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ORIGINAL ARTICLE

Quantitative Assessment of Geodiversity in Ecuadorian Amazon—Case Study: Napo Sumaco Aspiring UNESCO Geopark

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Abstract
Geodiversity is considered the abiotic equivalent of biodiversity; it can be explained in three main fields such as scientific, educational, and tourism. In sixteen geosites of Napo Sumaco Geopark, a quantitative assessment of geodiversity was carried out using the methodology proposed by Brilha (Brilha, Geoheritage 8:119–134, 2016). This work has a field data collection phase in the geosites Shunku Rumi and Pungarayacu Quarry, where for the first time a geological sketch and stratigraphic columns were made. Regarding the quantitative assessment, it was found that the geosites Sumaco Volcano and Guagua Sumaco Lagoon and Outlook have a high scientific value, the geosite Pungarayacu Quarry has a high potential for educational use, and the Puerto Misahualli's Bookcase has a high potential touristic use. In terms of degradation risk assessment, Pungarayacu Quarry and Hollin River geosites have a high and moderate degradation risk respectively. The remaining fourteen geosites show a low risk of degradation because there are no activities that cause degradation, and are protected by the people of communities and local guides. Finally, this work shows the need for more scientific research, improvement in the security conditions, promotion of the geosites, and development of didactic material.

Keywords Geodiversity · Geopark · Geodiversity assessment · Ecuadorian amazon

Introduction

Geodiversity is considered the abiotic equivalent of biodiversity (Gray 2008). It has been defined by Nieto (2001) as "the number and variety of structures (sedimentary, tectonic, geomorphological, hydrogeological and petrological) and geologic materials (rocks, minerals, fossils, and soils) that form the natural physical substrate of a region." Gray (2004) considers geodiversity as "the natural range (diversity) of geological (rocks, minerals, fossils), geomorphological (landform, processes), and soil features. It includes their assemblages, relationships, properties, interpretations, and systems. Serrano and Ruiz-Flaño (2007) add hydrologic and topographic elements, and systems produced by natural and anthropogenic processes.

Geodiversity can be exploited from three main fields such as scientific, educational, and tourist, where Geoparks have infrastructure used for its adequate exploitation and conservation (Ruban 2017). Geoparks are geographically defined places (Brilha 2009) that are used as tools for the conservation of geologically important territories and the development of local communities in a sustainable way (Sánchez-Cortez and Simbaña-Tasiguano 2018).

Geodiversity provides a variety of benefits that allow economic development and the well-being of people (Gordon et al. 2012; Kubalíková 2020). It offers knowledge, materials for construction, sources of inspiration for the artist, and resources for therapeutic, recreational, educational, and tourist activities (Gordon et al. 2012). Therefore, knowledge of geodiversity distribution is important for implementing sustainable use of resources and recognizing high-priority

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conservation zones (Kaskela and Kotilainen 2017). Several methodologies have been developed to assess geodiversity using qualitative (Gordon et al. 2012; Gray et al. 2013; Hjort et al. 2015), quantitative (Ruban 2010; Manosso and de Nóbrega 2016; Dias et al. 2021), and qualitative-quantitative methods (Neches 2016; Poch et al. 2019; Zakharovskyi and Németh 2021). Quantitative methods are based on various parameters and indicators used to calculate the elements of geodiversity in the area; qualitative methods are descriptive and use expert knowledge and experience (Zwoliński et al. 2018).

Geodiversity assessments in Ecuador are few and these have focused on the Sierra and Costa regions (Carrión-Mero et al. 2018; Carrión-Mero et al. 2020a, b; Herrera-Franco et al. 2020a, b; Morante-Carballo et al. 2020; Carrión-Mero et al. 2021), while in the Ecuadorian Amazon, this type of analysis has not yet been developed. Therefore, the aim of this paper is to quantitatively assess the geodiversity of the sites of interest in Napo Sumaco Geopark through the methodology proposed by Brilha (2016).

Napo Sumaco Geopark: a Territorial Description

Napo Sumaco Geopark (NSG) is located in the Republic of Ecuador, in the northwestern of South America (Fig. 1a), specifically in the Napo province (Fig. 1b), in Tena and Archidona cantons, with an area of approximately 1780 km^2 and 68,000 inhabitants (Sanchez-Cortez et al. 2022). There are 16 sites of interest denominated geosites by Napo Sumaco Geopark and most of these geosites have

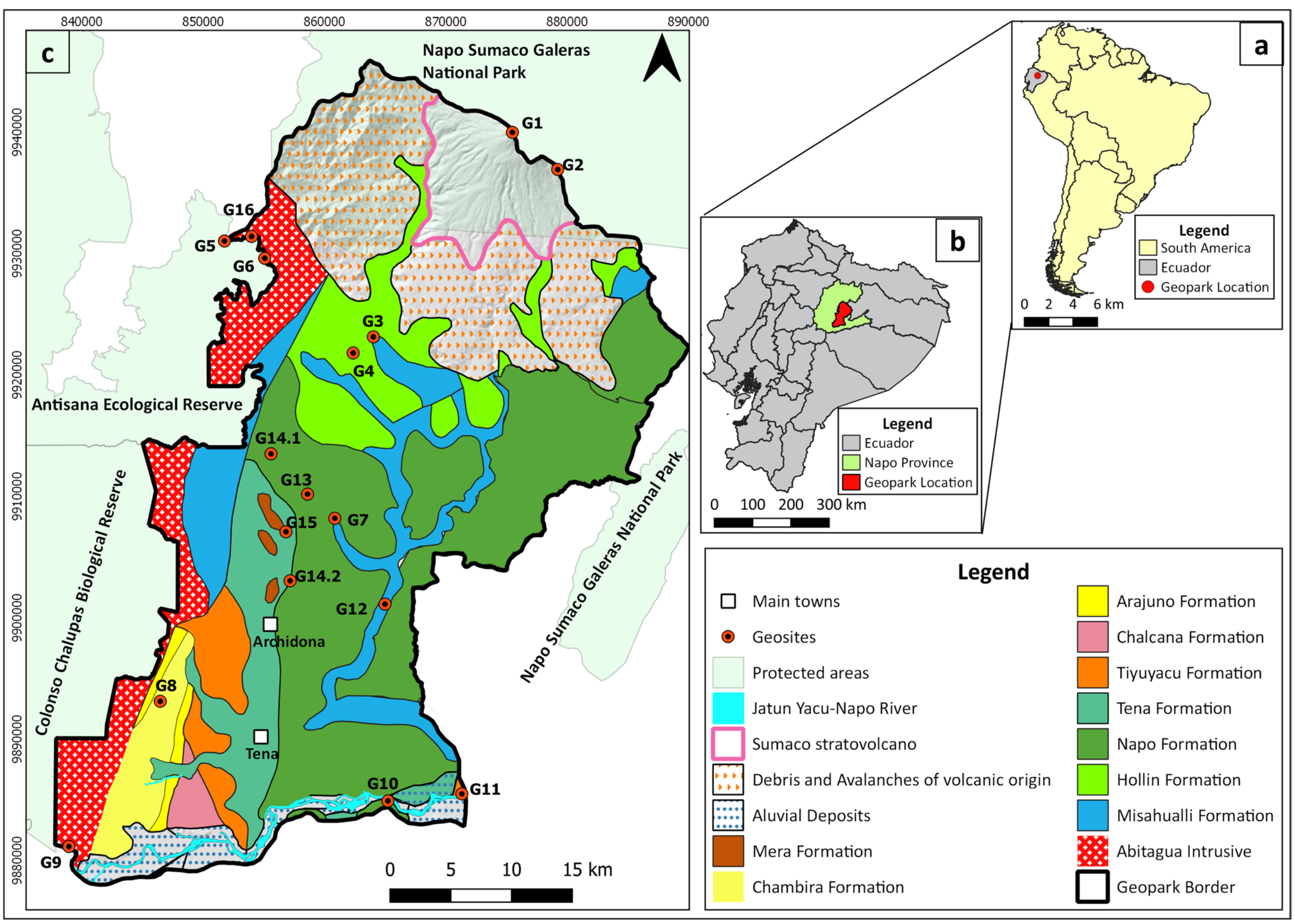


Fig. 1 Location of geosites of interest identified in Napo Sumaco Geopark. (**a**) Location of Napo Sumaco Geopark in Ecuador and South America. (**b**) Location of Napo Sumaco Geopark in Napo province. (**c**) Geological map with the location of geosites, identified as follows: **G1** Sumaco Volcano, **G2** Guagua Sumaco Lagoon and Outlook, **G3** Hollin Waterfall, **G4** Pungarayacu Quarry, **G5** Virgen de Guacamayos Outlook, **G6** Los Guacamayos Granite and the Gringos's Stone, **G7** Ñachi Yacu River Grand Canyon, **G8** Chiuta Hill, **G9** Waysa Yacu and the Jatun Yacu River, **G10** Napo River Labyrinths, **G11** Puerto Misahualli's Bookcase, **G12** Hollin River, **G13** Churo, **G14.1** Usayaku Caverns-Karst relief, **G14.2** Jumandy Caverns-Karst relief, **G15** Cotundo Petroglyphs, and **G16** Shunku Rumi. The geological formations were adapted from the Geological Map of the Republic of Ecuador, scale 1:1,000,000 and the protected areas were taken from the interactive map of the Ministry of the Environment, Water and Ecological Transition http://ide.ambiente.gob.ec/mapainteractivo/)

Kichwa names. They are Sumaco Volcano, Guagua Sumaco Lagoon and Outlook, Hollin Waterfall, Pungarayacu Quarry, Virgen de Guacamayos Outlook, Los Guacamayos Granite and the Gringos's Stone, Ñachi Yacu River Grand Canyon, Chiuta Hill, Waysa Yacu and the Jatun Yacu River, Napo River Labyrinths, Puerto Misahualli's Bookcase, Hollin River, Churo, Usayaku Caverns-Karst relief, Jumandy Caverns-Karst Relief, Cotundo Petroglyphs and Shunku Rumi (Fig. 1c).

From a geologic point of view, in the north of Geopark lies part of the Napo uplift, this positive structure is 70 km wide and 150 km long (Balseca et al. 1993). In the northwest, there are outcrops of Jurassic granitic intrusive and to the east, there are massifs of volcanic rocks and compacted sediments presumed to be 176 million years old and 110 to 25 million years old, respectively (Sanchez-Cortez et al. 2022). There are also a variety of karst landscapes formed by the erosion of limestone of the Napo Formation (Sanchez-Cortez et al. 2022). In addition, Cretaceous (Hollin, Napo, and Tena) (Rivadeneira and Almeida 2014) and Cenozoic (Tiyuyacu, Arajuno, and Chalcana) geological formations are found in this territory (Christophoul et al. 2014).

The Hollin Formation (Lower Cretaceous) outcrops mainly in sectors of the Napo uplift have a thickness of 80 to 240 m and it is composed of white quartz sandstones and fractures (Baldock 1982; Brookfield et al. 2009). The Napo Formation (Lower to Upper Cretaceous) has thicknesses between 200 and 700 m, composed of black shales, gray to black limestones, and calcareous sandstones. The Tena Formation (Upper Cretaceous) has a thickness of 1000 to less than 300 m and consists of sales with sandstone intercalations and few conglomerates, also has a smaller proportion of marls and arenaceous limestones (Baldock 1982).

Likewise, the Tiyuyacu Formation (upper Paleocene-Eocene) has a thickness of 100 to 250 m, composed of basal conglomerates and sandstones intercalated with red, greenish, and gray shales. The Arajuno Formation (upper Miocene) has a thickness of more than 1000 m, composed mainly of sandstones and conglomerates intercalated with bentonite clays and reddish clay. And the Chalcana Formation (upper Oligocene – middle Miocene) composed of claystones and siltstones interbedded with thin lenses of fine to medium sandstones (Baldock 1982; Christophoul et al. 2014).

Moreover, this territory is surrounded by some protected areas such as Antisana Ecological Reserve, Sumaco Napo Galeras National Park, Colonso Chalupas Biological Reserve, and Biosphere Reserve (Fig. 1c). In addition, GSN is culturally rich. Its inhabitants identify themselves as Amazonian Kichwas and associate the geological elements with their culture and costumes (Sanchez-Cortez et al. 2022). GSN also includes the Petroglyphs of the Valle Sagrado of Cotundo, declared a Cultural Heritage of Ecuador in 2005.

Methods

The quantification of 16 geosites was evaluated. The information used was collected by us (during the fieldwork, interviews with people from the geosite communities and literature review) and by the NSG researchers' team. During the fieldwork, a new site was identified, so we proceeded to obtain information from the geosite denominated Shunku Rumi. Likewise, a stratigraphic column was made in the Pungarayacu Quarry geosite. Both geosites were studied in detail in this work. This allowed us to complete the available information (Pungarayacu Quarry) or to obtain for the first-time information from one of the geosites (Shunku Rumi).

Likewise, Karst relief (geosite number 14) is composed of 34 inventoried caverns, distributed in the NSG territory. In this work just two caverns were evaluated, which received the following names and codes: Usayaku Caverns-Karst relief (G14.1) and Jumandy Caverns-Karst relief (G14.2). These caverns were selected according to (i) their location, one to the north and the other to the south, and (ii) their length, one large and the other small. This allowed us to evaluate the effectiveness of the assessment method in geosites composed of different parts where each part has singular characteristics. For this reason, from here we report the results of each cavern separately.

This work also included the macroscopic and microscopic petrographic analysis of rock samples from the Shunku Rumi geosite carried out at the Geosciences Laboratory of the Amazonian Regional University Ikiam. A geological sketch was made with a drone image and the information obtained from the analysis (Fig. 2). The lithology used was modified from U.S. Geological Survey (USGS) (2006). Likewise, a sedimentological study was carried out in the field at the Pungarayacu Quarry, which allowed the elaboration of a stratigraphic column (Fig. 3). The lithology and symbology used were adapted from Nichols (2009) and Tucker (2003). In both cases, the Inkscape 1.1 software was used and the lithology codes (RGB) are available on the USGS website (https://mrdata.usgs.gov/catalog/lithclass-color.php).

Finally, with all the information obtained, the evaluation was applied, using quantitative assessment based on the methodology proposed by Brilha (2016). This assessment method focuses on the evaluation of the scientific value (SV), degradation risk (DR), potential educational use (PEU), and potential tourist use (PTU). The evaluation of SV focuses on seven criteria: representativity, key locality, scientific knowledge, integrity, geological diversity, rarity, and use limitations. Each criterion had indicators that were scored with 0, 1, 2, or 4 points. The evaluation of PEU and PTU is based on ten common

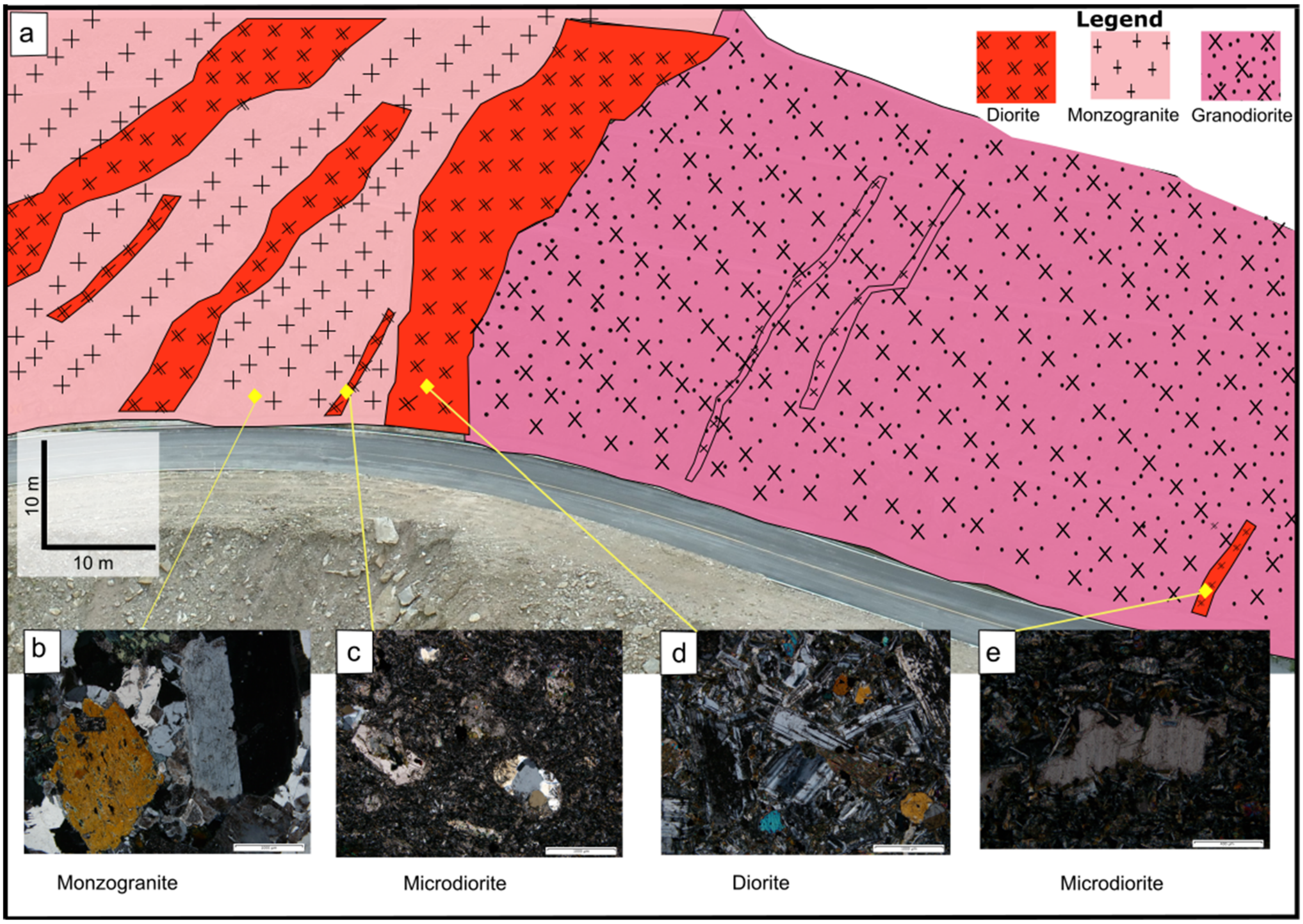


Fig. 2 (**a**) Sketch of geological features found at the Shunku Rumi geosite. (**b**) Petrographic image of a sample of monzogranitic rock in crossed nicols. (**c**), (**d**), and (**e**) are petrographic images in crossed nicols of a dike of diorite composition. Lithology modified from U.S. Geological Survey (2006) and the lithology codes RGB were available on the USGS website (https://mrdata.usgs.gov/catalog/lithclass-color.php)

criteria: vulnerability, accessibility, use limitations, safety, logistics, density of population, association with other values, scenery, uniqueness, and observation conditions. In addition, PTU also includes three criteria: interpretative potential, economic level, and proximity of recreational areas. PEU also evaluates two additional criteria: didactic potential and geological diversity. On the other hand, the degradation risk is focused on five criteria: deterioration of geological elements, proximity to areas/activities with potential to cause degradation, legal protection, accessibility, and density of population. All criteria were scored from 0 to 4 points. Finally, SV, DR, PEU, and PTU are obtained by the weighted sum of each criterion (Table 1) and are classified according to Table 2.

For a better application of the evaluation methodology to the socioeconomic context of the NSG, the following adaptation will be made: (i) In the safety criterion for potential educational and touristic use, the following were considered: distance to emergency centers, safety facilities, and the accompaniment of guides prepared to act in case of emergency.

Results

The quantitative assessment proposed by Brilha (2016) was applied to 16 geosites of NSG. New data were acquired for two of them (Pungarayacu Quarry and Shunku Rumi), and here these are present in a first term. Then, the results of the evaluation are reported.

Fieldwork and Laboratory Analysis

We studied Shunku Rumi (a new geosite), in kichwa means Shunku = heart and Rumi = stone. It corresponds to a rocky outcrop associated with the Abitagua batholith (Jurassic) with an age of 162 Ma (Drobe et al. 2013).

It is an outcrop approximately 200 m wide, where intrusive rocks are found. The left section consists of monzogranite intruded by dikes of diorite composition (Fig. 2), while the right section is composed of granodiorites intruded by diorite and granodiorite dykes. It can be observed that the intrusion processes have not been homogeneous because the outcrop has been intruded by bodies of different composition. Likewise, these rocks present minerals such as quartz, feldspars, plagioclase, biotite, calcite, epidote, and chlorite.

Pungarayacu Quarry Geosite is a 2.6 ha open pit mining structure that is in active state and extracts asphalt material. Its name has a kichwa meaning Pungara = tar and Yacu = river. This quarry is inside the Pungarayacu Field that has the largest accumulation of crude oil in the Oriente Basin with 4 billion barrels (Rivadeneira and Baby 2014). For the first time, a detailed stratigraphic column 46 m thick was made and divided into three sections for ease of study. However, the sections were continuous, except between sections II and III, because the conditions of the outcrop did not allow obtaining a continuous section. Figure 3 shows the summarized stratigraphic column and to obtain the complete column, see Appendix 1. Section I shows the contact between the Misahualli and Hollin formations, and it is composed of hydrocarbon impregnated sandstone and a siltstone layer. Section II is composed of predominantly massive sandstone and some hydrocarbon impregnated layers. Section III is sandstones intercalated with siltstones; the sandstones are impregnated with hydrocarbons. In addition, sections I and III show organic matter, carbon, and sedimentary structures such as ripples, parallel lamination, cross-stratification, and flaser bedding.

Geosites Evaluation

Based on the characteristics of the 16 geosites of the Napo Sumaco Geopark briefly presented in Table 3, a quantitative evaluation of the scientific value, degradation risk, potential educational use, and potential tourist use was carried out. The scores for each criterion of the quantitative assessment of the geosites are shown in Table 4 and the resulting total values are represented in Fig. 4.

The results show that the geosites with high scientific value are Sumaco Volcano and Guagua Sumaco Lagoon and Outlook with scores of 330 and 310 respectively (Fig. 4a). The nine geosites that have moderate scientific value are Jumandy Caverns-Karst relief, Shunku Rumi, Pungarayacu Quarry, Cotundo Petroglyphs, Churo, Ñachi Yacu River Grand Canyon, Chiuta Hill, Waysa Yac, and the Jatun Yacu River and Hollin Waterfall. And the six geosites with low scientific value are Usayaku Caverns-Karst relief, Napo River Labyrinths, Puerto Misahualli's Bookcase, Hollin River, Los Guacamayos Granite and the Gringos's Stone, and Virgen de Guacamayos Outlook.

The results of the evaluation also show that the geosites of the NSG have potential touristic and educational use. Puerto Misahualli's Bookcase geosite has a high potential tourist use with a score of 305 points (Fig. 4b), and fifteen geosites have moderate potential tourist use with scores ranging from 210 to 300 points. Likewise, Pungarayacu Quarry has a high potential with 330 points and the remaining fifteen geosites have moderate potential educational use (Fig. 4c).

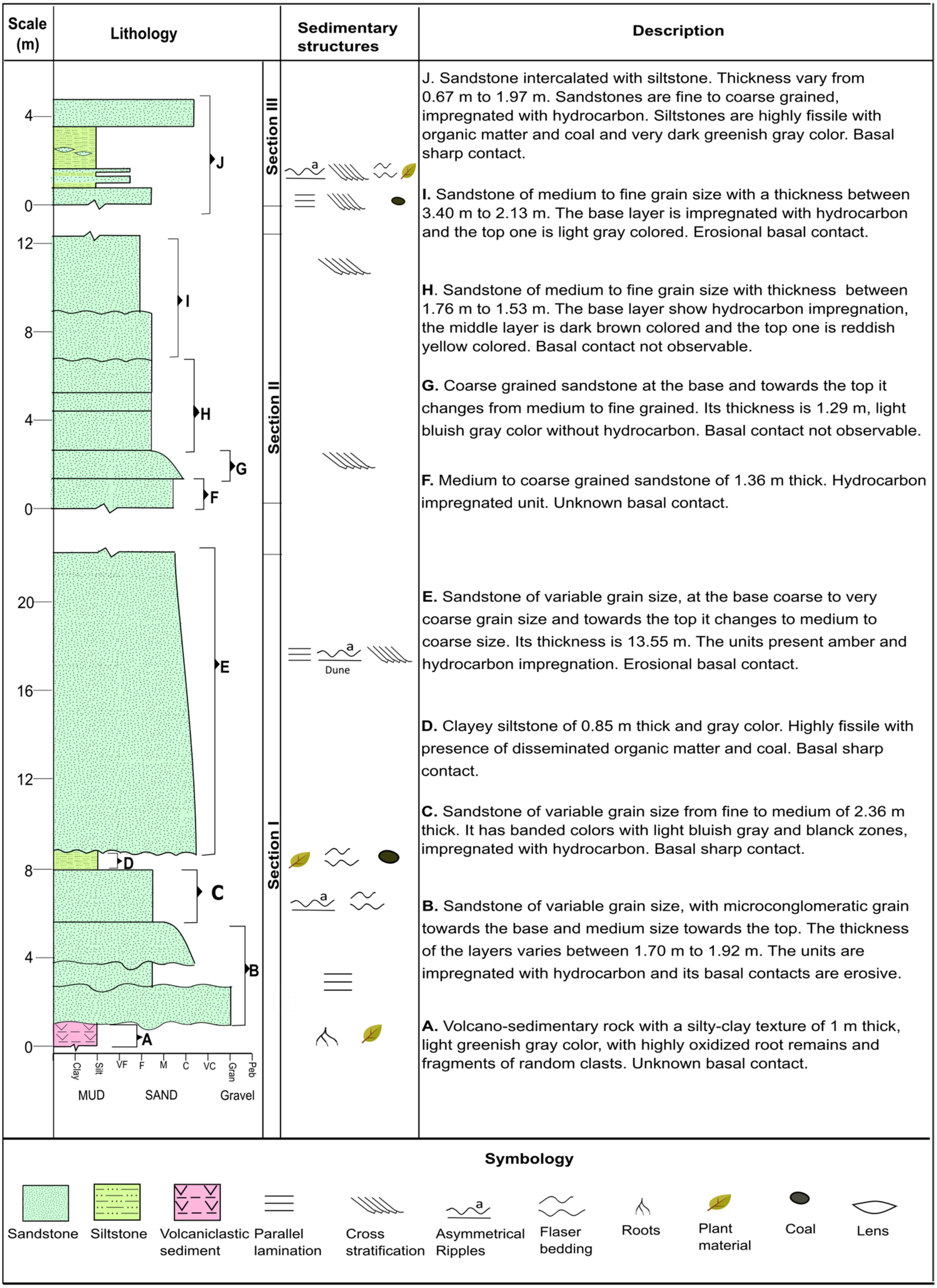
In what concerns degradation risk assessment (Fig. 4d), Pungarayacu Quarry geosite has a high risk with a score of 330. Likewise, Hollin River geosite has a moderate risk and the other fourteen geosites have a low risk of degradation.

Discussion

Based on the results obtained in this work, the scientific value, touristic and educational potential, and degradation risk of the 16 geosites of NSG can be analyzed (Fig. 5). This chapter will begin with the discussion of the results of the quantitative evaluation of the geosites and then some recommendations to improve the weaknesses of the geosites and increase the final rating of potentials in future evaluations.

Potential of Geosites

In general, the geosites of the Napo Sumaco Geopark are characterized by moderate scientific value. Geosites G1 and G2 located in the volcanic edifice of the Sumaco volcano with geosites have a high scientific value associated with geodiversity linked to its alkaline geochemical particularity that makes it different from other volcanoes in an Ecuadorian calc-alkaline subduction geodynamic context. These geosites are used by national and international science and have scientific publications (Bourdon et al. 2003; Garrison et al. 2018; Salgado et al. 2021), while of the remaining fourteen geosites, nine have moderate value and six low value, because these geosites are not yet recognized as key localities and their detailed studies are just beginning (Cadena et al. 2018; Salgado et al. 2021; Sanchez-Cortez et al. 2022). Scientific knowledge is also a limiting criterion because it only considers publications in scientific journals and participation in international events. However, it does not take into account monographs and theses (Tavares et al. 2020). Brilha (2016) mentions that the lack of scientific publications does not indicate that the geosites have no



Scale (m)
Lithology
Sedimentary structures
Description
Section III
Section II
Section I
J. Sandstone intercalated with siltstone. Thickness vary from 0.67 m to 1.97 m. Sandstones are fine to coarse grained, impregnated with hydrocarbon. Siltstones are highly fissile with organic matter and coal and very dark greenish gray color. Basal sharp contact.
I. Sandstone of medium to fine grain size with a thickness between 3.40 m to 2.13 m. The base layer is impregnated with hydrocarbon and the top one is light gray colored. Erosional basal contact.
H. Sandstone of medium to fine grain size with thickness between 1.76 m to 1.53 m. The base layer show hydrocarbon impregnation, the middle layer is dark brown colored and the top one is reddish yellow colored. Basal contact not observable.
G. Coarse grained sandstone at the base and towards the top it changes from medium to fine grained. Its thickness is 1.29 m, light bluish gray color without hydrocarbon. Basal contact not observable.
F. Medium to coarse grained sandstone of 1.36 m thick. Hydrocarbon impregnated unit. Unknown basal contact.
E. Sandstone of variable grain size, at the base coarse to very coarse grain size and towards the top it changes to medium to coarse size. Its thickness is 13.55 m. The units present amber and hydrocarbon impregnation. Erosional basal contact.
D. Clayey siltstone of 0.85 m thick and gray color. Highly fissile with presence of disseminated organic matter and coal. Basal sharp contact.
C. Sandstone of variable grain size from fine to medium of 2.36 m thick. It has banded colors with light bluish gray and blanck zones, impregnated with hydrocarbon. Basal sharp contact.
B. Sandstone of variable grain size, with microconglomeratic grain towards the base and medium size towards the top. The thickness of the layers varies between 1.70 m to 1.92 m. The units are impregnated with hydrocarbon and its basal contacts are erosive.
A. Volcano-sedimentary rock with a silty-clay texture of 1 m thick, light greenish gray color, with highly oxidized root remains and fragments of random clasts. Unknown basal contact.
Dune
Clay Silt VF F M C VC Gran Peb
MUD SAND Gravel
Symbology
Sandstone
Siltstone
Volcaniclastic sediment
Parallel lamination
Cross stratification
Asymmetrical Ripples
Flaser bedding
Roots
Plant material
Coal
Lens

◂**Fig. 3** Generalized stratigraphic column of Pungarayacu Quarry geosite. The lithology and symbology were adapted from Nichols (2009) and Tucker (2003). The lithology codes RGB were available on the USGS website (https://mrdata.usgs.gov/catalog/lithclass-color.php)

scientific value, perhaps they have been recently discovered (Shunku Rumi case, discovered in 2020), and are located in a place with few research groups (just one university is located in the NSG place) or are not dedicated to geological studies.

Regarding the tourist potential, Puerto Misahualli's Bookcase geosite has the best score, this is because the geosite is located in Los Monos beach, which is a known tourist destination in the province. It also is easy to access, has no limitations of use, and has no obstacles that make difficult the observation and it is located a few kilometers from restaurants and hotels. The remaining fifteen geosites present moderate potential use because several of them are accessible through trails, and have use limitations (entrance and guide fees). Most of the geosites are located in areas without mobile coverage, so the scoring took into consideration the fact that tourists will always be accompanied by guides trained in first aid and wilderness rescue and the nearest health center. And they are also located in rural areas, which means less than 100 inhabitants/km^2 (Prefectura de Napo 2020) and the household income is lower than the national average (INEC 2012). Therefore, these criteria obtained the lowest score (1 point), impacting the final rating of the geosites. Despite the fact that most of them are recognized as tourist attractions by the Ministry of Tourism (MINTUR 2004) and have a national and local tourist demand (Prefectura de Napo 2020).

In what concerns potential educational use, the Pungarayacu Quarry geosite was the best scored. This is because it is easy to access, has no limitations of use, there are no obstacles that impede the observation of the geological elements, and there are restaurants and hotels located a few kilometers from the geosite. It also has a diversity of geological elements (rocks, minerals, sedimentary structures, and amber) and these cannot be destroyed by students. Likewise, Quarries have educational potential because they allow students to learn about the history of the earth, they show outcrops that are not possible to observe in other places, and allow direct observation of rocks, sedimentary structures, fossils, and exploitation methods (Gajek et al. 2019). On the other hand, the remaining fifteen geosites have moderate potential due to the fact that the educational curricula of the primary and secondary education levels in Ecuador do not include topics related to geology. The topics that could be found are rock cycle, volcanoes, and associated risk (Ministerio de Educación del Ecuador 2019). Therefore, most of the geosites were affected because they obtained a low score in this criterion (didactic potential) and its weighting is 20%. Additionally, studies indicate that in some countries, geological aspects are taught in conjunction with other disciplines (e.g., in the natural sciences). In other cases, geology is eliminated from secondary education or is absent from university access exams (Fermeli et al. 2015). Similarly, low population density and that some geosites have common geological characteristics in the country also affected the final score.

On other hand, the results of the degradation risk assessment show that the Pungarayacu Quarry geosite has a high risk because it is an operation mining structure. However, it has moderate scientific value and potential tourist use, and a high potential educational use; therefore, conservation and management measures should be implemented, because continued exploitation could destroy all the geological elements of interest. The Hollin River geosite also shows a moderate risk of degradation due to the presence of mining in sectors of this site. The remaining fourteen geosites show a low risk. However, in Jumandy Caverns-Karst relief, Ñachi Yacu River Grand Canyon geosites livestock farming and vandalism were observed. In general, the geosites have a low risk of degradation because they are in protected areas and each site is always visited with guides, who inform visitors of the measures they should take to avoid damaging the geosites.

Improving the Weaknesses of NSG

In the Napo Sumaco Geopark territory, some activities have been carried out to improve its potential. Currently, several research studies are being developed in the geosites that will improve their scientific knowledge. Likewise, the NSG started with the divulgation of topics related to earth sciences and the environment to primary and secondary school students in the Napo province, using attractive didactic material such as infant games and multimedia elements (Simbaña Tasiguano et al. 2020). Also, social networks such as YouTube have been used to educate and show the geodiversity of the Napo Sumaco Geopark geosites during the first months of the COVID-19 pandemic. Likewise, together with different institutions, local guides have been trained in exploration and characterization of caves (Sanchez-Cortez et al. 2022).

However, some weaknesses need to be resolved. To improve the educational potential, it is necessary to develop didactic material such as pamphlets, guide books, and path cards, implement didactic trails for students, and develop interpretation points or museums, where unusual

Table 1 Weights for the criteria used for assessment of scientific value, potential touristic use, potential educational use, and degradation risk (adapted from Brilha 2016)

Potential educational use		Potential touristic use		Scientific value		Degradation risk	
Criteria	Weight (%)	Criteria	Weight (%)	Criteria	Weight (%)	Criteria	Weight (%)
Vulnerability	10	Vulnerability	10	Representativeness	30	Deterioration of geological elements	35
Accessibility	10	Accessibility	10	Key locality	20	Proximity to areas/activities with potential to cause degradation	20
Use limitations	5	Use limitations	5	Scientific knowledge	5	Legal protection	20
Safety	10	Safety	10	Integrity	15	Accessibility	15
Logistics	5	Logistics	5	Geological diversity	5	Density of population	10
Density of population	5	Density of population	5	Rarity	15		
Association with other values	5	Association with other values	5	Use limitations	10		
Scenery	5	Scenery	15				
Uniqueness	5	Uniqueness	10				
Observation conditions	10	Observation conditions	5				
Didactic potential	20	Interpretative potential	10				
Geological diversity	10	Economic level	5				
		Proximity of recreational areas	5				

Table 2 Classification of scientific value, potential touristic use, potential educational use, and degradation risk into three classes: low, moderate, and high (adapted from Brilha 2016)

Total weighted	Value, potential use, and risk
< 200	Low
201–300	Moderate
301–400	High

geological elements are exhibited and can be used for teaching and demonstration (Gajek et al. 2019; Huber and Iakovleva 2021). Another important factor to consider for visitors to the NSG, both tourists and students, is safety; it is recommended to improve trail signage, install safety structures to protect visitors, and promote the construction of restaurants and hotels (Huber and Iakovleva 2021; Nascimento et al. 2021). Better promotion of the geosites should also be developed; it is recommended to organize and promote outdoor events where a historical or cultural recreation of the geosites is performed; this could attract local and national population (Huber and Iakovleva 2021).

Likewise, to improve some low indicators associated with the variables of research, education, and tourism and reduce the high indicators at risk of degradation of some of the geosites, an increase in joint work could be proposed through networks of scientific, business, and local governance cooperation. Something that is already being developed in Ecuador by the Imbabura Geopark in which there is an inter-institutional collaboration between the various actors of the geopark territory. Through a campaign called "FRIENDS of the Imbabura Geopark Project," essential components such as education, geotourism, and conservation are fulfilled, in which a consolidated management committee promotes the generation of projects that enhance the development and dissemination of knowledge, improvement of installed capacities, and support for economic-productive activity (Arellano Guerrón et al. 2019).

Finally, in this study, it was found that Brilha's methodology should be adapted to the context of each geopark because several criteria cannot always be applied due to the location of geosites (rural areas) or that they have not yet been studied in detail and this influences the final scoring of the geosite potential. Additionally, it was identified that in sites that have not yet been studied in detail (in the case of the NSG geosites) it is easier to apply the evaluation when the researcher obtained the information for each geosite compared to using information previously obtained by other researchers.

Table 3 Geological characterization of 16 geosites identified in Napo Sumaco Geopark

Code	Geosite	Coordinates	Geological and geomorphological description
G1	Sumaco Volcano	77° 37′ W 0° 32′ S	Symmetrical cone Stratovolcano, potentially active, with unique geochemical characteristics in the country. It has rocks such as phonolites, basanites, and tephrites. Its lavas have phenocrysts of haüyne, leucite, augite, and plagioclase (Fig. 5a)
G2	Guagua Sumaco Lagoon and Outlook	77° 35′ W 0° 34′ S	Crater in a volcanic cone with a lagoon, located in the middle of the Amazon jungle. It has volcano sediments of Sumaco volcano
G3	Hollín Waterfall	77° 43′ W 0° 41′ S	It is an imposing waterfall of approximately 20 m high. It shows different outcrops of geological formations, volcanic deposits, and textures (Fig. 5b)
G4	Pungarayacu Quarry	77° 44′ W 0° 42′ S	It is an open pit mining structure; it has different rocks, sedimentary structures, amber, and hydrocarbon (Fig. 5c)
G5	Virgen de Guacamayos Outlook	77° 50′ W 0° 37′ S	This Outlook allows us to observe the sub-Andean landscape of the Napo province and interpret the formation of the Cosanga River Valley
G6	Los Guacamayos Granite and the Gringo's Stone	77° 48′ W 0° 38′ S	It is an outcrop associated with the Abitagua batholith and presents a diversity of rocks and minerals and fracture families that make it an ideal site for geostructural and geomechanical analysis
G7	Ñachi Yacu River Grand Canyon	77° 45′ W 0° 49′ S	The geosite is a canyon approximately 10 m high formed by the chemical and physical erosion of the rock massif. Ñachi Yacu River Grand Canyon shows erosive processes and sedimentary structures
G8	Chiuta Hill	77° 53′ W 0° 57′ S	It is a plateau of 150 m high, 250 m wide, and 450 m long. It is composed of siliciclastic sedimentary rocks (Fig. 5d)
G9	Waysa Yacu and the Jatun Yacu River	77° 57′ W 1° 4′ S	It is a morphology formed by the outcropping of the Abitagua batholith and the crystalline water from Colonso Chalupas Reserve. It shows mechanical weathering processes (Fig. 5e)
G10	Napo River Labyrinths	77° 43′ W 1° 2′ S	Lapies field covering 4 hectares, formed by chemical erosion and collapse of caverns. The site presents black limestones with fossils (Fig. 5f)
G11	Puerto Misahualli's Bookcase	77° 39′ W 1° 2′ S	This site has the appearance of books placed on a bookcase due to the inclined arrangement of the rocks
G12	Hollin River	77° 45′ W 0° 56′ S	It is a 10-km-long river that originates in the Guacamayos mountain range and the Sumaco Volcano and crosses outcrops of the Misahualli, Hollin, and Napo geological formations
G13	Churo	77° 46′ W 0° 48′ S	It is a rock labyrinth covering 2 hectares formed by the collapse of caverns, its outcrops between 13 and 53 m high. It also has karstic forms typical of endokarst and an abundance of ammonites
G14.1 G14.2	Usayaku Caverns-karts relief Jumandy Caverns-karst relief	77° 47′ W 0° 46′ S 77° 47′ W 0° 52′ S	Usayaku is a cavern with partially flooded galleries. It has stalagmites, stalactites, and lava flows Jumandy caverns have wide galleries and a permanent river. It has speleothems in abstract figure shapes such as a giant cauliflower (Fig. 5g)
G15	Cotundo Petroglyphs	77° 47′ W 0° 50′ S	Petroglyphs engrave on giant granitic rocks associated with the Abitagua batholith and Misahualli formation, located on a trail that ends in a doline associated with the Napo formation (Fig. 5h)
G16	Shunku Rumi	77° 49′ W 0° 37′ S	It is an intrusive outcrop with different rocks and minerals. It shows the intrusion of dykes and is an ideal site for structural analysis (Fig. 5i)

Conclusion

According to the results, it is evident that the geosites of Napo Sumaco Geopark have potential to be used for science, education, and tourism. In the case of scientific value, the geochemical characteristics of the Sumaco volcano lavas make it uniquely attractive for research, and for this reason, several studies have been carried out in geosites G1 and G2. The tourist potential of the geosite G11 is given by the infrastructure, the ease of access, and the lack of limitations of use. The educational potential of geosite G4 is due to the diversity of geological

Table 4 Score of each criterion for the quantitative assessment of 16 geositios of Napo Sumaco Geopark. *SV* scientific value, *DR* degradation risk, *PEU* potential educational use, and PTU potential touristic use

Assessment of scientific value, degradation risk, and potential educational and tourist use	Geosites																
	G1	G2	G3	G4	G5	G6	G7	G8	G9	G10	G11	G12	G13	G14.1	G14.2	G15	G16
Representativeness	4	4	2	4	1	2	4	4	4	2	1	1	4	2	4	4	4
Key location	2	1	1	1	0	1	0	0	0	0	0	0	1	0	2	0	0
Scientific knowledge	4	4	0	4	0	0	0	0	0	0	0	0	0	0	4	0	0
Integrity	4	4	4	1	4	4	2	4	4	4	4	4	4	4	4	2	4
Geological diversity (SV)	2	2	1	2	0	0	0	0	0	0	0	0	2	1	1	2	1
Rarity	4	4	4	4	4	2	4	4	4	2	4	4	2	1	1	4	4
Use limitations (SV)	2	2	2	4	2	2	2	2	2	2	4	4	2	2	2	1	2
Vulnerability	4	4	4	4	4	4	4	4	4	4	4	4	3	3	3	4	4
Accessibility	0	0	4	4	4	3	0	0	2	4	4	2	3	3	3	3	3
Use limitations (PEU and PTU)	2	2	2	4	4	2	2	2	2	2	4	4	2	2	2	2	2
Safety	3	3	2	2	3	2	2	2	3	3	4	2	3	2	2	4	2
Logistics	2	2	3	3	4	3	4	4	4	4	4	4	4	3	4	4	4
Population density	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Association with other values	2	1	1	2	4	4	3	3	2	3	1	2	3	2	4	4	2
Scenery	2	2	2	1	1	1	4	1	4	1	4	1	2	2	4	1	0
Uniqueness	3	1	1	3	1	1	2	1	3	2	1	1	2	1	1	1	3
Observation conditions	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
Interpretative potential	4	3	4	3	2	2	2	3	3	2	2	2	3	3	3	3	2
Economic Level	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Proximity of recreational areas	4	4	2	3	0	0	4	4	4	3	4	4	4	3	4	4	0
Didactic potential	4	1	1	4	1	1	1	1	1	1	1	1	1	1	1	1	1
Geological diversity (PEU)	4	3	3	4	1	3	3	2	2	2	2	2	4	3	3	2	4
Deterioration of geological elements	0	0	0	4	0	0	3	0	0	1	0	3	0	0	0	0	0
Proximity to areas/activities with potential to cause degradation	0	0	0	4	0	0	0	0	0	0	0	0	0	0	4	0	0
Legal protection	1	1	3	2	2	1	3	3	3	3	4	4	3	3	3	1	1

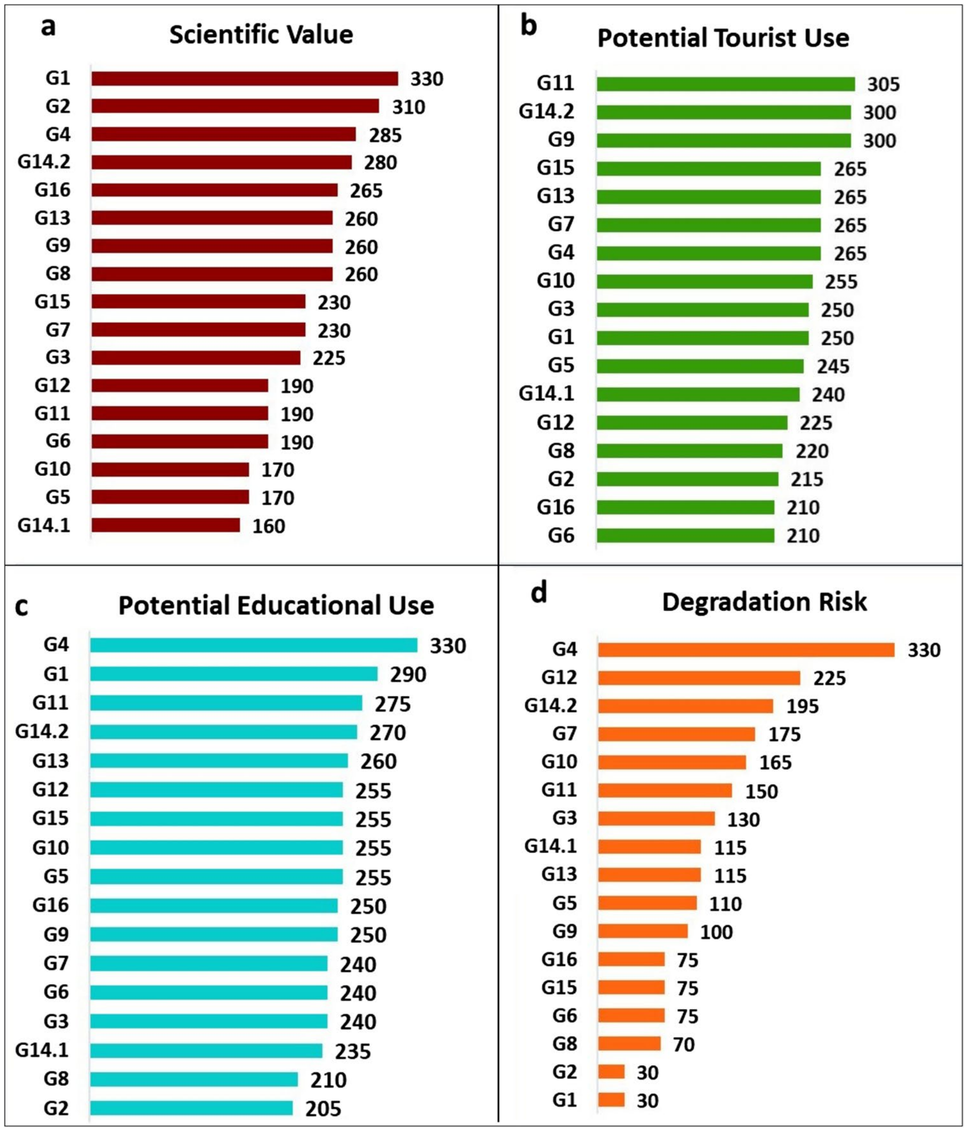


Fig. 4 Final assessment quantitative. (**a**) Scientific value. (**b**) Potential tourist use. (**c**) Potential educational use. (**d**) Degradation risk of each site of interest in Napo Sumaco Geopark

characteristics, didactic potential, accessibility, infrastructure, observation conditions, the lack of limitations of use, and the low risk of students damaging the geological elements. However, the geosites could increase their score by resolving some weaknesses such as developing more research studies, better security conditions, improving geosites promoting, generating didactic material, and developing inter-institutional collaboration. Additionally, geosite G4 has a high risk of degradation due to the high possibility of deterioration of the geological elements because it is an active mining structure. Therefore, it is necessary to develop conservation plans.

Regarding the methodology proposed by Brilha, this work revealed that it needs to be adapted to the context of the geoparks because some criteria are not applicable in all territories and this affects the final rating of the geosites.

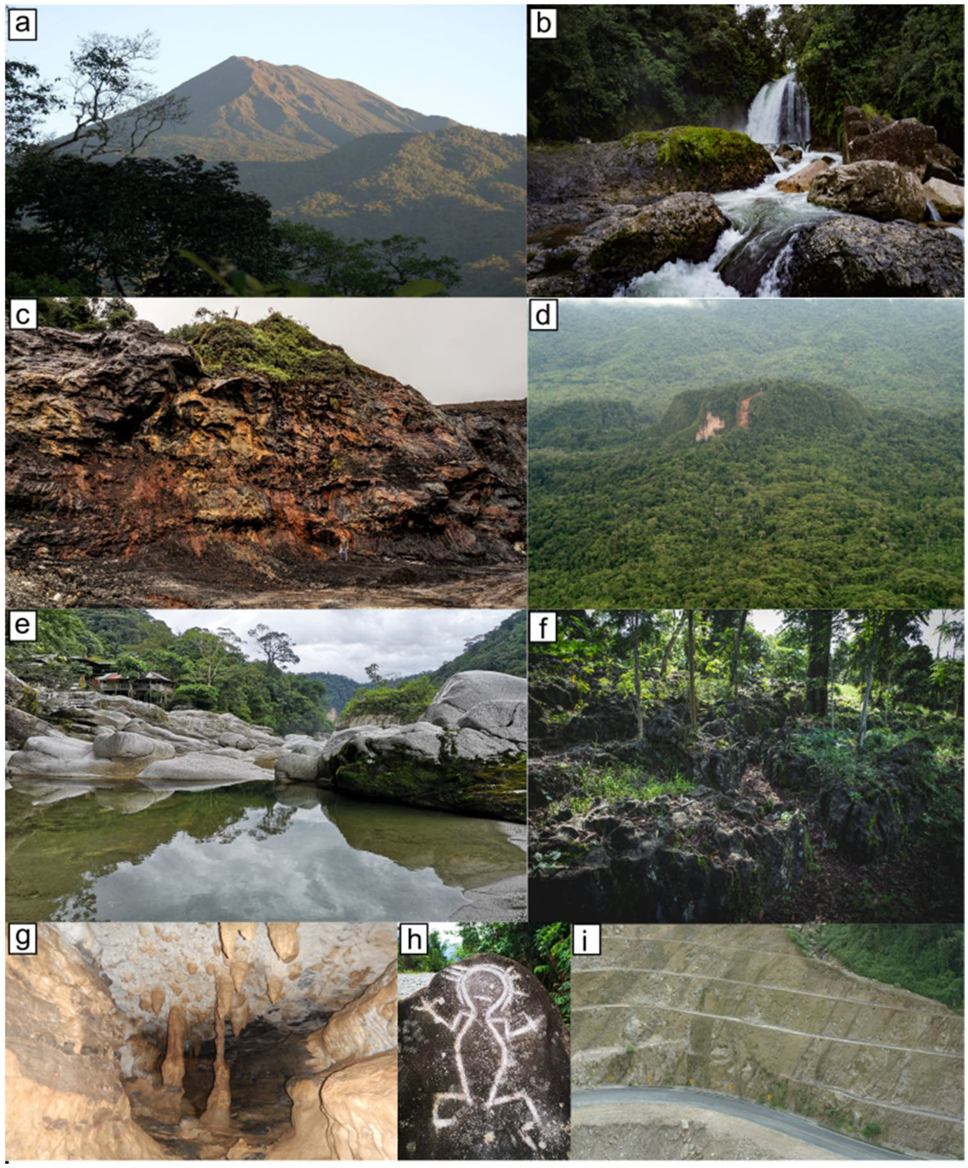


Fig. 5 Geosites. (**a**) Sumaco Volcano (G1), (**b**) Hollin Waterfall (G3), (**c**) Pungarayacu Quarry (G4), (**d**) Chiuta Hill (G8), (**e**) Waysa Yacu and the Jatun Yacu River (G9), (**f**) Napo River Labyrinths (G10), (**g**) Jumandy Caverns-Karst relief (G14.2), (**h**) Cotundo Petroglyphs (G15), and (**i**) Shunku Rumi (G16)

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Declarations

Conflict of Interest The authors declare no competing interests.

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