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ORIGINAL ARTICLE

Guidelines for Management of Geoheritage: an Approach in the Sertão Central, Brazilian Northeastern Semiarid

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Abstract
The characterisation of geoheritage and the understanding of the physical and socio-cultural features of a territory are essential to achieve the major geoconservation goals: protection and sustainable use of exceptional elements of geodiversity. This research was done in the Sertão Central, an economic vulnerable area in the hinterland of northeast Brazil, remarked by the Caatinga Biome and a rocky, semiarid landscape. The area comprises an assemblage of deformed igneous and metamorphic rocks, such as gneisses, TTG rocks, schists, and granites. Starting from a regional geoheritage inventory done in 2015, fourteen geosites were selected and assessed, representing a wide regional tectonic evolution from the Precambrian West Gondwanan orogenesis to the Cenozoic development of particular examples of Brazilian granitic inselbergs. In addition to the inventory of geosites, six geodiversity sites were also evaluated, along with five geocultural sites, highlighting the cultural value of geodiversity in the area. Based on the available information, an analysis with the main features and spatial configuration of the geoheritage was developed, allowing to designate the most appropriate use for each geological site. Considering geoconservation as a geoscientific fostering for the sustainable development, our study suggests a set of general guidelines for the management of geoheritage, in order to facilitate the decision-making process by local managers and stakeholders as well as to promote the discussion on geotourism strategies for the region. Organised according to well-defined geoconservation strategies, these guidelines could enhance the sustainable development of vulnerable regions, such as Sertão Central itself.

Keywords Brazil · Caatinga · Geoconservation · Geosite · Inselberg

Introduction

Geoconservation is a modern applied geoscience that deals with the recognition and management of remarkable geodiversity elements, connecting nature conservation and sustainable development from a geological focus (Brilha 2005; Henriques et al. 2011). Geoconservation involves dynamic and multidisciplinary processes to provide strategies that meet local demands focused on sustainable activities, such as education and geotourism. Concerning geoconservation methods, the inventories are already established as the first and essential step for any geoconservation strategy (Lima et al. 2010) and should be accompanied by the quantitative assessment, necessary to order the priorities of protection and promotion of the geological sites, underlying their strengths and weaknesses, allowing a detailed analysis of the local geoheritage.

Many studies on geoconservation have been focused on methods for conservation and management of geological heritage (e.g., Santos-González and Marcos-Reguero 2019; Vegas and Díez-Herrero 2018; Fuertes-Gutiérrez and Fernández-Martínez 2010). Prosser et al. (2018) proposed a generic conservation framework based on audit and selection of geosites; analysis of conservation needs (regarding uses, characteristics, and threats) and a conservation and delivery plan, establishing a threat response plan, a management plan, and delivering responsibilities. In response for a demand of a Romanian aspiring geopark, Popa et al. (2017)

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have developed a management model based on the scientific, educational, and aesthetic value of geosites, considering their attractiveness or unattractiveness from the visitors' perspective. Both works seek to provide local managers with proper information for enhancing the protection and sustainable use of geosites.

As in many countries, geoheritage conservation in Brazil is a challenge due to the large size, limited application of environmental policies for the protection of geosites, and lack of education in geodiversity concepts (Lima et al. 2010; Mansur 2010). Geoconservation strategies based on solid and systematic geoheritage inventories are rare and most of the studies are performed as academic research (see Romão and Garcia 2017; Ruchkys et al. 2017). Even if this scenario fosters the development of geoconservation as a science, these institutions do not have legal attributions and financial capacity to carry out the geoconservation actions delineated by researchers. Some initiatives have been developed within the Brazilian Geological Survey (Rocha et al. 2016; Schobbenhaus and Silva 2012) and in territories aspiring to UNESCO Global Geopark but occasionally and without any framework of public policies.

In the State of Ceará, Northeast Brazil, a geoheritage inventory and assessment focused on the scientific value has identified 52 geosites related to the geodynamic evolution of the South American continent. Based on these results, a pilot area — the Sertão Central — was selected for the evaluation of geodiversity sites with potential for geotourism and development of a geoheritage management plan (Moura et al. 2017, 2018). Sertão is a hinterland, semiarid region, characterised by long periods of drought and a rocky, flat landscape with stony soils where the Caatinga Biome predominates. The local landscape holds a rich *sertaneja* culture closely related to the geodiversity, conditioning the use of land, and likewise expressed in toponymies, cultural symbols, and popular tales.

Although the landscape attracts a considerable number of visitors, there is no strategy promoting and conserving the geodiversity, except for a few protected areas. Another important issue is the absence of staff in local administrations dedicated to nature conservation. For this reason, any geoconservation guidelines in the area should be clear to non-experts. In this context, the aim of this research is to elaborate guidelines for a management plan based on the evaluation of geological sites regarding their protection and potential to be used to promote the conservation and the geotourism in the area studied.

Study Area

The study area has a surface of about 9720 km^2 and is included in the Sertão Central administrative unit of the state of Ceará (Ceará 2015), comprising the municipalities of Mombaça, Pedra Branca, Quixadá, Quixeramobim, and Senador Pompeu. Almost 260 thousand people live in those cities (39% in rural zones) with a population density of about 28 inhabitants/km^2 (UNDP - United Nations Development Programme 2013). Vulnerable socioeconomic conditions predominate, with a Human Development Index of 0.621, below the Brazilian national average (0.727) (UNDP - United Nations Development Programme 2013).

Geologically, Sertão Central comprises an assemblage of deformed igneous and metamorphic rocks, representing almost 2.9 Ga of geological history (Fig. 1). To the northwest, the oldest units are Palaeoproterozoic gneisses surrounding an Archaean nuclei composed of TTG rocks (tonalite-trondhjemite-granodiorite), metavolcano-sedimentary sequences (greenstones sequences), and a mafic/ultramafic complexes (Brito Neves et al. 1999; Costa et al. 2015). To the southeast, Palaeo- to Neoproterozoic supracrustal sequences related to the Ceará Complex occur (Fetter et al. 2000; Santos et al. 2015). Neoproterozoic to Ordovician post-collisional and anorogenic alkaline granite bodies are widespread in the whole area (Castro et al. 2012). The entire set was affected by low-angle tangential tectonics creating predominantly NE-SW-oriented strike-slip ductile shear zones (Arthaud et al. 2008).

The landscape is dominated by a large peripheral flat depression with inselbergs and residual massifs scattered throughout the area (Lima et al. 2000). Particularly in the eastern part of the study area, these inselbergs present diversified forms, from cohesive concave-convex to fractured shapes, responding to differential weathering acting over diverse lithologies (Maia et al. 2015). Residual crystalline massifs are also spreading along the peripheral depression, mostly dissected in convex-pointed slopes (Lima et al. 2000). As in the most part of Northeast Brazil, the Sertão Central is affected by a harsh semiarid climate characterised by sparse and irregular rainfall and intense evaporative conditions.

Methods

Based on the set of sequential steps that constitute a geoconservation strategy, this work began with the general recognition of the geodiversity of the study area, followed by the selection of its exceptional elements in order to identify the qualities and conservation needs of these geological sites. This assessment made it possible to outline management proposals, taking into account sustainable use and the enhancement and promotion of geodiversity for local communities.

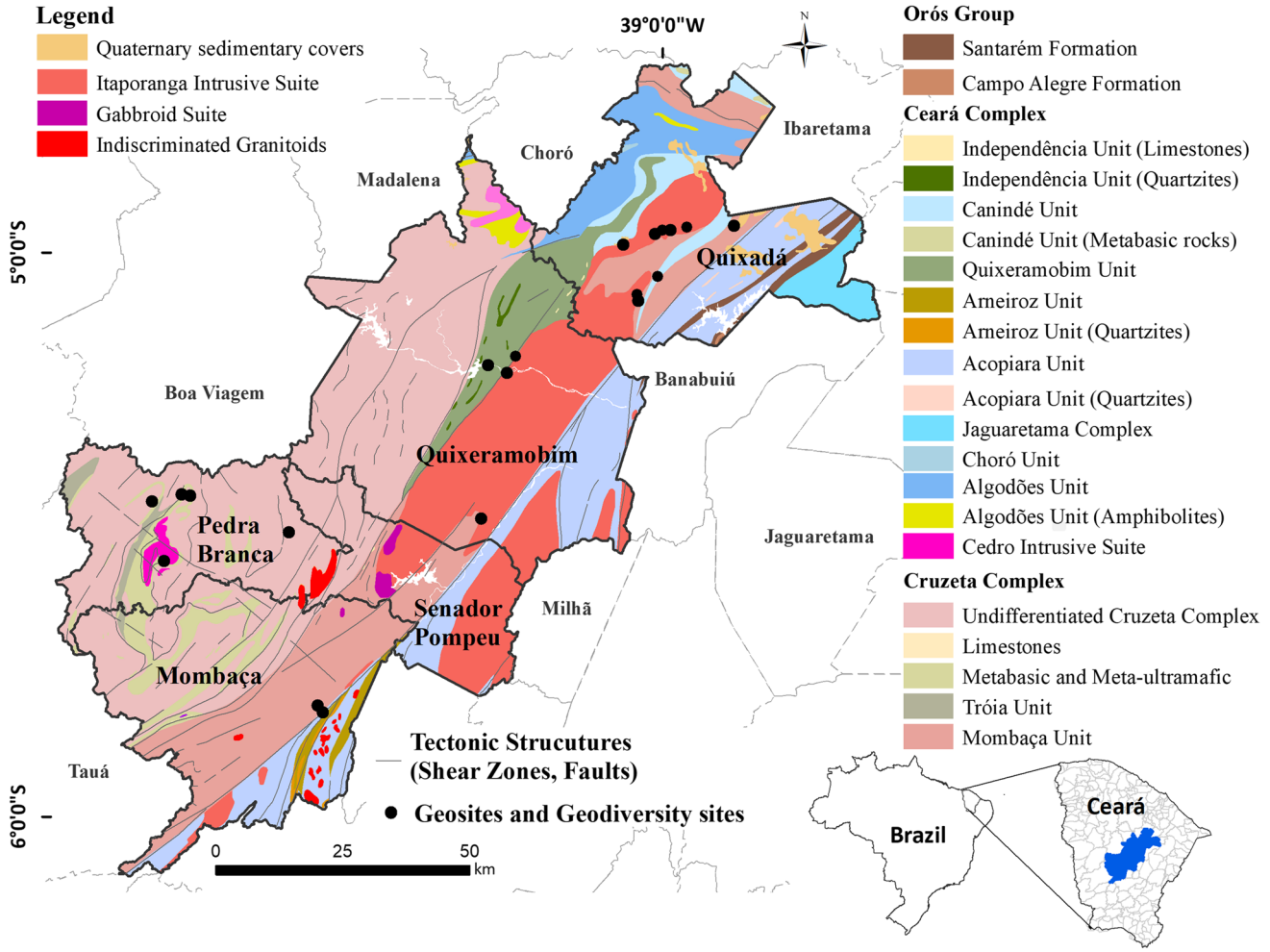

Fig. 1 Simplified geological map of the study area (Adapted from Cavalcante et al. 2003)

Inventory and Assessment of Geological Sites

This work follows the nomenclature proposed by Brilha (2016), in which geoheritage is a set of geosites with scientific value, and a geodiversity site is a geological site with any other type and level of value. Here, the geosites were selected from a previous geoheritage inventory focused on scientific value and developed according to Brilha's (2016) method. This inventory was based on geological frameworks seeking to select the most representative geosites, considering the regional tectonic evolution, mainly that related to the West Gondwana orogenesis. A list of potential geodiversity sites was created based on previous geosite inventories, tourism advertisement materials and literature review about natural heritage, and cultural and tourism aspects. Fieldwork was done to collect in situ data and to characterise both the site and the surrounding areas. Geodiversity sites were selected using the following qualitative criteria: scenery, interpretative potential, accessibility, and safety (Brilha 2016).

The quantitative assessment was done using the System of Register and Quantitative Assessment of Geosites and Geodiversity Sites — *GEOSSIT* (https://www.cprm.gov.br/geossit/) developed by the Geological Survey of Brazil (Rocha et al. 2016). Based on information supplied by the user, this online system automatically calculates the scientific value, potential educational and touristic uses, and degradation risk. *GEOSSIT* system is based on Brilha (2005, 2016) and Garcia-Cortés and Carcavilla-Urquí's (2009) methods. It consists of assigning numerical values within parameters available in distinct sets of criteria. The parameters are scored from 0 to 4 and each criterion has different weights (Table 1).

The site typology of Fuertes-Gutiérrez and Fernández-Martínez (2010) was used to characterise both geosites and geodiversity sites according to their size and geometry: area, complex area, point, viewpoint, and section.

Table 1 Summary of criteria applied for the quantitative assessment in *GEOSSIT* system

Scientific value	Degradation risk	Educational use potential	Geotourism use potential
-Representativeness (30%) -Key locality (20%) -Scientific knowledge (5%) -Integrity (15%) -Variety of geological elements (5%) -Rarity (15%) -Use limitations (10%)	-Deterioration of geological elements (35%) -Proximity to areas with potential to cause degradation (20%) -Legal protection (20%) -Accessibility (15%) -Density of population (10%)	-Vulnerability (10%) -Accessibility (10%) -Use limitations (5%) -Safety (10%) -Logistics (5%) -Density of population (5%) -Association with other values (5%) -Scenery (5%) -Singularity (5%) -Observation of conditions (10%) -Didactic potential (20%) -Variety of geological elements (10%)	-Vulnerability (10%) -Accessibility (10%) -Use limitations (5%) -Safety (10%) -Logistics (5%) -Density of population (5%) -Association with other values (5%) -Scenery (15%) -Singularity (10%) -Observation of conditions (5%) -Outreach potential (10%) -Economic level (5%) -Proximity of recreational areas (5%)

Source: Brilha (2016)

Selection of Geocultural Sites

A brief selection of geocultural sites — in the sense of Reynard and Giusti (2018) — was done to identify resources that could support a holistic and broader concept of geotourism (Arouca 2011). These sites were selected according to the existence of a clear geological relation with (a) local toponymy; (b) cultural symbols; (c) historical monuments; (d) sacred and archaeological sites, and (e) examples of use of local stone as building material. This selection was based on data from the Brazilian Institute of National Historic and Artistic Heritage (IPHAN), from the State of Ceará Council for the Preservation of Cultural Heritage (COEPA), and from tourism advertising material of each municipality of the study area.

Defining Guidelines for a Management Plan

Results from the quantitative assessment gathered in this work and the results obtained in a previous geoheritage inventory were integrated and analysed taking into account the vulnerability (degradation risk) and potentialities of each geological site. The geosites and geodiversity sites were organised into three distinct categories of sustainable use, indicating the most appropriate use: (i) geological sites that should be considered only for scientific purposes and for the training of professionals and future geoscientists; (ii) geological sites that can be used by students of various age levels, and (iii) geological sites suitable for the most varied sustainable uses, especially for geotourism activities.

Based on this information, promotion actions (e.g., tourism advertisement and dissemination to the local community and schools) should be directed to specific audiences and the monitoring periods were defined. At this stage, the statutory protection and the physical integrity conditions of geological sites were also evaluated, and priority measures for site conservation were suggested, following geoconservation practices already described in the literature, such as signage and structural interventions.

This set of measures allowed the definition of guidelines for a management plan, with recommendations of suitable use, considering proposals for the protection of physical integrity, actions to valuating and promotion, and frequency for in situ monitoring.

Selecting the Exceptional Elements of Geodiversity in the Sertão Central

Geosites

Fourteen geosites were identified in the study area, taken from the first systematic inventory developed in the State of Ceará (Moura et al. 2017; 2018). Their scientific value is strongly related to the Precambrian geological evolution of the South American continent, especially the West Gondwana orogenesis during the Neoproterozoic. These geosites represent six geological frameworks that were defined to systematise the key events of the geological history of Sertão Central (Table 2).

Geodiversity Sites

Six geodiversity sites with geotourism relevance were identified in this work (Fig. 2). A qualitative touristic assessment indicates good interpretative potential for all types of audience. Some of those sites are already attracting visitors due to scenic values and peculiar geomorphology. All sites are also easily accessible by car (Table 3). The rocks cropping out in these sites are of different types, namely

Table 2 Summary of geological frameworks and geosites in Sertão Central

Geological frameworks	Geosites
Archaean and Palaeoproterozoic terranes Oldest lithological group from Sertão Central and one of the oldest from Northeastern Brazil, constituting the basement of the study area	-Tonalitic Gneiss of Mombaça (SV:365/DR:370/PEU:215/PTU:210) -Tonalitic Gneiss of Extrema (SV:305/DR:175/PEU:200/PTU:175) -Tonalitic Gneiss of Pedra Branca (SV:245/DR:265/PEU:200/PTU:190) -Pedra Branca Greenstone Sequence (SV:345/DR:370/PEU:195/PTU:175)
Supracrustal sequences Comprises various associations of Palaeo- to Neoproterozoic terrigenous metasedimentary rocks whose depositional processes are related to the breakup of Rodinia supercontinent	-Metasedimentary Megaxenoliths of Juatama (SV:265/DR:110/PEU:280/PTU:245) -Garnet Schist of Quixeramobim (SV:265/DR:195/PEU:225/PTU:220)
Shear zones Records of intense Neoproterozoic tectonism, characterised by strike-slip ductile shear zones and nappe structures	-Evidences of Thrusting of Pedra Branca (SV:305/DR:370/PEU:205/PTU:185) - Gneiss Mylonitic of Quixadá (SV:265/DR:245/PEU:220/PTU:210) -Mylonites of Mombaça (SV:195/DR:370/PEU:180/PTU:160)
Granite rocks Diverse granite assemblage associated to the Brasiliano-Pan African Cycle, with predominance of high-K calc-alkaline composition	-Quixadá Granite (SV:195/DR:300/PEU:280/PTU:225) -Quixeramobim Granite (SV:295/DR:245/PEU:265/PTU:210
Mineralisation Different types of mineral deposits, some of them with high economic value	-Chromitites of Tróia (SV:260/DR:320/PEU:165/PTU:150)
Geomorphological units The most representative landforms of the study area, strongly influenced by the Neoproterozoic structural control and the climate variability	-Inselberg Fields of Quixadá (SV:300/DR:210/PEU:325/PTU:310) -Inselberg of Pedra do Cruzeiro (SV:265/DR:190/PEU:335/PTU:320)

The numerical values correspond to the quantitative assessment (*SV*, scientific value; *DR*, degradation risk; *PEU*, potential educational use, and *PTU*, potential touristic use). Quantitative assessed values range from 0 to 400. Modified from Moura et al. (2017; 2018)

granites, gneiss-migmatites, and mylonites. Inselbergs are the main typical landform in the Sertão Central landscape. Other small-scale landforms formed by dissolution and fracturing processes also occur (flutes, honeycombs, and tafoni, etc.).

The geodiversity sites were quantitatively assessed according to their degradation risk and educational and touristic potential uses. Results showed both significant educational and touristic potential uses, ranging from 205 to 345 and from 185 to 320, respectively, in a total of 400 points. The risk of degradation ranges from 120 to 215, in which four geodiversity sites have low risk (< 200) and two sites moderate risk (200–300) (Table 3).

Geocultural Sites

Some geodiversity elements have a particular cultural meaning in Sertão Central, namely as symbols of some municipalities and as justification for a *sense of belonging* among the communities (Fig. 3). A good example is the name of Pedra Branca (White Stone) municipality that is related with a fragment of milky quartz that is exposed in the central square of the town and protected by a glass dome. The Pedra da Galinha Choca (Broody Hen Stone), one of the inselbergs from the Inselbergs field of Quixadá geosite, is the major cultural symbol of the city and is included in the county's flag and arms.

In Sertão Central, some geodiversity elements have religious meanings, such as the Inselberg of Pedra do Cruzeiro, where religious ceremonies were celebrated until mid-1990s, the São Francisco de Assis Grotto devoted to this catholic saint, and the Urucum Mountain where a Christian sanctuary is located.

In the entire Sertão Central, there are many examples about the use of local stone as building material. Archaeological sites with rock paintings and engravings occur widespread in the whole area, as the rock paintings on granite from the Fofô Lake (Fig. 3). Besides that, the Nossa Senhora Rainha do Sertão Church, the Chapel of São Francisco de Assis, and the sculpture of Santo Antonio in the Historical Centre of Quixeramobim city were built using local granite and mylonite from nearby quarries (Fig. 4).

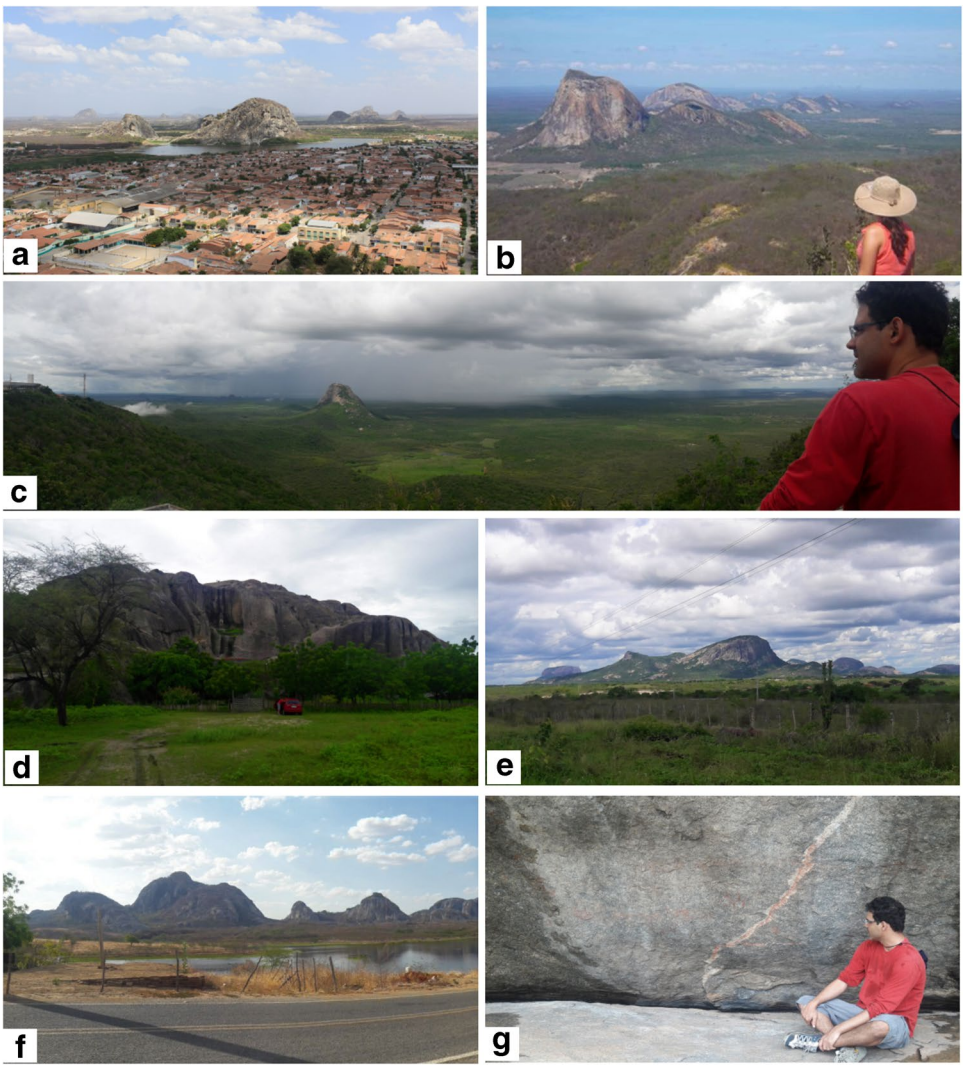

Fig. 2 Geodiversity sites in Sertão Central. **a** Lagoa dos Monólitos. **b** View from Pedra dos Ventos. **c** View from Serra do Urucum. **d** São Francisco de Assis Grotto. **e** Pedra da Baleia. **f/g** General perspective and detail of granite at Lagoa do Fofô

Assessment and Proposals for Geoconservation

Geosites and Geodiversity Sites Analysis

The scientific value of geosites ranges between 195 and 365, being the Greenstone Sequence and the Tonalitic Gneiss of Mombaça sites the most significant ones. Concerning the potential for educational use, the values range between 165 and 345, similar to the potential touristic use (150–320), where the Inselberg of Pedra do Cruzeiro, Monólitos Lake, Urucum Mountain, and Pedra dos Ventos sites stand out.

The degradation risk is low (< 200) in 40% of the geological sites and moderate (200–300) in 35% sites. Among them, geological sites included in one of these categories are predominant: area, complex area, or viewpoint. Most of these sites (75%) have a geomorphological character which contributes to a low to moderate risk of degradation, while only seven are under a statutory protection. The degradation risk is low (< 300) in 25% of total sites, increasing for point and section categories, because their surface is usually smaller and because they are in areas with no statutory protection (Fig. 5).

The geological sites of Mombaça present a high risk of degradation and have no statutory protection. In Pedra Branca, there are geological sites with different risk of degradation; however, none of them have statutory protection or potential for tourism. The scientific value is the main reason for the conservation of geological sites in both municipalities (Fig. 6).

Quixadá city contemplates most of the assessed geological sites, mostly inselberg and other geomorphological forms. The risk of degradation of the geological sites ranges from low to moderate, and only two sites are not located in areas with statutory protection (Gneiss Mylonitic of Quixadá and Quixadá Granite). The sites of the municipality have high tourist value, and many of them are already used in regional tourism strategies. In Quixeramobim, the risk of

Table 3 Main characteristics of the six geodiversity sites

General description	Observation conditions	Interpretative elements	Accessibility	Safety and logistics
São Francisco de Assis Grotto It is an inselberg with a small artificial grotto. The site is already a touristic attraction in Quixadá due to the existence of a catholic chapel built with local stones (granite and mylonitic gneiss) and a garden	Geological elements presented in a very clear and expressive way to all types of public	Minerals of igneous rocks; use of geodiversity elements as building stones	Accessible by paved road with parking for vehicles	Stairs, handrails, fences, rest area with roofing Mobile phone coverage Located less than 10 km form emergency services
	Category: Area	PEU 325	PTU 275	DR 205
Monólitos Lake It comprises an inselberg and a small water reservoir (*Eurípides Pinheiro* Dam) both located in the urban area of Quixadá. The inselberg is composed of porphyritic granite and characterised by dissolution landforms, as flutes and *tafoni*	Geological elements in a very clear and expressive way to all types of public	Dissolution landforms; relationship between natural elements and uncontrolled urbanisation	Accessible by paved road with parking for vehicles	Food and beverage, resting area with roofing Mobile phone coverage Located less than 5 km form emergency services
	Category: Area	PEU 335	PTU 320	DR 190
Pedra dos Ventos (Wind Stone) It is an inselberg with gneiss-migmatite composition surrounding the granite inselbergs of Quixadá. Good viewpoint to several landforms in this arid semiarid landscape	Geological elements in a very clear and expressive way to all types of public	Structures of metamorphic rocks; variety of landforms and inselbergs	Accessible only by 4×4 vehicles or by hiking trail with medium–high difficulty	Hotel, handrails, fences, and rest area with roofing Unstable mobile phone coverage Located less than 5 km form emergency services
	Category: Area	PEU 335	PTU 310	DR 170
Urucum Mountain Small gneiss-migmatite ridge where a catholic sanctuary was built. Many inselbergs and the large depression as well as urban area of Quixadá can be observed from its top	Geological elements in a very clear and expressive way to all types of audience	Natural and cultural elements building the landscape; cultural value of geoheritage	Accessible by paved road with parking for vehicles	Restaurant, stairs, handrails, fences, rest area with roofing Mobile phone coverage Located less than 10 km from emergency services
	Category: Viewpoint	PEU 345	PTU 320	DR 190
Pedra da Baleia (Whale Stone) Gneiss-migmatite inselberg which represents a recognised and remarkable toponymy of the region, marking the border between Quixadá and Quixeramobim municipalities. Looking from the distance, the contour of the inselberg resembles a whale	Geological elements in a very clear and expressive way to all types of audience	Landforms; cultural value of geoheritage	Accessible by paved road with parking for vehicles	Without any safety or infrastructure facilities Mobile phone coverage Located less than 10 km from emergency services
	Category: Area	PEU 305	PTU 205	DR 215

Table 3 (continued)

General description	Observation conditions	Interpretative elements	Accessibility	Safety and logistics
Fofô Lake Inselberg field of Quixeramobim in the contact between the Neoproterozoic granites and the Palaeoproterozoic migmatites. The site is home of several rock engravings, greatly affected by weathering	Geological elements in a very clear and expressive way to all types of audience	Landforms; use of geodiversity elements through the human history	Accessible by a gravel road without parking for vehicles	Without any safety or infrastructure facilities Unstable mobile phone coverage Located less than 20 km from emergency services
	Category: Area	PEU 250	PTU 185	DR 120

PEU, potential educational use; *PTU*, potential touristic use; *DR*, degradation risk. The numerical values range from 0 to 400

degradation ranges from low to moderate and only one site has no statutory protection. The geological sites in both municipalities present high educational value and potential for increasing tourism value through promotion and valuating actions (Fig. 6).

Guidelines for Sites Management

These preliminary guidelines intend to help local managers with suggestions of actions to assure the integrity, valuating, promotion, and monitoring of geoheritage in the study area (Table 4). This plan represents a general framework for the conservation action. From here, more detailed and specific plans can be derived for each geological site.

The integrity of a geological site is essential in any geoconservation strategy and it might be related with the statutory protection and its physical integrity. Regarding statutory protection, the Monoliths of Quixadá Natural Monument is a protected area established by the Ceará State. Pedra da Galinha Choca hill is under protection as natural heritage according to the Brazilian Institute of National Historic and Artistic Heritage (IPHAN, process number 1403/1997), and there is also a study aiming to protect all the surrounding landscape (process number 1377/1996). The Pedra do Cruzeiro Inselberg and the Monoliths Lake sites are both protected by the Quixadá Municipal Master Plan. For its turn, the Fofô Lake site is protected due to its archaeological features, since in Brazil, all archaeological sites have a specific statutory protection under the auspices of IPHAN. Also, in Brazil, some areas are classified as Area of Permanent Preservation (APP) to protect the water resources, landscape, soils, geological stability, and biodiversity, according to the Brazilian National Forest Code. Finally, the sites Garnet Schist of Quixeramobim and Metasedimentary Xenoliths of Juatama are both located inside an APP. For all these sites, the statutory protection is already ongoing.

For the remaining sites without a statutory protection, since they are small and isolated outcrops, we suggest the use of specific environmental protection zones, as part of the municipal master plan. Currently, Pedra Branca, Quixadá, and Quixeramobim municipalities have already legislation regarding environmental protection zones (BRASIL 2018) with a possible application to some of these sites.

Considering the physical integrity of sites, we propose a set of actions that should be implemented in a short term for each geological site or for a set of geological sites with similar characteristics. Firstly, the people responsible for geological sites in private areas should be reported to the municipality, and the area of the site must be delimited with a geoconservation expert's help. Publicity actions and scientific dissemination should be implemented in the communities, showing the scientific significance and explaining which activities are appropriate for each geoheritage site.

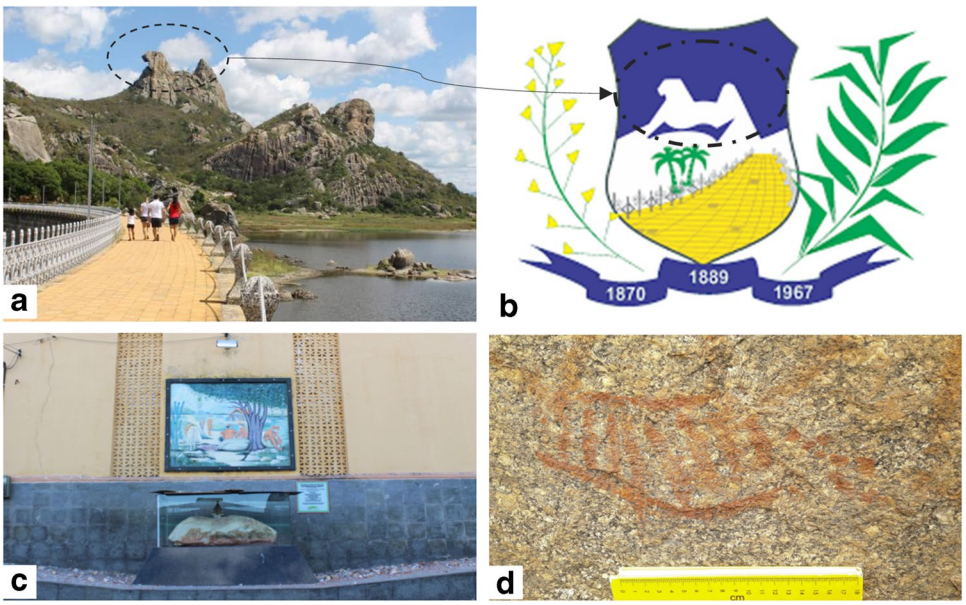

Fig. 3 Examples of the cultural value associated with geodiversity elements in the study area. **a** The Cedro Dam, a water reservoir, and the Pedra da Galinha Choca inselberg. **b** Quixadá's arms showing the contour of Pedra da Galinha Choca (Source: Quixadá 2010). c White stone (milky quartz) that gave the name to Pedra Branca city. d Example of rock paintings on granite in Quixeramobim city

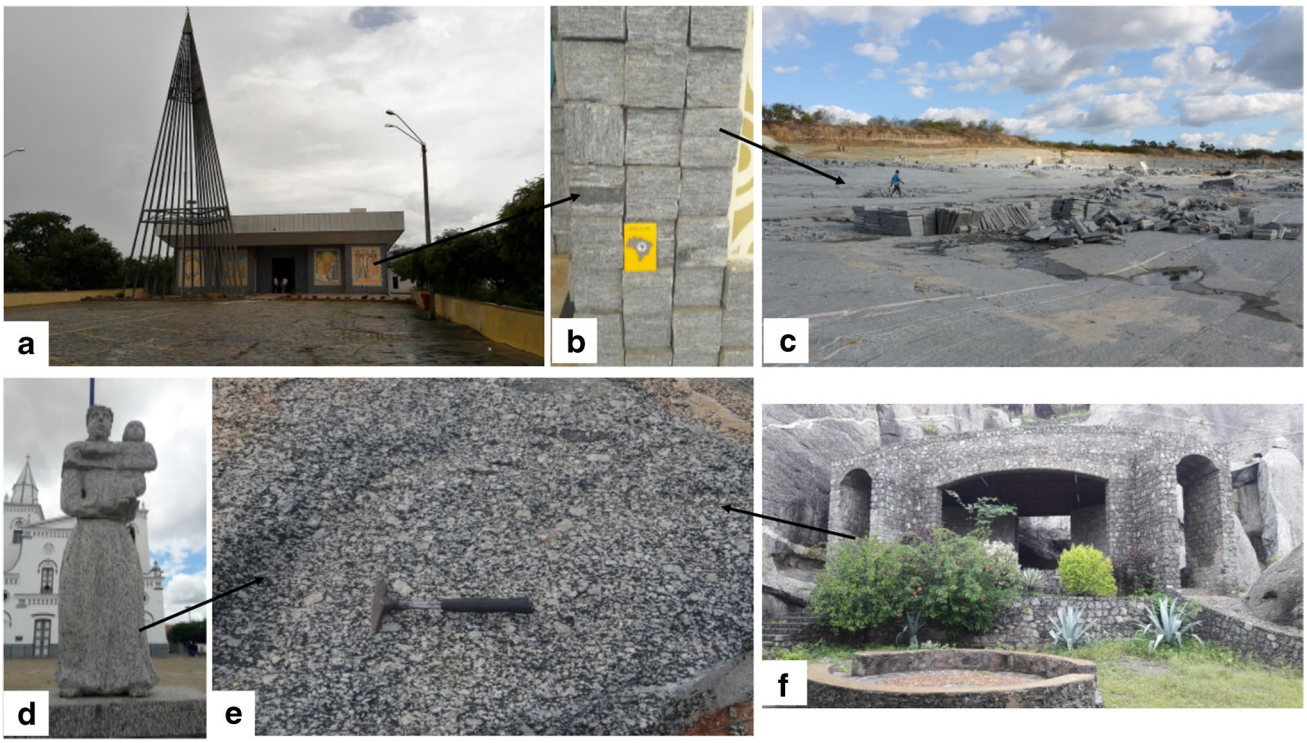

Fig. 4 Examples illustrating the use of local stone as building material in the study area. **a** Nossa Senhora Rainha do Sertão Church located on the top of Urucum Mountain geosite. **b** Mylonites used in the church walls. **c** Quarry of mylonite gneiss geosite use in the church. **d** Stone sculpture of Santo Antonio, in the centre of Quixeramobim city. **e** Detail of granite used in the chapel of São Francisco de Assis and in the stone sculpture. **f** São Francisco de Assis chapel made with the local granite and mylonite from quarry above mentioned

Additionally, we also suggest the installation of signage, prohibition of unmarked trampling and the removal of vegetation cover that might be affecting the site. Annual monitoring is recommended for sites with low risk of degradation, biannual for sites with moderate risk, and quarterly for sites with a high risk of degradation. Specific monitoring actions should be defined together with local managers, considering the logistics and infrastructure of each municipality.

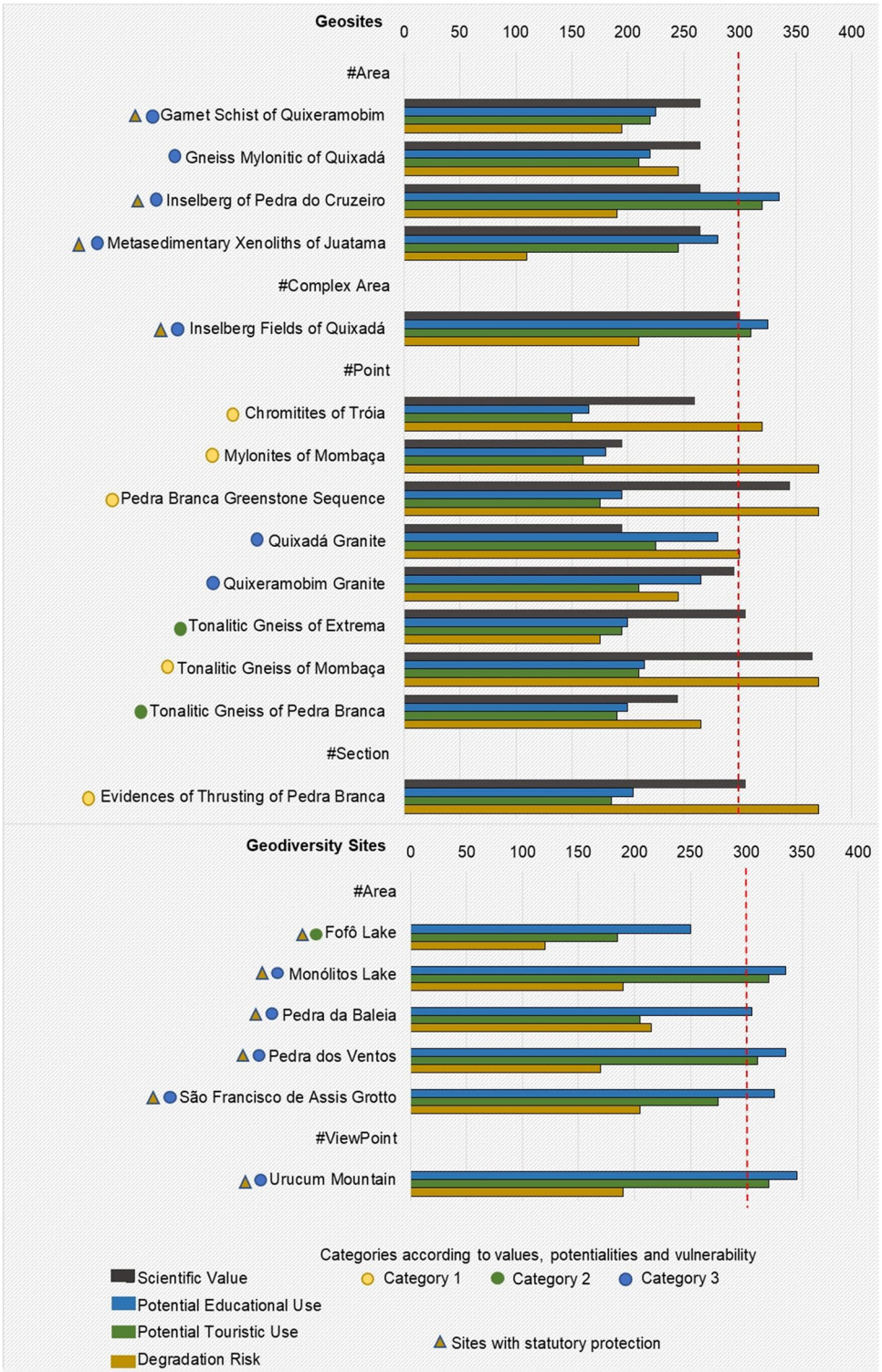

Fig. 5 Scientific value, degradation risk, educational and touristic potential uses, and recommended use of the geosites and geodiversity sites in Sertão Central, assorted by typological categories. Degradation risk classes: low (< 200), moderate (201–300), and high (301–400). The red dashed lines indicate a high DR (above 300 points)

Category	Degradation Risk	Potential Use
Only for scientific purpose and for training of professionals and students	high degradation risk (>300)	regardless potential use or associated value
Scientific and educational purposes	moderate (>200 and <300) or low degradation risk (<200)	potential educational use >200 and potential touristic use <200 or sites with archaeological records associated
Suitable for any sustainable use, especially for geoturism activities	low degradation risk (<200)	educational and touristic potential use >200

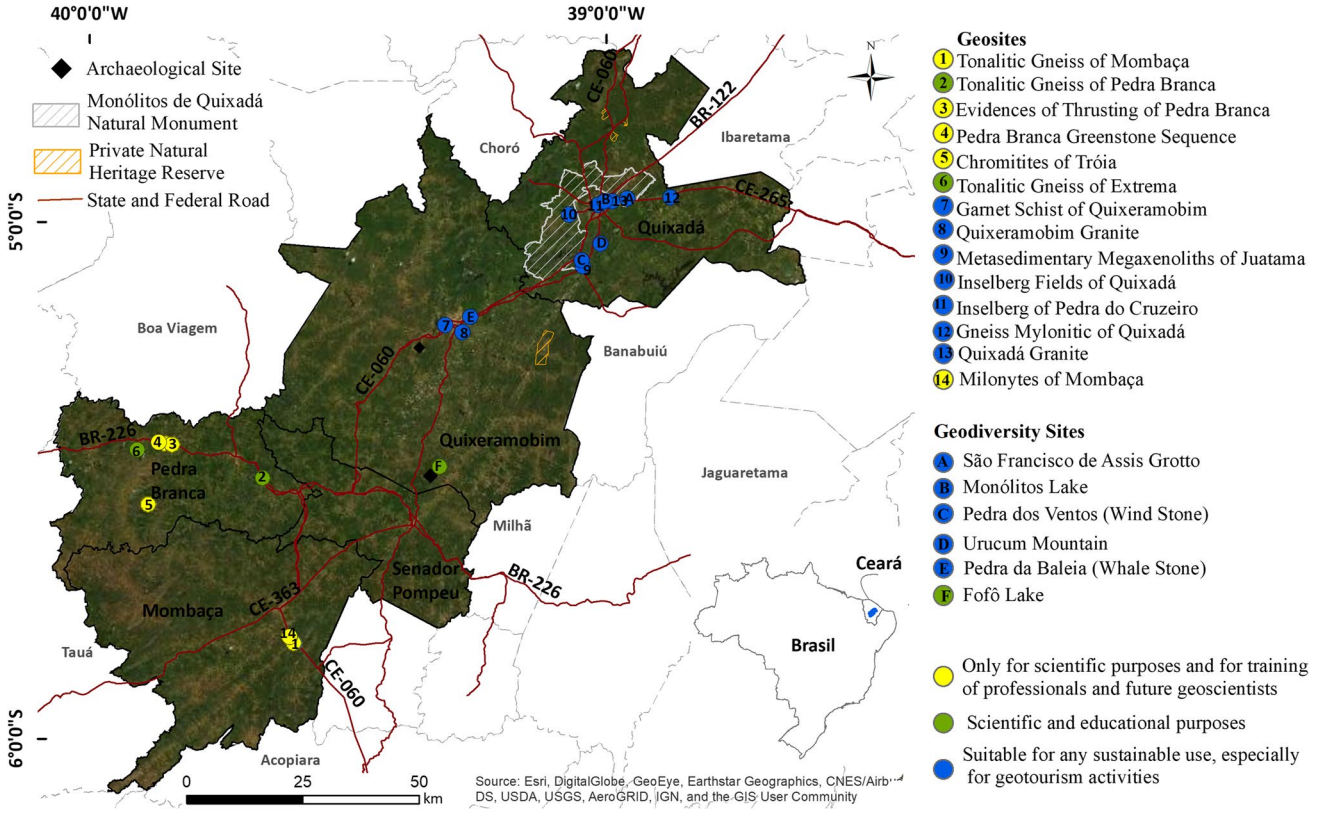

Fig. 6 Distribution of geosites and geodiversity sites according to the recommended use

After ensuring that the physical integrity is maintained, management actions should seek to valuate and promote the geological sites, namely the setup of footbridges, handrails, safety railings, sitting, and roofing facilities, as well as the marking of trails and the installation of interpretative panels.

In a further stage, it will be necessary to define the interpretation strategy. We propose to define the target audience for each site based on the risk of degradation and its potential use, considering as audience the local community, schoolchildren, and tourists (local, regional, and national visitors).

Schoolchildren are the main audience for 50% of geological sites, and, considering the number of students in the study area (including elementary and high school education), according to Brasil (2018), the dissemination actions have the potential to reach approximately 47,000 students from 248 schools. The numbers are also encouraging for those geological sites recommended for tourists as the semi-arid of the Ceará received about 238,000 tourists in 2016 (CEARÁ 2016), and many of them could be attracted to a sustainable geotourism offer in the Sertão Central.

Seabra (2007) had already indicated the potential of geodiversity for tourism strategies in the hinterland of Northeastern Brazil. Our results reaffirm that the granite and gneiss-migmatite sites with diversity of landforms are a strong starting point to promote geotourism activities in Sertão Central. For instance, the inselbergs of Quixadá are internationally recognised as a remarked landscape feature by the World-Famous Mountain Association (WFMA). Indeed, many geosites and geodiversity sites are already well-known touristic places, but most often, the geological interest is not even mentioned.

The Sertão Central landscape also offers a range of possibilities for geotourism activities such as hiking trails, cycling tours, photo tours, and leisure, as well. Such elements can be included in a geotourism planning once supported by a tourist guide, guidebooks, and/or interpretative panels. Commonly adopted by managers of UNESCO Global Geoparks, the development of geological routes as a strategy for geotourism has shown positive results, as in the Arouca and Basque Coast UNESCO Global Geoparks (Hilario 2012; Rocha 2016). This strategy could be also applied in Sertão Central in order to join diverse natural and cultural elements of the territory. A study made by Lima (2016) in Quixadá municipality has also identified a high potential for the development of geotourism in this area.

In conclusion, the proposed guidelines require the participation of decision-makers to assure the implementation of conservation practices, while the selecting, assessing, and planning actions can be proposed by geoscientists. Prosser

Table 4 Preliminary proposed actions for management of geosites and geodiversity sites in the Sertão Central's municipalities

Geosites and geodiversity sites	Statutory protection	Protection of physical integrity	Actions to valuating and promotion	Audience	Monitoring
Mombaça					
Tonalitic Gneiss of Mombaça and Mylonites of Mombaça	Application of environmental protection zones	Area delimitation Signalling Communicating those responsible for the area Removal of vegetation	Valuation actions must include maintenance and cleaning Place one interpretative panel next to the site and one in the central area of the municipality	Local community, especially students, but without encouraging tourism	Every 3 months
Pedra Branca					
Chromitites of Tróia, Evidences of Thrusting of Pedra Branca and Pedra Branca Greenstone Sequence	Application of environmental protection zones, except for the Chromitites of Tróia, which depends on the landowner	Area delimitation Signalling Communicating those responsible for the area Removal of vegetation	Place one interpretative panel next to the site and one in the central area of the municipality	Local community, especially students, but without encouraging tourism	Every 3 months
Tonalitic Gneiss of Pedra Branca	Application of environmental protection zones	Area delimitation Signalling Communicating those responsible for the area	Place one interpretative panel next to the site and one in the central area of the municipality	Local community, especially students, but without encouraging tourism	Every 6 months
Tonalitic Gneiss of Extrema	Application of environmental protection zones	Signalling No further interventions required	Place one interpretative panel next to the site and one in the central area of the municipality	Local community, especially students, but without encouraging tourism	Annual
Quixadá					
Inselberg Fields of Quixadá	Protected Area (Decree n 26.805/2002)	Signalling No further interventions required	Cleaning and demarcation of the trail to the top of the Pedra da Galinha Choca Inselberg (Broody Hen Stone). Place one interpretative panel next to the recreational area of Cedro Dam and one information panel in the central area of Quixadá	Local community and national tourism	Annual
Gneiss Mylonitic of Quixadá	Depending on the landowner	Communicating those responsible for the area Delimitation of preservation area together with those responsible for the front of the crop	Place one interpretative panel next to the site	Local tourism, depending on the owner's authorisation	Every 6 months
Quixadá Granite	Application of environmental protection zones	Area delimitation Signalling	No structural measures are needed, just cleaning the site	Local community, especially students, but without encouraging tourism	Every 3 months
São Francisco de Assis Grotto[1], Pedra dos Ventos[2], and Urucum Mountain[2]	Protected Area[1] (Decree n 26.805/2002) and Federal Law n 12.651/2012[2]	Signalling No further interventions required	Place one interpretative panel next to each site. As for the Pedra dos Ventos, the access depends on the authorisation of the landowner	Local community, especially students, and regional tourism	Annual

Table 4 (continued)

Geosites and geodiversity sites	Statutory protection	Protection of physical integrity	Actions to valuating and promotion	Audience	Monitoring
Inselberg of Pedra do Cruzeiro	Quixadá Master Plan, 2000	Signalling No further interventions required	Actions of maintenance, cleaning, and demarcation of the trail to the top of the inselberg. Installation of footbridge, handrails, and safety railings along the trail. Installation of seats, roofs, and one interpretative panel at the base of the inselberg	Local community and national tourism	Annual
Monólitos Lake	Quixadá Master Plan, 2000	Signalling No further interventions required	The viewpoint needs cleaning and installation of valuation structures, such as seats, roof, and interpretative panel	Local community and national tourism	Annual
Metasedimentary Megaxenoliths of Juatama	Federal Law n 12.651/2012	Signalling No further interventions required	Place one interpretative panel at the base of the inselberg, emphasising the access restrictions due to security conditions	Local community, especially students, but without encouraging tourism	Annual
Quixeramobim					
Garnet Schist of Quixeramobim	Federal Law n 12.651/2012	Signalling No further interventions required	Geosite is formed by the rock outcrops at the base of the Quixeramobim dam, with partial or total access depending on the water level. Place one interpretative panel next in the restaurant adjacent to the dam	Local community, especially students and local tourism	Annual
Quixeramobim Granite	Depending on the landowner	Signalling No further interventions required	Place one interpretative panel No further structural interventions required, just cleaning the site	Local community, especially students, and local tourism, depending on the owner's authorisation	Every 6 months
Fofô Lake	Federal Law n 25/1937	Due to archaeological content, interventions on this geodiversity site should only be carried out after IPHAN's authorisation		Local community, especially students, but without encouraging tourism	Annual
Pedra da Baleia (Whale Stone)	Federal Law n 12.651/2012	Signalling No further interventions required	Place one interpretative panel next to the best viewpoint	Local community and regional tourism	Every 6 months

et al. (2018) defend that a joined-up approach between academics, authorities, and local communities is essential to support geosites conservation.

Conclusions

The work presented here results from an extensive geoconservation analysis, from the inventory of geological sites to the writing of management proposals, following known methods to select and evaluate geoheritage. Our approach aims at the protection and sustainable use of exceptional elements of geodiversity, based on the characterisation of geoheritage, the recognition of the physical and socio-cultural aspects of the territory, and the understanding of how these characteristics can enhance sustainable development.

The integration of several inventories made in the Sertão Central resulted in the identification of 20 geological sites related to the geological history of the area, from the Late Archaean to the Quaternary. In this assemble, we emphasise the set of inselbergs and their relevance to the palaeoenvironmental interpretation and geomorphological evolution studies in the Northeast Brazil. These new geodiversity sites have a good interpretative potential for all types of public, as well as good natural conditions for tourism (landscape and integrity). However, they lack safety infrastructures for visitors, which make their implementation necessary. The assessment of the cultural value of geodiversity in Sertão Central has identified sites that correspond to the concept of geocultural sites, improving the sense of place and raising awareness of geological conservation within communities.

Regarding territorial organisation, the municipalities of Quixadá and Quixeramobim concentrate the geological sites with higher landscape value, higher educational and tourist potential, and lower risk of degradation. Therefore, these municipalities should be urged to implement geotourism activities in their territories. In the other municipalities, the sites are mainly represented by small vulnerable outcrops with no aesthetic value and therefore with low tourist appeal. However, these sites have significant scientific value and should therefore be used for scientific and educational purposes.

From a statutory protection perspective, although some geological sites are directly or indirectly protected by environmental laws or by laws protecting the historical and cultural heritage, these legal statuses do not guarantee human and financial resources for their conservation. Furthermore, in Brazil, much has been discussed about the integration of geoheritage within the protected areas law, following the Brazilian Federal Law 9985/2000. The cases observed in our study suggest that incorporating these geosites into municipal master plans may be a more effective and rapid way to ensure their protection, especially for the geoheritage sites in the urban areas. Nevertheless, the development of educational and scientific dissemination actions for the local communities is essential to guarantee the protection of the geoheritage, highlighting the significance of these sites.

Our analysis allowed us to identify the most appropriate use for each geological site, organising them into distinct categories, which represents a first attempt for the protection and sustainable use of geological sites of Sertão Central, developed to assist the local administration in the geoconservation process. In small towns in the interior of Brazil, such as in the Sertão Central region, few agencies are dedicated to nature conservation, so these guidelines can help non-expert managers to implement geoconservation actions.

Challenges for the future refer to the need to overcome the barrier of academic communication in order to create a friendly presentation of this study to local stakeholders and the importance of carrying out detailed studies in partnership with local stakeholders regarding the delimitation of sites and the identification of specific criteria for site monitoring.

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Declarations

Conflict of Interest The authors declare no competing interests.

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