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

Revista Brasileira de Geomorfologia

v. 25, nº 2 (2024)

http://dx.doi.org/10.20502/rbg.v25i2.2497

Research Article

Morphological patterns and distribution of Inselbergs in Quixadá and Quixeramobim – Northeastern Brazil

Padrões Morfológicos e Distribuição dos Inselbergs em Quixadá e Quixeramobim – Nordeste do Brasil

Eliomara Leite Meira Gomes [1], Rubson Pinheiro Maia [2] e Anna Sabrina Vidal de Souza [3]

[1] Federal University of Ceará, Department of Geography, Fortaleza, Brazil. eliomaraleite@hotmail.com
ORCID: https://orcid.org/0009-0006-3977-8575

[2] Federal University of Ceará, Department of Geography, Fortaleza, Brazil. rubsonpinheiro@yahoo.com.br
ORCID: https://orcid.org/0000-0002-1688-5187

[3] Federal University of Ceará, Department of Geography, Fortaleza, Brazil. annasabrinavidal@gmail.com
ORCID: https://orcid.org/0000-0001-5070-8208

Received: 24/10/2024; Accepted: 19/02/2024; Published: 14/06/2024

Abstract: Inselberg fields are found on several continents, including South America, North America, and Africa. In Brazil, one of the largest assemblages of these landforms is the Quixadá-Quixeramobim inselberg field, which is composed of 195 inselbergs organised in two clusters corresponding to the Quixadá and Quixeramobim granitic plutons. In general terms, studies related to spatial distribution and morphological patterns of inselbergs based on morphometric parameters are still scarce. The aim of this work is to analyse the distribution of inselbergs in relation to morphological and morphometric patterns and to point out the main factors influencing their distribution on granitic plutons, in order to support the understand of the evolution of these landforms. Radar and optical images with different spatial resolutions were used for the morphometric analysis of the inselbergs. Their boundaries were manually vectorised using GIS programs and their minimum and maximum heights were automatically extracted using an analysis and measurement tool inserted in the QGIS 3.28.4 Firenze software. Six core areas were identified with a high density of inselbergs, reaching 1,5 inselbergs per square kilometre. The distribution patterns are generally related to the geological/faciological characteristics of the plutons and their structural configuration.

Keywords: Inselbergs; Distribution; Morphometry

Resumo: Campos de inselbergs estão presentes em diversos continentes, incluindo a América do Sul, América do Norte e África. No Brasil, um dos maiores agrupamentos desses relevos é o campo de Inselbergs de Quixadá-Quixeramobim, composto em 195 inselbergs organizados em dois agrupamentos correspondentes aos plútons graníticos Quixadá e Quixeramobim. Em termos gerais, estudos relativos à distribuição espacial e padrões morfológicos de inselbergs com base em parâmetros morfométricos ainda são escassos. Este trabalho tem como objetivo analisar a distribuição dos agrupamentos de inselbergs em relação a padrões morfológicos e morfométricos e pontuar os principais fatores que influenciam sua distribuição nos plútons graníticos, a fim de auxiliar na compreensão da evolução dessas formas de relevo. Para realizar a análise morfométrica dos inselbergs, foram utilizadas imagens de radar e ópticas com diferentes resoluções espaciais. Seus limites foram vetorizados manualmente por meio de programas SIG e suas altitudes mínimas e máximas foram extraídas automaticamente utilizando uma ferramenta de análise e medidas inserida no *software QGIS 3.28.4 Firenze*. A partir do mapeamento realizado, foram identificadas seis áreas *core* com alta densidade de inselbergs, chegando a 1,5 inselbergs por quilômetro quadrado. Os padrões de distribuição, em geral, estão relacionados com as características geológicas/faciológicas dos plútons e sua configuração estrutural.

Palavras-chave: Inselbergs; Distribuição; Morfometria.

1. Introduction

Granite terrains display a morphological diversity that makes it difficult to characterize a typical "granite landscape" (MIGOŃ, 2004a). One of the most frequent and distinctive landforms in these areas are inselbergs, residual reliefs that rise abruptly from a flattened surface (WILLIS, 1934; CAMPBELL, 1997; MIGOŃ, 2004b). Inselbergs are widely recognized as one of the main types of granitic landforms, although they are not exclusively limited to granite (GERRARD, 1988; MIGOŃ, 2013). They are found in various parts of the world, such as Namibia, Australia, Angola, California (MIGOŃ, 2006, 2010; TWIDALE, 1995; GOUDIE, 2023), with Brazil being one of the countries with the highest occurrence of these forms, ranging from the semi-arid region in the Northeast (Ceará, Bahia, Paraíba, and Rio Grande do Norte) to intertropical portions of the Southeast (Minas Gerais, Espírito Santo and Rio de Janeiro).

The morphology of inselbergs is the result of long-term erosive processes that act in a differential way, reflecting both structural and lithological control (MIGOŃ, 2006; MIGOŃ; VIEIRA, 2014; KAMENOV; BILLI; MIGOŃ, 2022; SOUZA *et al.*, 2023). The morphological classification of inselbergs is traditionally based on the relationship between structure (geological factors) and shape (MIGOŃ, 2021), which promotes a diversity of individual morphologies. In this regard, types of inselbergs have been described according to the appearance of their hillslopes (TWIDALE, 1981b; GERRARD, 1988).

The morphology of inselbergs can be complemented by quantifying their morphometric variables. The combination of traditional inselberg descriptions with morphometric analysis is proving to be a fundamental resource for characterizing and classifying these landforms. This approach makes it possible to assess their geometric attributes quantitatively and qualitatively, as well as associating these attributes with the processes that play a fundamental role in their formation and evolution (FLORINSKY, 2017).

To date, understanding the variations in the shape and density of inselbergs has been limited. However, some studies have been conducted in this direction, such as that by Gibbons (1981), which revealed wide variations in the shape and density of inselbergs in eight distinct types of crystalline rocks in Swaziland. In addition, Römer (2005) examined the spatial distribution of inselbergs in Zimbabwe and their correlation with geomorphological, lithological, and structural factors in granitoid rocks. However, there is clearly a need to develop a more comprehensive and systematic method to fully understand the characteristics of granite inselbergs and the factors that influence their distribution and morphology.

This paper proposes a method for the morphological and morphometric analysis of granitic inselbergs in the Quixadá and Quixeramobim plutons based on remote sensing and field data. The aim is to identify the main parameters that define the types of inselbergs and the factors that influence their spatial and morphological distribution. This approach is promising for further work focusing on quantitative and qualitative analysis of inselbergs as a subsidy for understanding the evolution of the relief.

2. Study area

The Quixadá-Quixeramobim inselberg field is located in the central region of the state of Ceará, in north-eastern Brazil. The inselbergs occur within the area of two granitic intrusive bodies, named the Quixadá and Quixeramobim plutons (Figure 1), part of the Itaporanga Intrusive Suite, formed during the Brazilian orogeny in the Neoproterozoic, composed of granodiorites, monzogranites, syenogranites, granites and monzonites, high potassium calcium-alkaline, medium, or coarse grained and porphyritic in texture (ARTHAUD, 2007; PINÉO *et al.*, 2020). According to Torquato *et al.* (1989), the Quixeramobim displays six facies: Muxerê Velho (diorites and quartz-diorites as enclaves and sinplutonic dykes), Muxerê Novo (medium-K calc-alkaline granitic series of porphyritic texture with k-feldspar megacrysts of 2-5 cm), Serra Branca (medium-K calc-alkaline granitic series of porphyritic texture with k-feldspar megacrysts of 6-20 cm), Boa Fé (medium-K calc-alkaline granitic series of porphyritic texture with k-feldspar megacrysts of 1-3 cm), Água Doce (low-K calc-alkaline granitic series with fine-grained texture) and Uruquê (high-K calc-alkaline granitic series with fine-grained texture). The Quixadá pluton in turn, is composed mainly by the Monzonite Facies (ALMEIDA *et al.*, 1995) with occurrence of dioritic mafic enclaves and centimetre to metre-thick synplutonic granitic dikes (SILVA, 1989). Two major shear zones occur close to the plutons and accomodated their emplacement: Quixeramobim Shear Zone to west and Senador Pompeu Shear Zone to east (NOGUEIRA, 2004).

The inselbergs in Quixadá-Quixeramobim rise from the regional erosion surface at approx. 50-250 m, defined as Superfície Sertaneja 1 (SS1) (COSTA *et al.*, 2020) (Figure 2), which is marked by flattening process. Based on the characterizations of forms and processes associated with granite reliefs in the study area (MAIA *et al.*, 2015; MIGOŃ; MAIA, 2020), the inselbergs were divided into four categories: 1) Inselbergs with a predominance of fracturing features and, it is common for collapsed blocks to lie at the foot of their escarpments; 2) Inselbergs with a predominance of dissolution features exhibit a concave morphology associated with dissolution, characterized by the marked presence of gnammas and fluting, and the absence of well-developed erosional features; 3) Predominantly massive inselbergs, with no significant dissection or erosion features, steep escarpments and convex morphology. 4) Nubbins, which are considered blocky inselbergs, form a chaotic rock group resting on a more coherent low-angle rock platform.

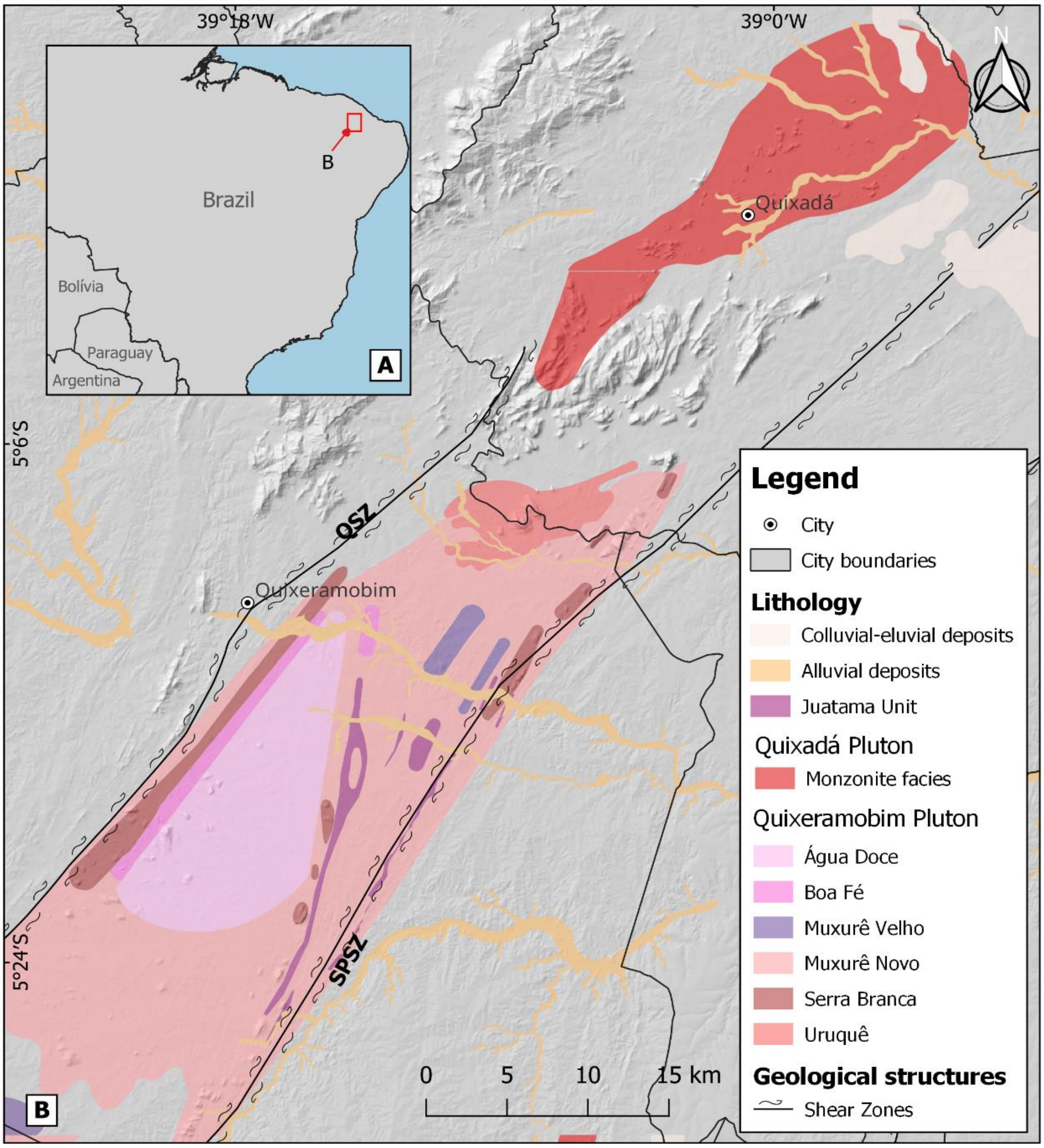

Figure 1. Location map and geological context of the study area. A - Study area in relation to South America. B - Geology of the Quixadá and Quixeramobim plutons, where QSZ (Quixeramobim Shear Zone) and SPSZ (Senador Pompeu Shear Zone) are indicated. Adapted from Parente *et al.* (2008).

Figure 2. Inselbergs in Quixadá, Ceará (Photo: Rubson P. Maia, 2022)

3. Materials and Methods

3.1. Cartographic survey

Cartographic data including maps, charts, vector files, and matrix files were gathered. The main digital resources obtained for the investigation were:

i) Geological maps in shapefile (.shp) format, at scales of 1:250,000 and 1:100,000, made available free of charge by the Companhia de Pesquisa e Recursos Minerais do Brasil (CPRM). These are Quixadá (SB. 24-VB-IV) and Itapiúna (SB. 24-XA-IV) (Costa and Palheta, 2017) and Folha Quixeramobim SB-24-V-D-III (Parente, Almeida and Arthaud, 2008).
ii) Google Earth Pro images acquired free of charge and online (2023).
iii) Synthetic Aperture Radar (SAR) data, in GeoTIFF format (.tif), referring to the Copernicus DEM 30 m, a digital surface model (DSM), under licence: All rights reserved (© DLR e.V. 2010-2014 and © Airbus Defence and Space GmbH 2014-2018), provided under COPERNICUS by the European Union and ESA.

3.2. Recognising and digitising inselbergs

The mapping of individual landforms included the manual digitalisation of the edges of each inselberg using optical and radar images. The main morphometric parameters used to recognise and characterise these forms were height and slope. Based on an extensive literature review on the description of inselbergs and the characteristics of the study area, this analysis established that inselbergs were granite elevations of more than 20 metres, surrounded by more than 50% of escarpments above 45°.

The calculation of the slope depends on the range of measurements adopted, and for this reason, the result obtained should be considered an estimate. In other words, the slope measured depends on the differences in altitude between nearby points and how far or close these points are from each other (Valeriano, 2008).

The slope map was made using the "Slope" tool derived from the GDAL DEM utility, available in the QGIS 3.28.4 Firenze software. The Slope tool is available in the "Raster" menu → Analysis → Slope/Declivity. In this study, we determined the slope values using the triangulation method between Height, Base length, and Slope length (Figure 3).

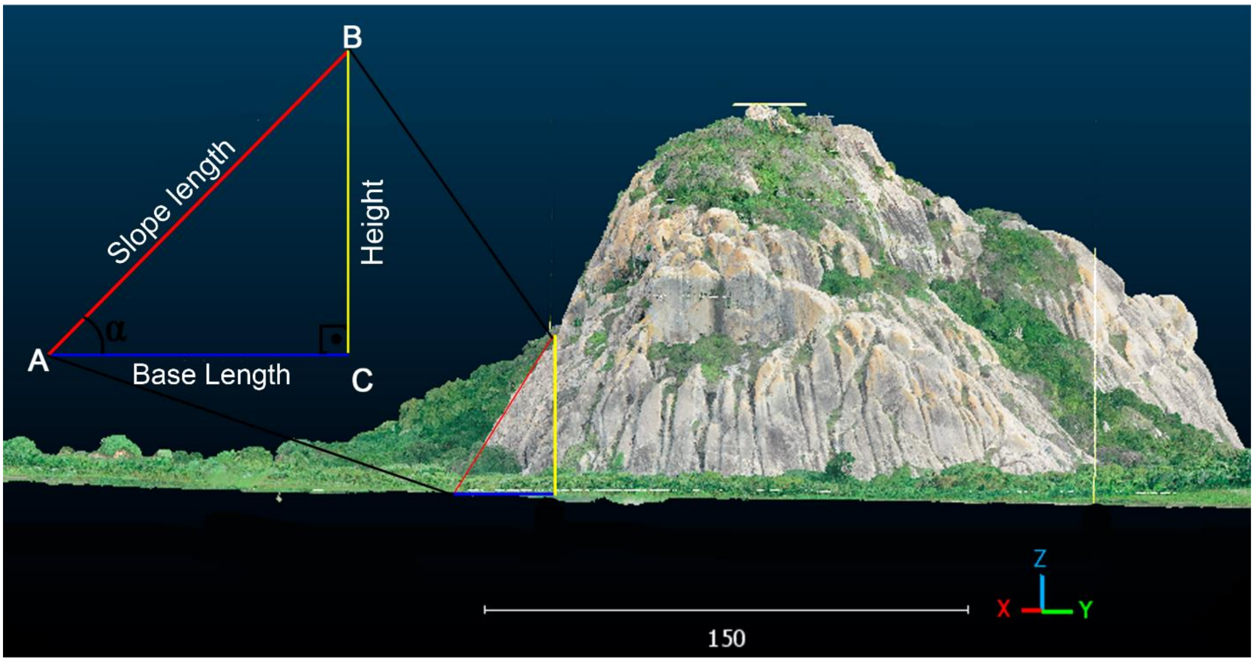

Figure 3. Representation of the height, base, and slope relationship in an orthomosaic (Source: Modified from Santos, Melo, and Rovani, 2017).

To better understand how the algorithm calculates the slope in the Geographic Information System (GIS), an analysis of the pixel values was conducted (Figure 4). The determination of slope in the context of GIS was based on a three-by-three moving mask applied to a Digital Elevation Model (DEM) to predict the slope of the central cell from its eight neighbours (DUNN; HICKEY, 1998).

Figure 4. Analysis of pixel values based on a three-by-three mobile grid, where each cell has an altimetric value (Source: Modified from Santos, Melo, and Rovani, 2017).

According to Dunn and Hickey (1998), this method does not consider the elevation of the centre point, which can lead to inaccuracies in areas with little depression, as well as in mountain ranges or valleys. It is important to note that the slope values on the map should be seen as an estimate and may vary depending on the quality of the image or the grid used. For instance, when using a high-resolution DEM, with a 1-meter grid, the influence of data accuracy becomes significant (Figure 5).

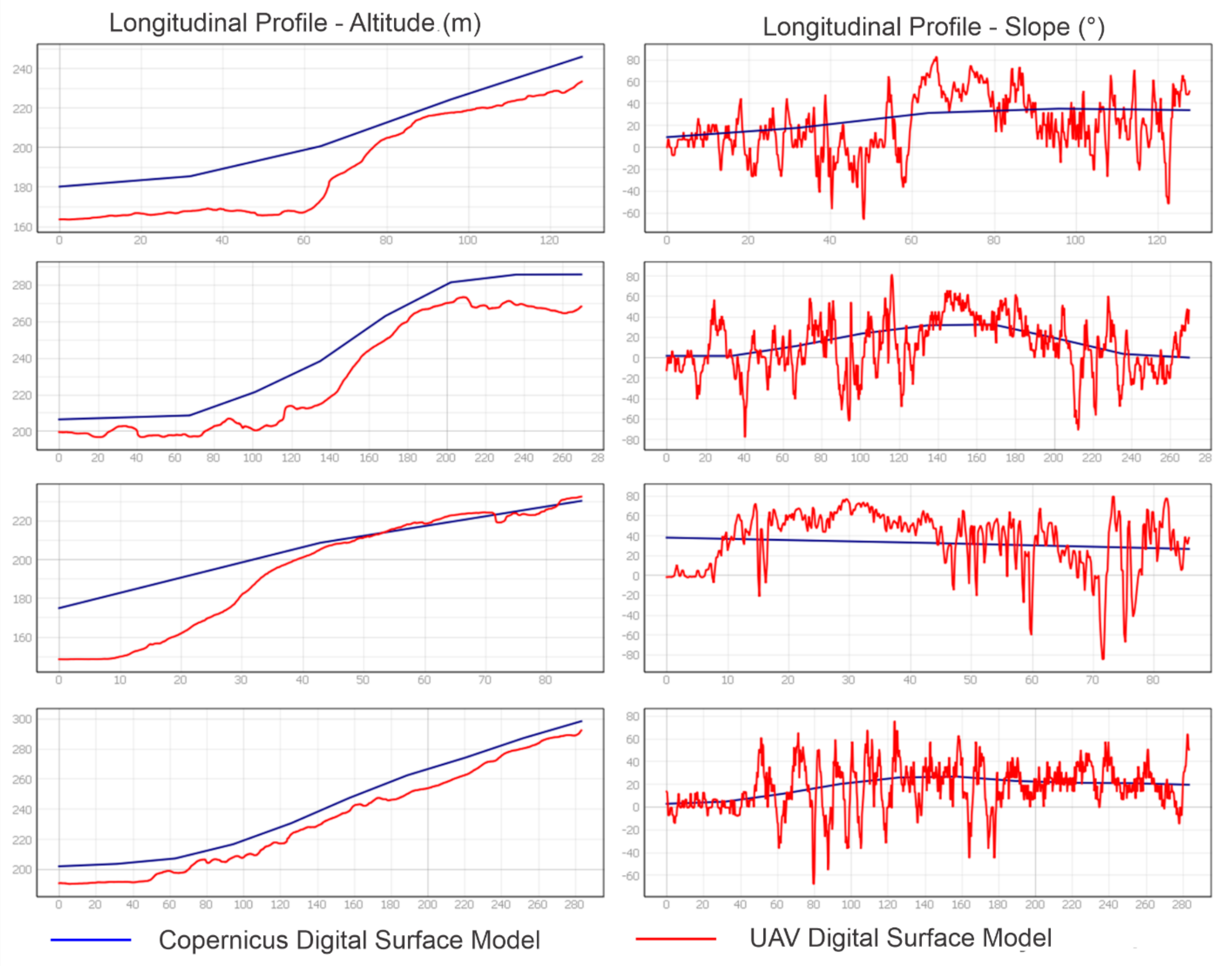

Figure 5. Areas of high slope in inselbergs: Comparison between the Copernicus DEM and the DEM generated by the UAV (Source: Authors, 2023).

Therefore, considering that models with a resolution of 30 metres show a variation regarding the slope parameter, we opted for an estimate in which areas with slopes greater than 30° would be considered as angles greater than 45°. This approach was subject to field recognition, and by Street View verification, and supported by DEMs data of a few inselbergs within the Quixadá-Quixeramobim area, acquired by UAV survey (Figure 6).

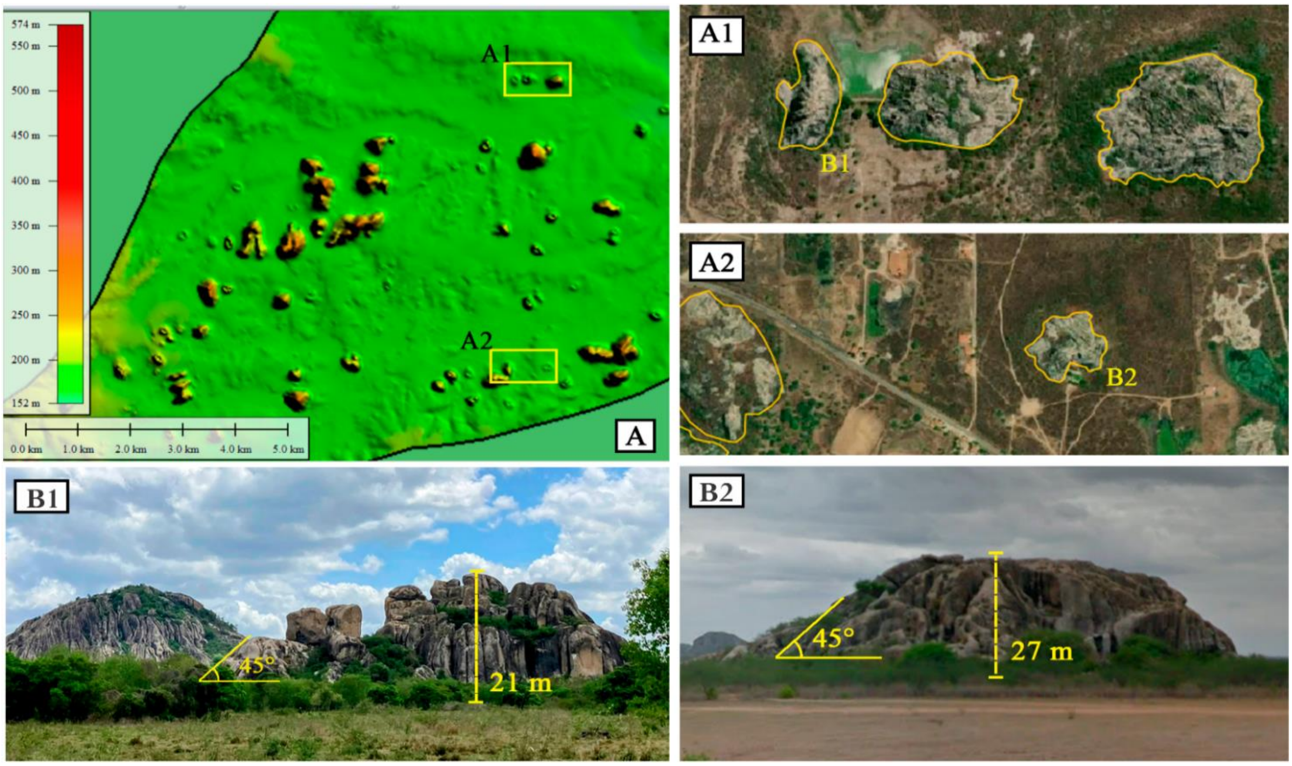

Figure 6. Delimitation and recognition of inselbergs. A - Altitude of inselbergs according to Copernicus DEM. A1 and A2 - Vertical view of nubbin inselbergs. B1 - Frontal photo of a nubbin inselberg. B2 - Frontal image taken using Street View (Google Maps) (Source: Authors, 2023).

To ensure greater precision in recognizing these landforms, the scale of analysis used in the GIS mapping was set at 1:10,000. To extract the elevation at the base and top, a buffer zone of 50 metres was created around the edge of each inselberg (Figure 7A). A 50 m buffer zone was chosen because it was large enough to be representative of the surrounding areas and small enough to mitigate the impact of nearby topographical features (i.e., other inselbergs, low outcrop).

To extract the minimum and maximum elevations, the “Zonal Statistics” processing tool was used, in which the statistics of a raster layer are calculated for each feature of an overlapping polygon vector layer. This approach optimized time and minimized potential extraction errors. Another field created by the “Zonal Statistics” tool was “range”, indicating the variation in height. To calculate this, the elevation of the lower surface of the pluton/base (Minimum Elevation) was subtracted from the elevation of the top (Maximum Elevation), as shown in Figure 7B.

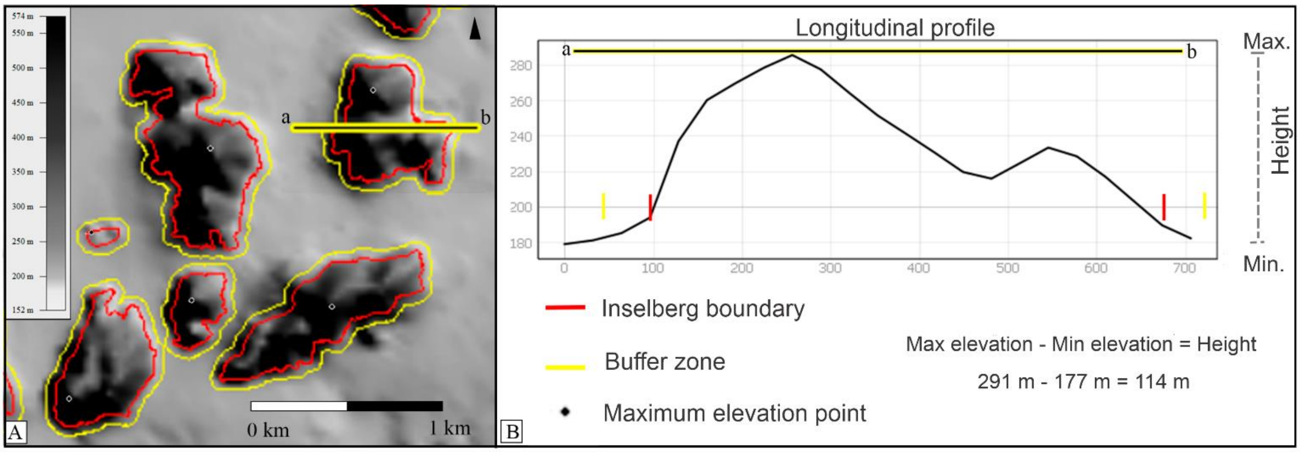

Figure 7. Extraction of zonal statistics from the DEM. A - DEM with individual margins of the inselbergs (red lines) and 50 m diameter buffers (yellow lines) around them, as well as dots (black with white) in the highest areas. B - Obtaining the altitudes and calculating the heights of the inselbergs (Source: Authors, 2023).

Regarding the morphological characteristics, the mapping enabled the identification of four types of inselbergs, categorised based on research by Maia *et al.* (2015) and Maia and Migoń (2020). 1) Inselbergs with a predominance of fracturing features are characterized by the presence of the talus ramp in approximately 75% of the area surrounding the inselberg, as well as the incipient development of dissolution features on its scarps (Figure 8). 2) Inselbergs with a predominance of dissolution features, in turn, reveal characteristics such as karren, gnammas, and dissolution tanks, as well as the absence of significant talus deposits (Figure 9). 3) Predominantly massive inselbergs are those reliefs whose escarpments show few weathering features and an absence or incipient collapse of blocks (Figure 10). 4) Nubbins are identified, above all, by the presence of a group of rounded blocks separated by fracture patterns (Figure 6 B1 and B2).

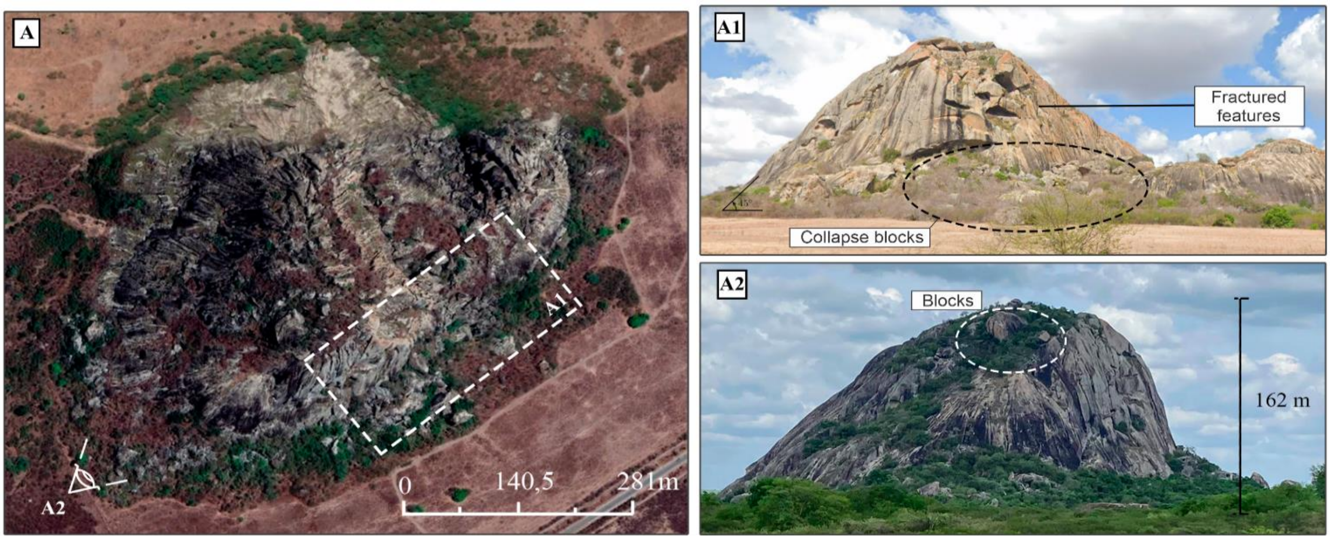

Figure 8. Characterisation of inselbergs with predominant fracturing. A - Vertical view of the Muxió inselberg, located in Quixadá. A1 - Front view in Street View showing the angle and collapse blocks. A2 - Photo from another perspective of the Muxió Inselberg (Source: Authors, 2023).

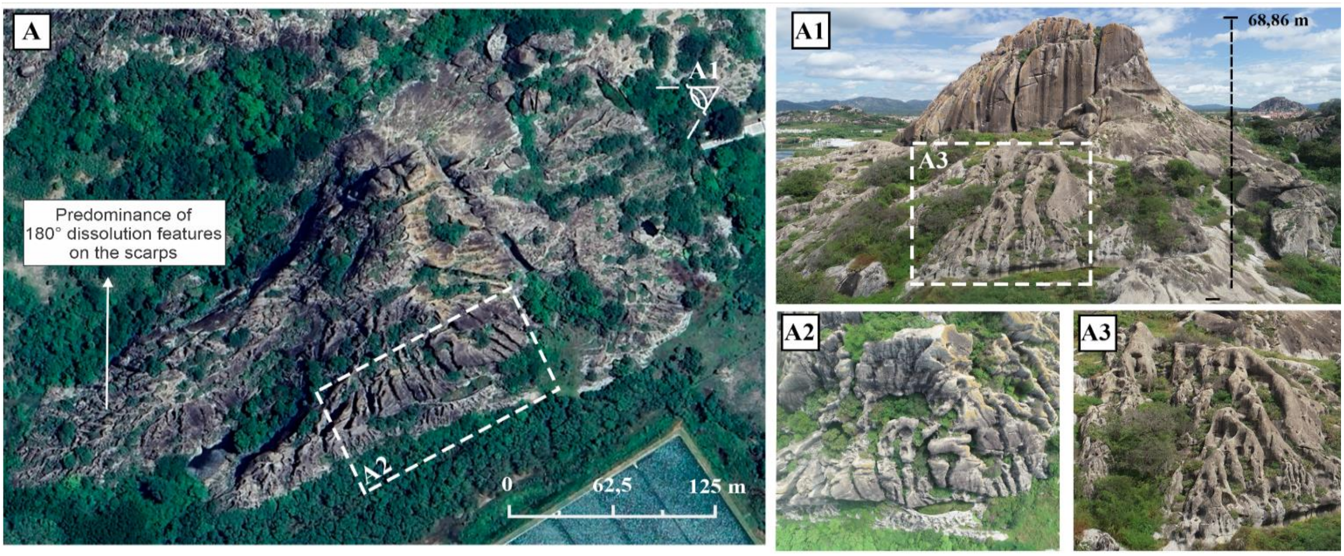

Figure 9. Characterisation of inselbergs with a predominance of dissolution. A - Vertical view of the Pedra do Herval inselberg, located in Quixadá. A1 - Oblique view of the inselberg. A2 and A3 - Vertical views showing escarpments with dissolution features (Source: Authors, 2023).

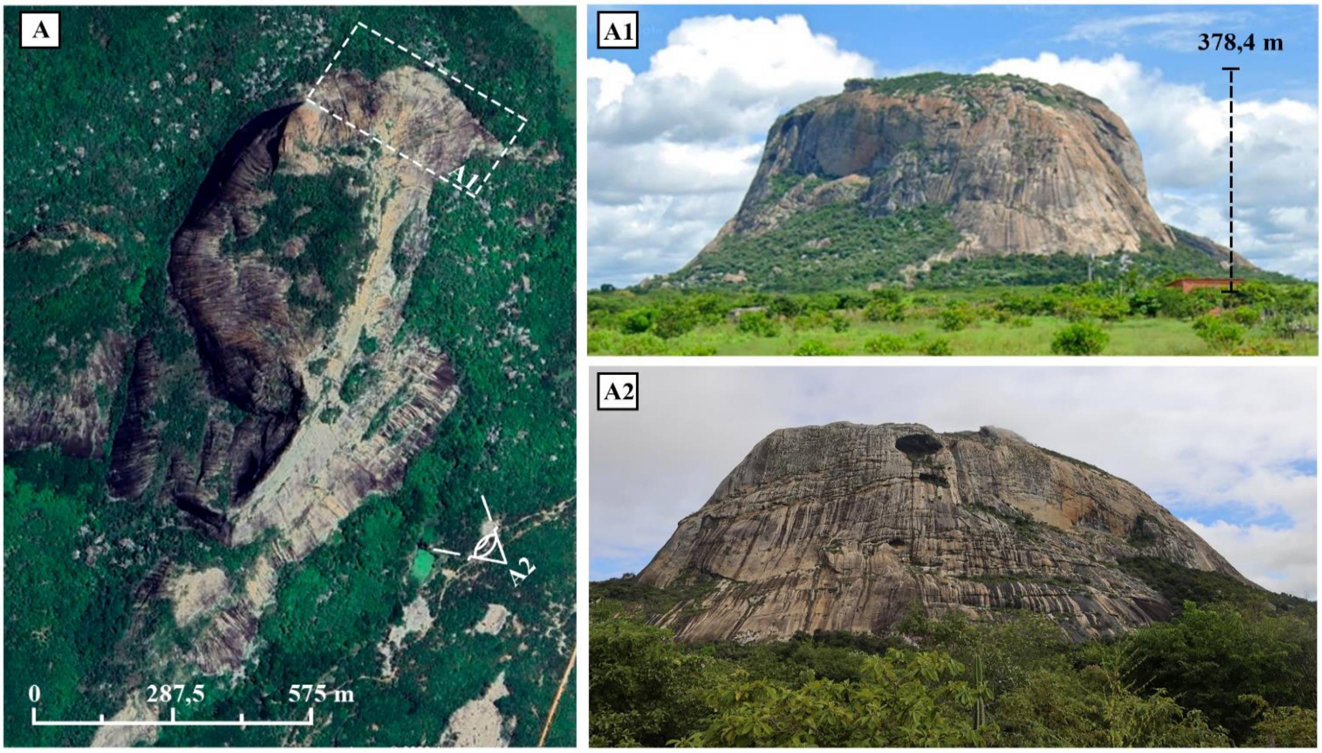

Figure 10. Characterisation of massive inselbergs. A - Vertical view of the Pedra do Bolo inselberg, located in Quixeramobim. A1 - Front Street View. A2 - Oblique photo taken in the field (Source: Authors, 2023).

To analyse the density of the plutons, the Kernel method was used, which consists of quantifying the relationships between points within a radius (R) of influence. A radius of influence of 3.5 km was used and based on the information obtained from the Kernel density map, core areas were created, which consist of the portion of the territory where the representative characteristics of the inselberg grouping predominate.

In this work, various grid dimensions were tested. However, due to the study area, a diamond-shaped grid with dimensions of 3.5 x 3.5 km was used to count the occurrences at points in the inselbergs. The count was entered into a table of attributes, and the core areas were then chosen because they had higher density levels.

In addition to the analyses already mentioned, a tool used in this study was the OpenStereo software, which enabled a rosette diagram to be drawn up to identify the preferred orientations of inselbergs with elongated shapes. It should be noted that many inselbergs do not have an elongated shape. In these cases, the preferred orientation was not extracted. The resulting rosette was then integrated into the map of inselberg types for a more complete and detailed visualization of the results.

3.3. Data Analysis

We analysed the statistical data using Excel software. To calculate the distribution of the inselbergs, we used some central statistical and dispersion measures. The dataset was divided into three sets: (i) the set relating to the Quixadá-Quixeramobim inselberg field, (ii) the set of inselbergs located in the Quixadá pluton, and (iii) the set of inselbergs located in the Quixeramobim pluton.

To characterise the quantitative data of the inselbergs, we used measures of central tendency that show the most typical or representative values of the datasets. The measures we used were mean (the result of dividing the sum of the values by the number of observations), median (the central value when the data is organized), and mode (the most often occurring value). These three measures helped us understand the properties of datasets and make comparisons between the three suggested sets.

We analysed the variability of the inselberg sets using dispersion statistics, which reveal the variation of the data around a central value, such as the mean or median. These measures allowed us to assess the homogeneity or heterogeneity of the data, with the standard deviation and the coefficient of variation (CV) being the measures chosen for this study. Both indicate the degree of variation in the inselberg data, being higher in situations of greater dispersion and lower when there is homogeneity.

4. Results

4.1. Mapping and distribution of inselbergs

The inselbergs were mapped based on morphometric parameters such as maximum altitude, minimum altitude, and average slope. In total, 195 inselbergs were identified in the Quixadá and Quixeramobim plutons. Of these, 86 inselbergs are in Quixadá, and 109 inselbergs are in Quixeramobim.

The density of inselbergs in the two plutons was verified by mapping and grouping six core areas, three in Quixadá (Figure 11, A1, A2, and A3) and three in Quixeramobim (Figure 11, B1, B2, and B3). The analysis revel that inselbergs are predominantly found in the NW and SW sectors of the Quixadá pluton, as well as in the NE, SE and SW sectors of the Quixeramobim pluton.

Table 1. Density of inselbergs in the Quixadá and Quixeramobim plutons.

Pluton	Number of Inselbergs	Area (km²)	Density (inselbergs/km²)
Quixadá	86	204,5	0,42
Quixeramobim	109	744,7	0,15

The Quixadá Pluton has a higher density of inselbergs incomparision with Quixeramobim Pluton (Table 1). This suggests that the distribution of inselbergs is more concentrated in a smaller area in the Quixadá pluton, while in Quixeramobim they are more widespread due to its greater extension.

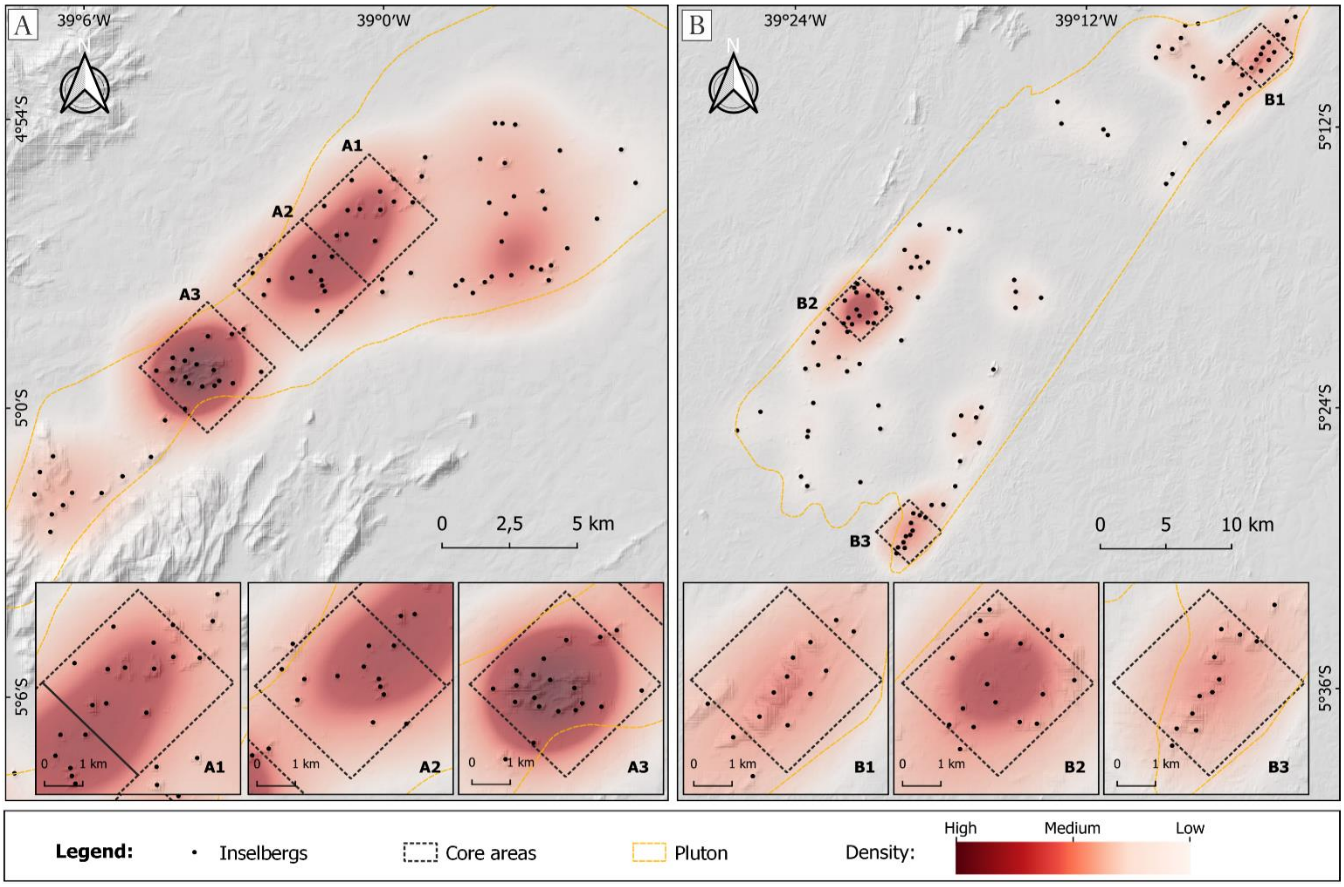

Figure 11. Mapping and distribution of inselbergs in the Quixadá and Quixeramobim plutons, A and B, respectively. Quixadá core areas A1, A2, and A3, and Quixeramobim core areas B1, B2, and B3.

The map shown in Figure 11 presents data related to the number of inselbergs, measured in square kilometres (km²). Table 2 show the values:

Table 2. Density of inselbergs in the core areas of the Quixadá and Quixeramobim plutons.

Core Area	**Number of Inselbergs**	**Core Area (km²)**	**Area occupied by Inselbergs (km²)**	**Density (inselbergs/km²)**
A1	12	12,5	1,3	0,96
A2	13	12,5	0,8	1,04
A3	18	12,5	1,9	1,44
B1	10	12,5	3,1	0,80
B2	14	12,5	3,4	1,12
B3	11	12,5	1,4	0,88

All core areas have the same extension (12,5 km²). However, the density of inselbergs varies in distinct parts of the pluton, being highest in areas A3 and B2, which indicates a significant concentration in these locations. Based on the data presented in Table 1, the average density of inselbergs in the core areas of Quixadá is 1,14 inselbergs/km² (43 inselbergs/37,5 km²), while the average density across the entire pluton is lower (0,42 inselbergs/km²). In addition, half of the inselbergs (50%) are in these core areas, distributed as follows: 14% in A1, 15% in A2 and 21% in A3, while the other half are dispersed outside the core areas.

The average density of inselbergs in the core areas of Quixeramobim is 0,93 inselbergs/km² (Table 2), representing six times the average density of inselbergs in the entire pluton. The distribution of inselbergs within Quixeramobim pluton shows that 32% are concentrated in the core areas, while 68% are scattered in other parts of the pluton.

The inselberg density values in the core areas of Quixeramobim are approximately four times lower than those in Quixadá. Although Quixadá pluton presents a higher count of inselbergs, in Quixeramobim, the inselbergs have larger dimensions, with areas of up to 7,8 km², twice as large as those found in Quixadá (around 4 km²). In Quixeramobim, areas B1 and B2 have a significant area occupied by inselbergs in relation to their total area, resulting in lower inselberg density. In contrast, in Quixadá, the central areas A1 and A2 have the same density of inselbergs, despite having different areas of occupation for the inselbergs.

4.2. Morphological classification of inselbergs

Following the morphological pattern proposed in earlier studies in the region (MAIA *et al.*, 2015; MIGOŃ; MAIA, 2020), we mapped the distribution of inselbergs based on their morphologies. The identified morphological categories include inselbergs with a predominance of fracturing features, inselbergs with a predominance of dissolution features, nubbins, and massive inselbergs.

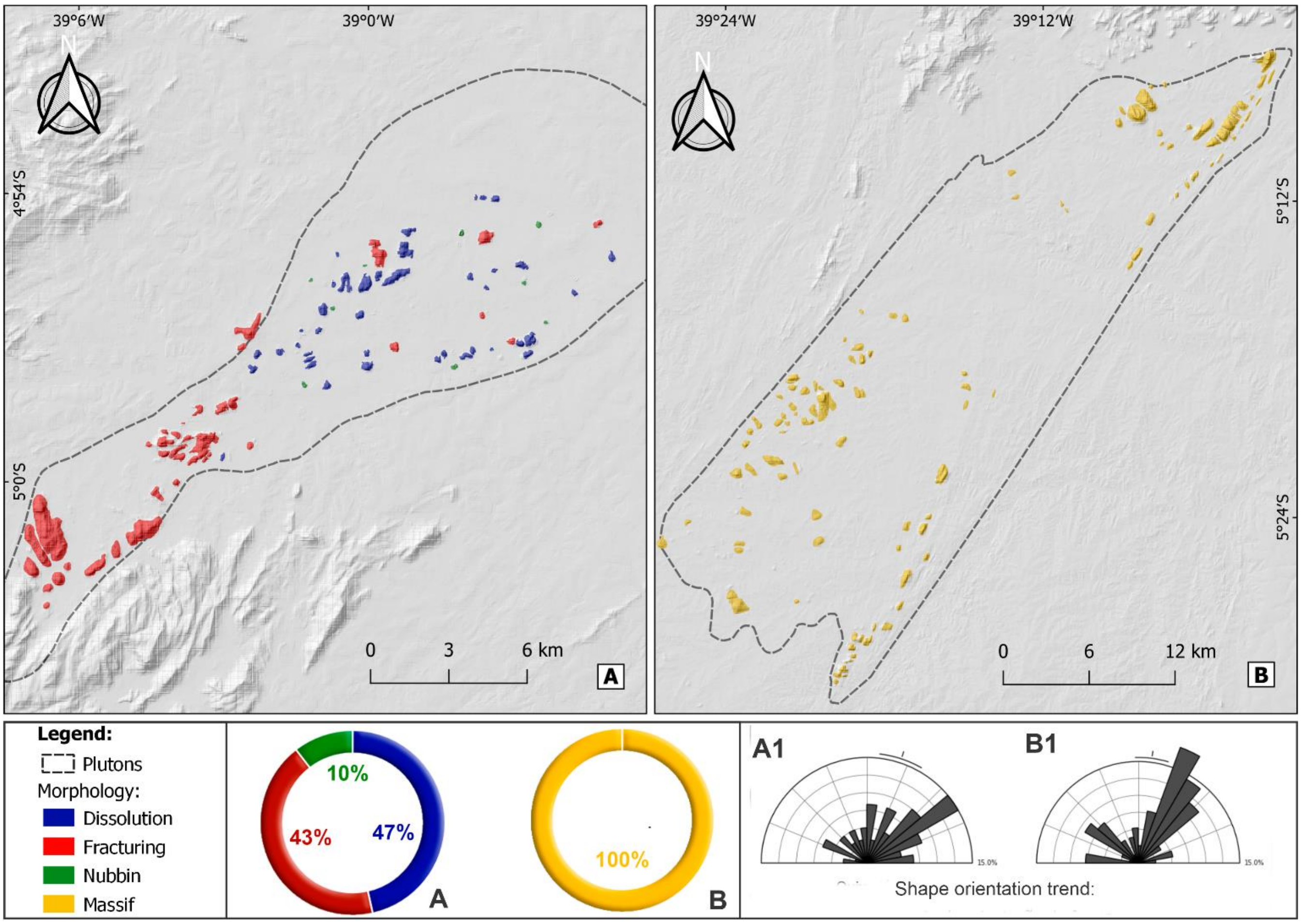

Figure 12. Distribution of inselbergs by morphology. A - Delimitation and distribution of inselbergs in the Quixadá pluton. B - Delimitation and distribution of inselbergs in the Quixeramobim pluton. A1 and B1 - correspond to the orientation trend of the inselberg distribution, where A1 corresponds to Quixadá and B1 corresponds to Quixeramobim.

In Quixadá, dissolution features predominate, representing 47% of the region and spreading throughout its entire length (Figure 12A). On the other hand, fracturing inselbergs, accounting for 43%, are typically found in the southwest of the pluton, in the Pedra da Galinha Choca Complex, and in some northern areas. Additionally, these inselbergs show a marked presence of talus ramps. Out of the 86 inselbergs identified in Quixadá, 40 are classified as dissolution, 37 as fracturing, and only 9 (10%) as nubbins. It is important to emphasize that no massive inselbergs were found in the area.

By integrating the morphology and distribution data, it can be observed that areas A1 and A2 (Figure 11) with 8 and 11 inselbergs, respectively, show a predominance of dissolution features, while in area A3, there is a concentration of 16 fracturing-type inselbergs. In this context, for the Quixeramobim pluton (Figure 11B), represented by areas B1, B2, and B3, there is no clear differentiation in terms of morphology due to the predominance of massive inselbergs in these areas.

Considering the entire Quixadá-Quixeramobim inselberg field, 75% of the analysed inselbergs were ellipsoidal, with a predominance of these forms in the Quixeramobim pluton. In Quixeramobim, it is possible to see a systematic pattern of arrangement of elongated shapes in the NE sector, where 6 inselbergs occur juxtaposed. The rose diagram expresses the preferential direction of the inselbergs with elongated forms in the two plutons. In Quixadá, the inselbergs elongate in a NE-SW direction (Figure 12, A1), and the inselbergs in Quixeramobim, NNE-SSW (Figure 12, B1).

4.3. Morphometric Properties of Inselbergs

Figure 13 depicts the classification of inselbergs based on their heights, calculated by determining the difference between the lowered surface of the pluton and the maximum height of each inselberg. The inselbergs were categorized into three groups according to their height: above 100 m, between 50 and 100 m, and below 50 m. In Quixadá, the classes < 50 m and 50 - 100 m have approximately the same percentage, while in Quixeramobim, the classes < 50 m and > 100 m exhibit similar values.

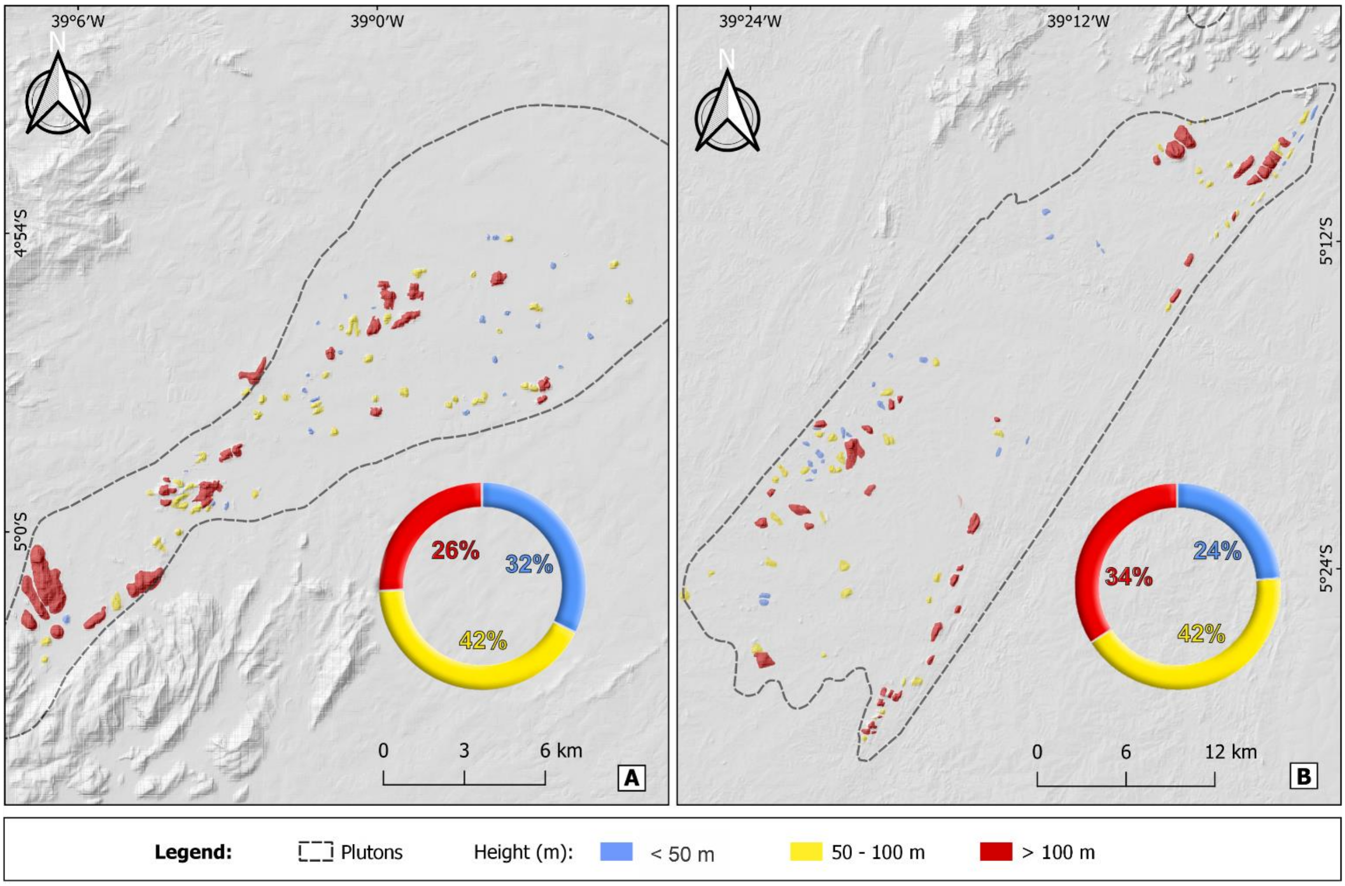

Figure 13. Classification of inselbergs according to height: < 50 m, 50 - 100 m, and > 100m. Panel A illustrates the delimitation and distribution of inselberg height classes in the Quixadá pluton, while Panel B displays the corresponding data for the Quixeramobim pluton.

The inselbergs in Quixadá-Quixeramobim exhibit a range of heights from 24 m to 381,6 m, with an average of 94 m. The median is 77 metres, meaning that half of the inselberg counts are less than or equal to 77 metres, and the other half are greater than or equal to 77 metres. This variation is remarkable, with a standard deviation of 62 m and a coefficient of variation of 66% in inselberg heights. As for the altitude data for this area, the values vary between 159 m and 576 m, with an average of 240 m.

There is a predominance of inselbergs with heights in the 50 to 100 m range in both plutons. Of the 195 inselbergs analysed, 86 (44%) are within this range. Additionally, there are 48 (25%) inselbergs with heights of less than 50 m and 61 (31%) inselbergs with heights of more than 100 m. The areas with the lowest inselbergs are found in the north of the Quixadá pluton and in the south-western sector of the Quixeramobim pluton.

In Quixadá, there are 86 inselbergs, 23 of which are less than 50 metres high (Figure 13A). The maximum height observed in Quixadá was 241 metres, with an average of 83 metres. The variation in height is low, with a standard deviation of 44 m and a coefficient of variation of 53%.

The inselbergs in Quixeramobim have higher maximum heights than those in the Quixadá pluton. The peak height observed in the former is 381,6 metres, while the highest inselberg in the latter reaches 241 metres. Looking at the statistics, dissolution inselbergs exhibit lower average heights compared to fracturing inselbergs and massifs. This suggests a more concentrated distribution of heights for dissolution inselbergs, while fracturing inselbergs and massifs tend to have higher averages (Table 3). It is worth emphasizing that each type of inselberg has a unique distribution of heights.

Table 3. Correlation between inselberg morphological types and basic height statistics.

Morphological Type of Inselberg	Average (heights)	Median (heights)	Amplitude (Variation between minimum and maximum height) *
Dissolução	72 m	66 m	120 m
Fraturamento	105 m	95 m	206 m
Nubbins	39 m	37 m	37 m
Maciços	103 m	81 m	357 m

It was observed that inselberg heights tend to increase with the size of their occupied area. In the inselberg field context, these reliefs cover an area ranging from 0,01 km² to 1,93 km², with an average of 0,21 km². Notably, massive inselbergs in the Quixeramobim pluton occupy larger areas and, so, exhibit greater heights compared to inselbergs of other morphological types.

5. Discussion

The results show that, despite the high concentration of inselbergs in the Quixadá and Quixeramobim plutons, the distribution of inselbergs and their morphological types vary in each of them, suggesting that geological, geomorphological, and topographical factors influence these parameters. The mapping of inselbergs revealed a non-uniform distribution in both plutons, emphasizing their concentration in specific areas, such as in the NW and SW sectors of the Quixadá Pluton and the NE, SE and SW sectors of the Quixeramobim Pluton. The distribution of core areas in the Quixeramobim Pluton may be related to the facies characteristics (Figure 1), since the greatest concentration of these reliefs occurs in the granitic (Muxerê Novo) and granodioritic (Serra Branca) facies (cf. TORQUATO *et al.*, 1989).

In spite of the relative lithological homogeneity of the Quixadá Pluton, primarily characterized by the monzonitic facies (ALMEIDA, 1995), the presence of a granitic sub-facies in the form of centimetric tabular bodies cutting through the main facies (SILVA, 1989) — concentrated particularly in the south-western sector of the Quixadá Pluton (NOGUEIRA, 2004) — may contribute to inselberg densification in this sector. Data from Souza *et al.* (2023) point out that the composition of the dykes, with a high silica content (> 70%), and the orientation of the swarms (low dip angles) favour the maintenance of cores of greater resistance, since they hinder vertical fracturing, corroborating the present observation.

An important factor influencing the distribution and density of landforms in the plutons is morphometry, particularly the size of the inselbergs. Results indicate that in the Quixeramobim Pluton, inselbergs exhibit larger individual areas, resulting in fewer inselbergs occupying the core areas and a subsequent decrease in density values. Conversely, in Quixadá, the individual area of inselbergs is twice as small as in Quixeramobim, leading to a higher density of inselbergs per square kilometre.

In this context, it is crucial to note that variations in the type and size of inselbergs are primarily linked to structural differences, specifically the heterogeneity of fracturing in the granite bodies. This heterogeneity favours the differential weathering processes assumed in the evolution of inselbergs (multi-stage models) (TWIDALE 1981a; RÖMER 2007). As erosion progresses, the distribution of these landforms tends to adhere to past structural patterns, particularly the density of fractures. In areas with intense erosion and planation processes, such as in the Quixadá-Quixeramobim inselberg field, the past configuration of these structures in the pluton is often unclear, requiring more detailed studies on the subject.

With respect to the local scale of inselberg morphology, mapping inselbergs based on their morphological typology—categorized into fracturing, dissolution, nubbins, and massifs—facilitated the quantification and spatial representation of relief diversity in the granite plutons, as previously highlighted by Maia *et al.* (2015). A notable observation is the contrast in morphological variation between the Quixadá pluton and the Quixeramobim pluton, which is characterized by massive inselbergs.

Maia *et al.* (2015) noted that facies characteristics of the granitoids in Quixadá contribute to the formation of microfeatures in inselberg scarps. Specifically, the results indicate that a majority of inselbergs in the Quixadá Pluton exhibit characteristics predominantly associated with dissolution processes. This finding aligns with mineralogical descriptions of the granitoids in this pluton, where the groundmass, primarily composed of amphiboles and biotites constituting 30 - 35% of the rock's total volume (TORQUATO *et al.*, 1989), features a widespread occurrence of mafic enclaves recognized as preferred sites for the development of dissolutions such as gnammas (MAIA *et al.* 2015; MAIA; NASCIMENTO, 2018). The authors (MAIA *et al.*, 2015) also asserted that dissolution inselbergs tend to have lower altitudes, a conclusion that aligns with the results of this study, as evidenced by lower average height values compared to fracturing inselbergs and massifs.

It is worth noting that the altimetric range of dissolution inselbergs is greater than that of fracturing inselbergs. This difference may be attributed to the variability in the characteristics of these inselbergs and the evolutionary terms of the dissolution features, especially runnels. For instance, in the Quixadá pluton, the Pedra do Cruzeiro inselberg, standing at 80 metres, exhibits deep grooves over 1 metre in depth along its entire escarpment. This contrasts with another dissolution-type inselberg, Pedra Riscada, reaching a height of 150.6 metres, which, in turn, displays grooves that are only centimetres deep. These variations result from the differential action of chemical weathering processes on the rocks in different sectors of the pluton, now manifested in the relief. It is likely that areas where these processes were more intense formed thicker mantles of alteration (THOMAS, 1965). Subsequent removal of these mantles exposed inselbergs with lower reliefs, compared to locations where the deepening of these features was less intense. Despite this, there is limited data available to fully understand these differentiations in the etchplanation stages of the pluton's processes. Therefore, further investigation is necessary to elucidate these mechanisms, which are reflected in the morphological patterns and heights of the inselbergs.

The nubbins exhibit limited representation within the mapped forms group, accounting for only 10%, and possess the lowest average heights. This is attributed to the loss of continuous escarpment morphology, as seen in other inselbergs. The intense individualization of sectors, driven by orthogonal fractures and the formation of boulders (TWIDALE, 1981b), sets these reliefs apart. A notable contrast appears between nubbins, heavily influenced by fractures in their evolution, and fractured inselbergs, which maintain heights similar to massive inselbergs. This discrepancy prompts an analysis of the factors contributing to the preservation of these heights despite fracturing. Some studies suggest that steep reliefs, controlled by intense fracturing, tend to form towers and pinnacles (CHIGIRA, 2021). In such cases, vertical fractures individualize reliefs, creating steep slopes that reflect the underlying structural pattern. This observation aligns with findings in our study area, exemplified by inselbergs such as Pedra da Galinha Choca.

The massive inselbergs exhibit the greatest heights and predominantly minor development of hillslope microforms. These characteristics are likely linked to the properties of the granites, whose fine-grained texture (in comparison to the granitoids of Quixadá) may promote the formation of scarps while inhibiting the effects of intergranular microweathering. In this context, Migoń and Vieira (2014) noted that fine-grained textures in granitic rocks can be more resistant than their coarse-grained counterparts. However, this relative reisstance is also influenced by mineralogy, such as the percentage of quartz, and structural factors.

Additionally, a distinctive feature of the Quixeramobim inselbergs, setting them apart from those in Quixadá, is the tendency for forms to exhibit orientation, particularly in the easternmost part of the pluton. It is plausible to suggest that the Senador Pompeu shear zone, which borders the granite body, played a role in the differential erosion and modeling of the relief in these sectors. This is supported by the observation that inselbergs closest to this zone are elongated in a preferential NE-SW direction, aligning with the regional structure. The influence of structural factors on granite plutons has been previously emphasized by Maia and Bezerra (2020); however, their focus did not extend to the scale of inselberg morphology.

6. Conclusions

The results of this study lead us to conclude that the distribution and concentration of inselbergs in the Quixadá and Quixeramobim plutons tend to be influenced by local geological factors, such as granitic facies characteristics. In this context, granitic facies, tend to favour the concentration and location of inselbergs within the plutons. Furthermore, we found that the assessment of the core areas of inselbergs (areas with a high density of forms) is responsive to the method of individually mapping inselbergs, where delimitations must consider the height and slope of their escarpments.

Morphological patterns of the inselbergs, associated with weathering processes on the escarpments, are correlated with morphometric characteristics. These, in turn, reflect factors in the evolution of the forms. The reliefs with the lowest heights are nubbins, a result of the prolonged process of rock core disintegration due to the individualization of sectors guided by fracture patterns, leading to the loss of escarpments. Among the inselbergs, those characterized by dissolution, on the other hand, have lower average heights and specifically show an inversely proportional correlation between the degree of evolution of the dissolution features and their heights.

Fracturing and massive inselbergs have greater heights and steeper escapes, both as a result of the structural configuration in the first case, and the cohesion given by the incipient development of microforms, influenced by different granite textures.

Authors' Contributions: E.L.M. Gomes: Conception, Methodology, Validation, Formal analysis, Data curation, Writing - initial version, Writing - revision and editing, Visualization. R.P. Maia: Conception, Methodology, Validation, Formal analysis, Resources, Writing - review and editing, Supervision, Project administration, Acquisition of financing. A.S.V. Souza: Conception, Methodology, Validation, Formal analysis, Writing - initial version, Writing - revision and editing, Visualization. All the authors have read and agreed to the published version of the manuscript.

Financing: The author(s) gratefully acknowledge funding from PROEX/CAPES, process no. 0348/2021/23038.008387/2021-53: Academic Excellence Programme and the research resources obtained by the project Inselbergs de Quixadá - Ceará - Brazil: Origin and Geomorphological Evolution by CNPq (National Research Council for Technological Development) in Brazil.

Agradecimentos: The authors gratefully acknowledge the research funding obtained by the project Inselbergs de Quixadá - Ceará - Brasil: Origem e Evolução Geomorfológica (Geomorphological Origin and Evolution) from CNPq (National Research and Technological Development Council) in Brazil. We appreciate the helpful comments of two reviewers who helped us improve the article.

Conflict of interest: The authors declare no conflict of interest.

References

1. ALMEIDA, A. R. de; ULBRICH, H. HGJ; MCREATH, I. O batólito Quixadá–petrologia e geoquímica. **Geologia**, v. 12, n. 1, 1999. Disponível em: <http://periodicos.ufc.br/geologia/article/view/1376>. Acesso em: 20 abr. 2023.
2. ARTHAUD, M. H. **Evolução neoproterozóica do grupo Ceará (domínio Ceará central, NE Brasil):** da sedimentação à colisão continental brasiliana. Tese (Doutorado em Geologia) - Universidade de Brasília, Brasília, 2007. 170 p.
3. CAMPBELL, E. M. Granite landforms. **Journal of the Royal Society of Western Australia**, v. 80, p. 101, 1997.
4. CHIGIRA, M. Rock pillars shaped by columnar joints in granite at Mt. Mizugaki, Central Japan. **Island Arc**, v. 30, n. 1, p. e12424, 2021. DOI: 10.1111/iar.12424
5. Copernicus Digital Elevation Model (DEM) was accessed on DATE from. DOI: https://doi.org/10.5270/ESA-c5d3d65.
6. COSTA, F. G. da; PALHETA, E. S. de M. **Geologia e recursos minerais das folhas Quixadá (SB. 24-VB-IV) e Itapiúna (SB. 24-XA-IV)**. CPRM, 2017. Disponível em: <https://rigeo.sgb.gov.br/handle/doc/19029>. Acesso em: 10 fev. 2023.
7. COSTA, L. R. F; MAIA, R. P.; BARRETO, L. L.; CLAUDINO-SALES, V. C. Geomorfologia do nordeste setentrional brasileiro: uma proposta de classificação**. Revista Brasileira de Geomorfologia**, São Paulo, v. 21, n. 1, p. 185-208, jan./mar. 2020. DOI: 10.20502/rbg.v21i1.1447
8. DUNN, M.; HICKEY, R. The effect of slope algorithms on slope estimates within a GIS. **Cartography**, v. 27, n. 1, p. 9-15, 1998. DOI: 10.1080/00690805.1998.9714086.
9. FLORINSKY, I. V. An illustrated introduction to general geomorphometry. **Progress in Physical Geography**, v. 41, n. 6, p. 723-752, 2017. DOI: 10.1177/0309133317733667.
10. GERRARD, A.J. Landforms on granitic rocks. In: Gerrard A.J., (ed.) **Rocks and Landforms**. Springer Netherlands, Dordrecht. P. 208–230, 1988.
11. GIBBONS, C. L. M. H. Tors in Swaziland. **Geographical Journal**, p. 72-78, 1981. DOI: 10.2307/633410.
12. GOUDIE, A. **Desert Landscapes of the World with Google Earth**. Springer Nature, 2023. DOI: 10.1007/978-3-031-15179-8
13. KAMENOV, B. K.; BILLI, P.; MIGOŃ, P. *Inselberg* Landscape of the Bur Area in Southern Somalia. In: BILLI, P. (Ed.). **Landscapes and Landforms of the Horn of Africa: Eritrea, Djibouti, Somalia**. Cham: Springer International Publishing, p. 249-263, 2022. DOI:1007/978-3-031-05487-7_11.

14. MAIA R.P; BEZERRA, F. H. R. **Structural geomorphology in northeastern Brazil**. Springer International Publishing, 2020. DOI: 10.1007/978-3-030-13311-5
15. MAIA, R. P., BEZERRA, F. H. R., NASCIMENTO, M. A. L., DE CASTRO, H. S., DE ANDRADE MEIRELES, A. J., & ROTHIS, L. M. Geomorfologia do campo de Inselbergues de Quixadá, nordeste do Brasil. **Revista Brasileira de Geomorfologia**, v. 16, n. 2, 2015. DOI: 10.20502/rbg.v16i2.651
16. MAIA, R. P.; DO NASCIMENTO, M. A. L. Relevos graníticos do Nordeste brasileiro**. Revista Brasileira de Geomorfologia**, v. 19, n. 2, 2018. DOI: 10.20502/rbg.v19i2.1295
17. MIGOŃ, P. Granite landscapes, geodiversity and geoheritage—Global context. **Heritage**, v. 4, n. 1, p. 198-219, 2021. DOI: 10.3390/heritage4010012
18. MIGOŃ, P. Inselberg. In: Goudie, A. S. **Encyclopedia of geomorphology**. Routledge, p. 564-566, 2004b.
19. MIGOŃ, P. Spitzkoppe: the world of granite landforms. In: Migoń P (ed) **Geomorphological landscapes of the world**. Springer, Dordrecht, pp. 155–162, 2010. DOI: 10.1007/978-90-481-3055-9_16
20. MIGOŃ, P. Structural control in the evolution of granite landscape. **Acta Universitatis Carolinae: Geographica**, v. 39, n. 1, p. 19, 2004a.
21. MIGOŃ, P. Weathering and Hillslope Development. In: John F. Shroder (ed.) **Treatise on Geomorphology**, Volume 4, pp. 159-178. San Diego: Academic Press, 2013. DOI: 10.1016/B978-0-12-374739-6.00075-0
22. MIGOŃ, P. **Granite landscapes of the world**. Oxford University Press Inc., New York, USA, 417p, 2006. DOI: 10.1093/oso/9780199273683.001.0001
23. MIGOŃ, P.; MAIA, R. P. Pedra da Boca, Pai Mateus, and Quixadá—Three Possible Key Geoheritage Sites in Northeast Brazil. **Geoheritage**, v. 12, n. 3, p. 51, 2020. DOI: 10.1007/s12371-020-00473-4
24. MIGOŃ, P.; VIEIRA, G. Granite geomorphology and its geological controls, Serra da Estrela, Portugal. **Geomorphology**, v. 226, p. 1-14, 2014. DOI: 10.1016/j.geomorph.2014.07.027
25. NOGUEIRA, J. F.. **Estrutura, geocronologia e alojamento dos batólitos de Quixadá, Quixeramobim e Senandor Pompeu** - Ceará central. Tese (doutorado) - Universidade Estadual Paulista, Instituto de Geociências e Ciências Exatas, 2004. 123p. Disponível em: <http://hdl.handle.net/11449/103013>.
26. PARENTE, C. V.; ALMEIDA, A. R. de; ARTHAUD, M. H. **Geologia da folha Quixeramobim SB. 24-VD-III**. CPRM, 2008. Disponível em: <https://rigeo.sgb.gov.br/handle/doc/10464>. Acesso em: 02 fev. 2023.
27. PINÉO, T. R. G; PALHETA, E. S. M.; COSTA, F. G.; VASCONCELOS, A. M.; GOMES, I. P.; GOMES, F. E. M. G.; BESSA, M. D. M. R.; LIMA, A. F.; HOLANDA, J. L. R.; FREIRE, D. P. C. **Mapa Geológico do estado do Ceará**. 2020. CPRM. Disponível em: http://rigeo.cprm.gov.br/jspui/handle/doc/20418. Acesso em: 02 fev. 2023.
28. RÖMER, W. The distribution of *inselbergs* and their relationship to geomorphological, structural and lithological controls in Southern Zimbabwe. **Geomorphology**, v. 72, n. 1-4, p. 156-176, 2005. DOI: 10.1016/j.geomorph.2005.05.008
29. RÖMER, W. Differential weathering and erosion in an inselberg landscape in southern Zimbabwe: A morphometric study and some notes on factors influencing the long-term development of *inselbergs*. **Geomorphology**, v. 86, n. 3-4, p. 349-368, 2007. DOI: 10.1016/j.geomorph.2006.09.008
30. SANTOS, R. L. R.; MELO, D. H. C. T. B.; ROVANI, F. M. Decifrando a ferramenta *SLOPE* com arquivo raster (MDE) no no ArcGIS. **Revista MundoGEO**. Curitiba: MundoGEO, ano 19, n. 82, jul. 2017. (Conteúdo Complementar, on-line). Disponível em: < http://mundogeo.com/blog/2017/07/26/artigo-decifrando-a-ferramenta-*slope*-com-arquivo-raster-mde-noarcgis/>. Acesso em: 03 jul. 2023.
31. SILVA, H. F. Alguns aspectos petrograficos e geoquimicos do batolito de Quixada, CE. **Revista brasileira de geociências**, v. 19, n. 1, p. 101-107, 1989.
32. SOUZA, A. S., MAIA, R. P., BEZERRA, F. H., MIGOŃ, P., & SIAME, L. L. Granitic inselberg erosion controlled by dike swarm array in semiarid Brazil. **Geomorphology**, p. 108865, 2023. DOI: 10.1016/j.geomorph.2023.108865
33. THOMAS, M. F. Some aspects of the geomorphology of domes and tors in Nigeria. **Zeit. Geomorph**. [s.l.], v. 9, 63–81, 1965.
34. TORQUATO, J.R.; ALMEIDA, A.R.; SIDRIM, A.C.G., MARANHÃO, C.M.L.; PARENTE, C. V.; NOGUEIRA, J. A., Neto; ANDRADE, J.F., P; SOUZA, J.V.; NOGUEIRA DE SOUSA, M.J.; ARTHAUD, M.H. Granitóides do Ceará - Região de Quixadá - Solonópple. **Rev. Geol**., 2(1,2):5-143. 1989.
35. TWIDALE, C. R. Bornhardts, boulders, inselbergs. **Cadernos Laboratory Xeolóxico de Laxe Coruña** 20:347–380, 1995.
36. TWIDALE, C. R. Granitic Inselbergs. In: SHARMA, H. S. (Ed.). **Perspectives in geomorphology**. Concept Publishing Company, p. 127, 1981a.
37. TWIDALE, C. R. Granitic inselbergs: domed, block-strewn and castellated**. Geographical Journal**, p. 54-71, 1981b. DOI: 10.2307/633409

38. VALERIANO, M. M. **Topodata:** guia para utilização de dados geomorfológicos locais. Boletim. São José dos Campos, SP: INPE: Coordenação de Ensino, Documentação e Programas Especiais. 72p. (INPE-15318-RPE/ 818), 2008.
39. WILLIS, B. Inselbergs**. Annals of the Association of American Geographers**, v. 24, n. 2, p. 123-129, 1934