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Research Article

Origin and evolution of solutional features on granitic inselbergs

Origem e evolução de formas de dissolução em inselbergs graníticos

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Abstract: Inselbergs are landforms shaped by a number of erosion processes. They can be characterized either by a predominance of dissolution features or fracturing and occasionally exhibit massive slopes. In this study we demonstrate the main structural mechanisms driving the formation of dissolution features, such as gnammas. In granitic rocks, mafic ellipsoidal enclaves can act as a starting point for differential erosion. The enclaves and their orientation control the early stages of dissolution features (ellipsoidal microcavities and gnammas). In the Pedra do Cruzeiro inselberg, located in Quixadá, northeastern Brazil, 99 enclaves were analyzed in a 230m SW-NE transect on the inselberg slope. The data show that the primary trend of enclave orientation (86E on average) coincides with the orientation of the majority (97%) of dissolution features in their first and second stages. In advanced erosion phases in which mega karren are developed, they are not solely controlled by preexisting structural patterns, attesting to the superimposition of the surface runoff of the inselberg over the structure (e.g., magmatic foliation and mafic enclave orientation).

Keywords: Inselberg; Karren; Gnamma; Mafic enclaves.

Resumo: *Inselbergs* são formas de relevo modeladas por diferentes processos erosivos. Por vezes, predominam feições de dissolução, por vezes, de fraturamento e, em alguns casos, exibem escarpas maciças. Neste trabalho, serão demonstrados os principais mecanismos estruturais que levam à formação de feições de dissolução, tais como *gnammas*. Em rochas graníticas, enclaves elipsoidais máficos podem servir como ponto de partida para erosão diferencial. Os enclaves e sua orientação, condicionam os primeiros estágios (microcavidades elipsoidais e *gnammas*) da formação de feições de dissolução. No *inselberg* Pedra do Cruzeiro, em Quixadá, Nordeste do Brasil, foram analisados 99 enclaves, a partir de um transecto de 230 m a NE-SW na escarpa do *inselberg*. Os dados mostraram que a direção preferencial dos enclaves (86E em média) coincide com a orientação da maioria (97%) das feições de dissolução em seu primeiro e segundo estágios. Já nas fases avançadas de erosão, em que mega *karrens* são formados, estes não seguem unicamente padrões estruturais pré-definidos, mostrando a superimposição do escoamento na superfície do inselberg sobre a estrutura (foliação ígnea e orientação dos enclaves máficos).

Palavras-chave: *Inselberg*; *Karren*; *Gnamma*; Enclaves máficos.

1. Introduction

There are notable examples of landscapes shaped in granitic rocks around the world, such as the Spitzkoppe, in Namibia, exhibiting a diversity of forms such as boulders, gnammas, and tafoni (Migon, 2010), the bornhardt Pão de Açúcar in Rio de Janeiro (Fernandes et al., 2010), and the inselberg field in Itatim, Bahia (Lima; Corrêa-Gomes, 2015). Various areas in northeastern Brazil feature granitic reliefs, including inselberg fields that hold significant importance for studies on geomorphological evolution (Maia et al., 2015).

Granitic landscapes are commonly interpreted through the lens of etchplanation models introduced by Büdel (1948, 1982) and later refined by Thomas (1965, 1974), considering landscape evolution as a gradual process involving the exhumation of a plain through multiple stages of deep chemical weathering. In this perspective, factors such as substrate resistance and superficial erosion processes play a fundamental role in shaping subsurface forms (Twidale, 1982).

Features shaping granitic escarpments in inselbergs often exhibit heterogeneous distribution. Some escarpments display more fracturing, while others are characterized by dissolution features. Regarding the latter, the prolonged action of chemical weathering on granitic rocks leads to the formation of various features, including microforms of weathering such as gnammas (dissolution basins, rock basins, or weathering pits) and karren (grooves).

Dissolution basins are rounded concave forms varying both in dimensions and shapes and are not confined to granitic outcrops, being reported in other lithologies as well (Twidale; Vidal Romaní, 2005; Migon, 2006; Travassos, 2019; Lima, 2019). Despite the recognition and description of these dissolution forms in granitic outcrops in various locations (Migon, 2006; Maia e Nascimento, 2018), little has been explored regarding their genesis and the primary conditioning factors of their origin.

Karren, in turn, is a generic term used for referring to dissolution features on exposed surfaces of soluble rocks, typically associated with carbonate rocks but also developing in other lithologies, such as granite. Karrens exhibit a notable variety of forms, including Rillenstaine (microgrooved lapiaz), rillenkarren (grooved lapiaz), and rinnenkarren (grooved lapiaz), covering scales from millimeters to over 10 meters in length (Travassos, 2019). Extensive stretches of sculpted rocks are spread over square kilometers, often displaying a characteristic pattern of grooves and furrows separated by pronounced ridges or crests, standing out in the landscape as karrenfields or lapiaz fields (Ginés, 2009; Travassos, 2019). In this context, the inselberg field of Quixadá in Northeast Brazil presents a diversity of forms associated with chemical rock dissolution, often characterizing most of the inselberg hillslopes (Maia et al., 2015).

In light of this, this study aims to identify and analyze the structural and faciological factors guiding the formation of dissolution features (particularly gnammas) in granitic inselbergs. For this purpose, the Pedra do Cruzeiro inselberg in Quixadá (CE, Brazil) was chosen for analysis, defined as an inselberg characterized by dissolution features (Maia et al., 2015) due to the widespread occurrence of these features on its escarpments.

2. Study area

The inselberg field of Quixadá is located in the homonymous municipality, 200 km from the capital of the state of Ceará in Northeast Brazil, and exhibts a semi-arid tropical climate, with average temperatures around 27 ºC (INMET, 2014). The rainfall regime is characterized by irregularity, with an annual average precipitation of approximately 700 mm and rainfall concentrated in the months of March and April (INMET, 2014; Maia et al., 2015; Maia; Nascimento, 2018).

The study area is situated within the geological context of the Quixadá Pluton (Figure 1), a neoproterozoic intrusion linked to the Brasiliano cycle (±560 Ma – 60 Ma). The Quixadá Pluton is comprised by the Itaporanga intrusive suite (Pinéo et al., 2020), composed of monzonites, monzogranites, quartz monzonites, and syenites. There is also a significant occurrence of two subfacies in the pluton: a dioritic facies characterized by mafic enclaves and a granitic facies composed of felsic dikes (Almeida, 1995).

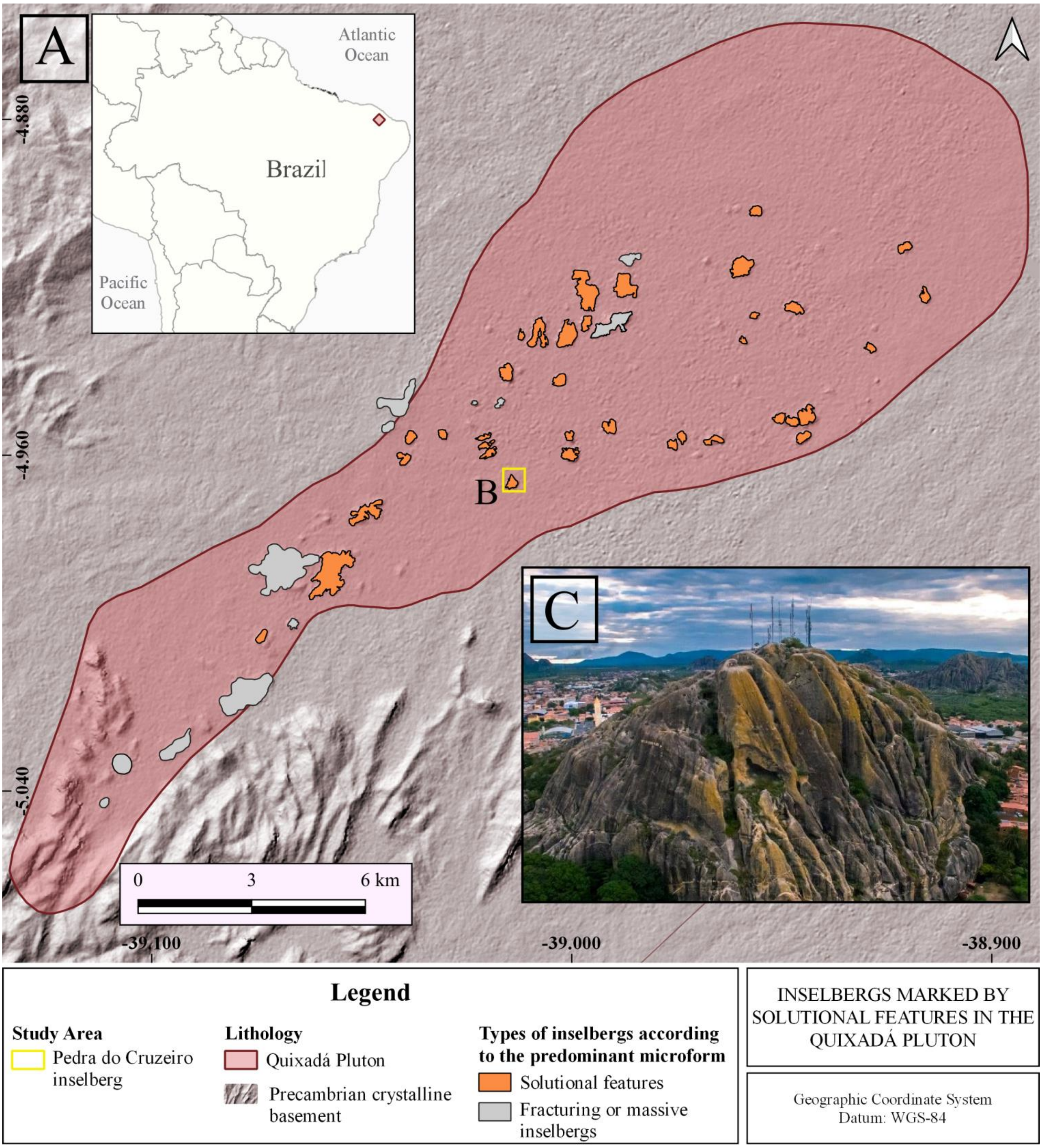

Figure 1. Location map of inselbergs characterized by solutional features in the Quixadá Pluton. A: Location of the pluton and identification of inselbergs marked by dissolution. B: Polygon of the studied inselberg. C: Photograph of the Pedra do Cruzeiro inselberg. Elaborated by the author (A and B); Silva, 2018 (C).

The pluton exhibits a heterogeneous distribution of foliation pattern, characterized by the orientation of feldspar megacrysts and mafic enclaves, predominantly in the NE-SW direction; the degree of magmatic foliation tends to decrease from the country rocks (pluton border) towards the center of the pluton (Nogueira, 2004).

Regarding the geomorphological context, area lies within the Sertaneja 1 Surface, with an altitude ranging from 50 meters to 250 meters and a predominantly flat or slightly undulating morphology (Costa et al., 2020). On the surfaces of some inselbergs in Quixadá, forms resulting from collapse such as talus ramps with the incidence of boulders are common. Moreover, microforms of weathering, such as gnammas, karren, tafone, alveoli, and flared slopes, are also abundant on the hillslopes (Maia; Nascimento, 2018). Considering this diversity of inselberg microforms, Maia et al. (2015) classified inselberg types based on the prevalence of the features, namely: 1 - inselbergs marked by dissolution, referring to the pronounced incidence of weathering microforms; 2 - inselbergs marked by fracturing, due to forms resulting from collapse; 3 - massive inselbergs, identified by a domical shape and escarpments without significant dissection features (Maia et al., 2015).

The Pedra do Cruzeiro inselberg (Figure 1 B) (4°58'S; 39°00'51.7"W) is situated in the center of the city of Quixadá and is considered a type 1 inselberg – marked by dissolution features (Maia et al., 2015); it has a height of 60 meters, with steep escarpments evident in the E and SE portions, and gentler edges in the N and SW portions, the latter being the more commonly used access point to the inselberg

3. Materials and methods

This study was conducted in five stages. The first stage involved a literature review on solutional features in granitic rocks and granitic reliefs in the Northeast and worldwide. The second stage included the acquisition and digital processing of regional data related to the geomorphology and geology of the area. The third stage comprised drone-based photogrammetry of the Pedra do Cruzeiro inselberg and the subsequent digital processing of the acquired data. The fourth stage involved fieldwork to collect geomorphological and geological data on the inselbergs. In the fifth stage, the collected primary and secondary data were organized and analyzed. Details and procedures for each stage are presented below.

First stage: The theoretical foundation was established based on theoretical definitions of topics related to the geomorphology of magmatic rocks, granitic reliefs, inselbergs and their characteristics, and dissolution features in granitic bodies. This foundation drew upon the works of Twidale and Vidal Romani (2005), Migon (2006), Sgarbi (2012), Neves (2012), Lima (2019), Maia et al. (2015), and Maia; Nascimento (2018).

Second stage: Geoprocessing and digital processing of ALOS-PALSAR satellite images were conducted using QGis 3.14.16 software to associate georeferenced data with the topography of the area and the distribution of inselbergs within the study area.

For the third stage, detailed imaging of the Pedra do Cruzeiro inselberg was performed using a Phantom 4 Pro drone at a manual flight height of 120 meters. The captured image, with dimensions of 4000 x 3000 px and a resolution of 72 dpi, was mapped based on classifications established by Twidale and Vidal Romani (2005) and Migon (2006) to identify karren and gnamma dissolution features in detailed scale. This mapping aimed to measure the distribution of these forms and the water flow direction in flow features, generating cartographic material.

The fourth stage involved field visits to recognize patterns and characteristics of inselbergs in Quixadá, particularly those characterized by dissolution features. In the analyzed inselberg (Pedra do Cruzeiro), a transect was defined from which the identification and characterization of microforms, petrographic aspects, and structural features were conducted. The procedure included the basic description of the granite outcrop and the abundant mafic enclaves in the area. A total of 99 mafic enclaves were sampled, including macroscopic descriptions of the outcrop (texture and coloration) and structural data (dimension and orientation of the largest axis of elongated enclaves).

In the fifth stage, analyses of structural data on enclaves and solutional features on inselbergs were performed. Using georeferenced vector information of dissolution features on the surface of Pedra do Cruzeiro and the orientation data of mafic enclaves collected in the field, two orientation rosettes were generated in the Stereonet 11.5.0 software. The first rosette represented the orientation of dissolution features on the inselberg surface, and the second highlighted the preferential direction of the major axis of the mafic enclaves. This allowed for the association of the preferential direction of enclaves with the presence of flow features.

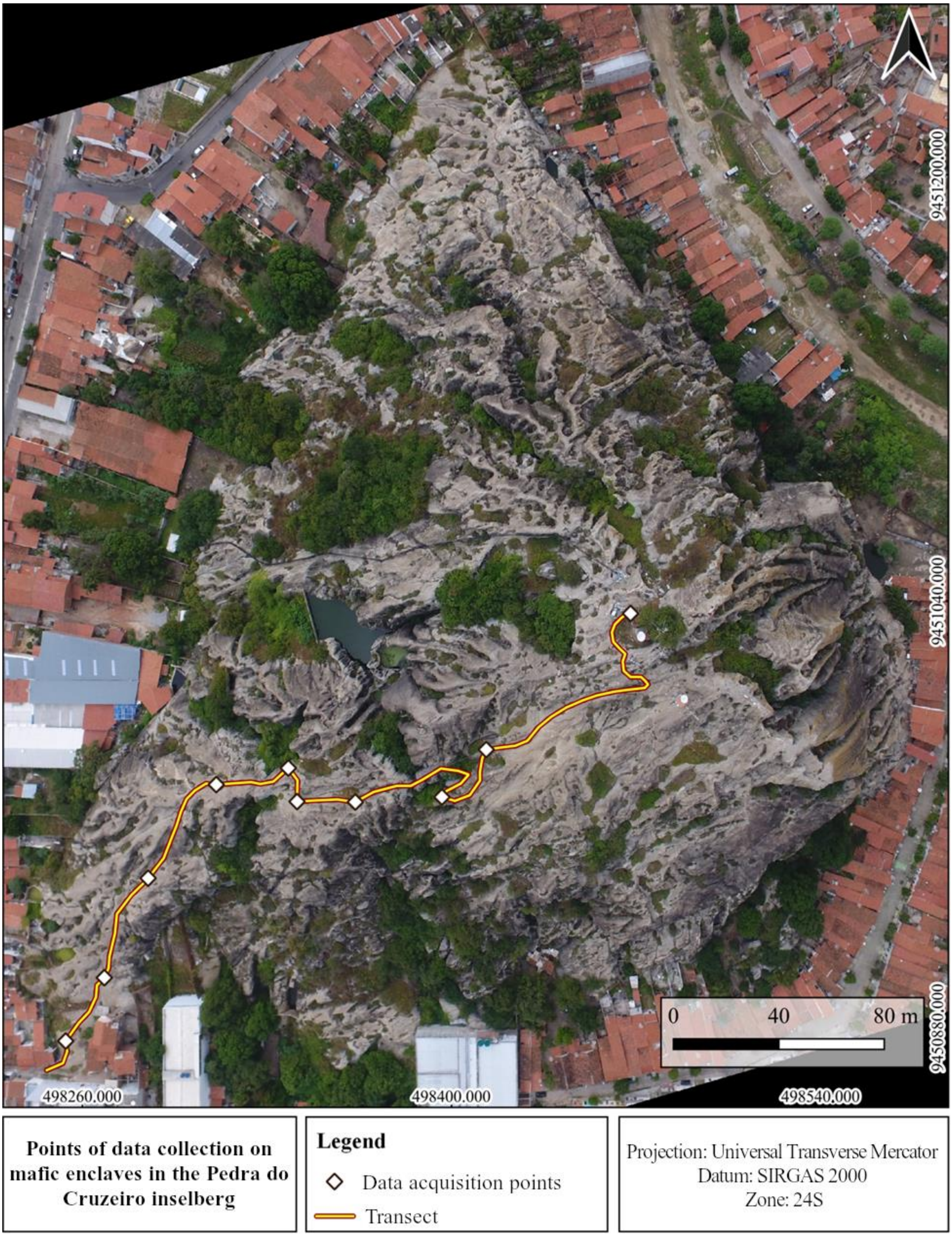

Figure 2. Orthophoto of Pedra do Cruzeiro inselberg with **l**ocation of data collection points on mafic enclaves. Location on figure 1B. Elaborated by the author.

4. Results

4.1. Karrens and gnammas on the Pedra do Cruzeiro inselberg

The Pedra do Cruzeiro inselberg, as well as various inselbergs in the Quixadá Pluton, is characterized by the prevalence of dissolution features (see Figure 1C). These features mostly include gnammas, ranging in size from metric to decametric dimensions, with a circular shape and with or without exutories. They typically occur on surfaces with low slope angles. Additionally, karren, continuous grooves on the escarpments where water flows during rainy periods, are observed. These karren features consist of channels up to 5 meters in width and 3 meters in depth, representing the maximum stage of observed dissolution features. Circular small cavities (alveoli) are also present on the escarpments. All these dissolution features cover 37.5% of the inselberg surface (2.6 ha) (see Figure 3A).

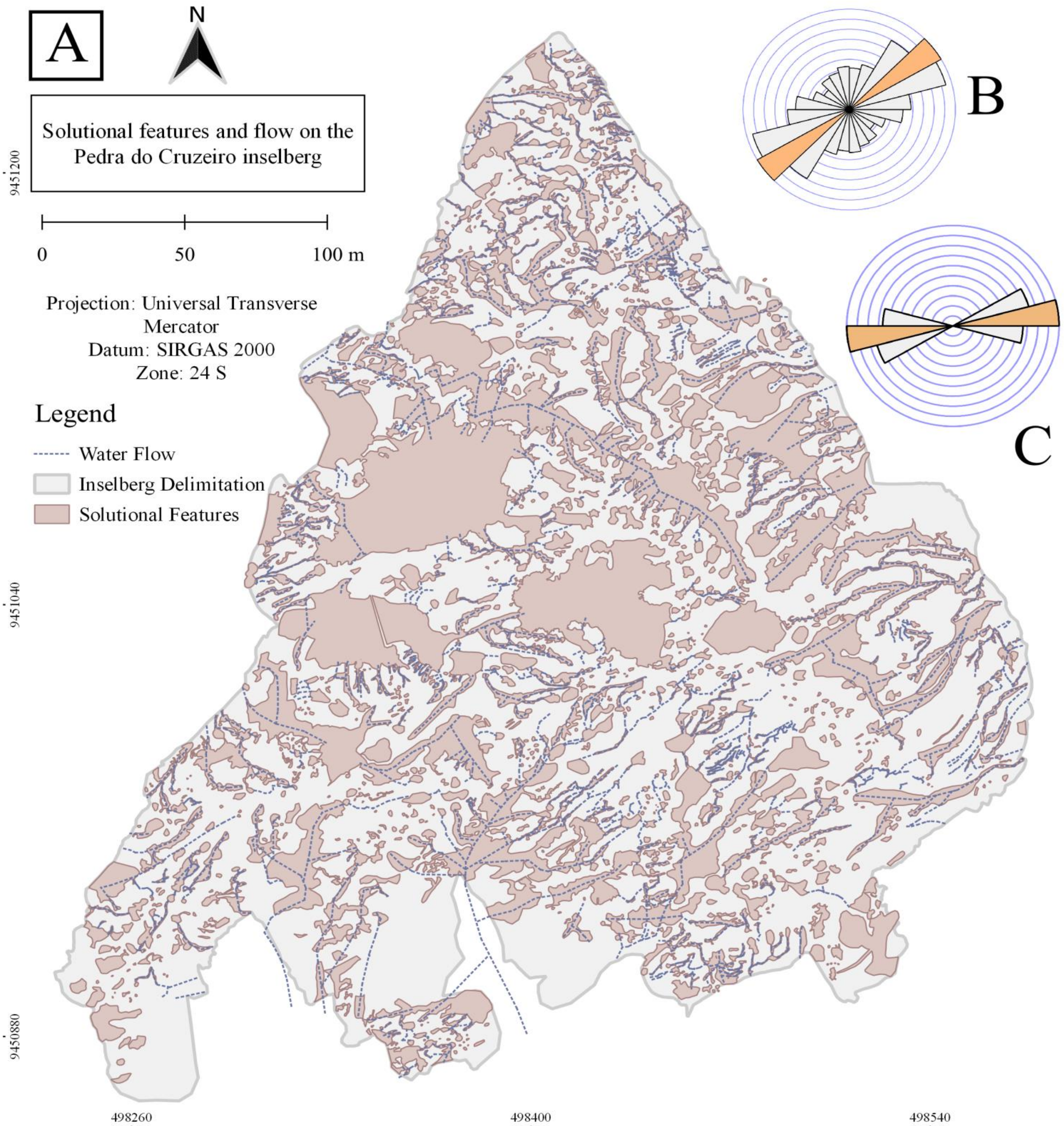

Figure 3. Solutional features and flow on the Pedra do Cruzeiro inselberg. A: Map of the Pedra do Cruzeiro inselberg with mapped solutional feature sand lines of water flow. B: Rose diagram showing the primary direction of flow on the inselberg. C: Rose diagram showing the primary trend of mafic enclaves' longer axis. Location on Figure B. Source: elaborated by the author.

The karren exhibit primary NE-SW trends and secondary E-W trends. Nevertheless, the rose diagram shows that the current flow occurs in all directions, as water flow follows the slope of the escarpments (see Figure 3B). The primary orientation of elongated mafic enclaves on the Pedra do Cruzeiro inselberg is E-W (see Figure 3C). The azimuths collected from mafic enclaves on the Pedra do Cruzeiro inselberg range between 73° and 102°, with an average angle of 86°. The degree of magmatic foliation in the surrounding rock is subtle and variable, occasionally aligning with the orientation of the enclave.

4.2. Enclaves máficos: ponto de partida para a dissolução

Microgranular mafic enclaves are ubiquitous in the Quixadá Pluton. The Pedra do Cruzeiro is an inselberg whose rock hosts these enclaves, which occur both in isolated form (Figure 4A and B) and as swarms (clusters of around 3 to 6 enclaves) (Figure 4C).

In terms of their petrographic characteristics based on hand specimen, the enclaves display mafic coloration (color index above 67%) and may exhibit either a microgranular texture with an aphanitic matrix, where the majority of crystals are not visible to the naked eye (Figure 4A), or a hybrid texture with the occurrence of euhedral feldspar crystals within the mafic matrix (Figure 4B). The contacts with the porphyritic host rock are predominantly sharp, displaying a texture contrast (Figure 4A). In some cases, portions of the contact may be gradational, with interaction between the two facies (Figure 4B).

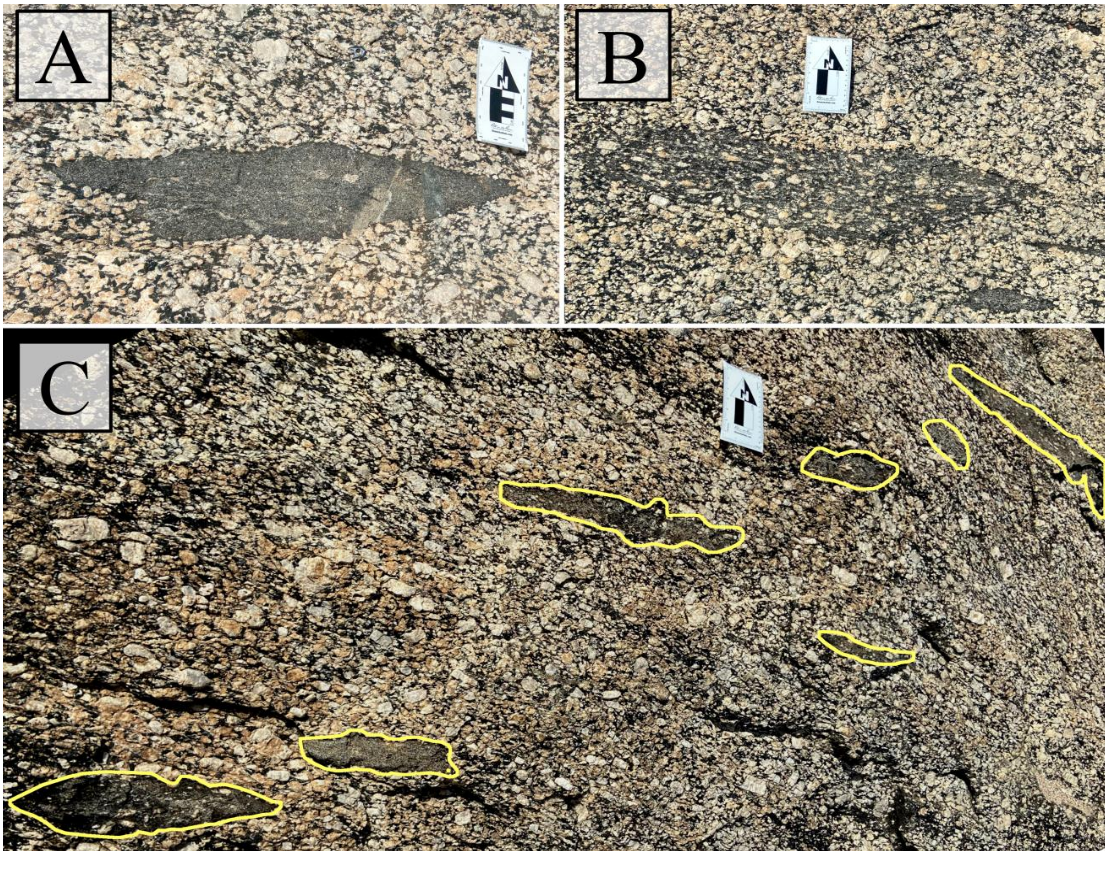

Figure 4. Mafic enclaves on the Pedra do Cruzeiro inselberg. A: Microgranular mafic enclave. B: Hybrid mafic enclave with feldpsar phenocrysts.C: Enclave swarm composed by seven mafic enclaves elongated in the same direction. The limits are defined by the yellow line. Source: Elaborated by the author.

The dimensions of the enclaves vary from 10 x 5 cm to 175 x 30 cm and commonly exhibit an ellipsoidal shape, with elongation along their major axis in the E-W direction. Occasionally, enclaves are observed to be consumed as a result of weathering of their mafic minerals and erosion. In this regard, different degrees of removal/erosion of the enclave in the Pedra do Cruzeiro inselberg were identified and defined: preserved enclave (Figure 4A), partially eroded enclave (Figure 5A and 5B), and completely eroded enclave (Figure 5C). The identification of the latter is possible due to the persistence of its original form on the outcrop surface.

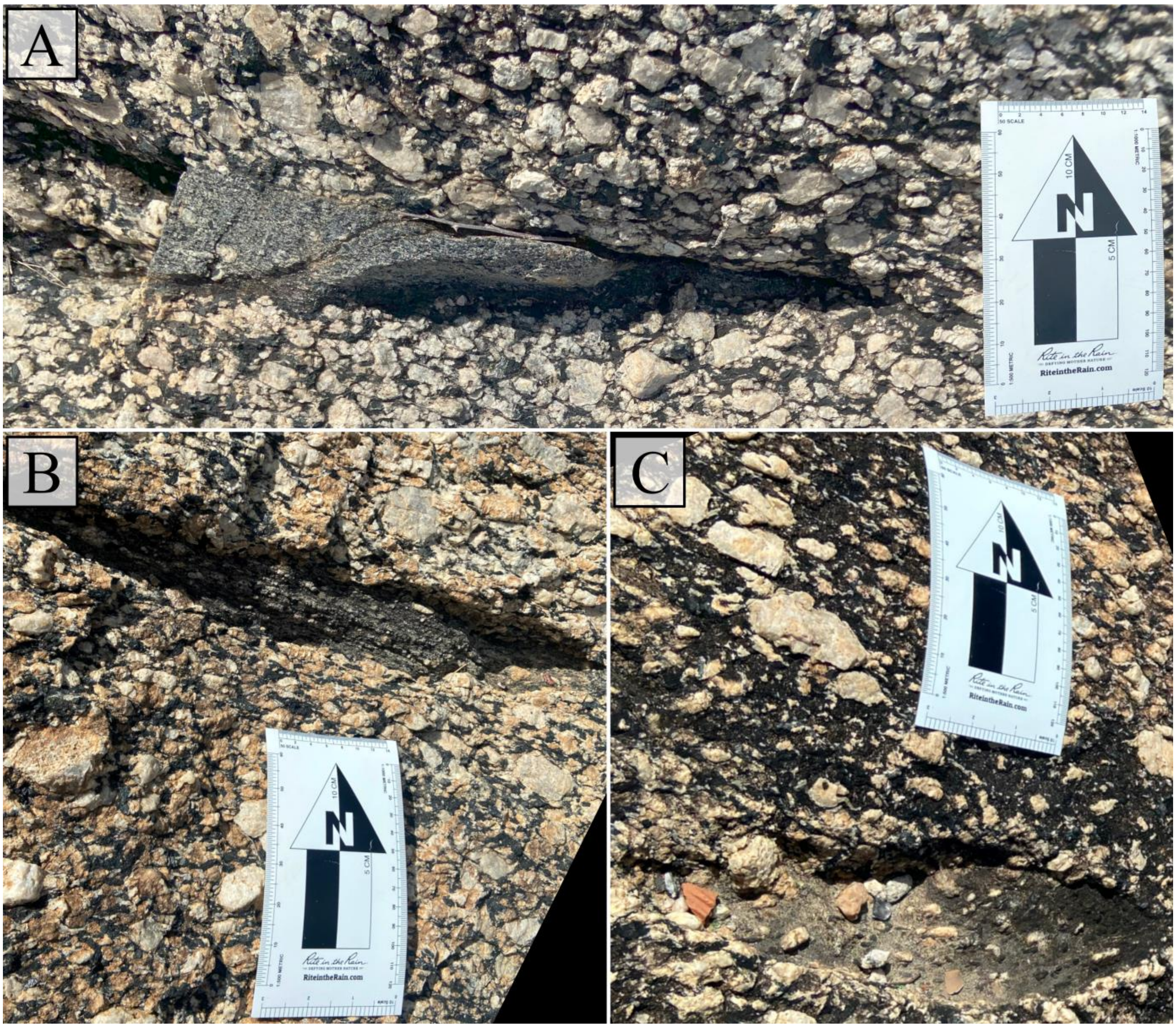

Figure 5. Mafic enclaves in different stages of erosion. A and B: Partly eroded enclave. C: Completely eroded enclave. Source: elaborated by the author.

The erosion of mafic enclaves leaves on the surface a concave dissolution feature of the gnamma type in an early stage of development, whose ellipsoidal morphology and dimension are a more direct result of the shape and size of the source enclave (Figure 5C). In more advanced stages of gnamma formation, it begins to expand, and an incipient weathering mantle is formed inside the cavity, progressively assuming the typical concave shape of the feature (Figure 6). From these observations, it is evident that there is a structural control influence related to the presence of mafic enclaves contributing to the genesis of these forms in their initial stages.

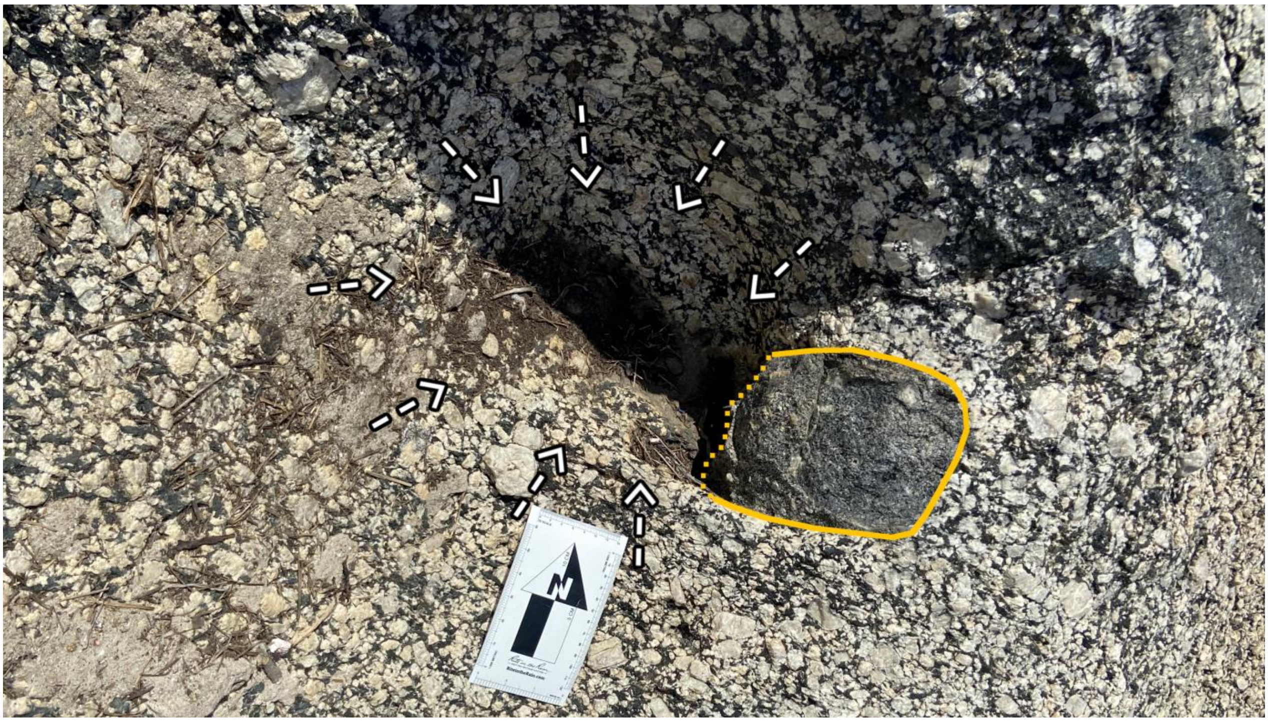

Figure 6. Partly eroded forming a gnamma. The yellow line defines the borders of the mafic enclave, the dotted line indicated the limits of the eroded portion. The white arrows point to concavity of the gnamma. Source: elaborated by the autor.

5. Discussion

Numerous factors can influence the genesis of dissolution features and, particularly, the formation of gnammas in granitic rocks. Commonly the genetic factor is no longer evident in the topography due to weathering and erosion responsible for gnamma formation (Twidale; Bourne, 2018). Factors related to the origin of gnammas include water pooling in small depressions on rock outcrops (Migon, 2006), but the origin of this irregularity on the surface can itself be considered a genesis factor for this feature, associated with positive feedback processes where moisture concentration favors its widening. Regarding the origin of these irregularities in granitic rocks, it is known that mineralogical differences in response to weathering tend to favor differential micro-weathering on the surface, generating an irregular appearance (Helgeson, 1971; Migon, 2006).

In the study area, it was demonstrated that the action of selective weathering on mafic portions of the rock is responsible for the initiation of the dissolution feature formation, as exemplified by the degrees of removal/erosion of mafic enclaves on the Pedra do Cruzeiro inselberg. The presence of partially or fully consumed mafic enclaves – evidenced by the elongated morphology of the enclave preserved on the relief – attests to the preferential action of weathering on portions of the rock with ferromagnesian minerals, which are more susceptible to alteration under surface conditions (Eggleton, 2021). Thus, concavities formed in the granite (initial stage of gnamma formation) preserve the heritage of their formative factor, in this case, the consumed mafic enclaves.

Observations and descriptions of gnammas made by Maia and Nascimento (2018) support the data presented in this study, as the authors point out that gnammas develop from the consumption of mafic enclave in four stages: 1 - partially consumed enclave; 2 - expansion of its axis, forming an ellipsoidal gnamma; 3 - development of a closed spherical-concave gnamma; 4 - opening of an outlet, facilitating drainage; at this stage, it may promote the development of karren. This pattern was verified on the Pedra do Cruzeiro, with a predominance of outlet gnammas and surface runoff.

Karren are also common forms on inselberg escarpments and occur in other lithologies similar to those presented in granite. White (1988) and Goudie (2009) assert that, like limestones and dolomites, sandstones and granites can exhibit a range of forms of different sizes.

In landforms built of carbonate rocks, megakarren develop in tropical areas or in glaciokarst, with development linked to karstification and/or climatic changes, resulting in distinct origins of the same feature in different lithologies (Perica, 2004; Veress, 2019). It is possible to draw parallels between the development of forms and understanding the dissolution factors.

Matias and Alves (2002), in studying the influence of petrographic and environmental factors on the patterns of deterioration and durability of granites in the monuments of Braga, Portugal, highlight that in rocks rich in biotite, medium to fine-grained, often porphyritic, and with the presence of heterogeneous elements (differential erosion of phenocrysts and enclaves), the deterioration process begins. The tectonic foliation of fine-grained leucogranitic stones affects the distribution of fissures, chips, and biological colonization, and it is possible to infer that the process occurs similarly for the formation of karren in the study area, including the presence of carbonic acid, organic acids (humic and fulvic), and nitric acid combined, for example.

Regarding the controls of differential erosion in the formation of solutional features, the presence of fissures was recognized by Twidale and Bourne (2018). Ortega et al. (2014) affirm that the formation of river erosion-related potholes indicates that structural discontinuities, particularly fractures, control the occurrence of these features. In this regard, it can be inferred that the discontinuity generated by the accommodation of the enclave, which has rectilinear edges, favors a point of action for differential weathering (TWIDALE; BOURNE, 2018), and consequently, controls the initiation of gnamma-type dissolution features on Quixadá inselberg surfaces.

Regarding the long-term evolution of forms and considering models of multiple stages in the formation of subsurface features (Thomas, 1965; Migon, 2022; Roqué et al., 2013), as advocated by Büdel (1983), Migon (2006) observes that gnammas in the arid zone of Namibia are much larger than the same features in wetter zones. This may suggest the preservation of these forms in arid climates, preserving tropical climatic conditions where the forms were molded. The same interpretative context can be applied to dissolution features in the study area. The concept of Büdel's (1982) etchplanation has been applied to tropical areas that exhibit seasonality and can support the geomorphological interpretation of tropical environment inselbergs. According to the etchplanation model, during wet periods, there is deepening of alteration, while surface erosion occurs more intensely during dry climate periods, promoting planation and, in some cases, exposing the alteration front (Figure 7).

With this in mind, we propose that the development of solutional features on inselbergs occurs through the following stages: A1 – Formation of the alteration mantle on the basement with igneous foliation and ellipsoidal mafic enclaves; A2 – Dissolution of mafic enclaves in epigenic conditions, forming the first stage of weathering pits; A3 – Concentration of weathering and erosion under the influence of structural and mineralogical factors, allowing widening and gnamma formation; A4 – Advanced stages of the evolution of dissolution forms and the action of water runoff, promoting the coalescence of gnammas and the formation of karren. In evolutionary terms, the removal of the alteration mantle can occur at any of the stages, exposing the forms modeled under the regolith.

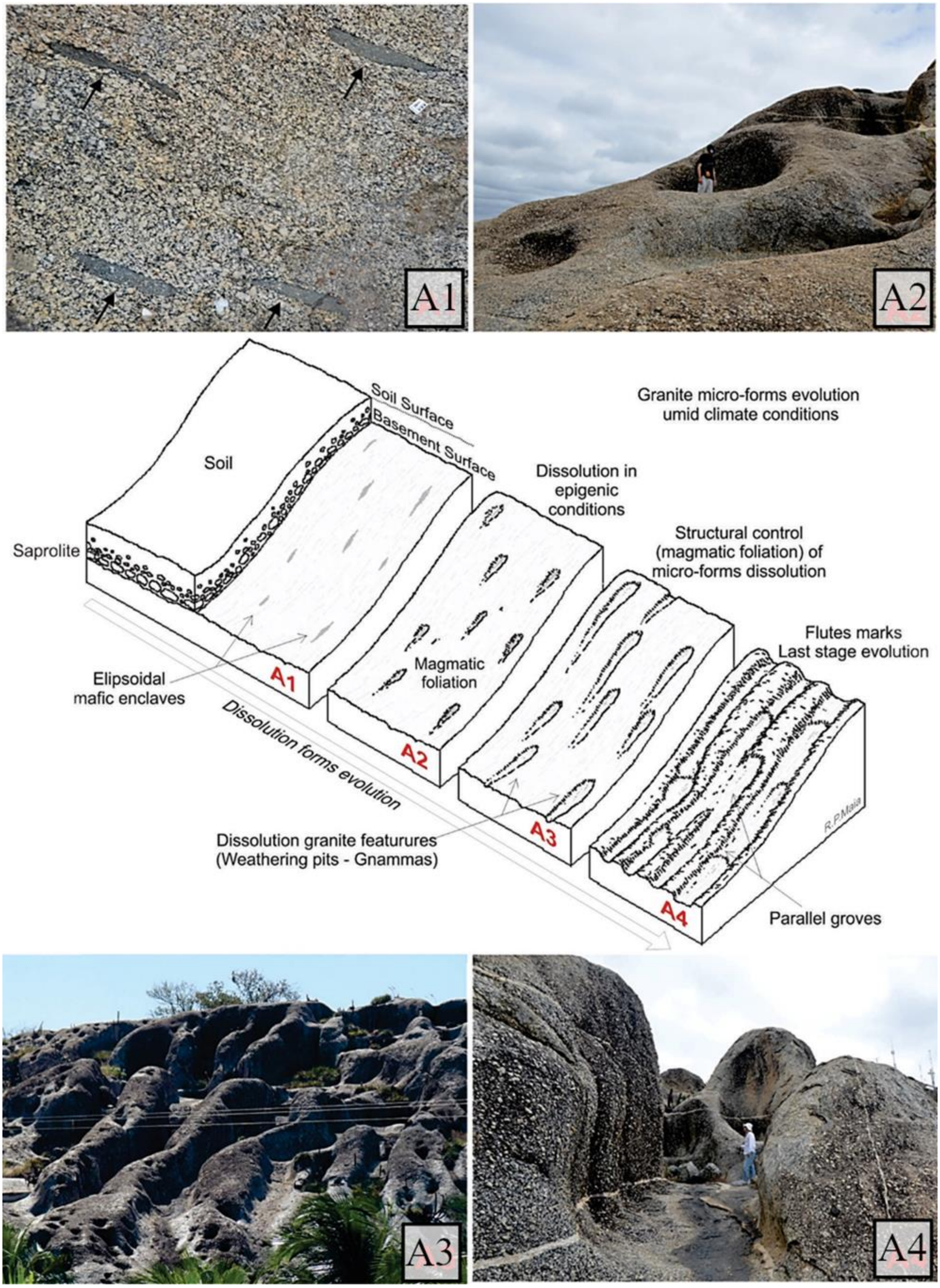

Figure 7. Evolutionary model for solutional features based on multi-stage models (etchplanation), adapted to microforms. The sequence of photographs A1, A2, A3 and A4 illustrate the stages of development of solutional features. A1 – Differential weathering processes under a regolith acting upon a surface with faciological variations. A2 – Formation of gnammas resulting from the erosion of mafic enclaves. A4 – Development of weathering pits following structural control related to igneous foliation. A4 – Coalescence of gnammas and karren formation.

Therefore, it can be considered that the genesis of gnammas is associated with weathering through dissolution, hydration, and hydrolysis, which disaggregates part of the rock, generating fragments and residues that are transported by water, creating a concavity in the form of an armchair that allows for water accumulation and the development of a gnamma (Twidale; Vidal-Romani, 2005). In the field, given more intense weathering actions in mafic enclaves, the erosion of the enclave generates a larger concavity, allowing for a greater development of the dissolution feature. It is also considered that the pattern of dissolution features (coalescence of gnammas and karren) and the pattern of surface water flow do not solely indicate structural control on differential erosion, given the complexity of processes that are continuously operating on granite surfaces

6. Conclusions

The results obtained in this study demonstrate that dioritic enclaves constitute the starting point for the formation of solutional features on granite inselbergs. The ellipsoidal geometry of the enclaves guides the dissolution process, which, in the initial stage, manifests this control in the form of dissolution basins connected by outflows. Thus, the early phases of the dissolution processes exhibit greater control exerted by the shape and orientation of the enclave, commmonly following the plane of igneous foliation.

For the Pedra do Cruzeiro inselberg, the axes of the mafic ellipsoidal enclaves are oriented in the E-W direction. This anisotropy favors an oriented dissection that directs the flow, forming sets of parallel karrens and gnammas. In intermediate and advanced phases of megakarren formation, there is a superimposition of drainage that tends to organize at the inselberg scale with a diffuse centrifugal radial pattern. At this stage, there is no longer a clear structural control over the forms that characterize the inselberg morphology, as evidenced by the variation in drainage orientations, which show a preferential NE-SW trend and a secondary E-W trend. These features (channels up to 5 meters wide and up to 3 meters deep) constitute the stage of maximum development of observed dissolution features.

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