Geoheritage (2020) 12: 51
https://doi.org/10.1007/s12371-020-00473-4

ORIGINAL ARTICLE

Pedra da Boca, Pai Mateus, and Quixadá—Three Possible Key Geoheritage Sites in Northeast Brazil

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Received: 6 January 2020 / Accepted: 20 May 2020 / Published online: 6 June 2020

Abstract
This paper subscribes to the concept of Key Geoheritage Area (KGA) which is currently being developed. Three localities in northeast Brazil are described as possible candidates for KGA. They represent the diversity of erosional granite landscapes found in cratonic areas. Pedra da Boca is an impressive cluster of tall domes rising from the marginal escarpment of Borborema Plateau, with gigantic tafoni. Pai Mateus is located on the Borborema Plateau and consists of a group of low granite elevations (ruware, whalebacks) with residual boulders scattered on their surfaces. These boulders are hollowed out by weathering, providing another very distinctive type of tafoni. Quixadá area is an inselberg landscape, with a few dozens of bedrock hills rising from the plain. Among minor features, karren are ubiquitous. Collectively, these three sites show different types of cratonic granite scenery, a multitude of medium-size and minor geomorphic features, and illustrate pathways for inselberg formation and decay through long-term weathering and erosion. Therefore, they are considered to fit the concept of KGA. In addition, each landscape has considerable aesthetic and scenic values, with great potential for geotourism and geoeducation. Nevertheless, their current conservation status is low and geointerpretation nearly nonexistent and these challenges are to be addressed in the future.

Keywords Granite landforms · Inselberg · Tafoni · boulders · Geoheritage · Geotourism

Introduction

Geoheritage is a well-established, widely recognized concept within science, outreach and conservation which underpins various activities undertaken at regional, national, and international level focused on protection, better understanding of the Earth history, bridging the gap between science and the public, and the development of sustainable tourism. Literature abounds in proposals how to assess geoheritage and geosites (see cf. Reynard 2009; Brilha 2016, 2018b) and whereas the idea of having an objective, transparent system of evaluation sounds very attractive, this is easier said than done. In particular, defining geoheritage of international significance (as opposed to regional or local one) is not an easy task.

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Currently, two global initiatives, both implemented under the umbrella of UNESCO, explicitly address the international significance of geoheritage. These are UNESCO World Heritage, within which areas may be inscribed on the World Heritage List in recognition of the outstanding universal values (OUV) of its geology and geomorphology (Migoń 2014, 2018a), and UNESCO Global Geoparks, which requires from the aspiring geoparks to have "geological heritage of international significance" (Brilha 2018a). Both these global undertakings have their limitations, arising from specific goals for each, and are unable to provide an adequate framework to protect all key geoheritage sites. To this end, another initiative is proposed, to work towards the network of Key Geoheritage Areas (KGAs) which would include localities selected purely on the basis of their significance for geosciences (Ju and Woo 2018; Woo et al. 2018). Thus, KGA do not need to have OUV as defined in Operational Guidelines (2019) neither are required to be in any way related to local sustainable development, particularly geotourism. Accessibility is not foreseen as a key criterion to nominate KGA, although tourist access may increase awareness of the locality. According to the working version of the proposal, KGA will cover various aspects of geosciences, from large-scale tectonic features to small-scale outcrops of global palaeontological, petrological, or mineralogical value. Among them are localities of primarily geomorphological significance. They will contain landforms which for various reasons may be considered globally important and relevant. These reasons may reside in uniqueness, dimensions, completeness of a geomorphic system of a particular kind, an informal role of a type locality played in the history of research (Migoń 2014, 2018b). For relatively common categories of landforms and geomorphic processes, the objectives of KGA initiative would be fulfilled by particularly good examples as the best representatives.

In this paper, we intend to contribute to the KGA initiative by providing examples of three possible key areas from north-eastern Brazil, each characterized by extraordinary geomorphology developed upon granite bedrock. NE Brazil is a cratonic area, dominated by metamorphic complexes intruded by granitoids of various composition and age. The latter give rise to spectacular landscapes and include classic inventories of granite landforms such as domes, inselbergs, tors, and minor features of selective weathering (Maia and Nascimento 2018). A comparison with global reviews published so far (e.g., Wilhelmy 1958; Twidale 1982; Twidale and Vidal Romaní 2005; Migoń 2006) reveals that granite landscapes of NE Brazil may be considered representative for certain types of granite relief in general, and they include specific landforms which stand out due to their dimensions and clarity. The three areas presented in this study—Pai Mateus, Pedra da Boca, and Quixadá—differ in terms of the main features of relief, thus illustrating the diversity of cratonic granite landscapes, but they also have a common theme which is the presence of gigantic tafoni, possibly some of the largest present anywhere globally. Despite their immense scientific and scenic values, these areas are almost unknown outside Brazil and even within Brazil the knowledge is limited. Although the geoheritage potential of northeast Brazil is slowly being realized (Peulvast and Bétard 2015), none of the three sites is protected specifically for geoheritage. In this paper, each locality will be presented in terms of landform inventories and geoconservation issues, followed by a brief discussion of their global context.

Study Areas

Regional Context

The study areas are located in the semi-arid northeast of Brazil, within the federal states of Paraiba (localities Pai Mateus and Pedra da Boca) and Ceará (locality Quixadá) (Fig. 1). Geologically, all sites are located within the limits of the Borborema Geological Province (Arthaud 2007), in the north-eastern (Pedra da Boca), south-eastern (Pai Mateus), and central-northern part of it (Quixadá). The origins of the Province go back to the times of Brazilian orogenesis, when various cratons confronted one another in a Himalayan-type oblique collision, producing, among others, a large deformation system associate with folding and granite plutonism (Fetter et al. 2000). Granite plutons are associated with NE-SW and E-W trending shear zones (Vauches et al. 1995; Almeida and Ulbrich 2003) which acted as conduits through which large volumes of fluids circulated (Trindade et al. 2008). Thus, a large number of orogenic granites are interpreted as the result of intrusions taking place in extensional regions associated with local and regional tectonic structures (Neves 2012). This structural framework provided a stage for long-term differential erosion, leading to excavation of ridges and valleys, preferentially aligned W–E and NE–SW (Maia and Bezerra 2020).

The geomorphic history that led to exposure of granite massifs in north-east Brazil is yet to be fully elucidated and consequently, temporal context of the development of granite landscapes remains sketchy. Various approaches to decipher the pattern and magnitude of long-term denudation were used, based on geology of sedimentary formations, morphological analysis, inter-regional correlations, and low-temperature thermochronology (Morais Neto et al. 2009, 2010; Japsen et al. 2012; Peulvast and Bétard 2015; Maia and Bezerra 2020). Despite persistent uncertainties, especially regarding causes of uplift of the Borborema Plateau, some key events in the long-term may be outlined basing on these findings. Following the break-up of the Gondwana, widespread deposition in both terrestrial and marine environment occurred in the post-rifting stage, sealing the preexistent Gondwana topography. Apatite fission track study by Morais Neto et al. (2009) performed on the Borborema Plateau (where Pai Mateus and Pedra da Boca sites are located) indicated the first substantial cooling event at 100–90 Ma which probably led to stripping of much of the sedimentary cover and (re-)exposure of crystalline basement. Fluvial Serra do Martins formation was deposited upon the basement, prior to 25 Ma, and subsequently considerably eroded, leaving only isolated tablelands. The second phase of cooling typifies the Neogene (20–0 Ma) and through climate-induced erosion the margins of Borborema Plateau were accentuated. Thus, it may be proposed that the granite landscape of Pedra da Boca, which occurs below the level of Serra do Martins formation, has developed with the Neogene age timespan. On the plateau itself long-term denudation rate is low and the temporal framework of Pai Mateus morphology may be longer. Inselbergs of Quixadá are products of long-term differential erosion which resulted in the regionally extensive Sertaneja surface of low relief, with scattered residual hills and larger massifs, with relative relief up to 800 m. This surface is complex and polygenetic, generally post-Cretaceous, but it incorporates exhumed pre-Cretaceous surfaces (Peulvast and Bétard 2015).

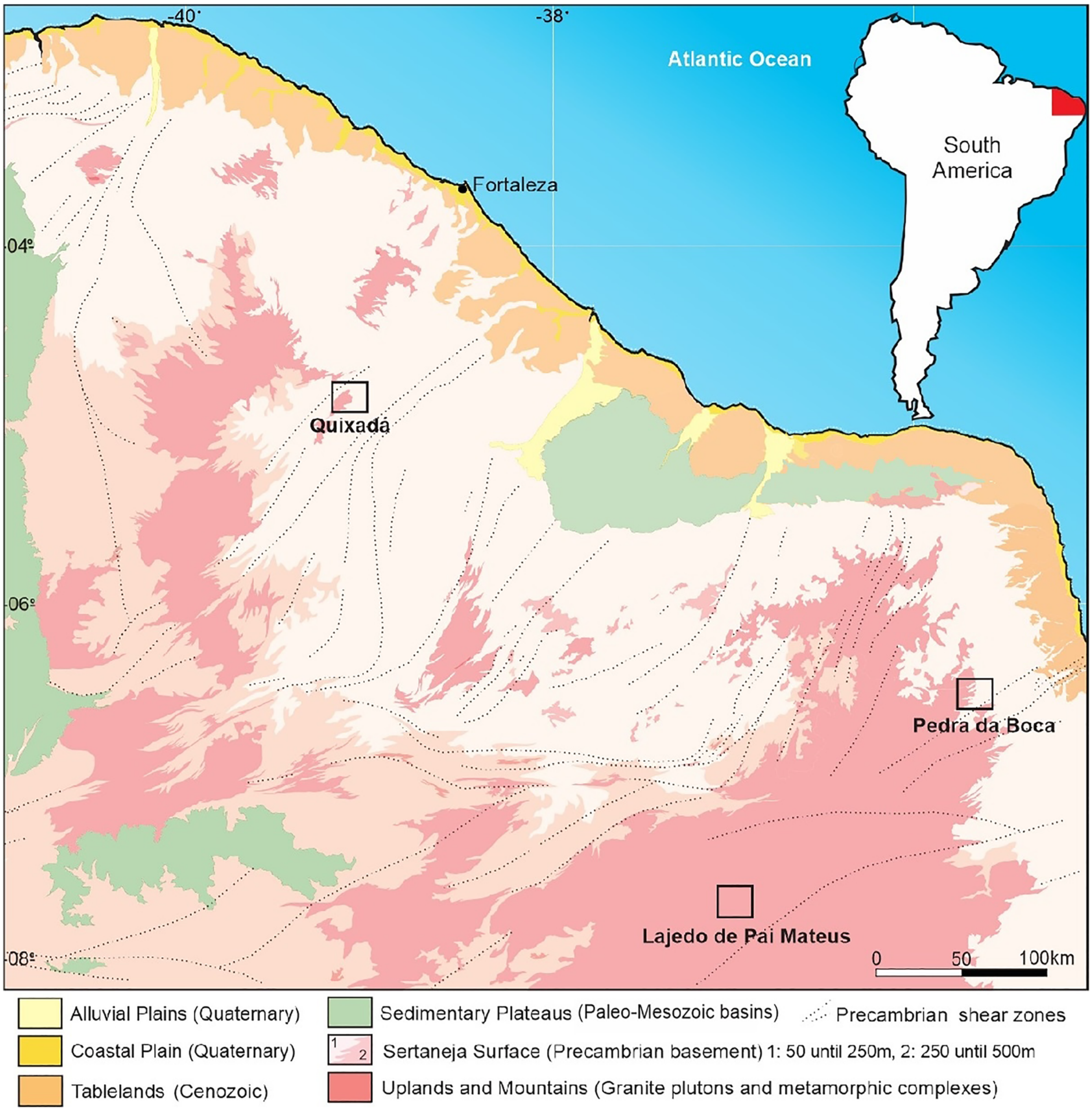

Fig. 1 Location of study areas and geological context (geology based on Atlas… 2003)

Although the rate of surface lowering around Quixadá cannot be constrained at present, long-term denudation history going back beyond the Neogene may be inferred. In summary, granite landscapes presented in this paper are certainly products of geomorphic evolution spanning the last 20–30 Ma, possibly longer in the case of Quixadá.

Pai Mateus

Pai Mateus is located ca. 50 km to WSW from the town of Campina Grande, within the vast Borborema Plateau, at an elevation of 500–600 m a.s.l. The name refers to a cluster of rather low domes and castellated hills rising 100–150 m above the plateau surface (Fig. 2a), within an oval of ca. 9 km long and 4 km wide, extended east–west. This positive topographic form reflects the presence of Bravo granite pluton, dated to ca. 580 Ma and intruded into much older biotite orthogneiss, granodiotites and migmatized monzogranites of Complexo Cabaceiras, dated for more than 2 billion years (Lages et al. 2013). The Bravo pluton itself is an ellipsoidal stock composed of amphibolite-biotite-bearing granodiorites (monzo- and syenogranites), of coarse and locally porphyritic texture, and contains dioritic enclaves and hybrid products (Lages et al. 2013).

Annual rainfall is below 700 mm and the yearly average temperatures around 22–24 °C (Alvares et al. 2013), with little seasonal change. Domes are predominantly bare whereas other rock outcrops and the intervening topographic depressions are under fairly dense, although not too tall forest and shrub communities. The area around the hills is an open woodland and used mainly for grazing cattle and goats, crossed by infrequent access roads.

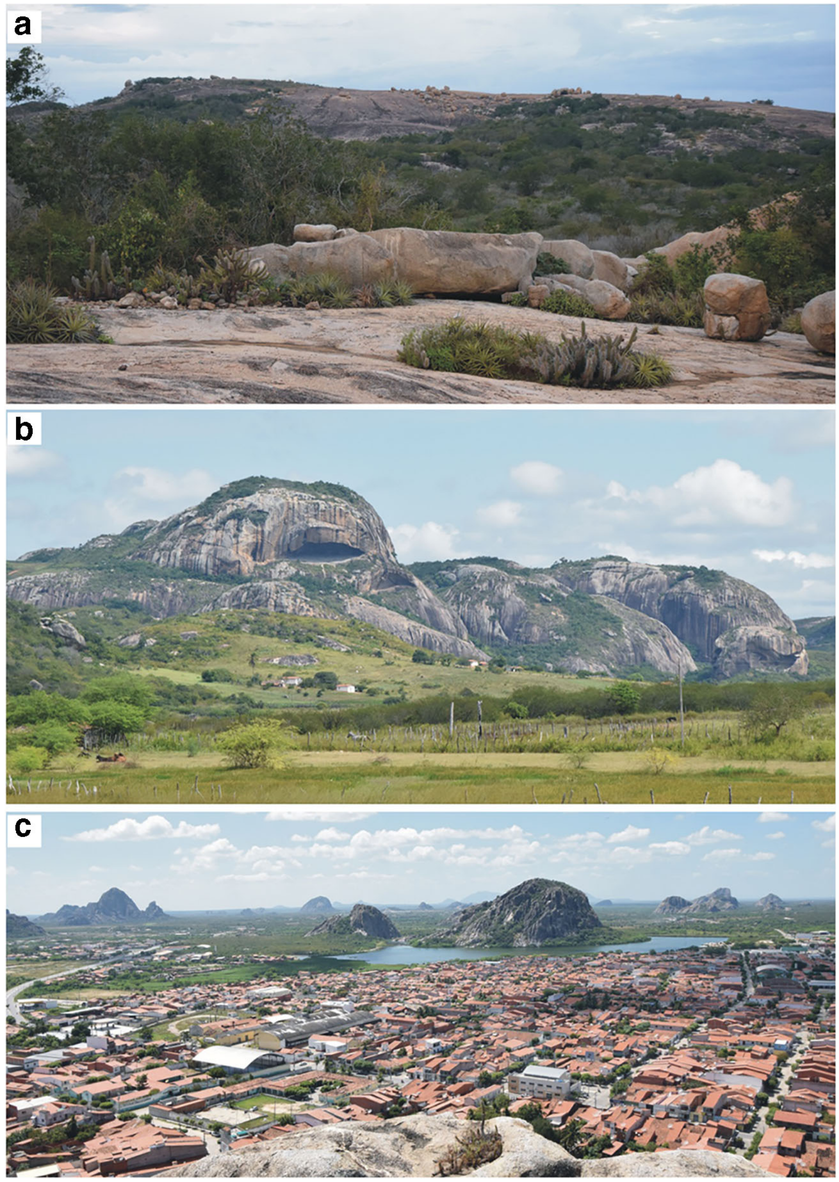

Fig. 2 Geomorphic landscapes of study sites. **a** Pai Mateus, dominated by low elevations with scattered boulders. **b** Pedra da Boca, with closely spaced domes and gigantic tafoni. **c** Inselberg landscape around the town of Quixadá

Pedra da Boca

Pedra da Boca is situated at the border between the states of Paraiba and Rio Grande del Norte, with the main cluster of domes located just south of this border which runs along the Curimataú river (Fig. 2b). The nearest larger town is Passa e Fica, some 4 km to NE, whereas the city of Natal is ca. 90 km to NE. The name Pedra da Boca, which can be translated as a "rock with a mouth" specifically refers to the highest and arguably most impressive granite dome, but it is applied here to the entire cluster which occupies an area ca. 3 × 1.5 km, extended from SW to NE. Around 20 domes of different size and height are present, reaching the altitudes between 300 and 400 m a.s.l. The igneous massif is a minor intrusion of latest Proterozoic age (ca. 573 Ma, Galindo et al. 2005; Nascimento et al. 2015) within the Borborema Geological Province and is composed of granites, granodiorites and monzonites (RADAMBRASIL 1981). Granites exposed within the locality are very coarse, porphyritic, with potassium feldspars as long as 5 cm showing linear arrangements.

Annual rainfall is around 1000 mm and temperatures rather steady, at 26 °C (Alvares et al. 2013). Except for exposed bare granite surfaces of the domes and marginal parts turned into agricultural use, the site is fairly densely covered by shrub and tree vegetation belonging to the Caatinga biome. Woodland is particularly dense in shaded places, in ravines and corridors between the domes.

Quixadá

Quixadá is the name of a provincial town in the northern part of Ceará state, located ca. 150 km to the SSW from the state capital of Fortaleza. The town itself, inhabited by some 80,000 people, sits between an expansive assemblage of granite inselbergs, elongated in WSW–ENE direction in a belt ca. 20 km long and up to 8 km wide (Fig. 2c). More than 30 individual granite inselbergs or their groups may be identified, rising to maximum elevation of 420 m a.s.l. The basal plain itself is at 200 m a.s.l. and the relative height of inselbergs varies from 20–30 to 150 m. Granites date back to the latest Proterozoic (Fetter et al. 2000) and have porphyritic texture with common mafic enclaves, whose elongation follows the WSW–ENE structural trend. Further to the south of the town the granite inselberg landscape gives way to much higher and larger bedrock elevations built of migmatites, whereas the lower ground is underlain by gneiss. The migmatite hills are distinctively massive and elongated according to the structural fabric, reaching 4–5 km long and more than 400 m relative height, providing evident contrast to granite residuals. The gneiss-migmatite complex was affected by contact metamorphism at the time of granite intrusion and usually does not show clear metamorphic foliation.

Annual rainfall is around 700 mm and the yearly average temperatures around 25 °C (Alvares et al. 2013), with little seasonal change. Inselbergs are mostly bare rock elevations, with trees and shrubs concentrated in shady places and within joint-aligned clefts. The surrounding plain is nearly entirely deforested, turned into agricultural and grazing land.

Landform Inventories

In the following part of the paper, granite landforms present at each site are categorized as large, medium-size and minor forms, occurring in a nested hierarchy. Large landforms are those which occupy an area of more than 0.5 km^2 and are well visible from a distance, thus decisive for the general appearance of the locality. They include inselbergs, big domes and castellated hills, large valleys and topographic basins, as well as plains from which all residual landforms rise. Within these large features, medium-size forms occur such as tors, whalebacks, big boulders, rock cliffs, amphitheatres on dome flanks, talus boulders, etc. Their dimensions are of the order of 10–100 m. Minor features are those typically described as “microforms” and considered as products of selective weathering at the local scale. They include weathering pits and pans, karren, tafoni, broken boulders, polygonal cracks and others (see Twidale 1982; Twidale and Vidal Romaní 2005; Migoń 2006 for comprehensive presentation of different types of granite landforms). However, while tafoni are typically a few meters long and deep (see Groom et al. 2015), examples from Brazil include giant hollows > 50 m long, so a clear-cut borderline between medium and minor landforms is difficult to follow.

Pai Mateus

Landform Pattern

Within an inventory of granite landforms at Pai Mateus, all three main groups identified by size may be distinguished. The main topographic features of the area include several east–west elongated hills, forming three parallel rows, and a group of rock ridges in the eastern part, which follow a parallel pattern along N–S discontinuities (Fig. 3). The W–E hills, even if they form nearly continuous highs, are morphologically diverse. Some have shapes of low, flattened domes with smooth slopes, whereas others are castellated, typified by more angular outlines in accordance with widely spaced, vertical joints (Fig. 4). Slope surfaces of the domes are generally low-angle (10–20°), but locally may be steepened to form near-vertical precipices or assume wavy morphology. The upper surfaces of the domes are often nearly horizontal and mantled by residual boulders. Topographic depressions occur between the hills, also elongated east–west. They are up to 1 km wide and mostly flat-floored, although groups of tors and low whalebacks may punctuate their floors. Products of in situ granular weathering (grus) and partly reworked grus are ubiquitous within the depressions, but the grus cover is clearly of variable thickness as attested by exposed rock platforms.

Residual large boulders are the most characteristic medium-size landforms at Pai Mateus, especially those on dome surfaces, as they are well visible from a distance (Fig. 5a). The dome in the southern part of the area (inset B on Fig. 3) is probably the best place to examine the boulders. Some of them are more than 10 m long and up to 4–5 m high. They occur in isolation or more often in clusters (Fig. 5b), nearly all rounded unless they have recently split along a central vertical fracture. The boulders are found along or near the morphological axis of the elevation, as well as within mid-slopes and at the base of the dome. Another impressive cluster of boulders occurs in the south-western extremity of the area, overlooking the river bed, where they are similarly up to 10 m long and 3–4 m high. In contrast to those described above, several rest on pedestals up to 1 m high in respect to the adjacent surface of the dome flank (Fig. 5c). Many of these residual boulders are hollowed out to form tafoni (see below). Other medium-size features within the domes are rock-cut amphitheatres 50–100 m across, terminated on the upslope side by steps a few meters high, and long gravity-induced clefts developed in response to tensional stresses on dome flanks.

On slopes of castellated hills individual tors may be recognized. A particularly good example is present in the south-western part of the property (Fig. 6a). The 12 m high tor represents a textbook example of a castle koppie (castellated

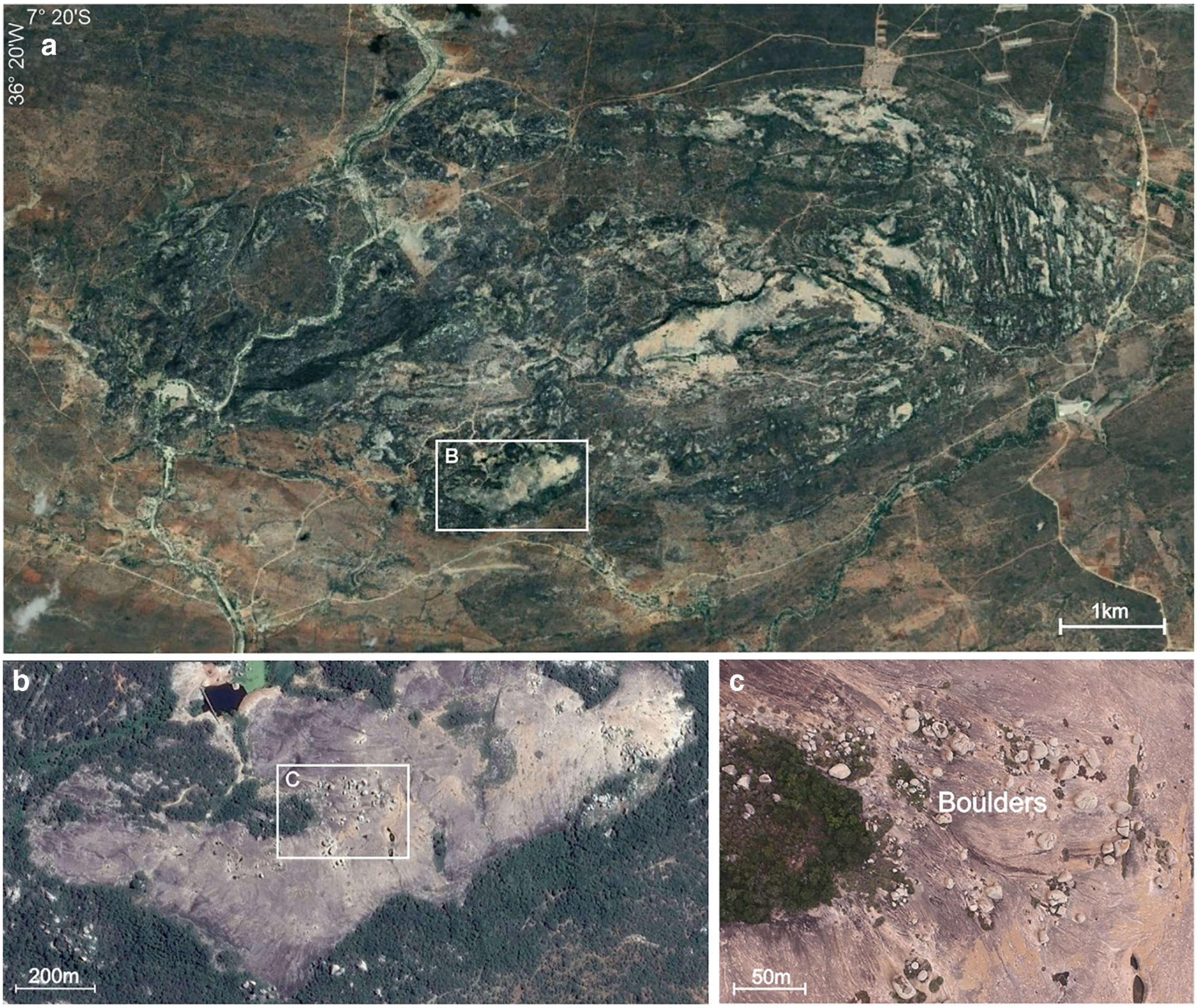

Fig. 3 Pai Mateus landscape. **a** General view of the granite bedrock outcrop emerging from the surrounding plain. Notice the co-existence of more massive (center) and densely jointed compartments (east). **b** Close-up of a dome in the southern part of the area. Notice very few traces of joints intersecting the dome surface and scattered boulders. **c** Cluster of residual boulders upon the dome, arranged in a few minor groups (for ground view of this cluster see Fig. 5b). Source of images: © CNES/Airbus, Google

tor), whose shape is perfectly adjusted to the network of continuous horizontal joints of ca. 1.5 m spacing and less continuous vertical joints. Tors may be also found within the major topographic depressions where they take various

Fig. 4 A whaleback dome (ruware) with residual boulders superimposed on its surface at Pai Mateus. These boulders are interpreted as remnants of more densely jointed outer shells

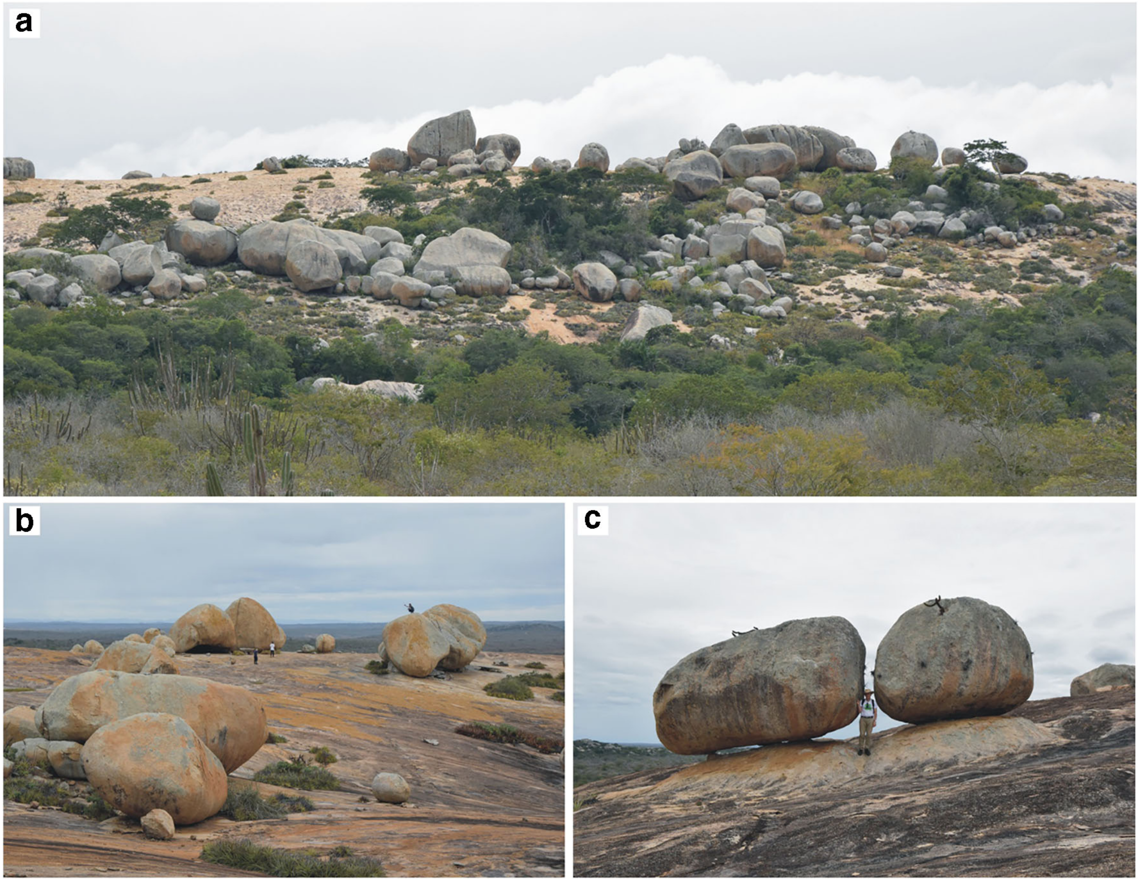

Fig. 5 Examples of boulders at Pai Mateus. **a** Distance view, with numerous boulders resting on gently sloping bedrock surfaces. **b** Close-up of boulder clusters on the top surface of a whaleback hill. Most of these boulders are hollowed out and host tafoni. **c** Boulders on pedestals

shapes. Some are angular, others are more rounded or consist of a pile of stacked boulders (bouldery tors). Among curiously shaped residual features is a big semi-spherical granite monolith, ca. 5 m long and 3 m high, supported by an extremely thin stem of 0.5 m height and width (Fig. 6b).

The Pai Mateus locality abounds in minor features which enhance geodiversity of the area. The most impressive ones, and also the most well known, are tafoni which have developed inside the large residual boulders on domes (Fig. 7). They are of at least two different kinds. The more "classic" ones are located on the sides of boulders and have fairly large openings (Fig. 7a). More curious ones have two or more entrances, which are often rather low (< 1 m high), and then grow up inside to a height of 3 m or so. Thus, the entire boulders are hollowed out (Fig. 7b). Combinations also occur in that there is a wide opening on one side and a low entrance on the opposite one. The dimensions of tafoni are obviously limited by the size of the host boulder, but caverns 10 m long

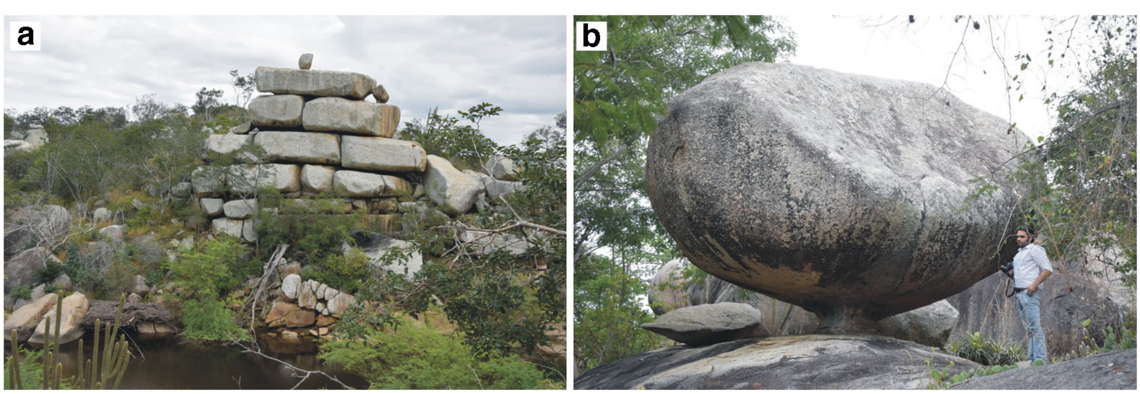

Fig. 6 Residual rock landforms at Pai Mateus. **a** Castellated tor. **b** Massive compartment on top of a thin stem

Fig. 7 Tafoni at Pai Mateus. **a** Large opening to a tafoni. **b** Low entrance under a boulder

and deep may be found. Flaking is common inside the tafoni, but nevertheless some cavern walls host indigenous rock art in the form of engravings or paintings, which add to the value of the site.

The impressive dimensions of tafoni are matched by equally impressive networks of runnels used by runoff waters (the name is used to describe channels incised into gently to moderately sloping rock surfaces, see Twidale 1982). They are very well developed on the northern side of a dome in the NW part of the property, where they form dendritic or broadly parallel patterns (Fig. 8). Runnels begin in wide and shallow concavities, some partly vegetated, and then continue downslope along straight or sinuous courses. They vary in depth and width, from wide shallow troughs to V-shaped incisions up to 2 m deep, with a range of intermediate shapes. An inventory of minor landforms at Pai Mateus includes karren on vertical rock surfaces, water-holding pans which may be as long as 18 m, networks of polygonal cracks and split boulders.

Origin of Granite Topography

The complete sequence of geomorphic events which produced the topography observed today cannot be recreated due to missing evidence. However, the widespread presence of grus weathering mantle in the topographic lows between the bedrock elevations makes credible a hypothesis that structure-controlled differential deep weathering (etching) followed by removal of saprolite was the principal pathway of landform evolution. Castellated tors are consistent with this scenario. Nevertheless, the association of whalebacks (low slope domes), castellated hills and residual boulders strewn across the gently sloping surfaces of the domes requires special explanation.

Boulders are clearly generally almost in situ, meaning that neither have they been transported from afar (no process would account for this), nor are products of rock fall from above (they occupy the highest position in the local relief). They are due to gradual reduction of joint-bound bedrock compartments by weathering focused on joint surfaces and

Fig. 8 Runnels on moderately sloping rock surfaces at Pai Mateus. The depth of these channels is 1–2 m. Notice high density of these linear features

their intersections. The size of monolithic boulders shows that joint spacing in the original rock mass must have been of the order of 5–10 m, possibly more. Interestingly, however, no regular joint pattern of comparable geometry can be identified within exposed rock surfaces of the domes which appear extremely massive. Thus, a model similar to one envisaged by Twidale (1981) for nubbins (= block-strewn inselbergs) seems applicable for Pai Mateus. We hypothesize an existence of structural compartments which consist of massive, poorly jointed core and outer shells cut by vertical fractures and separated by planar discontinuities (Fig. 9). The succession of both subsurface and then surface weathering processes resulted in disintegration of the outer shells into boulders, which have remained in place due to low slope angles of the emergent domes. Boulders stacked one upon another indicate that they are derived from more than one shell. According to this model, the highest castellated hill in the area has retained its orthogonally fractured outer shells until nowadays, whereas the lower domes in the surroundings have already lost the analogous shells, except the remnant boulders.

The exposed granite surfaces have been subject to further weathering, both at the surface, leading to granular disintegration, flaking and induced cracking of perched boulders, as well in the epigene, subsoil environment. The most complex is the origin and development of large tafoni, which will be analyzed separately below.

Pedra da Boca

Landform Pattern

In the Pedra da Boca area, the dominant landforms are closely spaced domes built of massive granite, with a few outlying domical hills to the north, forming together a spectacular cluster of large residual landforms rising from the regolith-covered ridges and above the flat valley floor of the Curimataú river (Figs. 2b and 10). Domes vary in ground dimensions and height, as well as in geometrical outlines. The largest domes are more than 0.5 km long and 0.3–0.4 km wide, the smallest ones are ca. 150 × 150 m. The highest domes in the area exceed 400 m a.s.l., having relative height of ca. 200 m; others are in the range of 100–200 m. Some domes have nearly circular ground plan, with the length-to-width ratio barely above 1, whereas others are more oval, with the respective ratio close to 3. Elongation of the domes is controlled by SSW–NNE structural trend, seen also in the strike of some vertical joints exposed on the flanks of the domes. Except marginal domes standing in isolation, the other ones are separated by narrow passages or even impassable clefts, thus

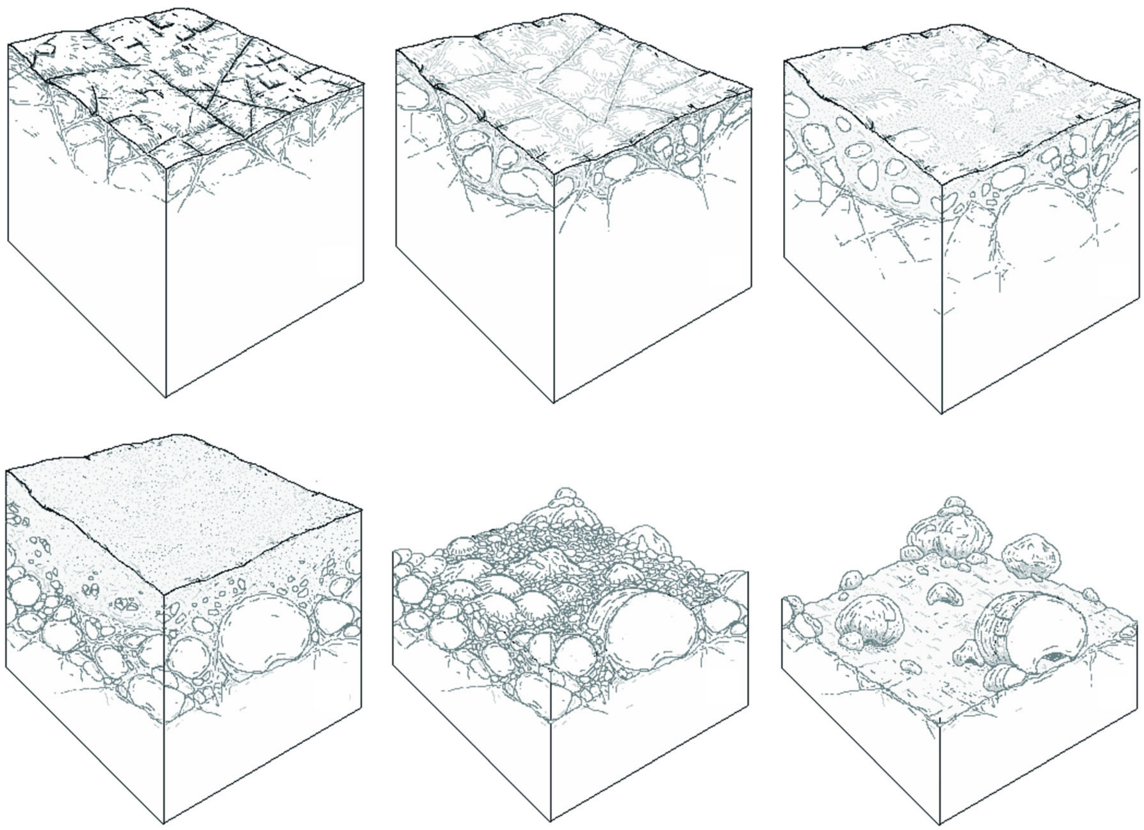

Fig. 9 Conceptual model of granite landform evolution at Pai Mateus through selective joint-guided deep weathering and stripping of regolith to exposed granite boulders

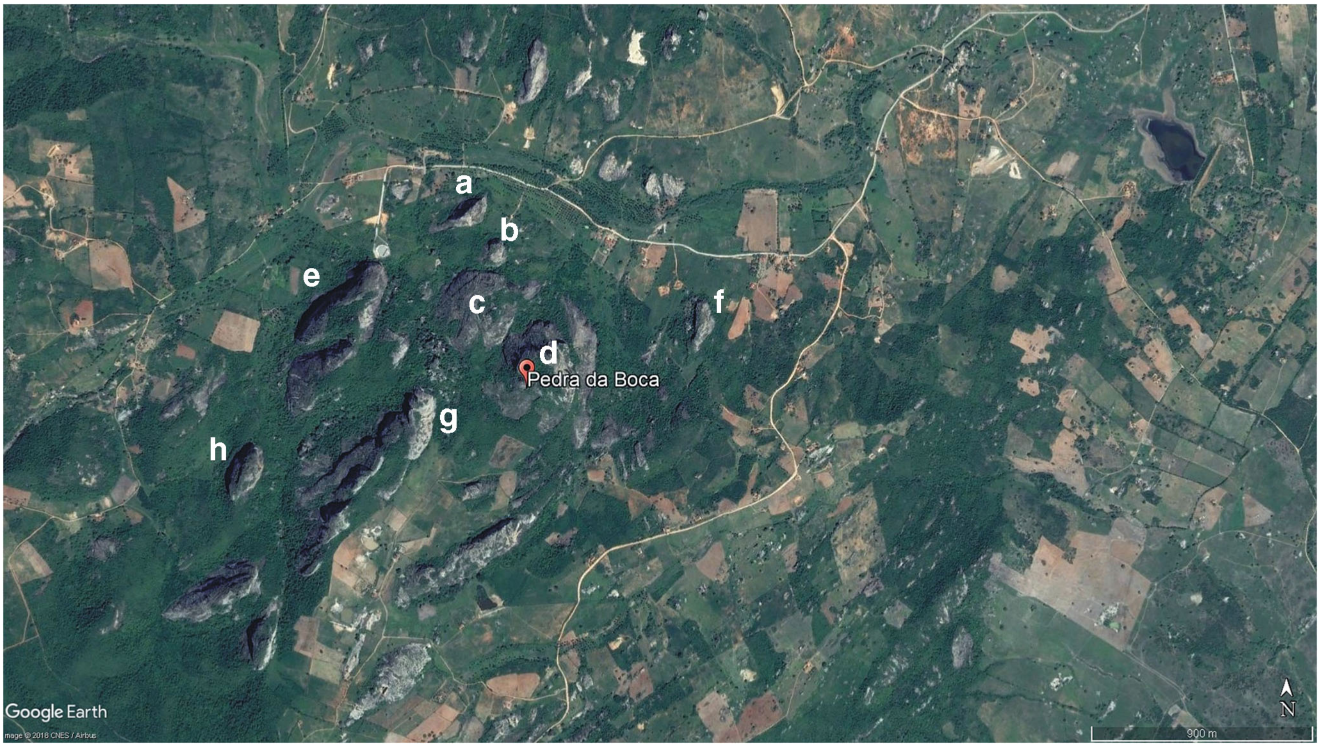

Fig. 10 Pedra da Boca landscape, with individual domes letter-coded (see text). Notice that domes occur within a SSW–NNE belt ca. 2.5 km wide and show elongation consistent with the strike of this belt. Otherwise bedrock outcrops within regolith-covered slopes are much smaller and more dispersed. Source of image: © CNES/Airbus, Google

being physically connected with one another. In between some domes are broader depressions filled with huge granite boulders interspersed with bedrock outcrops, apparently indicating the presence of more jointed bedrock compartments.

The morphology of the domes, especially if seen from a distance, illustrates well the key morphological characteristics of this kind of landforms (see Thomas 1965, 1978; Twidale 1982; Migoń 2006). They have bare, convex slopes, in sections turning into nearly vertical, and flattened summit surfaces. Very few residual blocks rest on the surface of rock slopes, but large boulders, up to 10 m long, may be found at the base, hidden in forest. Locally hillslope morphology is more complex, with partly vegetated benches separating very steep slope sections. Others have one side convex, whereas the opposite one is nearly vertical, and so they may be termed half-domes. Thus, morphology of the domes shows the control exerted by both local curved sheeting joints, arranged in an onion-skin pattern, and intersecting vertical joints (fracture zones) which follow the regional trend. The latter account for both the outlines of certain hills and the presence of cliffs within the hills.

Two main types of minor landforms within the domes are caverns/tafoni and runnels/karren. Several domes have impressive large caverns inset into their steep slopes. These mega-cavernous features vary in shape. Some may be considered as typical tafoni, having interior larger than the opening and growing upward beyond the entrance (Fig. 11a). The entrances have the width and height approximately equal. The outer walls are crusted and the inside part is affected by flaking and granular disintegration. Caverns in domes A and B provide examples. Others are like giant horizontal slots cut into the rock slopes, with the width of the opening 40–50 m long and narrowing towards the rear of the cavern (Fig. 11b). These exist on domes D and E. The cavern in the dome E is the only one accessible without the necessity of rock climbing and occurs just beyond a local modern church. It is > 40 m long at the opening, ~ 10 m deep, and up to ~ 20 m high at the opening. Apart from common flaking and granular disintegration, the roof of the cavern hosts second-order hollows which may be likened to honeycomb (alveolar weathering) features. However, while typical honeycombs are centimeter-scale (see Groom et al. 2015), the ones inside the cavern are a few tens of centimeters long and deep. Their spatial patterns are irregular, with coalescing and nested forms present.

Runnels/karren are ubiquitous on the flanks of the domes, particularly on domes C, E (west-facing side), and J. Similarly to caverns, these linear incisions vary in appearance. Most evident are those on nearly vertical rock slopes, where they form parallel patterns (Fig. 12a). However, where the slope becomes truly vertical or overhanging, the karren disappear. Their courses are clearly controlled by gravity and the direction of maximum slope rather than preexisting structures within granite. This is seen on the flank of the dome C, where karren cross a number of steeply dipping quartz veins and

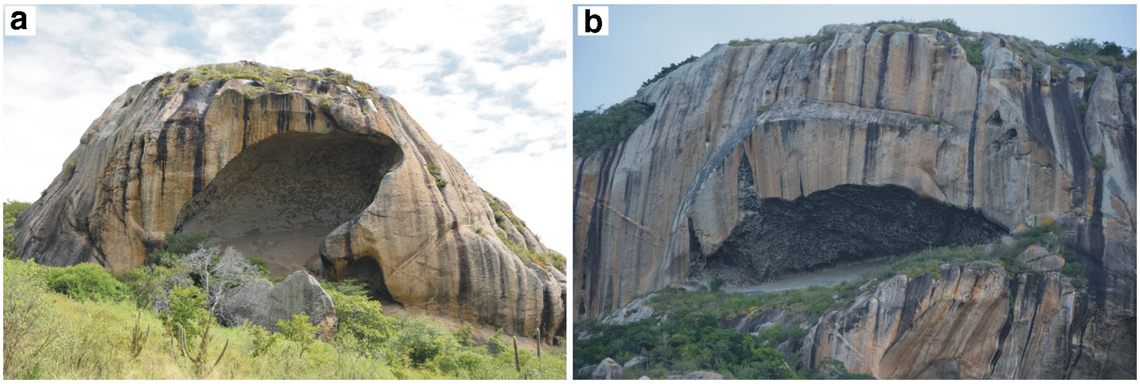

Fig. 11 Tafoni at Pedra da Boca (**a**, **b**). These large openings are 30–50 m long and up to 20 m high. The floor of tafoni on **b** follows the sheeting plane. Notice the abundance of minor features of selective weathering on the ceilings of both tafoni

the presence of veins has no effect on the karren extension. The spatial pattern of incisions is more complex on less-inclined slope segments, where jagged ridges and troughs of various depth and width occur (Fig. 12b), resembling *Spitzkarren* fields known from limestone outcrops (Veress 2010). Troughs are partly vegetated and one can therefore consider that biological activity and release of organic acids contributes to the deepening of runnels, which otherwise act as runoff channels. On both domes C and E, one can trace gradation from less regular karrenfield to more orderly parallel pattern of karren, consistent with increasing inclination of the slope surface.

Origin of Granite Topography

The occurrence of massive domes separated by broadly parallel terrain depressions indicates significant bedrock control on erosional topography. Weathering and erosion, of whatever kind in detail, exploited the SW–NE trending zones of structural weakness, leaving more massive and therefore more resistant granite compartments in between. Processes at work may be divided into two main groups: those leading to the emergence of domes and those acting upon exposed domes, contributing to their decay. The nature of field evidence is such that the latter can be identified with greater confidence, whereas the former can be only hypothesized, in relation to the evolutionary models developed elsewhere.

Domes (bornhardts) are generally considered as results of two- or multi-stage evolution, the essence of which is the gradual emergence of massive bedrock compartments concurrent with the lowering of the adjacent terrain underlain by less-resistant bedrock (Thomas 1965; Twidale 1981). The emergence may be preceded by a prolonged phase of deep weathering, so that the future domes assume their final form already in the subsurface, prior to excavation, or it is more gradual, with weathering and erosion going hand in hand. Unfortunately, there are hardly clues available to decide which scenario applies to the domes of Pedra da Boca, although the simple two-phase model seems rather unlikely given the height of the domes. The gently rolling ridges to the north

Fig. 12 Karren on a dome at Pedra da Boca. Notice the downslope change of surface inclinaction, from moderately sloping above to vertical below, and corresponding change in karren morphology

are underlain by a mantle of weathered rock but its thickness is unknown and probably not more than 10 m, as inferred from occasional shield-like solid granite outcrops. On the plateau to the south, low bedrock outcrops are common and occur next to one another, leaving little room for extensive deep weathering mantle beneath the plateau. The geomorphic setting of the locality is such that it is part of the marginal escarpment zone of the Borborema Plateau. The elevated position of the plateau is due to ongoing Cenozoic uplift (Peulvast and Bétard 2015; Rodriguez Tribaldos et al. 2017), and it is likely that domes were emerging concurrently with erosion focused on the escarpment zone, with the Curimataú river valley being an effective sediment transport corridor.

The emergence of domes sets the stage for their destruction and both catastrophic and non-catastrophic processes play the role. The former include rock slope failures which are of different types. Smooth vertical sections of rock slopes, without caverns or rills, indicate places where detachment of rock blocks occurred and in certain places they can be matched by talus composed of big boulders at the base of the slope (e.g., dome A). On steep flanks of the domes failures are probably accomplished by sliding, aided by surface lubrication during rain, leading to accumulation of rock slabs near the base. Both mechanisms lead towards gradual reduction of the domes, mainly by slope retreat rather than lowering from the top, explaining the presence of half-domes such as elevations F and J.

Noncatastrophic processes include ongoing granular disintegration and flaking observed on exposed rock surfaces, erosion, and biochemical corrosion leading to the development of runnels on inclined rock slabs, as well as the complex of processes involved in the origin and enlargement of tafoni.

Quixadá

Landform Pattern

The geomorphic landscape in the Quixadá area is marked by a large number of inselbergs rising abruptly from a flat surface. There are several clusters of granite hills along the inselberg belt, with the largest ones located west of the town, overlooking the Açude do Cedro reservoir, and to the north-east of the town center, with Pedra Riscada as the highest one (Figs. 2c and 13). Other inselbergs stand in isolation or there are two/three in close proximity, separated by an expanse of the intervening plains. The plain, however, is not entirely flat but is punctuated by minor elevations a few meters high—ruwares, whalebacks, and boulder clusters. Inselbergs have a range of dimensions, from 200 m to 1.2 km long, being either circular or elongated in ground outline, with the length-to-width ratio up to 3:1.

Inselbergs vary in terms of shape. Domes (bornhardts) dominate (Fig. 14a), although there are very few examples of smooth rounded outlines and uninterrupted convex slopes. Much more common are complex outlines due to intersection of vertical joints and large-scale sheeting surfaces. These include vertical and even overhanging rock cliffs reaching > 50 m high (Fig. 14b). In the most elevated parts rock towers may occur (such as the peak of Pedra Galinha; Fig. 14c) or blocky remnants of outer sheets remain, often in precarious positions. Some of the lower inselbergs fit the category of castellated ones, with outlines determined by the multitude of intersecting vertical joints. Finally, nubbins (= boulder inselbergs) occur, with apparently chaotic boulder groups crowing a more coherent rock pedestal (Fig. 14d).

Boulder taluses are distinctive landforms associated with inselbergs, being transitional features between steep rock slopes and the surrounding plain. They may consist of a few large blocks located below an overhang, but may also form large clusters, 270 × 100 m, such as at the northern footslope of Pedra da Galinha (Fig. 15).

Granite inselbergs of Quixadá host an impressive inventory of minor surface features. The most conspicuous and ubiquitous are karren (runnels) developed on steep and vertical bedrock surfaces. They occur as parallel furrows of variable depth, from a few tens of centimeters to more than 1 m, separated by sharply pointed ribs (Fig. 16a). On less-inclined surfaces, complex patterns of deep karren have developed, with Pedra do Cruzeiro in the centre of Quixadá town being the most accessible example. Here, karren take the form of linear troughs up to 5 m deep, lined by vertical walls and separated by convex ribs. Long profiles of the troughs are often stepped, with flat-floored sections alternating with steps 1–2 m high (Fig. 16b). Pans and pits are also common on bedrock surfaces of low inclination (< 10°).

Large tafoni also occur in the Quixadá area. Some have developed along horizontal partings intersecting outer surfaces of the domes and these may reach lateral extensions up to 50 m or more (Fig. 17a), extending into the rock for more than 10 m (Fig. 17b). Others are more symmetrical in terms of length-to-height ratio, but still attain considerable dimensions, more than 10 m long and high. Honeycombs often occur on the ceilings within the tafoni.

Origin of Granite Topography

The origin of inselberg landscape in the surroundings of Quixadá has been explained in terms of the etchplanation model (Maia et al. 2015). Granites were unroofed after their metamorphic cover was completely stripped off from the axial part of the igneous dome (Fig. 18). Exposed granites were characterized by different density of fracturing, with the more fractured compartments having been subject to more efficient deep weathering under tropical conditions. As a result, clusters of residual hills as well as

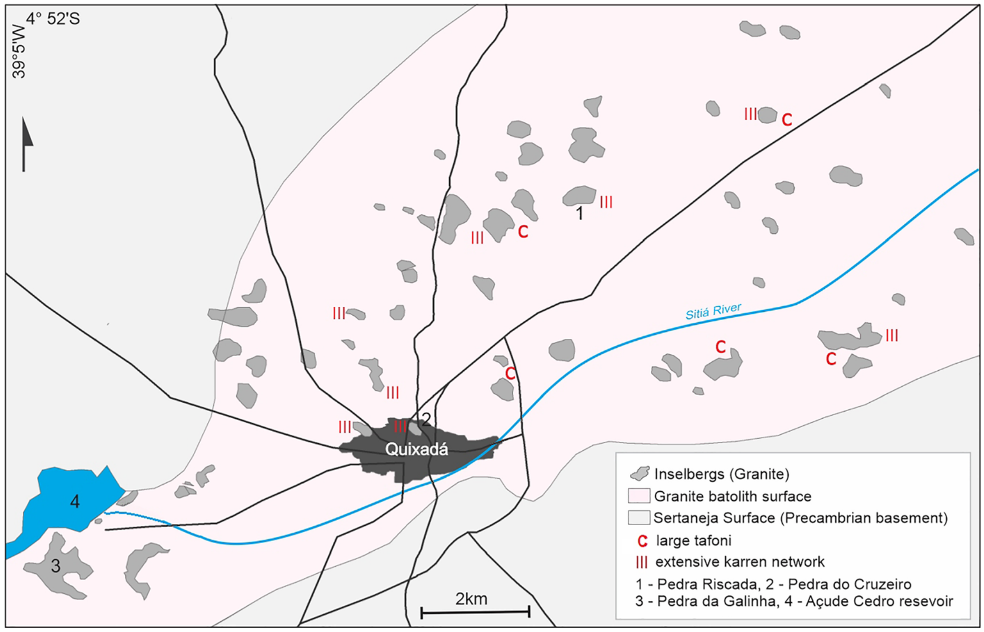

Fig. 13 Location map of the inselberg landscape around Quixadá

solitary elevations were left upstanding after saprolitic cover was eroded away. Bedrock alteration was focused along SW–NE and SE–NW trending fractures, and hence, some inselbergs are distinctively elongated. It is hypothesized that inselberg clusters originated in places where fracture density was at its minimum.

After emergence from the saprolite, inselbergs continued to develop in subaerial conditions, with the main morphogenetic role played by weathering and mass movement. Secondary fractures, formed in response to topographic unloading, reduce the strength of an otherwise very massive granite and progressively open, leading to rock slope collapses. Large

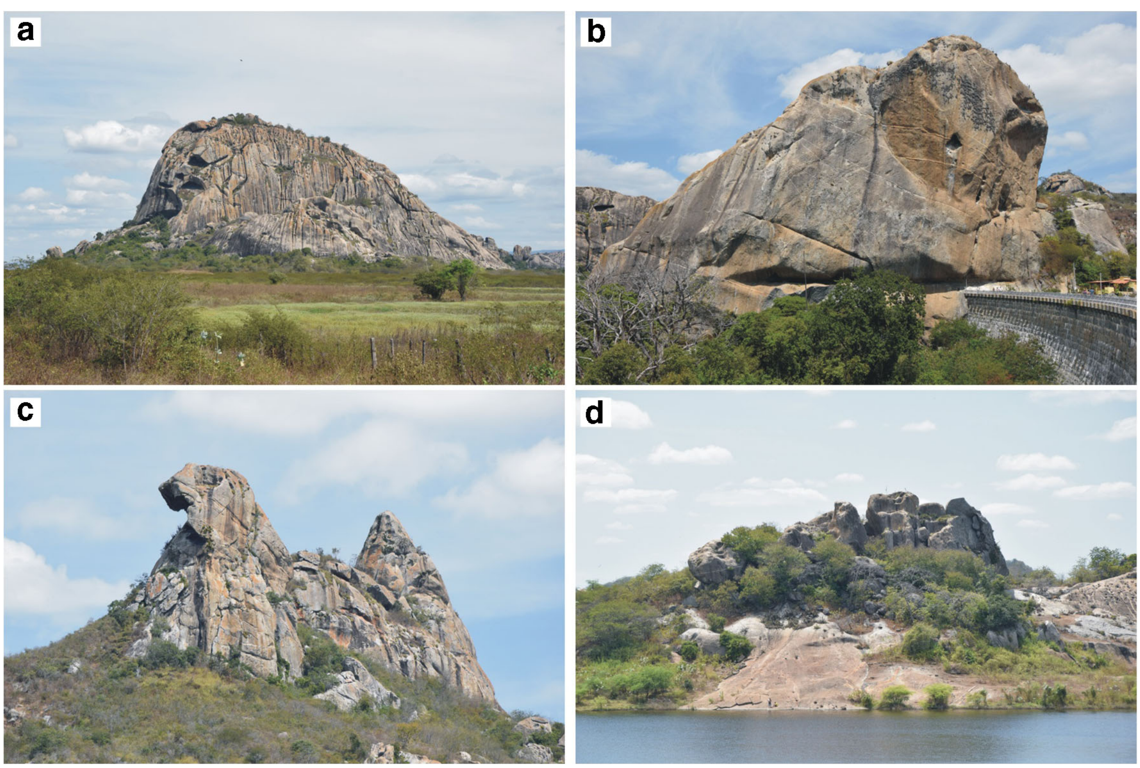

Fig. 14 Diversity of inselbergs in Quixadá area. **a** Dome. **b** Vertical side of a dome. **c** Two-peak Pedra da Galinha inselberg. **d** Nubbin inselberg built of smaller compartments and lacking large sloping surfaces

Fig. 15 Large talus below Pedra da Galinha (on the right) attests to sporadic catastrophic rock slope failures

blocks and irregular talus accumulations at the slope/plain junction testify to the importance of this process within steep-sided domes. Lower, castellated inselbergs are less prone to catastrophic slope collapses and are mainly reduced in size by weathering. Bedrock inhomogeneities are important, especially quartz veins and mafic enclaves. The former are more resistant, whereas the latter are preferentially weathered and evolve into networks of pits, hollows and troughs, giving the slopes very irregular, rough appearance. Within this framework, large tafoni grow.

Origin of Large Tafoni

Large tafoni (caverns) are common at all three localities presented here, although the nature and shape of tafoni differ from site to site. In particular, tafoni at Pai Mateus are distinctive, being developed within large residual boulders rather than into solid rock slopes as is the case at Pedra da Boca and around Quixadá. The formation of caverns depends on a number of factors such as anisotropy degree of the rock, the presence of enclaves, veins and dikes, non-uniform fracture density, differences in texture and composition of the host rock, playing a role in isolation or conjunction. Each of these structural factors can act as a nucleating starting point for tafoni development, and therefore, caverns have more than one origin. In some instances, reasons for tafoni development can be inferred from both lithological and structural conditions within them, as well as associated deposits in the vicinity of the caverns. There are also cases, however, where the origin of tafoni remains enigmatic.

Fig. 16 Runnels and pans at Pedra do Cruzeiro inselberg

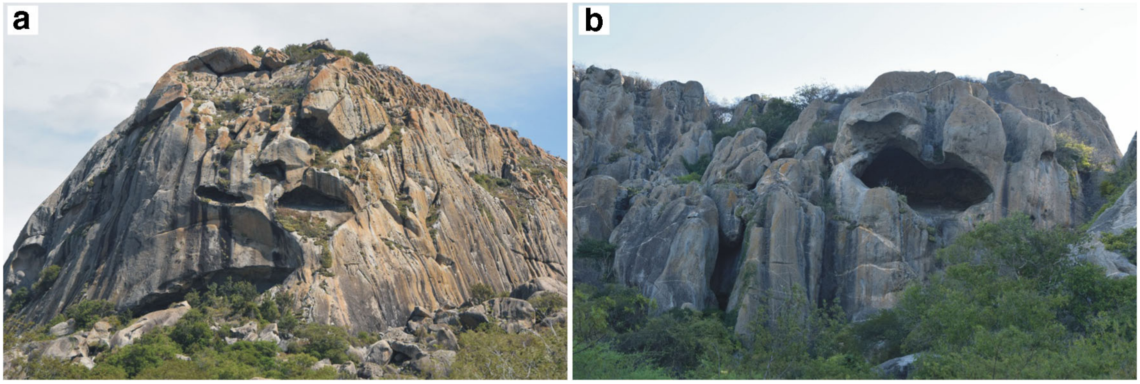

Fig. 17 Tafoni in Quixadá area (**a**, **b**). Their sloping floors and horizontal rather than vertical extension (particularly on **a**) show the role of sheeting joints and surfaces in guiding tafoni development

Some cavities within rock faces are generated by localized rock slope collapses (Fig. 19). Multidirectional fracturing, consisting of both primary and secondary (decompression) joints, favours separation of individual compartments through weathering, leading to their ultimate fall or slide. Occasionally, dense fracturing may be associated with the presence of veins and selective weathering at the contacts further weakens the rock towards its disintegration. Large detached blocks (talus) at the footslope provide of evidence of collapse origin.

Other tafoni are initiated by selective weathering away from major structural discontinuities. One evolutionary scenario involves the growth of micro-cavities (cm-size) in the opposite directions from the vein, focused on mafic minerals (mica and amphibole) and/or feldspar, leading to the formation of granular waste known as grus. In other cases, the process seems to start with the origin of small alveolar hollows (honeycombs) within minor, structure-controlled rock overhangs. They grow to decametric dimensions and may coalesce, to form larger cavities. Honeycombs are common

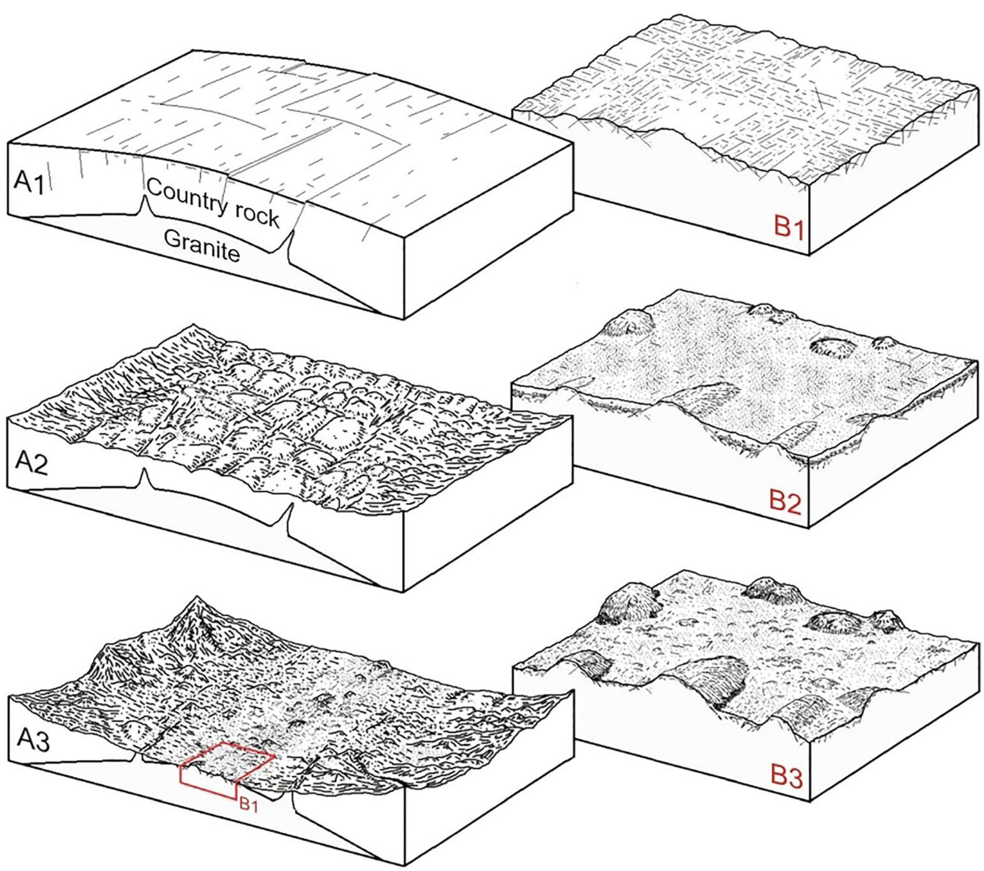

Fig. 18 Conceptual model of the origin of inselberg landscape around Quixadá (after Maia et al. 2015)

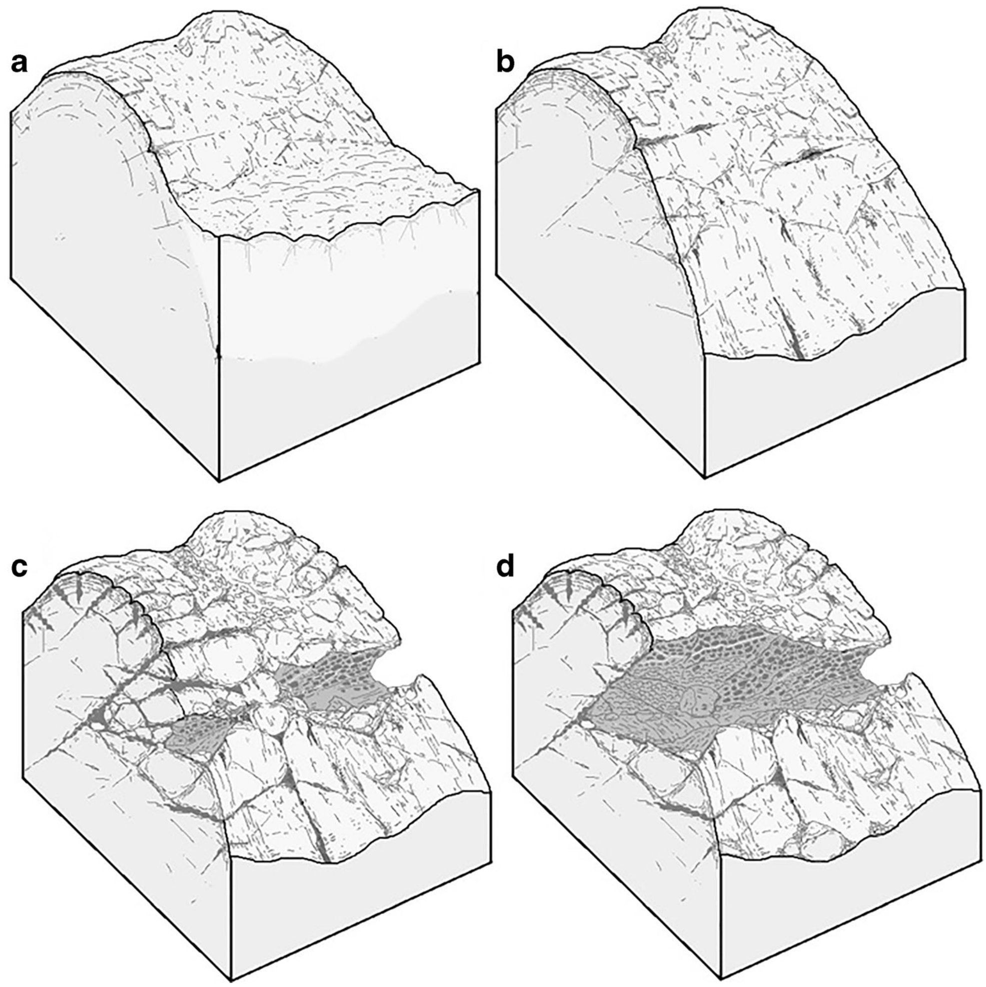

Fig. 19 Evolution of tafoni within inselberg slopes

within collapse caverns, perforating their roofs and walls and contributing to further growth into the rock slope. The presence of enclaves enhances the development of ceiling honeycombs, as exemplified by the largest cavity at Pedra da Boca.

The direction of tafoni growth is clearly controlled by structure. If the host rock is isotropic, no preferred pathway occurs and the hollow resembles a vaulted dome. However, rock anisotropy, especially the presence of foliation and elongation of mafic enclaves, favours asymmetric growth and lateral extension. Continuous sub-horizontal partings play an analogous role. Large horizontal openings at Pedra da Boca and in some inselbergs around Quixadá probably reflect combination of these controls. Maia et al. (2018) suggested that some horizontal tafoni may have evolved from flared slopes—features initiated below the ground surface, due to enhanced moisture-driven subsurface weathering (see Twidale 1962).

At Pai Mateus, the main types of tafoni shape are basal cavities undermining residual blocks of granite. They expand from the base of the granite block inward, consuming its interior. This expansion extends to the point of breaking the side of the block, thus generating access to the interior. In the interior, expansion of the cavity occurs by the progressive flaking of the internal surfaces, accompanied by the granular disintegration. However, the starting point seems to be a low weathering slot formed along the irregular contact with the surface of the underlying rock slab. Chemical breakdown within the moist, shaded environment inside the boulder is more efficient than predominantly physical disintegration of the outer surfaces, so the inward growth proceeds at a faster rate than exfoliation-driven retreat of outer boulder shells (Fig. 20).

Global Context

Comprehensive global comparative analysis of the sites presented in this paper is not feasible due to space limitations and the format of such analysis for KGA is yet to be established. Nevertheless, a survey of major publications related to geomorphology of granite terrains (e.g., Wilhelmy 1958; Twidale 1982; Twidale and Vidal Romaní 2005; Migoń 2006) and numerous papers referred to in these summary works reveals that Pedra da Boca, Pai Mateus, and Quixadá are indeed localities of considerable value for geosciences, as type

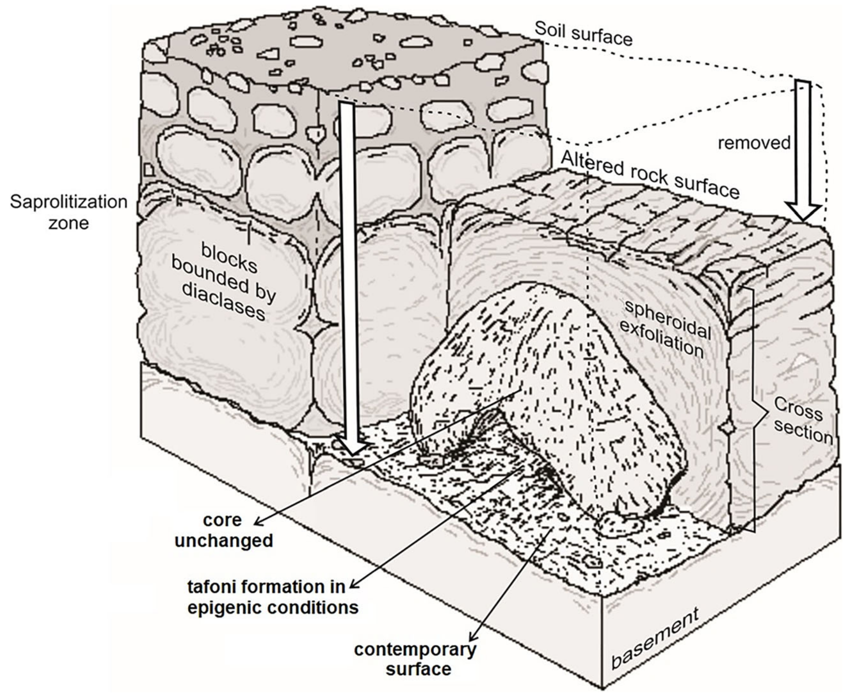

Fig. 20 Evolution of tafoni within residual boulders

localities of certain types of erosional landscapes in basement rocks and medium to minor geomorphic features in granite. It is not asserted that the granite landscapes presented in this paper are unique. In fact, domes and inselbergs are a repetitive theme in many cratonic areas, both in Brazil (Lima and Corrêa-Gomes 2015; Varajão and Alkmin 2015) and on other continents (central Africa, e.g., Thomas 1965, Pye et al. 1986; India, e.g., Gunnell et al. 2007; Australia, e.g., Twidale 1981, 1986). However, the global importance of Brazilian areas may be claimed for the following reasons. Of particular note is their location within one climatic realm, BSh zone according to Köppen's classification (Alvares et al. 2013). Hence, collectively, they demonstrate how geological background and topographic setting provide key controls on landform development. Regarding large-scale geomorphology, the sites provide a spectrum of landscapes due to protracted erosion, from initial emergence of granite pluton within a plateau, far from contemporary incision lines (Pai Mateus), through an example of escarpment topography (Pedra da Boca) to an inselberg landscape, apparently formed by long-term surface lowering and its reduction to a hill-dotted plain (Quixadá). Thus, while each locality is valuable in itself, they also form a cluster linked by two common themes: rock control and landform evolution over time. Although access and visual appearance are not the decisive criteria for KGA, all three sites can be relatively easily reached and appreciated, increasing their role as potential KGA. Last but not least, these areas are relatively well researched already and more work is planned to increase our understanding of their origin, evolution and controls. Thus, the claimed significance of the sites has its basis in scientific inquiry, not just the scenery. However, as indicated above, global comparative analysis will provide an ultimate answer regarding the importance of NE Brazilian localities. It is worth to note here that low-latitude granite sceneries are poorly represented within the UNESCO World Heritage, and none of the sites currently on the WH List was inscribed in recognition of their geoheritage values. They were nominated and inscribed for cultural reasons (Matopo Hills, Zimbabwe; Hampi, India; Rio de Janeiro , Brazil; see whc.unesco.org; access date 2019-10-26). Thus, the complementary role of KGA network to UNESCO World Heritage may be demonstrated.

At the minor scale, tafoni warrant particular attention. Tafoni have long attracted attention of geomorphologists (e.g., Klaer 1956; Dragovich 1969; Wilhelmy 1977) and continue to do so (e.g., Roqué et al. 2013; Inkpen and Hall 2019). Recent reviews by Paradise (2013) and Groom et al. (2015) provide background to evaluate global significance of tafoni from north-east Brazil. First, both authors attempted to show global distribution of tafoni on maps and north-east Brazil is strikingly missing on either map, despite Wilhelmy's (1958) comments about their occurrence in the region. Second, both publications leave an impression that tafoni are at most of metric size, with dimensions of a few meters being exceptional. In fact, most quantitative studies of tafoni focus on small-scale features, easy to measure (e.g., Inkpen and Hall 2019). The gigantic dimensions of these Brazilian tafoni, reaching 50 m long and > 10 m high, also documented elsewhere in the country (Auler et al. 2007; Lima and Corrêa-Gomes 2015), stand out and these morphometric features alone make them significant in the global context. However, ongoing work will hopefully foster their better understanding in terms of rock control and timescale of evolution, increasing their international relevance. Nevertheless, even if the origin of large tafoni is not yet fully understood, they illustrate the extreme power of selective long-term weathering and provide reference data not to be ignored. Therefore, they have the potential to become a type locality for tafoni, at least in igneous rocks. Likewise, entirely hollowed-out boulders at Pai Mateus may play the role of a reference site and acquire the status of type locality for this sub-category of tafoni.

Geoconservation Issues

Although details of the KGA project are yet to be agreed, it is no doubt that sites granted this distinction should not be under immediate pressure detrimental to the scientific and other values of the locality. Likewise, if possible, they should not remain known to the narrow circles of geoscientists only, but their significance should be more widely appreciated. Thus, geo-interpretation facilities should be developed.

Among the three sites presented here, Pedra da Boca locality is protected as a state park which covers 157 ha, with regulated access to the site. Around Quixadá, Quixadá Monoliths Natural Monument (*Monumento Natural dos Monólitos de Quixadá* in Portuguese) was established in 2002 on the area of 16,635 ha (SEMA 2019). In both cases, geomorphological scenery is considered as an asset of a territory, but for scenic rather scientific reasons. However, threats and pressures are different in each case. Pedra da Boca is located in a relatively remote area and the state park is partially fenced off, so that no immediate threats seem to exist. By contrast, Quixadá Monoliths include an area around a sizeable town, with a typical range of pressures such as littering, defacing of rock outcrops, uncontrolled vegetation, soil and rock removal, building construction activities and others. Information about protected status of the area is poorly exposed.

Tourist accessibility varies from site to site. Pai Mateus is located within a private property and only guided visits led by a locally hired guide are possible. At Pedra da Boca, access is controlled but the scenery and one of big tafoni can be viewed from public ground near the religious sanctuary at the base of one the hills. The inselberg landscape around Quixadá can be easily appreciated from public roads and several viewing spots, including Pedra de Cruzeiro in the center of the town. The most famous Pedra da Galinha inselberg may be climbed. There are trails to most inselbergs in the area, but they cross private properties and therefore require authorization to enter.

Geo-interpretation is nonexistent at the moment, and these sites lack on-site facilities which would help understanding of landforms and geology by visitors. Neither interpretative panels exist nor mobile applications have been used. Pai Mateus site is covered in the Web-based database of Brazilian geosites (Lages et al. 2013), although the description is biased toward rock record rather than landforms, and the surroundings of Quixadá and Pai Mateus feature in an illustrated popular science presentation of granite sceneries of the Brazilian Northeast (Maia et al. 2018).

Conclusions

It is increasingly realized that geoheritage requires various forms of protection, conservation, and promotion, to account for its diversity, significance, and possible impact beyond the discipline of geosciences. Therefore, the concept of Key Geoheritage Area project is being discussed. This paper contributes to the subject by presenting three localities from northeast Brazil, each characterized by spectacular landform assemblages developed upon granite intrusions within a cratonic setting. Collectively, they illustrate archetypal granite sceneries: low domes within a plateau, a cluster of tall domes within an escarpment and an inselberg landscape. Each of these landscapes hosts diverse medium-size and minor landforms due to weathering, mass movements and surface runoff. Among them, gigantic tafoni, hollowed out boulders and deep karren provide some of the best examples of its kind globally. Being relatively easily accessible, with some tourist infrastructure already present, these sites seem good candidates as reference localities within the Key Geoheritage Area project.

Acknowledgments The authors are grateful to two anonymous reviewers whose comments helped us to strengthen the argument and improved presentation. The authors are grateful for the funding granted by CNPq (National Council for Scientific Research) in Brazil.

References

Almeida AR, Ulbrich HGJ (2003) O Batólito Granítico Quixeramobim-Ce. - Aspectos estruturais internos e mecanismo de alojamento crustal. Revista de Geologia UFC, Fortaleza

Alvares CA, Stape JL, Sentelhas PC, Gonçalves JLM, Sparovek G (2013) Köppen's climate classification map for Brazil. Meteorol Z 22:711–728

Arthaud (2007) Evolução Neoproterozóica do Grupo Ceará (Dominio Ceará Central, NE Brasil): da sedimentação à colisão continental brasiliana. PhD Thesis, Instituto de Geociências da Universisade de Brasília

Atlas digital de geologia e recursos minerais (2003) Mapas na escala 1: 500,000. Serviço Geológico do Brasil – CPRM (digital midia)

Auler AS, Cassimiro R, Lima TF, Maio MM (2007) Morphology and genesis of large tafoni in eastern Brazil. In: Vidal-Romaní JR (ed) Proceedings International Conference on Granite Caves, La Coruña, p 15

Brilha J (2016) Inventory and quantitative assessment of geosites and geodiversity sites: a review. Geoheritage 8:119–134

Brilha J (2018a) Geoheritage and Geoparks. In: Reynard E, Brilha J (eds) Geoheritage. Assessment, protection and management. Elsevier, Amsterdam, pp 323–335

Brilha J (2018b) Geoheritage: inventories and evaluation. In: Reynard E, Brilha J (eds) Geoheritage. Assessment, protection and management. Elsevier, Amsterdam, pp 69–85

Dragovich D (1969) The origin of cavernous surfaces (tafoni) in granitic rocks of southern South Australia. Z Geomorph NF 13:163–181

Fetter AH, Schmus WRV, Santos TJS, Neto JNN, Arthaud MH (2000) U-Pb and Sm-Nd geochronological constraints on the crustal evolution and basement architecture of Ceará State, NW Borborema Province, NE Brazil: implications for the existence of the Paleoproterozoic Supercontinent “Atlantica”. Rev Brasileira Geociências 30:102–106

Galindo AC, Souza ZS, Dantas EL, Antunes AF, Dias LGS, Alves da Silva FC, Laux JH (2005) Geocronologia U-Pb de granitóides tipo Itaporanga (Monte das Gameleiras e Serrinha), Maciço São José do Campestre, NE do Brasil. In: SBG/Núcleo Nordeste, Simp Geol Nord 21, Recife, Boletim 19: 150–152

Groom K, Allen CD, Mol L, Paradise TR, Hall K (2015) Defining tafoni: re-examining terminological ambiguity for cavernous rock decay phenomena. Prog Phys Geogr 39:775–793

Gunnell Y, Braucher R, Bourlès D, André G (2007) Quantitative and qualitative insights into bedrock landform erosion on the south Indian craton using cosmogenic nuclides and apatite fission tracks. Geol Soc Am Bull 119:576–585

Inkpen R, Hall K (2019) Universal shapes? Analysis of the shape of Antarctic tafoni. Geosciences 9:154

Japsen P, Bonow JM, Green PF, Cobbold PR, Chiossi D, Lilletveit R, Magnavita LP, Pedreira A (2012) Episodic burial and exhumation in NE Brazil after opening of the South Atlantic. Geol Soc Am Bull 124:800–816

Ju SO, Woo KS (2018) A proposal of the Key Geoheritage Site program in IUCN. In: Vogel B, Woo KS, Grunewald R, Crofts R, Stolpe G (Eds), Global Geoheritage – International Significance and Biodiversity Values. Workshop Proceedings. BfN-Skripten 500. Bundesamt für Naturschutz (BfN), Bonn, Germany, pp 49–51

Klaer W (1956) Verwitterungsformen in Granit auf Korsika. Petermanns Geogr Mitt, Erg 261:1–146

Lages GA, Marinho MS, Nascimento MAL, Medeiros VC, Dantan EL, Fialho D (2013) Mar de Bolas do Lajedo do Pai Mateus, Cabaceiras, PB. Campo de matacões graníticos gigantes e registros rupestres de civilização pré-colombiana. In: Winge M, Schobbenhaus C, Souza CRG, Fernandes ACS, Berbert-Bonn M, Sallun Filho W, Queiroz ET (Eds) Sítios Geológicos e Paleontológicos do Brasil. SIGEP 068. http://sigep.cprm.gov.br/sitio068/sitio068.pdf (access date: 15-07-2018)

Lima GMP, Corrêa-Gomes LC (2015) Itatim geomorphological site: largest concentration of inselbergs in Brazil. In: Vieira BC, Salgado AAR, Santos LJC (eds) Landscapes and landforms of Brazil. Springer, Dordrecht, pp 371–380

Maia RP, Bezerra F (2020) Structural geomorphology in northeastern Brazil. SpringerBriefs in Latin American Studies. Springer, Cham

Maia RP, Nascimento MAL (2018) Relevos graníticos do Nordeste Brasileiro. Rev Brasileira Geom 19:373–389

Maia RP, Nascimento MAL, Bezerra FHR, Castro HS, Meireles AJA, Rothis LM (2015) Geomorfologia do campo de inselbergues de Quixadá, Nordeste do Brasil. Rev Brasileira Geomorf 16:239–253

Maia RP, Bastos FH, Nascimento MA, Lima DLS, Cordeiro AMN (2018) Paisagens Graníticas do Nordeste Brasileiro. UFC, Fortaleza

Migoń P (2006) Granite landscapes of the world. Oxford Uni Press, Oxford

Migoń P (2014) The significance of landforms – the contribution of geomorphology to the World Heritage Programme of UNESCO. Earth Surf Process Landf 39:836–843

Migoń P (2018a) Geoheritage and World Heritage Sites. In: Reynard E, Brilha J (eds) Geoheritage. Assessment, protection and management. Elsevier, Amsterdam, pp 239–247

Migoń P (2018b) Recognizing landforms of international significance. In: Vogel B, Woo KS, Grunewald R, Crofts R, Stolpe G (Eds), Global Geoheritage – International Significance and Biodiversity Values. Workshop Proceedings. BfN-Skripten 500. Bundesamt für Naturschutz (BfN), Bonn, Germany, pp 53–55

Morais Neto JM, Hegarty KA, Karner GD, Alkmin FF (2009) Timing and mechanisms for the generation and modification of the anomalous topography of the Borborema Province, northeastern Brazil. Mar Pet Geol 26:1070–1086

Morais Neto JM, Vasconcelos PM, Stone J (2010) Tuning the landscape evolution in the Borborema Province, northeastern Brazil, by reconciling low-temperature thermochronology and 10Be isotope analysis. In: VII SSAGI. South American Symposium on Isotope Geology, Brasília, 25th–28th July 2010

Nascimento MAL, Galindo AC, Medeiros V (2015) Ediacaran to Cambrian magmatic suites in the Rio Grande do Norte domain, extreme Northeastern Borborema Province (NE of Brazil): current knowledge. J S Am Earth Sci 58:281–299

Neves SP (2012) Granitos Orogênicos**:** da geração dos magmas à intrusão e deformação. Synergia, Rio de Janeiro

Operational Guidelines for the Implementation of the World Heritage Convention (2019). UNESCO World Heritage Centre, Paris (https://whc.unesco.org/en/guidelines; access date: 2020-04-17)

Paradise TR (2013) Tafoni and other rock basins. In: Shroder JF (ed) Treatise on geomorphology, vol 4. Academic Press, San Diego, pp 111–126

Peulvast J-P, Bétard F (2015) Landforms and landscape evolution of the equatorial margin of Northeast Brazil. Springer, Cham

Pye K, Goudie AS, Watson A (1986) Petrological influence on differential weathering and inselberg development in the Kora area of central Kenya. Earth Surf Process Landf 11:41–52

RADAMBRASIL (1981) Folhas SB-24/25 Jaguaribe/Natal: Geologia e mapeamento geológico, Geomorfologia, Pedologia, Vegetação e Uso potencial da terra. Levantamento de recursos naturais 23, Rio de Janeiro

Reynard E (2009) The assessment of geomorphosites. In: Reynard E, Coratza P, Regolini-Bissig G (eds) Geomorphosites. Pfeil Verlag, München, pp 63–71

Rodriguez Tribaldos V, White NJ, Roberts GG, Hoggard MJ (2017) Spatial and temporal uplift history of South America from calibrated drainage analysis. Geochem Geophys Geosyst 18:2321–2353

Roqué C, Zarroca M, Linares R (2013) Subsurface initiation of tafoni in granite terrains – geophysical evidence from NE Spain: geomorphological implications. Geomorphology 196:94–105

SEMA (2019) Monumento Natural Monólitos de Quixadá. https://www.sema.ce.gov.br (access date: 10-10-2019)

Thomas MF (1965) Some aspects of the geomorphology of domes and tors in Nigeria. Z Geomorph NF 9:63–81

Thomas MF (1978) The study of inselbergs. Z Geomorph NF, Suppl-Bd 31:1–41

Trindade IR, Martins SÁJ, Macedo MHF (2008) Comportamento de elementos químicos em rochas mineralizadas em ouro na Faixa Seridó, Província Borborema. Revista Brasileira de Geociências 38:303–318

Twidale CR (1962) Steepened margins of inselbergs from north-western Eyre Peninsula, South Australia. Z Geomorph NF 6:51–69

Twidale CR (1981) Granite inselbergs: domed, block-strewn and castellated. Geogr J 147:54–71

Twidale CR (1982) Granite landforms. Elsevier, Amsterdam

Twidale CR (1986) Granite platforms and low domes: newly exposed compartments or degraded remnants? Geogr Ann 68A:399–411

Twidale CR, Vidal Romaní JR (2005) Landforms and geology of granite terrains. Balkema, Rotterdam

Varajão CAC, Alkmin FF (2015) Pancas: the kingdom of bornhardts. In: Vieira BC, Salgado AAR, Santos LJC (eds) Landscapes and landforms of Brazil. Springer, Dordrecht, pp 381–388

Vauches A, Neves S, Caby R, Corsini M, Egydio-Silva M, Arthaud M, Amaro V (1995) The Borborema shear zone system, NE Brazil. J S Am Earth Sci 8:247–266

Veress M (2010) Karst environments. Karren formation in high mountains. Springer, Heidelberg

Wilhelmy H (1958) Klimamorphologie der Massengesteine. Braunschweig, Westermann

Wilhelmy H (1977) Verwitterungskleinformen als Anzeichen stabiler Grossformung. Würzb Geogr Arb 35:177–198

Woo KS, Ju SO, Brilha J (2018) Key Geoheritage Area: a potential new programme in IUCN for geoheritage conservation. In: Głowniak E, Wasiłowska A, Leonowicz P (Eds), Geoheritage and conservation: modern approaches and applications towards the 2030 Agenda. 9th ProGEO Symposium, Chęciny, Poland, 25-28th June 2018. Programme and Abstract Book. Faculty of Geology, University of Warsaw, p 20