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Geological diversity fostering actions in geoconservation: An overview of Brazil

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ABSTRACT

The geodiversity of Brazil is associated with the geological evolution of the South American Platform, the part of the South American Plate that behaved as a stable portion during the formation of the Andean and Caribbean mobile belts, in the Mesozoic and Cenozoic. It reflects a geological history that can be identified in the rocks, sediments, landforms, soils and active processes. As the abiotic component of natural diversity, the knowledge of this geological diversity is important to implement territorial plans and public policies, and this can only be done with adequate communication to society. This paper aims to present the geological bases that generated the geodiversity of Brazil and trace an overview of how geodiversity is being approached in the country in the light of geoconservation and its relationship with biodiversity. On the bases of a survey including bibliographic and media sources, our results are based on four aspects: i) studies on geodiversity - 5 states and 8 local areas with geodiversity indexes maps, and the Geodiversity projet of the Geological Survey of Brazil (CPRM); ii) inventories and other surveys - ongoing or finished geoheritage inventories in 5 states, 4 geological units and 5 national parks, 182 sites in the Brazilian Commission of Geological and Paleobiological Sites (SIGEP)'s list, 461 sites in the geoheritage indicative list of CPRM and 10 sites in the World Heritage list; iii) geoparks - 3 UNESCO Global Geopark (UGGp) and about 35 geoparks' applicants and projects to the International Geosciences and Geoparks Program, being 2 aspiring and 31 projects in distinct levels of development; iv) geotourism and outreach - initiatives on interpretative panels, dissemination books, virtual products, events and places. The Brazilian flora and fauna are strongly conditioned by the distinct habitats, which in turn compound ecosystems that integrate geodiversity and biodiversity in many protected areas. All this constitutes a variety of both extractable and non-extractable geological resources that may be used in a sustainable way.

1. Introduction

The concept of geodiversity started to be developed in the 1990s (Gray, 2013; Sharples, 2002), as we know it today, and emerged as a contrast to biodiversity, which refers to the biological elements of the natural environment. The term geodiversity (or geological diversity) alludes to the number and variety of geological elements available in a given area, which are the result of its geological evolution (Carcavilla, Durán, & López-Martínez, 2008; Serrano Cañadas & Ruiz Flaño, 2007). Gray (2013), in a

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broader definition, includes the diversity of abiotic nature. In any case, the relationship of geodiversity with biodiversity is strongly represented in the ecosystem's interactions, since these are composed both by biotic and abiotic components.

The elements of geodiversity have been the origin of natural resources for many civilisations from Prehistory to the present day. The adequate knowledge of geodiversity of a certain region may contribute to territorial planning, including mineral and energy resources, infrastructure and constructions, as well as enhance the establishment of public policies related to nature conservation, science, education, tourism, etc. This strengthens the potential of geodiversity for economic, social and cultural uses. The fraction of geodiversity with specific values for human society is called geological heritage. Some approaches consider as geological heritage only those sites with relevant geoscientific values; others also consider tourist, educational, and cultural values, among others (Brilha, 2016; García-Cortés & Carcavilla Urquí, 2009). Both geodiversity and geoheritage are the foci of a set of actions known as geoconservation, the branch of geosciences that have the aim of identifying, evaluating, protecting and disseminating their relevant elements (Henriques, dos Reis, Brilha, & Mota, 2011; Sharples, 2002).

One of the great challenges of nature conservation and, in particular, of geological heritage, is to find ways of disseminating geological knowledge to non-specialized audiences. In this sense, geotourism, a tourism segment that has geological elements as main attractions (Dowling & Newsome, 2018; Hose, 1995), can be useful. One of its great strengths is to promote the integration between geodiversity, biodiversity, history and local culture, which increases the tourist potential of the region. The use of geotourism and education in the promotion of geological heritage gains clear contours and materialises in a concept of territory called geopark. Geoparks are "unified and unique geographic areas in which sites and landscapes of international geological importance are managed according to a holistic concept of protection, education and sustainable development" (UNESCO, 2022), in which conservation and sustainable development are combined to raise awareness of environmental issues and bring benefits to the population.

Although of this relevance, geodiversity has not received the same attention of biodiversity, either in public or private decisions or in nature management. This is due, in part, to the notion that abiotic elements are durable and last forever (Gray, 2013), which is not true, but also to a great lack of communication with society regarding the importance of geodiversity in our cotidian. This includes not only the general public, but also local to regional managers and decision-makers. One way that may contribute to spreading out the concept is to explore the relationship between geodiversity and geoheritage in the context of a geoconservation framework, which embraces steps such as diagnosis, conservation and promotion (Garcia, Nascimento, Mansur, & Pereira, 2022). Another main subject that gains a particular interest is the connection with biodiversity, considering ecosystem services and the role of these elements in protected areas.

In this context, Brazil is a country of continental dimensions, which geodiversity is marked by geological units that range from Archaean to the recent, developed as a result of local- to global, both internal and external related geological episodes and that may be grouped as seven geosystems (Silva, 2008). These compartments are related not only to physical elements, but also to aspects such as land use, natural resources and economic potential. Together with climate variations, these elements are responsible for the development of several biomas, such as the Amazon and the Atlantic forests, the Cerrado, similar to the Savannahs and the Caatinga, a semi-arid, dry vegetation, as well as the Marine biome. All these elements comprise rich, highly threatened ecosystems whose protection is essential for the maintenance of goods and services, specifically with regard to geodiversity.

On the bases of these assumptions, this paper has as its main objective to present the geological bases that generated the geodiversity of Brazil, register the main actions and initiatives under the scope of geoconservation and discuss its association with biodiversity. With this summary, we intend to trace an overview of how Brazilian geological diversity has been approached and how it can be used in public policies.

2. Brazilian geological and tectonic context and relationship with geodiversity

The South-American continent is composed of three main tectonic units: the South-American Platform, the Andean unstable areas (Caribbean, Northern, Central and Southern Andes) and the Patagonian block (Almeida, Brito Neves, & Dal Ré Carneiro, 2000; Schobbenhaus & Brito Neves, 2003).

The Andean, to the west, and the Caribbean, to the north, constitute active mobile belts that started to develop in the Mesozoic and Cenozoic. The Patagonian block, to the south, is a lithospheric microplate that was docked during the Variscan (Hercynian) orogeny, in the Triassic. The block that behaved as a stable portion during the development of these main features is known as the South American Platform. It is in this unit that the whole Brazilian territory is included, occupying >75% of its area, and it is with its geological evolution that the geodiversity of Brazil is mainly associated.

The current configuration of the South American Platform is a result of a geological history that starts from its basement, with rocks ranging from the Paleoarchean (around 3.5 Ga) to the Eo-Ordovician (0.50 to 0.48 Ga). These are the result of geological processes that can be linked to successive, world-scale events of orogenesis (terrane accretion, collision and amalgamation of supercontinents, *syn*- to late magmatism, metamorphism) and taphrogenesis (dispersion, continental drifting, rifting, volcanism) acting along the geological time. Records of these events are found in rocks and structures in the Brazilian territory and represent ancient supercontinents such as Atlantida (Paleoproterozoic), Columbia (beginning of the Mesoproterozoic) and Rodinia (end of the Mesoproterozoic).

At the end of the Neoproterozoic and beginning of the Ordovician, the amalgamation of the supercontinent Gondwana marked an important contrast in the geological evolution of the South-American Platform. The records of this orogenic cycle, the Brasiliano-Pan African, are observed only in the central-eastern part of Brazil, the so-called Brasiliano Domain (Brito Neves & Fuck, 2013, 2014). To the north-northwest, the Amazonian Domain holds strong affinities with Laurentia, a supercontinent that

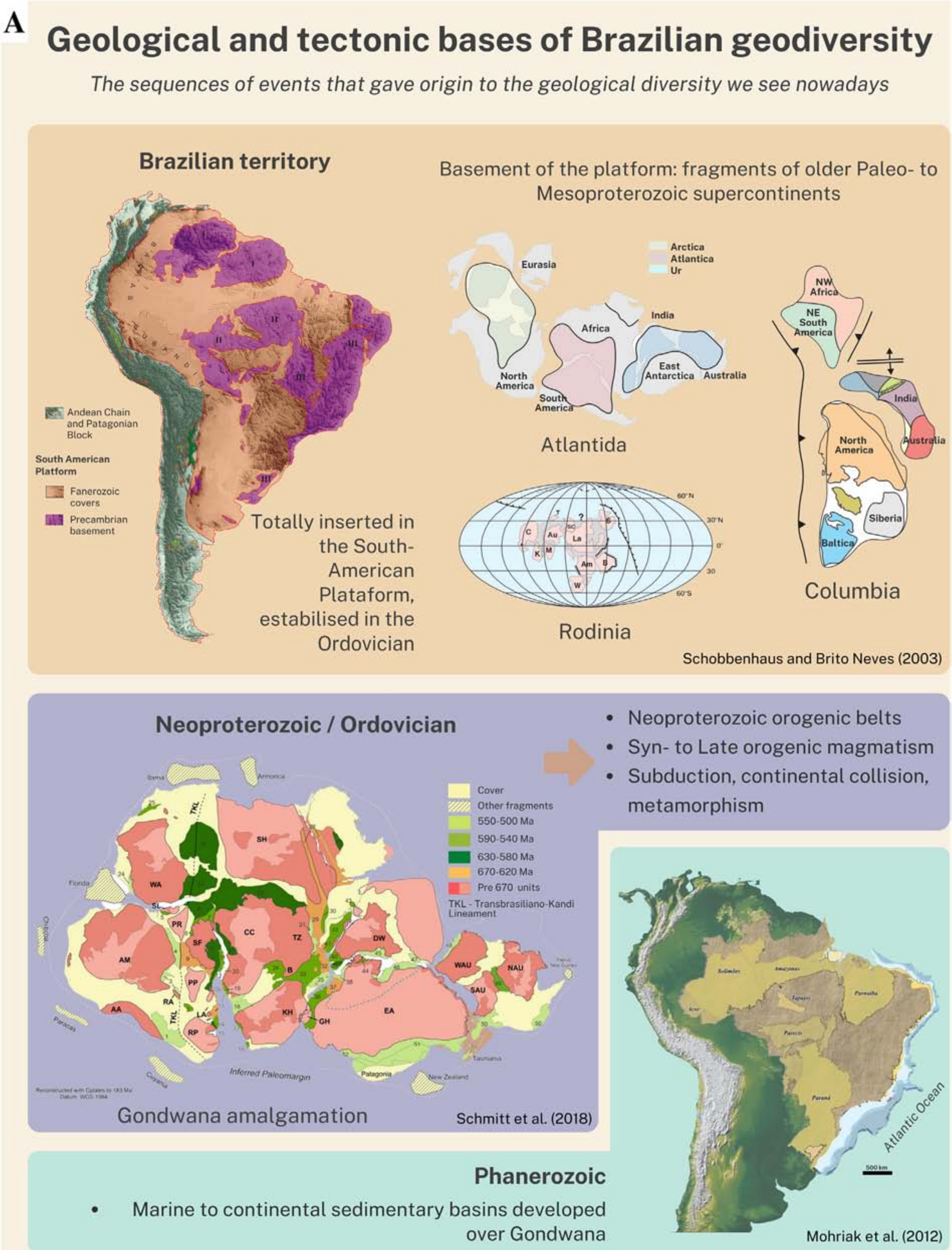

Fig. 1. Illustrated abridged sketch of Brazilian geological and tectonic history. (A) From Paleoproterozoic to Gondwana. (B) From Gondwana heritage to the recent. Based on data from Brito Neves and Fuck (2013), Mohriak (2003), Mohriak, Szatmari, and Anjos (2012), Rockett, Ketzer, Ramírez, and van Den Broek (2013), Schmitt, Fragoso, and Collins (2018), Schobbenhaus and Brito Neves (2003), Svensen et al. (2017).

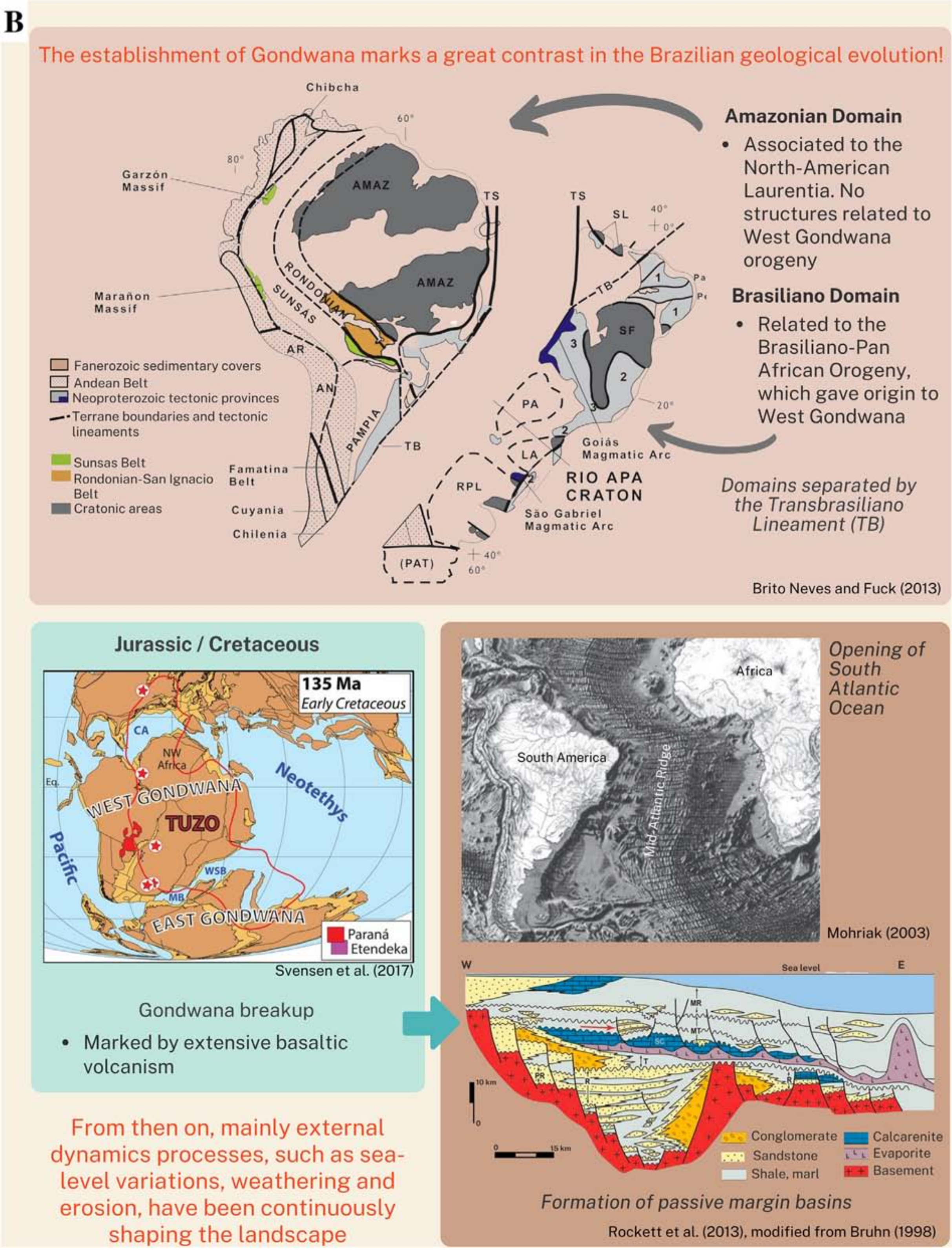

Fig. 1 (*continued*).

existed in the Mesoproterozoic and may be represented by the current North America. Separating these two domains lies the more than 4500 km long Transbrasiliano Lineament, which extends to Africa.

Once Gondwana was agglutinated, a series of large, intracratonic sedimentary basins were developed. These basins are named Acre, Amazonas, Solimões, Parnaíba, and Paraná. They hold expressive sedimentary sequences with important contributions of marine and continental rock assemblages, which recorded climatic changes, from cold and glacial conditions to hot and desert environments (Late Permian and Triassic).

In the Middle Triassic, the global agglutination of continental masses gave origin to the supercontinent Pangea. Its later breakup, in the Jurassic/Cretaceous, was marked by extensive basaltic magmatism and allowed the opening of the South Atlantic Ocean and the development of the passive or Atlantic continental margin both to the north and to the south-southeast. From then

Fig. 2. Selected representative elements of Brazilian geodiversity. (A) Mairi Gneiss Complex, formed by mafic and felsic banded gneisses (3.6 Ga), one of the oldest rocks in South America. Photograph: Elson P. Oliveira. (B) Itabirite, an iron-rich quartzite representative of one of the largest iron deposits in the world. Serra da Piedade, Caeté municipality. Photograph: Paulo T. A. Castro. (C) The rounded, typical relief of the Pão de Açúcar (Sugar Loaf) in Rio de Janeiro, a Brazilian postcard composed of Facoidal (Augen) Gneiss, an important ornamental rock. Photograph: Antônio Queiróz. (D) The Iguazu Falls, in the homonymous national park, one of the most outstanding example of the volcanic rocks of the Paraná-Etendeka Province. (E) Ilhas Dois Irmãos (Two Brothers Islands), in Fernando de Noronha, a residual relief formed on Pliocenic ankaratrite volcanic rocks. (F) Active sand dunes and freshwater lagoons from the Lençóis Maranhenses National Park, example of Quaternary evolution. Photographies D, E and F: from the authors.

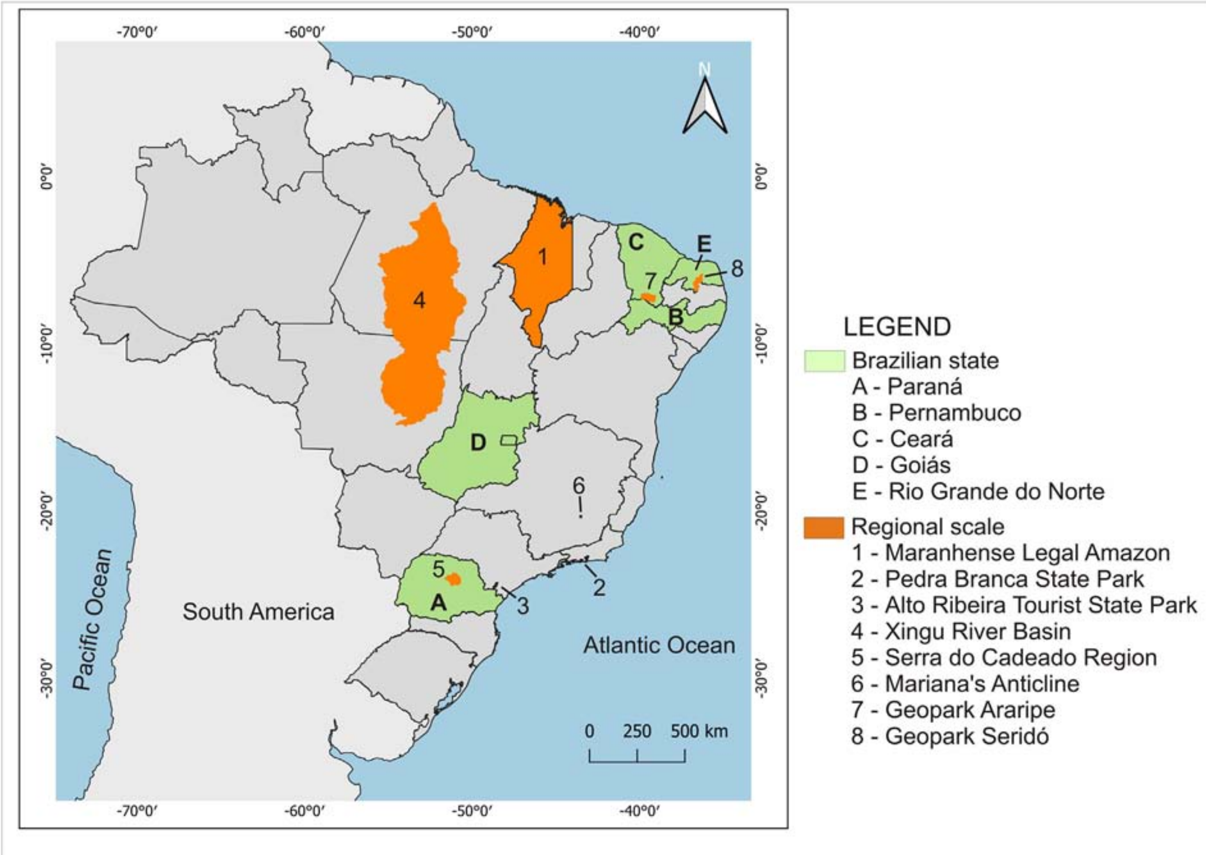

Fig. 3. Location of geodiversity index maps, separated by states and areas on a regional scale. *Source:* Adapted from Dias et al. (2021).

on, mainly external dynamics processes are continuously shaping the landscape. An illustrated summary of this evolution is shown in Fig. 1A and B.

All this geological history gave origin to the rich geodiversity of Brazil. It comprises rock types, structural features, mineral deposits, landforms, soils and fossils, and other elements representing the events and processes that culminated with the current distribution of the Brazilian geological diversity. Among these elements are geological units such as the Mairi Gneiss Complex, which contains rocks dated at 3.65 Ga, one of the oldest of the Brazilian territory and South America (Oliveira, McNaughton, Zincone, & Talavera, 2020) (Fig. 2A). They also include lithotypes such as the banded iron formations (BIFs) of the Iron Quadrangle (Quadrilátero Ferrífero, in Portuguese), one of the largest iron ore deposit in the world and deposited in shallow marine passive margin settings at circa 2.4 Ga (Babinski, Chemale, & Van Schmus, 1995; Spier, Oliveira, Sial, & Rios, 2007) (Fig. 2B), and the *syn*-collisional orthogneiss of the Pão de Açúcar (Sugar Loaf) in Rio de Janeiro, dated at 560 Ma and that is a milestone in the amalgamation of the Gondwana Supercontinent, in the Neoproterozoic (Silva & Andrade Ramos, 2002) (Fig. 2C). The continental flood basalts of the Paraná-Etendeka Igneous Province, which mark the beginning of the South Atlantic Ocean (Gomes & Vasconcelos, 2021) (Fig. 2D) and the Miocenic to Pliocenic alkaline volcanic and subvolcanic rocks of the Fernando de Noronha Archipelago, formed along an *E*-W-oriented oceanic fracture zone (Almeida, 2002) (Fig. 2E). Modern sedimentary environments are also represented elsewhere in the country, such as in the Lençóis Maranhenses, a national park, which represents the largest dune field of South America (Santos, Borges, Silva Junior, Piedade Junior, & Bezerra, 2019) (Fig. 2F).

3. Materials and methods

Most of the scientific knowledge on Brazilian geodiversity is written in Portuguese and published in national journals, making it difficult for the scientific community to access these data. The gathering of these data in a single paper and written in English is essential for the greater dissemination of what is being done in the Brazilian territory. For these reasons, this work also intends to be a review paper. Considering the above mentioned facts, the following steps were carried out in order to reach the objectives:

i. Review of the literature. This step was carried out in order to do an overview of the main publications regarding Brazilian tectonic and geological history and to build a schematic synthesis;

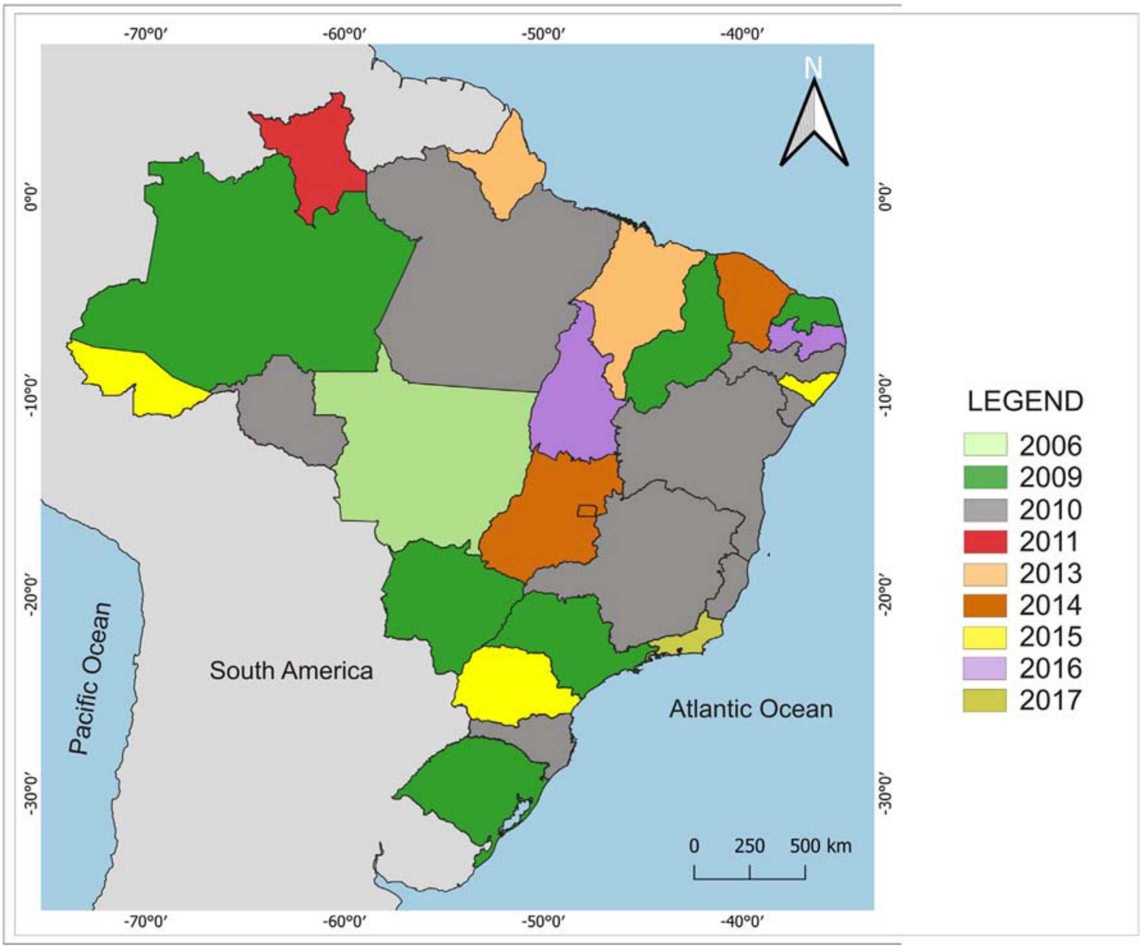

Fig. 4. Location of geodiversity maps developed by the Geological Survey of Brazil (CPRM), by year.

ii. Search on the scientific publications. In this step, themes associated to geodiversity and geoconservation were reviewed in papers, master's and PhD theses, and reports in order to gather as much as information to be the database of the following step.
iii. Systematisation of data. This step consisted of clustering the data considering the following topics: geodiversity assessment, inventories of geological sites, status of geoparks, geotourism and outreach initiatives.
iv. Discussion. This step was carried out in order to highlight the strong relationship of the research on geodiversity and biodiversity, showing the importance of the abiotic part of nature for the maintenance of the ecosystems.

4. Initiatives in geoconservation associated with Brazilian geodiversity

In this section we list the main actions and activities that have geodiversity and/or its fraction showing relevant values, the geological heritage, as main bases. These events are classified according to their relationship with geodiversity and geoheritage, whether in data collection, the several ways of assessing them, management schemes and efforts to link them to society.

4.1. Studies on geodiversity

The geological characteristics of Brazil result in a distinctive geodiversity, which understanding demands a detailed assessment of the territory. In order to perform this assessment, both qualitative and quantitative approaches may be used.

In this context, the geodiversity index map, a quantitative approach, has become popular among Brazilian researchers (Crisp, Ellison, & Fischer, 2020). These kinds of maps evaluate geodiversity from the sum of maps of the physical environment using geographic information software. As Brazil has official bodies that provide maps of the physical environment for the entire country, the development of index maps is facilitated. This methodology can be applied at different scales of work, which helps research in a country with continental dimensions, as is the case of Brazil.

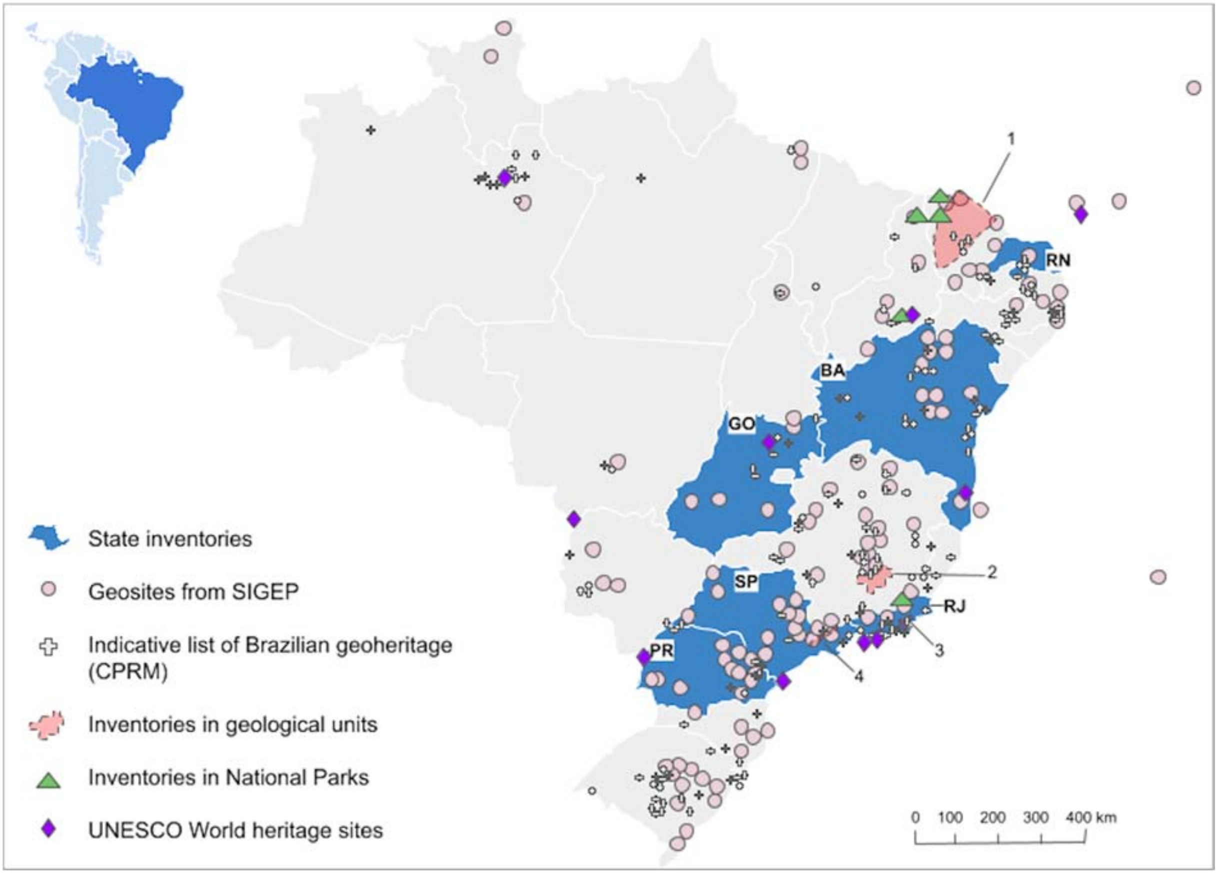

Fig. 5. Schematic map showing the distribution of the inventories of geological sites and other surveys in Brazil.
Sources of the data: State inventories (Nascimento et al., 2022); SIGEP's geosites (http://sigep.cprm.gov.br/mapindex/mapindex.htm); Brazilian indicative list of geosites (http://www.cprm.gov.br); inventories in geological units and in national parks (see references in the text); UNESCO World heritage sites (https://whc.unesco.org/).
Note: In State inventories, RN represents Rio Grande do Norte; BA represents Bahia; GO represents Goiás; RJ represents Rio de Janeiro; SP represents São Paulo; PR represents Paraná. Geological units: 1 - Ceará Central Tectonic Domain; 2 - Iron Quadrangle (in Portuguese, Quadrilátero Ferrífero); 3 - Cabo Frio Tectonic Domain; 4 - Taubaté Sedimentary Basin.

Pereira, Pereira, Brilha, and Santos (2013) developed a method for the state of Paraná that meets the specificities of the Brazilian territory and has been used as a basis for the elaboration of index maps of different locations. Surveys with geodiversity index maps are distributed throughout the country, from the entire territory (Silva et al., 2021) to more detailed scales, such as states, hydrographic basins, protected areas, geoparks, and municipalities.

Of the 26 Brazilian states, 5 have index maps: Paraná (Pereira et al., 2013), Pernambuco (Ferreira, 2014), Ceará (Araújo & Pereira, 2018; Bétard & Peulvast, 2019), Goiás and the Distrito Federal (Pinto Filho, 2019) and Rio Grande do Norte (Dias et al., 2021).

The regional scale is used in areas where the boundaries are larger than the municipalities, but do not yet include the entire state. Thus, there are index maps in protected areas - Maranhense Legal Amazon, Silva and Barreto (2014), Pedra Branca State Park, Santos (2014) and Alto Ribeira Tourist State Park, Silva and Nakashima (2018); in watersheds - Xingu River Basin, Silva, Rodrigues, and Pereira (2015); in relief units - Serra do Cadeado Region, Manosso and Nóbrega (2016) and Mariana's Anticline, Nascimento and de Tarso Amorim Castro (2019); and geoparks - UGGp Araripe, Carvalho Neta, Corrêa, and Bétard (2019) and UGGp Seridó, Silva, do Nascimento, and Mansur (2019) (Fig. 3).

In addition to geodiversity index maps, the Geological Survey of Brazil (CPRM) developed geodiversity maps. They were prepared between 2006 and 2017 and represent the geodiversity of Brazilian states (Fig. 4). Each map presents the physical environment in geological-environmental units (geology, geomorphology, soils, hydrography, and mineral resources) and describes the main activities that can be developed. The purpose of geodiversity maps is to present the environment to different professionals, from students, and mining companies to public managers who work with territorial planning. With an accessible language the map highlights geodiversity, facilitating its use in public policies.

Fig. 6. (A) Map with the distribution of the Geoparks projects (red), aUGGp (blue) and UGGp (green) in Brazil (Modified from Nascimento, da Silva, et al. (2021)). Geosites from the UNESCO Global Geoparks in Brazil. (B) Geosite "Pontal da Santa Cruz", in the Araripe Geopark (Photograph by the authors). (C) Geosite "Brejuí Mine", in the Seridó Geopark (Photograph by Getson Luís). (D) Geosite "Canyon Fortaleza", in the Caminhos dos Cânions do Sul Geopark (Photograph retrieved from https://canionsdosul.org/). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4.2. Inventories and other surveys

Some places are particularly important in the representation of the geodiversity of a territory. In these places, the geodiversity elements have values considered exceptional, being selected by means of inventories on the basis of specific criteria. They constitute the geological heritage of a region, which can be used for any specific purpose, e.g. the protection of relevant scientific places, the development of a geopark project or the establishment of geotourism routes, among other uses. They are excellent places to disseminate geodiversity.

According to Romão and Garcia (2017), initiatives on inventories have increased significantly in Brazil in recent years. By means of a data analysis based on both inventory and quantification methods, as well as the geographic distribution of geosite inventories in the whole territory, the authors identified the most common references used in these studies, such as Brilha (2005, 2016), Rocha, Lima, and Schobbenhaus (2016) and Pereira (2010), among others. The most common criteria used to guide the inventories are the scientific, touristic and educational.

On national-scale, the most iconic initiative on inventories in Brazil is the Brazilian Commission on Geological and Paleobiological Sites (SIGEP). Created in 1997, it gave origin to a series of three volumes in which 116 geosites, plus 66 approved but not published, both originated in ad hoc-based surveys, are described, constituting a National Inventory (SIGEP, 2001). In 2018, with the approval of the project to produce the Geological Heritage Map of South America on a scale of 1: 5,000,000 by the Commission for the Geological Map of the World (CGMW), the inventory of Brazilian geoheritage was included in the Geological Survey of Brazil (CPRM)'s agenda. The activities related to this national inventory are being carried out by the CPRM's regional offices. These data are being systematised with the use of the GEOSSIT, an online platform developed by CPRM and fed by researchers (Rocha et al., 2016) with the approval of a scientific commission. The platform uses Brilha (2016) and García-Cortés and Carcavilla Urquí (2009) as evaluation bases for scientific and degradation risk and potential educational and tourism uses. Up to December 2021, 461 geosites arranged according to 21 themes and classified in high, moderate and low scientific value are inscribed in GEOSSIT, constituting the indicative list of the Brazilian geological heritage (CPRM - Geological Survey of Brazil, 2020).

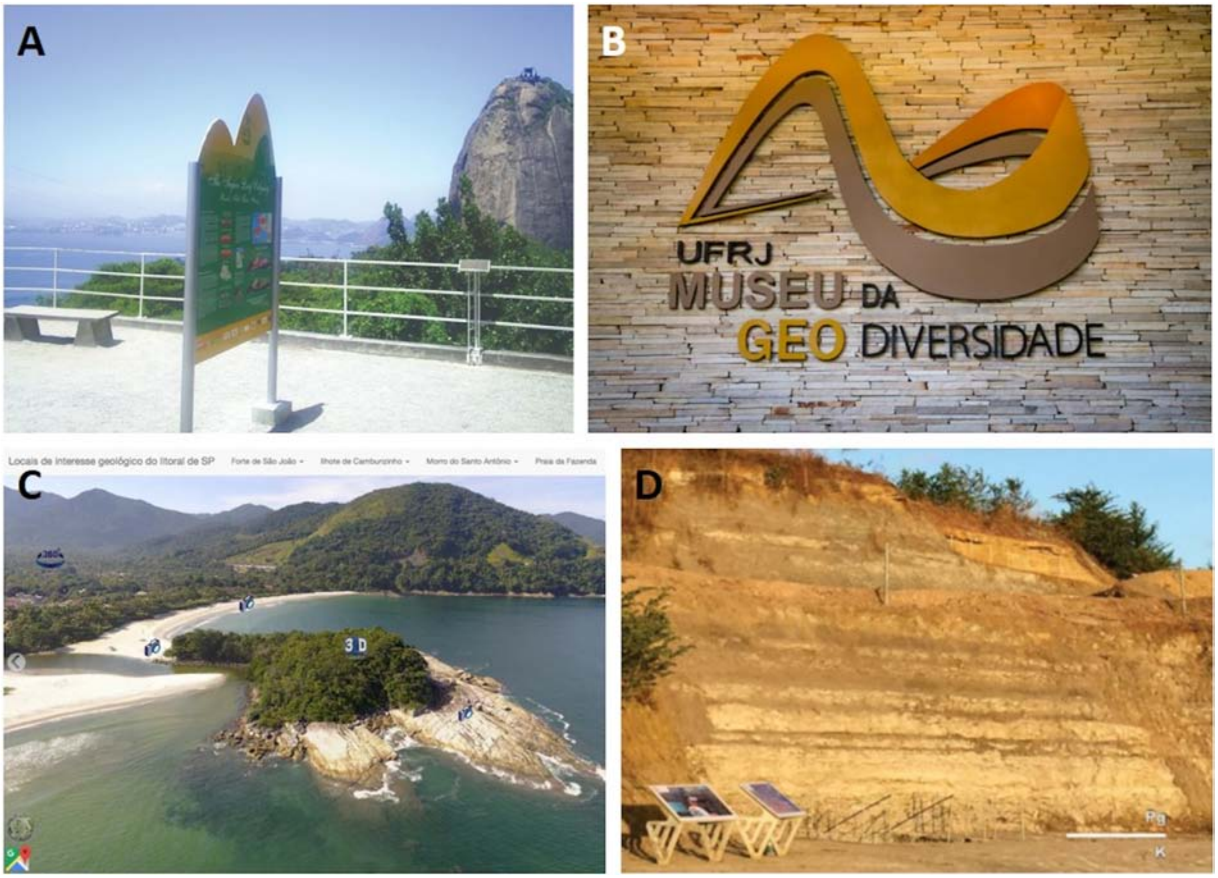

Fig. 7. Selected examples of geotourism and outreach initiatives associated with geodiversity in Brazil. (A) Interpretative panel of the Caminhos Geológicos (Geological Paths) Project of the State of Rio de Janeiro installed in the Sugar Loaf. Photograph by Kátia L. Mansur. (B) Museum of Geodiversity of the Federal University of Rio de Janeiro. Photograph retrieved from https://conexao.ufrj.br/2022/05/role-ufrj-2-museu-da-geodiversidade/. (C) 360° panoramic virtual tour in the north coast of São Paulo. Photograph retrieved from https://geohereditas.igc.usp.br/. (D) View of the geosite K-Pg Poty Mine, open to educational visits. Photograph by Barreto and Polck (2021).

Depending on the main aim of the inventory, it can be performed according to several kinds of limits. Administrative limits, for example, can be useful to handle a database designed to subside public policies. It is the case of the State inventories, such as São Paulo (Garcia et al., 2018), the first on a systematic basis in Latin America, and a summary of these inventories in Brazil can be found in Nascimento, da Taveira, da Silva, and de Medeiros (2022). On the other hand, tectonic or litho-stratigraphic domains can also be used to identify the best geosites under specific geological contexts, a potential strategy that can be used as a basis for the national inventory. Examples of the use of these kinds of limits can be found in Azevedo (2007), Mansur (2010), Reverte, Garcia, Brilha, and Moura (2019) and Moura, Garcia, Brilha, and Amaral (2017). Studies on the relationship between geo- and biodiversity can be highly enhanced with the application of inventories in protected areas. In the Brazilian territory, initiatives in national parks are found in the Sete Cidades National Park (Lopes, Araújo, & Nascimento, 2013), Itatiaia National Park (Mucivuna, de Garcia, Reynard, & Rosa, 2022), Jericoacoara National Park and Ubajara National Park (Meira & de Morais, 2018; Meira & de Silva, 2021), Serra da Capivara National Park (Prochoroff & Brilha, 2017).

Besides national surveys, ten of the Brazilian sites inscribed in the UNESCO World Heritage List are related to geodiversity, being seven natural (Iguazu National Park, Atlantic Forest South-East Reserves, Discovery Coast Atlantic Forest Reserves, Central Amazon Conservation Complex, Pantanal Conservation Area, Brazilian Atlantic Islands: Fernando de Noronha and Atol das Rocas Reserves and Cerrado Protected Areas: Chapada dos Veadeiros and Emas National Parks), two cultural (Rio de Janeiro: Carioca Landscapes between the Mountain and the Sea and Serra da Capivara National Park) and one mixed (Paraty and Ilha Grande – Culture and Biodiversity). Fig. 5 shows a synthesis of the inventories and other surveys related to geodiversity in the Brazilian territory.

4.3. Geoparks

According to Nascimento, da Silva, de Almeida, and dos Costa (2021), there are 35 territories in which projects in geoparks are being developed in Brazil. The authors classify these proposals regarding the specific stage of development, such as projects, when pioneering research and development of the proposal is being built; aspirants, with an official candidacy to the UNESCO

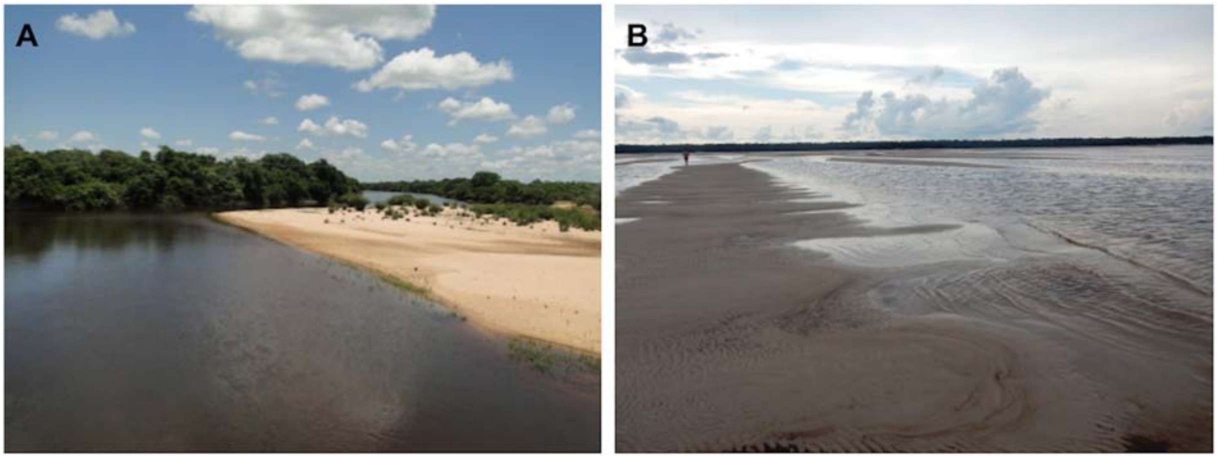

Fig. 8. Representative examples of areas where bio- and geodiversity show a strong relationship. (A) Pantanal, in the Central-Western, a fault-controlled modern sedimentary basin with permanently flooded areas. One of the most important tropical wetlands in the world. The picture shows the Nhecolândia region, characterised by more than 10,000 shallow lakes bordered by sand bars. Photograph: Deborah Mendes. (B) Anavilhanas National Park, a series of fluvial islands along Negro River, inserted in the intracratonic Amazonas Basin. The area has great ecological relevance for studies regarding the sedimentar dynamics and the response of biodiversity to geomorphological changes in the islands.

International Geosciences and Geoparks Program (aUGGp); and UNESCO Global Geopark (UGGp), for those endorsed by the organisation (Fig. 6A). Among these territories, 2 are included in the North region, 16 in the Northeast (two of them UGGp), 5 in the Central-West, 6 in the Southeast and 6 in the South (two of them is aUGGp and one is UGGp).

The first territory to be accepted in the Global Geoparks Network was the Araripe Geopark, in 2006 (Fig. 6B). In this same year the Geological Survey of Brazil (CPRM) started the Geopark Project in order to identify and describe potential areas for the creation of geoparks in the country. Over these years, several geoconservation initiatives have been implemented in these territories, regardless of their status, such as geological heritage research (e.g. Nascimento, da Costa, de Borba, & Sell, 2021; Ziemann & Figueiró, 2017), educational activities (e.g. Universidade Federal do Rio de Janeiro, 2020; http://geoparkararipe.urca.br/?page_id=1560), and geotourism and outreach (e.g. Bezerra, Silva Filho, Oliveira, & Nascimento, 2014; https://canionsdosul.org/georroteiros/, further details of such activities are set out in the following section). Such efforts contributed to the inclusion of two territories in the UNESCO's world Geopark network in 2022: the Seridó Geopark (Fig. 6C) and the Caminhos dos Cânions do Sul Geopark (Fig. 6D). Despite the great number of projects started along the years, many of them still need to improve their geoconservation strategies before applying for a UNESCO candidacy.

Therefore, in order to lead debates and reflections on the topic of Geoparks, share knowledge on the subject and give institutional support for Geoparks' projects, in 2018 the Commission on Geoparks was created within the Brazilian Geological Society. In cooperation with UNESCO, the Brazilian Ministry of Tourism also engaged on the subject and published a set of four publications that consist of guidelines for the development of tourism projects in Geoparks (Ministério do Turismo, 2022).

4.4. Geotourism and outreach

The dissemination of geodiversity and geoheritage is an essential step to illustrate their importance to society. The first effort to disseminate geological information to Brazilian society took place in 1988 at Serra do Rio do Rastro (Santa Catarina), where 17 landmarks were placed along the highway where the White Column is located (a stratigraphic column of the Parana Basin with excellent records of the Gondwana Supercontinent in Brazil). It is one of the first geotouristic signs installed in Brazil (Mansur, 2009; Mansur et al., 2013).

The Geological Survey of Brazil and some state-level geological surveys have invested their efforts in the dissemination of local geodiversity through interpretative panels. The first and pioneering initiative was the Caminhos Geológicos (Geological Paths) Project of the State of Rio de Janeiro (2001) (Fig. 7A), which inspired many other states, such as project Bahia in 2003, project Paraná in 2003, project Rio Grande do Norte in 2006 and project Minas Gerais in 2007 (Mansur, 2022; Mansur et al., 2013), as well as the northern coast of the state of São Paulo (https://geohereditas.igc.usp.br/).

Following this trend, two thematic institutions focused on the dissemination of geodiversity were created. The Museum of Geodiversity of the Federal University of Rio de Janeiro (Fig. 7B) was opened in 2008, aiming to show that geodiversity is the substrate for life (Mansur, 2009, 2022), and the Museum of Natural Sciences of the State University of Ponta Grossa was created in 2020 to promote the scientific collections of regional geodiversity and biodiversity (Liccardo, Bosetti, Guimarães, Santos, & Peyerl, 2021).

Given the difficulty of the general public to understand geological terms, many outreach books with simplified language have been published. Among them, we highlight the books focused on geotourism (e.g. Liccardo, Piekarz, & Salamuni, 2008; Piekarz, 2011), geopark projects and UNESCO geoparks (e.g. Kuhn & Santos, 2021; Mansur et al., 2021; Nascimento, Silva, & Reis, 2020), geoheritage (e.g. Garcia, 2021) and for kids (e.g. Bodenmuller & Anelli, 2019; Liccardo & Liccardo, 2006; Toledo & Imbernon, 2003; Vasconcelos, 2011).

With the improvement of informational technologies in the last decades, many advances have been made to disseminate geoscientific knowledge to the general public through virtual products. Such actions have become even more significant with the restrictions imposed due to the pandemic of COVID-19 in Brazil and worldwide. Virtual geotours, panoramic 360° tours (Fig. 7C) and interactive geotourism maps were used to disseminate information about the geodiversity and geoheritage of the coast of the state of São Paulo (Ibanez, Garcia, & Mazoca, 2021), the Seridó Geopark (e.g. Costa, Nascimento, & Silva, 2022) and the old centre of São Paulo City and Jaraguá State Park (https://geohereditas.igc.usp.br/passeios-virtuais/). Three-dimensional models are key resources to interpret geological structures, monitoring geosites, and disseminate geoscientific concepts in Serra das Russas - Pernambuco (Santos, Henriques, Mariano, et al., 2018; Santos, Henriques, Mariano, & Santos, 2021), the coast of the state of São Paulo (https://geohereditas.igc.usp.br/modelos-3d/) and Seridó UGGp (http://geoparqueserido.com.br/?page_id=9537).

In order to bring society closer to geosciences, many events, such as geological excursions focused on the general public, have been carried out to disseminate the local geodiversity in recent years. These activities took place in projects and aspiring geoparks, such as in the Costões e Lagunas and Caçapava, and municipal parks, such as in The Mutirama Park - Goiás. The increase and spread of local outreach activities resulted in the organisation of the First Geoday in 2021 at a national level sponsored by the Brazilian Association for the Defense of Geological and Mining Heritage (AGeoBR).

Furthermore, other initiatives are worthy of special mention, such as the good practices for promoting the geosites Varvite of Itu and K-Pg Poty Mine (Fig. 7D) and the visitation of the Lagoa Salgada and its Holocene stromatolites by schools and universities students (Garcia et al., 2022).

5. Discussion

According to Garcia et al. (2022), Brazilian initiatives regarding geoconservation are mainly concentrated in the steps of diagnosis (data collection and evaluation) and promotion (dissemination actions). The step of conservation, especially legal protection, is less developed, probably due to the fact that most of the people involved in diagnosis and promotion are geoscientists and academics, whereas conservation demands the participation of national or local managers. However, recent efforts have been made by the Geological Survey of Brazil to integrate these data into the national inventory (Schobbenhaus et al., 2021).

Besides the rich geodiversity, the geological knowledge in the Brazilian territory is very heterogeneous. This fact is reflected, for example, in the distribution of the initiatives in geodiversity and geoheritage, which are mainly concentrated along an easternmost, coastal zone. Along with the continental dimensions, this is one of the difficulties found when dealing with inventories and other surveys (Fig. 5), as pointed out by Lima, Brilha, and Salamuni (2010) and Ribeiro, Garcia, and Higa (2021). As pointed out by Romão and Garcia (2017), in many of the publications there is no information on the methods and criteria used, which makes it hard to check the similarities and dissimilarities regarding other areas. This heterogeneity is also an obstacle to the achievement of an integrated assessment of geosites in relation to their main potentialities. In the Brazilian indicative list of geosites, based on GEOSSIT's database, assessment criteria are grouped into scientific value, degradation risk and potential educational and tourism use, which are used to calculate priorities related to protection. In the inventory of geoheritage of the State of São Paulo, Higa (2019) used these values, together with data on property and geosite typology, to indicate an index for management priority.

When analysing the distribution of geoparks projects, aUGGp and UGGp (Fig. 6A), as well as geotourism and outreach initiatives, the same pattern is observed. A possible explanation is the non-egalitarian distribution of universities, particularly on a Federal level, which are the main sources of research in geodiversity and geoheritage. Another issue is related to the demographic density, which is much higher in these areas.

In this sense, the elaboration of geodiversity index maps and geodiversity maps may open an important path on the knowledge of the variety of geological materials and features that occur in the Brazilian territory. The identification of the distribution and frequency of the geodiversity elements of a place helps so that the geodiversity is known and can be inserted in the territorial planning and in public policies.

A key element that should be considered is the fact that geodiversity provides goods and services that are essential to society, the so-called Ecosystem Services supplied by geodiversity (Brilha, Gray, Pereira, & Pereira, 2018; Gray, 2013). These services can be classified into 5 functions (regulating, provision, support, cultural and knowledge) and, being directly related to the maintenance of modern society's way of life, constitute an promising argument for raising awareness on the need of conserving natural environments. Furthermore, this concept may be important to discuss approaches such as payments for ecosystem services, sustainable use of natural resources and mitigation and adaptation to climate change, since human activities broadly influence the capacity of ecosystems of yelding society with their goods. In terms of geodiversity research, it can reinforce the importance of describing and assessing the distribution of geological elements.

Areas biologically diverse are commonly associated with diverse substrates (Crofts et al., 2020). Likewise, it is possible that highly geodiverse areas may also be related to a larger amount of ecosystem services provided by geodiversity. Nevertheless, despite Brazil's rich geodiversity, there are still few studies on ecosystem services related to this abiotic part of nature, such as Garcia (2019), in the coastal region of São Paulo, and Silva and do Nascimento (2020), in the Seridó UGGp. Reverte, Garcia, Brilha, and Pellejero (2020), in a study in the Taubaté Sedimentary Basin, evaluated and quantified the losses on the offer of ecosystem services provided by geodiversity in highly urbanised areas. The authors pointed out that anthropogenic activity is the main aspect that modifies the availability of these services, including fundamental resources such as water. Although there are several ecosystem services with a focus on biodiversity, increasing knowledge about the goods and services provided by geodiversity is essential for the development of policies for the preservation of ecosystems (Queiroz & Garcia, 2022).

Ecosystem services can also argue for the establishment of protected areas, which represent places where natural systems are minimally preserved and, together with their buffer zones, may work as pilot areas to understand the functioning of these systems and to predict losses. According to Mucivuna, de Garcia, and Reynard (2022), between 1937 and 2018, 74 national parks were created in Brazil, being present in all of the large tectonic domains that comprise the territory. In twenty-five of these national parks, 41 studies regarding geoconservation have been carried out between 2002 and 2020. Thirteen of them are located in the Precambrian basement, being four in cratonic and nine in Neoproterozoic fold belt domains and ten in the Phanerozoic covers. One of them lies in the overlap of domains and one is outside of the mapped area. Many of the inventories of geological sites are partially inserted in national parks. This brings important perspectives on the use of geodiversity in the management of these areas (Mucivuna, de Garcia, Reynard, & Rosa, 2022), having as the main approach the need of broader conservation plans that include all natural diversity. Moreover, this reinforces the importance of systematic inventories considering the scale of work.

The Brazilian flora and fauna are strongly conditioned by the distinct habitats, which in turn compound ecosystems that have been integrating geodiversity and biodiversity along geological time until now. These connections gave origin to key areas for understanding the relationship between the evolution of the physical environment and the growth and development of life on our planet.

In the Pantanal, a modern sedimentary basin whose subsidence is controlled by faulting, the development of large, permanently flooded areas led to the formation of one of the most important tropical wetlands in the world (Assine et al., 2015) (Fig. 8A). These areas host outstanding aquatic ecosystems with rich biodiversity that includes numerous species (Junk et al., 2006). The basement also holds important fragments of early Earth History, including the evolution of the Gondwana Supercontinent and the Ediacaran period (Warren et al., 2014).

In the Amazon region, a series of ancient east-west trending sedimentary basins separated by structural highs are overlying and bounded north and south by Precambrian continental basement rocks (Pedreira da Silva, Lopes, Vasconcelos, & Bahia, 2003). These basins are the result of a history that includes the uplift of the Andean Chain and the formation of the Amazon fluvial system.

The Anavilhanas National Park, located in the Negro River, in an area where the river divides into multiple channels and islands, has its origin associated with environmental changes resulting from rainfall variations in the South American Monsoon System for the last 7 ky (Cunha, 2017). The study of the age and chronology of deposition and stabilisation of the archipelago's sedimentary bars, as well as climate, tectonic and landscape research, can bring light to important issues related to the origin of biodiversity in the Amazon (Fig. 8B).

These examples show that understanding modern dynamic natural systems environments is essential to create public policies aiming at achieving sustainable development, including nature conservation and education. In such landscapes, the scientific studies about the geological history and about how the several active geological systems operate are crucial to subside actions on their sensible use and occupation, as well as the conservation of these areas. In this context, geoconservation strategies ranging from diagnosis to the promotion of geosciences, including statutory structure, play an important role.

6. Concluding remarks

Studies and activities related to geodiversity and its associated subjects have been growing in recent years. These initiatives comprise aspects that range from general studies on geodiversity, particularly index maps, that may or not be applied to issues such as relationship with protected areas, groundwater distribution, among others, to many kinds of outreach efforts, which make the fundamental link with society.

In this sense, an important aspect to be noticed is the heterogeneous distribution of the initiatives in these several fields of actions along the whole Brazilian territory. This reflects the fact that actions to promote geodiversity and geological heritage are still quite punctual, and probably related to academic research. In this context, national initiatives to integrate these strategies are necessary to create a national programme for disseminating Brazilian geodiversity.

On the other hand, being the source of fundamental natural resources that have been progressively demanded, the adequate knowledge of geodiversity across a territory allows the optimisation of their exploitation and use. Moreover, it allows identifying alternatives and guarantees good practices in the use of the geological resources. This goes through, for example, the understanding and assessment of geodiversity and geoheritage in protected areas and its role in the dissemination of information about their importance. This is also related to the way these themes are being communicated to society as a whole.

Geodiversity is part of natural diversity and is present in almost all aspects of people's daily life. To understand its relevance and its role on the composition and functioning of Earth's systems, as well as the impacts caused by its exploitation, may empower people in the sense of making sustainable choices that count for the future of this and the next generations. Now that the International Geodiversity Day will be an official event, we hope that the efforts to spread awareness of the importance of disseminating this concept will flourish even more.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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