formaciones graníticas; inselberg; geoparque; nordeste brasileño.

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1. Introduction

Research on granite landscapes contribute to the understanding of Earth's history. As they are explored and studied, these remarkable formations enhance the knowledge of our planet's dynamic processes and provide valuable insights into landscape evolution and environmental changes over geological timescales. For this reason, granitic landscapes offer a rich field for scientific research, combining geological, geomorphological, and aesthetic aspects.

Granitic landscapes commonly have steep cliffs. The occurrence of such fields is common in arid and semi-arid climates (Matmon et al., 2013), but their origin is associated with erosion systems related to tropical and sub-tropical environment (Romer, 2007), where deep weathering gave rise to thick regoliths (Goudie, 2004) whose removal will occur in drier climates (Matmon et al., 2013).

Thus, it can be said that granitic relief is shaped by weathering and erosion processes influenced by climatic conditions and rock properties. This geomorphological action results in features such as massifs, inselgebirgs (grouping of large inselbergs: Dresch, 1957), inselberg fields and granitic platforms, among other features, which form relief patterns associated with fracturing and, above all, differential weathering due to the characteristics of the rocks.

The study of granitic landscapes is increasing in the last decades, as seen for example in the studies of Souza et al. (2023), Maia et al. (2022), Migón (2021), Vidal-Romaní et al. (2014), and following the works of Migón (2006) and Vidal-Romani and Twidale (2005), among others. Nevertheless, there are still much more to be done, considering that many features and particular granitic geoforms are not yet well understood (Souza et al., 2023).

The present paper aims to contribute to the dissemination of the scientific literature on granitic landscapes, considering the landscape of Northeastern Brazil. Effectively, granitic features are found in different areas of Northeastern Brazil, where ancient plutons were exposed due to tectonic activity in Neoproterozoic shear zones (Maia & Nascimento, 2018).

Until recently, these features were not recognized as the result of chemical weathering in a semiarid context. However, recent studies suggest that chemical weathering, associated with differential erosion, is responsible for transforming the rock surfaces in this region. The phases of chemical weathering that shaped these features occurred because of alternating wet and dry climates throughout the Cenozoic. The presence of inselbergs also indicates climatic changes throughout the Quaternary, and the theory of etchplanation suggests that the relief was shaped by the interaction between processes of chemical weathering and mechanical erosion affected by fluvial and pluvial erosion (Twidale, 2002; Bastos et al., 2022).

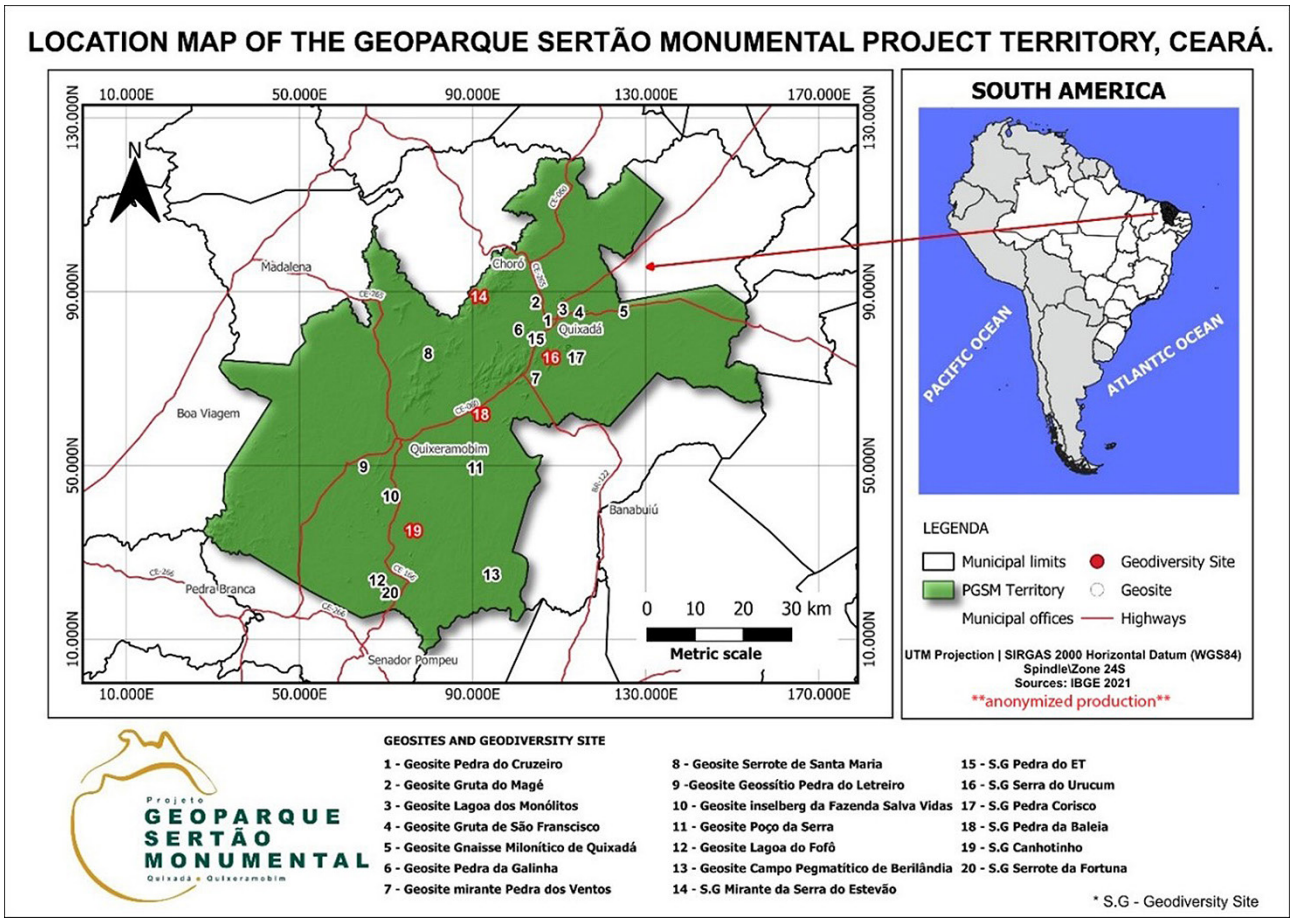
The article aims to identify and classify granitic relief features within the territory of the Sertão Monumental Geopark Project – a project that is in development, in order to be included in the list of UNESCO Global Geoparks in the future, covering a vast area in the municipalities of Quixadá and Quixeramobim, in Northeastern Brazil. For Geopark, it is understood a defined area where sustainable development is encouraged trough geoturism and geoconservation of the geodiversity (United Nations Educational, Scientific and Cultural Organization [UNESCO], 2024). The present analysis of granitic landscape can thus be considered as a tool to help promote geodiversity.

2. Methodology

In the central hinterland of Ceará there is a granitic landscape with unique features and scenic beauty, made up of vast fields of inselbergs, located in the Quixadá - Quixeramobim batholiths. Within this territory comes the proposal to implement the Sertão Monumental Geopark (Figure 1), which covers the municipalities of Quixadá and Quixeramobim. In the area of this proposed geopark, 13 geosites and 7 geodiversity sites have been identified.

As far as the research method of this study is concerned, it was taken into consideration the etchplanation theory as the basis for explaining the current modeling of the granitic relief. The theory of etchplanation was proposed by Wayland (1933) to account for well-developed surfaces of erosion which the author proposed that were etched into a summit peneplain, in the terms proposed by Davis (1899) – which means, with horizontal evolution of the process of erosion (downwearing), but in tropical conditions. As attested by Goudie (2004), the etchplanation theory was only effectively accepted by the scientific community after a publication of Büdel in 1957. Though Büdel (1957) did not use the term etchplanation in this paper of 1957, he linked the theory of double planation to the theory of etching surfaces (Goudie, 2004).

Figure 1. Territory of the Sertão Monumental Geopark Project and location of its respective geosites and geodiversity sites



Source: Instituto Brasileiro de Geografia e Estatística (IBGE), 2023. Own elaboration

Few decades after Büdel's (1957) discussion, Thomas (1989) detailed these ideas and presented a classification of different types of landscapes shaped by etching processes, including the type called "complex etchplain". The complex etchplain is related to the removal of saprolite by pedimentation ("pedimented etchplain"), following the theory of pedimentation of King (1966).

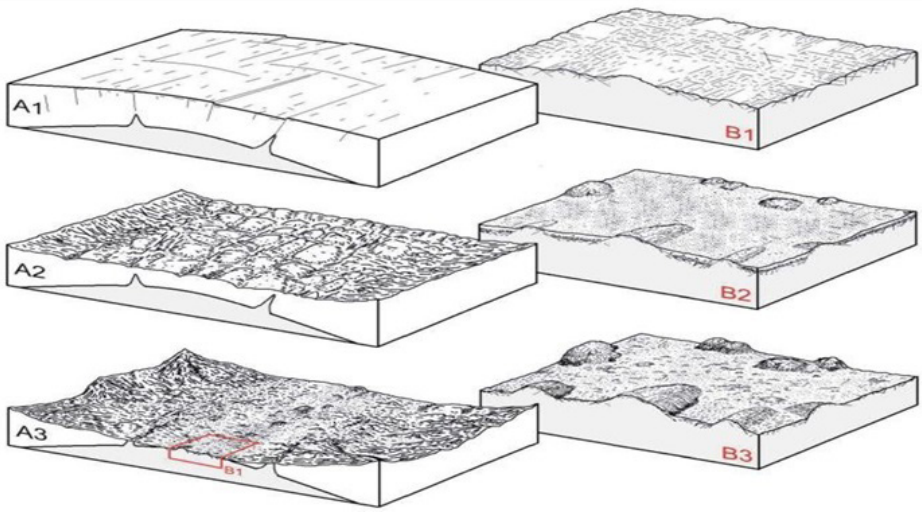
Later, in 1982, Büdel proposed that inselberg's evolution was directly linked to the theory of ecthplanation and pedimentation, as it was explained by Peulvast and Vanney (2001) and Peulvast and Claudino-Sales (2005). In this work, Büdel (1982) considered that the slopes evolved by a vertical process of subsequent retreat (backwearing) in semiarid conditions, also associated with alternation of climate humidity throughout geological times and evacuation of saprolites. In the present work, we follow Büdel (1982) proposition for the evolution of inselbergs, considering the study area's landscape a pedimented etchplain, as it will be explained in the sequence.

The theory of dynamic etchplanation (Büdel, 1982), as presented here, brings to light *etchplains* linked to the geochemical and pedogenic processes of the alteration front associated with pedimentation. As it is stated by Büdel (1982) and explained by Salgado (2007), plateaus are formed and evolve through the double front mechanism by the exhumed *washing surface* and the basal weathering surface (*leaching surface*). Thus, the washing surface is the surface of the model, with mechanical processes predominating, while the basal weathering surface is irregular, located in the subsurface where the rock is leached, and chemical denudation predominates.

According to Maia et al. (2015), Büdel's (1982) double planation model highlights that during wet periods there is a deepening of the alteration of the weathering mantle, while surface erosion occurs more vigorously during dry weather phases. With the progressive differential deepening of the alteration front, associated with surface erosion, the sectors of the basal weathering surface that have not undergone alteration gradually rise to the surface, giving place to inselbergs (Vitte, 2001; 2005).

The concept has been applied to tropical areas and can support the geomorphological interpretation of the development of granitic features in a semiarid environment (Maia et al., 2018). In the study area, the concepts of *backwearing*, i.e. parallel retreat of the slopes in a semiarid context (King, 1977), and especially etchplanation (Figure 2) were considered as the processes responsible for the genesis and evolution of the granitic landforms (A1 and B1).

Figure 2. Block diagram with geochemical and pedogenetic processes based on Büdel's theory (1982)



Source: Maia et al. (2015)

The figure 2 shows differential erosion and exhumation of batholiths. In A1, the magma rises and exerts pressure on the overlying crust, producing fracturing. In A2, fractures condition erosive processes, intensifying dissection. In A3, there is the formation of a depression surrounded by residual relief that allows the batholith to emerge. B1 shows the exhumed surface of the batholith. In B2, fractures facilitate the surface weathering process, creating a mantle of alteration. B3 is an erosional phase, where the alteration mantle is removed, exposing the irregularities of the basement, creating inselbergs. Steps B1, B2 and B3 were based on Büdel's (1957; 1982) double planation model.

The technical stages of the research were a bibliographical survey on the subject, following the works of Vitte (2001; 2005), Migón (2006), Salgado (2007), Maia et al. (2018), Maia and Nascimento (2018), Rocha et al. (2019), Bastos et al. (2022), Rodrigues et al. (2022). Fieldwork was then carried out, during which it was possible to identify and record in photographs the micro and macro features of granitic reliefs based on the taxonomic classification and hierarchization proposed by Bastos et al. (2022) and Maia and Nascimento (2018).

Field work allowed the classification of macro and microforms. This systematic permitted to better understand the dynamics and the evolution of the regional features throughout time. Macroforms were considered the larger relief structures present ins the study area, resulting from of long-lasting, large-scale geomorphological processes such as differential erosion. Classifying macroforms helped to identify geomorphological units, facilitating the understanding of the main features of the region's relief, and how the external forces shaped the territory over millions of years.

Microforms are smaller (or internal to larger forms) relief features. These shapes are generally the result of faster and more localized processes, such as the action of wind, water and gravity. The classification into microform was useful for providing a more detailed and accurate view of terrain variations on a smaller scale, and allowed to understand how processes such as weathering act on smaller and faster scales.

This classification in macro and microforms was essential for the geomorphological study of the Sertao Monumental Geopark Project, as it allowed a more complete and detailed analysis of the different scales of processes and forms that shaped the study area surface over time.

3. Results

The main objective of this research is to identify the granitic geoforms in the study region. The proposition of pedimented ectplain is of the fundamental theoretical bases for understanding the geomorphological evolution

of the granitic reliefs in the territory of the Sertão Monumental Geopark Project, considering the weathering-erosion processes associated with natural factors. In fact, this proposition is essential for explaining the origin of the reliefs found in the research area, providing solid and comprehensive support for understanding these geological features.

The impressive granitic landscapes that characterize the area analyzed in the present study are part of the geomorphological unit of the planed surface present in semiarid Northeastern Brazil and include *inselgebirgs, inselbergs, bornhardts, granitic platforms, boulders, tors, gnammas, flutings, tafoni* and more, all macro and micro geoforms present in the study area are explained in detail in the sections below.

Given the intricate complexity inherent in these features, it is crucial to consider both, their distinctive morphological nuances and their underlying genetic aspects. To this end, we present a categorization approach based on the distinction between macro and microforms, with subdivisions based on their dimensions and morphological characteristics.

The macroforms are the large-scale landforms that dominate the granitic landscape. Examples include inselgebirgs and inselbergs. The macroforms provide a broad perspective on the overall structure and topography of the area. The microforms are small-scale features, such as individual tafone and karren. They help us understand localized processes and interactions within the landscape.

While macro and micro cover the extremes, it is worth to mention that there isn't a specific "mesoform" category: The combination of macro and micro provides a comprehensive framework for analyzing landscapes, from large-scale patterns to fine details, and suffice to explain the landscape, encompassing both the big picture and intricate details.

The formation of these features in granitic rocks results from processes prior to their exposure on the surface, as discussed by several authors, including Bastos et al. (2022) and previous works such as Maia et al. (2015; 2018), Maia and Nascimento (2018) and Rodrigues et al. (2022).

The main granitic features found in the research area are shown in the Table 1, that gives a general overview of the hierarchy of the taxonomic classification of the macroforms and microforms of granitic reliefs found within the territory of the Sertão Monumental Geopark Project.

Table 1. Macroforms and Microforms identified in the territory of the Sertão Monumental Geopark Project, in the municipalities of Quixadá and Quixeramobim. From the left to the right, the table is giving details of the type of features

Macroforms	*Inselgebirg*		
	Inselbergs (Dissolution, Fracturing, Domic (Bornhardts) and Mixed)		
	Flagstones and vertical outcrops.		
Microforms	*Granitic blocks*	*Boulders*	*Large Boulders*
			Block Chaos
		Tors	*Castle Koopies*
			Nubbins
			Pedestal Rock
	Forms of dissolutions		*Tafoni, Karren, Gnammas, Flared Slopes*
	Forms of fracturing		*Split rock and polygonal cracking*

Source: Maia et al. (2015, 2018); Maia & Nascimento (2018); Claudino-Sales (2020) and Bastos et al. (2022). Own elaboration

3.1. Macroforms (inselgebirg, inselbergs, granitic platforms and vertical outcrops)

In the Sertão Monumental Geopark Project, the macroforms are extensive plutonic bodies that stand out in areas of planation relief, exhibiting diverse morphogenetic characteristics and varying sizes. Their formation is related to the exposure of resistant matrix rock to weathering processes while still below the surface (Rodrigues et al., 2022; Bastos et al., 2022; Maia et al., 2018; Maia and Nascimento, 2018; Peulvast and Claudino-Sales, 2005). In the project territory, *inselgebirg, inselbergs*, granitic platforms and vertical outcrops have been identified.

3.1.1. Inselgebirg and Inselbergs

A residual form present in the study region is the *inselgebirg*, granitoid bodies with topographic elevations that can be elongated, isolated or grouped together. They represent groups of aligned inselbergs, or large inselbergs that do not reach the size of massifs. Within this hierarchical perspective in terms of the size of the residual reliefs, the inselberg can be classified as the smallest (<10 km^2) and the *inselgebirg* with an intermediate size (between 10 and 50 km^2 (Bastos et al., 2022).

The "Serra dos Macacos" *inselgebirg* (Figure 3) is classified as a clustered type, with an area of around 45 km$^{2.}$ Macroforms such as *inselgebirg* play significant roles in the landscape and in understanding the geological evolution of the region, demonstrating the complex interaction between geodynamic and geomorphological processes over time.

Figure 3. *Inselgebirg* called "Serra dos Macacos" on the banks of the CE-060, Ouro Preto, Quixadá, Ceará

Photograph by Alexandre Pinheiro de Alcantara

3.1.2. Granitic Platforms and vertical outcrops

Granitic Platforms, also known as Flagstones (lowered granitic surfaces), as well as vertical outcrops, were also classified as macroforms (Figure 4). These are outcrops that are associated with the limitations of pedogenetic actions, both due to slope and severe climatic conditions (Bastos et al., 2022).

In the territory of the Sertão Monumental Geopark Project, these features are distributed in various places, from areas surrounding the base of the *inselberg* to grouped areas of low relief on the planed surface.

Figure 4. A: Extensive granitic platform. B: Vertical outcrop with collapsed cliffs, Quixeramobim, Ceará

Photograph by Alexandre Pinheiro de Alcantara

The flagstones outcrop at various points in the Quixadá and Quixeramobim batholiths, mostly with the presence of cavities "filled" with sediments transported from adjacent elevated areas and later developing the colonization of rupicolous vegetation.

3.2. Microforms

The microforms of granitic reliefs are features mostly present inside the macroforms, representing details of the larger features. They can be isolated forms, and have horizontal, vertical and irregular disposition. The microforms can reach dozens of meters, and correspond to features associated with granitic blocks (*boulders, block chaos*, *tors, nubbins*, *castle koopies and pedestal rock*), dissolution forms (*tafoni, alveoli/honeycombs*, karren, *dissolution basins and flared slopes*) or fracturing (*split rock* and *polygonal cracking*) (Maia et al., 2018).

3.2.1. Microforms associated with weathering and erosion processes (boulders and block chaos)

These features are remnants of the rock alteration process, the *grus*, which are loose blocks of the parent rock. They reveal evidence that the erosive phases, which occurred during periods of intense morphogenetic activity, partially removed the friable debris resulting from the initial weathering. These traces bear witness to the evolution of the relief over time and provide valuable information about the geological characteristics of the region (Maia et al., 2018).

In the territory of the Sertão Monumental Geopark Project, prospecting has revealed saprolite microforms, including boulders, block chaos, tors, castle koopies and pedestal rock.

Boulders, granitic formations common in various climatic regions, are resistant and originate in the mantle of subsurface weathering. When exposed at the surface, they are called *in situ* boulders (Migón, 2006). According to Bastos et al. (2022), *boulders* form in the alteration mantle as part of the saprolitization process, later developing into *grus. Boulders* are sensitive to subsurface physical-chemical weathering processes, resulting in spheroidal exfoliation, where their edges round off to form rounded, elongated chips. When the weathering mantle is completely eroded, the boulders are exposed on the surface, now known as *corestone* or *boulder in situ* (Figure 5). This process illustrates the transformation of rock formations over time due to the action of weathering and erosion.

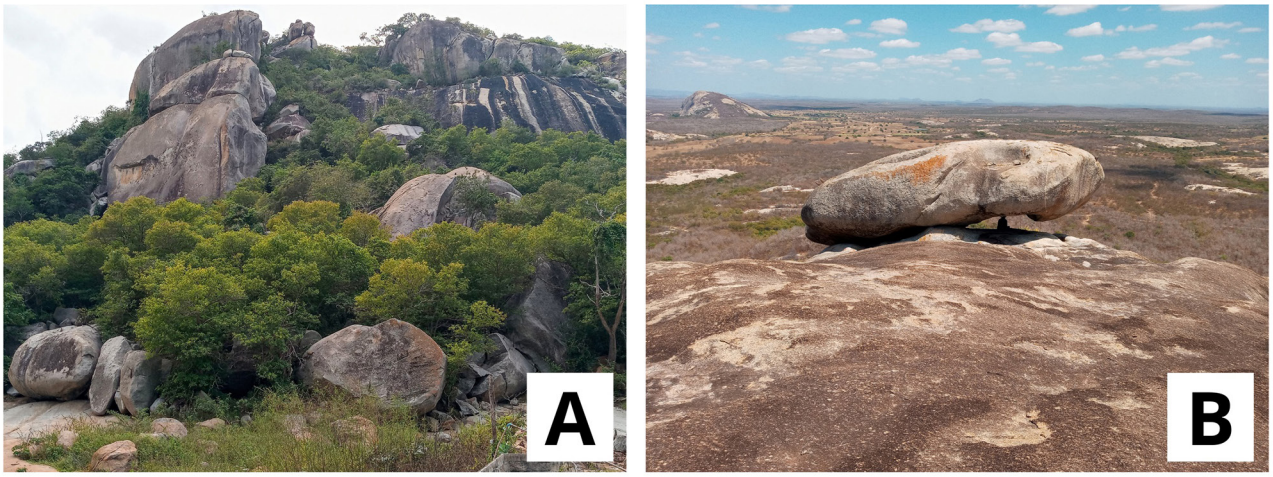
Figure 5. Example of an *in situ* boulder with decametric proportions and an advanced process of rounding (spheroidal exfoliation) located at the Inselbergs geosite at Fazenda Salva Vidas, Quixeramobim, Ceará

Photograph by Alexandre Pinheiro de Alcantara

The block chaos (Figure 6a) represents rock cores unaffected by weathering within the weathering mantle. After the production of grus, these cores can remain in their original position or be moved along steep slopes by the action of gravity. In rugged terrain, blocky chaos forms dense concentrations of *corestones*, often found in valley bottoms.

Another common feature of saprolitization in granitic reliefs is the *tor* (Figure 6b). Several theories seek to explain their origin, and Büdel's *Etchplanation* Theory (1982) is widely accepted as the most coherent explanation for the development of these formations. According to Rocha et al. (2019), *tors* are residual granitic blocks exposed and supported by underlying rocks that were later released onto rock surfaces. The author highlights the two-stage theory (*etchplanation*) as the most suitable for explaining these relief features, which involve a double process of planing.

Figure 6. A: Chaos of blocks on the "Pedra do Corte" inselberg, Inselbergs Fazenda Salva Vidas geosite, Quixeramobim, CE; B: Isolated tor located on top of Inselberg, Serra do Meio. Quixeramobim, Ceará



Photograph by Alexandre Pinheiro de Alcantara

Tors appear in isolated or grouped forms (alignment of blocks) and are found on high reliefs (tops of inselbergs) or shallow reliefs (vertical outcrops). As well as being common in crystalline terrain, there are *tors* in other lithologies with mineralogical characteristics such as sandstones in sedimentary and metamorphic regions through quartzite or gneiss (Migón, 2006; Bastos et al*.,* 2022).

Castle koopies (figure 7), also known as "castle *inselbergs*", are formed by blocks of rock literally stacked on top of each other. Unlike *tors*, which are quite common in various types of lithological terrain, *castle koopies* are less common features, although they are found in various climatic zones.

Figure 7. Castle Koopies feature in the municipality of Quixadá, Ceará

Photograph by Alexandre Pinheiro de Alcantara

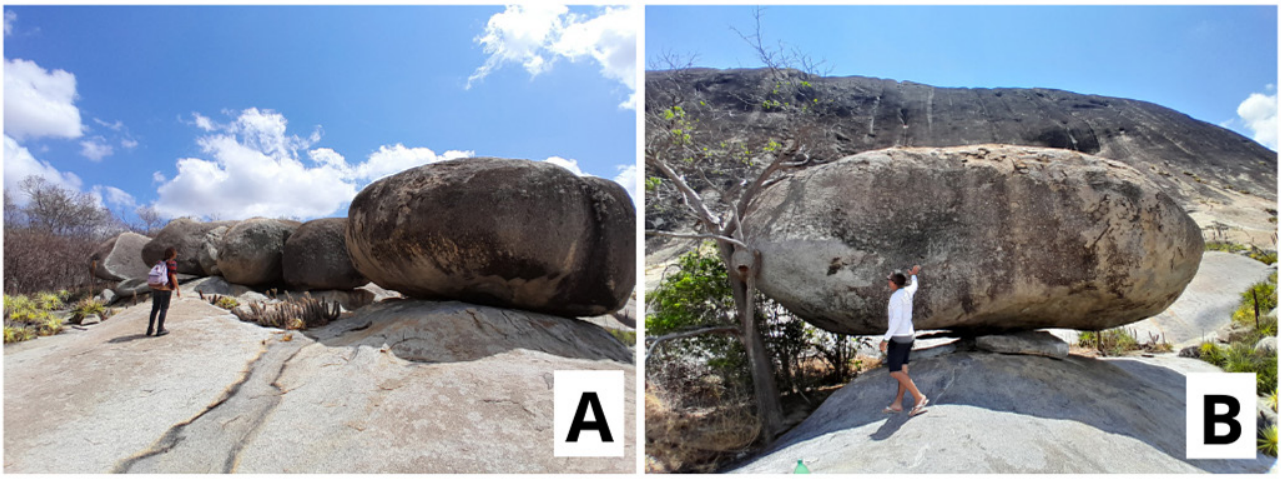
As it is a microform of saprolitic origin, its development also takes place in the subsurface, even before the alteration mantle (*grus*) is removed, so once it is exhumed, it will be structured by a massive lower base, while the upper part will be formed by orthogonal blocks fractured with edges (Migón, 2006; Maia et al*.,* 2018; Maia & Nacimento, 2018).

Generally speaking*, castle koopies, in terms of* topographic elevations, are smaller than *Bornhardts* and have a lower and less extensive morphology, as well as being features that are only found *in situ* (Bastos et al*.,* 2022).

Other common forms with scattered blocky residues of accreted forms are *nubbins* (Figure 8a). According to Migón (2006), nubbins are described as a chaotic mass of detached rock compartments, which can have angular, rounded or beveled shapes. They are characterized by being disorganized due to the exposure of their features and the evacuation of grus (loose rock fragments). *Nubbins* are rock formations that appear to be the result of processes of weathering and exposure in specific geological environments and can have a variety of shapes and characteristics according to the conditions in which they were formed.

The last feature in the group of saprolitization microforms is the *pedestal rock* (Figure 8b). According to Migón (2006) and Lima and Bastos (2018), *pedestal rock* basically consists of a pillar or rod that will support a much larger top and the base at the bottom, the result of efficient subsurface weathering.

Figure 8. A: Nubbins agglomerated in rectilinear shapes; B: Pedestal Rock with a lower pillar supporting a rock block of decametric dimensions, both located in Serra do Meio, Quixeramobim, CE



Photograph by Alexandre Pinheiro de Alcantara

3.2.2. Microforms associated with dissolution (Tafoni, “honeycomb”, karren, gnammas and flared slopes)

In the Sertão Monumental Geopark Project, various dissolution microforms have been identified, including *tafoni, alveoli/honeycombs*, *karrens*, *gnammas* and *flared slopes*. *Tafoni* are cavities present on rock surfaces, varying in size and shape, and are common in medium to coarse-grained granitics, metamorphic and sedimentary rocks. Generally found at high points *in inselbergs*, *tafoni* have polygenic and polyform characteristics intensified by weathering. Migón (2006) classifies *tafoni* into three types (Figure 9) depending on the position of the cavity opening: wall *tafoni*, basal tafoni and collapse *tafoni.* The origin of *tafoni*, although present in various climatic zones, is still the subject of research (Migón, 2006; Lima & Bastos, 2018).

Figure 9. A: Red arrows indicate the distribution of wall tafonis, Quixadá, Ceará; B: Decametric boulder with large basal tafone cavity, Quixadá, Ceará; C: Picture shows the formation of tafone in the initial process at the Fazenda Salva Vidas inselberg geosite, Quixeramobim, Ceará

Photograph by Alexandre Pinheiro de Alcantara

The formation of *tafoni* is an initial weathering process, occurring mainly along fractures, where water can percolate or be retained, as observed by Maia et al. (2022). These fractures act as preferential paths for water infiltration, accelerating weathering. The action of water, over time, widens the internal depressions through flaking and granular disintegration.

During the fracturing phase, before collapse, the cavity enlarges, creating weathering niches where the temperature and humidity conditions vary in proportion to the removal of material. In the collapse phase, the cavity expands through the formation and coalescence of patterns leading to the formation of tafoni. Basal tafoni are also worth mentioning, as they form at the bases of rock blocks.

This phenomenon, according to Maia and Nascimento (2018) and Bastos et al. (2022), occurs due to the irregular contact of the rock blocks with the surface, forming openings which, over time, suffer progressive flaking and granular disintegration, intensified by the chemical wear on the rock and the protection provided by the solar shadow zone.

Inside the tafoni (Figure 10), there are microforms of cavernous weathering known as *honeycombs,* related to arid and semiarid environments. The granulometry of the rock influences the size of the honeycombs, being smaller in fine grains and larger in large grains, as observed by Maia et al. (2018) and Maia and Nascimento (2018).

Figure 10. Advanced stage collapse tafoni with numerous honeycombs in the inside the cavity, in the "Witch's Head" (Cabeça da Bruxa) inselberg, Quixadá, Ceará

Photograph by Alexandre Pinheiro de Alcantara

However, in terms of size, the honeycombs have smaller spatial features and are distributed in the shape of circular concave niches. Their appearance is reminiscent of the honeycombs in bee hives, which in some scientific texts are called by this denomination. Their origin is still not very well explained.

Karrens are grooved features generally found in transverse positions on inclined or vertical rock surfaces, varying in size and sinuosity (Migón, 2006). Internationally, the terminology "*karrens*" is the most widely used, while regionally, in northeastern Brazil, the popular term "caneluras" is used. The geographical distribution of *karrens* around the globe is most common in climatic zones of arid and semiarid regions (Migón, 2006).

Karrens (Figure 11) can be identified on the rock surface in isolation or in groups, by means of U-shaped grooves followed by parallel lines from top to bottom, forming a kind of drainage network associated with the surface runoff of rainwater. Although these features are commonly associated with karst lithologies, such as limestone, there are many examples in granitic landforms, such as *inselbergs* and *boulders*, developing on sloping and vertical surfaces.

According to Bastos et al. (2022), *karrens* play an important role in the flow of water from rainfall, forming drainage concentrations of shallow and narrow furrows. At specific points, very wide and deep furrows can

form, known as "mega *karrens*" (Maia et al., 2018), where at points of deposition of transported sediments they will form installations of rupicolous vegetation (Olímpio et al*.,* 2021). According to Maia et al*.* (2018), karrens are more frequent in rocks that have a higher incidence of mafic minerals composed of biotite and porphyritic textures, as rocks with small phenocrysts, immersed in a fine-grained to dense matrix; or in felsic granitics with higher incidences of quartz and feldspar minerals.

Figure 11. Karrens distributed in lines of parallel furrows on support Abrupt rocky outcrop in the "Pedra da Gaveta" Inselberg, Inselbergs geosites of Fazenda Salva Vidas, Quixeramobim, Ceará

Photograph by Alexandre Pinheiro de Alcantara

Gnammas or dissolution basins, also known as "weathering *pits*", have different names in different regions of the world. In Australia, they are called *gnammas*. In German, they can be referred to as *verwitterungsnäpfe, opferkessel, baumverfallspingen, felsschüssel and dellen*. In Poland, they are known as *kociolki*. In Spanish, the names vary between pias, cassolas and pilancones. In French, they are called tanks and *vasques* (Migón, 2006).

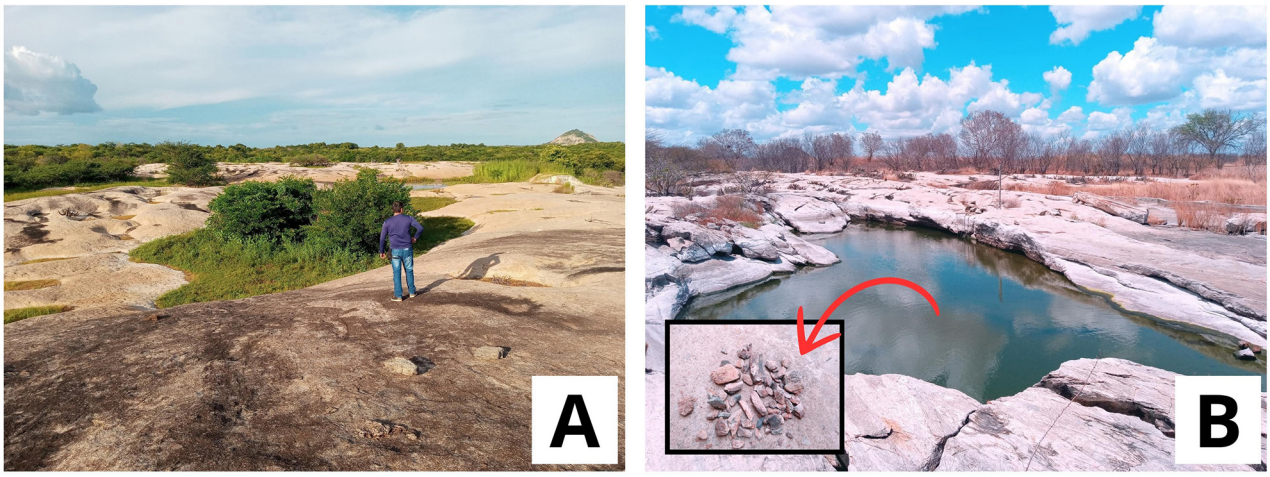
Gnammas are cavities exposed in rocky substrates and are common in various terrains of different lithologies. They are often found in granitic terrain rocks and are widely distributed in various climatic zones of the globe (Bastos et al., 2022). They have ellipsoidal, oval or circular features, with diameters ranging from 0.5m to decametric proportions, and can occur in isolated or interconnected forms, serving as exultories for storing water.

The *gnammas* (Figure 12) are well-known features in inland areas of northeastern Brazil, known as "tanks" or "sinks", places where the countryside people remove the sediment deposited at the bottom of the concave depression through excavations, in order to store rainwater and guarantee a water supply for a few months during periods of drought. It offers availability of water for fauna and, later, for the local population during periods of drought. In some cases, fossils from Pleistocene megafauna are found filled in by sandy-clay sedimentary deposits, with fossil content from Cenozoic megafauna.Thus, and according to Waldherr et al*.* (2022), tanks are stockpiles and storage areas.

Flared slopes are associated with paleo-levels of weathering occurring at the base of vertical outcrops (Migón, 2006) and can be decimetric to metric in size. They can occur at various altimetric levels one above the other, known as *multiple flares*. This feature is described in various parts of the world and is best developed in granitic terrain, occurring more frequently in basal areas of inselbergs and on the sides of rock blocks (*boulders*).

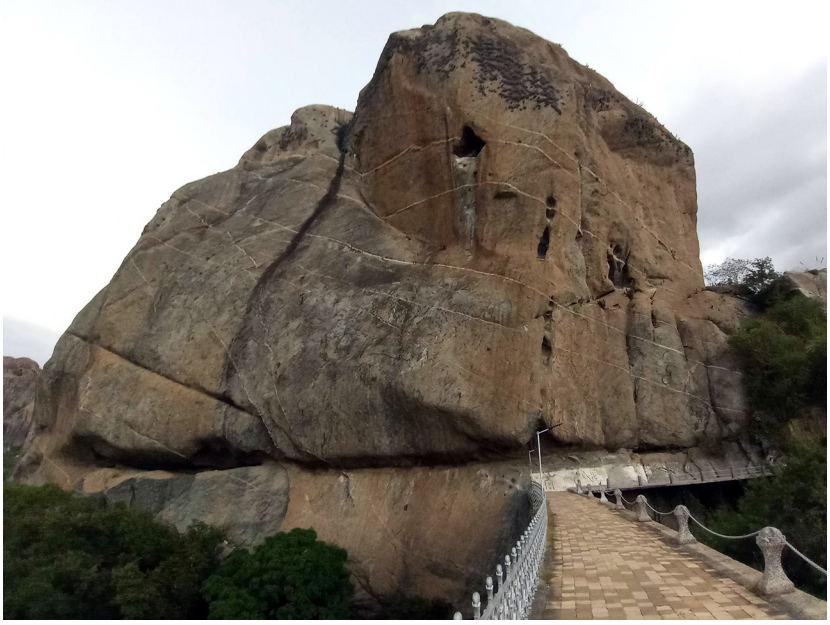
According to Maia et al*.* (2018), *flared slopes* (Figure 13) represent a particular corrosion feature or *weathering front* that develops at the foot of foothill escarpments, resulting from the attack of moisture on massive rocks that have subsequently been exposed. According to Bastos et al. (2022), the etchplanation model explains the evolution of these forms. This model suggests that *flared slopes* develop in the subsurface during a period of surface stability and are later exposed, revealing their characteristic configuration.

Figure 12. A: Arrows indicating *gnammas* filled with sediment and vegetation cover; B: Gnamma excavated to store rainwater. Traces of fossils of Pleistocene megafauna are usually found inside. Quixeramobim, Ceará



Photograph by Alexandre Pinheiro de Alcantara

Figure 13. Flared slopes concavity associated with paleo-level weathering on the middle slope of the "Pedra Faladeira" inselberg, Cedro reservoir, Quixadá, Ceará



Photograph by Alexandre Pinheiro de Alcantara.

3.2.3. Microforms associated with fracturing (Split Rock and Polygonal Cracking)

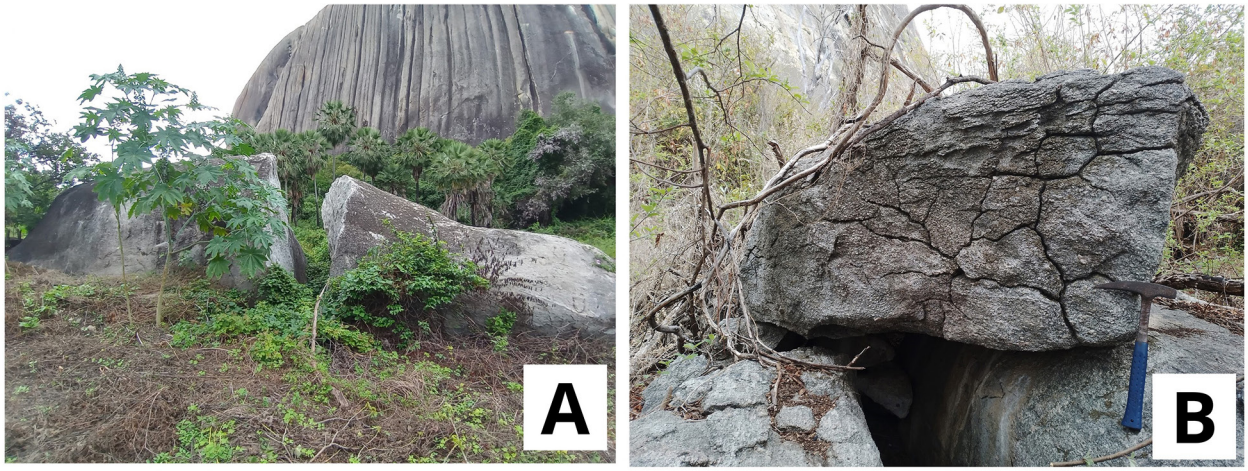
Microforms associated with fracturing occur in the area studied: *Split Rock and Polygonal Cracking. They* were classified due to their morphological aspects of fracturing, as well as their singularities and lesser occurrences.

These features were categorized in this way because their morphology indicates that they originated from fracturing processes. It is important to note that some dissolution features also have fractures associated with their formation and development (Maia et al., 2018). The development of the *split rock* (Figure 14a) is related to the fragmentation of large rocks along a single fracture, resulting in the splitting of these rocks into two parts. This occurs because the action of gravity exerts stress on the rock, causing it to break along a single fracture (Lima & Bastos, 2018).

Polygonal cracking (Figure 14b) involves the formation of a network of diaclases on the surface of rock outcrops, with varying geometries. When this network of diaclases is well developed, the rock takes an appearance similar to a turtle shell (Migoń, 2006). As for its origin, Maia and Nascimento (2018) indicate that it is the result

of the joint action of chemical and physical weathering processes, which act along the rock's fractures. In short, fracturing microforms, such as *split rock* and *polygonal cracking,* represent geomorphological patterns that originate from fracturing processes in rocks.

Figure 14A: *Split Rock* in a fractured rock block resulting from gravity and stress on the rock; B: *Polygonal Cracking* with cracks on the surface of rock outcrops, Quixeramobim, Ceará



Photograph by Alexandre Pinheiro de Alcantara

While *split rock* involves the breaking of large rocks along a single fracture, polygonal cracking forms an intricate network of fractures on the surface of the rocks. The formation of these features can be influenced by the combined action of chemical and physical processes, playing an important role in shaping geological landscapes.

4. Discussion of results

The interest in identifying relief features in granites is related to understanding the geomorphological and paleoclimatic evolution of the study region. Granites, due to their strength and structural characteristics, form distinct landscapes that can reveal a lot about geological and climatic processes over time.

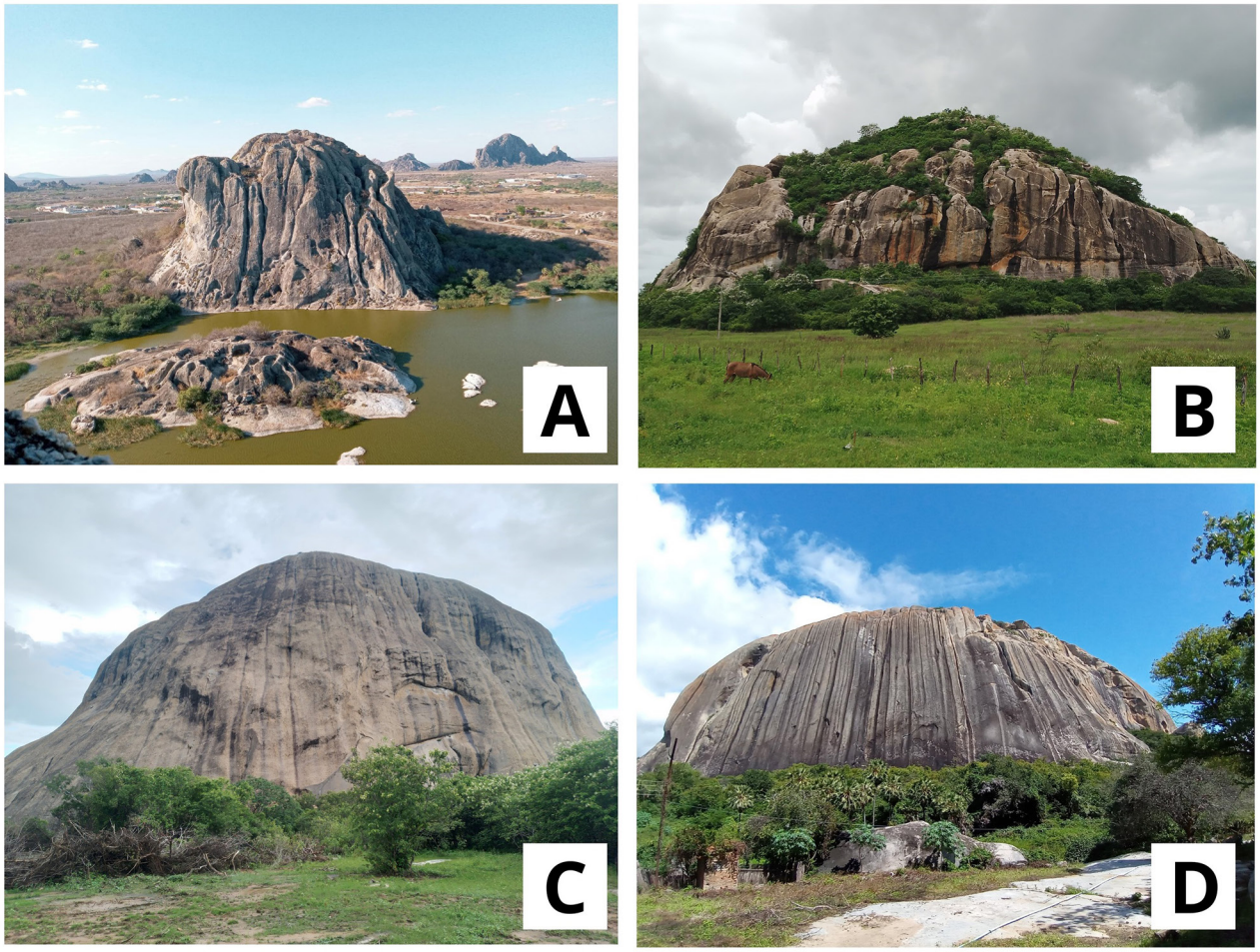
The results obtained from the research indicates that the area is effectively very rich in terms of these granitic features. The inselberg field of Quixada and Quixeramobim is indeed one of the most expressive concentrations of such geoforms in the world (Souza et al., 2023). This context seems to result of the combination of the occurrence of an important neoproterozoic geological structure (a batholith of large proportions: Pineo et al., 2020) with climatic shifting conditions (from dry to more humid) during the Neogene.

It is worth noting that the term *"Inselberg",* originally from German, means something like "rock island", or "mountain island", and was proposed by *Wilhelm Bornhardt* at the end of the 19th century. The concept is commonly associated with relief formations that arise from the lowering of surrounding areas. These formations are common in arid and semiarid climates, as the Quixada and Quixeramobim area, although their origin is mainly linked to tropical and subtropical erosion processes. In these environments, the removal of thick regolith, formed by deep weathering, results in these characteristic topographic elevations.

A study by Maia et al. (2015) investigated the *inselbergs of* Quixadá, classifying them into three types: 1) Dissolution, characterized by dissolution features such as karrens and *gnammas*; 2) Fracturing, predominantly marked by fractures and block collapse; 3) Domic, showing intact rocky escarpments as shown in Figure 3. Claudino-Sales (2020) added a fourth type, the "mixed", in which an inselberg shows characteristics of dissolution and fracturing, for example, in the same granitoid (Figure 15). These are the mainly characteristics that were found in this study, as was seen in item 3, what corroborates these authors' points of view.

In the study area, it was possible to conclude that the macroforms of granitic relief have their origin intrinsically linked to rocky bodies of remarkable spatial extension. These unique features emerge from rocky portions that exhibit less fracturing compared to the surrounding areas. This marked difference in the rate of ablation over time results in these macroforms being more clearly projected onto the landscape, standing out as dominant and iconic elements.

Figure 15. The 4 types of inselbergs according to the morphogenetic classification of Maia et.al (2015) and Claudino-Sales (2020). A: Type 1, dissolution, Complexo do Eurípedes geosite, Quixadá, CE; B: Type 2, fracturing, São João dos Pompeus, Quixadá, CE; C: Type 3, dome (massif), Lagoa do Fofô geosite, Encantado, Quixeramobim, CE; D: Type 4, mixed, geosite Inselbergs da Fazenda Salva Vidas, Quixeramobim, CE



Source: Alexandre Pinheiro de Alcantara

On the other hand, the genesis of granitic relief microforms is substantially more diverse. These microforms have their origins linked to different processes. The granitic blocks that make up some of the microforms were previously individualized below the surface and then exposed by geological processes. In contrast, the microforms related to weathering are the result of the selective dissolution of less resistant minerals, while those originating from fracturing are the result of physical breaks in the granitic blocks.

In this context, the etchplanation model, combined with morphodynamic processes, has served as a fundamental tool for understanding the formation and evolution of both macroforms and microforms in granitic settings. However, despite considerable progress, there are still gaps in understanding, particularly regarding the intricate development of structures such as tors, tafoni and honeycombs.

Studying these features helps to understand the weathering and erosion processes that shape the relief. Furthermore, the identification of these features has practical applications, such as in geotourism planning and environmental conservation, as many of these formations are of great scenic and scientific value.

In terms of geodiversity, the geomorphic elements of the Quixada and Quixeramobim inselberg field are much more important than any other constituent of the abiotic environment. If we consider that the geomorphological landscape attracts more attention than any other element of the physical environment, it is obvious that it increases the possibilities of the development of geoturism activities, what is crucial for the establishment of a Geopark. The inventory of the geomorphic features, as exposed here, increases the chances of the growth of important economic activities linked to geoturism in the area. This will induce the installation of a sustainable development on the region, which would be anchored on the inselbergs' dynamics analysis and popularization, by the means of geoeducation, what helps to develop actions of geoconservation. These

elements are necessary, they are even the basis, for the existence of a Geopark in the territory of Quixada and Quixeramobim, in the Northeast region of Brazil.

5. Conclusions

Studies on granitic features from around the world reveal a fascinating diversity in geological processes, weathering patterns, and landscape formations. Features like boulders, tors, and inselbergs are prominent in granite landscapes. These formations give granite terrains their distinctive appearance and have been studied extensively to understand their geological formation and evolution – but not their geomorphology. Effectively, despite their importance, they are underrepresented in geosciences research all over the world. Nevertheless, granite landscapes are significant components of global geoheritage It is here considered that studies as the one presented here enhance the understanding of granite's role in shaping the Earth's surface and its significance in geoheritage and geodiversity, and should be reproduced in other regions of the world.

Indeed, the present study contributes to the better understanding of the granitic geoforms, not only in the research area, but also from a general perspective. Effectively, many regions of the world present granitic landscapes, but the classification of the features, especially at the micro level, still lack of details. Such a situation is exemplified considering the relatively scarcity of specific publications in the international literature that go in this direction. The complexity of these phenomena suggests that future research is essential to fill these gaps and deepen our understanding of the origin and evolution of these fascinating manifestations of granitic relief.

The aesthetic values of granitic landscapes are inducing the growth of geoturism all over the world (Migon, 2021). For this reason, it seems imperative that we know better the processes responsible for its formation, to contribute not only to the production of knowledge about these features, but also to help improve geoturism itself - and as much important as that, to promote geoconservation. These elements, together, are essential for the installation of a Unesco Global Geopark in the study area.

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