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Identification of priority geosites for public use management: application to the geological heritage inventory of São Paulo state

Identificação de geossítios prioritários para gestão do uso público: aplicação ao inventário do patrimônio geológico do estado de São Paulo

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Abstract

The characterization of the elements of geodiversity, through different inventory and quantitative evaluation methods, in the past decades, has allowed the identification of the most representative sites of the regional geological evolution of the state of São Paulo. Between 2013 and 2016, the first phase of the inventory of the geological heritage of São Paulo state was carried out. At the end of this stage, 142 geosites integrated into 11 geological categories were defined, which were characterized and quantitatively evaluated according to their scientific value and degradation risk, to establish future management priorities. Between 2017 and 2019, in the second phase of the research, the data obtained in the inventory were submitted to an analysis aiming at the diagnosis of use and protection and the proposal of strategies for management and public use of these geosites. Currently, the inventory of the geological heritage of the state is composed of 143 geosites, of which, based on their scientific value, 57 were evaluated as potential candidates to be integrated into the inventory of the national geological heritage. Despite this, there are still few works that systematically apply the stages of conservation and monitoring of geological sites. In this context, this study presented the initial phase of the definition of a methodology for the assessment of the evolution of the state of conservation of the geological heritage and its application in the state of São Paulo, to subsidize future actions of management and preservation of this heritage. In this stage, 129 state geosites were evaluated based on three defined criteria. This evaluation preliminarily resulted in the identification of 10 priority geosites, which will be covered in the subsequent stages.

Keywords: Geosites; Geoconservation; Geoindicators; Conservation status.

Resumo

A caracterização dos elementos da geodiversidade, por meio de diferentes métodos de inventário e avaliação quantitativa, nas últimas décadas, tem permitido identificar os sítios mais representativos da evolução geológica regional do estado de São Paulo. Entre os anos de 2013 e 2016, realizou-se a primeira fase do inventário do patrimônio geológico do estado São Paulo. Ao fim dessa etapa, foram definidos 142 geossítios integrados em 11 categorias geológicas, os quais foram caracterizados e avaliados de forma quantitativa de acordo com seu valor científico e risco de degradação, com o intuito de estabelecer prioridades de gestão futura. Entre os anos de 2017 e 2019, na segunda fase da pesquisa, os dados obtidos no inventário foram submetidos a uma análise visando ao diagnóstico de uso e proteção e à proposição de estratégias para a gestão e uso público desses geossítios. Atualmente, o inventário do patrimônio geológico do estado é composto de 143 geossítios, dos quais, com base no valor científico, 57 foram avaliados por como potenciais candidatos a integrar o inventário do patrimônio geológico nacional. Apesar disso, ainda são poucos os trabalhos que aplicam de forma sistemática as etapas de conservação e monitoramento de sítios geológicos. Nesse contexto, este trabalho apresenta a fase inicial de definição de uma metodologia para a avaliação da evolução do estado de conservação do patrimônio geológico e sua aplicação no estado de São Paulo, a fim de subsidiar futuras ações de gestão e preservação desse patrimônio. Nesta etapa foram avaliados 129 geossítios estaduais com base em três critérios definidos. Esta avaliação resultou, preliminarmente, na identificação de dez geossítios prioritários, os quais serão abrangidos nas etapas subsequentes.

Palavras-chave: Geossítios; Geoconservação; Geoindicadores; Estado de conservação.

INTRODUCTION

Applied geoconservation (Henriques et al., 2011) consists of a set of techniques and actions developed to conserve and protect geological heritage, including associated promotion and awareness-raising activities, as well as data or specimen recording of resources and sites threatened with loss or damage (Worton, 2008; Prosser, 2013).

In this context, in the past decades, different methods have been developed to systematize, discuss, and propose measures for the conservation and sustainable management of geological heritage. These methods have often been grouped into a sequence of steps that constitute the geoconservation strategies, which include inventory, assessment, classification, conservation, valorization, dissemination, and monitoring (Brilha, 2016, 2018). According to Brilha (2016, 2018), conducting inventories (identification and characterization) and evaluations (quantitative and/or qualitative) of geological sites are already established worldwide as initial and fundamental steps in any geoconservation strategy.

Recently, in view of the need for sustainable management of geological sites, many works have focused on the development of methods and guidelines for conservation and monitoring of geological sites (e.g., Fuertes-Gutiérrez and Fernández-Martínez, 2010; García-Cortés et al., 2012; Vegas et al., 2015; Fuertes-Gutiérrez et al., 2016; Fernández Martínez et al., 2017; Urquí et al., 2017; Díez-Herrero et al., 2018; Moura et al., 2018, 2021; Prosser et al., 2018; González and Reguero, 2019; Gordon, 2019; Santos, 2019; Canesin et al., 2021; Wignall et al., 2023). García-Cortés et al. (2012) proposed a system of geoindicators that allow establishing a diagnosis of the conservation status of geological sites and their evolution over time, so that appropriate management measures can be evaluated. Vegas et al. (2015) designed a system of geoindicators to quantify the evolution and monitor the state of conservation of the geological heritage at geological sites subjected to anthropic activities. Díez-Herrero et al. (2018) and Canesin et al. (2021) presented the evaluation of different techniques for monitoring geological sites that allow establishing proposed conservation measures and assessing the state of conservation of geosites. Wignall et al. (2023) identified the main similarities and different approaches of the geosites condition monitoring program in the four countries of the United Kingdom and evaluated the results produced between 1999 and 2019.

However, corroborating the study by Moura et al. (2021), in many countries the management of geological sites, particularly conservation and monitoring, is still a major challenge. As most of the initiatives in geoconservation are carried out in the academic field, in most cases, these institutions do not have legal authority to establish the conservation of geological heritage and lack financial resources for the development of concrete actions. In Brazil, in the past decades, different initiatives related to geoconservation were developed. Among them is the creation of GEOSSIT for the registration of geological sites in the country and the realization of state inventories (e.g., Garcia et al., 2018; Xavier, 2022). The management of geological sites has been addressed in geopark territories (e.g., Seridó, Araripe, and Caminhos dos Cânions do Sul) and in conservation units [e.g., Itatiaia National Park (Mucivuna et al., 2022) and Serra do Mar State Park (Balaguer et al., 2022)].

Despite the several studies about geoconservation in Brazil, there are still few studies that apply in a systematic way the conservation and monitoring stages of geological sites – fundamental stages to evaluate the conservation status and safeguard the main geological elements. It is important that the inventory and evaluation of sites follow appropriate and careful parameters, which ensure that the sites to which they will be applied are the most representative and priority ones. In this context, this study presents the initial phase of the definition of a method for assessing the evolution of the state of conservation of the geological heritage of the state of São Paulo for subsidizing future actions of management and conservation of this heritage. The results presented here correspond to the phase of evaluation of the geosites management priorities and to the identification of priority geosites, which will be addressed in future steps.

Study area

The state of São Paulo has an area of approximately 250,000 km^2, with an estimated population of 46 million inhabitants (IBGE, 2022). According to Garcia et al. (2018), in the past 70 years, representative sites of the state's geodiversity have been the target of different scientific research. Many outcrops and landscape representatives of the geological history of the region have been described and researched, and many samples have been collected and analyzed. Furthermore, many of these sites are used in field activities in different disciplines and scientific events, according to the same authors. However, the use of many of these sites is made impossible due to natural degradations (e.g., weathering and erosion) and intense urban growth (Garcia et al., 2018). Thus, according to Higa (2019), the development of geoconservation measures in the state of São Paulo is crucial for the preservation of the most representative sites of geological history in the state's territory. According to this author, the evaluation of the potentiality of use of geosites allows directing management strategies and public use in order to respect the characteristics, fragilities, and vulnerabilities of geosites, minimizing the damage caused to them.

In recent years, the geodiversity of São Paulo state has been the target of different works that apply measures or strategies of geoconservation. Many of these methodological studies are focused on the inventory and quantitative assessment of geological sites (e.g., Santos, 2014; Mucivuna, 2016; Queiróz, 2018; Romão, 2018; Reverte et al., 2019; Santos, 2019; Somekawa, 2019). These and other works constitute systematic approaches to geological heritage at the municipal level.

Between 2013 and 2016, the first stage of the inventory of the geological heritage of the state of São Paulo was carried out. The project was carried out under the general coordination of the Universidade de São Paulo (USP) and the Universidade do Minho, Portugal (UMinho). It is the first systematic state inventory in Brazil. At the end of this stage, the inventory was composed of 142 geosites integrated into 11 geological frameworks (Table 1), which were characterized and quantitatively assessed according to their scientific value (SV) and degradation risk (DR) to establish future management priorities (Garcia et al., 2018). In the second phase of the research (2017–current), the inventory of the state of São Paulo was submitted to an analysis of the geosites that composed it, with a diagnosis of use and protection and a proposition of strategies for management and public use (Higa, 2019). Currently, the inventory of the geological heritage of the state is composed of 143 geosites,

Table 1. Geological frameworks of the inventory of geoheritage of the state of São Paulo.

Geological framework	Description	Number of geosites
Precambrian terranes	It represents the domains included in the Mantiqueira (Ribeira and Apiaí orogens) and Tocantins provinces (southern portion of Brasília Orogen), which have a general configuration related to the events of the Brasiliano-Pan African Cycle, in the Neoproterozoic.	21
Shear zones	It reflects the structural organization of the Precambrian terranes, formed by different units occurring as elongated strips bounded by strike-slip shear zones with local thrust components in a 1000-km length and 200-km-wide megastructure.	09
Granitic rocks	More than 200 kilometric to metric granitic bodies, associated with extensional tectonics and collisional events during the Neoproterozoic, occur in the region.	11
Precambrian metallic mineralization	Represented by the Mesoproterozoic metavolcano-sedimentary succession of the Serra do Itaberaba Group, whose metamorphism gave origin to tourmalinites and the metamorphic product of Algoma-type iron formation, enriched with syngenetic gold mineralization.	07
Paraná Basin	Formed by volcano-sedimentary rocks ranging from the glacial-interglacial cycle during the Upper Carboniferous-Lower Permian interval to the continental environment at the end of the Permian and arid climates that completed the tendency to continentalization during the Mesozoic.	21
Mesozoic magmatism	It represents the intense tectonic magmatic processes represented by the basaltic flows of the Serra Geral Formation (Paraná Basin), dike swarms, and alkaline complexes associated with the evolution of the Paraná Basin.	10
Bauru Basin	It is mainly represented by Upper Cretaceous continental sandstones formed within the South American platform, corresponding to a period of isostatic adjustment subsidence after the breakup of Gondwana and opening of the South Atlantic Ocean.	14
Continental Rift of Southern Brazil	A 900-km-long Cenozoic tectonic feature, whose evolution is related to the latest stage of the tectonic activation event in the South American Platform and is associated with the fragmentation of the Gondwana supercontinent and the formation of the South Atlantic Ocean.	12
Continental and coastal Neogene and Quaternary evolution	It represents the processes that formed the current physiography of the state, resulting from a sequence of events controlled by geological, geomorphological, climatic, and oceanographic processes.	09
Geomorphological units and landforms	Represented by two main domains, the Atlantic Shield, with limited sedimentary deposits and Jurassic-Paleocene intrusions, and the platform cover, which reflect the general geological setting of the state.	14
Caves and Karst Systems	Most of the caves are mainly composed of sink-resurgence systems, forming river caves, with high depths, and common vadose shafts. Pseudokarst caves in granite/gneiss and other non-carbonate caves also occur.	14

Source: adapted from Ribeiro et al. (2021) based in Garcia et al. (2018).

of which 57 were evaluated by Ribeiro et al. (2021) with the potential to integrate the inventory of the national geological heritage, mainly due to their high SV. The geosites that integrate the São Paulo state inventory are described in the "geological interactive map" created by the Centre for Support to Research in Geological Heritage and Geotourism of the Universidade de São Paulo (GeoHereditas, 2022).

METHODS

The methods applied in this study are divided into the following three stages: literature review, management priority (MP) assessment, and identification and selection of priority geosites.

Literature review

This study began with the review of previous works carried out in the state of São Paulo, mainly in the scope of geoconservation, to identify actions related to the conservation of the geological heritage. Furthermore, considering the dynamic character of the geological sites inventory and the need for frequent updates (Brilha, 2016), it was carried out a review of the updates in the São Paulo inventory, both for the identification of the inclusion of new geosites and the removal of others. It was necessary to update names and geological categories. All updates were made based on the "interactive geological map" created by the Centre for Research Support in Geological Heritage and Geotourism of the Universidade de São Paulo (GeoHereditas, USP), in which all information about the state geosites is compiled, such as justification of the SV and main interests (GeoHereditas, 2022).

Assessment of management priority

The potential evaluation of tourism and/or didactic use of geosites, as well as the establishment of MP, is fundamental to subsidize measures and actions for the sustainable public use of geosites. In addition, it allows an analysis of conservation needs by means of anthropic and natural fragilities and vulnerabilities (Prosser et al., 2018).

As previously explained, the MP of the geosites of the state of São Paulo was established by Higa (2019) from the quantification of the geosites in the GEOSSIT platform of the Serviço Geológico do Brasil (SBG-CPRM, 2022) and the elaboration of a method to establish the MP. Based on the analysis of the results for protection priority [which are based on the addition of SV, DR, potential tourist use (PTU), or potential educational use (PEU)] obtained in the platform, the author proposes the attribution of different weights for SV, DR, PEU, and PTU. Besides, it emphasizes the need for using different criteria for the calculation of the MP of the geosites. The calculation of the MP proposed by Higa (2019) is based on the weighing of four parameters:

I. (1) SV, PTU, and PEU;
II. (2) typology of the geosite;
III. (3) DR;
IV. (4) protection regime.

Based on the results of Higa (2019), in this work stage, a review and analysis considering the SV were carried out.

Identification of priority geosites

The conservation of geosites often requires the development of interventions to safeguard the physical properties of the geosite and, at the same time, to ensure that it is accessible to the public according to its geotourism, pedagogical, scientific, or other interests (Brilha, 2016). In this sense, the same author stated that, in a management strategy, the conservation of geosites with high SV should be prioritized regardless of their educational and/or touristic uses. However, conservation for public use only makes sense if these geosites are effectively used as educational and geotourism resources.

Thus, in this work stage, the selection of priority geosites was based on the following three criteria:

I. geosites with higher values of MP in relation to SV;
II. geosites identified by Ribeiro et al. (2021) with the potential for inclusion in the national inventory of the geological heritage, and/or included in Garcia (2021) among the 50 geosites of the State of São Paulo;
III. geosites identified in (i) and (ii) with higher values of MP in relation to potential tourism (PTU) and didactic use (PDU).

Regarding criterion (i) MP in relation to SV (SVMP), the results obtained by Higa (2019) provided values ranging from 146 to 371. Thus, within the scope of this study, three levels of MP were established:

A. SVMP $\leq$ 200 (low);
B. 201 $\leq$ SVMP $\leq$ 299 (medium);
C. SVMP $\geq$ 300 (high).

Concerning criterion (ii), it is worth mentioning that the evaluation and selection of the geosites of the São Paulo inventory with the potential to integrate the Brazilian national inventory, carried out by Ribeiro et al. (2021), was based on the SV criterion. Following the method of Brilha (2016), the geosites that reached a SV $\geq$ 300 were selected. Geosites that reached values lower than 300 but constitute a single representative of a geological element or event were also included.

Higa (2019) established the MP in relation to a potential touristic and didactic use for the geosites that reached values higher than 250 in the quantification of the touristic and educational values (Brilha, 2016) within each geological category established by Garcia et al. (2018). Considering the results obtained by the author, criterion (iii) was applied, allowing the identification of the geosites with higher values of MP in relation to their potential touristic and didactic use among those identified based on criteria (i) and (ii).

The 14 geosites inserted in the geological category "geomorphological units and landforms" were excluded because they constitute more extensive areas, for which it would be difficult to associate adequate geoindicators and arrange monitoring activities.

RESULTS

The review of the updates of the inventory of the state of São Paulo allowed the identification of 16 geosites that were included between 2019 and 2022, and therefore, the MP in relation to SV was calculated in the scope of this study. A total of 14 geosites belonging to the geological category "geomorphological units and landforms" were excluded due to the difficulty in arranging monitoring activities, which is primarily the aim of the selection. Thus, 129 geosites were evaluated based on criteria (i)–(iii).

The selection based on criterion (i) resulted in the evaluation of 113 geosites that had the SVMP calculated by Higa (2019) and 16 within the scope of this study. Among them, 53 were classified with high SVMP, 48 with medium SVMP, and 28 with low SVMP.

Based on criterion (ii), 53 geosites were evaluated, of which 25 were preliminarily identified (Table 2). Finally, from the 25 geosites to which criterion (iii) was applied, 10 priority geosites were identified (Table 3 and Figure 1) — they will be evaluated in the following work stages: identification of geoindicators, monitoring, evaluation of the conservation status, and proposals for conservation.

DISCUSSION

The initiatives in geoconservation in Brazil have contributed to the promotion of geoconservation as a science, as

Table 2. Geosites identified based on criteria (i) to (iii).

GEOSITES	Criterion (i) SVMP	Criterion (ii)		Criterion (iii)	
		Ribeiro et al. (2021)	Garcia (2021)	MP PDU	MP PTU
Phytofossils and palynomorphs from Itaquaquecetuba	371				
Metasediments of the Pico do Itapeva Formation	370			359	366
Pillow lava of Pirapora do Bom Jesus	364				
Type-section of the Presidente Prudente Formation	361			350	333
Fossiliferous site of Pirapozinho	356			330	
Negative flower structure of Taubaté	356				
Temperate rainforest of the Itararé Group	354				
Hornblenda gneiss milonitic of the Atuba Complex	347			321	
TTG of Atuba Complex	346				
Section-type of Vale do Rio do Peixe Formation	346			344	321
Calcretes of the Marília Formation	344			350	322
Cyanite migmatitic paragnaisse of the Turvo-Cajati Formation	343				
Metaconglomerates of the São Roque Group in the Rodoanel	342				
Contact between the Araçatuba and Vale do Rio do Peixe formations	334			351	
Folds in the Apiaí Marble	327			312	314
Clastic dykes of Bandeirantes Highway	326				
Itapira Complex in the Itu-Jundiuvira Shear Zone	324				
Cabuçu Topazites	321			351	342
Pariquera-Açu Mafic Syenite	319				
Ichnofossils from Porto Primavera	318				
Ubatuba Beachrock	312				
Dikes with mantle xenoliths from the Praia Vermelha	311			296	296
Mauá Granites with enclaves	307				
Paleoproterozoic granitoids Rio Capivari	304				
Itaguaré marine terrace cliffs	304				

Table 3. Description of the selected geosites based on criteria (i) to (iii).

Geosites	Geological Framework	Type	Justification of Scientific Value	Main Interests	Protection Regime
Metasediments of the Pico do Itapeva Formation	Precambrian terranes	Point	The outcrop is composed of rhythmic metarenites and deformed metaconglomerates, exhibiting milonitic foliation but with preserved sedimentary structures. The lithotypes represent the Pico do Itapeva Basin, with a lozenged shape and oriented in a NE-SW direction, with about 14 km in the major axis. It is a pull-apart basin, formed from movements of the Jundiuvira and Buquira shear zones.	Petrological Tectonic	APA (public area)
Milonitic Hornblende gneiss of Atuba Complex	Precambrian terranes	Point	This is a good exposure of milonitic rocks of the Atuba Complex (Riacian), representatively thrusting over Neoproterozoic metasedimentary rocks of the Turvo-Cajati Formation. Outcrop was submitted for detailed petrological and microstructural analyses.	Petrological Tectonic	APA (public area)
Folds in the Apiaí Marble	Precambrian terranes	Point	Metric folds in dark gray calcitic marble record the regional deformation in ductile character. The presence of parasitic folds and the difference in competence between the layers that form the primary stratification in the marble, which register the deformation in a heterogeneous way, are noteworthy.	Structural Petrological Stratigraphic	Private area
Cabuçu Topazites	Precambrian metallic mineralization	Point	Margarite-corundum shales (marundites) are very rare metamorphic rocks, both in Brazil and worldwide. In volcano-sedimentary sequences metamorphosed to medium grade, they constitute guide rocks of great importance to be used in gold prospecting works. In this geosite, the Cabuçu marundites constitute boulders and blocks in situ, associated with other lithotypes that are part of the gold mineralizing system.	Mineralogical Petrological	Public area

Continue...

Table 3. Continuation.

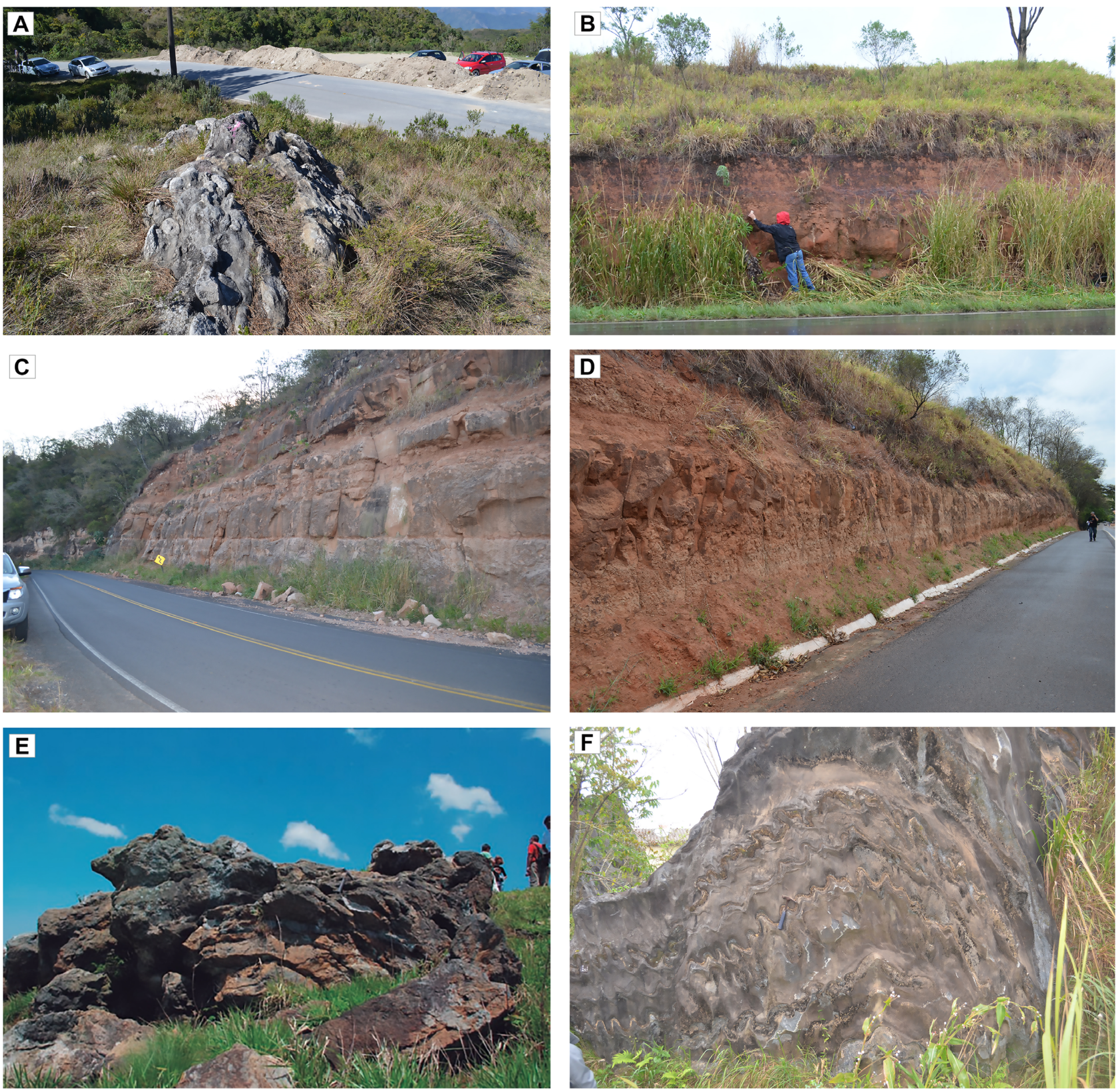
Geosites	Geological Framework	Type	Justification of Scientific Value	Main Interests	Protection Regime
Dikes with mantle xenoliths from the Praia Vermelha	Mesozoic magmatism	Point	The outcrop shows a lamprophyre dyke with mantle xenoliths that formed at about 100 km depth. Secondarily, structures interpreted as explosion cones in lamprophyre magmas are found.	Petrological Tectonic	Marine area and APA
Type section of the Presidente Prudente Formation	Bauru Basin	Point	Set of architectural elements and facies association is hardly exposed.	Sedimentological Stratigraphic	Public area
Pirapozinho fossiliferous site	Bauru Basin	Point	Unusual concentration of well-preserved Cretaceous chelonian hooves. In addition to the chelonian material, remains of reptiles, lamellibranchs, carophytes, and crustaceans (ostracods) can be found along the outcrop.	Paleontological	Public area
Vale do Rio do Peixe Formation	Bauru Basin	Point	Facies associations of semi-arid to desert context, composed of eolian deposits of sand sheets, low dunes, and ephemeral lagoons (lamites), as well as desert rivers/wadis (wadis), correspond to the Vale do Rio do Peixe Formation.	Sedimentological Stratigraphic	Public area
Calcretes of the Marília Formation	Bauru Basin	Point	Occurrence of calcrete levels in the Marilia Formation. Such formation is constituted by sandstones with carbonate horizons intensely cemented (calcretes), which set sustains the relief of regional plateaus in elongated spikes of flat top, limited by scarps of slightly more than a hundred meters of height.	Stratigraphic	Public area
Contact between the Araçatuba and Vale do Rio do Peixe formations	Bauru Basin	Point	Remarkable exposure of geological contact is hardly found, due to the vulnerability to the weathering of the sandy units.	Stratigraphic Sedimentological	Public area

Source: adapted from the Interactive map of the São Paulo Geoheritage Inventory (GeoHereditas, 2022) and Higa (2019).

stated by Moura et al. (2021) and Ribeiro et al. (2021), and to the dissemination of geoscientific knowledge. However, as explained above, most of these initiatives are focused on conducting inventories of geological sites and are limited to the academic environment and/or institutions that do not have the legal power to apply conservation measures. Garcia et al. (2022) pointed out that the conservation and monitoring stages, especially legal protection, are less developed, probably due to the demand for the participation of national or local managers. There are still great limitations in terms of research time and financial resources to give continuity in concrete actions focusing on geosites management. This scenario often justifies the lack of studies and the development of concrete actions toward the conservation and monitoring stages of geosites — due to the time required for the application of techniques which are often expensive. As a result, there are many geological sites that have been identified and properly characterized, but there is a great absence of public use management planning.

The definition of a systematic method for the evaluation of the state of conservation and monitoring of geosites requires the establishment of adequate critical parameters, which ensure that the sites to which they will be applied are the most representative ones. Thus, the stages of methodological definition, developed in this study, are synthesized in Figure 2.

In this study, considering the dynamic character of the inventory and the updates that were performed, the geosites that integrate the inventory of the geological heritage of the state of São Paulo were evaluated in relation to the MP. As a



Source: Interactive map of the São Paulo Geoheritage Inventory (GeoHereditas, 2022).

Figure 1. Examples of geosites selected based on criteria (i)–(iii). (A) Metasediments of the Pico do Itapeva Formation; (B) section-type of Vale do Rio do Peixe Formation; (C) Calcretes of the Marília Formation; (D) contact between the Araçatuba and Vale do Rio do Peixe formations; (E) Cabuçu Topazites; (F) Dobras in the Apiaí Marble.

starting point, the MP diagnosis performed by Higa (2019) was analyzed, which assesses, in addition to SV, potential uses, and DR, the typology and protection regime of geosites. This approach has presented promising results in the evaluation of geosites in different studies (e.g., Fuertes-Gutiérrez and Fernández-Martínez, 2010; Ballesteros et al., 2019; Bruschi and Sánchez-Carro, 2019; Lima, 2019), as it allows for more realistic conservation actions, considering the real scenario of legal protection of geosites, and identifying those that already have monitoring of natural elements and public use.

From the analysis of the MP, three criteria were established, which allowed the identification of the priority geosites in strategic stages of management: conservation and evolution of the conservation status. Among the 143 geosites that make up the inventory, 129 were evaluated based on the established criteria. Among them, 41% were classified as high MP in relation to SV, 37% were classified as medium MP, and 22% were classified as low MP. Considering that the conservation of geological sites is justified by the SV, they represent, whether added or not, the potential educational and tourist use, the geosites identified with a high MP in relation to the SV were analyzed in relation to the MP in relation to the potential educational and tourist use. Thus, 10 geosites were identified and preliminarily selected (Table 3).

In analyzing the selected geosites, an important aspect to highlight is that among the typologies adopted by Higa (2019) based on the study by Fuertes-Gutiérrez and Fernández-Martínez (2010), and based on the criteria established herein, the 10 geosites represent a single typology: point (consisting of outcrops) (Figure 1). According to the same authors, typology is a concept that defines, in an approximate way, the size, shape, disposition, fragility (DR facing natural threats), and vulnerability (DR facing anthropic threats) of each geosite. In general, the geosites of the point type present greater fragility, high vulnerability, and low resistance to threats and, therefore, need measures of protection and management before their use. Thus, during the calculation of the MP, the geosites of this typology result in higher scores.

However, the selected geosites, when evaluated in relation to MP in relation to public use (tourist and educational), show the need for a critical evaluation of this diagnosis and the established criteria (refinement) (in particular, criterion iii) for the selection of those that should be prioritized for future stages of work. This is because the geosites evaluated here, although they have been classified

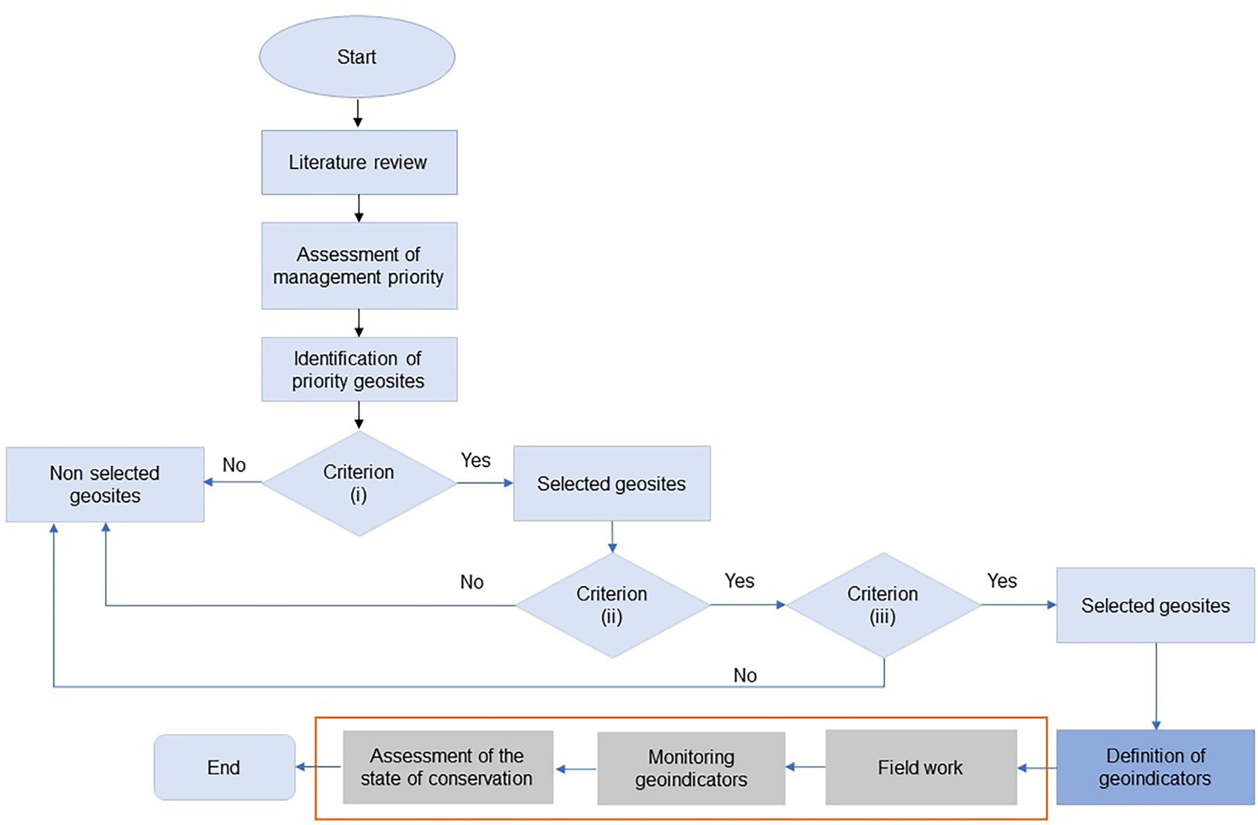


Figure 2. Steps of methodological definition for the evaluation of the evolution of the state of conservation of geological sites.

with high priority and during the seriation process, are considered the potential uses (i.e., the possibilities of uses). The same, when compared to those which already have "mass" public use (e.g., Santana Cave, Morro do Ouro), do not translate the "real" need for priority management of the geosites that integrate the inventory of the geological heritage of São Paulo.

Furthermore, as observed in Table 2, some geosites selected by criteria (i) and (ii) were excluded when criterion (iii) was applied. This is because Higa (2019) evaluated the PG in relation to the public use only for the geosites that achieved scores higher than 250 in the quantification of the touristic and educational values. In this way, the application of this criterion led to the exclusion of geosites that already have some type of use and require immediate management actions. The geosites Pillow Lava of Pirapora and Itaguaré marine terrace cliffs, for example, consist of outcrops inserted into field class scripts of geosciences higher education courses. In this sense, corroborating Santos (2019), one should consider the discrepancies between the (numerical) results obtained in the geological sites seriation phase and what is observed in the reality of a geosite or set of geosites and seek ways to make the "real public use" compatible to overcome them.

The conservation of geological heritage consists of the interventions carried out to safeguard the physical properties of the geosite while ensuring that it is accessible to the public according to its tourist, educational, scientific, or other interest (Brilha, 2005). A set of effective interventions for the conservation of geological sites may vary according to the management objectives. To this end, a set of principles becomes necessary to help guide the type of conservation appropriate for each geosite (Prosser et al., 2018). Among them are the establishment of the type of uses for the geosite, the identification of its vulnerabilities and fragilities in relation to natural and anthropic threats, and its susceptibility to different threats (Prosser et al., 2018).

In this sense, as already explained, successful approaches for the conservation of geological sites involve the identification and monitoring of geoindicators, which enable the assessment of the evolution of conservation status and sustainable management planning and measures. According to García-Cortés et al. (2012) and Díez-Herrero et al. (2018), the definition and monitoring of a set of geoindicators allows knowing, controlling, and mitigating both natural impacts and impacts (changes) of anthropic cause in a geological site. The same authors stated that geoindicators must be quantifiable, so that one can estimate the impacts of active geological processes in geological sites of public use.

To quantify the evolution of the conservation status of the geosites, it will be necessary to identify a set of indicators or geoindicators, which should be monitored through different techniques and periodically evaluated, to allow estimating the evolution of their conservation status. In this context, based on the literature and the descriptions made during the inventory and review phases, for each geosite selected in this stage of work, a set of indicators or geoindicators is being identified, preliminarily based on the proposal of Berger and Iams (1996) and compiled by Hirai and Augusto Filho (2008) (Figure 2). During the field work (next work stage), descriptions and analysis of the geosite integrity (e.g., main conditions, geological characteristics, implementation of infrastructure, public use activities, among others) will be done. This step will allow the identification of the fragility and vulnerabilities of the geosites in relation to natural threats and public use. The monitoring consists of the analysis of the geosites, based on regular measurements of defined indicators (Lima, 2019). In this stage, the geosites should be periodically monitored to verify and analyze the integrity of the main geological characteristics and the evolution of their conservation status.

It is worth mentioning that the future stages of the study will include data integration, which will consist of the verification of the geo-indicators preliminarily identified and their respective monitoring techniques, as well as the evaluation of the geosites carrying capacity. In the end, the results obtained in the previous steps will be evaluated to determine the conservation status of the geosites focused on the research (Figure 2).

Based on the results obtained in this study, and considering the research stages to be developed, aiming at the development of management and conservation actions for the geological heritage of the state of São Paulo, some guidelines can be preliminarily defined (Figure 2). Briefly, a method for evaluating the evolution of the conservation status of geological sites must start with the investigation on the geoconservation actions developed in the focused territory; once the MP of the identified sites is established, these data must be evaluated considering mainly the SV, which justifies the inclusion in the inventory; well-defined criteria must be established in order to identify the priority sites, which will be the target of the monitoring; and the results obtained must be evaluated in relation to the public use — considering if there is some kind of use of these sites or not.

CONCLUSION

Based on the sequential steps that compose the geoconservation strategies (adopted in this study), the conservation and monitoring of geological sites, as well as the evaluation of the conservation status, are still challenges to be overcome in Brazil and worldwide. However, recent approaches aimed at defining geoindicators and monitoring techniques have proven effective for conservation practice in countries such as Spain, Portugal, and the United Kingdom. In the case of Brazil, although the SBG-CPRM in recent years has developed a number of consistent initiatives in geoconservation, one of the important factors to consider is that most national initiatives are focused on conducting inventories of geological sites and are limited to the academic environment and/or institutions that do not have the legal power to apply conservation measures. Thus, a significant challenge to be overcome by the geoscientific community is the communication of academic research both to society and to the organizations and authorities responsible for public policies for the management and conservation of geological heritage. On the contrary, it is up to the public to recognize the importance of basing decisions related to the conservation of the geological heritage on the scientific knowledge produced in academic institutions.

In the state of São Paulo, the development of the systematic inventory of the geological heritage in its different stages subsidized new actions in geoconservation in Brazil (e.g., the realization of new state inventories; Xavier, 2022). However, there is still a lack of management planning, especially related to the conservation and monitoring of geosites. Therefore, this study is the first phase of a methodological investigation of the evaluation of the conservation status of geosites based on geoindicators.

The study presented herein results from a detailed analysis of the diagnosis of priority management of the geosites that integrate the inventory of the geological heritage of the state of São Paulo. Based on three established criteria, this analysis resulted in the (preliminary) selection of 10 geosites that will be the target of future stages of research. The procedures adopted in this study allowed the definition of (preliminary) guidelines for a method to evaluate the conservation status of geological sites.

The evaluation of the geosites MP provides systematic information that associates the risk of degradation, SV, potential use, legal framework, and geosite typology. Although this approach has proven efficient (internationally), it was found that the results obtained should be critically evaluated to overcome possible discrepancies with the reality of geosites, particularly regarding public use. In this sense, a challenge to be overcome is to reconcile the "potential public use" with the "real public use" of geological sites in the process of evaluating the MP in relation to tourism and educational use.

Regarding the criteria established for the identification and selection of priority geosites, the criteria (i) geosites with higher values of MP in relation to SV and (ii) geosites identified by Ribeiro et al. (2021) with potential for inclusion in the national inventory of the geological heritage and/or included in Garcia (2021) are considered effective. Both criteria prioritize the identification and selection of geosites with higher SVs, which justifies the priority of management actions and the conservation of geological heritage — based on the evaluation of the evolution of the conservation status. However, criterion (iii) may present a weakness of the methods applied herein. This is because, in light of the current reality of public use of the geosites that integrate the inventory of the state of São Paulo, those selected as priorities compared to other nonselected geosites, when applied the criterion (iii), excluded important sites where some type of use already exists. Therefore, this criterion should be refined so that this fragility is overcome. Among the future possibilities for the refinement of criterion (iii) are: (a) to evaluate the real use of the geosite for those who already have some type of activity and (b) later to evaluate the potential public use for those who do not have any type of use. However, as already explained, this is a complex challenge, as the traditional methods of geological sites seriation do not match the real "public use" in the quantitative assessment — resulting in "potential uses," which are sometimes far from the real use.

Thus, in this study, the main challenges encountered were the definition of criteria that allow an analysis of the MP of all the geosites that integrate the inventory of the geological heritage of São Paulo, so that the priority (most representative) geosites could be identified for the evaluation of the conservation status.

Finally, it is expected that the results obtained in this study will contribute to the establishment of guidelines and to future planning and management actions (management) of the state geosites, as well as to actions in geoconservation in Brazil. It is expected that the presentation of proposals for actions for the conservation of geological heritage in the state of São Paulo may contribute to the creation of measures by the competent authorities for the protection of geological heritage.

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REFERENCES

Balaguer, L. P., Garcia, M. G. M., Ribeiro, L. M. A. L. (2022). Combined assessment of geodiversity as a tool to territorial management: application to southeastern coast of State of São Paulo, Brazil. *Geoheritage*, 14, 60. https://doi.org/10.1007/s12371-022-00696-7

Ballesteros, D., Martínez, E. F., Urquí, L. C., Sánchez, M. J. (2019). Evaluación patrimonial de cuevas kársticas para su gestión en espacios protegidos: Parque nacional de los Picos de Europa (N de España). *In*: Martín-González, E., Bravo, J. J. C., Salamanca, J. V. (Eds.). *El Patrimonio Geológico: una nueva visión de la tierra*, p. 35-40. Spain: Instituto Geológico y Minero de España. Available at: https://www.igme.es/museo/publicaciones/cuadernos/PATRIMONIO%20GEOMINERO%20Sin%20NIPO.pdf. Accessed on: Mar 8, 2023.

Berger, A. R., Iams, W. J. (1996). *Geoindicators:* assessing rapid environmental changes in earth systems. Rotterdam: A. A. Balkema.

Brilha, J. B. (2005). *Património geológico e geoconservação:* a conservação da natureza na sua vertente geológica. Braga: Palimage. Available at: http://www.dct.uminho.pt/docentes/pdfs/jb_livro.pdf. Accessed on: Mar 8, 2023.

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

Brilha, J. (2018). Geoheritage: inventories and evaluation. *In*: Reynard, E., Brilha, J. (Eds.). *Geoheritage:* assessment, protection, and management, v. 1, p. 69-85. Elsevier. https://doi.org/10.1016/B978-0-12-809531-7.00004-6

Bruschi, V. M., Sánchez-Carro, M. Á. (2019). Propuesta metodológica para la evaluación del potencial turístico del patrimonio geológico subterráneo. *In*: Gonzáles, E. M., Bravo, J. J. C., Salamanca, J. V. (eds.). *El Patrimonio Geológico:* una nueva visión de la tierra, p. 41-47. Madrid: Instituto Geológico y Minero de España. Available at: https://www.igme.es/museo/publicaciones/cuadernos/PATRIMONIO%20GEOMINERO%20Sin%20NIPO.pdf. Accessed on: Mar 8, 2023.

Canesin, T. S., Pereira, P., Vegas, J., Selmi, L., Coratza, P., Santos, V. (2021). Addressing indicators for geoheritage monitoring based on degradation risk and scientific value quantitative assessment. *EGU General Assembly*, EGU21-15024. https://doi.org/10.5194/egusphere-egu21-15024

Díez-Herrero, A., Vegas, J., Carcavilla, L., Gómez-Heras, M., García-Cortés, Á. (2018). Techniques for the Monitoring of Geosites in Cabañeros National Park, Spain. In: Reynard, E., & Brilha, J. (Eds.). *Geoheritage:* assessment, protection, and management, v. 1, p. 417-430. Amsterdam: Elsevier. https://doi.org/10.1016/B978-0-12-809531-7.00024-1

Fernández Martínez, E., Carcavilla Urquí, L., Heredia Carballo, N., Santos González, J., Ballesteros, D., Fuertes, I., Adrados, L. (2017). Propuesta de inventario y geoindicadores en el Parque Nacional de Picos de Europa. *Cuadernos del Museo Geominero*, (21), 137-142. Available at: http://hdl.handle.net/10612/10709. Accessed on: Jan 30, 2023.

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, 57-75. https://doi.org/10.1007/s12371-010-0012-y

Fuertes-Gutiérrez, I., García-Ortiz, E., Fernández-Martínez, E. (2016). Anthropic Threats to Geological Heritage: Characterization and Management: A Case Study in the Dinosaur Tracksites of La Rioja (Spain). *Geoheritage,* 8, 135-153. https://doi.org/10.1007/s12371-015-0142-3

Garcia, M. D. G. M. (2021). *Patrimônio geológico paulista:* uma viagem no tempo geológico em 50 geossitios. São Paulo: Funep.

Garcia, M. G. M., Brilha, J., Lima, F. F., Vargas, J. C., Pérez-Aguilar, A., Alves, A., Campanha, G. A. C., Duleba, W., Faleiros, F. M., Fernandes, L. A., Fierz, M. S. M., Garcia, M. J., Janasi, V. A., Martins, L., Raposa, M. I. B., Ricardi-Branco, F., Ross, J. L. S., Sallum Filho, W., Souza, C. R. G., Bernardes-de-Oliveira, M. E. C., Brito Neves, B. B., Campos Neto, M. C., Christofoletti, S. R., Henrique-Pinto, R., Lobo, H. A. S., Machado, R., Passarelli, C. R., Perinotto, J. A. J., Ribeiro, R. R., Shimada, H. (2018). The inventory of geological heritage of the State of São Paulo, Brazil: methodological basis, results and perspectives. *Geoheritage*, 10, 239-258. https://doi.org/10.1007/s12371-016-0215-y

Garcia, M. G. M., Nascimento, M. A. L., Mansur, K. L., Pereira, R. G. A. F. (2022). Geoconservation strategies framework in Brazil: Current status from the analysis of representative case studies. *Environmental Science & Policy*, 128, 194-207. https://doi.org/10.1016/j.envsci.2021.11.006

García-Cortés, Á., Vegas, J., Carcavilla, L., Díaz-Martínez, E. (2012). Un sistema de indicadores para la evaluación y seguimiento del estado de conservación del patrimonio geológico. *Geo-Temas*, 13, 1272-1275.

GeoHereditas (2022). *Núcleo de Apoio à Pesquisa em Patrimônio Geológico e Geoturismo*. Available at: https://geohereditas.igc.usp.br/. Accessed on: Nov 14, 2022.

González, J. S., Reguero, A. M. (2019). Applying the geological heritage in land management: Cartography and management proposals of geosites in Burgos Province (Spain). *Geoheritage*, 11(2), 485-500. https://doi.org/10.1007/s12371-018-0301-4

Gordon, J. E. (2019). Geoconservation principles and protected area management. *International Journal of Geoheritage and Parks*, 7(4), 199-210. https://doi.org/10.1016/j.ijgeop.2019.12.005

Henriques, M. H., Reis, R. P., Brilha, J., Mota, T. (2011). Geoconservation as an emerging geoscience. *Geoheritage*, 3, 117-128. https://doi.org/10.1007/s12371-011-0039-8

Higa, K. K. (2019). *Geoconservação no estado de São Paulo:* panorama geral e diagnóstico de uso e proteção dos geossítios do inventário do patrimônio geológico. Dissertação (Mestrado). São Paulo: Instituto de Geociências - USP. https://doi.org/10.11606/D.44.2019.tde-04072022-094013

Hirai, J. N., Augusto Filho, O. (2008). Avaliação ambiental por meio de geoindicadores: aplicação de erosão de solos e sedimentos. *Revista Minerva*, 5(1), 35-44.

IBGE – Instituto Brasileiro de Geografia e Estatística (2022). *Portal*. Available at: https://www.ibge.gov.br/cidades-e-estados/sp.html. Accessed on: Oct 20, 2022.

Lima, E. A. (2019). *Definição de metodologia de gestão do património geológico:* aplicação ao arquipélago dos Açores. Tese (Doutorado). Portugal: Faculdade de Ciências e Tecnologia, Universidade dos Açores.

Moura, P., Garcia, M. G. M., Brilha, J. (2018). Identificação de Sítios Geológicos para Gestão Prioritária: Propostas para a Geoconservação no Domínio Ceará Central, Nordeste do Brasil. *Anuário do Instituto de Geociências*, 41(2), 252-267. https://doi.org/10.11137/2018_2_252_267

Moura, P., Garcia, M. G. M., Brilha, J. (2021). Guidelines for Management of Geoheritage: na Approach in the Sertão Central, Brazilian Northeastern Semiarid. *Geoheritage*, 13, 42. https://doi.org/10.1007/s12371-021-00566-8

Mucivuna, V. C. (2016). *Estratégias de geoconservação aplicadas à geodiversidade do município de Bertioga-SP e às fortificações do litoral Paulista*. Dissertação (Mestrado). São Paulo: Instituto de Geociências - USP. https://doi.org/10.11606/D.44.2018.tde-28062018-084601

Mucivuna, V. C., Garcia, M. G. M., Reynard E., Rosa, P. (2022). Integrating geoheritage into the management of protected areas: A case study of the Itatiaia National Park, Brazil. *International Journal of Geoheritage and Parks*, 10(2), 252-272. https://doi.org/10.1016/j.ijgeop.2022.04.004

Prosser, C. D. (2013). Our rich and varied geoconservation portfolio: the foundation for the future. *Proceedings of the Geologists' Association*, 124(4), 568-580. https://doi.org/10.1016/j.pgeola.2012.06.001

Prosser, C. D., Díaz-Martínez, E., Larwood, J. G. (2018). The conservation of geosites: principles and practice. *In*: Reynard, E., Brilha, J. (Eds.), *Geoheritage:* assessment, protection, and management, v. 1, p. 193-212. Elsevier. https://doi.org/10.1016/B978-0-12-809531-7.00011-3

Queiróz, D. S. (2018). *Patrimônio geológico e construído em áreas fortemente urbanizadas: um estudo na Baixada Santista (SP)*. Dissertação (Mestrado). São Paulo: Instituto de Geociências, Universidade de São Paulo - USP. https://doi.org/10.11606/D.44.2019.tde-30052019-101833

Reverte, F. C., Garcia, M. G. M., Brilha, J., Moura, T. T. (2019). Inventário de geossítios como instrumento de gestão e preservação da memória geológica: exemplo de geossítios vulneráveis da Bacia de Taubaté (São Paulo, Brasil). *Pesquisas em Geociências*, 46(1), e0779. https://doi.org/10.22456/1807-9806.93252

Ribeiro, L. M. A. L., Garcia, M. G. M., Higa, K. K. (2021). The geological heritage of the state of São Paulo: potential geosites as a contribution to the Brazilian national inventory. *Journal of the Geological Survey of Brazil*, 4(1), 45-54. https://doi.org/10.29396/jgsb.2021.v4.SI1.5

Romão, R. M. M. (2018). *Métodos de inventário e avaliação quantitativa de locais de interesse geológico no Brasil:* visão geral e aplicação ao municíio de Cananéia, Litoral sul de São Paulo. Dissertação (Mestrado). São Paulo: Instituto de Geociências - USP. https://doi.org/10.11606/D.44.2018.tde-17072018-142750

Santos, P. L. A. (2014). *Patrimônio Geológico em áreas de proteção ambiental:* Ubatuba-SP. Dissertação de (Mestrado). São Paulo: Instituto de Geociências - USP. https://doi.org/10.11606/D.44.2014.tde-05022015-145425

Santos, P. L. A. (2019). *Patrimônio Geológico na área do Parque Estadual Turístico do Alto Ribeira (PETAR), Vale do Ribeira, SP Brasil:* a capacidade de carga na definição de estratégias de gestão para o uso público de sítios geológicos. Tese (Doutorado) Portugal: Escola de Ciências - UMINHO. Available at: https://hdl.handle.net/1822/77857. Accessed on: Jan 30, 2023.

SBG-CPRM - Serviço Geológico do Brasil (2022). *Sistema de Cadastro e Quantificação de Geossítios e Sítios da Geodiversidade (GEOSSIT)*. Available at: https://www.cprm.gov.br/geossit/. Accessed on: Oct 20, 2022.

Somekawa, S. (2019). *Inventário e avaliação de locais de interesse geológico em Iguape e Ilha Comprida (SP):* bases para o uso turístico e educativo em áreas protegidas costeiras Paulo. Dissertação (Mestrado). São Paulo: Instituto de Geociências - USP. https://doi.org/10.11606/D.44.2019.tde-15102019-091356

Urquí, L. C., Herrero, A. D., Vegas, J. (2017). Monitorización en cascadas y saltos de agua para la valoración de su "espectacularidad o belleza" y sus implicaciones para su uso público: El caso de la chorrera de los navalucillos. *In*: Carcavilla, L., Duque-Macías, J., Giménez, J., Hilario, A., Monge-Ganuzas, M., Vegas, J., Rodríguez, A. (Eds.). *Patrimonio geológico, gestionando la parte abiótica del atrimônio natural*, p. 149-154. Madrid: Instituto Geológico y Minero de España.

Vegas, J., Mata, M. P., Sanchez España, J., Morellón, M., Salazar, Á., Rodríguez, J. A., Carcavilla, L. (2015). Evolución del estado de conservación de lugares de interés geológico sometidos a modificaciones antrópicas. *Cuadernos del Museo Geominero*, (18), 221-226.

Wignall, R. M. L., Dempster, M., Roberts, R., Townley, H. C. (2023). Geosite condition monitoring in the UK 1999–2019. *Proceedings of the Geologists' Association*, 134(1), 25-40. https://doi.org/10.1016/j.pgeola.2022.08.002

Worton, G. J. (2008). A historical perspective on local communities and geological conservation. *Geological Society, London, Special Publications*, 300(1), 137-146. https://doi.org/10.1144/SP300.11

Xavier, F. C. B. (2022). *Inventário do Patrimônio Geológico do Paraná*. Tese (Doutorado). Paraná: Setor de Ciências da Terra - UFPR. Available at: https://hdl.handle.net/1884/77531. Accessed on: Mar 10, 2023.