



Inventory of the Geological Heritage of the State of Rio Grande do Norte, NE of Brazil

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Abstract

The Earth landscapes were not always as what they present themselves today, thanks to the interaction with the internal and external dynamics of the Earth. Thus, it is clear that the rocks are true “files” where what can informally be called “key files” capable of telling the history of a territory are stored. Threats against outcrop protection demand urgent management actions. Because of it, making an inventory of the geological heritage of a place makes it possible to delimit these places of interest and through a quantitative assessment to support measures for the geoconservation of this natural heritage. The present work consists of the first steps of the elaboration of an inventory of the geological heritage in the state of Rio Grande do Norte (RN), northeast of Brazil, and one of the first state inventories in progress in the country. In this text, it is exposed how the potential geosites were selected based on different bibliographic sources, filtered according to their uniqueness or regional representativeness, to then be organized in a uniform database, with general information about each point for consultation by the scientific community. Cartographic and graphic products were also generated to represent the information obtained in each location of geological interest. This study can be constantly updated and aims to direct future work on the inventory of geological heritage or with emphasis on specific topics such as geomorphological, paleontological, and mineralogical in RN.

Keywords Inventory · Geoconservation · Geological heritage · Geosites

Introduction

The Earth landscapes were not always as they present themselves today, thanks to the interaction with the internal and external dynamics of the Earth. Because of it, the different periods that followed the formation of the Earth were imprinted over time mainly on rocks, through mineral occurrences, structures or even fossils, at their different scales.

Thus, it is visible that the rocks are true “files” where what can informally be called “key files” are stored, capable of telling the history of a territory, be it complete or partial (due to the gap of information that can have been suppressed naturally or anthropogenically). In addition, geology, as a study of the Earth, has the mission of trying to organize the pieces of this “puzzle,” also seeking to protect these fundamental records for the history of our planet's evolution. Therefore, according to Romão and Garcia (2017), many threats, such as poor planning of urban expansion, economic interests or intense weathering processes in important outcrops, often used to describe type-sites, demand urgent protection actions.

If the ecosystem is formed by biotic and abiotic elements, only the conservation of biotic elements is not enough to cover the need to protect the Earth. So, identifying and inventorying the geological heritage of a place allows delimiting these places of interest and, through a quantitative assessment—to reduce subjectivities—to support geoconservation measures of this part of the natural heritage.

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Rio Grande do Norte has one of the most complete and beautiful geological Brazilian patrimonies, which is a result of the numerous natural processes to which the state has been subjected throughout geological time (Nascimento et al. 2004; Oliveira and Nascimento 2019). There is in the Potiguar territory a diversity of lithologies/geological structures constituting scientific-didactic examples in the geological time scale that are true heritage of the Earth's history, enabling the understanding of geological evolution and geoscientific development.

Therefore, the importance of prior/strategic planning for the development of actions aimed at characterizing these places, such as an inventory, is emphasized. Based on the premise that it is only possible to conserve something if there is prior knowledge, this inventory and all other activities aimed at geoconservation will enable the maintenance of these locations of geological interest (LIGs) for scientific and/or educational and/or tourist studies. Therefore, this work corroborates for this purpose, through the survey, analysis, and results regarding the collected data that can support and motivate conservation strategies for these places.

Study Area

As this is the inventory of LIGs in Rio Grande do Norte (Fig. 1), the study area is the Potiguar State itself, with an area of 52,809,602 km². The study region is located in the extreme northeast of Brazil, whose borders are the State of Ceará to the west and Paraíba to the south, bordered to the north and east by the Atlantic Ocean.

International and National Inventories

The first initiative to inventory places of geological interest was made in 1944 in the UK, with a multidisciplinary team that produced a list of 390 points in the British territory, most of which were integrated into the 1949 article as Sites of Special Scientific Interest (SSSIs) (Wimbledon 1996). Since then, many other countries such as Spain, Portugal, and France began to carry out an inventory of their geological heritage.



Fig. 1 Location map of Rio Grande do Norte. Source: Dias 2022

According to the historical survey proposed in the work of Romão and Garcia (2017), the first Brazilian initiative related to geoconservation took place in 1997 with the creation of the Brazilian Commission of Geological and Paleobiological Sites (SIGEP), which aimed to identify places of geological interest in the country, with the help of public and private entities represented by the geological communities (Nascimento et al. 2018). There are also 61 inventory initiatives spread throughout Brazil, identified by Romão and Garcia (2017) in 17 of the 26 Brazilian states: Rio Grande do Sul, Santa Catarina, Paraná, São Paulo, Mato Grosso do Sul, Goiás, Mato Grosso, Minas Gerais, Rio de Janeiro, Bahia, Alagoas, Pernambuco, Piauí, Paraíba, Rio Grande do Norte, Ceará, and Manaus. The authors also point out that the states of Mato Grosso, Mato Grosso do Sul, and Manaus have only the aforementioned national publication of the CPRM as the only initiative aimed at identifying places of geological interest in these territories.

Geological Context

Geologically, the state is located in the northern portion of the Borborema Province (Almeida et al. 1977), covering rocks from the Jaguaribeano, Rio Piranhas-Seridó and São José de Campestre domains (Fig. 2), covered by Phanerozoic covers from the Potiguar and Paraíba. These domains, according to Angelim et al. (2006), are characterized by the presence of metaplutonic and metavolcano-sedimentary lithotypes of Archean to Neoproterozoic (São José de Campestre), Paleoproterozoic to Neoproterozoic (Rio Piranhas-Seridó), and Paleoproterozoic (Jaguaribeano) ages, including a suite of peak gneisses. Paleoproterozoic granites (Rio Piranhas-Seridó), which constitute the basement for the supracrustals of Neoproterozoic ages of the Seridó Group, mainly in the Rio Piranhas-Seridó and São José de Campestre domains, which include the Jucurutu formations (predominantly paragneisses with lens of marbles and associated calcosilicates), Ecuador (quartzites and

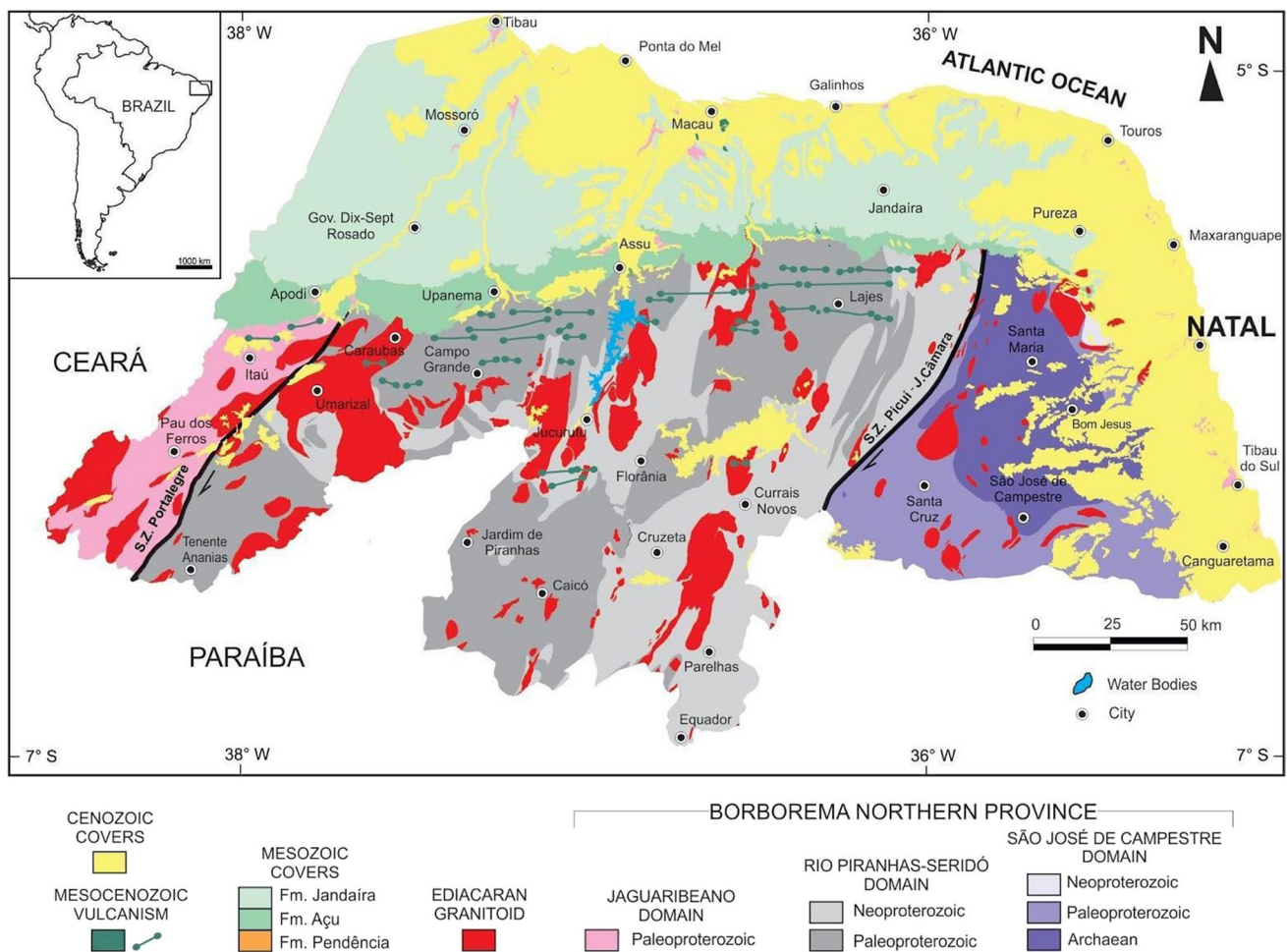


Fig. 2 Simplified geological map of Rio Grande do Norte. Modified from Oliveira and Nascimento (2019). Source: Oliveira and Nascimento (2019)

associated metaconglomerates) and Seridó (predominantly micaschists), these lithologies being affected by several igneous bodies, of different chemical composition, associated with Ediacaran plutonism. Still within these domains, Mesocene volcanic rocks are observed (Basalt and Diabasios Rio Ceará-Mirim and Basalto Macau) and, finally, Mesozoic covers.

The separation of Gondwana in the Lower Cretaceous generated a rift system that allowed the deposition of thick sedimentary layers that came to compose the Potiguar Basin, located in the northern portion of the state, and also generated space for the intrusion of E-W diabase dikes into the south of the basin (Pessoa Neto et al. 2007). The geology of Rio Grande do Norte is also complemented by several sedimentary rocks (some inserted in the Paraíba Basin, to the east of the state) and different types of sediments.

Materials and Methods

In view of what Wimbledon (1996) states, a question arises: How to discern strategies to “judge” what is subject to valuation in the Earth’s history recorded in rocks over more than 4.5 billion years (records of plate tectonics, fossils, deformation events, magmatism, among others) and, thus, make the cut of these LIGs considered carriers of scientific relevance? In addition, other questions also arise: How to select these locations? What criteria to use to ensure that the sites are really the ones that should be protected? How to select the most threatened sites? The key to these answers is to initially carry out an inventory of the geological heritage.

As an initial phase of this inventory work, bibliographic research was carried out on different types of documents, provided by professionals and students of geosciences or extracted from scientific publications available on the Internet. Emphasis is given to (a) discipline field scripts with reports; (b) discipline field scripts without reports; (c) field scripts of scientific events; (d) field scripts for professional training; (e) publications in scientific articles or events; (f) publication in book chapters; and (g) research report, totaling 43 bibliographic bases. Then, 200 LIGs were extracted from these bases.

After cataloging these locations of geological interest, they must be allocated in different thematic categories. In Rio Grande do Norte, there was already a categorization for LIG in the work of Medeiros (2018) who defined the following thematic categories for the state based on the tectono-structural, lithostratigraphic, paleontological, and speleological context of the state (Table 1).

These thematic categories elaborated by Medeiros (2018) was adapted in nomenclature, aiming at simplifying the understanding, in relation to what Medeiros (2018) proposed, described in Table 2.

Table 1 Thematic categories proposed by Medeiros (2018)

Frameworks
Jaguaribeian Domain
Rio Piranhas – Seridó Domain
São José do Campestre Domain
Neoproterozoic Metasedimentary Rocks of the Seridó Group
Neoproterozoic Magmatism (Ediacaran)
Cretaceous Siliciclastic Sedimentary Rocks of the Potiguar Basin
Cretaceous Carbonate Sedimentary Rocks of the Potiguar Basin
Sedimentary Rocks of the Cretaceous Inland Basin
Basic Magmatism Mesozoic
Cenozoic Continental Toppings
Cretaceous Fossiliferous Record of the Potiguar Basin
Pleistocene Fossiliferous Record of Megafauna Vertebrates
Speleological Heritage
Pegmatitic Province of Borborema
Metallogenetic Province of the Seridó Region (RN)

Source: Medeiros (2018)

Table 2 Adapted thematic categories

Frameworks adapted in this work
Shear Zone
Archean Basement
Paleoproterozoic Basement
Metasupracrustals of the Seridó Group
Brasilian Plutonism
Siliciclastic Rocks of the Potiguar Basin
Carbonate Rocks of the Potiguar Basin
Rocks of the Inland Basins
Meso to Cenozoic Vulcanismo
Sedimentary Rocks and Cenozoic Sediments
Fossiliferous Record
Landscapes and Geomorphological Units
Caves and Cartic Systems
Pegmatitic Province of Borborema
Metallogenetic Province of Seridó

Source: adapted from Medeiros (2018)

With this information, an Excel spreadsheet was created with the following information extracted from the bibliographic databases: outcrop name; which bibliographic base(s) cited it; and their respective geographic coordinates, in order to transform it into a vector file, in.shp (shapefile) and.kmz format for eventual uses. Then, to obtain the outcrop repetition count, tools from QGIS 3.10.6 were used. With these products, it was possible to start the spatialization of this data.

Because of the context of the COVID-19 pandemic, the on-site verification stage of these collected data was

compromised, as there was no possibility of field excursions in order to verify each LIG cataloged in person. Although, many of these places were already known for the recurrence with which they are visited.

Therefore, this investigation only use the software Google Earth PRO to do a remote visit to the 200 previously LIGs cataloged. In this way, it was possible to remove some LIGs from the list based on the following exclusion criteria:

- a) Coordinate error or for not being found;
- b) Difficulty in accessing the LIG and/or even because it is in a geological risk and/or public safety location;
- c) Have low geodiversity, with a number of lithologies/structures occurring in the same outcrop and their repetition in other locations with higher counts; and
- d) Quality of exposure.

Because of it, the final list ended with 175 potential geosites. In it, new information about the LIGs was added, and the table in excel now contains the following columns described below:

- Outcrop number: the outcrop number was defined arbitrarily, from 1 to 175, totaling 175 outcrops.
- Count: is the frequency with which the outcrop was visited/cited in the bibliographic databases. To arrive at the final value, it was necessary to create a grid on the shapefile of the state of RN, with dimensions of 500 × 500 m, because, in this way, it was possible to automatically count the outcrops that occurred within a maximum radius of 500 m per grid. This counting methodology was based on the fact that, sometimes, the same outcrop

had coordinates that varied a few meters from each other, depending on the base that cited it. Therefore, a central point (centroid) was generated for each square, which was later relocated to the location that contained the highest number of occurrences of the same outcrop, thus assuming a pair of standard coordinates for this place of geological interest (Fig. 3).

- Outcrop name: The LIG nomenclature aimed the simplification and the easy understanding of the geological interest contained in the outcrop, the following models were adopted (Table 3).

It is noteworthy that the sites known by a specific (c) nomenclature were kept. And yet, the places where there is mineral extraction for industrial purposes remained with the (d) industrial name.

- Lithology described in the bases: each bibliographic base has a brief description of the outcrops listed.
- Municipality: this column describes the municipality where the LIG is inserted.
- Thematic categories: this is an adaptation of the work by Medeiros (2018).
- Thematic classification (primary and secondary): based on the types of interest defined by Schobbenhaus et al. (2002).
- Geological unit: was defined based on the unit of the geological map of the state of Rio Grande do Norte, proposed by Angelim et al. (2006).
- Lithotypes (CPRM 1:500,000): the primary and secondary lithotypes were established based on the

Fig. 3 Default coordinate creation for the outcrop. Source: Dias 2022

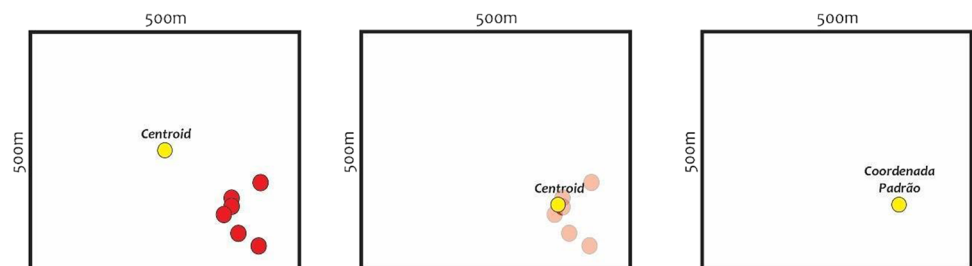
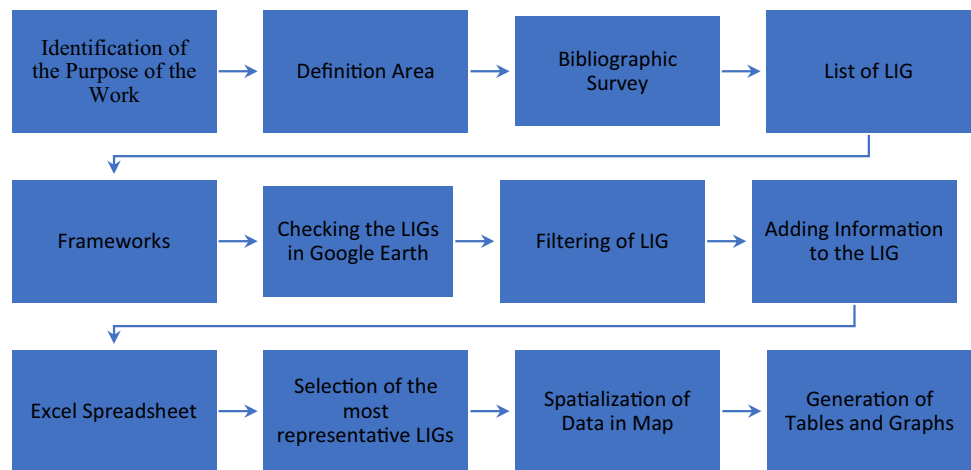


Table 3 Outcrop naming standards

Type	Model	Example
A	Lithology + Toponymy	Riacho do Galo Quartzite, Xiquexique Quartzite, Filite in Cruzeta
B	Lithology + Main structure + Toponymy	Folded Filonite of Jardim do Seridó, Milonitic Augen Gnaiss of Serra de Portalegre
C	Specific nomenclature	Lajedo Soledade, Capoeira Pegmatite, Morro do Careca, Parque das Dunas
D	Industrial name	Brejuí Mining, Bonfim Mining
E	Geomorphology + Toponymy	Inselberg of Serra Caiada, Cliffs of Pipa, Basaltic Plug Cabelo de Nego

Source: Dias 2022

Fig. 4 Methodological sequence used in the inventory process of the geological heritage of the state of Rio Grande do Norte. Source: Dias 2022



- geological map of the state of Rio Grande do Norte (Angelim et al. 2006).
- Era and period: refers to geological time, assigning to each outcrop the era (Paleozoic to Cenozoic) and geological period (Cambrian to Quaternary) of rock formation.
- Geological unit in the simplified geological map of Rio Grande do Norte: refers to the simplified geological map of the state of Rio Grande do Norte proposed by Oliveira and Nascimento (2019).

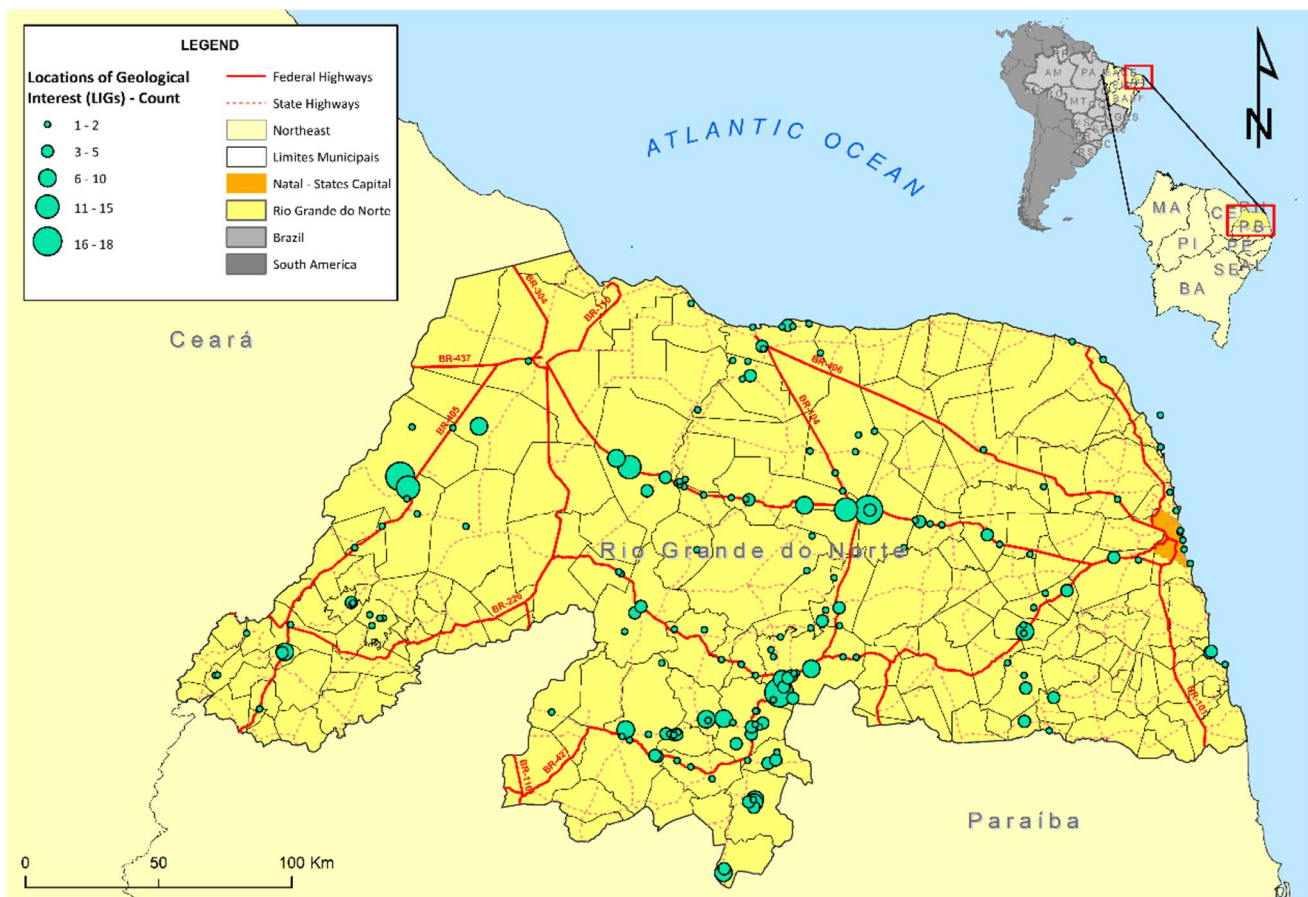


Fig. 5 Location map of places of geological interest cataloged in this inventory. Source: Dias 2022

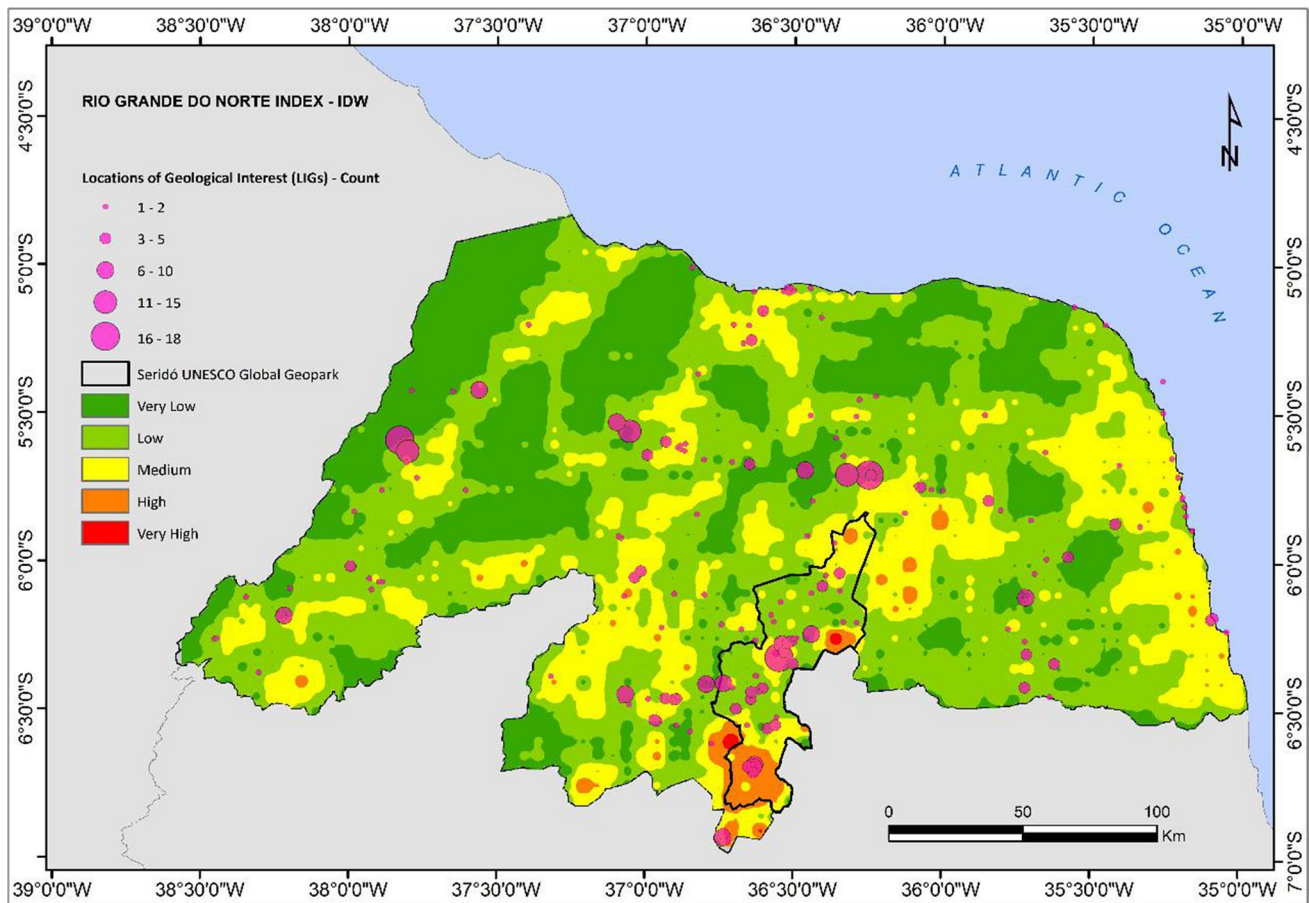


Fig. 6 Geodiversity index map and points of this inventory. Source: adapted of Dias et al. (2021)

- Rock class: assigns the rock class (igneous, metamorphic or sedimentary) to the outcrop that defines it and is directly related to the column “lithology described in the bases”.
- Geographic coordinates: the WGS 1984 Geographic Coordinate System was adopted, in decimal degrees, to locate the latitude and longitude of the inventory points.

PowerBi software was used to formulate and support the results obtained, through interactive graphics with the information contained in the spreadsheet.

Furthermore, the inventory method used in the outcrops followed the recommendations of de Lima (2008), Lima et al. (2010), Pereira (2010), Pereira et al. (2013), and Brilha (2016).

According to these references, it was defined that the object of this study is the Potiguar geological heritage, the value is its scientific relevance, and the scale refers to the geographic limit of the state of Rio Grande do Norte; therefore, state scale and the utility are the possible future management and geoconservation measures of these cataloged sites.

The entire methodology used in the work of inventories of the geological heritage of the state of Rio Grande do Norte is summarized in Fig. 4.

Results and Discussions

The geographic distribution of the points collected is represented in the location map below (Fig. 5), where it is possible to perceive the disposition of the outcrops, especially along the main highways of the state. The gradual symbology indicates that the larger the circle, the greater the number of citations about it in the bibliographic bases consulted and the opposite is also true.

The choice of the most representative LIGs of this inventory, for better exposition of the aforementioned results, was made through a quantitative analysis involving the number of repetitions and the amount of LIG for each repetition. For example: there are 76 LIGs that only repeat one time; on the other hand, there is only one LIG that repeats 18 times.

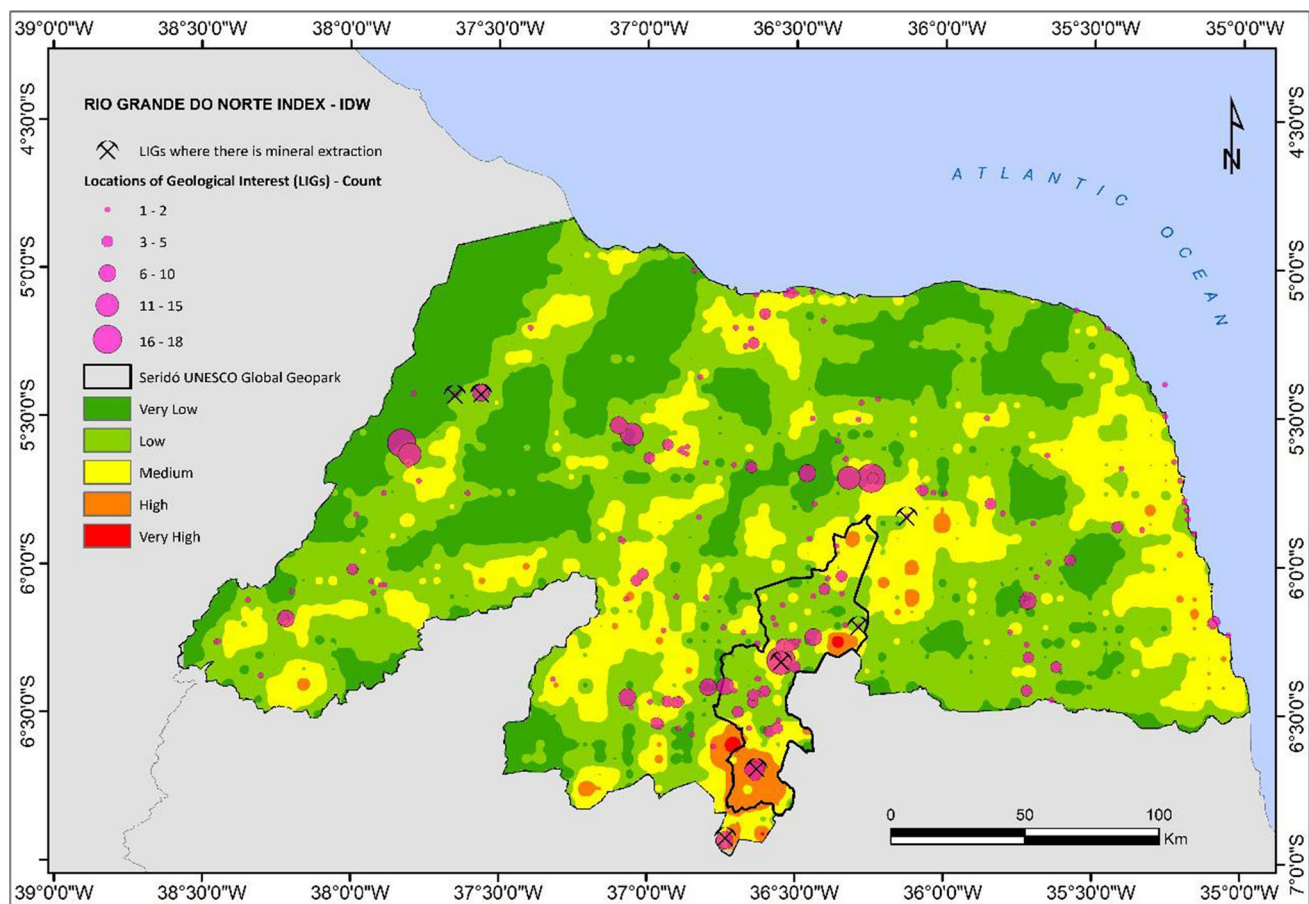


Fig. 7 Geodiversity index map and LIG indication where there is mineral extraction. Source: adapted of Dias et al. (2021)

It is still possible to say that the predominance of LIGs on highways concerns, above all, the points commonly visited in field disciplines. Thus, they are directly related to the fact that, didactically, the road cuts are easily accessible and very favorable for the visualization of lithotypes and their structures.

About the geologic context, the points are mainly distributed over the state's metamorphic rocks. According to Oliveira and Nascimento (2019), this is the rock class with the highest percentage of representation in RN. It is also possible to emphasize that there is an expressive “agglomeration of LIG” in the Seridó Potiguar, which is justified by the diversity of minerals, lithotypes, landforms, and mineral resources in this region.

It was observed that the most expressive thematic category is the Metasupracrustals of the Seridó Group and the least is fossiliferous records. This is justified by the high number of bibliographic bases consulted that cite the outcrops of the Seridó Belt in contrast to the few that cite the LIGs with paleontological themes.

Based on the map that represents the LIGs contrasted with the geodiversity index of the RN of Dias et al. (2021)

in Fig. 6, it is possible to observe a pattern of these with high counts in locations with low to medium index of geodiversity, which indicates the continuous—or rather, homogeneous—repetition of geomorphology, pedology, lithology, mineral occurrences, and water resources in these regions. On the other hand, if the LIGs visited with high frequency were in regions of high geodiversity, it would be possible to conclude that they would be in terrains of high geological, mineralogical, geomorphological, pedological, and hydrological heterogeneity.

In addition, it is noted that most LIGs where there is mining activity are located in areas of low to high geodiversity, which reinforces and supports the diversity of these elements in these regions (Fig. 7).

Thus, it is observed that the region of the Seridó UNESCO Global Geopark coincides with a high concentration of LIG (and of LIG with mineral extraction), also containing the range of highest counts, ranging from 11 to 18 repetitions, in addition to the Sertão Central and the Vale do Assu. In the sequence, the region of the Midwest and North Coast is also highlighted. It is also clear that there

is a high concentration of LIG in the regions called “High and Very High” of the index, which only reinforces the great geodiversity potential of these points.

The municipalities with the highest number of outcrops are in the central mesoregion of Rio Grande do Norte, most of them located in the Seridó Potiguar, a fact that is due to several factors, among the main ones: because they are located in the region of the crystalline basement rocks of the state, especially the metasupracrustals, the magmatism, mainly the plutonic, as well as in the metallogenic provinces of RN. It is worth mentioning that they mark important events in the Potiguar and/or even Brazilian geological evolution; therefore, they have scientific value. In addition, municipalities closer to the coastline, such as Macau, are also highlighted for having LIG associated with beaches and Macau magmatism. This justification also applies to the thematic categories that, mostly, contemplate the Seridó Belt, the Brazilian granite genesis, the relief sculptures in these units and the Meso to Cenozoic magmatism. These constraints also explain the predominance of primary and secondary thematic classifications, metamorphic, and tectono-structural, respectively.

The geological units that have more LIGs cataloged in this inventory are the Seridó Formation, with its scientific and economic relevance; the Itaporanga Suite, as being the most expressive granite genesis in the state and Province of Borborema, as well as for also tending to form inselbergs, morphosculptures of the relief that stand out in the northern-rio-grandense landscape; the Jandaíra Formation, which includes limestones, used for the civil construction industry, but also very important for paleontological and speleological purposes; the Jucurutu Formation, extremely important especially for the ornamental stone industry, in the extraction of marble; and the Macau magmatism, among other things, as being an important conditioning event in the maturation and final migration of oil in the Potiguar Basin, for having induced the heat flow in the region (Almeida and Jardim de Sá 2001). The latter also includes in the state one of the most important geosites in the representation of this event: Pico do Cabugi, which is also listed in the inventory of Brazilian geological heritage.

Thus, based on the results obtained, it can be seen that they are directly related to the content that predominates in the bibliographic bases consulted. It is also worth noting that the trend found in this work was not intentional. But this explains, for example, the fact that we always have low results on the paleontological theme—few databases were consulted on the subject. This premise can even guide thematic inventories, in order to select a specific topic of research in bibliographic sources, also directing results to a specific objective.

Conclusions

According to Brilha (2005), a geoconservation strategy is based on several successive stages: inventory, assessment, conservation, interpretation and promotion, and, finally, site monitoring. This work comprises only the first of these steps, that is, there is a possibility of continuing this geoconservation strategy from the realization of the next steps in future works, for example, doing the quantitative analysis of all mapped LIGs.

But an inventory is never finalized, but interrupted. In this way, new LIGs can be incorporated into the present study, and new analyses can be carried out on them, following the methodology used or even bringing adaptations to it.

Finally, the products generated so far based on this work are graphics, maps, shapefiles, KMLs, description sheets, and presentations at events (ProGEO 2021, ECICT 2021). However, there is a range of possibilities for generating content based on this database and/or after updates for dissemination purposes, such as the following:

- a) Audiovisual materials: updating and production of LIG images and videos, starting with the eight main ones;
- b) Website: virtual availability of the inventory database, with detailed description sheets about each LIG, interactive graphics generated in PowerBi, audiovisual materials, and space for suggesting new LIGs.
- c) Virtual interactive map: map where the user can click on the LIG point, check information about it, photos and consult paths, and routes there;
- d) Potiguar Geological Heritage Book: as was prepared by Garcia (2021), to be prepared after updating and completion of this inventory;
- e) Teaching materials: production of illustrative teaching materials for elementary school telling the history of the geology of Rio Grande do Norte in a playful way;
- f) Itineraries: proposal of thematic itineraries, for example, by thematic category, of the eight main LIGs, by rock class, among others, to be made available to the scientific community for didactic or research purposes.

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