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ORIGINAL ARTICLE

Method for the Characterization and Quantification Assessment of Geological Heritage Adapted to Paraná State, Southern Brazil

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Abstract
Identification and evaluation of geosites are essential to the management and conservation of geological heritage. However, the only systematic geoheritage inventory done so far in a wide area of Brazil is the one in São Paulo State. In order to contribute little by little to a national systematic geoheritage inventory, this paper presents and discusses the method used in the inventory done in Paraná State. As most of the geoheritage inventory and assessment methods were developed in European contexts, it was necessary to include in the method some adjustments related to local particularities aimed at increasing the sensitivity of the method to elements of cultural value related to indigenous people and communities of former black slaves (quilombolas), as well as some ecological aspects. It is expected that the proposed method for the Paraná State can be adopted by other Brazilian states to allow a comparison of the results between the states, which is essential to cover in the future the whole country with a systematic geoheritage inventory.

Keywords Geoheritage · Geoconservation · Geosite · Inventory

Introduction

Despite the growing awareness of the importance of conserving geological heritage, especially in the first two decades of the twenty-first century (Larwood et al. 2013), sites that are key to understand the planet's geological evolution are at increasing risk of total or partial deterioration, mainly as a result of anthropic activities. In Brazil, knowledge and conservation of geological heritage still lack attention from public agencies and policies, educational and research institutions and society in general.

The lack of systematic geological heritage inventory renders the legal protection of a given territory unfeasible, turning it subject to irremediable destruction (Brilha 2016). According to Wimbledon et al. (2000), geoconservation is fundamental to the maintenance and preservation of geological heritage, as the lack of conservation of important sites would eventually compromise the progress of science.

Geoconservation also serves land management and nature conservation as it allows the statutory protection of geosites. In order for geoconservation to be effective, a legal framework is necessary addressing the needs of a given geological heritage (Carcavilla Urquí et al. 2007). Unlike Spain, Portugal and Great Britain, for instance, where specific laws are in force to protect geological heritage, the Brazilian legislation is mainly aimed at protecting biodiversity, whilst abiotic resources are addressed only secondarily (Pereira et al. 2008).

Spain (García-Cortés et al. 2019), Norway (Erikstad 1984), The Netherlands (Gonggrijp 1988), Ireland (Daly 1990), Switzerland (Grandgirard 1996; Bruschi 2007), and the UK (UKRIGS 2001) were the first countries to develop geoheritage inventory methods. A detailed historical approach on this subject is presented by García-Cortés et al. (2019). After studying quantitative valuation methods applied to geosites in several countries, García-Cortés et al. (2019) pointed out the lack of a universal unifying valuation system. These authors recommend that existing literature

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should be reviewed as valuation criteria need to be adapted to each territory, scale, and inventory purpose.

Despite the increasing number of studies carried out in Brazil over the recent years, only São Paulo state has reached a state-level inventory that identifies and quantifies its geological heritage in terms of vulnerability and scientific value (Garcia et al. 2018).

The geoheritage inventorying methods most frequently applied to Brazil were conceived in European countries with a vast accumulated scientific knowledge. Compared to these countries, the geological knowledge of the Brazilian territory is limited due to its size, available resources and accessibility constrains to some vast areas.

Another weakness of some Brazilian geoheritage inventories concerns the lack of criteria related to the presence of certain human groups, such as indigenous peoples and quilombolas (communities of black slaves descendants). Such criteria allow for a greater sensitivity in recognising cultural and ecological geosites value. In some areas, particularly on the outskirts of large cities the lack of safety conditions to allow geoscientists to develop fieldwork is another difficulty to face in some countries like Brazil.

Carrying capacity assessment is another criterion to be considered in the vulnerability analysis of sites where that could be damaged by treading or sites where delicate structures, sedimentary features or rocks could be easily destroyed.

The geological heritage quantification method applied to geosites of Paraná involved: (1) detailed characterization of geosites based on published literature and fieldwork and (2) quantitative analysis of criteria according to pre-established scores. The systematic description of geosites, its assessment and final rankings were stored in spreadsheets.

Geoheritage Assessment Methods Most Frequently Applied to Brazil

It was only a few decades ago that geoheritage inventories initiatives started in Brazil. The first one dates back to 1993, when the Brazilian National Department of Mineral Production (DNPM)—now the National Mining Agency (ANM)—collaborated with the UNESCO to establish an inventory of sites to be included in the World Heritage List (Lima et al. 2010). It was only in 1997, however, that systematic inventorying of the Brazilian geological heritage begun (Schobbenhaus et al. 2002), with the establishment of the Brazilian Commission for Geological and Paleobiological Sites (SIGEP). Until 2012, this Commission has selected 116 geosites (Fig. 1), of which 11 are located in Paraná.

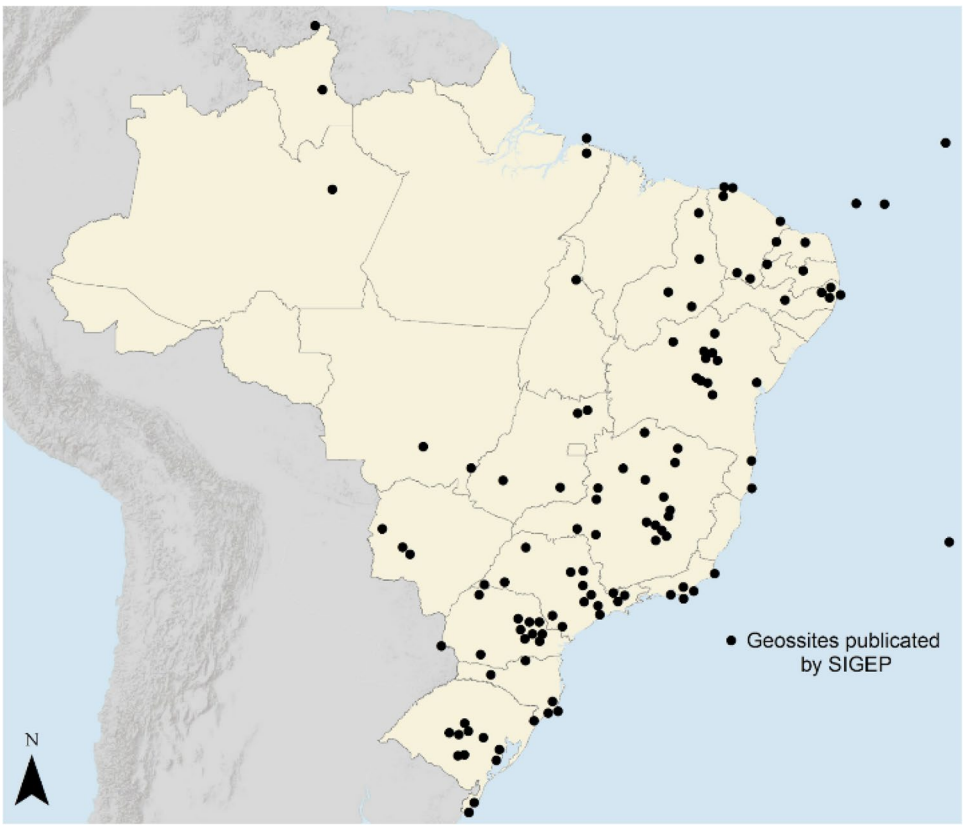

Fig. 1 Brazilian geosites on SIGEP database. Northeastern, southeastern and southern parts of the country are those of higher geosite concentration which correspond to areas with higher geological knowledge

The Geoparks of Brazil project was established in 2006 by the Geological Survey of Brazil (CPRM). This project involved identification, description and evaluation of Brazilian geosites in areas with geological potential where geopark projects could be implemented. Their results were published in the 2012 *Geoparques do Brasil: propostas volume*, which presents an inventory of 17 areas including 362 geosites. Two of these geoparks proposals are located in the Paraná state.

Another relevant inventory initiative made by CPRM is GEOSSIT, an online application for the evaluation of geosites and geodiversity sites (Rocha et al. 2016). The purpose of GEOSSIT is to maintain a national database where researchers across the country can store and evaluate geological sites of geological interest under a unified inventory method.

Regarding the main geoheritage quantification methods applied to Brazil, Romão and Garcia (2017) point out that those by Brilha (2016) and GEOSSIT are the most frequently applied ones (e.g., Azevedo et al. 2012; Guimarães et al. 2012; Vieira Júnior et al. 2012; Wildner and Ferreira, 2012; Prochoroff 2014; Arruda et al. 2015; Covello and Horn Filho 2015; Santos et al. 2015; Oliveira and Goya 2016; Moura and Garcia 2016; Reverte et al. 2016; Albani et al. 2020; Nascimento et al. 2020; Tavares et al. 2020). Some inventories were carried outbased on the García-Cortés and Carcavilla Urquí (2009) and Lima et al. (2010) methods (e.g., Mansur 2010; Pocidonio 2015; Almeida 2016).

The method by Lima et al. (2010), which is an adaptation of the one proposed by the Junta de Andalucía (2002), was precursor of the discussion about inventories in Brazil. In thhis method, the *didactic* (10 criteria) and *recreational* (10 criteria) values and the *degradation risk* (5 criteria) of geosites are evaluated. Each criterion comprises parameters with values from 1 to 4. The arithmetic mean value assigned to each criterion is classified into three potential intervals for *educational* or *recreational* purposes as low (100 to 200), medium (201 to 300) and high (301 to 400).

The results achieved by applying the method of Lima et al. (2010) indicate the most appropriate use for a geosite and management and conservation measures. However, it does not include a quantification of the scientific value which is justified by the authors due to the fact that inventoried geosites already have a recognized scientific value. However, the ranking of a set of geosites is impossible to do without assigning each geosite a scientific value.

In Brilha (2016) method, geosite refers to an in situ occurrence with scientific interest (and eventually other types of values), whereas geodiversity site is related with educational, aesthetic, ecological and/or cultural values. eAccording to his proposal 37 criteria are evaluated comprehending scientific value (7 criteria), potential use for education (12 criteria) and for tourism (13 criteria) and risk of degradation (5 criteria). The criteria, which are divided into sub-criteria, are attributed weights ranging from 1 to 4. The final score of the site is given by the weighted sum of values assigned to each criterion.

For the assessment of the scientific value Brilha (2016) includes the use limitations criterion, which addresses the geosite's potential use rather than its scientific value. The inclusion is justified by the need to evaluate potential limitations to the site's use for scientific research. The method also calculates the potential use of the site for touristic and educational purposes rather than its scientific use. According to Brilha (2016), such a distinction results from the understanding that geosites must be preserved for their scientific value regardless of immediate its effective use. The same does not apply for sites of educational and/or touristic value, whose protection is mainly justified for such purposes.

Brilha (2016) makes a clear emphasis on the scientific value. According to this author, geological sites with little or no scientific value (geodiversity sites), even those of high scenic, cultural or touristic values should not be considered as geoheritage, which does not mean that geodiversity sites should be neglected in a geoconservation strategy. The main aspect to point out when discussing the method of Brilha (2016) is that its application to countries of large extension, great geological diversity and, as mentioned above, limited scientific knowledge, especially regarding geosites of global relevance, as is the case of Brazil, makes most places sites of geodiversity. The need to evaluate cultural aspects has been discussed by authors such as Gravis et al. (2017, 2020a, b, Fepuleai et al. 2017; Nemeth and Cronin 2009, Nemeth et al. 2017, Nemeth and Fepuleai 2017) . According to these authors, greater weights should be attributed to cultural aspects in the assessment of geological heritage through the methods currently used, which would allow such aspects to be addressed more explicitly and representatively as a basis for community education and, consequently, conservation of the identified sites.

The GEOSSIT application, accessible at http://www.cprm.gov.br/geossit/—*in Portuguese*, was originally structured following the inventory methods of Brilha (2005) and García-Cortés and Carcavilla Urquí (2009). The application was subsequently revised to adopt the method and concepts of Brilha (2016), with minor adaptations to criteria such as key-locality, geological diversity, proximity to areas/activities with a potential for causing damage; safety, association with other values, and geological diversity. GEOSSIT is an open access tool, developed to standardize the inventory and quantification of geological sites at country-wide scale. The application operates on a specific database of the GEOBANK system, on which all information about the geosite is stored, thus enabling further computer processing (Schobbenhaus et al. 2015).

Thirty-seven parameters are evaluated by GEO SSIT, each one comprising different items with assigned values ranging from 0 to 4. Sites are evaluated in terms of scientific value, educational and touristic potential use and degradation risk. The application presents unified information about geosites but its main limitation is that criteria which are essential to Brazilian context, such as the distinction between natural fragility and man-made vulnerability, carrying capacity, personal safety and ecological and cultural aspects are not taken into account.

The inventory method of García-Cortés et al. (2019) was developed in order to evaluate Spanish geological heritage of national relevance. Spain is administratively divided into autonomous regions. By the time the method was presented, several regions had already carried out their own geological heritage inventories. Therefore, the purpose of the method was to standardize the quantification of geological heritage in the various regions of the country according to scientific (7 criteria), didactic (13 criteria), and touristic (11 criteria) values. Vulnerability to anthropogenic threats (9 criteria) is also calculated. A value ranging from 0 to 4 is assigned to each subcriterion, the sum of which being multiplied by the corresponding criterion weight. The method also allows the calculation of the natural vulnerability, which depends on its fragility and presence of natural threats, its susceptibility to natural or anthropogenic degradation, and its degradation risk, which determines its degree of protection priority.

A remarkable aspect in the method of García-Cortés et al. (2019) is that, unlike other methods, geosites located in regions of low socioeconomic level are attributed higher scores than those in regions where per capita income is higher than the regional average, thus aiming to encourage socioeconomic development actions. Criteria and weights of the inventory methods most frequently applied to Brazil are summarized in the Fig. 2.

Figure 2 reveals differences of criteria and respective weights between Brilha (2016) and GEOSSIT methods. Some criteria were added by García-Cortés et al. (2019) especially regarding educational and touristic values and degradation risk. Discrepancies exist in the weights assigned to some criteria, which is also observed in the method of Lima et al. (2010), which reflects the knowledge evolution over decades of research.

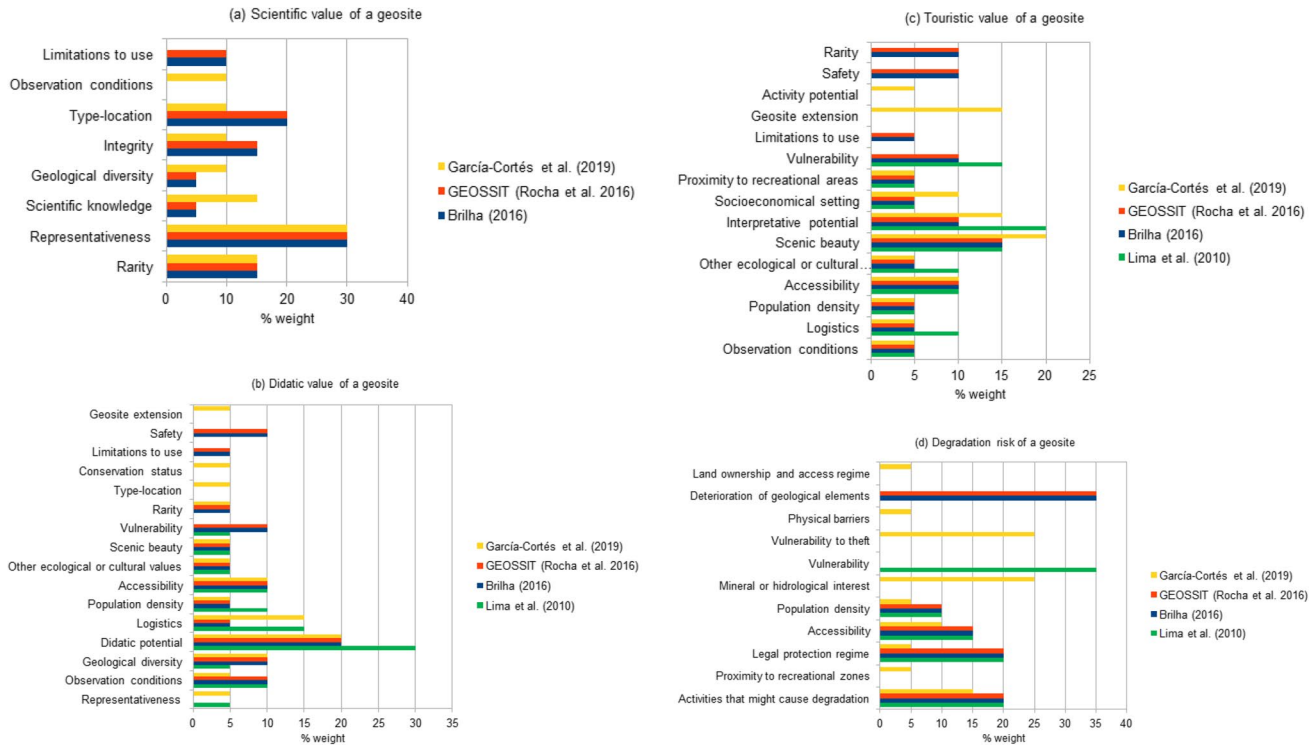

Fig. 2 Criteria and weights in the geological heritage inventory methods most frequently used in Brazil. Horizontal scales represent attributed weights: (**a**) scientific value, (**b**) educational value/potential, (**c**) touristic value/potential, (**d**) risk of degradation/vulnerability

The Adjusted Method Applied to the Geological Heritage Inventory of Paraná

Since the first geoheritage inventories that the need for geosite conservation has been assessed based on its scientific importance. However, other interests (educational, cultural, recreational, scenic and historical) have also been considered. As geological heritage can be assessed both by strict scientific evaluation and incorporation of educational, touristic and cultural values, two types of inventories can be carried out, the systematic and the reconnaissance or advanced reconnaissance ones (García-Cortés et al. 2019).

In systematic inventories, the geological context is compartmentalized into thematic blocks that correspond to, e.g., chronostratigraphic units, sedimentary and/or structural domains, or even metallogenetic domains. Representative sites are selected by specialists based on previous knowledge and/or fieldwork. Only criteria of scientific value are considered in this type of inventory. In reconnaissance or advanced reconnaissance inventories, in the sense of Carcavilla Urquí et al. (2007), sites are selected by specialists who are familiar with the geodiversity of the inventoried area by using Delphi or similar methodology. In such cases, specialists can propose relevant sites based not only on scientific value. Therefore, in this second type of inventory, quantitative assessment criteria must necessarily consider all types of values (García-Cortés et al. 2019).

Considering mainly the extension, geological knowledge and available funding, an adjusted reconnaissance or advanced reconnaissance approach in the sense of Carcavilla Urquí et al. (2007) was chosen to by applied to the state of Paraná. The inventory involved bibliographical research, thematic categorization, selection of representative geological sites and consulting to experts. As previously mentioned, in such heritage inventories specialists are not prevented from proposing sites considered relevant not only for their primarily scientific value, but also for other types of values. In a state-wide geological heritage inventory, i.e., of regional character considering the extension of Brazil, the educational and touristic relevance were also considered.

Compared to the quantitative assessment methods mentioned above, only minor modifications were introduced to the scientific criteria, mainly in weights attributed to some criteria. The more extensive adaptations regard the didactic and touristic values, which are not addressed as "potential educational and tourist use," but as values, since, as previously mentioned, specialists are not prevented from selecting geosites as relevant based on such values in reconnaissance inventories. The main modifications concern social and cultural aspects of geosites, with greater evaluation emphasis being placed on ecology and culture-related elements, as well as elements related to original human groups such as indigenous peoples and quilombolas (former black slaves). Personal safety was another criterion included, as some geosites are located in areas where visitors would be subject to inconveniences such as theft, robbery or even to being hit by vehicles. Another evaluation highlight is the distinction, in vulnerability analysis, between natural fragility and anthropogenic vulnerability, which, unlike in the methods of, e.g., Wilson (2013) and García-Ortiz et al. (2014), are not taken into account in the methods of, e.g., Brilha (2016) and GEOSSIT, the most frequently ones applied to Brazil. The item carrying capacity was included in the vulnerability analysis in order to assess the sensitivity of geosites constituted by sediments or easily disaggregated rocks, which usually contain delicate structures that could be damaged by treading. The adapted method presented here proved to efficiently evaluate geosites when applied to the geological heritage of Paraná, indicating its potential for use in similar territories.

Geosite Characterization

Each geosite selected by experts under each geological framework was characterized using an adapted form (Table 1).

Three elements of information guided the standardization of geosite names. The first one regarded the element under consideration. The second one regarded rock age. The third one regarded toponymy (Vegas et al. 2011). The naming convention applied was flexible, with exceptions being raised for excessively long names (García-Cortés et al. 2019) and geosites with already established names.

Site typology was based on the definitions of Fuertes-Gutiérrez and Fernández-Martínez (2010). Point refers to an isolated site less extensive than 10.000 m^2. Section refers to an extensive linear rock outcrop, riverbed, canyon, road or highway. Viewpoint refers to a site located away from the geomorphological feature. For the purposes of the present study, a viewpoint consists of two elements: the landscape/landform and the best place to observe it. Geosites were described and evaluated according to both these components. The inventoried landforms are usually large, which reduces their risk of degradation. Viewpoints, on the other hand, can be subject to various different threats. Such locations can be suppressed due to, e.g., road widening works. Area refers to a site larger than 10.000 m^2 containing simple geological elements. Complex area refers to a large site aggregating several points, sections, areas and/or observation points.

In geosite location, well-known public establishments or highways in the region were adopted as locational references. Access refers to the route from a highway or road to the site. In classification, the main thematic classification,

Table 1 Geosite data form, modified from The European Association for the Conservation of the Geological Heritage–ProGEO/Portugal (Brilha 2005), GEOSSIT (Rocha et al. 2016) and García-Cortés et al. (2019)

IDENTIFICATION						
Geological category						
Name						
Type						
Does it have a MINEROPAR panel?				Does it take part in any geopark proposal?		
SIGEP reg. no				Visitation () free () controlled () paid () free		
LOCATION						
Coordinates				Elevation		
Municipality				Place name		
nearest landmark						
Access						
THEMATIC CLASSIFICATION						
Geologic classification						
astrobleme ()	speleological ()				stratigraphic ()	geomorphological ()
hydrogeological ()	marine ()				metallogenetic ()	mineralogical ()
paleoenvironmental ()	paleontological ()				petrological ()	sedimentological ()
tectono-structural ()	other ()					
Non-geologic classification associated with						
archaeological	low ()		medium ()			high ()
ecological	low ()		medium ()			high ()
aesthetic value	low()		medium ()			high ()
scenic expression	low ()		medium ()			high ()
cultural	low ()		medium ()			high ()
Potential use						
scientific	low ()		medium ()			high ()
educational	low ()		medium ()			high ()
touristic	low ()		medium ()			high ()
other	low ()		medium ()			high ()
PRELIMINARY EVALUATION						
access	easy()	moderate ()			difficult ()	
width (m)		height (m)				
area (m^2)						
observation conditions	good ()		satisfactory ()			bad ()
anthropogenic vulnerability	high ()				medium ()	low ()
natural vulnerability	high ()				medium ()	low ()

Table 1 (continued)

type of threat				
geosite in rural area		forest ()		agricultural ()
geosite in non-rural area		industrial zone ()		urban zone ()
CONSERVATION				
public	municipal ()		state ()	federal ()
private				
listed	yes ()		no ()	
conservation unit	full protection ()		sustainable protection ()	
Name of the conservation unit				
Subject to indirect protection?				
Does it need conservation?				
GEOLOGICAL FRAMEWORK				
Age				
Unit				
Formation				
Geological contact?				
PALEONTOLOGICAL FRAMEWORK				
Fossil content				
historical significance ()	cultural significance ()		exceptional preservation (*fossil-lagerstätte*) ()	
exceptional diversity ()	exceptional amount (eg *bone beds*) ()		exclusive fossils ()	
other ()				
GEOLOGICAL CHARACTERIZATION				
Sedimentary record				
Ancient environments	continental ()		marine ()	transitional ()
Types of ancient environments				
Litotype (s)				
Structural / Sedimentary features				
Stratigraphic discontinuities				
Igneous record				
Litotypes				
Textures				
Igneous structures / features				
Observations				
Metamorphic record				

Table 1 (continued)

Type of metamorphism	
Metamorphic facies	
Litotypes	
Textures	
Metamorphic structures / features	
Observations	
Deformation	
Type of deformation	
Tectonic regime	
Linear structures	
Planar structures	
GEOMORPHOLOGICAL FEATURES	
() Passive geomorphological site	() active geomorphological site
HYDROGEOLOGICAL/HYDROLOGICAL FEATURES	
MINERAL DEPOSITS/INDEX MINERALS	
DOCUMENTS	
photos () sketches () geological map () stratigraphic section or column ()	
REFERENCES	
Date	
Observations	

*MINEROPAR: Defunct Geological Service of Paraná

**SIGEP: The Brazilian Commission for Geological and Paleobiological Sites reg

associated secondary classification and potential use were marked as of A (high), M (medium), or B (low) value. For sites where one or more such items were absent, the corresponding classification cell was left blank.

In main thematic classification, geosites were ranked in descending order of importance as being of main (3), secondary (2), or tertiary (1) interest. The corresponding cell was left blank for sites where no interest was identified.

Remnants (artifacts, paintings, bones etc.) belonging to the culture and/or lifestyle of past human groups were considered to be elements of archaeological interest. Sites of ecological interest were those containing relevant biotic elements. Scenic expression refers to the relationship between a site and its surrounding landscape as an expression of regional beauty. Aesthetic value refers to the particular beauty of the elements that constitute a site, such as mineral forms and/or structures.

In preliminary evaluation, sites were considered to be easily accessible when no physical barrier could prevent visitors from reaching them. Access was moderately easy where only a few physical barriers made access to the sites somewhat difficult. Access was considered difficult where many physical barriers could impede visitors to reach the site. Natural or man-made obstacles such as vegetation, walls, fences, etc. are examples of such barriers.

In cases where no obstacle masked or hindered the observation of geological elements, the site was considered to be of good observation conditions. Observation was considered satisfactory where minor obstacles could be found between visitors and the geosite elements. Observation conditions were considered poor in sites whose geological elements were completely masked by obstacles.

Vulnerability, which corresponds to the possibility of a geosite being deteriorated by anthropogenic and/or natural causes, was classified as high, where all geological elements could be affected; average, where the main geological elements could be deteriorated; low, where secondary elements of the site were susceptible to deterioration; and very low where the possibility of deterioration was considered minimal. Erosion, floods, and mass movements are examples of natural threats. Anthropogenic threats are those represented by, e.g., mining, road construction, land occupation or any other human activity capable of damaging a geosite.

Rural sites were those located in municipalities of reduced urban extension, kept outside the city perimeter by municipal law and characterized by the rustic use of large land tracts and low housing density (IBGE 2014). Rural sites were subdivided into forested, i.e., those located in areas larger than 500 m^2 with vegetation taller than five meters (FAO 2012), and agricultural ones, i.e., areas used for cultivation or grazing outside the urban perimeter. Non-rural sites were those located in municipalities of predominantly urban occupation, established through municipal law for either taxation or urban planning purposes (Master Plan, zoning etc.) (IBGE 2014). Non-rural sites were subdivided into those located in industrial zones concentrating industrial or business activities and those located in urban zones characterized by continuous occupation. Permanent Protection Areas (PPA), ecological corridors, conservation units, areas inhabited by traditional populations and buffer zones are other examples of indirect protection adopted in Conservation.

Regarding paleontological framing, sites of historical significance where those bearing an original fossil record, i.e., sites where a particular fossil type was first described. Fossils of cultural significance were those bearing some cultural relation with the population that inhabited in the vicinities of a geosite. Exceptional preservation (fossil-lagerstätte) referred to geosites with a high degree of fossil record preservation. Exceptional diversity referred to geosites bearing fossils of different taxa. Exceptional amount (e.g., bone beds) referred to geosites with a large fossil content. Geosites of unique fossil content were those showing a fossil content identified as pertaining exclusively to a given age and/or environmental context.

Geomorphological, hydrogeological/hydrological, mineral deposits and mineral indices of geosites were recorded in the corresponding field of the survey form. In particular, a distinction following the concept of Reynard (2009) was made in geomorphological features between passive or active geosites. According to the aforementioned author, active geomorphological sites are those that allow for the observation of ongoing geomorphological processes, whereas in passive geomorphological sites relief forms are inherited from past, no longer operating natural processes.

Quantification of the Geological Heritage of Paraná

The state-wide quantitative geological heritage inventory of Paraná was based on the method of Wilson (2013), which in turn corresponds to an adaptation to that of García-Cortés and Carcavilla Urquí (2009), which was applied to the Cajón del Maipo region, Chile. Wilson's (2013) method proved to be a good development platform for the purposes of the present study, which prepares the first geological heritage inventory of Paraná. By adapting the method of García-Cortés and Carcavilla Urquí (2009) to a Latin American scientific and cultural context, the Chilean author took advantage of the renowned Spanish inventory approach. By considering natural vulnerability a geosite response to natural processes, the method also allows for setting conservation priorities.

The method assesses geological heritage according to their scientific, educational and touristic values. Vulnerability is also evaluated, which can support geosite management. These parameters are evaluated based on 24 indicators, each one being scored 1, 2, or 4 or, in some cases, zero. Each criterion is assigned a value according to four degrees of importance: very high (5), high (4), medium (3), and low (1), in order to allow fundamental evaluation criteria to be properly highlighted and valued. The Scientific value of a geosite is evaluated according to 06 criteria. Educational values and touristic value are evaluated according to 14 criteria each. Vulnerability is evaluated according to 06 different criteria.

Scientific Value

In the inventory method applied to the geological heritage of Paraná, the scientific value of a geosite is assessed based on criteria of **representativeness**, which reflects how adequately the elements and processes of its geological category are represented at state-wide scale; **rarity**, which reflects its importance given the scarcity of similar geological elements or processes on statewide scale; **integrity**, which reflects the extent to which its features of geological interest are preserved; **type-locality/type-species**, which refers to the bibliographic account of its being the geographic locality where a given geological unit, fossil content or mineral species was first described; **degree of scientific knowledge**, which refers to its geoscientific interest as assessed by the amount of published scientific information on it or its estimated potential for future research; and **geological diversity**, which reflects the number of additional geological interests (tectonic, paleontological, mineralogical etc.) identified based on the evaluator's previous experience and recognized at fieldwork. Table 2 presents the criteria used to assess the scientific value of geosites and their respective weights. Extra details on the weights applied are presented as supplementary material.

No significant modifications were introduced to the assessment method applied to Paraná compared to the other analyzed methods in relation to scientific value. The most important scientific value criterion in the methods of Brilha (2016) and GEOSSIT is *representativeness*, followed by type-location. In the methods of Brilha (2016) and

Table 2 Scientific value (SV) criteria applied to the geological heritage inventory of Paraná. SVW: Scientific value weight

Criteria / Indicators		Score
A	Representativeness (SVW = 5)	
	The geosite best exemplifies its geological category elements/processes in Paraná	4
	The geosite is a good example of its geological category elements/processes in Paraná	2
	The geosite partially represents it geological category elements/processes in Paraná	1
B	Rarity (SVW = 5)	
	The geosite is the only known example of its geological category in Paraná	4
	Two or three examples of its geological category are known in Paraná	2
	Examples (four or more) of its geological category are commonly found in Paraná	1
C	Integrity (SVW = 3)	
	The geosite is well preserved	4
	The geosite shows a certain degree of deterioration	2
	Deterioration of the geosite hinders observation of its main geological elements	1
D	Type location / Type species (SVW = 3)	
	The geosite is a type location or type species for its geological category or the site where a fossil or mineral form was first described	4
	The geosite is a secondary type location or type species (complements the type location or type species for its geological category)	2
	The geosite does not represent a type location or type species of its geological category	0
E	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
F	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

GEOSSIT, the most important scientific value criterion is *representativeness*, followed by *type location*. In the method of García-Cortés et al. (2019), *representativeness* is the most important criterion, followed by *rarity* and *degree of scientific knowledge*. In our method, representativeness and rarity were considered the most important criteria, both being attributed a weight of 5. The emphasis on rarity is justified by the fact that if, in addition to being the most representative of each area, the geosite is also the rarest or unique occurrence, such heritage could be replaced in the event of partial damage or destruction.

Integrity and *type location/type species* were considered criteria of intermediate importance, both being attributed a weight of 3. Integrity is the third most valued criterion in both the method of Brilha (2016) and the GEOSSIT application, and the third most important one in the method of García-Cortés et al. (2019). *Type location* is the second most important criterion in both the Portuguese method and in the Brazilian application, and the third most important one in the Spanish method. The characterization notes for this criterion in the GEOSSIT application were made more objective in order to prevent misevaluation of geosites. A more objective wording with less specific terminology ensures greater response accuracy from evaluators. The definition of type species, i.e., the place where a fossil taxon was first described and/or the place where a certain mineral form was first described was also included.

In *degree of scientific knowledge*, technical reports from state-owned companies were included as valid literature in the evaluation of the scientific interest of geosites. The CPRM, for example, is a state-owned entity that carries out research. However, much of their research on, e.g., regional geological cartography is presented in the form of internal reports, with a maturation period prior to publication. Our method also considers geosites indicated by specialists as being of potential scientific interest, even if not yet mentioned in scientific publications.

In Brazil, where scientific research and investigation is more recent compared to European countries, it is not uncommon that sites of scientific importance be discovered or new scientific knowledge added. For this reason, the possibility of sites being considered of important scientific potential by specialists even in the absence of published knowledge.

Like in the Portuguese method and the Brazilian application, *geological diversity* and *degree of scientific knowledge* were attributed a weight of 1 for being considered of lesser importance when compared to other criteria.

Limitations to use, one of the criteria used in the method of Brilha (2016) and in the GEOSSIT application, was not considered. It is assumed that when the scientific importance of a geosite is evaluated, it is reasonable to consider the geosite's potential for other uses, but only the scientific importance of the site.

Observation conditions, as evaluated by the method of García-Cortés et al. (2019), was not considered in our method, on the basis that this criterion is more relevant to the educational and touristic values. The scientific importance of a geosite is not affected by its observation conditions.

Touristic and Educational Value

In terms of educational value, the geosites of Paraná were evaluated based on their representativeness, rarity and geological diversity criteria, according to which **educational content** reflects the potential use of the geosite in teaching geosciences and/or reporting the importance and usefulness of geodiversity; **observation conditions** reflects the degree of ease with which the geosite can be properly observed from its surroundings; **accessibility** addresses the difficulty in accessing the geosite; **cultural diversity** reflects the geosite cultural interests, e.g., those related to the culture of original human groups such as indigenous peoples and quilombolas, and also archaeological interests; **ecological diversity** reflects the geosite interests relating to biodiversity, such as the varieties of flora and fauna presente; **scenic value** estimates the natural beauty of the landscape in which the geosite is located; **access regime** indicates use restrictions dictated by the legal designation of property of the site; **service infrastructure** regards the availability of services such as accommodation and food in the vicinities of the geosite; **natural safety** evaluates risk and natural hazards that might affect the geosite; **personal safety** evaluates the possibility of risks being posed by the geosite to the physical integrity of visitors, such as theft, robbery, being hit by vehicles and acidentes; and **health and well-being infrastructure** refers to the availability of health services such as hospitals and emergency care centers near the geosite.

The assessment of the touristic value of a geosite is similar to the assessment of its educational value, being based on criteria of integrity, observation conditions, accessibility, diversity of interests, scenic value, access regime, service infrastructure, natural safety, personal safety, and health and well-being infrastructure. In addition to these criteria, others are considered, according to which **informational content** refers to the geosite potential for geological interpretation by tourists; **recreational and cultural environment** reflects the geosite's touristic potential in association with ecotourism activities (climbing, rafting, bathing, paragliding etc.) and cultural-related interests (historical monuments, museums); **population density** refers to the number of inhabitants per km^2 in the municipality where the geosite is located; and **economic level** reflects the Human Development Index

Table 3 Criteria and weights by which the educational and touristic values of geosites was assessed in Paraná. *EVW: Educational value weight; TVW: Touristic value weight

	criteria / indicators	score
A	Representativeness (EVW=1, TVW=0)	
	The geosite is the best known example of elements and/or processes of its geological category in Paraná.	4
	The geosite is a good example of elements and/or processes of its geological category in Paraná.	2
	The geosite is a partial example of elements and/or processes of its geological category in Paraná.	1
B	Rarity (EVW=1, TVW=0)	
	The geosite is the only example of its geological category known in the state of Paraná.	4
	Two or three examples of the geological category of the geosite are known in Paraná.	2
	The geosite is a common example (four or more) of its geological category in Paraná.	1
C	Geological diversity (EVW=3 TVW=0)	
	Other the main geological interest, the geosite is of four or more geological interests.	4
	Other the 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
D	Educational content (EVW=5, TVW=0)	
	The geosite is commonly used for educational purposes and is of potential use by any visitor profile, whether layperson or specialist.	4
	The geosite has an educational potential for any visitor profile, whether laypersons or experts.	2
	The geosite has an educational potential, but only for visitors with specific knowledge in geosciences.	1
E	Observation conditions (EVW=1, TVW=1)	
	All geosite elements of interest are easily observable.	4
	Despite some external masking elements, almost all interesting geosite features can be observed.	2
	External elements difficultate observation of the geosite features of interest.	1
F	Accessibility (EVW=3, TVW=4)	
	The geosite is directly accessible by car or bus (up to 100 m walk).	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
G	Cultural diversity (EVW=3 TVW=3)	
	The geosite has more than three elements linked to cultural diversity.	4
	The geosite has up to two elements linked to cultural diversity.	2
	The geosite does not have any element linked to cultural diversity.	0
H	Ecological diversity (EVW=3, TVW=3)	
	The geosite has more than three elements linked to ecological diversity.	4
	The geosite has up to two elements linked to ecological diversity.	2
	The geosite does not have any element linked to ecological diversity.	0
I	Scenic value (EVW=1, TVW=5)	
	The geosite has four or five of the following characteristics: high relief amplitude, river courses of high flow/large water depths, remarkable chromatic variety, showy fossils or showy minerals.	4
	The geosite presents up to three of the above characteristics.	2
	The geosite does not present any of the above characteristics.	0
J	Access regime (EVW=1, TVW=1)	
	The geosite is located in a free access area.	4
	The geosite is located in a protected/restricted area, visitation depending on prior authorization.	2
	The geosite is located in a protected/restricted area, visitation being only possible upon prior authorization and/or admission payment.	1
K	Services infrastructure (EVW=4, TVW=3)	
	One or more lodging (camping, hotel, etc.) or food (supermarket, cafeteria, restaurant, etc.) establishments with a minimum capacity of 20 people less than 10 km from the geosite.	4
	At least one lodging (camping, hotel, etc.) or food (supermarket, cafeteria, restaurant, etc.) establishment with a minimum capacity of 20 people within 10 to 30 km of the geosite.	2
	At least one lodging (camping, hotel, etc.) or food (supermarket, cafeteria, restaurant, etc.) establishment with a minimum capacity of 20 people between 30 and 50 km from the geosite.	1
L	Natural safety (EVW=3, TVW=3)	

Table 3 (continued)

	criteria / indicators	score
	The geosite presents little or no risk of natural accidents (mass movements, very strong watercourses, etc.) to visitors.	4
	The geosite presents a moderate risk of natural accidents (mass movements, very strong watercourses, etc.) to visitors, requiring precautionary measures when used for touristic and/or educational purposes.	2
	The geosite presents a high risk of natural accidents (mass movements, very strong watercourses, etc.) to visitors, requiring mitigation measures before its touristic/educational use is permitted.	1
M	Personal safety (EVW=3, TVW=3)	
	The geosite presents little or no risk of robbery/theft, being hit by vehicles or accidents to visitors.	4
	The geosite presents a moderate risk of robbery/theft, being hit by vehicles or accidents to visitors, requiring precautionary measures when used for touristic and/or educational purposes.	2
	The geosite presents a high risk of robbery/theft, being hit by vehicles or accidents to visitors, mitigation measures being necessary before its touristic/educational use is permitted.	1
N	Health and well-being infrastructure (EVW=4, TVW=3)	
	The geosite has a health and well-being infrastructure (hospital, police station, mobile communication network) less than 10 km away.	4
	The geosite has health and well-being infrastructure (hospital, police station, mobile communication network) within 10 to 30 km.	2
	The geosite has health and well-being infrastructure (hospital, police station, mobile communication network) between 30 to 50 km.	1
O	Informational content (EVW=0, TVW=4)	
	The geosite is regularly used for informational activities.	4
	The geosite clearly and expressively informs groups of any cultural level about the importance or usefulness of Geology.	2
	The geosite informs clearly and expressively groups with some level of cultural development.	1
P	Recreational and cultural surroundings (EVW=0, TVW=1)	
	The geosite is commonly used for recreational activities linked to nature (climbing, rafting, bathing, paragliding, etc.) and/or cultural activities.	4
	The geosite is located less than 10 km from the area where some recreational and cultural activities related to nature (climbing, rafting, bathing, paragliding, etc.) and/or cultural activities take place.	
	The geosite is located more than 10 km from the area where recreational and cultural activities related to nature (climbing, rafting, bathing, paragliding, etc.) and cultural activities take place.	
Q	Population density (EVW=0, TVW=1)	
	The geosite is located in a municipality with more than 100 inhabitants/km^2.	4
	The geosite is located in a municipality with a population between 25 and 100 inhabitants/km^2.	2
	The geosite is located in a municipality with less than 25 inhabitants/km^2.	1
R	Economic level (EVW=0, TVW=1)	
	The geosite is located in a municipality of HDI lower than the Paraná average.	4
	The geosite is located in a municipality of HDI equal to the Paraná average.	2
	The geosite is located in a municipality of HDI higher than the Paraná average.	1

(HDI) of the surroundings as compared to the HDI of Paraná average. Table 3 shows the criteria and weights by which the didactic and touristic values of geosites were assessed in Paraná.

Association with other values, a criteria in the inventory methods mentioned, was broken down into *cultural diversity* and *ecological diversity*, both related to the assessment of cultural (archaeological, indigenous and traditional communities) and biodiversity-related elements found in geosites. These two criteria were attributed higher scores than in the inventory methods most commonly used in Brazil. As in other Brazilian states, many geosites of Paraná are associated with such elements.

Regarding *scenic value*, the approach proposed in the method of García-Cortés et al. (2019), according to which parameters such as high relief amplitude, large water depth and chromatic variety minimize the evaluator's subjectivity.

Safety, as approached in the method of Brilha (2016) and in the GEOSSIT application, was broken down into *natural safety*, which concerns the potential of the area for for natural accidents, and *personal safety*, which refers to potential threats and inconveniences posed by the geosite to the physical integrity of visitors, such as theft, robbery, being hit by vehicles or other traffic incidents. In Paraná, as in other regions of the country, many sites are in areas of poor social development on the outskirts of urban centers, where visitors might be subject to personal integrity risks. This was another methodological adaptation to Brazilian territories as they form a context that is different from that of European countries, where established inventory methods were developed.

Recreational and cultural surroundings, referred to in other methods as proximity to recreational areas, was assessed according to specific parameters such as activities related to nature and/or culture. The *population density* of the area in which a geosite is located is expressed as the number of inhabitants per square kilometer, which is adequate to Brazilian regional scenarios. According to Paraná's Institute for Economic and Social Development (IPARDES), based on 2010 data, large parts of Paraná does not correspond to densely inhabited areas. For this reason, population density has been classified into ranges of less than 25, between 25 and 100 and more than 100 inhabitants per square kilometer.

Economic level, which is characterized by the Human Development Index (HDI) of the municipality where a geosite is located, remained similar to that proposed by García-Cortés et al. (2019). Socioeconomically deprived municipalities, i.e., those of lower HDI, received higher scores to encourage their development through tourism. The average Paraná's HDI was used for comparison in each municipality where geosites were present.

Regarding weights by which the educational value is assessed, similarly to the other inventorying methods mentioned, *educational content* was considered the most important criteria, being attributed a weight of 5. This criteria is followed in importance by *service infrastructure* and h*ealth and well-being infrastructure*, both attributed a weight of 4. *Geological diversity*, *accessibility*, *cultural diversity*, *ecological diversity*, *natural safety* and *personal safety* were attributed a weight of 3. Finally, considered of lesser relevance are the criteria of *representativeness*, *rarity*, *observation conditions*, *scenic value* and *access regime*, which were assigned a weight of 1.

For the assessment of the touristic value of geosites, *scenic value* was considered, like in the other methods mentioned, the most relevant criterion, being assigned a weight of 5. *Information content* and *accessibility* received a weight of 4, followed by *cultural diversity*, *ecological diversity*, *service infrastructure*, *health and well-being infrastructure*, *natural security* and *personal security*, which were attributed a weight of 3. Finally, *observation conditions*, *access regime*, *economic level*, *population density* and r*ecreational and cultural environment* were considered the least relevant ones, with a weight of 1.

Vulnerability

Along with *accessibility* and *access regime*, in our inventory method the vulnerability of a geosite is assessed based on criteria of **anthropogenic vulnerability**, which reflects the potential of certain human activities to cause its degradation; **natural fragility**, which reflects its potential use in view of natural degradation processes; **protection regime**, which reflects its protection status when located in a protected are; and **carrying capacity**, which indicates the number of visitors it can accommodate over a given period of time without irreversible damage to the environment or impairment of visitation quality. Table 4 presents the set of criteria by which the vulnerability of geosites was assessed in Paraná.

One of the main modifications in the geoheritage inventory method that was applied to Paraná was that, in order to better assess potential degradation, damage to geosites was considered to result from both *anthropogenic vulnerability* and *natural fragility*, and not just from deterioration of its components as in the methods of Lima et al. (2010), Brilha (2016) and GEOSSIT, in which *deterioration risk* is assessed without distinguishing among its causes. Such a modification, already present in the methods of Wilson (2013) and García-Ortiz et al. (2014), possibilitates distinguishing potential degradation as due to natural (floods, mass movements and erosion) or human (mining, intense traffic or the proximity to large urban centers) causes. Both these criteria were considered the most relevant ones, being assigned a weight of 5.

Accessibility and *protection regime*, which are also considered in the other inventory methods mentioned, were fundamental criteria in assessing the vulnerability of Paraná's geosites, both assigned a weight of 3. *Access regime* and *carrying capacity* were both attributed a weight of 1. A detailed description of assessment criteria weights is provided as supplementary material. *Access regim*e is assessed along with legal protection aspects in the methods of Brilha (2016) and GEOSSIT. A similar approach is taken in the method of Lima et al. (2010), in which both criteria are jointly referred to as protection regime. In the method applied to the geological heritage of Paraná, the legal protection of the geosites was taken into account to address their use as either sustainable use or full protection areas according to Federal Law 9985, which established the National System of Conservation Units (Brasil 2000). It must be stressed that the aforementioned law has been primarily intended for the protection of biodiversity, geosites being addressed in a secondary way.

Carrying capacity was included in the inventory method applied to Paraná in order to evaluate cases when the maximum recommended number of visitors per period of time should be calculated by specialists due to the fragility of the geosite. The calculation is essential, for example, in geosites consisting of sediments or sedimentary rocks that can be easily disaggregated or damaged by treading, or when elements of speleological, mineralogical or paleontological interest are susceptible to damage. Unlike low visitation sites consisting of rocks and/or structures hardly subject to degradation and wear, sites that already are or are predicted to be of high visitation are recommended to have their carrying capacity calculated. This was another adjustment aimed

Table 4 Vulnerability assessment criteria for the geosites of Paraná. VUW: vulnerability weight

criterion/indicator		score
A	Accessibility (VUW = 3)	
	The geosite is directly accessible by car ou bus or (up to 100 m walk)	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
B	Access regime (VUW = 1)	
	The geosite is located in an area of free access	4
	The geosite is located in a protected/restricted area, being visited only upon authorization	2
	The geosite is located in a protected/restricted area, and is only visited upon authorization and/or payment of an entrance fee	1
C	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 to 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
D	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 not vulnerable to natural alteration processes (floods, mass movements, erosion, weathering), that would compromise its integrity in the short term	1
E	Protection regime (VUW = 3)	
	The geosite is located in an unprotected area	4
	The geosite is located in a Conservation Unit for sustainable use or is under some other form of protection	2
	The geosite is located in a conservation unit of integral protection	1
F	Carrying capacity (VUW = 1)	
	It is essential to take the carrying capacity of the geosite into account	4
	Depending on the expected number of visitors/use of the geosite, the carrying capacity must be calculated	2
	Carrying capacity must not be taken into account	1

Table 5 Vulnerability intervals in the inventory method applied to geosites of Paraná

Value	Vulnerability
$18 \leq \text{value} \leq 31$	low
$31 < \text{value} \leq 58$	medium
$58 < \text{value} \leq 72$	high

at improving vulnerability assessment that possibilitates a better management of geosites in Paraná.

Table 5 presents the vulnerability intervals in our geological heritage inventory method. Geosites of low or medium vulnerability must be monitored to prevent their integrity from being compromised by human activity. Great attention must be given to geosites of high and very high vulnerability.

Conclusions

Although regional and local studies on the Brazilian geological heritage have grown in number over the recent years, in most cases by employing inventory methods designed for application in European contexts, only the state of São Paulo has a state-scale inventory.

A reconnaissance or advanced reconnaissance inventory in the sense of Carcavilla Urquí et al. (2007) was the approach chosen for the geological heritage inventory of Paraná due to its territorial extension, its current geological knowledge degree and the financial resources available. The inventory involved bibliographical research, establishment of thematic categories, selection of sites of geological interest and checking by specialists. The selection method adopted does not prevent specialists from including geosites not only for their primarily scientific value, but also for other interests. Since the inventorying was carried out at state-wide scale, i.e., of a regional character given the

territorial extension of Brazil, geosites had their educational and touristic values assessed along with their scientific value and vulnerability.

The inventory method was applied in two stages. In the first one, geological heritage was characterized by from information about each geosite, the relevant data being systematically stored as a database according to frameworks initially defined for large sedimentary and/or structural domains. With minor modifications, the data collection spreadsheets follow guidelines proposed in García-Cortés et al. (2019), ProGeo/Portugal (Brilha 2005) and GEOSSIT. The adaptations consisted in the inclusion of data fields for local information such as the presence or not of informational displays installed by former MINEROPAR (the geological survey of Paraná), the record number in the SIGEP (the Brazilian Commission on Geological and Palaeobiological Sites), the inclusion of the geosite in any geopark proposal, its form of visitation (free, controlled, paid), listing record and new paleontological framing parameters. The second application stage was designed and adjusted based on the method described in Wilson (2013), which was developed for the Cajón del Maipo region in Chile. The main modifications from this method address cultural and social aspects and weighting of some criteria. Weights ranging from 1 to 5 were assigned to each criterion according to five degrees of importance: very high (5), high (4), medium (3), and low (1) and, in some cases, zero. Thus, the fundamental evaluation criteria are properly distinguished.

No major modifications were introduced to the calculation of the scientific value of geosites, *representativeness* and *rarity* being considered the most important criteria. *Type-species*, the geographic location where a particular fossil or mineral was first described was combined to *type-location*. The corresponding explanatory notes were made more objective in order to data collection mistakes. Technical reports from state-owned companies were considered valid publications in assessing the scientific knowledge degree of geosites. Geosites not mentioned in the literature but recognized by experts as being of scientific potential were also inventoried. The inclusion of this item encourages recognition of potential geosites. In Brazil, as areas with less detailed knowledge of the territory are still common in the country.

In order to calculate the educational and touristic values of geosites, *cultural diversity* (archaeological, indigenous and traditional community) and *ecological diversity* (ecological) aspects of the geosites. The weights attributed to these criteria emphasize their role in the integrated assessment of geological heritage. Geosites are in the state of Paraná and other parts of the Brazilian territory that must be inventoried given their close association with these parameters. *Natural safety* refers to natural risks posed to the integrity of visitors by the geosite. *Personal safety* refers to risks of visitors being subject to inconveniences such as theft/robbery and traffic incidents.

Educational content, with a weight of 5, *service infrastructure* and *health and well-being infrastructure*, with a weight of 4, *geological diversity*, *accessibility*, *cultural diversity*, *ecological diversity*, *natural safety* and *personal safety*, with a weight of 3 were the highest valued criteria by the educational value of the geosites were assessed. *Representativeness*, *rarity*, *scenic value* and *access regime* received each a weight of 1.

In the assessment of the touristic value of the geosites, *scenic value*, with a weight of 5, was the criterion of highest importance, followed by *information content* and *accessibility*, both receiving a weight of 4. *Cultural diversity*, *ecological diversity*, *service infrastructure*, *natural safety*, *personal safety* and *health and well-being infrastructure* received a weight of 3. *Observation conditions*, *access regime*, *economic level*, *population density* and *cultural and recreational environment* received a weight of 1.

In the assessment of vulnerability, *anthropogenic vulnerability*, which corresponds to the potential that certain human activities have to cause the geosite degradation, and *natural fragility*, which reflects the potential that natural processes have to cause geosite degradation were the most important criteria. Such a distinction makes it possible to identify threats as man-made or not. *Carrying capacity*, which sets the number of people that a geosite can accommodate over a given period of time without being subject to damage. The criterion was included so that the need for its calculation could be assessed according to the geosite substrate and its rate of visitation. Sites consisting of easily disaggregated sediments or sedimentary rocks, which can be damaged by treaddind and sites susceptible to damage such as those of speleological, mineralogical or paleontological interest could thus be identified.

The methodological adaptations in our geological heritage inventory of Paraná aimed to improve its assessment accuracy, thus contributing to a better management of the state's geological geosites. We hope that the method will be applied to other units of the Federation as well. The results will be fundamental to the implementation of future geoconservation strategies in Paraná and the national inventory of geological heritage as well.

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References

Albani RA, Mansur KL, Carvalho IS, Santos WFS (2020) Quantitative evaluation of the geosites and geodiversity sites of João Dourado Municipality (Bahia—Brazil). Geoheritage 12:46. https://doi.org/10.1007/s12371-020-00468-1

Almeida MC (2016) Avaliação quantitativa de valores da geodiversidade em geossítios do projeto geoparque Seridó. Monograph, Universidade Federal do Rio Grande do Norte

Arruda KEC, Garcia MGM, Del lama EA (2015) Geological Heritage Inventory as a Subsidy for Geotourism: Caraguatatuba - São Paulo State, Brazil. In: International Progeo Symposium, 68–85

Azevedo UR, Machado MMM, Castro PTA et al (2012) Quadrilátero Ferrifero. In: Schobbenhaus C. & Silva, C.R. (orgs) Geoparques do Brasil: propostas. CPRM, Rio de Janeiro, pp 183–220

Brasil (2000) Lei 9.985, DE 18 DE JULHO DE 2000. n° 9.985, de 18 de julho de 2000. Regulamenta o Art 225, § 1o, incisos I, II, III e VII da Constituição Federal, institui o Sistema Nacional de Unidades de Conservação da Natureza e dá outras providências. http://www.planalto.gov.br/ccivil_03/leis/L9985.htm. Accessed 17 April 2020

Brilha J (2005) Património geológico e geoconservação: a conservação da natureza na sua vertente geológica. Palimage Editores, Braga

Brilha J (2016) Inventory and quantitative assessment of geosites and geodiversity sites: a review. Geoheritage 8(2):119–134. https://doi.org/10.1007/s12371-014-0139-3

Bruschi VM (2007) Desarrollo de una metodología para la caracterización, evaluación y gestión de los recursos de la geodiversidad. Tesis, Universidad de Cantabria

Carcavilla Urquí L, López Martinez J, Durán Valsero JJ (2007) Patrimonio geológico y geodiversidad: investigación, conservación, gestión y relación con los espacios naturales. Instituto Geológico y Minero de España, Madrid

Covello C, Horn Filho NO (2015) Inventário de potenciais geossítios e sítios de geodiversidade da ilha de Santa Catarina – Florianópolis In: Simpósio Brasileiro de Patrimônio Geológico, resumos:191–194

Daly D (ed) (1990) The conservation of Earth Science areas of scientific interest. Geol. Surv. of Ireland, Dublin

Erikstad L (1984) Registration and conservation of sites and areas of geological significance in Norway. Norsk Geogr Tidskr 38:199–204

Fepuleai A, Weber E, Nemeth K, Muliaina T, Iese V (2017) Eruption Styles of Samoan Volcanoes Represented in Tattooing, Language and Cultural Activities of the Indigenous People. Geoheritage 9(3):395–411

Food and Agriculture Organization of the United Nation - FAO (2012) FRA 2015 - Terms and definitions (forest resources assessment). FAO Forestry department, Roma

Fuertes-Gutiérrez I, Fernández-Martínez E (2010) Geosites inventory in the Leon Province (Northwestern Spain): A tool to introduce geoheritage into regional environmental management. Geoheritage 2(1–2):57–75. https://doi.org/10.1007/s12371-010-0012-y

Garcia MGM, Brilha J, Lima FF et al (2018) The inventory of geological heritage of the state of São Paulo, Brazil: Methodological basis, results and perspectives. Geoheritage 10(2):239–258. https://doi.org/10.1007/s12371-016-0215-y

García-Cortés A, Carcavilla Urquí L (2009) Documento metodológico para la elaboración del inventario español de lugares de interés geológico (IELIG). Instituto Geológico y Minero de Espanã, Madrid

García-Cortés A, Vegas J, Carcavilla Urquí L, Díaz-Martínez E (2019) Bases conceptuales y metodología del inventario Español de Lugares de Interés Geológico (IELIG). Instituto Geológico y Minero de Espanã, Madrid

García-Ortiz E, Fuertes-Gutiérrez I, Fernández-Martínez E (2014) Concepts and terminology for the risk of degradation of geological heritage sites: fragility and natural vulnerability, a case study. Proc Geol Assoc 125:463–479. https://doi.org/10.1016/j.pgeola.2014.06.003

Gonggrijp GP (1988) Earth Science Conservation: the GEA Project – Ann. Rep. Res. Inst. Nature Management 93–101

Grandgirard V (1996) Gestion du patrimoine naturel, l'inventaire de géotopes géomorphologiques. Ukpik, Institut de Géographie. Université De Fribourg Rapports De Recherches 8:181–195

Gravis I, Németh K, Procter JN (2017) The Role of Cultural and Indigenous Values in Geosite Evaluations on a Quaternary Monogenetic Volcanic Landscape at Ihumātao, Auckland Volcanic Field. New Zealand Geoheritage 9(3):373–393

Gravis I, Nemeth K, Twemlow C, Nemeth B (2020a) The Ghosts of Old Volcanoes, a Geoheritage Trail Concept for Eastern Coromandel Peninsula. New Zealand Geoconservation Research 3(1):40–57

Gravis I, Nemeth K, Twemlow C, Nemeth B (2020b) The Case for Community-Led Geoheritage and Geoconservation Ventures in Mangere, South Auckland, and Central Otago. New Zealand. Geoheritage 12(1):1–24

Guimarães GB, Melo MS, Piekarz GF, Moreira JC, Licardo A, Mochiutti NF (2012) Campos Gerais (PR). In: Schobbenhaus C. & Silva, C.R. (orgs) Geoparques do Brasil: propostas. CPRM, Rio de Janeiro, pp. 617–646

Instituto Brasileiro de Geografia e Estatística - IBGE (2014) Manual da base territorial. IBGE, Rio de Janeiro

Instituto Paranaense de Desenvolvimento Econômico e Social - IPARDES (2010) Densidade demográfica 2010. Disponível em Base Demográfica e Social, http://www.ipardes.gov.br/. Accessed 21 july 2020

Junta de Andalucía (2002) Propuesta de estrategia Andaluza para la protección de la geodiversidad. Consejería de Medio Ambiente, Andalucía

Larwood JG, Badman T, McKeever PJ (2013) The progress and future of geoconservation at a global level. Proc Geol Assoc 124:720–730. https://doi.org/10.1016/j.pgeola.2013.04.001

Lima FF, Brilha J, Salamuni E (2010) Inventorying geological heritage in large territories: A methodological proposal applies to Brazil. Geoheritage 2(3):91–99. https://doi.org/10.1007/s12371-010-0014-9

Mansur KL (2010) Diretrizes para Geoconservação do patrimônio geológico do estado do Rio de Janeiro: o caso do Domínio

Tectônico Cabo Frio. Universidade Federal do Rio de Janeiro, Tese

Moura P, Garcia MGM (2016) Inventário e avaliação do patrimônio geológico do domínio Ceará Central: Metodologia e resultados preliminares. In: Congresso Brasileiro de Geologia, SBG, Porto Alegre

Nascimento MAL, Silva MLN, Almeida MC et al (2020) Evaluation of Typologies, Use Values, Degradation Risk, and Relevance of the Seridó Aspiring UNESCO Geopark Geosites, Northeast Brazil. Geoheritage 13:25. https://doi.org/10.1007/s12371-021-00542-2

Nemeth K, Cronin SJ (2009) Volcanic structures and oral traditions of volcanism of Western Samoa (SW Pacific) and their implications for hazard education. J Volcanol Geoth Res 186(3–4):223–237

Nemeth K, Fepuleai A (2017) The underutilized volcanic geoheritage values of Upolu, Western Samoa; challenges to develop sustainable geotourism programs incorporating Polynesian heritage. Geosci Soc N Z Misc Publ 147A:78–80

Nemeth K, Fepuleai A, Muliaina T (2017) Samoa Geopark Project: a strategic plan to promote the volcanic geoheritage of Savai'i Island, Samoa. Conference: STAR 2017 - The Pacific Islands Science, Technology and Resources Conference [26-29 June 2017] At: Nadi, Fiji. https://doi.org/10.13140/RG.2.2.19607.68009

Oliveira SC, Goya SC (2016) Caracterização da geodiversidade do Guarujá/SP. In: Congresso Brasileiro de Geologia, SBG, Porto Alegre

Pereira RGFA, Brilha J, Martinez JE (2008) Proposta de Enquadramento da Geoconservação na Legislação Ambiental Brasileira. Publ Museu Lab Mineral Geol Univ Coimbra Memórias Notícias 3:491–499

Pocidonio EAL (2015) Inventário de geomorfossítios e sítios de geodiversidade do município de Angra dos Reis (RJ) – Um novo olhar para a atividade turística. Dissertação, Universidade Federal do Rio de Janeiro

Prochoroff RO (2014) Patrimônio geológico de Ilhabela - SP: estratégias de geoconservação. Universidade de São Paulo, Dissertação

Reverte FC, Garcia MGM, Moura TT (2016) Desafios para a Geoconservação em áreas vulneráveis: o exemplo da Bacia de Taubaté, Rifte Continental do Sudeste do Brasil. Rev Geociênc Nordeste 2(2016):1181–1190

Reynard E (2009) Geomorphosites: definitions and characteristics. In: Reynard E, Coratza P, Regolini-Bissig G (eds) Geomorphosites. Pfeil, München, pp 9–20

Rocha AJD, Lima E, Schobbenhaus C (2016) Aplicativo GEOSSIT - Nova versão. Congresso Brasileiro de Geologia. http://cbg2017anais.siteoficial.ws/anais48cbgcompleto.pdf. Accessed 21 July 2020

Romão RMM, Garcia MGM (2017) Iniciativas de inventário e quantificação do patrimônio geológico no Brasil: Panorama atual. Anuário Inst Geociênc 40(2):250–265. https://doi.org/10.11137/2017_2_250_265

Santos WFS, Carvalhom IS, Brilha J, Leonardi G (2015) Inventory and assessment of Palaeontological Sites in the Sousa Basin (Paraíba, Brazil): Preliminary study to evaluate the potencial of the area to become a Geopark. Geoheritage 8(4):315–332

Schobbenhaus C, Campos DA, Queiroz ET, Winge M, Berbert-Born MLC (2002) Sítios Geológicos e Paleontológicos do Brasil. CPRM, Brasília

Schobbenhaus C, Rocha AJD, Winge M, Lima E (2015) Inventário de Sítios do Patrimônio Geológico do Brasil. Simpósio brasileiro de patrimônio geológico. https://www.researchgate.net/publication/297743925_Inventario_de_Sitios_do_Patrimonio_Geologico_do_Brasil. Accessed 21 July 2020

Tavares GND, Boggiani PC, Moraes Leme J et al (2020) The Inventory of the Geological and Paleontological Sites in the Area of the Aspirant Geopark Bodoquena-Pantanal in Brazil. Geoheritage 12:28. https://doi.org/10.1007/s12371-020-00437-8

UKRIGS (2001) Notes to accompany RIGS recording, assessment, designation and notification sheets. UKRIGS Conference

Vegas J, Lozano G, García-Cortés A, Carcavilla Urquí L, Díaz-Martínez E (2011). Adaptación de la medología del Inventario Español de Lugares de Interés Geológico a los inventários locales de patrimônio geológico: município de Enguídanos (Cuenca). Avances y retos en la conservación Del Patrimonio Geológico en España. Actas de la IX Reunión Nacional de la Comisión de Patrimonio Geológico (Sociedad Geológica de España). Universidad de León, pp 271–276

Vieira Júnior HT, Moraes JM, Paula TLF (2012) Chapada dos Guimãraes (MT). In: Schobbenhaus C, Silva CR (orgs) Geoparques do Brasil: propostas. CPRM, Rio de Janeiro, pp 283-316

Wildner W, Ferreira RV (2012) Fernando de Noronha (PE). In: Schobbenhaus C, Silva CR (orgs) Geoparques do Brasil: propostas. CPRM, Rio de Janeiro, pp 317-360

Wilson JMB (2013) Patrimonio Geológico Del Proyecto Geoparque Cajón Del Maipo (Región Metropolitana - Chile). Dissertation, Universidade do Minho

Wimbledon WAP, Ishchenko AA, Gerasimenko NP, Karis LO, Suominen V, Johansson CE, Freden C (2000) Geosites - An IUGS Initiative: Science Supported by Conservation. In: Barettino D, Wimbledon WAP, Gallego E (eds) Geological Heritage: Its Conservation and Management. Instituto Geológico y Minero de España, Madrid