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Research Article

Inselbergs shaped by collapse: considerations on the structural control on granitic scarps

Inselbergs modelados por colapso: considerações sobre o controle estrutural em escarpas graníticas

Rubson Pinheiro Maia [1], Anna Sabrina Vidal de Souza [2]

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

[2] Universidade Federal do Ceará, Departamento de Geografia, Fortaleza, Brasil. annasabrinavidal@gmail.com. ORCID: https://orcid.org/0000-0001-5070-8208

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Abstract: Inselbergs characterised by fracturing features correspond to the geomorphological manifestation of break-up of the rock mass and collapse. The steep slopes partially covered by angular boulders scattered chaotically reveal, in evolutionary terms, the predominance of the morphostructural controls, given by the presence of veins/dikes, sheeting joints, and vertical fractures. These structural planes in turn create anisotropies guiding fracturing directions and rockfall. In this work, we propose a model of geomorphological evolution of granitic *inselberg*s subjected to a structural propensity to fracturing. For this purpose, we analysed the Pedra da Galinha Choca inselberg (PGC) and Pedra Faladeira (Quixadá, NE of Brazil) inselbergs, whose morphologies attest to mechanical disintegration processes. Data extraction and interpretation were based on fieldwork and UAV photogrammetry, which provided products such as high-resolution models, orthomosaic, and DEM. Networks of multidirectional fractures were observed to promote an arrangement of interlocking blocks, allowing the maintenance of steep slopes (>60°), in which solutional features tend to be incipient due to the structural instability promoting collapse. Thus, the main features on the hillslopes are cavities like collapse tafone (CT) and large collapsed boulders (LCB). As a result of this structural setting, the inselberg displays sharp outlines, steep slopes, and wide talu deposits.

Keywords: Fractures; Scarp; Blocks; Collapse.

Resumo: *Inselberg*s caracterizados por feições de fraturamento correspondem à manifestação geomorfológica do desmembramento do corpo rochoso e colapso. As escarpas íngremes e parcialmente recobertas por blocos angulosos dispostos caoticamente revela, em termos evolutivos, a predominância dos controles morfoestruturais, dados pela presença de veios/diques, sheeting joints, e fraturas verticais. Esses planos estruturais, por sua vez, criam anisotropias que orientam as direções de fraturamento e queda de blocos. Nesse trabalho, propõe-se um modelo de evolução geomorfológica de *inselberg*s graníticos submetidos a uma pré-disposição estrutural ao fraturamento. Para tanto, foram analisados os *inselbergs* Pedra da Galinha Choca (PGC) e a Pedra Faladeira (Quixadá, NE do Brasil) cujas morfologia atestam processos de desintegração mecânica. A extração e interpretação de dados baseou-se em trabalhos de campo e levantamento aerofotogramétrico com drone, cujos produtos são modelo digital de alta resolução, ortomosaico e MDE. Observou-se que redes de fraturamentos multidirecionais promovem o encaixe de blocos, permitindo a manutenção de escarpas íngremes (>60°), nas quais feições de dissolução tendem a ser incipientes dada a instabilidade estrutural que promove colapso. Assim, as principais feições de ornamentação nesses relevos são cavidades do tipo tafone de colapso (TC) e megablocos colapsados (MBC). Como resultado desse contexto estrutural, tem-se *inselberg* com feições angulosas, escarpas íngremes e amplos depósitos de tálus.

Palavras-chave: Fraturas; Escarpa; Blocos; Colapso.

1. Introduction

Landforms dominated by fracturing features are predominantly characterised by the break-up of the rock mass. Block collapse and mechanical disintegration result from fracture propagation, which responds to a set of processes, from tectonic and gravitational stresses to climatic conditions (e.g., thermoclasty) and erosive process (e.g., unloading during the exhumation of granite bodies) (Eppes, 2022). Fracturing tends to occur along rock heterogeneities, i.e., late intrusions and intergranular contacts (Gomes-Heras et al., 2006; Shang, 2020) or to develop parallel to the surface (e.g., sheet joints) (Martel, 2006). While promoting gradual fracturing on rocks, mechanical weathering gives the condition for the instability of steep and fractured slopes, whose geomorphological evolution holds significant influence of the structural control, as pointed out by several authors (Brideau et al., 2009; Sted and Wolter, 2015; Matasci et al., 2015; Neely and DiBiase, 2020).

Recent studies that performed high-resolution remote sensing analyses demonstrated that joint sets and systems of veins and dyke intrusions generate discontinuities exploited by erosion, such that landforms such as towers, pillars and boulder fields reveal the structural configuration of granite rocks (Chigira and Kato, 2023; Chigira, 2021; Chigira and Hirata, 2021). Despite the acknowledged influence of structural inheritance on the survival of residual relief, such as inselbergs, after regional erosive processes (Migon, 2004; Vidal-Romani, 2008), the diversity of morphological patterns of inselbergs is still poorly explored in the geomorphological literature, especially concerning the structural controls on slope appearance. Thus, the varied forms and shapes that inselbergs can exhibit as a consequence of fracture propagation still require attention.

Generally, inselbergs are typically characterised by massive and convex slopes (domical inselbergs) (Twidale, 1981). When they present intense fracture patterns that formerly guided chemical weathering producing separation of blocks or boulders in situ, they are defined as nubbins (boulder-strewn inselbergs) or Castle Koppies (castellated inselbergs) – which do not display the form of continuous slope. However, several landforms (e.g., inselbergs, pillars, and towers) built of granitoid rocks present patterns of multidirectional fracturing and rockfall-derived features, for instance, the Dedo de Deus (Teresópolis, RJ), Pedra do Frade (Itapajé, CE), Pico dos Pontões (ES) in Brazil, and Spitzkoppe (Namib) (cf. Fernandes et al., 2010; Bastos et al., 2021; Dantas et al., 2014; Migon, 2010). All these places also converge in one aspect – the formation of an iconic geomorphological landscape due to the shapes of their vertical scarps.

Among the studies on the evolution of fractured rock slopes, it should be noted that inselbergs typified by such features are not often the focus of geomorphological investigations. In this regard, the inselbergs Pedra da Galinha Choca and Pedra Faladeira (Quixadá, Brazil), analysed in this work, are representative examples of landforms in terms of structural control by fracturing and collapse, evidenced by their fractured slopes and the occurrence of talus deposits. Given this, we aim to verify the correlation between the structural setting of the granite rock and the slope morphology, in comparison with other similar examples, in order to contribute to the comprehension of geomorphological evolutionary processes in fractured rock slopes.

2. Study area

The Quixadá Inselberg field is located in the central part of the State of Ceará, Northeastern Brazil, near the homonymous city. According to the most recent geomorphological proposal, they are inserted in the Sertaneja Surface (SS1), a unit marked by planation processes in the brazilian north-east that resulted in flat or gently sloping topographies, with occurrence of residual relief (Costa et al., 2020). In Quixadá, the surface surrounding the inselbergs is predominantly plane and is at approx. 170 m a.s.l. The inselbergs in turn present altitudes varying from 200 to 400 m a.s.l (Figure 1). In the southwest portion of the inselberg field, there are crystalline massifs built of metamorphic rocks, surpassing 400 m of altitude (Maia et al., 2015).

The predominant climate type in the study area is semi-arid, according to the Koppen classification (Alvares et al., 2013). The mean annual precipitation is 700 mm (FUNCEME, 2021) with a rainy season concentrated from February to May, and mean temperatures varying from 26° to 28° (Zanella, 2014). The common soil associations are Planosols, Lithic neosols and Halomorphic soils (EMBRAPA, 2017) and with arboreal-shrub caatinga vegetation (Gomes et al., 2010).

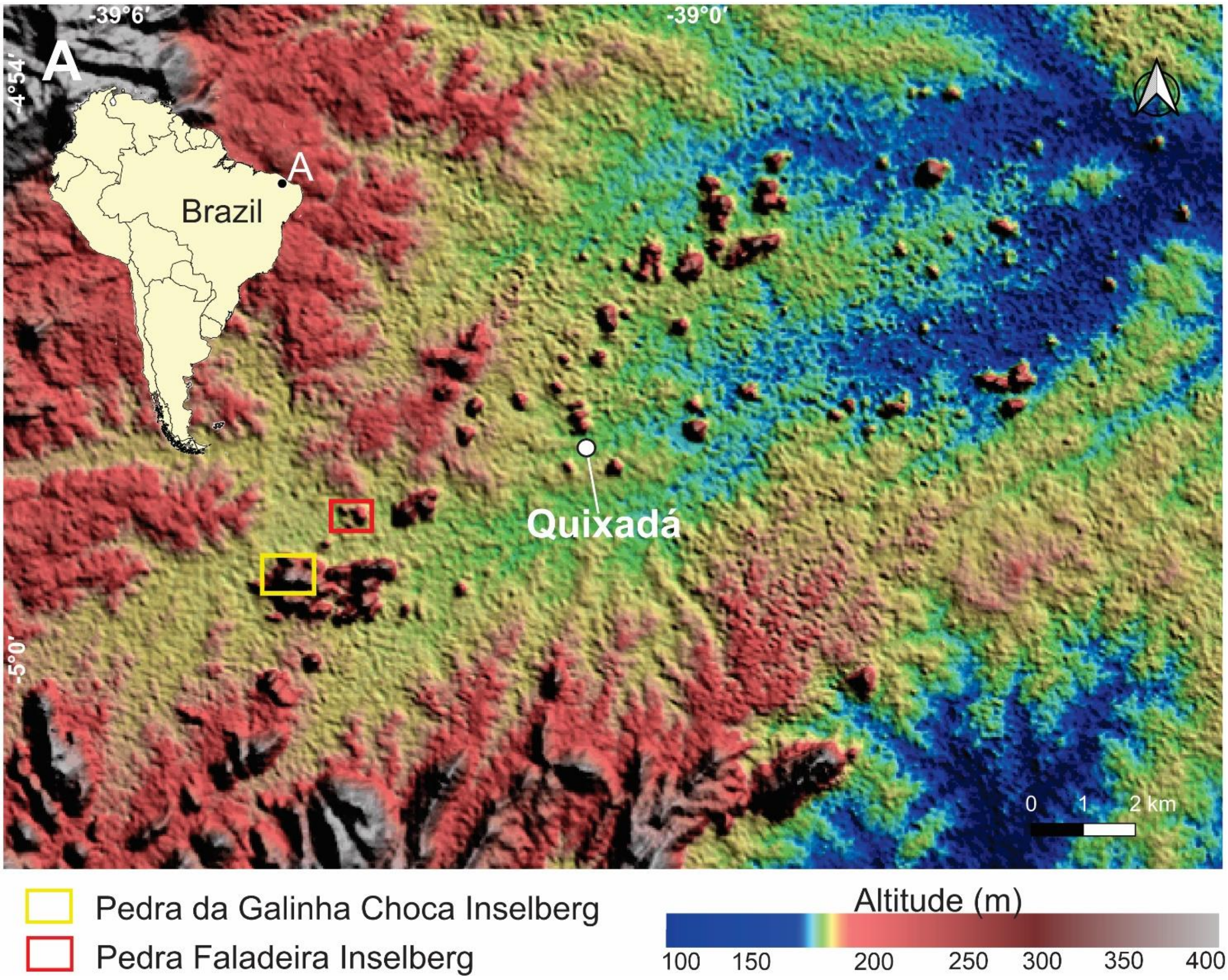

Figure 1. Digital elevation model of the study area, which encompasses the Quixadá inselberg field, in Central Ceará, Northeastern Brazil, near the city of Quixadá. The rectangle indicates the localization of the Pedra da Galinha Choca Inselberg (yellow) and Pedra Faladeira Inselberg (red). Source: Elaborated by the authors.

The inselbergs are situated in the northern part of Borborema Province, whose structure was inherited from the Neoproterozoic Brasiliano Orogeny (640 – 570 Ma), responsible for the conformation of shear zones. The configuration of these structures was followed by ubiquitous granitic plutonism, one of the main characteristics of the Borborema Province (Almeida et al., 2000). Among the neoproterozic granite bodies is the Quixadá Pluton (585 Ma) (Nogueira, 2004), classified as Itaporanga Intrusive Suite, composed of amphibole-biotite granodiorites, monzogranites, sienogranites, alkali-feldspar granites and quartz- monzonites, generally coarse-grained and with porphyritic texture (Pinéo et al., 2020).

The Quixadá Pluton has approx. 260 km ^{2} and is predominantly composed of the Quixadá Facies or Monzonite Facies - monzonites to quartz-monzonites, of porphyritic texture with microcline megacrysts immersed in an amphibolitic groundmass (Torquato et al., 1989; Almeida, 1995). Mafic microgranular enclaves of dioritic to quartz-dioritic composition are abundant and constitute a second petrographic type associated with the Quixadá Facies (Silva, 1989). These rocks are also intensely crosscut by syn-plutonic felsic dykes mainly of granitic to granodioritic composition, which exhibit low dip angles (Almeida, 1995; Silva, 1989; Nogueira, 2004).

Similar to other granite landforms in Northeastern Brazil, the Quixadá inselbergs present a geomorphology inherited from the differential weathering driven by lithological and structural aspects (Maia et al., 2015; Maia and Nascimento, 2018; Maia et al., 2018; Rodrigues et al., 2019; Lima and Corrêa-Gomes, 2015). Considering the morphological diversity of inselbergs at the local scale, this work is based on the classification of Maia et al. (2015) which categorized the inselbergs in Quixadá according to their morphogenetic character and the influence of faciological properties on the erosional features. The authors (op.cit.) distinguished: inselbergs dominated by solutional features (Type 1), marked by the occurrence of karren and gnammas, usually related to mafic portions of the rock; inselbergs dominated by fracturing (Type 2), featured by fractured slopes, collapsed blocks and talus deposits; and massive inselbergs (Type 3), which present a domical shape, cohesive and continuous slope, without or with limited development of solutional forms.

In the studied area, several inselbergs present slopes shaped by collapse and rockfall; for this work two landforms in the southwest portion of the Quixadá inselberg field were chosen as they are typical examples of these process: the Pedra da Galinha inselbergs (PGC), where a more detailed analysis was carried out regarding the structural configuration and its relationship to the morphological attributes of the inselberg, and the Pedra Faladeira inselberg, which is ~1.5 km from the PGC and presents a similar geomorphological context (Figure 1).

It is worthwhile to note that the PGC was pointed as a fracturing inselberg, type 2 (Maia et al., 2015) and constitutes one of the most expressive landforms in terms of area and height in the pluton (Migon and Maia, 2020). The inselberg Pedra da Galinha is marked by a complex outline due to the intersection of vertical and large surfaces of rock exfoliation (Migon and Maia, 2020); in addition, it is noticeable the incipient development of solutional feature and its extensive talus slope, aspect that contributed to their definition as a fracturing inselberg (cf. Maia et al., 2015).

3. Materials and Methods

The methodology in this work consisted of bibliographic revision, fieldwork and elaboration of digital models through aerophotogrammetry. The bibliographic revision allowed us to collect data on the typical granite landforms, particularly inselberg, and on the structural factors reported as controlling the morphology of rock slopes in granites and in other lithologies. Revision of bibliographies concerning the relation of structural aspects and the stability of fractured scarps. The aerophotogrammetric survey was carried out in the fieldwork using an Unmanned Aerial Vehicle (UAV) (Phantom 4Pro – DJI), covering the area of the Pedra da Galinha Choca inselberg. This procedure was performed according to the photogrammetric acquisition protocol, adapted for the context of inselbergs (Figure 2). The survey was carried with nadir photos taken with frontal and lateral overlap of 70%, oblique photos (45°) and horizontals in specific parts where more detail is required. The data were processed in the Metashape Agisoft PhotoScan using the Structure from Motion algorithm (SfM), allowing a generation of a detailed model (18.1 points/m²) of the morphological and textural characteristics of the inselberg slopes.

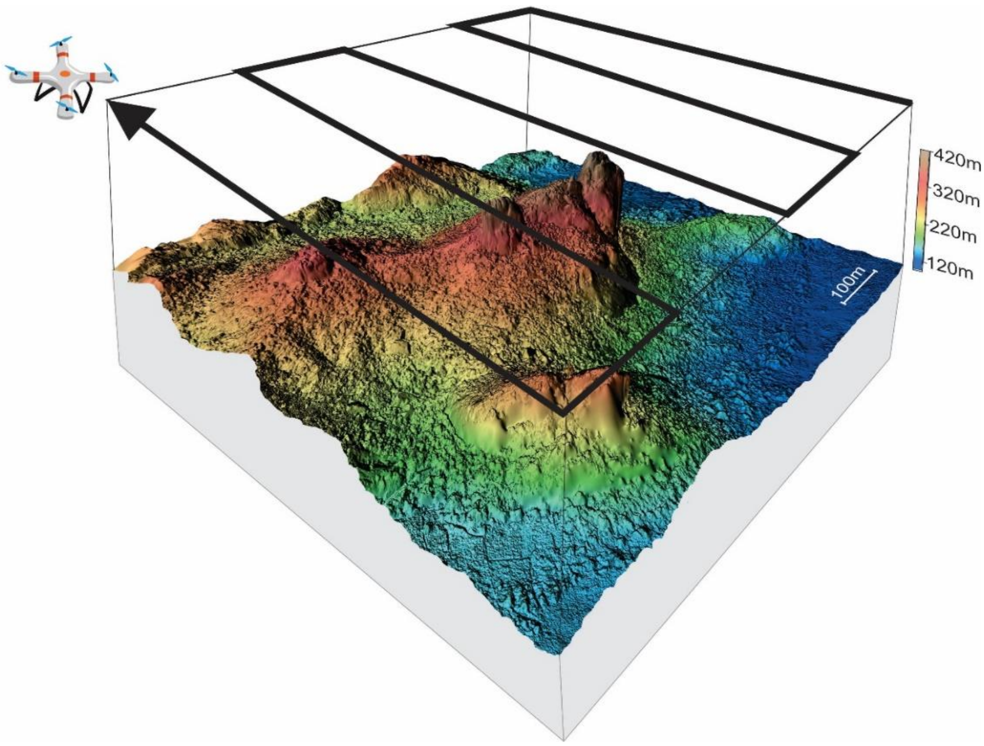

Figure 2. Aerophotogrammetric acquisition protocol for the generation of orthomosaic and digital elevation model of the inselberg. Source: Elaborated by the authors.

The Digital Elevation Model and the orthomosaic (23.5 and 7.2 cm of resolution, respectively) allowed the elaboration of the map of structural lineaments of the Pedra da Galinha Choca Inselberg, through the manual extraction of linear features, including fractures and dykes, in the GIS platform (QGIS software 3.16). The high resolution of the images enables detailed identification (sub-metric features) of fracture sets. As a product of the mapping still on the SIG environment, a rose diagram of the lineaments' preferential orientation was generated using the Rose Direction Histogram. It is important to cite that the point cloud of the inselberg, with a ca.20 cm resolution, manipulated in the Cloud Compare software, functioned as a support to the lineament extraction, since it permits the tridimensional visualization of the relief and their detailed structural features, bringing an advance in the limited data acquisition on 2D images. In addition, measurements of joints parallel to the surface of the inselberg were taken, using the tool Point Picking on the Cloud Compare, by which two points are selected in the 3D model and the distance is computed. These data were important in defining these types of structures as sheet joints (classified as those with thickness >30 cm) (Migon, 2006).

From the point cloud, data on the fracture angles were also extracted (12 measurements) using the tool Virtual Compass>Plane tool, in which a virtual plane is positioned on the surface of the fracture plane in the 3D model, and the dip angle and dip direction are measured; for this study, only the dip angles were computed to analyse the arrangement of multidirectional fracturing. Generally, the horizontal fractures were defined as those <45°, and vertical those > 45°.

In order to elaborate a lineament density map of the PGC inselberg, a 10 m x 10 m grid was generated in GIS software, from which a line count in each cell was computed =, based on the lineament previously mapped. For this purpose, the Intersection algorithm allowed the extraction of the overlapping parts of the features in each layer (lineaments and grid), to unite the attribute of both. Following, the lineament count in each cell was performed by vector analysis, with the algorithm Statistics by categories, by which a table is obtained with a column named "Count". After this stage, the grid layer is joined with the statistic layer (Properties> Union). For better visualization on the map, the algorithm Centroid was applied from the grid layer, generating a new layer, in which the count data are united in the centroids. Therefrom it was possible to interpolate the data (IDW), generating raster data, in which the sample points are weighting of sample points, providing a gradational visualisation from the minor to the major counting value. Based on this data, a false-colour was applied in five categories of equal intervals, to discriminate the following lineament densities: very low/low/medium/high/very high, correspondent to the counting of 1-3/3-6/3-9/9-12/12-15 lineaments/10m2, respectively.

From the digital elevation model of the PGC inselberg, a declivity map was elaborated, using a colour palette to distinguish the declivities in equal intervals of 0-20°; 20-40°; 40°-60°, and 60-80°. This product allows to analyse the morphometric aspects of the slopes in relationship to the structural configuration of the inselberg. In addition to this, large collapsed blocks (LCB) on the talus ramp were mapped based on the orthophoto. The LCB were defined as those rock fragments with angular edges and minimum dimensions of 5m x 5 m. The measurements of their diameters were made on the QGIS software using the tool Line. The distinction between collapsed blocks and in situ boulders – which also occur in this area – was done by field recognition and based on previous descriptions of granite features. Thus, boulders were differentiated from the collapsed blocks mainly because the former usually exhibit a rounded shape as a consequence of spheroidal weathering acting on the edges and commonly hold minor features such as karren and weathering pits (Twidale and Bourne, 1976), contrasting with the sharp edges of blocks resultant form slope failure.

In the Pedra Faladeira inselberg, the analysis of structural features and identification of collapse forms in the scarp was carried out based on drone images and fieldwork. Therefrom, it was possible to recognize particular geological features, such as metric dukes. The observations in this area were used as a comparison with the more detailed analysis of the PGC inselberg since they are situated in a similar geological and geomorphological context.

4. Results

Considering that fracturing inselbergs are those whose slopes are marked by brittle disintegration (type 2 inselbergs of Maia et al., 2015), it was verified that the Pedra da Galinha and Pedra Faladeira inselbergs, Quixadá, CE (Brazil) present morphological features that attest to the processes of mechanical breakdown, namely: sharp slope outlines resulting from rockfall due to fracture propagation, and talus deposits adjacent to c=the cliffs (Figure 3).

These morphological features arising from fracturing, commonly found in sandstones and quartzite rocks (Young et al., 2009) are also displayed in granite rocks. In these, it was noted that fracture propagation tends to occur along intrusive bodies (e.g., veins) and as a result of erosive processes inherent to the exhumation of the granite body (unloading joints). This structural predisposition to fracturing created a context for the disintegration and collapse of blocks, as will be shown herein.

Figure 3. Pedra da Galinha Choca, predominantly constituted of fracturing features: steep slopes with sharp outlines and talus deposit. The altitude data indicated in the figure were extracted from the digital Elevation model of the PGC obtained by aerophotogrammetry. Source: Elaborated by the authors.

The structural lineament analysis in the Pedra da Galinha inselberg allows us to verify that the fracture set displays an NE-SW preferential orientation (Figure 4). This trend is mirrored by the slope morphology, mostly seen in the alignment of both peaks of the inselberg. The lineament density reveals that the high- very high fracture count (9 to 15 lineament/10 m2) occupies a larger area in the NE segment, whereas the SW segment has fractures concentrated in one sector of the slope. This is likely due to the fact that in the NE sector, the lineament density is related to the intersection of vertical and horizontal fractures, a similar context observed in the NW portion (see red areas in the map). On the other hand, the lineament concentration in the SW portion of the inselberg is due to the presence of sheet joints, which separates large parts of the slope with thicknesses between 7 m and 9 m, which are not fully detached and are still connected to the slope (see pre-collapse blocks in Figure 6). In the central part of the inselberg, the high densities are a response to the presence of fracture parallel to the slope as well, with a thickness of ca. 2 m, and probably result from the exhumation and unloading of the granite pluton.

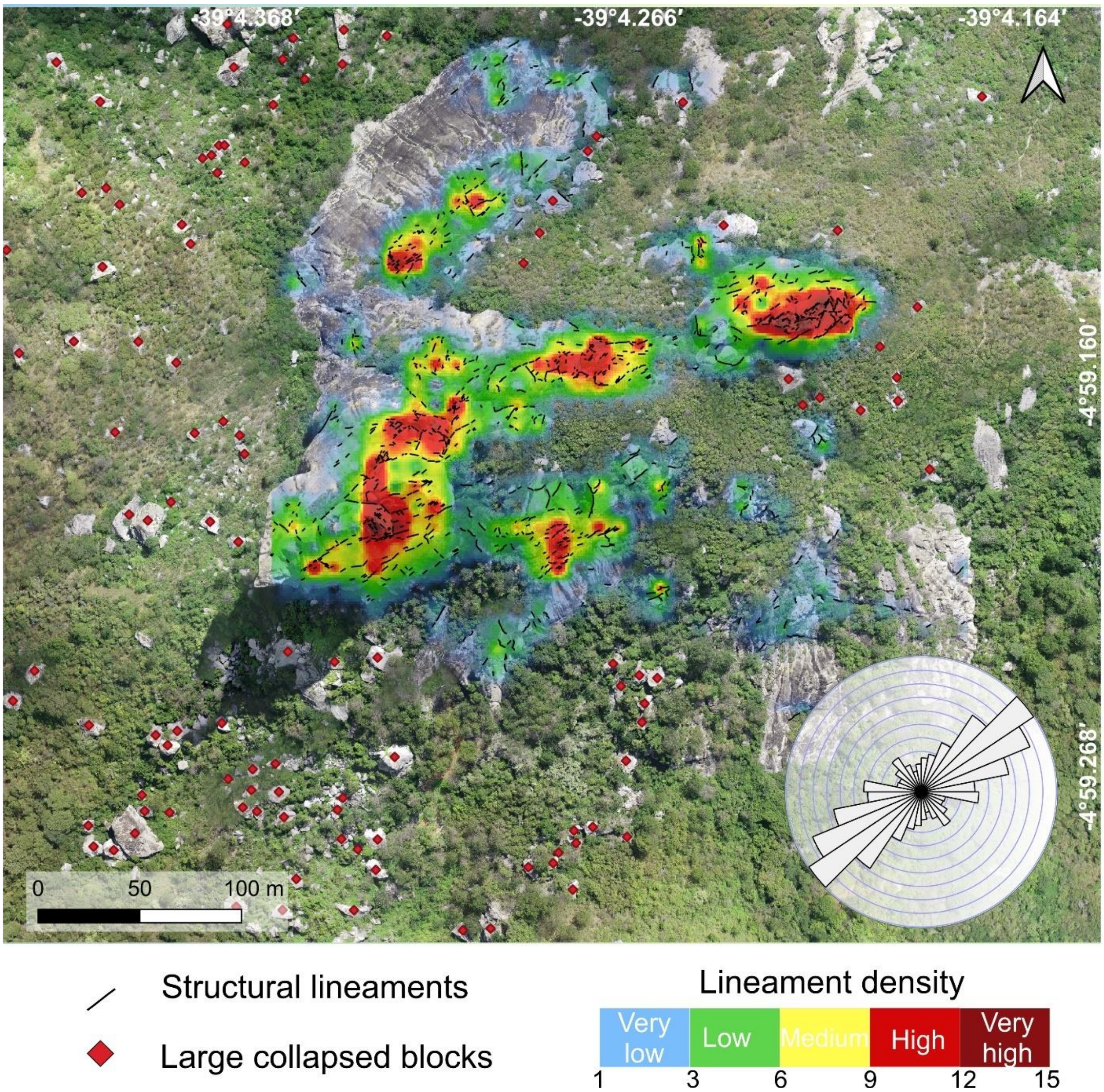

Figure 4. Aerophotogrammetric mosaic of the Pedra da Galinha inselberg with structural lineaments (Fractures) and distribution of large collapsed blocks in the talus ramp. The rose diagram indicates the preferential orientation of the lineaments. The value attributed to the lineament density corresponds to the lineament count for each 10 m². Source: Elaborated by the authors.

The mapped structural features include extensional fractures and fractures along centimetre-thick dykes. It is important to note that the low angle of dike plunges in the analysed area (8°-34°) makes their identification in the nadir visualisation to be always parallel to the slopes. The other fractures, as observed in the fieldwork and by 3D model assessment, are vertical (angles varying from 66° to 80°). The vertical fractures can either intersect horizontal fractures or to be parallel to the steep slopes (>60°) (Figure 5).

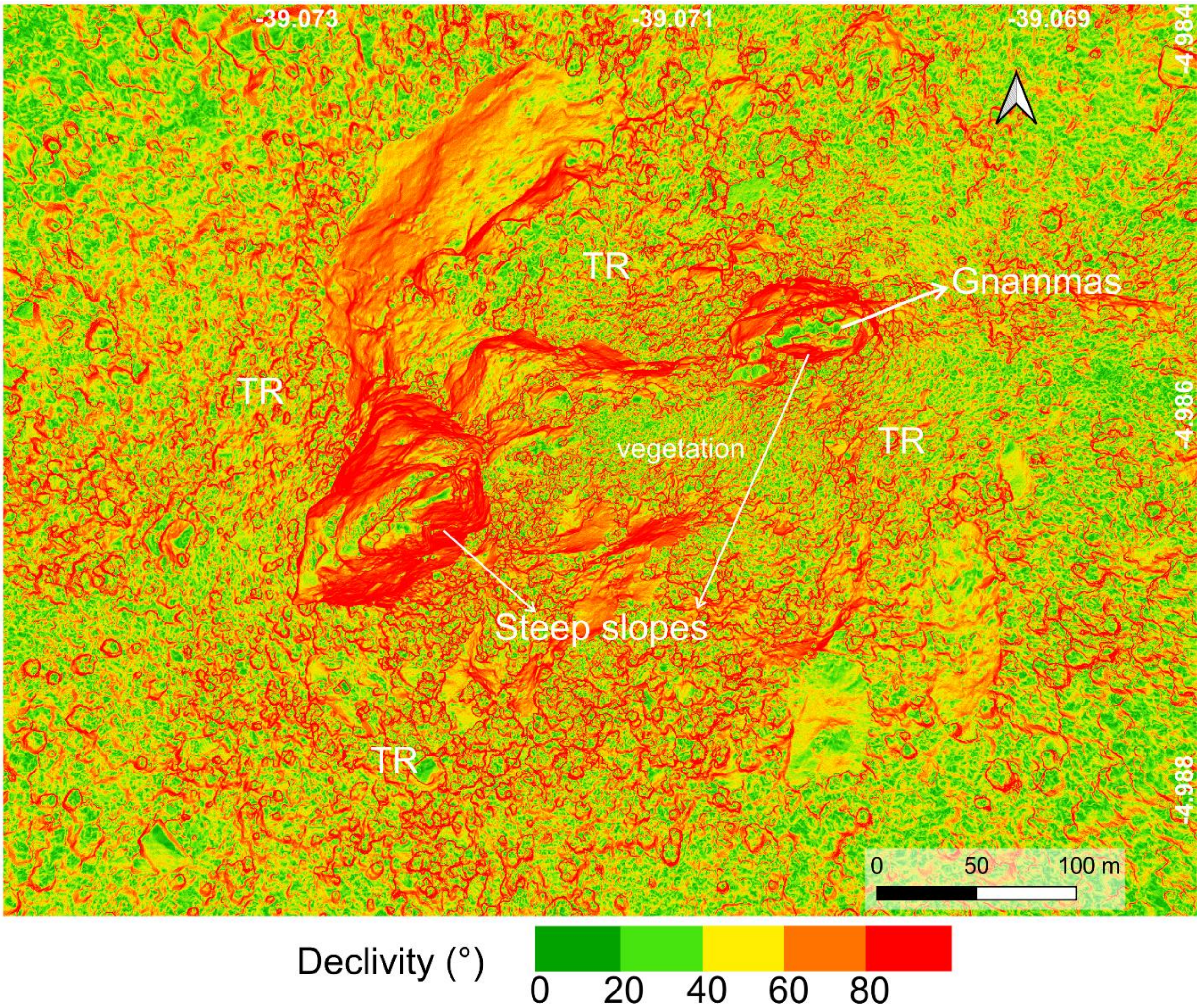

Figure 5. Declivity map of Pedra da Galinha Choca inselberg, Quixadá, Brazil. The parts with low declivity correspond mostly to the talus ramp (TR) or to vegetated areas, while sectors with declivity above 60° represent the inselberg slopes. On the top of the peaks with lower inclinations, features such as weathering pits (gnammas) occur. Source: Elaborated by the authors.

The fracture arrangement along structural planes (dykes and veins) combined with that generated by vertical fractures and unloading joints form a network of multidirectional fracturing in the inselberg slope, favouring the gradual block collapse. This process is attested by the widespread presence of large collapsed boulders (with dimensions varying from 5 m x 5 m to 29 m x 14 m), mapped mainly near the more densely fractured scarp – medium to high density (see Figure 4), as expected since they tend to provide more rock fragments for the talus deposit. It is noticeable that the sectors that most produce blocks for the talus tend to be covered by it; sometimes these areas tend to present lower declivities (20 – 40°) (note TR in Figure 5). It must be observed that in the central part of the inselberg the low declivity is due to the presence of a dense vegetation, not corresponding to talus deposits. On the narrow low inclined surfaced on the peaks of the inselberg, on the other hand, concentrate features derived from solutional processes of the granite, such as weathering pits (WP) (gnammas) with diameters around 2 m.

The steep slopes (>80°) in turn can be massive, when the intersection between horizontal and vertical fractures is less frequent and, therefore, the production of blocks is limited, favouring the maintenance of their height. The sectors SW and NW are examples of this situation, where the fracture intersection is rather localized. On the other hand, the scarp can present an arrangement in which horizontal and vertical fractures crosscut each other more frequently, providing a structural context for the detachment of blocks from the slopes. In this context, however, the blocks stay *in locu* while the structural setting composed of a dense network of horizontal and vertical fractures allows for the interlocking of blocks. This configuration permits the slope to remain with a high declivity notwithstanding the presence of this fracture sector, such as is observed in the sector NE of PGC. The maintenance of joint-bounded blocks in the scarp can be characterised as a pre-collapse phase (see PCB, Figure 6A) and results from the interlocking effect, generated by the multidirectional fracturing. Examples of this disposition occur in Castle Koppies.

When the blocks collapse from the slope, they tend to leave cavities that can form tafoni, in this case, generated exclusively from the rockfall. This form on the scarp attests to the effects of the geomorphological evolution of rock masses that undergo brittle disintegration. For instance, it is observed a collapse tafone (CT) with dimensions of 20 m x 30 x in one of the Pedra da Galinha peaks (Figure 6A). The scarps dominated by collapse features are usually associated with a talus ramp (TR) composed of large collapsed blocks (LCB), of metric to decametric dimensions and sharp, preserving the fracture planes that promoted their detachment from the scarp. More rounded blocks also occur near the cliffs, but, on the other hand, they are likely boulders isolated in situ.

In Figure 6B, it is possible to observe how the structural arrangement on the inselberg slope is related to the development of mechanical disintegration features. In this context, the setting of fracture planes provides a predisposition to the isolation of blocks, and the features testify to the rockfalls.

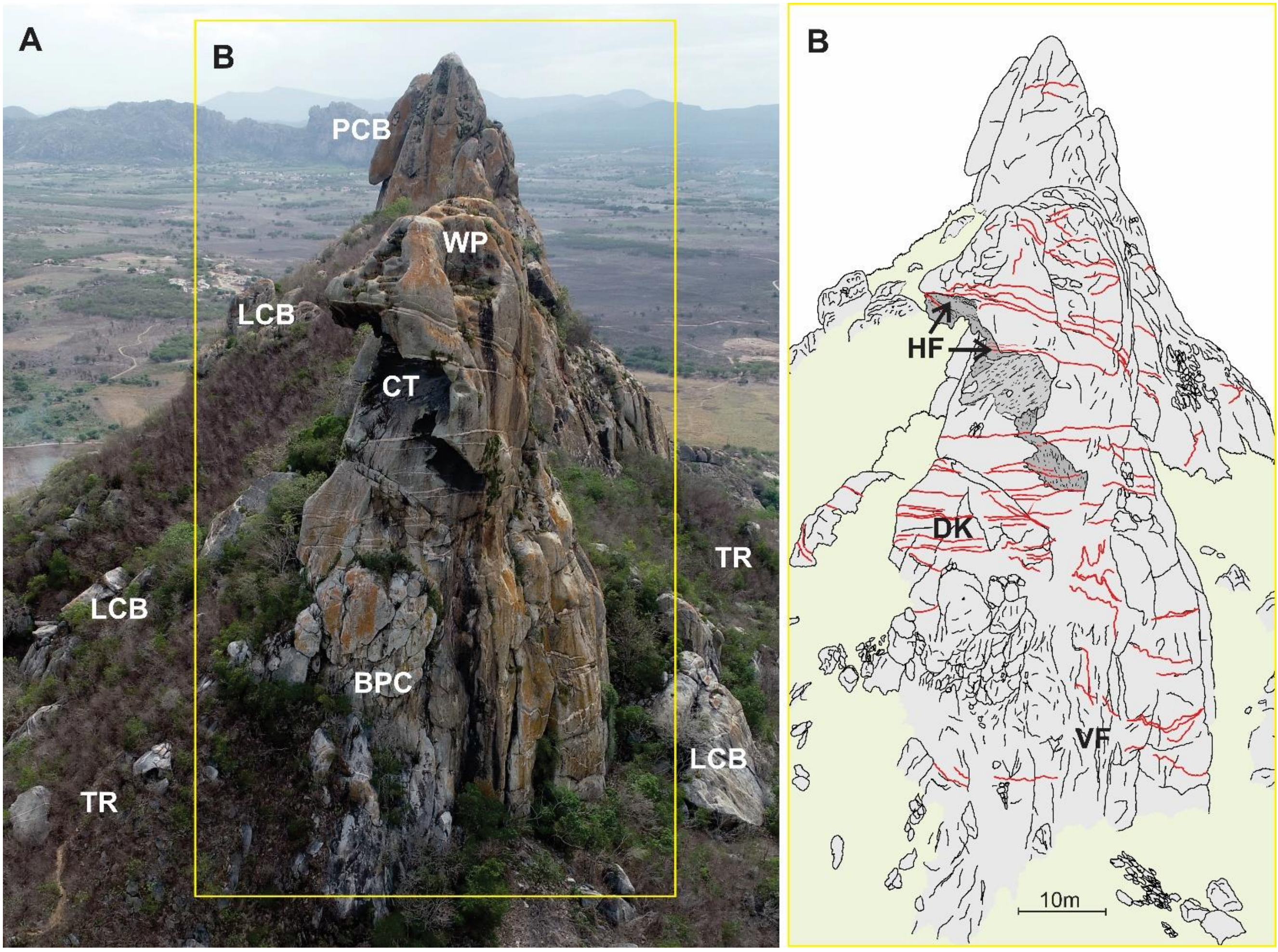

Figure 6. Typical features of fracturing inselbergs (Pedra da Galinha Choca – Quixadá, CE): (a) Landform features associated with collapse processes. PCB: Pre-collapse block, LCB: Large collapsed block, TR: Talus ramp, CT: Collapse tafoni, WP: Weathering pits; (b) Identification of structures on the scarp. HF: Horizontal fractures, DK: Dykes (red lines), VF: Vertical fractures. Source: Elaborated by the authors.

The Pedra Faladeira is an inselberg 30 m high and is approx. 1.5 km to the northeast from the PGC and exhibits fracturing features and large block detachment, mainly due to vertical fracturing. The inselberg has a vertical and massive rock slope, with rockfall scars (RS) parallel to the slope (Figure 7A), which indicate the failure plane. The dimensions of the large block on the talus near the scarp allow us to visualize that the fracture spacing prior to block detachment was of metric dimension. Similar to the PGC, the angular shapes of blocks attest to their derivation from collapse; boulders, in contrast, were not observed in this sector.

Furthermore, an increase in fracture spacing and consequent generation of smaller rock fragments arising from LCB is observed. Figure 7B shows that angular blocks undergo mechanical disintegration particularly in relation to a metric dyke (whose contact is indicated by the red dotted line). Which presents roughly parallel vertical joints (red arrows). These fractures propagate in one of the block's axis promoting their split and generating smaller fragments.

Figure 7. Oblique view of the Pedra Faladeira inselberg with structurally influenced rockfalls. (a) Inselberg with features of rockfall scar (RS) suggesting the failure plane of blocks. The large collapsed blocks (LCB) on the cliff talus; (b) LCB with a higher fracture spacing given the presence of a dyke (DK), whose contact zone is indicated by the red dotted line; the dyke presents fractures and generated smaller fragments (red arrows). Source: Elaborated by the authors.

5. Discussion

Fractures are among the key factors in guiding the geomorphological evolution of many landforms, whose morphology attests to the geometry and pattern of brittle structures (Ericson et al., 2005). In the analysed inselbergs, we observed a network of brittle structures, in which dykes and fractures of varied geometry intersect, promoting the formation of features associated with fracturing and collapse. It has been stated that the fracturing and resistance of a rock mass with dykes/veins are primarily due to the orientation of these structures, which control de fracture mode (Turichshev and Hadjigeorgiou, 2017). On the PGC inselberg, dykes with main low-angle orientations promote fracture planes according to their geometry, constituting an arrangement of horizontal fractures. This is on account of the rupture that occurs preferentially along dyke-rock interface, a fracture configuration predisposition for dykes or veins relatively more resistant than their host rocks (Shang, 2020), as in the observed instances, where dykes are silica-rich (Almeida, 1995).

In granite rocks, the textural variability can be a favourable factor to fracture propagation in the microscale. Eppes (2022) has pointed out that intergranular fracturing is favoured in porphyritic rocks, such as those observed in the study area encompassed by Quixadá Pluton (Almeida, 1995). On the Pedra da Galinha and Pedra Faladeira inselbergs, beyond the textural aspects and the fracturing along dykes, there is a wide occurrence of slope-parallel fractures which may arise from the unloading of the granite body or in response to gravitational stress (Hencher et al., 2011). The development of these fractures is typical during the exhumation of granitic bodies, and they can vary from centimetre-scales (slabs) to a few metres of thickness (sheet joints), generally superposing to preexisting structures (Migon, 2006). In this regard, authors maintain that the presence of fracture in diverse scales, and particularly the latter (sheeting joints), promotes and accelerates the overall erosion, as they constitute the locus for concentrated chemical and mechanical weathering, leading to a progressive fracturing until reaching the critical state for collapse (Vidal Romani and Twidale, 1999; Hencher et al., 2011; Eppes, 2022). Therefore, on steep slopes, the fracture plane of sheeting joints is usually the failure plane of rock blocks (Sted and Wolter, 2015).

Fracture networks formed within igneous bodies from their early stages of crystallization to their exhumation were demonstrated to be significant to the evolution of slope morphology. In this respect, Chigira and Kato (2023) and Chigira (2021) suggest that different sorts of fractures including the intersection of joints, dykes and conjugated pairs of vertical fractures render predisposition to the evolution of towers and pillars in granites. Similarly, the peaks of Pedra da Galinha have been described as towers (Migon and Maia, 2020), owing to their geometric morphology resulting from the intersection of multidirectional fracturing. Thus, the structural configuration of various fracture systems can lead to the delineation of geometric shapes in the relief, which preserves the pattern of pre-existing fractures.

Several examples of fractured scarps on granitoid rocks display a fracture pattern similar to that observed on the Quixadá inselbergs. Multidirectional fracturing has been also reported in landforms such as Dedo de Deus (RJ, Brazil), where an evident structural control by vertical fractures on a macro scale and by fractures in different angles promoted the maintenance of a pillar (Fernandes et al., 2010). On inselbergs, the landform evolution guided by fracture networks was argued for one of the most elevated inselbergs in the world with steep slopes – Spitzkoppe (Namib) (Migon, 2010).

In the Northeast of Brazil, landforms bulti of porphyritic granitoids with a wide occurrence of felsic dykes such as the inselbergs on Açude Gargalheiras (RN) (Figure 8A) and Pedra da Caveira (PB) (Figure 8B) (Dantas et al., 2021). In these areas, fracture patterns preferentially along dykes and unloading joints are abundant and the slope outline reveals processes of mechanical disintegration, including large talus deposits and collapse tafoni. Likewise, Migon and Maia (2020) described collapse features associated with sheet joints and vertical fractures on the Pedra da Boca site, where is located the inselberg on Figure 8B.

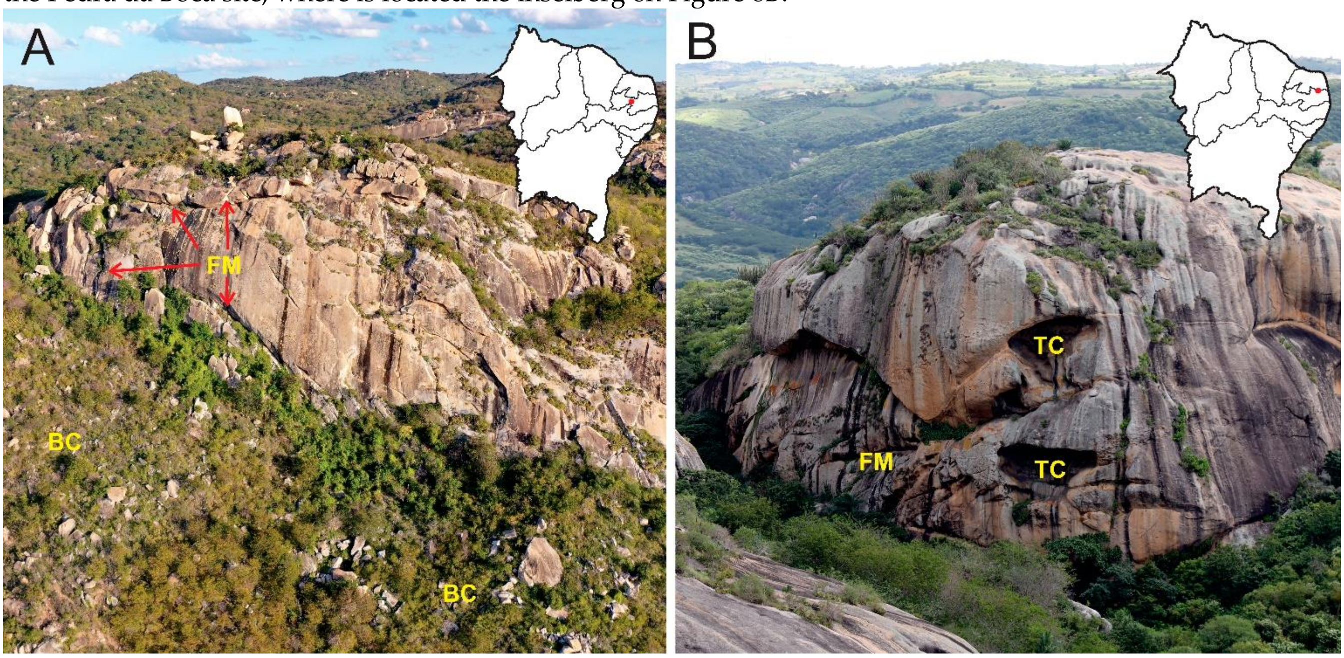

Figure 8. Fractured slopes underlain by granite rock of Itaporanga Suite (granitoids of porphyritic texture) – the same lithological unit of the study area. Note that the collapse features are similar to those reported in this study. FM: Multidirectional fracturing, BC: Collapsed blocks on talus cliff, TC: Collapse tafone. (a) Scarp of an inselberg in Açude Gargalheiras (RN). (b) Pedra da Caveira inselberg (PB). Source: Elaborated by the authors.

Based on the analyses of the typical joint and fracture pattern in granite landforms with fractured slopes in the study and in other places in the brazilian northeast, similarities in the structural configuration generating collapse features have been observed, as proposed hereafter (Figure 9). The existence of low-angle dyke swarms (D) creates a pattern of horizontal parallel anisotropies, which causes the fractures along the dyke-rock contact surface to form a vertical stacking pattern (1). Associated with this system, the vertical fractures (VF) intersect the horizontal ones (JF), promoting block detachment in places, which keep *in locu* while they are interlocked (2). The rockfall from the slope (3), in addition to leaving a cavity behind, also leaves a hanging area, leading gradually to an upward collapse (UC), a process that results from the lack of support given the block removal underneath (4). Concerning the interlocked blocks, Krabbendam et al. (2022) argued that the irregular fracture network caused by the intersection of discontinuities within the rock occasions the isolation of blocks in a pattern named “interlocking fractured pattern”, in which the blocks are bounded by interconnected fractures which confer resistance to the rock mass, retarding the disintegration of the relief. Therefore, this pattern can be interpreted as efficient in maintaining steep slopes and scarps, although fractured.

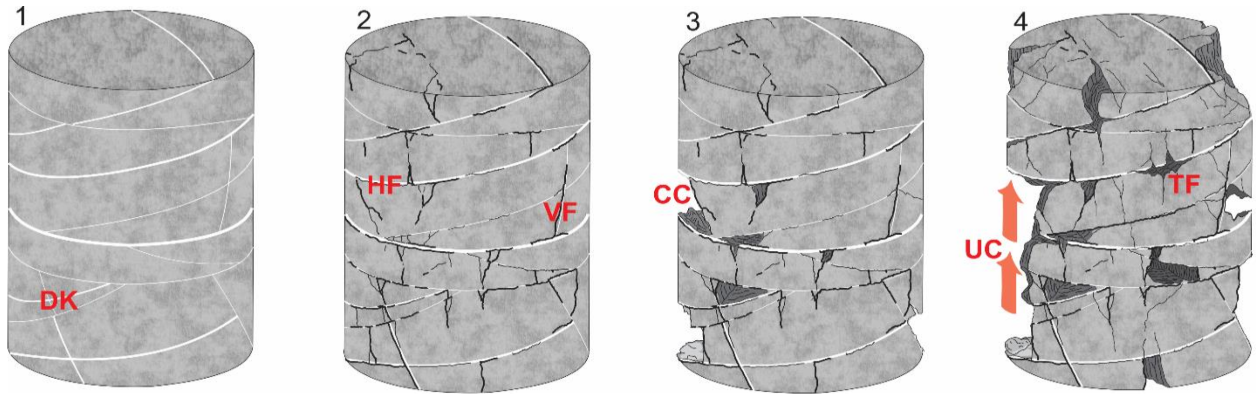

Figure 9. Sketch representative of the development of collapse features arising from the cross-cutting of horizontal and vertical fractures. Stages 2,3 and 4 show the process of disintegration of the rock mass, formation of tafoni and the consequent production of blocks. DK: Dykes. HF: Horizontal fractures along dyke planes, VF: Vertical fractures, CC: Collapse cavity, UC: Upward collapse, TF: Tafoni. Source: Elaborated by the authors.

During the processes of evolution of scarps by collapse or rockfall, the isolation and block detachment can be triggered by tectonic or recent climatic processes. Regarding the latter aspect, Collins and Stock (2016) demonstrated that the detachment of rock slabs parallel to cliffs can be fastened as a function of daily variation in heating and cooling of the rock surface (thermoclasty), such that they promote a progressive deformation and separation of the sheet joint, and ultimately their collapse.

Considering that fracturing and collapse constitute erosive processes particularly common in steep slopes/scarps (Matasci et al., 2015), the manner in which they occur in the relief can be assessed through their resulting features. For instance, a talus ramp attests to the structural configuration that propitiated the rockfall and accumulation of block in a massive, as concluded by Verdian et al. (2021). In the Pedra da Galinha inselberg, the adjacencies of the sector with higher fracture density on the slope (medium-high) tend to be areas of greater block accumulation on the talus, as demonstrated by the lineament analysis and mapping of LCBs (see Figure 4). Similarly, Lee and Dan (2005) pointed out a correlation between instability of slopes and fracture occurrence, from the mapping of lineaments.

Despite the morphological configuration of the PGC inselberg being marked by fracture and block collapse, it differs from other inselbergs characterised by fracture networks. For example, nubbins are typical inselbergs formed by blocks and boulders isolated due to the arrangement of fractures and joints on a granite body, and castellated inselbergs also display a morphology that results from an orthogonal fracture pattern (Twidale, 1981). Nonetheless, they are distinct from the inselbergs observed in the study area since those do not maintain steep, and defined continuous slopes because the erosion was once guided by the structural setting isolating blocks, which stand in situ.

In this context, boulders seen on nubbins tend to display a rounded shape, as an inheritance from probable weathering action under regolith (Migon, 2006). The rocky blocks that arose from the rockfall on PGC, in turn, present an angular aspect and tend to keep the characteristics of the slope fracture pattern. That is to say, their dimensions evidence the fracture spacing on the slope (Verdian et al., 2021). The pre-collapse blocks (PCB) that are gradually isolating from the scarp due to the multidirectional fracturing can be related to the latent sediments (op. cit.), meaning that they are portions of the scarps that will compose the larger fragments in the talus during the process of evolution by rockfall. Hence, according to the authors, the fracture spacing defined the initial fragment size of the large collapse blocks.

Aside from the collapsed blocks, other slope features attest to the structural control, such as the collapse tafone (CT), observed in the NE peak of Pedra da Galinha. Although solution and chemical weathering are acknowledged processes in the widening of cavities (Mellor et al., 1997; Huang and Wang, 2017), tafoni are polygenetic features. It was recently demonstrated that brittle structures and discontinuities in granites control the formation or initiation of cavities on rock slopes (Maia et al., 2022) and that these forms tend to maintain the orientation and dimensions of fracture planes that control their formation (Eppes, 2022). In the case of inselberg whose morphology is predominantly marked by mechanical disintegration, mechanisms such as upward collapse allow for block detachment along fracture planes, forming cavities directly associated with collapse.

Keeping in mind that complex arrays of discontinuities in the rock reduce the integrity of rock mass and favour the rockfall (Brideau et al., 209), we propose here that the evolution of fractured inselbergs occurs from the control generated by different sorts of brittle structures which guide erosion and favour the destabilization of the emerging scarp. An important factor for fragmentation and block detachment from slopes and its progressive mechanical disintegration is the presence of through-going fractures (Eppes, 2022), which are persistent fractures that cut across a block capable of splitting it into two parts.

Based on the present observations, it was verified that the intense fracture propagation requires discontinuities that concentrate the various stresses that the rock mass experiences, with tectonic or climatic. Thus, in the early stages of weathering and landform shaping in epigenetic conditions, primary anisotropies inherited from pre-crystallization phases of the granite body, such as systems of dykes and veins and magmatic flow fabrics (even incipient and heterogeneous), will concentrate and drive the selective weathering (Figure 10A) (Vidal Romani, 2008).

With the gradual exhumation of the granite body to the surface and the formation of unloading joints parallel to the surface, the complexity of the structural setting and the fracture intersection increases. As a result, the collapse of blocks is proportional to the degree of fracturing, and talus deposits are formed adjacent to slopes. Given the slope instability relative to intense mechanical disintegration, the steep slopes of inselbergs do not display well-developed solutional or chemical-weathering-related features (e.g., gnammas and karren), which demand certain stability to evolve. In this stage, the fracturing and rockfall promotes scarp retreat (Migon, 2006) (Figure 10B).

In more advanced stages of the evolution of fractured scarps, these tend to give place to a talus slope, which is not only a sector of the inselberg at this point but constitutes the ultimate morphology derived from the intense mechanical breakdown (Figure 10C).

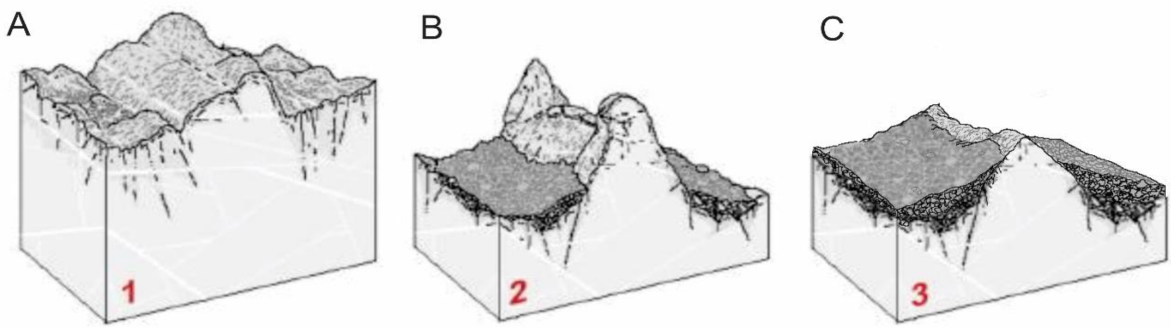

Figure 10. Schematic evolutionary model for fracturing inselbergs (type 2): (a) Phase 1 – the erosion reaches a zone of different orientations of dyke and fracture planes. (b) The steep and angular morphology of inselberg slopes results from the structural setting generated by dyke sets and unloading joints. (c) The progressive fracturing and collapse produce blocks that compose the talus ramp, which evolves and characterises the most advanced stage of mechanical disintegration. Source: Elaborated by the authors.

6. Conclusions

Scarps characterised by multidirectional fracture networks, talus ramps, and incipient development of solutional features evidence the preponderance of block collapse processes as the primary morphogenetic element. It was verified that these processes, when occur in granite rocks, result from fracturing along dyke/veins planes, sheeting joints (parallel to the surface) and vertical fractures, which tend to reduce the integrity of the rock mass leading to a progressive mechanical disintegration.

Inselbergs marked by fracturing features, such as the Pedra da Galinha Choca (Quixadá, NE of Brazil), were observed to display a structural setting similar to those reported in forms such as pinnacles and towers, usually supported by an array of multidirectional fracturing and whose shape evolves by catastrophic erosive processes (related to collapse). Moreover, it is possible to conclude that this propensity to erosion mainly driven by fracturing and block detachment, common in diverse lithologies, is favoured in coarse-grained granite rocks, in which intergranular microfractures auxiliary the propagation of persistent fractures.

Therefore, we propose that the structural control on the evolution of fractured inselbergs occurs once the intersection of fractures derived from past tectonic process and exhumation of the granite body promotes, on the one hand, the interlocking block pattern on the slope, which stays steep and maintaining the structural configuration. On the other hand, the progressive erosion along discontinuities provokes instability of the slopes, which tend to be shaped by collapse features. Collapse blocks on the scarp adjacencies form, in turn, wide talus deposits, which attest to advanced stages of mechanical weathering.

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