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ORIGINAL ARTICLE

Syn- and Post-collisional Granitoids Geosites of the Rio Doce Magmatic Arc, Espírito Santo State, Southeastern Brazil

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Abstract
Geosites in syn- and post-collisional granitoid rocks of the Rio Doce Magmatic Arc are important markers of the tectonic environments associated with the amalgamation of the western portion of Gondwana during the Neoproterozoic. Another aspect that stands out in these geosites is the relief that resulted from the breakup of Pangea with the opening of the South Atlantic Ocean and the action of the climate propitiating the alteration of the rocks and the soil erosion during the Cenozoic, leaving a landscape full of inselbergs that allow us to reach minerals, rocks, and structures that were formed between 630 and 480 Ma. The morphology of syn-collisional granitoid geosites is controlled by NNW-SSE fractures of Colatina lineament, and secondarily, by a shear fracture pair of WNW-ESE and WSW-ENE directions. In post-collisional granitoid geosites, the main control is the shape of the intrusion, and secondarily, a pair of shear fractures of WNW-ESE and WSW-ENE directions. The State of Espírito Santo has a strong connection between rural communities and cities with the local geology. Several initiatives to preserve this landscape can be noticed in the different tourist areas, such as the Pontões Capixabas Natural Monument and Pedra Azul State Park. Espírito Santo is a good example of geoconservation in Brazil, but at the same time, it needs to be aware of its geotourism potential, which can contribute to the local rural communities. For this, actions are needed to spread geological knowledge in schools, by training guides and taking this information to rural communities through new routes and using existing routes combined with geological knowledge, geodiversity, and cultural manifestations of the region.

Keywords Geosite · Inselberg · Magmatism · Araçuaí orogeny

Introduction

Granitic rocks represent around 15% of the continental area and are very common in the tectonically stable areas of the continental lithospheric plates and in recent orogenic areas affected by uplift and erosional unroofing (Gutiérrez and Gutiérrez 2016). There is a great diversity of landforms supported by granitic rocks, on a variety of scales, from microrelief on exposed rock surfaces to regional landscape types (Migon 2006). Granite landscapes are important components of global geoheritage, for example in Spitzkoppe (Namib Desert), La Pedriza (Spain), Torres del Paine (Chile), Manovo-Gounda St Floris (Central Africa Republic), Mont Saint-Michel (France), Rio de Janeiro (Brazil), Ambohimanga (Madagascar), and Yosemite (USA) (Migon 2021).

In Brazil, geosites in granitic rocks are predominantly distributed in the northeast semi-arid regions in Bahia, Ceará, Paraíba, and Rio Grande do Norte states, whilst others are located outside the semi-arid domain, including Espírito Santo, Rio de Janeiro, and Amazonas states, which are all in sub-humid to humid regions (Lima and Correia-Gomes 2015). Most of these geosites are in Neoproterozoic granitic rocks of the Borborema Province and Mantiqueira Orogenic System (northeast and southeast regions of Brazil). The main geosites are Quixadá inselbergs of Ceará state (Maia et al.

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2015), Lajedo do Pai Mateus of Paraíba state (Lages et al. 2013), Itatim Inselbergs of Bahia state (Lima and Correia-Gomes 2015), Pontões Capixabas of Espirito Santo state (Varajão and Alkmim 2015), and Pão de Açucar of Rio de Janeiro state (Silva et al. 2015). In this paper, we present a discussion of the geological evolution of the region with an emphasis on the syn- and post-collisional granites of the Rio Doce magmatic arc, an analysis of the structural controls and processes that gave rise to the relief of the region, as well as a quantitative assessment of the geosites highlighted.

Espírito Santo State is known for being the largest producer of ornamental stones in Brazil, for its beaches, and incredible landscapes. The rocks of the Neoproterozoic Rio Doce magmatic arc cover almost the entire territory and only 25% of the territory is covered by Cenozoic sedimentary formations. The state has great geotourism potential due to its diversity of natural environments located in the highland regions, for example, Pontões Capixabas Natural Monument in Pancas region, which stands out for its high quantity of monoliths that have attracted tourists due to their aesthetic beauty and for the practise of sports, such trekking, mountaineering, and rock climbing, besides observation of the fauna and the Atlantic forest. The historical and cultural tourism is related mainly to the presence of German and Italian immigrants who occupied the region from the first half of the nineteenth century, who, through coffee farming, propitiated the insertion of the state in the national economic context at the end of the nineteenth century and beginning of the twentieth century (Abreu 1967, Lucena 2004, Ghizenlini and Almeida 2022).

Geological Setting

The study area is part of the Mantiqueira Orogenic System, which extends for about 3000 km from southern Bahia to Rio Grande do Sul and Uruguay (Alkmim 2018) (Fig. 1). Part of this orogenic system is composed of the Araçuaí and Ribeira orogens that formed during the amalgamation of the Western Gondwana at the end of the Neoproterozoic (Novo et al. 2018). In the area outcrop, the rocks of the Rio Doce magmatic arc composed of plutonic rocks with ages between 630 and 480 Ma. The magmatic arc is composed for five supersuites that were defined by Pedrosa-Soares (2011) and by metasedimentary and metavolcanic rocks of the Rio Doce, Nova Venécia, Italva and São Fidelis groups with ages between 630 and 585 Ma. These groups represent metavulcano-sedimentary sequences related to the magmatic arc in an active continental margin environment (Novo et al. 2018) (Fig. 2).

In the southwestern portion, in the Serra do Caparaó region, inliers of the basement occur tectonically intercalated with paragneiss of the Rio Doce Group. These rocks with ages around 2195±15 Ma belong to the Caparaó, Ipanema, and Serra do Valentim complexes (Vieira and Menezes 2015). In the northeastern part of the state and in the coastal strip, sedimentary rocks of the Barreiras Group and unconsolidated sediments of Cenozoic age predominate. The Caparaó Complex is composed of granulitic and charnockitic rocks with crystallisation ages around 2176 ± 30 Ma and metamorphism at 586 ± 6 Ma (Silva et al. 2002). The complex was divided in two units by Horn (2006). One unit is composed of partially migmatitic orthogneiss with hypersthene and garnet, containing occasional intercalations of paragneiss, kinzigite, and charnockite; the other unit is composed by granite with hypersthene, locally foliated, and with mafic enclaves. The Ipanema Complex borders the Caparaó Complex, an elongated band composed of biotite gneiss, biotite-garnet gneiss, and mylonitic gneiss with intercalated lenses of quartzite, quartz-mica schists, steatites, gabbro, and amphibolites (Angeli et al. 1983). The Serra do Valentim Complex is isolated as an embasement inlier composed of norites, enderbites, charnockites, and charno-enderbites (Vieira and Menezes 2015).

The Rio Doce Magmatic Arc is composed of five intrusive supersuites, and backarc and forearc basins represented by the Rio Doce, Nova Venécia, Italva, and São Fidelis groups. According to Pedrosa-Soares et al. (2011), the plutonic supersuites represent a crustal segment with ages from the Neoproterozoic to Cambro-Ordovician, formed in the period between 630 and 480 Ma. It is also the site of the East Brazilian Pegmatite Province which is considered to be the largest pegmatite province in Brazil. The Mantiqueira Orogenic System in the region of the Araçuaí Orogen was subdivided into four tectonic accretionary stages: pre-collisional (630–585 Ma), syn-collisional (585–560 Ma), late-collisional (560–530 Ma), and post-collisional (530–480 Ma). In its southern portion, rocks of the Ribeira Orogen are represented by the Juiz de Fora and Cambuci domains (Figs. 1 and 2). The pre-collisional G1 supersuite represents the building of the calc-alkaline magmatic arc formed in response to the subduction of oceanic lithosphere between 630 and 585 Ma. The syn-collisional G2 supersuite was generated primarily by partial melting of metasedimentary rocks associated with further crustal thickening caused by thrusting and folding that would have occurred between 585 and 560 Ma. The G3 supersuite is late post-collisional (545–525 Ma) and was related to late-collision at a transitional stage with the decline of convergent forces into a phase of crustal relaxation accompanied by delamination and convective removal of the lithospheric mantle. The supersuites G4 (530–500 Ma) and G5 (520–480 Ma) are post-collisional, and include plutons that intersect the regional fabric and concordant intrusive bodies that are associated with faults, shear zones, and fractures (Pedrosa-Soares et al. 2000, 2001, 2008). The post-collisional stage

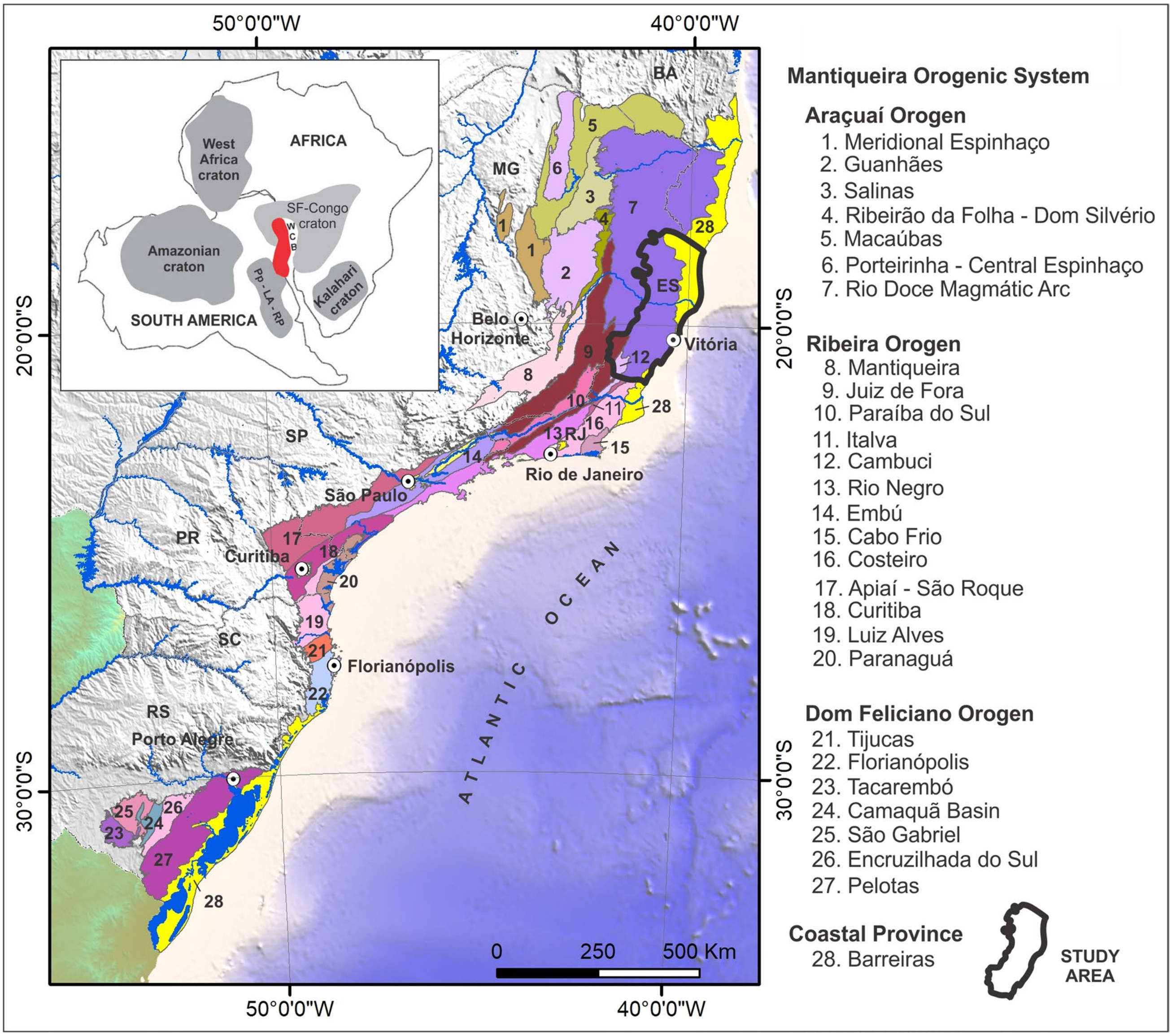

Fig. 1 Mantiqueira orogenic system and its location in Western Gondwana. Extract from the Tectonostratigraphic map of Brazil (Schobbenhaus et al. 2022. unpublished, Silva et al. 2005). SF-Congo craton — São Francisco - Congo craton; WCB — West Congo belt; Pp-LA-RP — Paranapanema-Luiz Alves-Rio de La Plata cratonic block. Brazilian states: BA — Bahia; ES — Espírito Santo; MG — Minas Gerais, SP — São Paulo; RJ — Rio de Janeiro; PR — Paraná; RS — Rio Grande do Sul

was related to the gravitational collapse of the orogen and rise of the asthenosphere.

Methodology

The geological heritage is the record of remarkable features of geodiversity, represented by geological sites of exceptional value to the geological memory of the country. These sites are key locations for the understanding of the origin and evolution of the Earth and life, which is why they need to be conserved. The quantitative assessment of geosites is mainly based on scientific criteria, but others are considered, for example, the educational value which is essential for the training of students and teachers at all levels of education. On the other hand, the touristic and cultural interest is important in promoting geology to the lay public and can contribute to the sustained development of local populations (Brilha 2016). The geosites may occur in the most diverse scales, from mega to micro scale, may involve large areas, profiles or points, and may also be in situ or ex situ.

The inventory of the geological heritage of the State of Espírito Santo has the geoconservation of geosites as its main objective through its description, quantitative

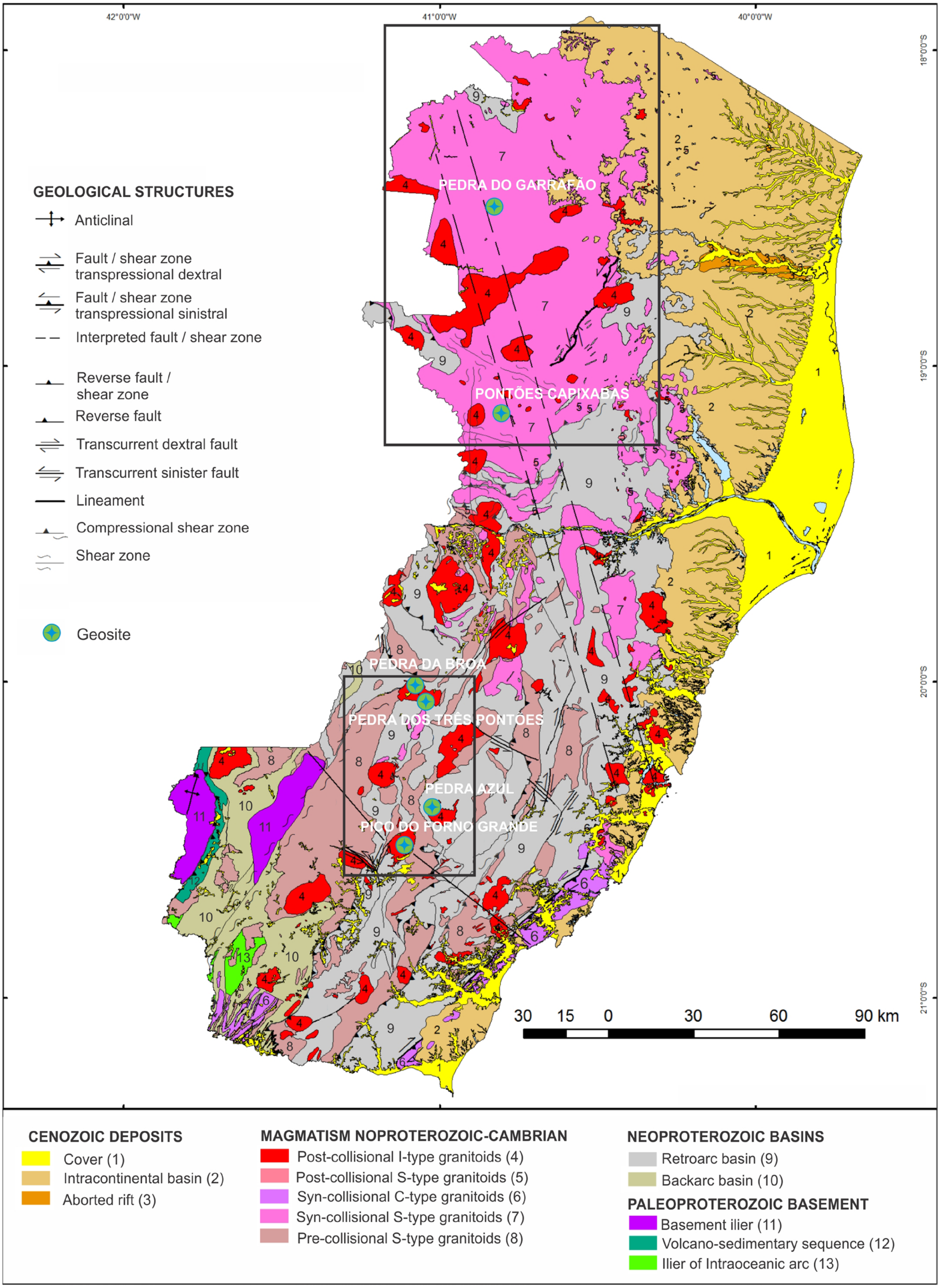

Fig. 2 Simplified geological map of Espírito Santo State with geosites and studied areas. Map compiled from Veira et al. (2018)

assessment, indication of mitigating measures of environmental impacts, and proposals for touristic and educational use. The inventory takes into consideration the geological context (tectonics, petrology, geomorphology) in which they are inserted, in an attempt to explain the geological history of this portion of the Mantiqueira orogenic system, during the Neoproterozoic and Cambrian.

The geological mapping of 19 charts, at the scale of 1:100.000, accomplished through several projects of the Geological Survey of Brazil and the agreement with the geosciences institutes of Federal University of Minas Gerais (UFMG), Federal University of Espírito Santo (UFES), and State University of Rio de Janeiro (UERJ), provided the production of the geological and mineral resources map of the Espirito Santo State, at the scale of 1:400.000, which was used as a base for the geological and tectonic contextualization of the studied geosites. The map and the report represent a synthesis of the geological knowledge of the state, based on the compilation of maps, theses, dissertations and papers, and on the use of unpublished data obtained from the geological field surveys, the interpretation of aerogeophysical data, and petrographic, geochemical, and geochronological analyses.

The inventory is being based on scientific (representativeness, integrity, rarity, and scientific knowledge), educational (potential for educational use, diversity of geological elements, accessibility and safety while using the space), and touristic (interpretative potential, scenic beauty, accessibility, and safety while using the space) criteria (Table 1). In this research, we consider geological heritage as a set of elements of geodiversity with high scientific value that outcrop naturally or by human action and that are being characterized and inventoried (Brilha 2016). Also, it can be understood as a set of elements that allow the understanding of the Earth's history and that are used by society for research, education, tourism, and sustainability actions of the communities involved (Brilha 2005).

The main objective of the geological heritage inventory is to identify, describe, and evaluate the scientific, educational, and touristic relevance with a view to its geoconservation and use it as a tool for popularisation of the geosciences, ensuring sustainable regional and local development through its educational/touristic use, providing means for the development of scientific research, as well as promoting the participation of local communities.

The quantitative assessment was carried out based on current methodologies and using mainly scientific, educational and geotouristic criteria (Lima 2008, Garcia-Cortez and Urquí 2009, Brilha et al. 2010, Brilha 2016), while taking into account the cultural aspects of the region. We consider sites of relevant geological value those that, due to their unique characteristics, can be related to one or several disciplines of the geosciences area, making it possible to know, study, and disseminate issues related to the origin, evolution, and composition of the Earth, as well as the processes related to the formation of relief, climate change, and evolution of life (Schobbenhaus et al. 2021).

Table 1 Criteria used in the quantitative assessment of geosites (based on the GEOSSIT platform)

Scientific value	Representativity (30%)
	Expressivity (20%)
	Scientific knowledge (5%)
	Integrity (15%)
	Geological diversity (5%)
	Rarity (15%)
	Limitation of use (10%)
Educational and Tourist value	Vulnerability (EV=10%); (TV=10%)
	Road access (EV=10%); (TV=10%)
	Accessibility (EV=5%); (TV=5%)
	Safety (EV=10%); (TV=10%)
	Logistics (EV=5%); (TV=5%)
	Population density (EV=5%); (TV=5%)
	Association with other values (EV=5%); (TV=5%)
	Scenic beauty (EV=5%); (TV=15%)
	Singularity (EV=5%); (TV=10%)
	Observation conditions (EV=10%); (TV=5%)
	Didactic potential (EV=20%); (TV=0%)
	Geological diversity (EV=10%); (TV=0%)
	Potential for dissemination (EV=0%); (TV=10%)
	Economic level (EV=0%); (TV=5%)
	Proximity to recreational areas (EV=0%); (TV=5%)
Degradation risk	Deterioration of geological elements (35%)
	Proximity to activities with degradation potential (20%)
	Legal protection (20%)
	Accessibility (15%)
	Population density (10%)

The thematic axes of this inventory were tectonics, petrology, and geomorphology. In the description of the geosites, the following data were collected: geographic coordinates; toponymy; accesses; level of difficulty and available infrastructure; geological characteristics, such as lithotypes, mineralogy, textures, and structures; geomorphological aspects; geodiversity elements; potential for scientific, pedagogical, tourist use and its relations with historical, archaeological, religious, and cultural elements.

In the quantitative assessment, the GEOSSIT platform of the Geological Survey of Brazil for geosites and geodiversity sites was used. The evaluation was based on scientific, educational, and touristic criteria, analysing the risk of degradation of the main and secondary elements of the geosites (Table 1). These criteria were based on the methodologies proposed by Brilha (2005), Cortés and Urquí (2009), and Brilha (2016).

Results

Geosites in Syn-collisional Magmatism of Carlos Chagas Suite

Pontões Capixabas

The Pontões Capixabas are located in Carlos Chagas batholith that has an area of about 5000 km^2, with beautiful inselberg-shaped outcrops (Fig. 3). The batholith was studied in detail by Roncato Jr. (2009) in his master's dissertation. According to this author, the Carlos Chagas batholith is very homogeneous in terms of composition, being composed of coarse grained leucocratic rocks, rich in potassic feldspar, and garnet porphyroclasts. It has xenoliths of paragneiss and calcissilicate rocks of the Nova Venécia Complex and Ataléia granite. The xenoliths usually have lenticular and boudin forms, as they are oriented according to the regional foliation. In mineralogical and petrographic terms, the rocks of the Carlos Chagas Suite have S-type granite characteristics, such as the presence of garnet, biotite, sillimanite, free apatite, monazite and ilmenite, high potassic feldspar content, and xenoliths of metasedimentary rocks. In the context of the suite, bodies of charnockite, norite, biotite granite, cordierite-granada-biotite granite, and porphyritic leucogranites were mapped. Roncato Jr. (2009) obtained age of 576 Ma for the granitoids of Carlos Chagas Suite. Using Condie's (1993) Rb versus Sr diagram, the results indicated the origin of deep crustal granitic magma crystallised at more than 30 km depth. The batholith has several late intrusions belonging to the G5 supersuite.

The shape of the Pontões Capixabas is mainly controlled by fractures in the NNW-SSE direction, and secondarily, by shear joints paired with WNW-ESE and WSW-ENE directions (Fig. 4a1 and a2). They have suggestive shapes and denominations, such as, "Pedra da Agulha", "Pedra do Camelo", "Pedra da Gaveta", and "Pedra da Boca" (Fig. 5a–e). The Pontões integrate the relief of escarpments of the Mantiqueira Mountain Range with portions of the plateau of the rivers Jequitinhonha and Pardo, and of the River Doce Delta. In the region, there are dozens of active quarries and a large number of abandoned quarries that can become important geological sites for educational uses that allow visualisation of the colours, structures, and mineralogy of these rocks.

In 2002, the Pontões Capixabas National Park was created. Subsequently, were included in the category "Natural Monument" through decree s/n° of 19 December 2002/ Law n° 11.686 of 02 June 2000, administered by ICMBio. The measure benefited, in particular, the communities of Pomeranian and Polish descent that have lived in the region for decades. With the change, they remained within the unit, maintaining their existing activities without altering the landscape. Ornamental stone extraction activities within the area have been banned. The communities living in the area have basically been farming as families for at least three generations, and some of them are recognized as traditional. Another very common activity in the region is coffee planting.

The local relief is favourable for trekking, climbing, mountaineering, rappelling, and free flying. In the region, there are also several waterfalls, such as the Bassani Waterfall (3 km from Pancas), Santa Ana Waterfall (40 km from the headquarters), São Luiz and Prainha do São Luiz waterfalls (2 km from the headquarters), and the Moraes Waterfall in the district of Vila Verde (Assembleia Legislativa do Espírito Santo 2023).

Pedra do Garrafão

Pedra do Garrafão is an inselberg with the highest point at an altitude of 1450 m, being 2940 m long and 860 m wide, formed of leucogranite of the Carlos Chagas Suite (Fig. 3). The rocks are medium-grained, yellowish white, and locally affected by shear zones. The large quantity of potassium feldspar phenocrysts and/or porphyroclasts in relation to the matrix indicates that most appropriate classification is syenogranite. The regional ductile deformation transformed the ocellar phenocrysts to sigmoidal and phytate (ribbon-like). The protomylonite-gneiss has a coarse to very coarse porphyroclastic texture and a matrix consisting of perthite potassic feldspar, quartz, sodic plagioclase, garnet, biotite, and sillimanite of lepidoblastic texture. There are also portions that can be defined as mylonite-gneiss and garnet ultramylonite. The shape of the inselbergs of Pedra do Garrafão is mainly controlled by fractures in NNW-SSE and WNW-ENE directions (Fig. 4b).

The place is still little explored, but full of natural beauties (Fig. 5f). The farm offers Pomeranian-style accommodation. The place is often used by cyclists and climbers. The Mols Waterfall, Granite Waterfall, and Sombra da Tarde Municipal Park are also located in the region.

Geosites in Post-Collisional Magmatism

Pedra Azul

Pedra Azul is a post-collisional pluton of the G5 supersuite described by Pedrosa-Soares et al. (2011), and has inverse zoning with monzogranite on the border and diorite in the central portion (Fig. 6). It is in contact with the surrounding rocks through a migmatitic zone in *lit-par-lit*

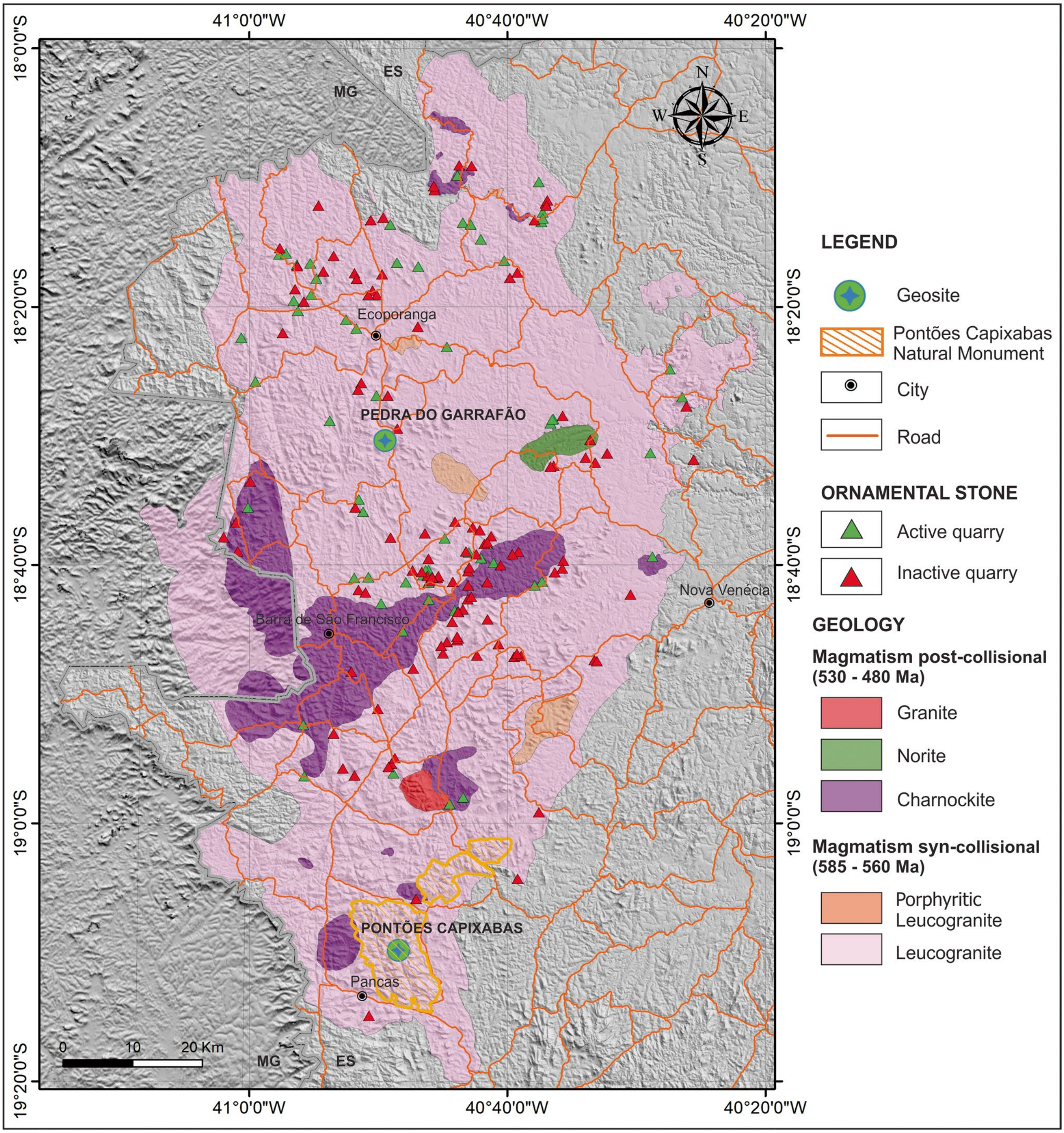

Fig. 3 Geological map of the Carlos Chagas batholith with geosites and ornamental stone quarries (modified from Vieira et al. 2018)

and nebulitic contacts. Medium-grained monzogranite sculpts the uppermost portions of the peaks and the edges and represents the first magmatic envelope of the structure (Wiedemann-Leonardos et al. 2002). There are several domains of tonalitic to granodioritic compositions that have been mapped within the pluton. The contacts between the monzogranite and the surrounding rocks are marked by mixed zones, where schlieren-like structures occur in contact with fine-grained mafic rocks, giving rise to pillow-like structures typical of mingling. The surrounding rocks are paragneiss of the Nova Venécia Complex, and in the contact zone, xenoliths of sillimanite-quartzite and garnet-sillimanite-quartz gneiss occur. The igneous flow structures present in the pluton are marked by magmatic lineation and enclave alignments (Costa de Moura et al. 1999, In: Campos et al. 2004).

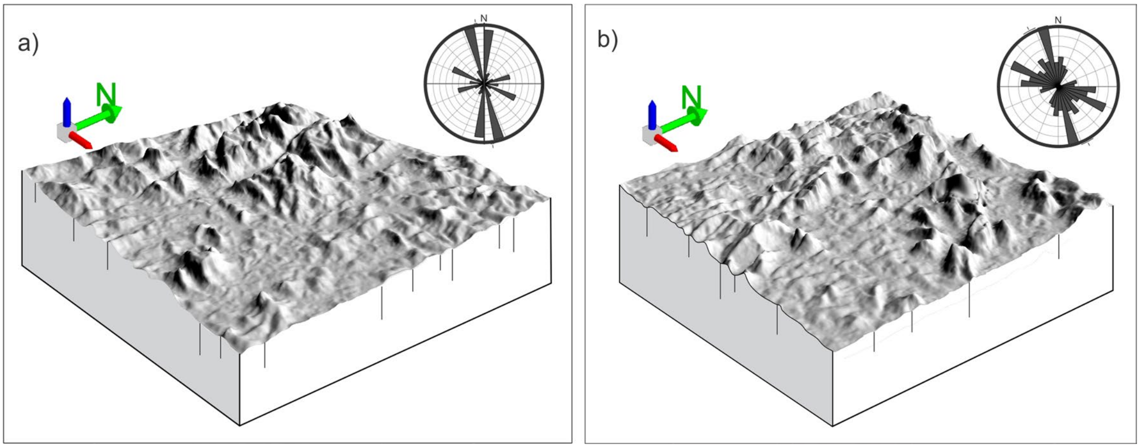

Fig. 4 Pre-collisional granitoids. Reliefs and rose diagram of the geosite areas: **a** Pontões Capixabas; **b** Pedra do Garrafão

The Pedra Azul pluton is situated in the mountainous domain, formed by aligned rock masses (Fig. 7). The relief is controlled mainly by the shape of the intrusion and secondarily by a pair of shear joints with NW-SE and ENE-WSW alignments (Fig. 8a). In the area, Pedra Azul State Park was created, which is an ecological corridor of the Atlantic Forest and one of the most important areas for the conservation of biodiversity in Espírito Santo (Fig. 8). The park is managed by the Institute of Environment and Water Resources of Espírito Santo (IEMA 2023a), and its management plan was drawn up using the ecological corridor concept. In addition to Pedra Azul, visitors can follow the route of the natural pools, 3 km away, passing by viewpoints that offer views of the Caparaó mountain range and Pedra do Forno Grande. The Pedra do Lagarto route is the main tourist attraction, as it offers not only beautiful scenery, but also inns, coffee shops and restaurants. Another attraction in the region is Fjorland Farm, where visitors can take ecological rides on Norwegian Fjord horses, on trails in native and reforested forest areas, with natural pools and woodland.

Forno Grande Pluton

The Forno Grande Intrusive Complex is an elliptical intrusion covering an area of 100 km^2, belonging to the G5 supersuite, of post-collisional character with ages between 524 and 489 Ma (Pedrosa-Soares et al. 2011, Macêdo 2020). An interesting feature of the intrusion is its inverted internal zoning with a diorite centre and granitic rim (Wiedemann-Leonardos et al. 2000, Campos et al. 2004) (Fig. 9 and Fig. 10b). At the contact between the granite and the diorite, a thin envelope of microdiorite has been mapped, composed of swarms of enclaves with different degrees of hybridisation with the granite. The centre of the intrusion is formed by medium-grained diorite, well defined mineral lineations and planar magmatic flow structures, quartz xenocrystals in the mafic lithotypes, and buttery feldspars of the rapakivi and antirapakivi types that can be observed in the outcrops (Wiedemann-Leonardos 2000).

In geomorphological terms, Forno Grande peak is included in the mountain domain, as is the Pedra Azul pluton (Silva and Machado 2014). The relief is controlled by the shape of the intrusion and secondarily by a pair of NW-SE and NNE-SSW shear joints (Fig. 10b).

The peak is located in the area of the Forno Grande State Park, a region where Italian colonisation was predominant. The immigrants who settled there identified the peak as a large representation of their bread ovens. The vegetation is characterised by the presence of endemic species and the formation of high altitude forests, very rare in the country. Its fauna includes animals on the verge of extinction, such as the brown jaguar (Sussuarana) and the eagle (Águia Pega-Macaco) (IEMA 2023b).

The Forno Grande peak is the second highest peak in Espírito Santo, reaching an altitude of 2039 m. It is located in the Forno Grande State Park, in the municipality of Castelo, in the south of the State of Espírito Santo, about 120 km from Vitória and 40 km from Castelo city. Its name was originally related to the name of the municipality of Castelo itself, given by gold seekers in the eighteenth century, due to the large elevation with a shape similar to that of a feudal castle, surrounded by other smaller elevations with the appearance of walls, then called Pedra and Castle Mountain. Later it was associated with the large shape of a bread oven, much used by the descendants of Italian immigrants in the nineteenth century. The peak is located in the tourist region of Capixabas Mountain, which has a strong influence of German, Italian, Austrian, Pomeranian, and Polish cultural traditions (music, dances, and gastronomy), where agrotourism is strong and where there are also numerous natural attractions.

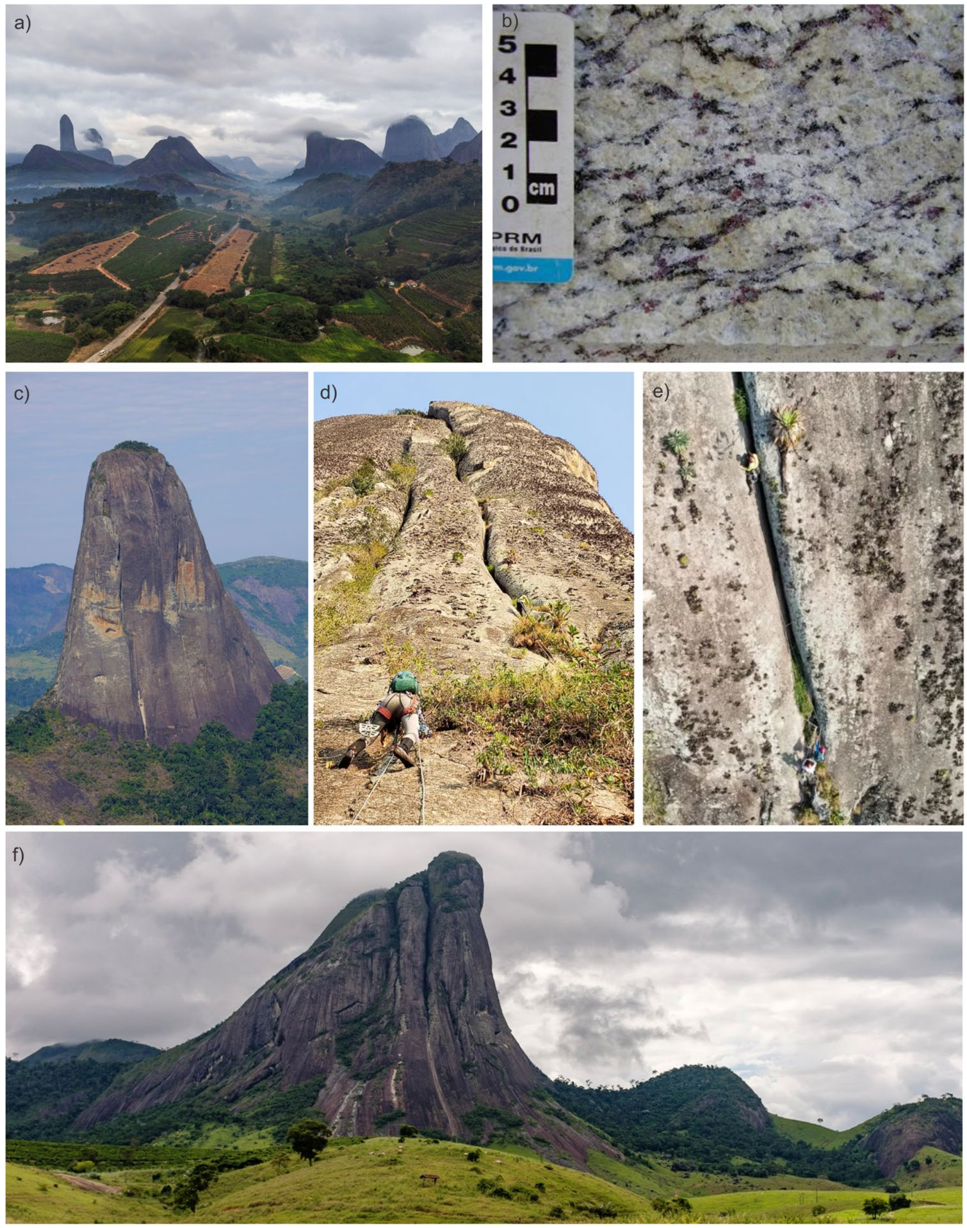

Fig. 5 Photos of geosites in pre-collisional granitoids. **a** Panoramic view from the free-flying ramp in Pancas; **b** leucogranite of Carlos Chagas Suite with incipient foliation (compiled from Rocanto Jr. 2009); **c** morphology of Pico da Agulha; **d** climbing route in fractures of Pedra da Agulha; **e** detail of climbing route of Pico da Agulha; **f** vertical fractures in the Pedra do Garrafão. Photos by Naoki Arima

Afonso Claudio Massif

The Afonso Claudio Massif occupies an area of 80 km^2 and is characterised by a high frequency of "pontões" with "Pão de Açúcar" morphology, displaced rocks and rounded surfaces that dominate the landscape (Fig. 9a and b). The pluton is in contact with sillimanite-granada-cordierite-biotite gneiss of the Nova Venécia Complex, and orthogneiss of the Muniz Freire Complex in the far west and the Santa Tereza Complex in the far east.

Paradella et al. (1978) mapped gabbroic and dioritic mafic rocks in the centre of the massif, surrounded by felsic rocks that occur at higher altitudes, creating a very abrupt difference in relief. The above authors have also mapped norites and monzonites. The contact with the sedimentary rocks has been described as abrupt, where there are also injections of porphyritic syenogranite and enclaves of sedimentary rocks assimilated by the porphyritic granite (Aranda et al. 2020). The porphyritic granite is composed of microcline megacrystals, which are 2 to 3 cm in size and can reach 4 to 5 cm (Signorelli et al. 1993). The matrix is medium to coarse grained. According to Aranda et al. (2020), between the felsic and mafic rocks there are mixing and blending zones characterised by the presence of mafic enclaves in the monzonite quartz, xenocrystals of k-feldspar, and plagioclase of the monzonite quartz within the mafic rocks, and injections of felsic magma into the mafic rocks. The contact zone with the surrounding rocks is characterised by

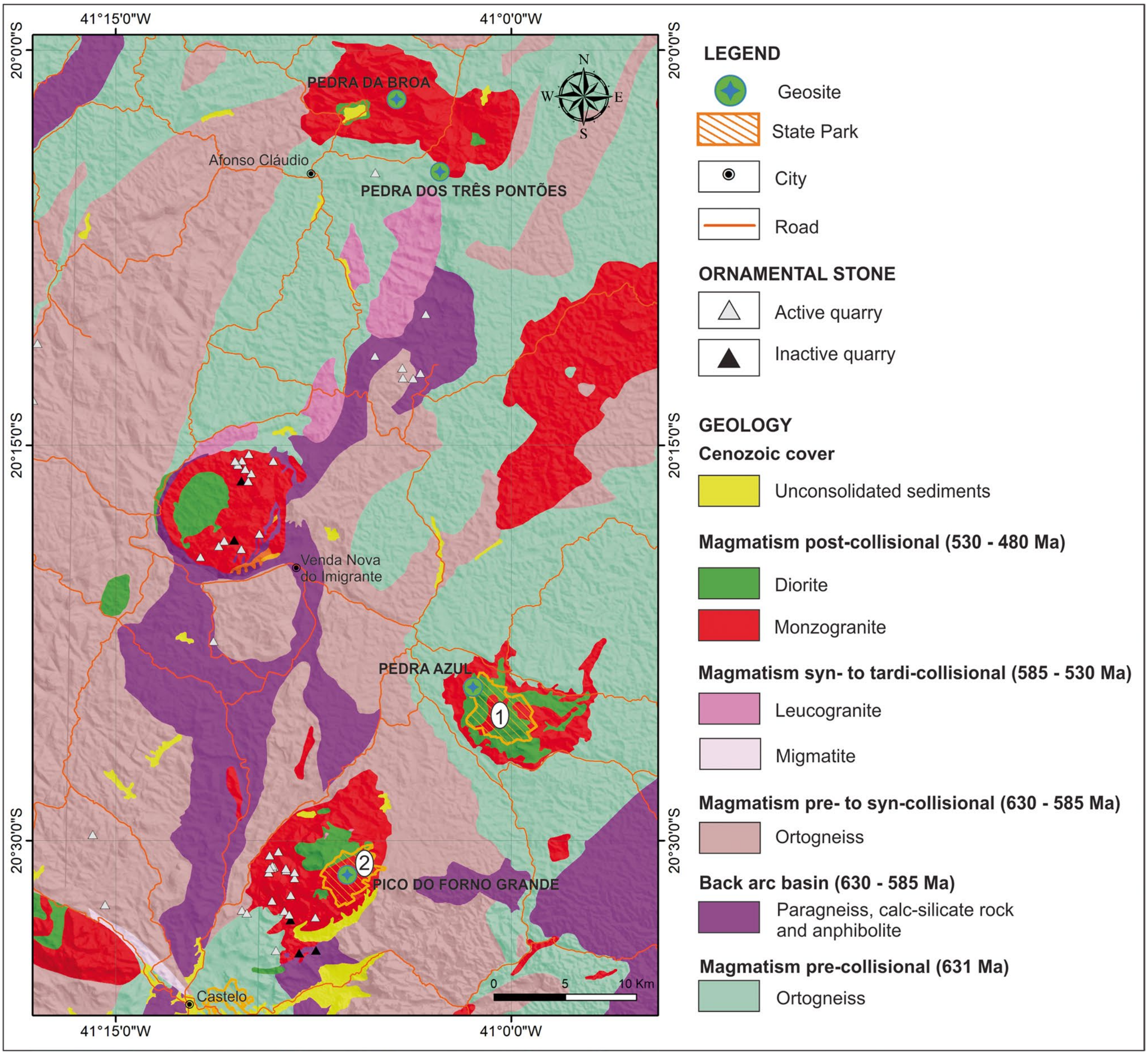

Fig. 6 Simplified geological map with the location of post-collisional plutons with inverse zoning, ornamental stone quarries and geosites. State parks: 1 — Pedra Azul; 2 — Forno Grande. Geological map compiled from Vieira et al. (2018)

the presence of granitic veining, dissonant with the foliation of the paragneiss. From a geomorphological viewpoint, the Afonso Cláudio pluton has a sigmoid shape, intruded in the context of a dextral shear zone. The joints associated with the shear zone have NW-SE and NNE-SSW main alignments (Fig. 8b).

In the region, the Municipal Natural Monument of Três Pontões is the symbol of the municipality of Afonso Cláudio, known for its beauty and magnificence, corresponding to one of the most beautiful rock monuments of the state (Fig. 9c, d, and e). On its top, there are three points where a Chilean eagle has built its nest. Geomorphologically, the geosite belongs to the "Mountain Domain", as well as the Pedra Azul pluton and the Forno Grande (Silva and Machado 2014).

The Pedra da Broa is one of the components of the Afonso Claudio massif (Vieira et al. 2018, 2021). The site offers opportunities for hang-gliding, rappelling and climbing, and has gained national prominence for the sports of highline and skydiving (Fig. 9f and g). Guided walks are available in the area and a large number of birds can be seen, attracting birdwatchers and tourists from many countries.

Fig. 7 Photos of Pedra Azul geosite. **a** Panoramic view of the geosite; **b** detail of Pedra Azul seen from the entrance of the park; **c** Pedra do Lagarto; **d** detail of the climbing route of Pedra Azul. Photos by Naoki Arima

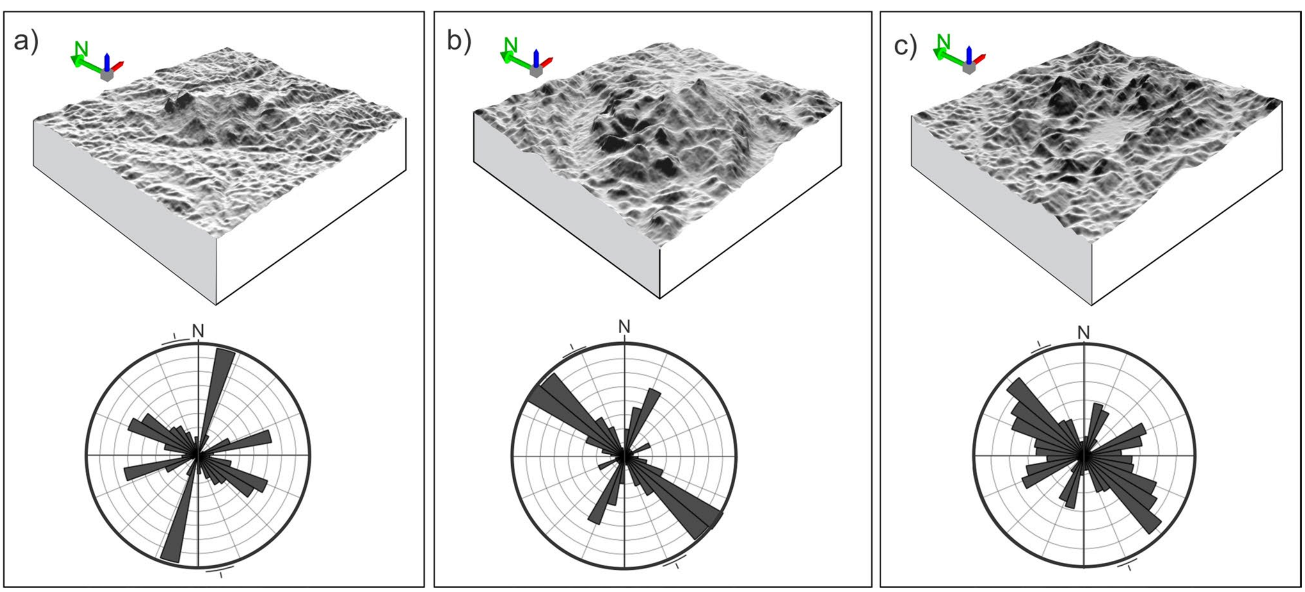

Fig. 8 Post-collisional granitoids. Reliefs and rose diagram of the areas of **a** Pedra Azul, **b** Forno Grande, and **c** Afonso Cláudio plutons

Fig. 9 Photos of the post-collisional plutons geosites and main landform. **a** Panoramic view of the Forno Grande pluton; **b** biotite monzogranite inequigranular (from Meyer 2017), **c** view of Três Pontões geosite; **d** climbing route of east face and tafoni features; **e** quartz monzonite outcrop showing a monzodiorite enclave; **f** panoramic view of Pedra da Broa; **g** quartz monzonite typical domain in high hills (from Aranda et al. 2020). Photo (b) from Meyer (2017), photo (g) from Aranda et al. (2020), and others by Naoki Arima

Quantitative Assessment of Geosites

The main themes represented at the geosites discussed here are tectonics, petrology, and geomorphology. These geosites are used as tourist facilities for their aesthetic beauty and for sports such as trekking, mountaineering and climbing (Table 2). The region is part of the Rio Doce Magmatic Arc, a large tectonic area located mainly in the states of Espírito Santo and Minas Gerais. In Minas Gerais, it is known for its abundance of pegmatites from which precious stones and collector minerals are extracted, and in Espírito Santo for its production of ornamental stone. In terms of geomorphology, there are regional studies on the morphostructural areas of the state, but there is a lack of studies on a local scale on the minor landforms that occur in association with the inselbergs, such as tafoni, karren, boulders, and weathering pits.

In the graphs relating to the scientific, educational and touristic relevance, it is noticeable that the geosites registered in the GEOSSIT platform have higher values in terms of tourist and educational interest (Fig. 10). In relation to the materials available on the Internet, none are about the geological aspects of geosites, which demonstrates the need to carry out dissemination work through the training of guides, lectures in local schools, and preparation of panels and explanatory folders. In terms of scientific publications about the Araçuaí Orogen and/or Rio Doce Magmatic Arc, the geosites studied are of national/regional and even international scientific importance. It is one of the most studied provinces in Brazil, where all the stages of formation of a continental orogen have been defined (Neves et al. 1986; Pedrosa-Soares et al. 2000, 2001, 2011; Pedrosa-Soares and Alkmin 2008; Wiedemann-Leonardos et al. 2000; Roncato Jr. 2009; Tedeschi et al. 2016, Meyer 2017, Novo et al. 2018; Aranda et al. 2020; Schannor et al. 2020).

The region also has expressive potential for the educational use of ornamental stone quarries, and thematic itineraries can be developed on the main types of ornamental stone, as well as basic concepts of geology (mineralogy, petrography, and tectonics), geomorphology, and soil.

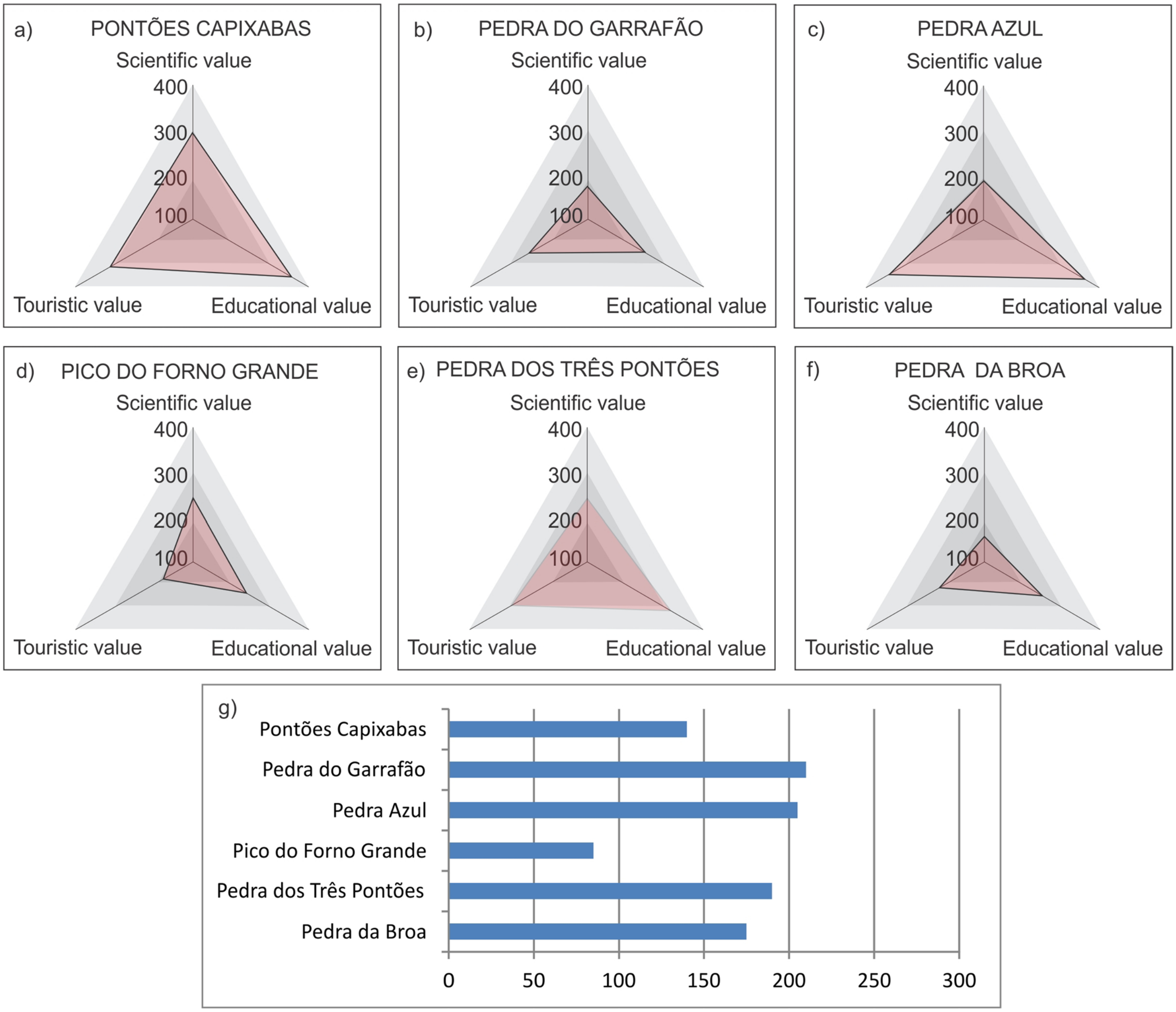

Fig. 10 Diagrams relating to the scientific, educational, touristic relevance (**a** to **g**) and degradation risk of the geological elements (**h**) of the geosites, based on the data available at the GEOSSIT platform

Table 2 List of studied geosites

Order	Geosite	Latitude	Longitude	Municipality	SV	EV	TV	DR	Grade
1	Pontões Capixabas	−19.1643848	−40.8067741	Pancas	295	360	310	140	Low
2	Pedra do Garrafão	−18.50635529	−40.8243027	Barra de São Francisco	180	230	235	210	Average
3	Pedra do Elefante	−18.7607670	−40.4591637	Nova Venécia	170	360	350	215	Average
4	Pedra Azul	−20.4032135	−41.0239372	Domingos Martins	190	355	335	205	Average
5	Pico do Forno Grande	−20.5219059	−41.1034050	Castelo	240	245	190	85	Low
6	Pedra dos Três Pontões	−20.0771122	−41.0447960	Afonso Cláudio	245	320	290	190	Low
7	Pedra da Broa	−20.0311985	−41.0722923	Afonso Cláudio	150	265	220	175	Low

SV Scientific value; *EV* Educational value; *TV* Tourist value; *DR* Degradation risk

Discussion

Landscapes formed in granitoid terrains have been interpreted in morphogenetic and in morphoclimatic terms, but field evidence points to structural control. Some features are developed only after exposure of the granitoid bodies because of the continuous stress occurring in the crust (Vidal Romaní and Twidake 2010). Climate is an important factor in the development of landscapes, but structural control and the shape of the intrusive igneous bodies have influence on the final morphology, and the interaction of granitoid with the atmosphere and hydrosphere leads to the weathering of minerals giving rise to regolith (Campbell 1997). The disintegration and/or alteration of the rock involve chemical reactions with the formation of new minerals (chemical weathering) and the physical break-up of the rock (physical weathering). According Campbell (1997), the main characteristics of granitoids that influence the rate of weathering are fracture density, mineralogical composition, and texture.

Granitoid terrains exhibit specific shapes that are determined by the characteristics of the rock and its spatial variability. These rocks are typically hard, homogeneous, crystalline with low primary permeability and the geometry can control the final shape of the landscape. Fractures are the first order elements that influence the structuring of rock masses into blocks and facilitate the penetration of meteoric water, favouring differential weathering and erosion which is responsible for the varieties of shapes attributed to exhumation due to irregular weathering and differential erosion (Twidale (1982).

One of the most peculiar relief forms in granitoid batholiths and plutons are inselbergs. This German term literally means "island hill" and has been used in the English language without adaptation (Migon 2013). These forms are not restricted to a single lithology, but are particularly common in granitoids. They vary in size and shape. Twidale (1982) described three main types, which they termed domes, blocks (boulder-strew inselberg), and castellated inselbergs. Inselbergs develop in rock masses with rather irregular joints, where, for example, castellated inselbergs form in orthogonally fractured rocks and the amount of remaining rock is relatively small. Domes are usually associated with massifs and non-orthogonal fractures where the distance between them can be tens of metres with geometric pattern not orthogonal. Other smaller but interesting and common forms in granitoid rocks are boulders, tafoni, karren, and weathering pits (Campbell 1997, Twidale and Vidal Romaní 2005, Migon 2006).

Regional Control of Landscape

The landscape of Espírito Santo is the result of Neoproterozoic structures correlated to the Brasiliano event, which were reactivated during the rupture of supercontinent Gondwana and with the opening of the South Atlantic rift. Observing the lineament map, it is possible to distinguish two structural domains, one in the north, where NNW-SSE and ESE-WNW lineaments are predominant, and another in the southern portion with predominance of NNE-SSW and NW-SE lineaments.

The main structure that stands out in the digital terrain model is Colatina lineament with NNW-SSE direction, described as "Lineament Vitória-Ecoporanga" in project RADAMBRASIL (1987), or "Colatina Shear Zone" according to Chang et al. (1992), or "Colatina Track" described by Novais et al. (2004). This Precambrian age structure related to the Araçuaí orogen was reactivated in the Cretaceous with the formation of the Brazilian Atlantic margin during the South Atlantean event (Schobbenhaus et al. 1984). In the southern domain the lineaments can be correlated to the Ribeira Orogen, which is approximately NE-SW. In the region near Vitória, there is a clear interference zone between the two structural domains (Fig. 10).

Origin of the Inselbergs

The geological history of inselbergs in Espírito Santo begins in the Neoproterozoic, around 640 Ma, during the Brasiliano Orogeny, which resulted in the amalgamation of the western part of the Gondwana supercontinent (Fig. 11). At this time, the continental crust was melting, producing magmas that intruded into the crust through deep structures such as fractures, faults, and shear zones, giving rise to pre-collisional complexes such as the leucogranitoids of the Carlos Chagas Suite. After the continental collision, new plutonic bodies intruded into the pre-collisional complexes and metasedimentary rocks associated with the basins that were formed as the magmatic arc developed. These plutonic bodies intruded high-grade metamorphic rocks (high amphibolite to granulite) between 530 and 480 Ma through high-angle shear zones and antiform structures and are examples of bimodal intrusion hosted at depths greater than 20 km for long periods (Wedemann-Leonardos et al. 2000). According to the same author, the geochemical data of the rocks indicate the presence of three magmatic suites (tholeiitic, calc-alkaline, and alkaline), the most prominent of which are calc-alkaline suites, which account for about 90% of the plutons in the region and is of middle to lower crustal origin, with an important mantle contribution.

The relief of the region between Vitória and Ecoporanga shows a series of linear features with an NNW-SSE alignment (Fig. 10). This feature was considered by some authors to be of Neoproterozoic age; however, it was reactivated in the Paleozoic with the intrusion of granitoid plutons (Guaratinga Intrusive Suite), in the Mesozoic with the intrusion of basic dykes (Fundão Intrusive Suite), in the Pleistocene-Holocene with the compressional (NW-SE) and extensional

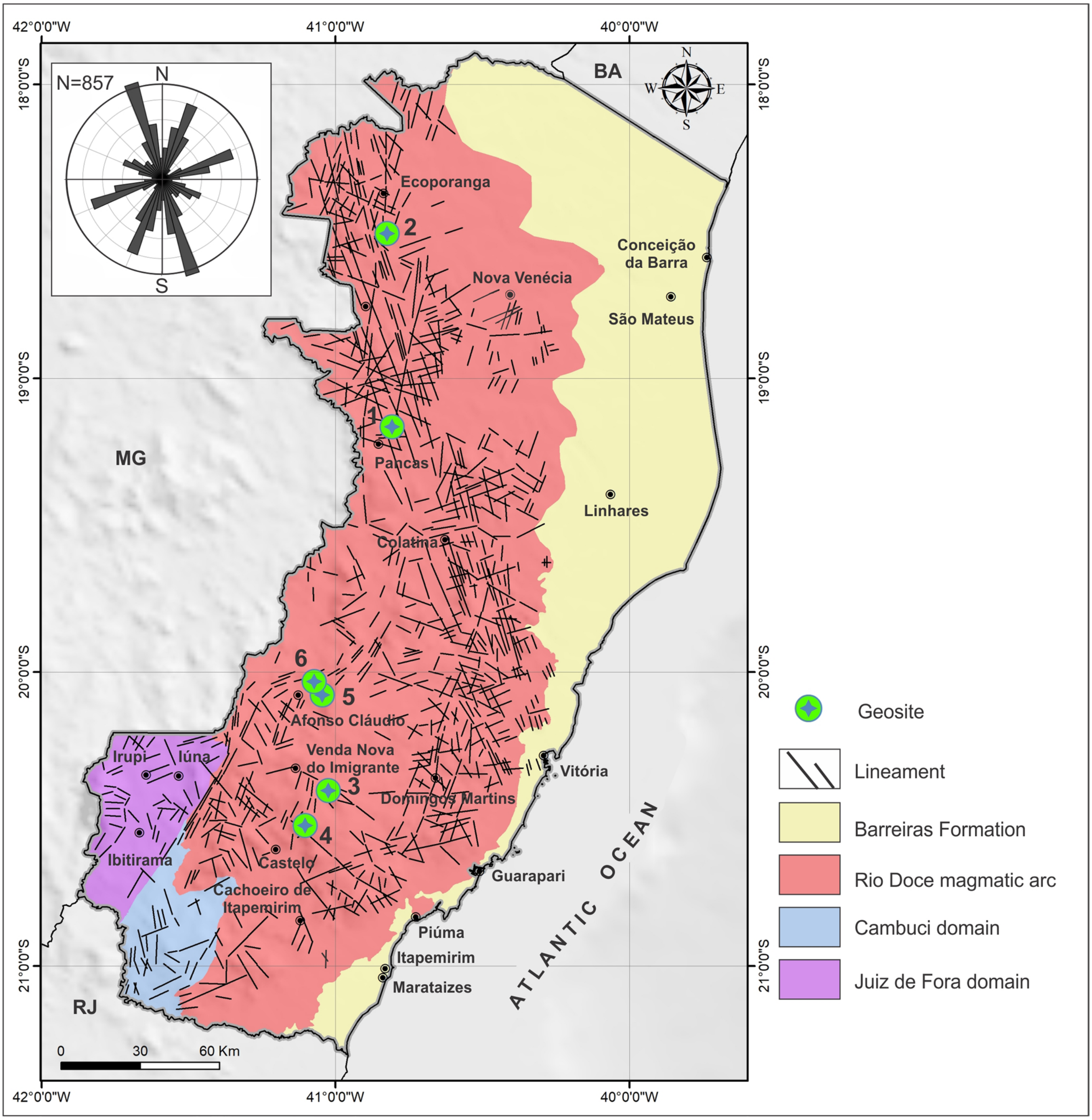

Fig. 11 Map of the tectonic domains of Espírito Santo State with lineaments, geosites, and rose diagram. (1) Pontões Capixabas; (2) Pedra do Garrafão; (3) Pedra Azul; (4) Pico do Forno Grande; (5) Pedra dos Três Picos; (6) Pedra da Broa

(NE-SW) fractures associated with a dextral transcurrent deformation, and finally by extensional event (NW-SE) during the Holocene (Riccomini 1989, Salvador 1994, Mello 1997, Mello et al. 1999, Ferrari 2001, Novais et al. 2004, Rodrigues 2005). In the southwestern Espírito Santo, the lineament configuration changes drastically from NNE-SSW to NE-SW, reflecting the general structure of the Ribeira belt (or Ribeira orogen).

The lineaments, together with the shapes of the intrusions, control the morphology of the outcropping rocks. In the area of the Carlos Chagas Suite, the structural control is clearly given by the Colatina lineament (NNW-SSE) and secondarily by the orientation of the ENE-WSW and ESE-WNW fractures. In the Afonso Cláudio pluton, where the Pedra dos Três Pontões and Pedra da Broa geosites are located, the structural controls are related to the pluton geometry and fractures related to the dextral shear zone that surrounds it, with the main direction given by the NW-SE lineaments and the secondary direction by the ENE-WNW and NEE-SSW lineaments.

All of these structures may have been reactivated during the separation of Gondwana and may still be active today as the continents continue to separate. As the continents broke apart, the crust was decompressed and uplifted, and erosional processes were intensified (Fig. 12). According to Almeida and Carneiro (1998), the origin of the Serra do Mar and Mantiqueira mountain systems probably dates back to the Paleocene.

The inselbergs are rock masses with isolated or grouped steep scarps along structural lineaments created by differential erosion (Goudie 2004). In addition to the structural controls mentioned above, the evolution of this landscape is related to the tectonic processes associated with the opening of the South Atlantic Ocean, the erosive systems that were installed and the climate of the region, which favoured the development of thick weathering mantles and their removal (Varajão and Alkim 2015). One of the theories used to explain the evolution of relief in granitoid rocks is etchplanation, in which plateaus are formed by the vertical advance of chemical weathering of the rocks, followed by erosion that removes the alteration mantle and exhumes the weathering front (Thomas 1978, Twidale 2007). Thus, environments with semi-humid tropical climatic conditions are conducive to the development of plateau surfaces due to the existence of dry and wet climatic seasons, high temperatures, and intense biological activity (Büdel 1982). Another

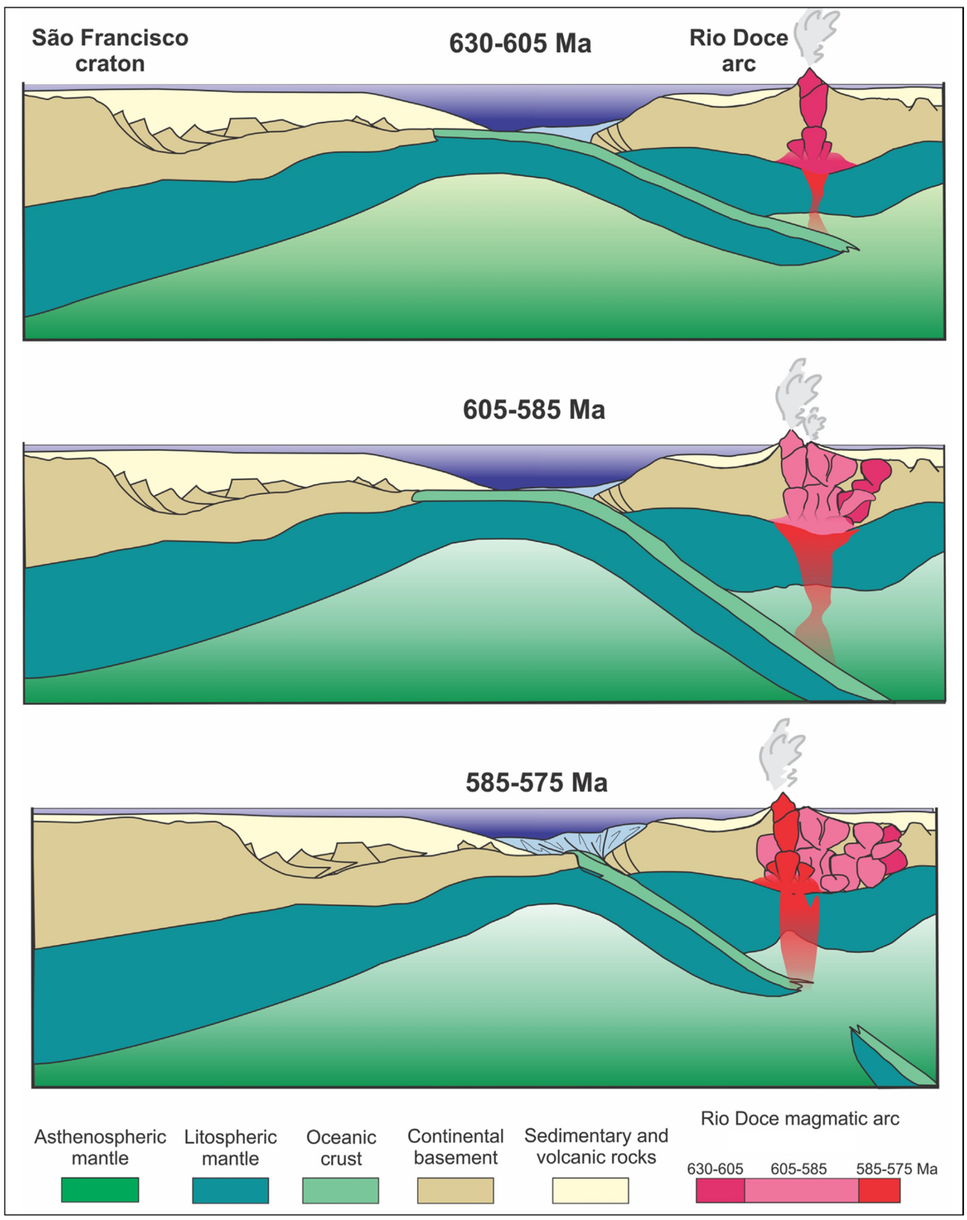

Fig. 12 Tectonic model for the central sector of the Rio Doce Magmatic Arc (not to scale). Compiled from Tedeschi et al. (2016)

factor influencing the development of relief is the density of fractures, which favours the infiltration of groundwater. The more fractured the rock, the greater the possibility of water infiltration and the greater the chance that the rock will be weathered. In this way, the reliefs in granitoid rocks almost always form landscapes with prominent shapes, due to the stability of the rock and its ability to resist the intense efforts of compression and traction (Rocha 2019).

Varajão and Akmim (2015) described the inselbergs of the Pancas region, where the Pontões Capixabas Natural Monument is located. The region is characterised by a spectacular landscape characterised by a high concentration of inselbergs of very different shapes, separated by extensive valleys and partially covered by remnants of Atlantic forest. The development of these shapes involves the following stages: nucleation of a system of spaced vertical fractures; intense weathering along the fractures during the Eocene; and uplift and subsequent erosion between the Miocene and Pliocene, leading to the appearance (exhumation) of the inselbergs.

In the geosites studied, the presence of minor landforms associated with the inselbergs is very common. The most common are tafoni, karren, and weathering pits, which usually occur in the higher parts of the rock masses. When tafoni reach metric dimensions, they can be characterised as caves (Fig. 13). They are forms that attract visitors because of their beauty and can even be used as recreational areas, as is the case with the weathering pits at the top of Pedra Azul, which are natural swimming pools (Fig. 14).

Mountaineering and Climbing Sports

Many geological and geomorphological sites occur in mountainous areas, which are also frequently used for climbing, mountaineering, trekking, bouldering, and other activities. These sites contribute to the understanding of the natural resources of this region, as well as to the planning of conservation, tourism, and educational activities (Ruban and Ermolaev 2020). UNESCO's 3GEO project launched in 2021 aims to enable geoparks and aspiring geoparks to use innovative tools to disseminate geological knowledge through geoclimbing and geotrekking. Natural climbing routes are rock outcrops that are trails for learning about the Earth's history. These climbing sites and trails are embedded in different landscapes that testify to the regional geodiversity (Escalante et al. 2022).

In Montestrutto (Austroalpine domain of Western Alps), some rock cliffs that have been locally equipped as sport climbing sites may also be used as sites of geological and geomorphological interest due to the combination of educational exemplarity and geohistorical importance increasing the scientific value of these sites (Bollati et al. 2014). In La Pedriza, Spain, visitors find a natural resource for practising sport, and developing scientific and educational activities

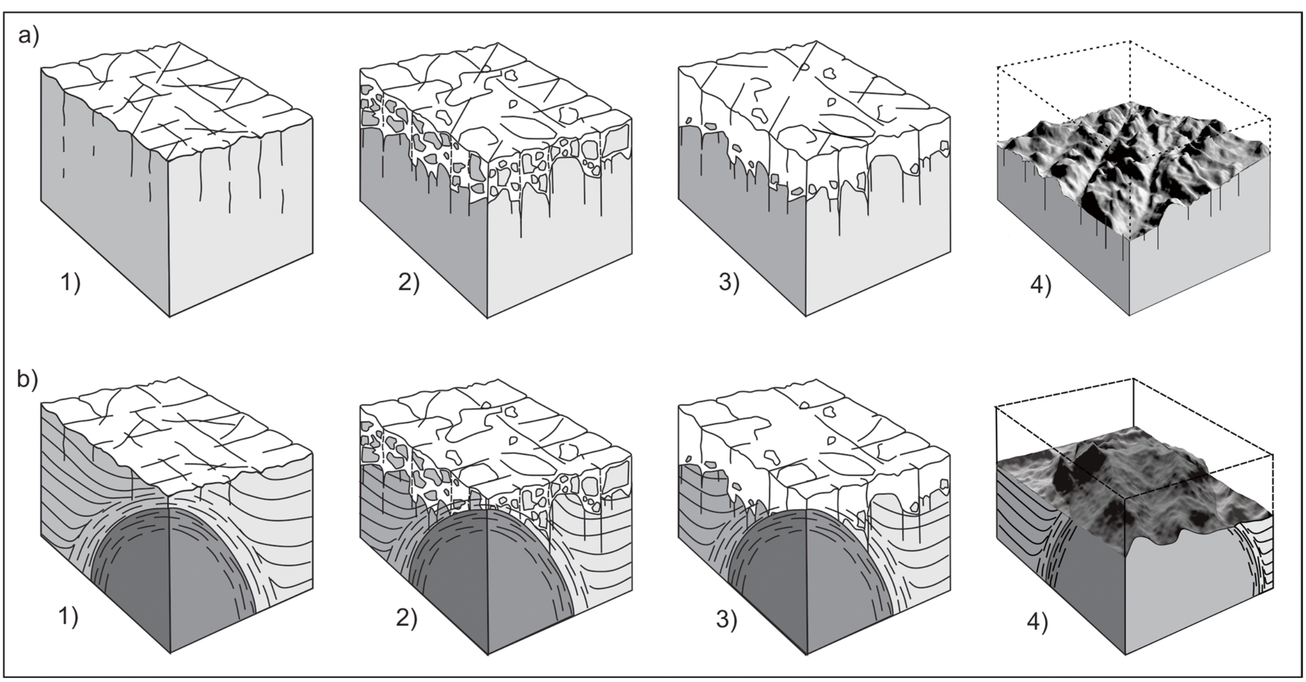

Fig. 13 Model of landscape evolution of syn-collisional and post-collisional granitoids. **a** Granitoids of the pre-collisional Carlos Chagas Suite; **b** detail of a post-collisional granitoid pluton. (1) Fractured healthy rock; (2) onset of rock weathering due to water circulation in the fractures; (3) development of deep weathering mantle and onset of erosion and uplift; (4) intense erosion processes causing the appearance of surface inselbergs. Adapted from Maia and Nascimento (2018)

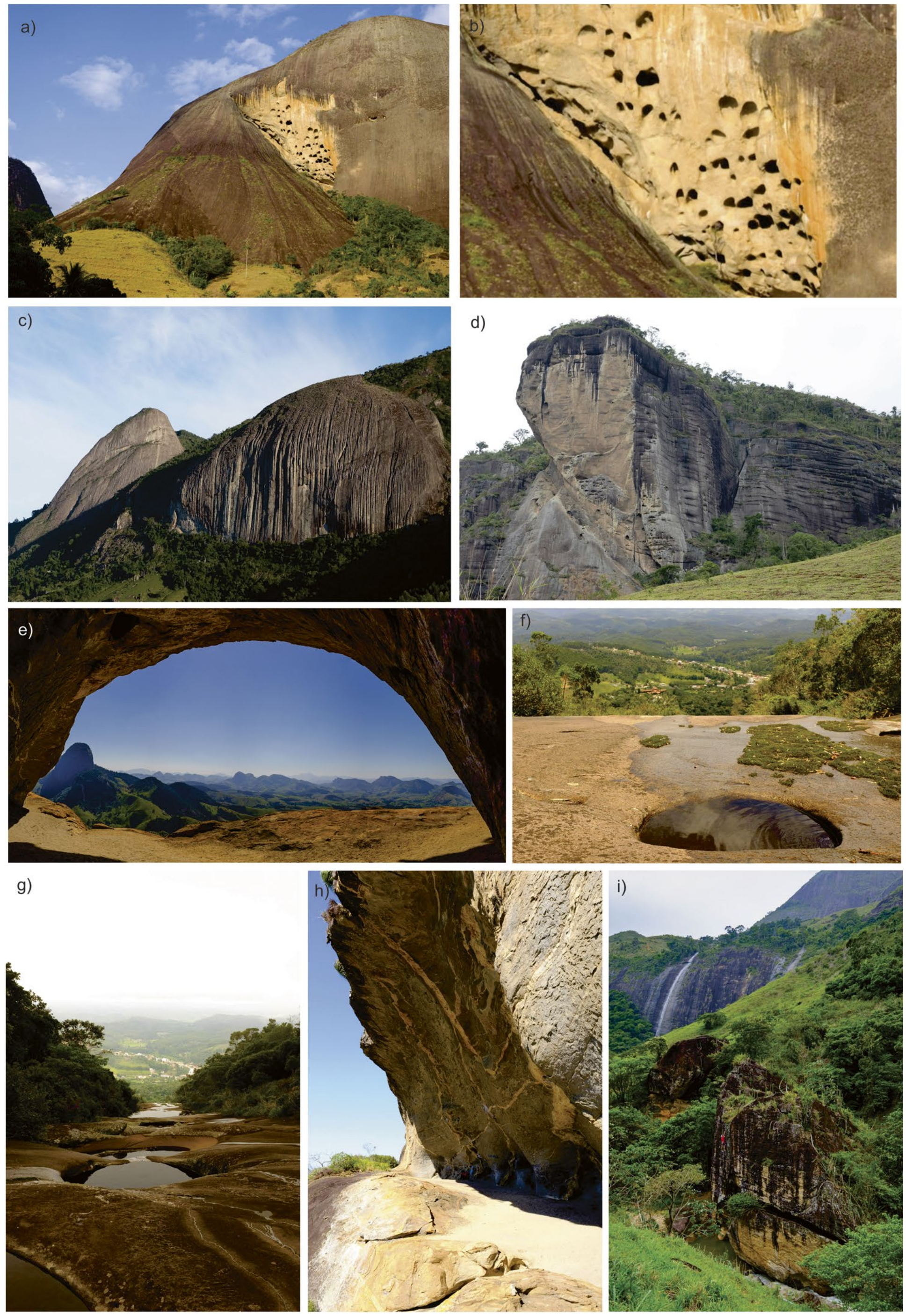

Fig. 14 Main minor landforms that occur in the studied geosites. **a** Tafoni; **b** detail of tafoni; **c** vertical karren; **d** horizontal karren and tafoni; **e** tafoni cave; **f** and **g** weathering pits; **h** flared rock; **i** boulder. Photos by Naoki Arima

through climbing routes that have been opened. Not only at La Pedriza, but also other areas of the world have proven to be ideal scenarios for studying geomorphologies that would be difficult to research without such routes and sporting activity (Bollati et al. 2014, Rodríguez and Escalante 2017). Rodríguez and Escalante (2017) described other examples in different countries with granite massifs and domal morphologies similar to La Pedriza's and where mountaineering is practised, including Yosemite National Park (USA), Spitzkoppe National Park (Namibia), Val di Mello Natural Reserve (Italy), Freycinet National Park (Australia), and Gorkhi-Terelj National Park (Mongolia).

Officially, mountaineering and climbing in Espírito Santo State began in 1947 with the conquest of Pico do Itabira, in Cachoeiro de Itapemirim, by climbers from the Centro Excursionista do Rio de Janeiro (Faria 2017). From the late 1940s to the mid-1990s, great achievements were made by mountaineers from Rio de Janeiro, who glimpsed the enormous potential of the state, conquering the main mountains of Espírito Santo State. It was not until the mid-1990s that the Capixaba mountaineering movement emerged, formed by a small group of local climbers. In 2003, the Associação Capixaba de Escalada (ACE) was created, and according to the last climbing census carried out in 2014, there are around 100 practitioners in Espírito Santo, with the vast majority in the metropolitan area and rarely climbers in the regions where the main mountains are concentrated (Garcez 2014). At present, Espírito Santo has about a thousand climbing routes of various difficulties, distributed from south to north of the state, with the Metropolitan, Mountain, and Northwestern regions of the state, being the places where the main climbing hubs are concentrated (Baldin 2017).

Due to the geological and geomorphological characteristics of the region, formed mainly by gneiss and igneous rocks of Neoproterozoic-Cambrian age, the main mountains sought for the practice of this sport are inselbergs, without extensive fracture systems, so that the predominant climbing style is adherence climbing, where the practitioner basically uses the friction of the shoes to progress up the mountain.

Conclusions

In geotectonic settings, the described geosites stand out for their Neoproterozoic geological history related to the building of the Rio Doce Magmatic Arc of the Araçuaí orogen, northern segment of the Mantiqueira Orogenic System. In geomorphological terms, the geosites have their origin related to the crustal uplift due to the rupture of Gondwana and the opening of the South Atlantic Ocean rift during the Cretaceous. The Pontões Capixabas and Pedra do Garrafão geosites are located in the Colatina belt and are structurally controlled mainly by NNW-SSE faults, and secondarily by ENE-WNW and ESE-WNW faults. The Pedra do Elefante geosite is located outside the Colatina belt and its structural control is related to the NNE-SSW, ESE-WNW, and ENE-WSW alignments. The Pedra Azul and Forno Grande geosites, located in the southwestern region, are structurally controlled mainly by NW-SE fractures and secondarily by NNE-SSW.

The quantitative evaluation of the geosites showed that they have national and regional relevance in relation to scientific, educational, and touristic uses. Specifically regarding the scientific relevance, the area where the geosites are located has a considerable volume of scientific publications, which are not specific to the geosites, but on a smaller scale (1:100,000 scale), involving large areas. In relation to the degradation risk, the geosites studied have a medium to low risk of degradation because most of them are located in tourist and/or protected areas, such as parks, natural monuments, and RPPNs. These factors provide a degree of security in terms of their conservation, but the advance of mining activity may mean an increase in risk. The Pontões Capixabas are located in a protected area, a Federal natural monument. The geosites of Pedra Azul and Pico do Forno Grande are located in state park areas. Pedra do Elefante is included in an APA. In the area of Pedra dos Três Pontões is located, there are two RPPN's. There are no protected areas around the Pedra do Garrafão and Pedra da Broa geosites. A more detailed inventory of the state will identify new areas of geological interest (geosites) and environmental interest, and a reassessment of these areas will be necessary.

The geosites of Espírito Santo have great aesthetic and cultural value, are used daily as tourist facilities and contribute to the development of local rural communities. They are used for nature observation (fauna and flora), and leisure and sports activities such as trekking, mountaineering, and climbing. However, little has been done to disseminate the geological knowledge of the region. Action in this direction is needed. Geotourism appears as another option for the development of cities and rural communities of the state. There are many options and opportunities that can be built from the elaboration of geotourism itineraries linked to the already existing ones as well as new itineraries involving local cultures, gastronomy, rural, and sports tourism. Many inactive ornamental stone quarries, which are now environmental passives, can be used as geomining sites and also as a source of raw materials for geoproducts such as didactic stone collections, handicrafts, and household utensils.

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Declarations

Ethical Approval Not applicable.

Conflict of Interest The authors declare no competing interests.

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