



Inventory and Quantitative Assessment of the Geological Heritage of Paraná State, Southern Brazil

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Abstract

The inventory of the geological heritage, along with the quantification of its value, is an essential task for the implementation of geoconservation strategies. Despite the Brazilian's rich geological heritage, only the state of São Paulo has concluded its systematic inventory. This paper presents the geological heritage inventory of Paraná State and a quantitative assessment of the scientific value of geosites and their vulnerability. The method applied for the geosites evaluation was adjusted after analyzing the most deemed protocols in international literature, taking into account the Brazilian socioeconomic and cultural conditions. The selection of geosites made by experts was based on the following criteria: representativeness, rarity, integrity, and degree of scientific knowledge. The inventory consists of 76 geosites, distributed in nine geological frameworks, which represent the geological evolution of Paraná. It is expected that this work may support future planning and management actions, which can safeguard the state's geological heritage, with efficient strategies, especially for those places with high risk of degradation.

Keywords Geoconservation · Geosites · Quantitative assessment · Brazil

Introduction

The initiatives to make geological heritage inventories in Brazil began to arise only a few decades ago, in part due to the large extension of the national territory, to the country's heterogeneous geological knowledge and, often, to the lack of public policies. The first Brazilian attempt to prepare a national geological heritage inventory took place in 1993, when the Brazilian National Department of Mineral Production (DNPM)—now the National Mining Agency (ANM)—collaborated with the UNESCO to assemble an inventory of sites for the List of World Heritage (Lima et al. 2010).

The systematic inventorying of Brazilian's geological heritage, however, only began in 1997, after the creation of the Brazilian Commission for Geological and Paleobiological Sites (SIGEP) (Schobbenhaus et al. 2002). The results of the commission's work established the inventory of 116 national geosites.

More recently, the “Geoparks of Brazil” project was created in 2006 by the Geological Survey of Brazil (CPRM). It promoted the identification, description, and assessment of Brazilian geological heritage in areas where potential geoparks could be developed. The project has identified 17 areas and a total of 362 geosites (Schobbenhaus et al. 2012).

Another relevant initiative for national geological heritage inventories was the development of an online database (GEOSSIT) by CPRM, with the goal of qualify and evaluate geosites and geodiversity sites (Rocha et al. 2016). The methods used by this database were based on García-Cortés and Carcavilla Urquí (2009) and Brilha (2016). Brazil, however, only has one systematic geoheritage inventory of scientific value, at a state scale, implemented in São Paulo state (Garcia et al. 2018). Furthermore, another methodological aspect that deserves an analysis concerns the adequacy of the main published

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methods applied to the quantitative assessment of Brazilian geosites. Such methods adopt criteria based on European historical and cultural context, often not adapted to the peculiarities of the Brazilian reality (Xavier et al. 2021).

The Paraná state covers an area of approximately 200,000 km², with more than 11 million inhabitants (IBGE - Instituto Brasileiro de Geografia e Estatística 2016). The first studies comprising the state's geology date back to 1875, carried by the Geological Chart of Brazilian Empire Commission (MINEROPAR - Minerais do Paraná SA. 2001). Since that time, several state and federal institutions, such as universities and geological surveys, have been developing research in Paraná territory. However, due to intensive urban development and increase of area occupied by agriculture, together with existent strong weathering conditions and frequent misuse of sites by tourists and even geoscientists, important and rare sites have been deteriorated. An example of this loss is the Salto das Sete Quedas site, also known as "Seven Falls of Iguaçu." The site was considered one of the world's largest falls in terms of water volume, located on the border between Brazil and Paraguay. This remarkable geosite was submerged in the late 1960s for the construction of Itaipu Hydroelectric Power Plant's lake. Likewise, pterosaur fossils found in Cretaceous sandstones at the northwest of the state correspond to an example of scientific vandalism. Shortly after the discovery of these well-preserved fossils, researchers quickly removed extensive blocks of stone to later extract fossils in the laboratory. As a result, countless fossils were lost and the geosite became lost part of its importance.

This work aims to present the inventory and quantitative assessment of geoheritage of Paraná state, which is a significant contribution to management and geoconservation actions.

Methods

Considering that the Paraná state is a large territory (200,000 km²), the geosites inventory was carried out based on the following activities (Fig. 1), as proposed by Brilha (2016).

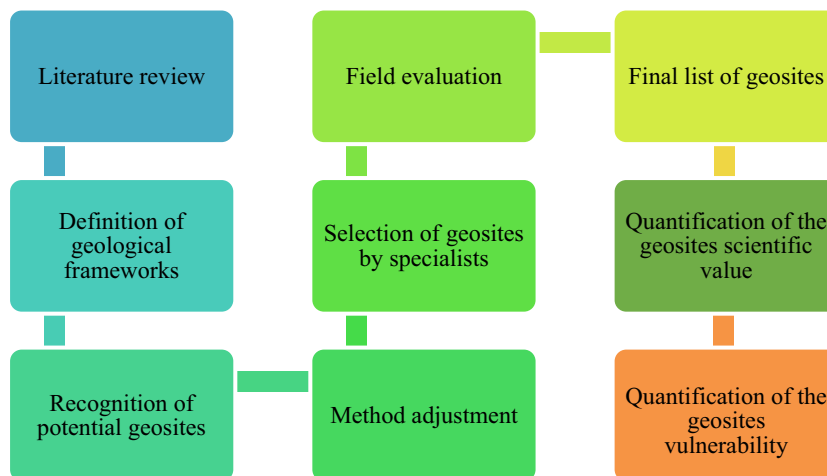
Literature Review

The starting point of this research was a literature review on the geology of Paraná state covering scientific publications, technical reports, and geological maps. Furthermore, a literature review of geological heritage inventory methods was carried out, based on those developed by ProGEO (International Association for the Conservation of Geological Heritage), which served as the framework for the initiatives implemented by the IUGS (International Union of Geological Sciences) in the scope of the Global Geosites Program, in Spanish (e.g., García-Cortés et al. 2001, 2019; Carcavilla Urquí et al. 2009; García-Cortés and Carcavilla Urquí, 2009) and Portuguese experiences (e.g., Brilha 2005; Brilha Pereira 2011; Brilha et al. 2013; Brilha 2016), in GEOSSIT (Rocha et al. 2016), in Latin American works (e.g., Wilson 2013) and in the method used in the geological heritage inventory of São Paulo state (Garcia et al. 2018).

Definition of Geological Frameworks

Geological frameworks are geological compartments of the area to be inventoried (Wimbledon 1996; Wimbledon et al. 1999; Gonggrijp 2000), which brings together stratigraphic, tectonic, magmatic, and metamorphic features, with well-defined geological boundaries (Brilha et al. 2010). This concept is very useful in systematizing the recognition of geosites bound to compose the inventory, since it allows the identification of sites according to their geological context,

Fig. 1 Sequential tasks done during the geoheritage inventory in Paraná



not only individually. Thus, the geological frameworks correspond to the themes that best represent the geological history of a territory (Brilha et al. 2010).

For the Paraná inventory, stratigraphic and tectono-structural criteria were applied to define the geological frameworks.

Listing Potential Geosites

After defining the geological frameworks, the step of recognizing potential geosites began and a survey was carried out by consulting field guidebooks published under the scope of scientific events. Rock exposures traditionally used in university field classes were also included, as well as the opinion of professors and researchers. All information of 192 potential geosites was stored in a database, created by the authors, comprising the geosite’s name, UTM system coordinates, location, municipality, and access roads; geological unit; description including information about the lithotype, contacts, and structures, along with other pertinent observations, such as land ownership and eventual existence of protected or conserved areas.

Method for the Quantitative Assessment

The method used for the quantitative assessment of geosites was based on Wilson (2013), which is an adaptation of García-Cortés and Carcavilla Urquí (2009), currently with an updated version (García-Cortés et al. 2019). The Wilson (2013) method proved to be a good starting point for this research because beyond adapting the method to Latin America’s scientific and cultural contexts, it also presents modifications to the Spanish method.

The method used by Xavier et al. (2021) assesses the scientific value (6 criteria) and vulnerability (6 criteria) of geosites (Tables 1, 2, and 3). Each criterion is evaluated by three indicators, scored with values from 0 to 4. Each criterion weights between 1 and 5: high (5), medium (3), and low (1).

Proposal of Geosites by Specialists

Experts of the Paraná’s geological frameworks, selected for being researchers in the specific areas, were asked to propose geosites, based on the following scientific criteria (Brilha 2016):

Table 1 Criteria used to quantify the scientific value of Paraná’s geological heritage

Criteria/indicators	Score
Scientific value	
Representativeness (SVW = 5)	
The geosite is the best-known example to represent elements and/or processes linked to its geological framework in Paraná	4
The geosite is a good example to represent elements and/or processes linked to its geological framework in Paraná	2
The geosite only partially represents elements and/or processes linked to its geological framework in Paraná	1
Rarity (SVW = 5)	
The geosite is the only known example of its geological framework in Paraná	4
There are two or three known examples of its framework in Paraná	2
The geosite is common. There are four or more known examples of its framework in Paraná	1
Integrity (SVW = 3)	
The geosite is well-preserved	4
The geosite shows a certain degree of deterioration	2
The degree of deterioration of the geosite hinders observation of its main geological elements	1
Type location/type species (SVW = 3)	
The geosite is a type location or type species for its geological framework or the site where a mineral form was first described	4
The geosite is a secondary type location or type species (it complements the type location or type species) for its geological framework	2
The geosite does not represent a type location or type species of its geological framework	0
Degree of scientific knowledge (SVW = 1)	
The geosite is described in international geoscientific literature	4
The geosite is described in national geoscientific literature or is mentioned in state-owned company reports, or has its scientific potential recognized by specialists	2
The geosite is not described in any form of publication	0
Geological diversity (SVW = 1)	
In addition to its main geological interest, the geosite is of four or more geological interests	4
In addition to its main geological interest, the geosite is of up to three geological interests	2
The geosite is of no interest other than its main one	0

Table 2 Criteria used to quantify the vulnerability of Paraná's geological heritage

Criterion/indicator	Score
Vulnerability	
Anthropogenic vulnerability (VUW = 5)	
The geosite is located less than 100 m away from activities that might cause its degradation (mining, busy road, highly populated area, recreational activities)	4
The geosite is located between 101 m and 1 km away from activities that might cause its degradation (mining, busy road, highly populated areas, recreational activities)	2
The geosite is located more than 1 km away from activities that might cause its degradation (mining, busy road, highly populated areas, recreational activities)	1
Natural fragility (VUW = 5)	
The geosite is vulnerable to natural alteration processes (floods, mass movements, erosion, weathering), at a scale that would compromise its integrity in the short term	4
The geosite is moderately vulnerable to natural alteration processes (floods, mass movements, erosion, weathering) that would not compromise its integrity in the short term	2
The geosite is slightly vulnerable to natural alteration processes (floods, mass movements, erosion, weathering), but they would not compromise its integrity in the short term	1
Protection regime (VUW = 3)	
The geosite is in an unprotected area	4
The geosite is in a Conservation Unit for sustainable use or is under some other form of protection	2
The geosite is in a Conservation Unit of integral protection	1
Accessibility (VUW = 3)	
The geosite is directly accessible by car/bus or located within an up to 100 m walking distance	4
The geosite is accessible after a 101 m to 1 km walk	2
The geosite is accessible after more than 1 km walk	1
Access regime (VUW = 1)	
The geosite is in an area of free access	4
The geosite is in a protected/restricted area, being visited only upon authorization	2
The geosite is in a protected/restricted area and is only visited upon authorization and/or payment of an entrance fee	1
Carrying capacity (VUW = 1)	
It is essential to take the carrying capacity of the geosite into account	4
Depending on the expected amount of visitors/use of the geosite, the carrying capacity must be calculated	2
Carrying capacity must not be taken into account	1

- i) *Representativeness*, geosite's ability of illustrating a geological process and/or product of the geological framework, in the most complete and expressive way possible.
- ii) *Rarity*, regarding the amount of geosites in the state with similar geological aspects.
- iii) *Integrity*, reflects the geosite's current conservation state, resulting from human and natural actions.
- iv) *Scientific knowledge*, expressed by the volume and quality of scientific publications related to the geosite, as well as its potential for future research.

García-Cortés et al. (2019) recommend the number of specialists per framework to be between two and seven. However, this number is conditioned by their availability, and by the extent and geodiversity of the geological framework. For the selection of geosites in Paraná, about 30 specialists have collaborated, with an average of 3 to 4 experts per geological framework. Some experts have also proposed

geosites related to more than one geological framework. The specialists were interviewed in person or by e-mail, following a standardized form for each geosite, including a brief geological description, location, geographic coordinates, eventual integration in protected areas, and description of the scientific value. Geosites not directly related with a specific geological framework could also be suggested by experts.

Table 3 Range of scores of the scientific value and vulnerability

	Minimum score	Maximum score	Classification
Scientific value	13	72	–
Vulnerability	18	31	Low
	32	58	Medium
	59	72	High

Geosites assessed/classified with “high” value were selected for field evaluation and quantification to establish the inventory of Paraná.

Field Work

Field work was crucial to verify the state of conservation of all potential geosites. Some geosites, mainly stratotypes, with high scientific value suggested by specialists are not available anymore due to urban development and weathering. During this stage, information about each geosite was updated and photos were taken to help the quantitative assessment.

Final Geosites List

After the field work, a final list with 76 geosites of Paraná was organized sorted by their scientific value and vulnerability. To build this list, it was considered that most geological units are represented, aiming to avoid that a certain geological framework would appear to have greater importance than another one due to its greater number of sites.

Results

Paraná’s geological history began approximately 2.8 Ga ago. These records, although intermittent, compose the basement of the South American platform, which outcrops in the east sector of the state. The basement consists of high-grade metamorphic rocks of Archean/Paleoproterozoic age, which encompass the Proterozoic acid magmatism, as well as the volcanic sedimentary and restricted sedimentary basins formed in the Ordovician, during the transition between the end of the Brasiliano cycle and the South American platform cratonization, at the end of the orogeny (MINEROPAR - Minerais do Paraná SA. 2001).

These rocks are the bedrock of sedimentary and volcanic rocks that occur in the central and western sectors of Paraná, constituting the intracratonic Paraná Basin, formed between the Devonian and Lower Cretaceous periods. The state’s geological history also comprises Triassic sedimentary rocks of continental origin, besides extrusive igneous rocks of predominantly basic composition and Cretaceous age, which constitute the Paraná Igneous Province. By the end of the Cretaceous, the sedimentary deposits of the northwest sector of the state were formed, establishing the Bauru Basin. Finally, Cenozoic unconsolidated sediments of continental and marine origin were deposited, partially covering older units (MINEROPAR - Minerais do Paraná SA. 2001).

Seventy-six geosites, distributed by nine geological frameworks, represent the geodiversity of the state (Fig. 2 and Table 4). The results of the scientific value and vulnerability quantification are presented in Table 5 and Fig. 3.

The geological framework with the highest number of geosites is Paraná Basin (37%), followed by Metamorphic Basement (16%), Granitic Rocks and Igneous Province of Paraná (12%), Cenozoic Sediments (11%), Bauru Basin (5%), Alkaline Rocks and Late-Orogenic Basins (4%), and Astrobleme (1%) (Fig. 3a). When there were no potential geosites for a certain framework, the specialists who evaluated such framework were required to suggest a geosite, following the criteria formerly established. On the other hand, when a geological framework with a reduced number of geological units had a high number of potential geosites, experts were asked to select only the most representative, rare, and well-preserved sites.

It was noticed that some formations under the Metamorphic Basement framework were not represented due to the inaccessibility to geosites and lack of experts. Similarly, the lack of geosites in certain formations under the Bauru Basin framework happened due to difficulties in carrying out field work during the COVID-19 pandemic. Another problem faced was the shortage of geosites that could exemplify the geological diversity of some categories, such as Alkaline Rocks. According to specialists, the locations that represented these units were totally deteriorated.

The high number of geosites corresponding to the Paraná Basin framework coincides with the Paraná’s geodiversity indexes (Pereira et al. 2013), which is due to the occurrence of different sedimentary lithotypes, most of them fossiliferous, along with the closeness to important universities in the state, which develop geological research in the region. As it can be noticed, this is the geological framework with the highest number of geomorphosites, causing the number of sites to increase in relation to other frameworks.

Regarding the type of geosites, 45% of the geosites correspond to pointillist, 33% to section, 18% to area, and 4% to viewpoint type sites, as defined by Fuertes-Gutiérrez and Fernández-Martínez (2010).

Most of the geosites (73%) have no statutory protection and 12% are located in conserved areas where sustainable uses are allowed. Geosites designated by the Secretary of Culture of Paraná State (State Law no 1.211/53) were also included in this category. 5.3% of the geosites have integral protection according to the Federal Law no 9.985/2000, which supports the Brazilian System of Protected Areas, and 10.5% have mixed protection (both sustainable use and integral protection) (Fig. 3c).

Most geosites (34%) have petrological interest as their main interest, followed by metallogenetic interest (15%). There are only four geosites, all suggested by experts, that were previously registered in GEOSSIT: Panelas Mine Marble (Neoproterozoic), Vila Velha ruiniform sandstone (Carboniferous), Três Morrinhos silicified sandstone hills (Cretaceous), and Curitiba Basin sediments (Paleogene). Nine geosites proposed by experts are also included in the CPRM’s “Geoparks of Brazil” project.

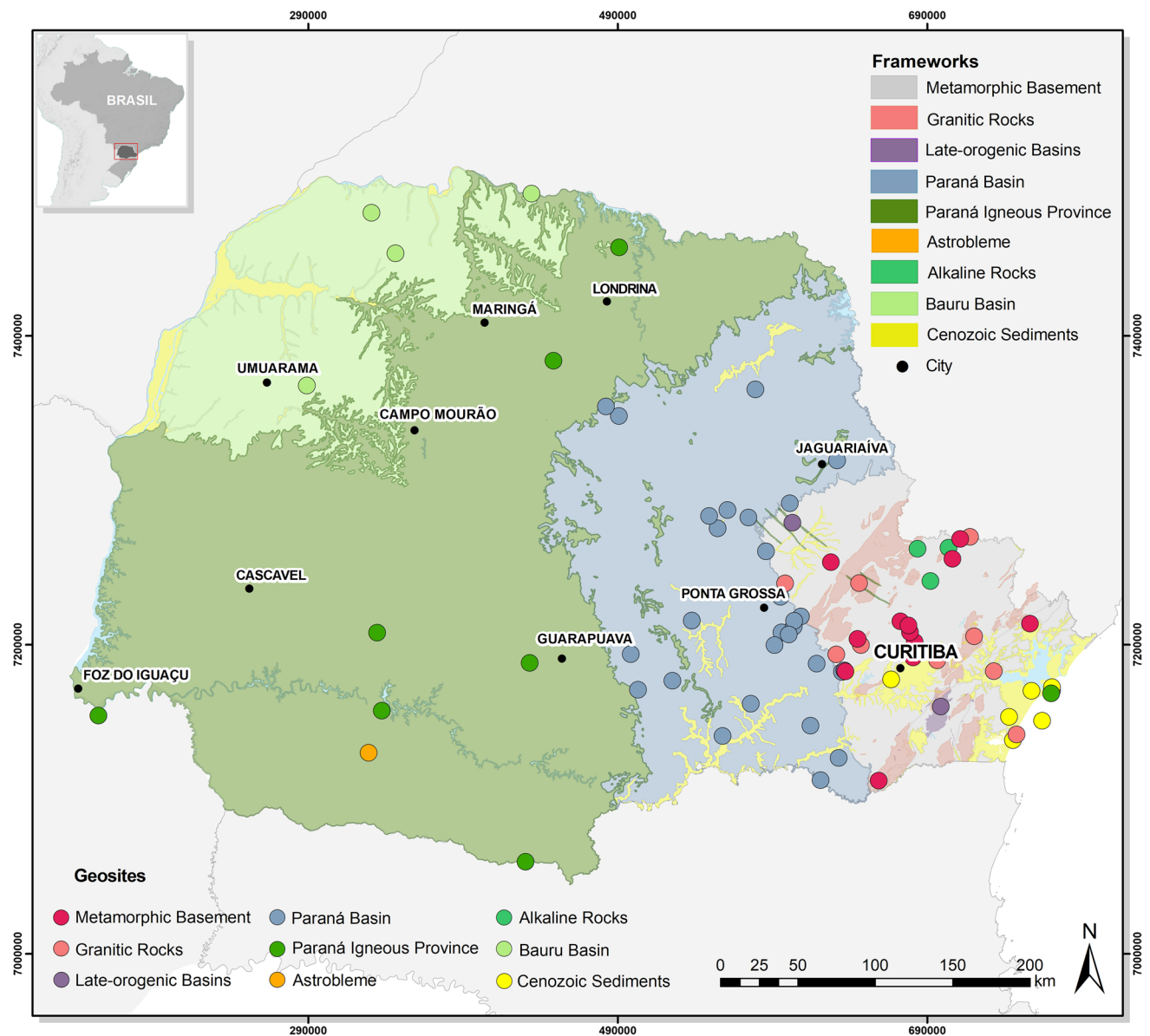


Fig. 2 Map of geological frameworks and geosites in the Paraná State. Brazilian Geological Survey's geological database (CPRM 2014)

Geological Framework: Metamorphic Basement

Paraná's metamorphic basement rocks belong to Ribeira Belt, a crustal segment parallel to Brazil's south-southeast coastline, forming a northeastern oriented zone. The belt constitutes an orogenic complex related to the Brazilian Orogeny, formed during the West Gondwana Supercontinent amalgamation (Almeida 1967; Hasui et al. 1975; Almeida et al. 2000; Heilbron et al. 2008; Hasui and Olivera 2013). This unit presents a polyphasic geological evolution, with segmented and elongated records of NE-SW orientation. It is composed of Paleoproterozoic basement rocks, Meso- and Neoproterozoic supracrustal metasedimentary and metavolcanosedimentary cover units, and, at last, Neoproterozoic

granite genesis and deformation (Cury 2009). In Paraná, these records are represented by Luís Alves Domain, Curitiba Microplate, and Apiaí Domain (Basei et al. 1992, 1998; Siga Jr. et al. 1993, Siga Jr. 1995; Yamato 1999; Harara et al. 2001; Sato et al. 2003; Campanha and Faleiros 2005; Heilbron et al. 2008; Cury 2009; Faleiros et al. 2011).

The two geosites with highest scientific value representing this geological framework are: Neoproterozoic-Devonian contact between Capiçu and Furnas Formations, and Archean-Paleoproterozoic Piên Ophiolitic Sequence. The Archean-Paleoproterozoic Piên Ophiolitic Sequence geosite (Fig. 4a and b) is located in southeastern Paraná and is associated with the Piên Mafic-Ultramafic Complex with 631 Ma. The rocks of this complex show a metamorphic

Table 4 Number of potential and selected geosites in each geological framework defined for the Paraná's geological heritage inventory

Geological frameworks	Number of potential geosites	Number of selected geosites
Metamorphic Basement	31	12
Granitic Rocks	21	9
Late-orogenic Basins	9	3
Paraná Basin	74	28
Paraná Igneous Province	24	8
Astrobleme	1	1
Alkaline Rocks	3	3
Bauru Basin	13	4
Cenozoic Sediments	16	8
Total	192	76

grade from the greenschist facies (biotite zone) to the beginning of the amphibolite facies (Harara 2001). The geosite presents an incomplete ophiolitic sequence where only the mantle section is exposed represented by peridotites (dunites, serpentized hazburgites, and serpentinites).

The Neoproterozoic-Devonian contact between Capiru and Furnas Formations geosite (Fig. 4c and d) is also located in southeastern Paraná showing the Neoproterozoic Capiru Formation, Açungui Group (Bigarella and Salamuni 1958) under the Devonian Furnas Formation, Paraná Group (Lange and Petri 1967). In this geosite, the Capiru Formation is represented by Morro Grande unit, an alternation of phyllites and quartzites (Fiori and Gaspar 1993), with regional metamorphism of greenschist facies, chlorite zone (Yamato 1999). The exposed part of Furnas Formation corresponds to its basal unit, which is composed of sandstones and conglomerates in contact with Capiru's phyllites by angular unconformity and abrupt geological contact.

Regarding vulnerability, the Mesoproterozoic Campo Largo phyllite (Fig. 4e) and the Neoproterozoic Columbus phyllite (Fig. 4f) are the most vulnerable sites in this geological framework. These geosites are directly accessible by car, do not have any form of legal protection, and are located less than 100 m away from roads with a large flow of vehicles and in areas with high population density. In addition, they have moderate natural vulnerability because phyllites are not so resistant rocks under weathering and erosion. The Campo Largo geosite is more vulnerable to human activity than the Columbus geosite since it is in an unrestricted access area. For more details about geosite scoring, check Xavier (2022).

Geological Framework: Granitic Rocks

Paraná's granite bodies are hosted by the metavolcanosedimentary sequences in the southeastern portion of the Ribeira Belt (Cury et al. 2008). In the Apiaí

Domain, these bodies occur as batholith stocks, formed in a compressional setting associated with the Brasiliano Cycle, having ages between 630 and 590 Ma (Prazeres Filho 2005; Guimarães 2000). Other smaller granite massifs represent late-orogenic magmatism events (560 Ma), which occurred in the same circumstances as the deformations present in the Apiaí Domain and Três Córregos-Cunhaporanga magmatic arc, related to the final stages of transpression, where their emplacement was closely associated with the transcurrent shear zones and development of large antiforms and synforms (Cury et al. 2008). The Curitiba Microplate bears the Rio Piên-Mandirituba Suite, which corresponds to granite complex with pre-collisional ages between 620 and 610 Ma and late-collisional ages between 605 and 595 Ma (Harara et al. 2001). The Serra da Graciosa Province represents an important magmatic event of an alkaline/peralkaline nature within the domains of the Luís Alves Microplate, Curitiba Microplate, and Paranaguá Terrain. It is represented by several granite massifs distributed in the vicinities of large shear zones, with crystallization ages in the range of 600–580 Ma (Siga 1995). The Paranaguá Terrain is represented, in almost its entirety, by an igneous complex that includes a wide variety of granitic rocks (Basei et al. 1990), formed by granites of Neoproterozoic ages (Cury 2009).

The geosites with highest scientific value are Neoproterozoic Ponta da Pita and Passa Três granites. These sites obtained maximum scores for the criteria representativeness, integrity, and degree of scientific knowledge. The Ponta da Pita Granite geosite (Fig. 5a and b) is located at the Paraná coast and comprises leucocratic, isotropic, medium-grained, inequigranular, rarely porphyritic, light gray to pinkish gray monzogranites, granodiorites, quartz-monzodiorites, and quartz-monzonites. The Passa Três Granite geosite is in the Curitiba's metropolitan region and presents two petrographic facies: melagranitic-syenogranite and leucogranitic-syenogranite with 616 ± 36 Ma (Picanço, 2000). There are aplite, pegmatite, and microgranite veins, in addition to quartz veins. Quartz veins are massive-textured, auriferous, internally sheared, with sulfide-filled fracturing (Fig. 5c) (Picanço, 2000).

The most vulnerable geosites in this framework are the Neoproterozoic Três Córregos (Fig. 5d) and Cerne granites (Fig. 5e). These sites are directly accessible by car in unrestricted access areas (roadcuts) and are vulnerable to weathering and erosion.

Geological Framework: Late-orogenic Basins

Late-orogenic basins are also known as South American platform transitional stage basins. In Paraná, these basins are in the Central sector of the Mantiqueira Province (Almeida and Hasui 1984) and are related with the

Table 5 Results of the quantification of the scientific value and vulnerability, type of geosite, and its statutory protection

No.	Geosite name (age)	Geological Framework	Scientific Value	Vulnerability	Geosite type	Statutory protection	
1	Piñ Ophiolitic Sequence (Archean-Paleoproterozoic)		56	medium	punctual	no	
2	Serra Negra Granulitic Gneiss (Archean-Paleoproterozoic)		35	medium	spot	no	
3	Atuba Quarry Migmatite (Paleoproterozoic)		46	medium	spot	no	
4	Calciosilicatic from Canoas I Mine (Mesoproterozoic)	Metamorphic basement	48	medium	spot	no	
5	Campo Largo Philite (Mesoproterozoic)		38	high	section	no	
6	Calpar Quarry Marble (Neoproterozoic)		48	medium	spot	no	
7	Gruta da Lancinha Metadolomite (Neoproterozoic)		46	medium	area	yes	
8	Motin Pavin Quarry Stromatolytic (Neoproterozoic)		41	medium	area	no	
9	Panelas Mine Marble (Neoproterozoic)		36	medium	spot	no	
10	Setuva Antiform Quartzite (Neoproterozoic)		46	medium	section	no	
11	Colombo Philite (Neoproterozoic)		28	medium	spot	no	
12	Contact between Capiru and Furnas Formations (Neoproterozoic-Devonian)		58	medium	viewpoint	no	
13	Ponta da Pita Granite (Neoproterozoic)		Granitic Rocks	48	high	spot	no
14	Três Córregos Granite (Neoproterozoic)			37	high	section	no
15	Serra do Carambé Granite (Neoproterozoic)	46		medium	area	no	
16	Itaoca Granite (Neoproterozoic)	42		medium	section	no	
17	Anhangava Granite (Neoproterozoic)	43		medium	spot	no	
18	Pico Paraná Granite (Neoproterozoic)	41		medium	area	yes	
19	Pico do Surfista Granite (Neoproterozoic)	43		high	spot	no	
20	Cerne Granite (Neoproterozoic)	35		high	spot	no	
21	Passa Três Granite (Neoproterozoic)	48		medium	spot	no	
22	Guaratubinha Basin conglomerates, andesites and acidic volcanics (Neoproterozoic)	Late-orogenic Basins		45	medium	spot	no
23	Malucelli Quarry ignimbrites and rhyolites (Neoproterozoic)			43	medium	area	no
24	Camarinha Basin breccias and conglomerates (Cambrian)		41	high	spot	no	
25	Iapó Formation Stratotype (Ordovician-Silurian)		62	medium	section	no	
26	Transicional Contact between Furnas and Ponta Grossa Formations (Devonian)		58	medium	section	no	
27	São Luiz do Purunã ichnofossils (Devonian)		42	high	spot	yes	
28	Jaguariaíva fossiliferous geosite (Devonian)		72	medium	section	no	
29	Rio Caniú fossiliferous geosite (Devonian)		63	high	spot	no	
30	Lilliput Effect fossiliferous geosite (Devonian)		66	high	section	no	
31	Tibagi fossiliferous geosite (Devonian)		55	high	section	no	
32	Santa Bárbara Waterfall rocks (Silurian-Devonian)		Paraná Basin	58	high	area	yes
33	Andorinhas Cave rocks (Silurian-Devonian)	57		high	spot	no	
34	Quebra-Perna river's sinkhole rocks (Silurian-Devonian)	60		high	area	yes	
35	Buraco do Padre Cave rocks (Silurian-Devonian)	50		high	area	yes	
36	Lagoa Dourada Senile Cave rocks (Silurian-Devonian)	58		low	area	yes	
37	Guartelá Canyon rocks (Silurian-Devonian)	48		low	section	yes	
38	Piraf do Sul Scarp's watching tower rocks (Silurian-Devonian)	56		medium	viewpoint	yes	
39	Vila Velha ruiniform sandstone (Carboniferous)	60		medium	area	yes	
40	Lapa sandstones (Permian-Carboniferous)	43		medium	section	no	
41	Campo do Tenente diamictites (Permian-Carboniferous)	43		medium	spot	no	
42	Witmarsum glacial striations (Permian-Carboniferous)	60		medium	spot	yes	
43	Pedra Caída Monument (Permian-Carboniferous)	52	medium	section	no		
44	São Mateus do Sul pyrobituminous shale (Permian)	48	medium	area	no		

Neoproterozoic multi-collisional processes occurred during the Brasiliano Cycle, which led to the amalgamation and consolidation of Western Gondwana (Brito Neves and Cordani 1991; Brito Neves et al. 1999; Campos Neto 2000).

In this context, the smaller crustal blocks, which were dispersed over the vast oceanic area, were diachronically coupled along the South American continental margins, in addition to subduction with consumption of oceanic crust,

Table 5 (continued)

45	Imbituva claystones and shales (Permian)	Paraná Basin	45	high	section	no	
46	Irati shales and sandstones (Permian)		45	medium	spot	no	
47	Ibaiti diamictites (Permian)		50	medium	section	no	
48	Pinheiro de Pedra fossiliferous geosite (Permian)		56	medium	spot	yes	
49	São João do Triunfo fossiliferous geosite (Permian)		44	high	section	no	
50	Serra do Cadeado fossiliferous geosite (Permian)		72	medium	section	no	
51	de Irati mudstones and sandstones (Permian-Triassic)		52	high	section	no	
52	Mauá da Serra sandstone (Jurassic-Cretaceous)		37	medium	spot	no	
53	Cataratas do Iguaçu basalt (Cretaceous)		41	medium	viewpoint	yes	
54	Guarapuava hypohyaline basalt flows (Cretaceous)		46	medium	section	no	
55	Sertanópolis volcanoclastic breccias (Cretaceous)	Paraná Igneous Province	46	medium	spot	no	
56	Cambira columnar jointing rocks (Cretaceous)		40	medium	spot	no	
57	Palmas rhyolites (Cretaceous)		48	medium	section	no	
58	Nova Laranjeiras hydrovolcanoclastic sequence (Cretaceous)		50	high	section	no	
59	Saudade do Iguaçu Vitroclastic tuffs (Cretaceous)		46	medium	spot	no	
60	Gruta das Encantadas dike (Cretaceous)		35	medium	spot	no	
61	Vista Alegre Astrobleme		Astrobleme	52	medium	spot	yes
62	José Fernandes alkaline gabros (Cretaceous)		Alkaline Rocks	58	medium	section	no
63	Tunas syenites (Cretaceous)			42	medium	spot	no
64	Mato Preto Carbonatite (Cretaceous)			58	medium	area	no
65	Rio Paraná Formation arenites (Cretaceous)	43		medium	section	no	
66	Três Morrinhos silicified sandstone hills (Cretaceous)	Bauru Basin	60	medium	area	yes	
67	Cruzeiro do Oeste fossiliferous geosite (Cretaceous)		72	medium	spot	yes	
68	Vale do Rio do Peixe Formation conglomerates and sandstones (Cretaceous)		48	medium	section	no	
69	Curitiba Basin sediments (Paleogene)		64	medium	spot	yes	
70	Alexandra Formation sediments (Neogene)		58	high	section	no	
71	Ilha dos Currais pebble beach (Holocene)		56	medium	spot	yes	
72	Ilha do Mel dune (Pleistocene)	Cenozoic Sediments	58	low	spot	yes	
73	Maciel river terrace (Holocene)		43	medium	section	no	
74	Guaratuba tidal delta (Holocene)		48	medium	area	no	
75	Ilha do Mel incipient dunes (Holocene)		43	medium	spot	yes	
76	Ilha do Mel Isthmus (Holocene)		56	medium	spot	yes	

closure of sub-basins, and crustal thickening caused by the stacking of nappes and continental flakes, resulting in a process of bonding, orogeny, and amalgamation (Teixeira et al. 2004). In the Paraná state, there are Camarinha, Castro, and Guaratubinha basins.

The geosite with the highest scientific value in this framework is the Neoproterozoic Guaratubinha Basin conglomerates, andesites, and acid volcanics (Fig. 6a), which obtained the maximum scores in the criteria representativeness, integrity, and degree of scientific knowledge. The site is located in Curitiba’s metropolitan region and represents the Guaratubinha volcano-sedimentary basin, a pull-apart type basin that results of a transtensional event caused by the activation of the Guaratubinha main fault. This basin developed over Archean-Paleoproterozoic high-grade metamorphic rocks from the Luiz Alves Terrain, at the end of the Neoproterozoic (Barão, 2017).

The geosite with highest vulnerability is the Cambrian Camarinha Basin breccia and conglomerates (Fig. 6b) because it is directly accessible by car, in an unrestricted and unprotected area (roadcut) exposed to weathering and erosion.

Geological Framework: Paraná Basin

The Paraná Basin is a large sedimentary region in the South American continent, comprising territorial portions of Brazil, Paraguay, northeastern Argentina, and northern Uruguay. Its current delimitations are defined by erosional boundaries largely related to the continent’s Meso-Cenozoic history (Milani et al. 2007). The tectono-stratigraphic evolution of the Paraná Basin in Gondwana’s cratonic interior occurred with the development of active collisional belts. The lithospheric flexure by tectonic overload propagated inland, from the foreland basin developed in the western portion of Gondwana, has been interpreted as an important subsidence mechanism during basin evolution (Milani et al. 2007). The geosites with highest scientific value are Jaguariaíva (Devonian) and Serra do Cadeado (Permian). Jaguariaíva geosite (Fig. 7a and b) is in central Paraná where the Jaguariaíva Member of Ponta Grossa Formation, Paraná Group crops out (Lange and Petri 1967). It has a Lower Devonian age (407 Ma, Milani et al. 2007) and is considered the type location of the unit (Petri 1948). Bergamaschi (1999) describes a succession of facies of

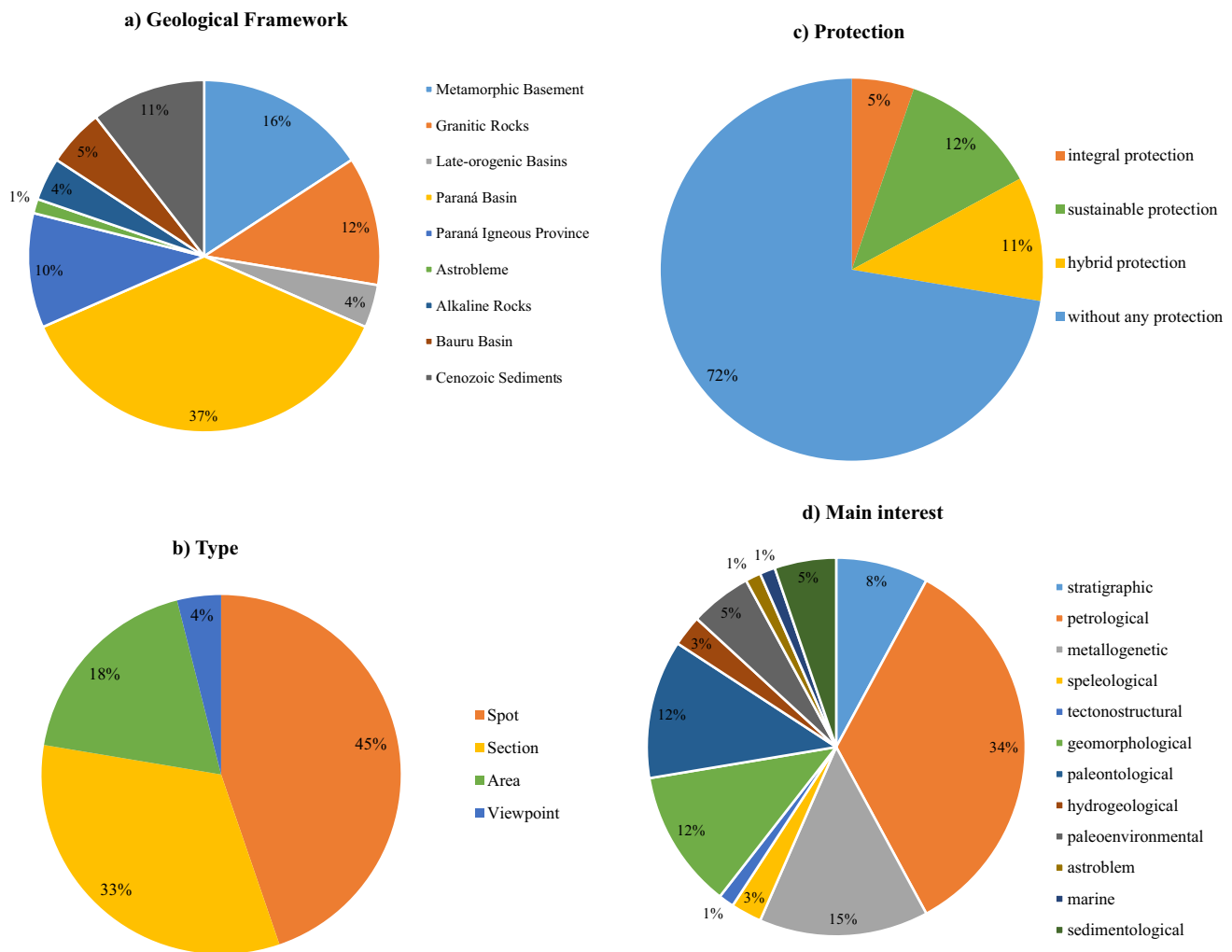


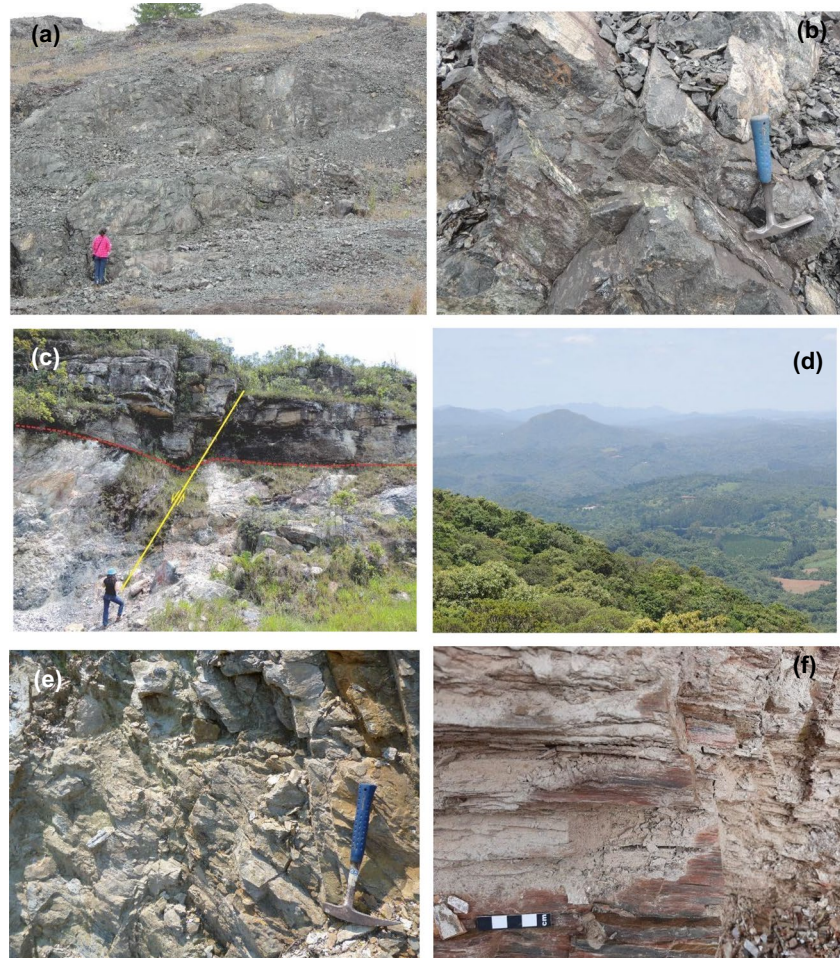
Fig. 3 Geosites selected by specialists, according to **a** geological categories, **b** types, **c** protection, and **d** main interest

light to medium gray-colored siltstone, with intercalations of very fine yellowish and intensely bioturbated sandstone, with a mottled appearance. The fossils found in the geosite belong to the Malvinokafrican fauna and present a great diversity of marine invertebrates: *Conulariida*, *Brachiopoda Articulata* and *Inarticulata*, *Mollusca Bivalvia* and *Gastropoda*, *Tentaculitoidea*, trilobita and *Crinoidea*. There are also microfossils such as plant cuticle, sporomorphs, *Chitinozoa*, *Acritarca*, *Tasmanacea*, and escolecodontes. At the site, the following ichnofossils were also described: *Planolites* sp., *Paleophycus* sp., *Bergaueria* sp., and *Zoophycus* sp., common in psamitic strata (Cruz and Soares 1996). Recently, Fraga and Vega (2020) described a new species of local starfish, *Paranaster crucis*, belonging to the class Asteroidea, Echinodermata Phylum, which has only one fossil specimen found in Paraná. The same authors also recognized the genus of sea snake *Encrinaster pontis* (Clarke 1913; Fraga and Vega 2020). Scheffler and Fernandes (2007) identified new crinoid species at the site, *Cyclocaudex paranaensis* and *Ophiucrinus stangeri*. The

latter was registered for the first time in rocks from South America, comprising the first species of crinoid described based on the calyx, for the Devonian of the Paraná Basin.

The Serra do Cadeado geosite (Fig. 7c) is in north-central Paraná showing Upper Permian (290 Ma; Milani et al. 2007) sedimentary rocks of Serrinha Member, Rio do Rasto Formation, Passa Dois Group. Gray, lilac to purple siltstones and claystones outcrop, along with fine whitish sandstones forming tabular to lenticular strata, which may locally bear calcareous lenses or horizons (Rohn 1994). The fossiliferous record is composed of plants (*Schizoneura*, *Glossopteris*, *Paracalamites*, *Pecopteris*), bivalves (*Leinzia*, *Palaeomutela*, *Terraia*), few gastropods, conchostraceans (*Pseudestheria*, *Monoleiolphus*, *Euestheria*, *Asmussia*, *Liograptia*), ostracods, and few insects, along with an especially significant tetrapod fauna. The latter includes the *Endothiodon* dicynodont, a small- to medium-sized terrestrial herbivorous animal, as well as two forms of temnospondyl “amphibians,” a long-faced, *Australerpeton cosgriffi*, and a short-faced, which together compose an important fauna

Fig. 4 **a** General view of the Archean-Paleoproterozoic Piên ophiolitic sequence geosite; **b** serpentinites with fine to very fine phaneritic granulation, green to dark gray color; **c** Neoproterozoic-Devonian contact between the Capiru and Furnas Formations geosite; note the presence of a normal fault; **d** gap between the first Paraná plateau formed by igneous and metamorphic rocks, and the lower second Paraná plateau constituted by sedimentary rocks; **e** Neoproterozoic Columbus phyllite geosite; **f** Mesoproterozoic Campo Largo phyllite geosite



of aquatic predators (Langer et al. 2009). Such tetrapod paleofauna constitutes the first amphibian and reptile fossil records in continental Tartarian sediments in South America (Barberena et al. 1980). Laurini (2010) described elasmobranch teeth, which represent the first record of this group in the region.

The geosites with highest vulnerability are the Devonian Rio Caniú fossiliferous geosite and the Devonian São Luiz do Purunã Ichnofossils. The former (Fig. 7d) is accessible by car and is located next to a highway with a large flow of vehicles and close to residences, with no legal protection or access restrictions. In addition, the shales occurring at this site are highly vulnerable to weathering and erosion. The São Luiz do Purunã geosite (Fig. 7e) is less vulnerable as it is listed by the Paraná State Department of Culture as a geological site, although it has no access control.

Geological Framework: Paraná Igneous Province

The Paraná Igneous Province has its origin in a large magmatic event that preceded the opening of the South Atlantic, being among the largest continental basalt provinces in the world (Marques and Ernesto 2004). It is classified as a

Large Igneous Province (LIP), a term used to designate large provinces composed of a significant volume of extrusive and intrusive igneous rocks, predominantly mafic (Coffin and Eldholm 1992). It originated from fissure volcanism, comprising the South American portion of the Paraná-Etendeka Igneous Province and extending over South America, through eight Brazilian states, Uruguay, Argentina, and Paraguay, during the Lower Cretaceous (Licht and Arioli 2020).

The Paraná Igneous Province volcanic rocks belong to the Serra Geral Group and constitute about 90,000 km² of the state's territory, corresponding to 60% of its total area (MINEROPAR - Minerais do Paraná SA. 2001). This geological framework also includes dikes of basic composition intruded in distensive fractures. The basic occurrences consist on diabase and diorite dikes, with a notable swarm of these intruding the state's metamorphic basement, generally in a northwest-southeast direction, associated with the structure called Ponta Grossa Arch (MINEROPAR - Minerais do Paraná SA. 2001).

The geosites with highest scientific value is Cretaceous Nova Laranjeira hydrovolcanoclastic sequence. This geosite (Fig. 8a and b) obtained maximum score in

Fig. 5 **a** General view of Ponta da Pita granite geosite; **b** pinkish gray monzogranites (Ponta da Pita geosite); **c** pinkish syenogranites with auriferous quartz veins and associated fluorite (Passa Três geosite); **d** syenogranite with alkali feldspar phenocrysts (Três Corregos geosite); **e** syenogranites (Cerne granite geosite)

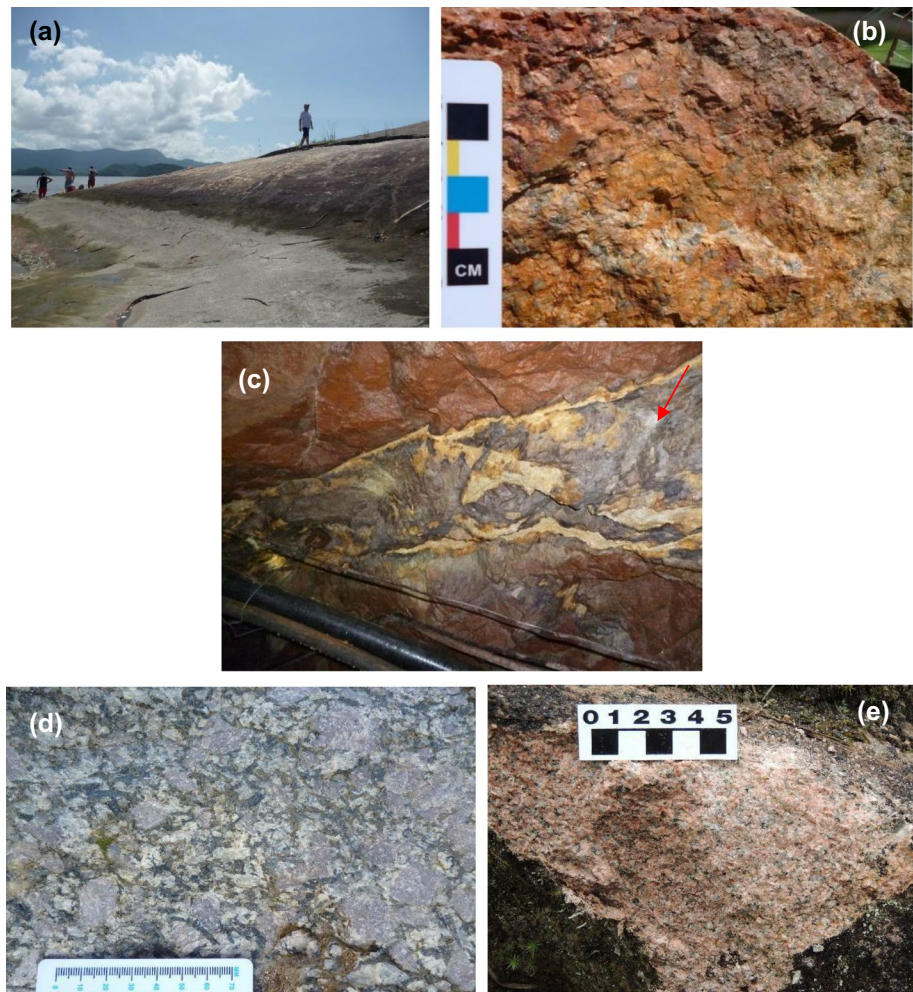


Fig. 6 **a** Ignimbrites belonging to the Neoproterozoic Guaratubinha Basin conglomerates, andesites, and acid volcanic rocks geosite. **b** The Cambrian Camarinha Basin breccias and conglomerates geosite

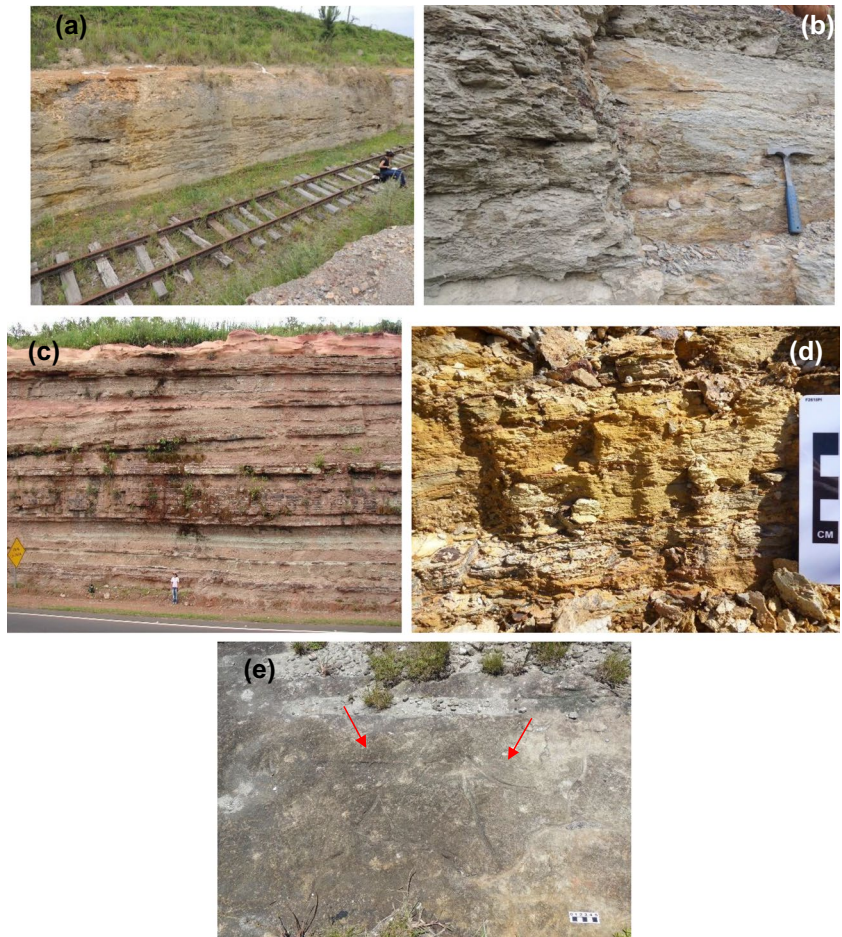


the representativeness and rarity criteria; is also located in southwestern Paraná, represented by Late Cretaceous rocks from the Pitanga Formation, Serra Geral Centro Norte Subgroup, Serra Geral Group (Arioli and Licht 2018; Licht and Arioli 2020). It represents a complete hydrovolcanic event consisting, from base to top, of gray, friable, vesicular basalt, with millimetric to centimetric amygdalas filled with microcrystalline silica and carbonates. Above, forming an irregular to wavy contact, there is a hydroclastic breccia composed of vesicular basalt with dimensions

that vary from 5 to 70 cm. On top of the section, there is a gray-greenish, fine-grained, phaneritic, and slightly vesiculated basaltic flow (Arioli and Licht 2018; Licht and Arioli 2020).

The geosites with higher vulnerability are the Cretaceous Nova Laranjeiras hydrovolcanoclastic sequence and the Cretaceous Pedras de Cambira columnar jointing. The former (Fig. 8a and b) is accessible by car and with no access restrictions. The roadcut is vulnerable to weathering and erosion and has no legal protection. The Pedras

Fig. 7 **a** Partial view of the Devonian Jaguariaíva fossiliferous geosite; **b** common aspect of the Devonian Jaguariaíva fossiliferous shale strata; **c** partial view of the Permian Serra do Cadeado fossiliferous geosite. Photo: Fernando Sedor; **d** Devonian Caniú River fossiliferous geosite with the presence of fossils from the *Arthropoda*, *Brachiopoda*, *Mollusca*, *Anellidae*, and *Echinodermata* phyla; **e** Devonian São Luiz do Purunã ichnofossil geosite, presence of ichnofossils of the *Cruziana* and *Rusophycus* genera



de Cambira geosite (Fig. 8c and d) is located near the city centre and as the same characteristics as Nova Laranjeiras geosite. Columnar jointing structures may be damaged by uncontrolled trampling.

Geological Framework: Astrobleme

In Paraná state, there is only one astrobleme located in the municipality of Coronel Vivida, in southwestern. Vista

Fig. 8 **a** Hydroclastic breccia belonging to the Cretaceous Nova Laranjeiras hydrovolcanoclastic sequence geosite; **b** general view of the Nova Laranjeiras geosite, from a section in hydrovolcanoclastic rock deposits. Height of cut: ~2.5 m; **c** hexagonal sections of columnar jointing rocks with about 40 cm in diameter, from the Pedras de Cambira geosite; **d** general view of Cambira geosite. Note the presence of vandalism. Photos: Otávio Licht



Alegre Astrobleme geosite corresponds to a meteoritic impact crater, approximately circular in shape, with a diameter of 9.5 km. It has steep edges, which reach topographic differences of up to 120 m between the outside and inside of the crater, and scarp-like edges. Although the exact age of this event is not yet known, the fact that the crater is in basaltic rocks of Serra Geral Group, apparently already consolidated, allows us to estimate a maximum age of 125 Ma, which is the minimum age of this basalts (Crósta et al. 2013).

In the geosite, there are polymitic breccias, generically known as “impactites” (Fig. 9a and b), with a thickness of about 10 to 12 m. These rocks are metallic gray in color, changing to shades of gray to light brown. The matrix is formed by a fine gray mass of fragments derived mainly from powdery-textured basalts, and subordinately by fragments of clastic and pelitic rocks. The largest fragments present millimetric to decimetric dimensions, angular shapes, and chaotic disposition, being composed of basalts, diorites, gabbros, sandstones, and siltstones. There is also the presence of small fragments of shatter cones immersed in the polymeric breccias formed because of the impact (Fig. 9b) (Crósta et al. 2004). The geosite obtained maximum score in the representativeness, rarity, and degree of scientific knowledge criteria. In relation to vulnerability, the geosite obtained maximum score in accessibility, protection regime, access regime, and anthropogenic vulnerability criteria, being classified as medium vulnerability.

Geological Framework: Alkaline Rocks

The alkaline magmatism that occurred in the southern region of the South American Platform has its origin in the Jurassic-Cretaceous Waldenian reactivation (Almeida 1967) due to the South Atlantic opening. The opening involved the reactivation of old faults and the formation of fault blocks, the uplift of arcs, the subsidence of coastal basins, and the accentuated subsidence of the Paraná Basin (Almeida 1983). This reactivation is also related to the bimodal volcanism of tholeiitic affinity that occurred in the Paraná Basin and

to the intrusion of dike swarms, besides the occurrence of where alkaline intrusions (Almeida 1983, 1986). The Lower Cretaceous intrusive bodies belong to the Ponta Grossa Arch Alkaline Province (Almeida 1983; Riccomini et al. 2005) but those dated from the Upper Cretaceous belong to the Serra do Mar Alkaline Province (Riccomini et al. 2005). The alkaline rocks outcropping in Paraná are associated with the São Jerônimo-Curiúva alignment, in the southeastern portion of the Ponta Grossa Arch (Vasconcelos 1995; Vasconcelos and Gomes 1998). They are emplaced in metamorphic basement rocks, forming intrusive complexes (e.g., Tunas) and pipes and plugs (e.g., Mato Preto).

The geosites with the highest scientific value are José Fernandes alkaline gabbros and Mato Preto carbonatite, both with maximum scores in the criteria representativeness, rarity, integrity, and degree of scientific knowledge. The José Fernandes geosite (Fig. 10a and b) is in the municipality of Adrianópolis, on the border between the São Paulo and Paraná states. It is included in the Lower Cretaceous Ponta Grossa Arch Alkaline Province, with an approximate age of 134 Ma, obtained by the U/Pb method in zircons. The geosite’s alkaline gabbro presents great mineralogical and textural diversity (Pieruceti 1973). Chmyz et al. (2011) identified nine facies, where the porphyritic inequigranular phaneritic ophitic facies is the most common. The Mato Preto geosite (Fig. 10c and d) is in the municipality of Cerro Azul, close to Adrianópolis. It integrates the Upper Cretaceous Mato Preto Alkaline Suite, with an approximate age of 66 Ma (Cordani and Hasui 1968). The carbonatite occurring at the geosite is essentially composed of calcite and ankerite series carbonates, being classified as calciocarbonatites (Ruberti 1998). Late-magmatic processes were responsible for the formation of fluorite and rock silicification, producing millimetric to centimetric late-stage veins filled with quartz, fluorite, apatite, and barite, associated with REE-enriched fluorocarbonates (synchisite-parisite) (Loureiro and Tavares 1983a, b).

Both geosites have the greater vulnerability within the Alkaline Rocks geological framework having received the higher scores in the criteria accessibility, protection regime, and anthropogenic vulnerability. The Adrianópolis site had

Fig. 9 **a** Polymitic impact breccia (“impactite”); **b** shatter cone aggregates formed in basalt fragments within the polymict breccia. Source: Crósta et al. (2013)



Fig. 10 **a** Partial view of the José Fernandes Alkaline Gabbros geosite; **b** detail of the porphyritic inequigranular phaneritic ophitic facies in the José Fernandes Alkaline Gabbros geosite; **c** partial view of the Mato Preto Carbonatite geosite, located in an active quarry; **d** detail of the Mato Preto carbonatite, note the presence of pyrite (golden) and fluorite (lilac)



the highest score in the accessibility criterion since it is located in an unrestricted area. On the other hand, the Cerro Azul site can only be accessed with prior authorization.

Geological Framework: Bauru Basin

The Upper Cretaceous Bauru Basin (Fernandes and Coimbra 2000) was formed in the south-central part of the South American Platform, between the Coniacian and the Maastrichtian (Fernandes and Coimbra 2000). The original depression was formed essentially by isostatic compensation, in response to the accumulation of a considerable section of basaltic flows during the Lower Cretaceous. The continental intracratonic type basin accumulated the Bauru Supersequence (Milani et al. 2007), a siliciclastic unit formed mainly by reddish sandstones and siltstones, with about 480 m of maximum preserved thickness. Menegazzo et al. (2016) considered that the Bauru Basin, and probably those of Solimões and Parecis too, are back-bulge foreland provinces, developed in western South America. In Paraná, the Bauru supersequence is composed almost exclusively by the Rio Paraná, Goio Erê, and Santo Anastácio Formations, from the Caiuá Group; and by the Vale do Rio do Peixe Formation, Bauru Group (more restrictedly). The Caiuá Group consists of eolian sandstones, deposited in the basin interior, in the ancient Caiuá desert setting.

The most scientifically important geosite is the Cretaceous Cruzeiro do Oeste fossiliferous geosite. It is in the extreme west of Paraná and belongs to the Caiuá Group, Rio Paraná Formation, Upper Cretaceous (Fernandes and Coimbra 2000; Langer et al. 2019). It consists of subarcosean quartz sandstones (Fig. 11a), with well-selected and rounded

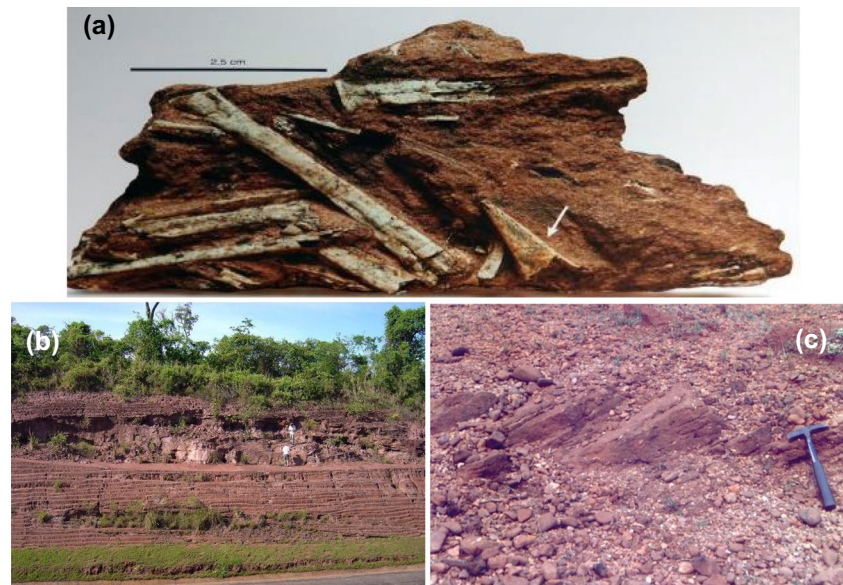
grains, mineralogically supermature, with good textural maturity. It presents a characteristic medium- to large-sized cross bedding. Manzig et al. (2014) reported the discovery of a bone bed of *Caiuajara dobruskii* pterosaurs, with at least 47 individuals. Kellner et al. (2019) recorded a bone bed of the *Keresdrakon vilsoni* pterosaur species. Langer et al. (2019), in turn, reported the discovery of a small theropod belonging to the *Vespersaurus paranaenses* species, with a body length of about 1 m. The *Caiuajara* pterosaur had more of a fragile skeleton and was considered frugivorous. *Keresdrakon* was an opportunistic predator, which usually fed on the remains of other animals such as *Vespersaurus*. The occurrence of these beings away from coastal regions represents a very rare appearance in the continent interior (Manzig et al. 2014).

Regarding vulnerability, the geosites with the highest risk of degradation are the Cretaceous Rio Paraná Formation sandstones (Fig. 11b) and the Cretaceous Vale do Rio do Peixe Formation conglomerates and sandstones (Fig. 11c). Both geosites are in roadcuts, accessed directly by cars and with no access restrictions.

Geological Framework: Cenozoic Sediments

The Cenozoic Sediments framework comprises the Alexandra and Guabiro tuba Formations, as well as relief features and geological processes situated on Paraná's coast. The Alexandra Formation's deposits are also exposed on the state coast and were dated by Lima and Angulo (1990) as of Lower Miocene age, based on the palynological content of its lignitic layer. Meanwhile, the Guabiro tuba Formation outcrops in the state capital and metropolitan region. This unit

Fig. 11 **a** Block extracted from the Cruzeiro do Oeste fossiliferous geosite, with centimetric fossil bones of pterosaurs of the *Caiuajara* genus. Source: Manzig and Weinschütz (2012); **b** partial view of the Rio Paraná Formation sandstones geosite; **c** Vale do Rio do Peixe Formation conglomerates and sandstones geosite



is part of the Curitiba Basin, which was originated during extensional tectonic events that created the Continental Rift of Southeast Brazil (Riccomini et al. 1989). The discovery of new a paleogenous fauna consisting of mammals, birds, and reptiles (Liccardo and Weinchütz, 2010; Rogério et al. 2012) places this unit in the Middle Eocene (Sedor et al. 2017).

The Curitiba Paleogenous Sediments geosite located in Curitiba obtained the highest scientific value score in this geological framework (Fig. 12a and b). It exposes the Guabirotuba Formation (Bigarella and Salamuni 1962), Curitiba Basin, southern compartment of the Continental Rift of Southeast Brazil. Immature mud and sand sediments, with intercalations of gravel, occur at this site. The sands are predominantly composed by quarts and feldspar, varying from very fine to very coarse-grained, with a muddy matrix (Lima et al. 2013). The fossil assemblage found at this geosite, which establishes the Guabirotuba fauna, is composed of invertebrates ichnofossils, *Gastropoda*, *Osteichthyes*, *Amphibia* (Anura), *Testudines* (Pleurodira), *Crocodylia* (*Sebecosuchia*),

birds (*Phorusrhacidae*), and *Mammalia* (*Meridiungulata*, *Metatheria*, and *Xenarthra*), classified as para-autochthonous (Cunha 2016). These fossils occur mostly fragmented with evidence of reworking and abrasion.

The Neogene Alexandra Formation Sediments geosite has the highest vulnerability. The site (Fig. 12c and d) obtained the maximum score in the accessibility, access regime, protection regime, and anthropogenic vulnerability criteria.

Final Considerations

The geological history of Paraná State was organized into nine geological frameworks, based on stratigraphic and tectono-stratigraphic criteria: Metamorphic Basement, Granitic Rocks, Late-Orogenic Basins, Paraná Basin, Paraná Igneous Province, Alkaline Rocks, Bauru Basin, and Cenozoic Sediments. In order to identify the most representative geosites for each one of these frameworks, 192 potential geosites, of which 76 selected by specialists, were assessed following the criteria proposed by Brilha (2016).

Fig. 12 **a** Geological section of archesan sand deposits from the Paleogene Curitiba Sediments geosite; **b** outcrop detail showing a clay layer in the upper portion of the site belonging to the Neogenous Alexandra Formation sediments geosite



The Paraná Basin is the geological framework with the highest number of geosites, followed by the Metamorphic Basement framework. More than 30% of all geosites have high petrological relevance and most geosites have no legal protection.

Three paleontological geosites obtained the maximum scientific value score: Jaguariaíva, Serra do Cadeado, and Cruzeiro do Oeste. The highest scores for paleontological geosites in detriment to other typologies are due to the fact that these sites, for the most part, are simultaneously the most representative example of their geological unit, are rare and well-conserved sites, present-type species, and have scientific publications in international journals. In addition, they present a higher number of other interests, such as stratigraphic, paleoenvironmental, petrological, and sedimentological.

In terms of vulnerability, the Rio Caniú fossiliferous geosite and the Três Córregos and Cerne granites obtained the highest scores. These sites are accessible by car, located in unrestricted areas, near to highways with a large flow of vehicles, and have high fragility in the face of natural processes.

The geosites that showed the lowest vulnerability were Lagoa Dourada senile cave, Ilha do Mel Dune, Guartelá Canyon rocks, and Ilha dos Currais pebble beach. They are located inside Integral Protection Conservation Units, National or State Parks and, as exemplified by the Lagoa Dourada geosite, are listed as protected areas or settled within Sustainable Protection Conservation Units, such as the Ilha do Mel geosite. As there is no specific Brazilian legislation to safeguard geological heritage, the Law No. 9.985/2000, which supports the Brazilian System of Protected Areas, can be a good alternative for conservation.

This is the second Brazilian initiative to inventory geological heritage on a state scale. It is expected that the inventory and quantification of geosites in the state of Paraná provide support for establishing conservation strategies regarding the territory's geological heritage, besides subsidizing practical and efficient actions so that such heritage is not irretrievably lost, due to lack of responsibility coming from the State and civil society.

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Declarations

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