PANGEA ERASMUS +

UMinho | 2024

Silas Samuel dos Santos Costa

Geoheritage and Mining in UNESCO Global Geoparks:
Challenges and Opportunities for Sustainable Development

Universidade do Minho
Escola de Ciências

Silas Samuel dos Santos Costa

Geoheritage and Mining in UNESCO Global Geoparks: Challenges and Opportunities for Sustainable Development

julho de 2024

Universidade do Minho
Escola de Ciências

Silas Samuel dos Santos Costa

Geoheritage and Mining in UNESCO Global Geoparks: Challenges and Opportunities for Sustainable Development

Dissertação de Mestrado
Mestrado em Geociências
Património Geológico e Geoconservação

Trabalho efetuado sob a orientação dos professores
Doutor Diamantino Manuel Ínsua Pereira
Doutor Marcos Antonio Leite do Nascimento

julho de 2024

Acknowledgements

I want to thank my supervisors and professors, Diamantino Pereira and Marcos Nascimento, for believing in me and contributing valuable ideas during our meetings. I must also acknowledge the insightful discussions with Dr. Manu Monge, whose encouragement has shaped several propositions in this work. Special thanks to Lucas Santos for his support with statistical methods and multivariate data analysis, which will yield further insights.

A heartfelt thank you to all members of UNESCO Global Geoparks who welcomed me and assisted throughout the production of this thesis: Janaína Medeiros and Brunno Andrade (Seridó UGGp and Mina Brejuí); Eva Lima (Azores UGGp); Luís Mampel (Maestrazgo UGGp); Miguel Reis, Bruno Pereira, and Nuno Pimentel (Oeste UGGp); Hércules Katsaros, Isidoros Kampolis, and the professors of the scientific committee of Lavreotiki UGGp. Also, professors José Brilha, Paulo Pereira, and Diamantino Pereira led my master's class on fabulous expeditions through Portuguese geoparks.

A special thank you to Maria Izabel Manes for her partnership during field visits, for sharing experiences, ideas, and frustrations and for being such a supportive companion. We travelled through various geoparks in different countries, and you were the best driver and companion I could have asked for. You made this thesis and master's much lighter and happier.

I also thank all scientific coordinators and geoscientists of UGGps who promptly responded to emails to provide data on mining-related geosites: Kimiya Ajayebi (Aras UGGp), Jochen Babist (Bergstrasse-Odenwald UGGp), Emmaline Gonzalez (Mixteca Alta UGGp), Miguel Cruz (Comarca Minera UGGp), Alessandra Casini (Tuscan Mining UGGp), and Iván Cortijo (Villuercas-Ibores-Jara UGGp). This demonstrates the strength of the Global Geoparks Network in defending geological heritage.

Thank you to the ERASMUS PANGEA Programme and the universities of Lille, Minho, and Athenas for such a rich and privileged academic experience. During this time, I had exceptional professors and colleagues. To my PANGEA friends, thank you for embracing me in such a unique experience.

Lastly, and on a more personal note, I thank God for being my rock and safe haven throughout this great global opportunity. I am grateful to my parents, Aldi and Inácia, for being my moral and motivational foundation. A special thanks to my friends Yago and Victor, my adoption brothers, who visited me during this long writing process. I am deeply thankful to my brother Lucas Santos, my best friend and academic inspiration. You motivate me to be better every day.

Statement of Integrity

I hereby declare having conducted this academic work with integrity. I confirm that I have not used plagiarism or any form of undue use of information or falsification of results along the process leading to its elaboration.

I further declare that I have fully acknowledged the Code of Ethical Conduct of the University of Minho.

Património Geológico e Mineração em Geoparques Mundiais da UNESCO: Desafios e Oportunidades em Desenvolvimento Sustentável

Resumo

A mineração e a conservação têm-se tornado completos antonimos e somente associadas negativamente em casos de extrema degradação ambiental, e quanto positivamente às tradicionais formas de recuperação de áreas degradadas voltadas à biodiversidade. Nos Geoparques Mundiais da UNESCO (GMUs), apesar dessas relações conflituosas, a mineração tem potencialmente apresentado-se como uma janela de exposição do património geológico de relevancia internacional. No contexto dos 213 GMUs, este trabalho propôs identificar várias e potenciais contribuíções da mineração para o património geológico numa escala global e também para a promoção do desenvolvimento sustentável nesses territórios. Múltiplas variáveis envolvendo aspectos geográficos, geopatrimoniais, de usos e infraestrutura e da mineração foram mapeadas. Esses dados foram coletados usandos dados documentais, suporte bibliográfico e atividades de campo. Os dados foram analisados com técnicas de estatística descritiva e regressão linear. Adicionalmente, um método de balanço de geodiversidade foi adaptado para entender a geração e perda de serviços geossistêmicos em geossítios em ambientes de mineração, sendo aplicado no caso do geossítio Mina Brejuí, Seridó GMU, Brasil. 53% dos GMUs tiveram suas principais cargas geopatrimoniais reveladas totalmente ou parcialmente por atividades de mineração. A proporção de geoparques com principal carga de património geológico revelada por mineração é crescente nos 20 anos de rede global. Geoparques com essa relação necessitaram de menor área territorial do que geoparques com ausência dessa relação para revelar o património geológico. Cerca de 28% dos GMUs têm minas ou pedreiras ativas em sítios geológicos inventariados. Os tipos geopatrimoniais paleontológico, estratigráfico, ígneo, tectónico, mineralógico e cosmogénico são os mais frequentemente expostos pela mineração. A mineração impactou os geoparques produzindo infraestruturas e ações que relacionam a atividade industrial, o geopatrimónio e as comunidades. A mineração ativa de scheelita no geossítio Mina Brejuí gerou um balanço positivo de serviços geossistêmicos, aumentados pelos benefícios culturais e de provisão. Em conclusão, a mineração é a principal fonte artificial para a exposição do património geológico em GMUs. A associação da mineração ao património geológico pode ser fundamental no desenvolvimento de projetos de geoparques no hemisfério sul, cooperação global nos GMUs para a sustentabilidade, planos para recuperação de áreas degradadas e parcerias entre geoparques e indústria mineira.

Palavras-chave: mineração; geopatrimónio; geoparques; sustentabilidade; ganho de geodiversidade.

Geoheritage and Mining in UNESCO Global Geoparks: Challenges and Opportunities for Sustainable Development

Abstract

Mining and conservation are often seen as opposing concepts. They are only positively associated with cases of severe environmental degradation and traditional rehabilitation efforts aimed at restoring biodiversity in degraded areas. In UNESCO Global Geoparks (UGGps), mining can act as a window to expose geological heritage despite these conflicting relationships. This study aimed to identify the diverse and potential contributions of mining to geological heritage within the context of the 213 UGGps designated up to 2024, and to promote sustainable development in these territories globally. Multiple variables related to geography, geoheritage, usage, infrastructure, and mining were mapped. Data were collected through documentary sources, bibliographic research, and field activities. The data were analysed using descriptive statistics and linear regression techniques. Additionally, a geodiversity balance method was adapted to understand the generation and loss of geosystem services in geosites within mining environments, applied to the Mina Brejuí geosite in the Seridó UGGp, Brazil. 53% of UGGps had their main geoheritage features fully or partially revealed by mining activities. Over the 20 years of the global network, the proportion of geoparks with their central geological heritage revealed by mining has increased. Geoparks with this relationship required a smaller territorial area to reveal geological heritage compared to those without this relationship. Approximately 28% of UGGps have active mines or quarries in inventoried geological sites. The paleontological, stratigraphical, igneous, tectonic, mineralogical, and cosmogenic geoheritage types are the most frequently exposed by mining. Mining also impacted the geoparks by creating infrastructure and initiatives that connect industrial activity, geoheritage, and communities. Active scheelite mining at the Mina Brejuí geosite exemplifies how mining can generate a positive balance of geosystem services, enhanced by cultural and provisioning benefits. In conclusion, mining is the primary artificial source for geoheritage exposures in UGGps. Mining and its association with geoheritage can be fundamental in developing geopark projects in the southern hemisphere, global cooperation within UGGps for sustainability, plans for rehabilitating degraded areas, and partnerships between geoparks and the mining industry.

Keywords: mining; geoheritage; geoparks; sustainability; geodiversity gain.

Contents

List of Figures

List of Tables

1. Introduction

The need for understanding development limits, especially in areas with exceptional natural and cultural significance, has been frequently studied in sustainability and conservation (Coglianese, 1999). This understanding is crucial to ensure a sustainable future for the next generations. From this perspective, mining is not just recognised but starkly highlighted as one of the most environmentally aggressive human activities, given its significant modifications to ecosystem services and adverse impacts on society (Neves et al., 2016). Due to these reasons, some conservation programs deliberately avoid any association with mining initiatives. Even related to geological heritage and geoconservation, mining is sometimes understood as one cultural romanticisation of environmental impacts generation (Chakraborty et al., 2015).

The network management entity plays a crucial role in the context of UNESCO Global Geoparks (UGGps). It guides aspiring territories undergoing evaluation (Geoparks Secretariat, 2006). This guidance includes advising management staff on establishing relationships with private mining companies through partnership programs, mainly in active mine sites where the geoheritage is linked to the mineral resources, characterising a relation of “geoheritage commerce”. This proactive approach guarantees that measures are in place to manage the conflicts between mining and geoheritage. Indeed, there are multiple examples where mining has damaged geoheritage (Szakács & Chirita, 2017; Poblete Piedrabuena, 2019), leading to the argumentation of mining and quarrying prohibition in geological sites of UGGps territories (Wu et al., 2021).

Despite these problematic visions about the relationship between mining and geoheritage, Prosser (2018) presented the creation of new geoheritage exposures, enhancement of geoconservation inventories, conservation of features and sites, rescuing and recording of geological specimens, research, education, public engagement and application for funding as opportunities generated by mining, especially in United Kingdom examples. Recently, the International Union for Conservation of Nature (IUCN) has not only recognised but also underscored in the 2020 World Conservation Congress a resolution highlighting the necessity to protect geoheritage features (e.g., karst cavities, fossils, minerals, geological structures) in mining environments (IUCN, 2020). This recognition from a prestigious international organisation validates the importance of our work in geoheritage conservation.

From this perspective, the following questions regarding global geoheritage, geoparks and its association with mining environments can be asked: “How has mining contributed to revealing the global geoheritage?”; “What are the global patterns of geoheritage expositions provided by mines?”; “Does mining performed a positive role for the UNESCO Global Geoparks' geoheritage?"; "Does active mineral resources exploitation match with the sustainable development strategy of geoparks?"; "How mining have collaborated for implementation of sustainable actions in the geoparks?; and "In what manner can we measure the geodiversity gains resulted from mining activities?".

Considering these research questions, this thesis's main objective is to **identify the contributions of mining to the global geoheritage and the promotion of sustainable development in UNESCO Global Geoparks (UGGps)**. To accomplish this aim, we adopted three specific aims:

- Identify geoheritage features discovered or better exposed by mining in the UGGps;
- Classify and correlate discoveries relevant to geopark's geoheritage charge with geographical, geological, mining techniques and sustainable uses characteristics;
- Present a method to evaluate geodiversity balance or net gain in the context of geological sites in active mining environments, applying in a UGGp case.

The collaboration of the mining extractive industry for geoparks goes far beyond just promoting the development of former mining regions that are deindustrialised or in the process of closure (Mairesse, 2019). This work intends to show the multiple facets of mining as a "generator" of geological heritage and, consequently, as a collaborator of UNESCO Global Geopark's development. Thus, it is hoped that we can collaborate to strengthen relations between geoparks and the mining industry, emphasise the relationship between development stakeholders, and present current examples and new suggestions for implementing the 2030 Agenda in mining environments. In addition, a geosystem services mechanism is suggested to evaluate the gains and losses caused by the active extractive industry in geological sites.

This thesis is structured following the specific objectives in three topics: mining and geoheritage relations, mining generating sustainability and evaluating geosystem services generated by active mining in a geological site. Achieving the first and second targets, we have collected, analysed and discussed the data from the literature, geoparks and network documents to fill up a database with geoheritage, geographical, mining, cultural, mining-related infrastructure and action characteristics in the 213 nominated UGGps until 2024. The infrastructure and actions data were analysed and discussed separately from the geoheritage aspects, generating results about the UN 2030 Agenda implementation in the geoparks. The third approach was conducted in an adaptation of the Reverte et al. (2020) method, allowing the quantification and discussion of gains and losses of geosystem services provided by mining in the Mina Brejuí geosite, Seridó UGGp in the Brazilian Northeast semiarid.

2. The UNESCO Global Geoparks

Historically, raised on the biodiversity and cultural heritage conservation strengths since the 1970s (Figure 1), the current established network of geoparks was institutionalised in the early 1990s. From the start point of national or global significance geosites programs (i.e., Global Indicative List of Geosites, International Union of Geological Sciences' Global Geosites - IUGS) to the gaps of the protection of geological records in these programs and other UNESCO programs (i.e., World Heritage Sites - WHS, Man and the Biosphere - MAB), emerging globally the necessity to promote geological heritage territorially – the geoparks new model of geoconservation for large areas connected with local people was conceived to encourage development (Du and Girault, 2018).

The conceptualisation of geoparks network is founded on the European Geoparks Network (EGN), created in 2000, in the following combination based on bottom-up management performance: international significance geological heritage protection; territories boundaries definition; sustainable development; promotion supported by conservation, tourism and education; society recognition; communities' engagement; region's cultural revitalisation mainly in rural environments; and governance management structuration according to the national legislation (Zouros, 2004; McKeever et al., 2010). The conceptual and structural overlaps of the EGN and the Chinese National Geoparks network allowed the arrangement of the first global network in 2004, supported by UNESCO. In this first moment, the Global Geopark Network (GGN) approved 25 territories (Eder & Patzak, 2004).

To ensure a balanced network expansion across continents and counter the rapid growth in Europe and Asia, fostering international geoscience collaboration and building peace through diplomacy was crucial. This approach was proposed during the 38th UNESCO General Conference 2015, establishing the UNESCO Global Geopark program (UGG) (or International Geoscience and Geoparks Program - IGGP). This initiative resulted in the creation of the International Geoscience Programme (IGCP) – a joint program between UNESCO and IUGS, with the latter serving as the advisory board. The GGN was also recognised as a non-governmental organisation with a mix of regional, national, and territorial institutions associated with UNESCO (Du and Girault, 2018).

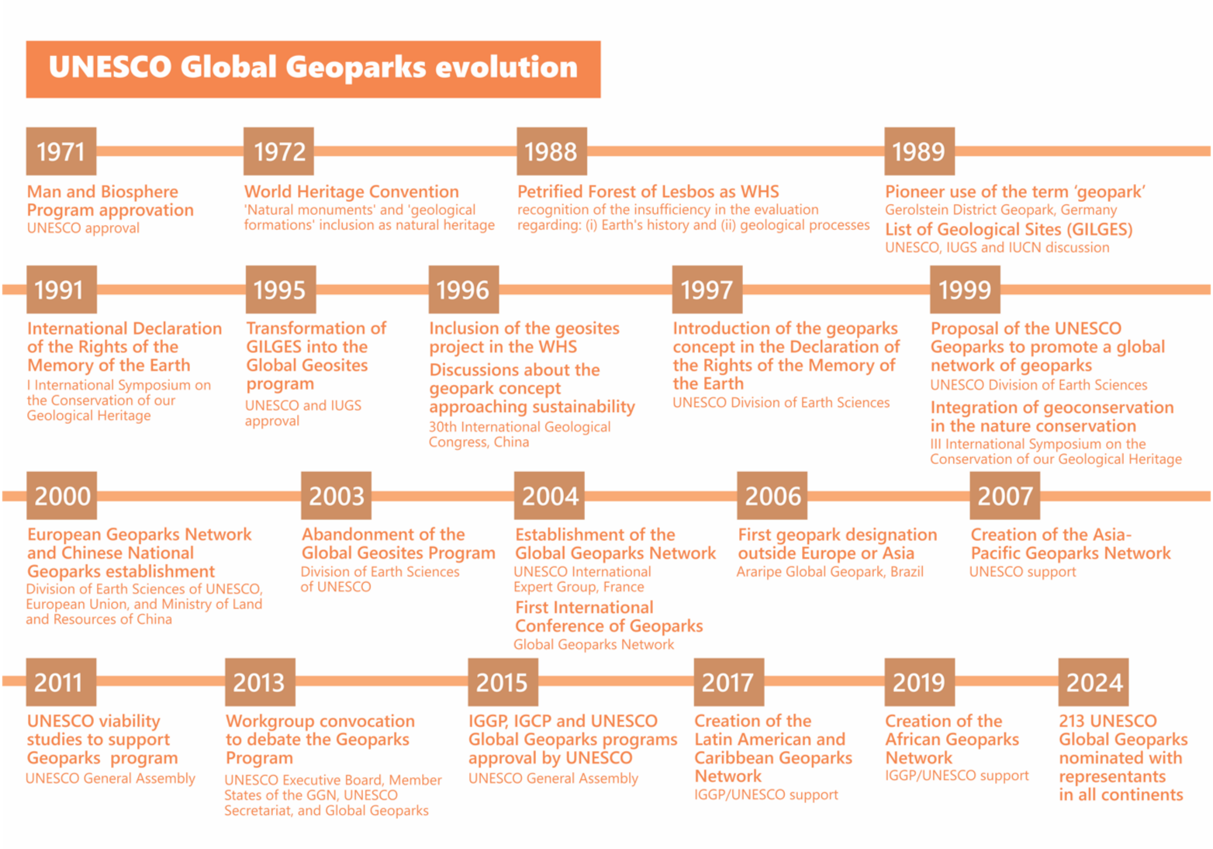

Figure 1. The recognition of geological heritage towards the current UNESCO Global Geoparks network

Despite the recognised progress of the UGG network in implementing targets of the 2030 UN Agenda (Rodrigues et al., 2021; Rosado-González et al., 2023), there are remaining multiple challenges for the UGG improvement, including also conflict resolution with the mining industry in the geoparks. On the one hand, the network proposes internal tasks as central aims to reduce these issues. Financial investments, geological heritage promotion, sustainable use of mineral resources, natural hazards and climate change mitigation, local development stimulation, community engagement and public outreach through geotourism and geoproducts are the main themes to be improved in the UGGps (Gonzalez-Tejada et al., 2017; UNESCO, 2020). Nevertheless, the UGG has not yet reached the potential to involve less developed countries in the program (i.e., Africa, Latin America, Southeast Asia, Middle East and Island countries). The large quantity of UGGps is concentrated in the highest human development countries (Ruban et al., 2023).

Today, celebrating 20 years of network, UGG has expanded its network to 213 UGGps territories in 48 countries. These territories are evaluated every four years to validate management advances and obtain consultancy to improve geopark activities based on holistic concepts of sustainability supported by international geological significance conservation (UNESCO, 2024).

3. Materials and Methods

3.1. Investigating Mining in the UNESCO Global Geoparks

3.1.1. Data Acquisition

In order to map the whole 213 UGGps nominated sites to analyse the relation with mining to reveal geological heritage, presence of active or inactive mining in geosites, mineral resources and contributions to sustainable development, 15 criteria were selected: geopark name, country, geopark area, designation year, main geoheritage interests, secondary geoheritage interests, geological highlight, mining reveals main geoheritage, the relevance of mining for geoheritage revealing, presence of geosites related to mining, description of mining geosites, presence of active mining in the geopark's inventory, mining heritage, infrastructure generated because geoheritage revealed in mining geosites, good practices of mineral resources use.

The *geopark name* refers to the name given by the territory. *Country* identifies national or transnational location. The *geopark area* indicates the size of the delimited region expressed in km^2. Some island's geoparks also included marine areas in their delimitation. The *designation year* refers to the date of entry of the geopark into the GGN. The *main geoheritage interests* mean the geopark's two main international geoheritage types. In other words, geoheritage reasons are used to present the candidacy for the network. The *secondary geoheritage interests* refer to the different themes of the inventory with national or local relevance. These categories of geological heritage were adapted from Brilha (2016) and Ruban (2017), regarding just the classes of geoheritage with an abiotic diversity approach and diminishing the number of classes (Table 1).

The *relevance of mining for geoheritage revealing* was proposed following the examples found in the criterion *description of mining geosites* (identification and characterisation of geological sites associated with mineral exploitation) and its contribution to main geoheritage interests' generation or exhibition. The description of geosites was fundamental to match if the main geoheritage interest was revealed by mining in the UGGps. The relation mining and geoheritage were divided into five classes of importance: 'None', 'Low', "intermediate', 'High' and 'Very High' (Table 2).

Table 1. Geological heritage typologies adapted from Brilha (2016) and Ruban (2017).

Geological heritage typology	Description
Mineralogical	Minerals discovery, assemblies, paragenesis, characteristics, rarity and deposit styles
Paleontological	Fossils discovery, taphonomy, paleogeographical and biostratigraphical significances
Igneous	Igneous rocks, structures and related phenomena
Metamorphic	Metamorphic rocks, structures and related phenomena
Sedimentary	Sedimentary rocks and unconsolidated sediments, structures and related phenomena
Tectonic	Geological structures, products and processes of the fragile or ductile dynamics
Geomorphological	Different scale landforms, exogenous processes and products contributing to relief evolution
Stratigraphical	Different scales of sequences of igneous, metamorphic and sedimentary rock strata along the geological time, allowing the reconstruction of various geological periods due to its characteristics
Glacial	Glaciation registers in sedimentary strata, landforms and landscape.
Hydrogeological	Water in landforms (rivers, lakes, lagoons) and underground reservoirs (aquifers, subterranean rivers, inundated caves)
Cosmogenic	Celestial rocks, meteorites and landforms, stratigraphical registers and rocks generated by cosmogenic events

Table 2. Relevance of mining to reveal geological heritage in the UNESCO Global Geopark.

Relevance class	Description
None	Mining exposures are not linked to the geoheritage charge of the geopark.
Low	Mining exposures are not essential to primary or secondary geoheritage interests.
Intermediate	Mining exposures are not essential to primary geoheritage interests, just relevant to exposing secondary geoheritage interests.
High	Mining exposures are essential to primary geoheritage interests.
Very High	Mining exposures are crucial to primary geoheritage interests. They expose the best geological sites or specimens and represent dependence on mining to reveal the main geoheritage charge.

The *presence of active mining* defined the existence of quarries, mines, wells and other types of mineral resources in current production related to the inventory or sites listed by the UGGps. The *mining heritage* criterion made it possible to record the classes of mineral resources already exploited or extracted in the territory. Based on the listed resources and the division of metallic and subtypes of non-metallic (Franks et al., 2023), the following classes were considered:

- 'Metallic minerals' (e.g., gold, silver, copper, iron, zinc, tin, tungsten, rare-earth elements – REE's, molybdenum, tantalum, lithium, caesium, mercury),
- 'Industrial minerals' (e.g., graphite, kaolin, baryte, lime, sinter, magnesium, sulphides),

- ‘Construction minerals’ (e.g., ornamental or dimensional stones, soapstone, sand, clay, aggregates, tuff),
- ‘Agriculture minerals’ (e.g., potash, nitrogen and phosphorus minerals, calcite, dolomite, diatomite, halite),
- ‘Gemstones’ (e.g., diamond, tourmaline, beryl, quartz),
- ‘Energetic minerals’ (bituminous slate, coal, uranium, radium, oil, gas);
- ‘Absence of mineral resources exploited’.

The two last criteria, *infrastructure generated because geoheritage revealed in mining geosites* and *good practices of mineral resources use*, were essential for identifying investments and actions directly or indirectly linked to mining activity in the geopark territories. In order to facilitate the analysis, the actions were grouped into the following classes: investment and infrastructure, conservation, education, stakeholders’ engagement, tourism, policy, culture and science.

The limitations of geoparks’ data sharing, few publications, and language limit the data acquisition. Some geoparks’ were contacted to supply or complement some criteria information, but we didn't always get an answer. Many other criteria ideas could be interesting for this research development, such as the number of geological sites, the proportion of mining-related geosites to non-mining geosites, mining methods identified in the mining geosites, etc.

The data was collected between January and April of 2024. This phase is a systematic review using mainly the UGG and GGN websites (UNESCO, 2024; GGN, 2024) for criteria such as geopark’s name, country, area, designation year and geological heritage interests and highlights. The geosites inventory measures, mining presence, industry activity, and mineral resources needed a deep analysis approach in geoparks’ website review, application documents, papers, and other scientific publications. The two final descriptions of infrastructure and good practices were also investigated in the UGGps’ websites and publications but systematically in the annual reports’ documents available on the GGN website. These reports described actions of the 2016-2023 years interval.

The field stages were realised to validate and provide observational data from some UGGps. The Seridó Geopark, in Northeast Brazil, was visited in August of 2022. All current Portuguese UGGps (Naturtejo, Arouca, Azores, Terra de Cavaleiros, Estrela, and Oeste) were visited in 2023. We visited the Black Country Geopark, in the west of England, at the end of 2023. In January 2024, the Lavreotiki UGGp, close to the Metropolitan region of Athens in Greece, was also visited. Finally, the Maestrazgo UGGp in Northeast Spain was visited in March 2024.

3.1.2. Data Analysis

The data was analysed using descriptive statistics, observing the average behaviour of the variables and their classes, correlating the quantities between multiple criteria, and using the UGGp network evolution over time to establish trends. Microsoft Excel, ArcGIS and Google MyMaps were used to apply the analysis and cartography techniques. The data regarding main geoheritage interests and mineral resources classes were discretised in binary code, being used to generate multivariate regressions to identify the intensity and significance of relations between resources presence and geoheritage types, according to the following equation:

$$Y_i = \beta_0 + \sum_{p=1}^{11} \beta_p \cdot X_p + \varepsilon_i$$

Wherein Y is the Mineral resources classes variation; i is a UNESCO Global Geopark; β_0 represents the average of mineral resources in the absence of geoheritage type; β_p corresponds to the variation coefficient; X_p indicates the geoheritage types, being p the 11 classes of geoheritage type representation (1 is sedimentary, 2 cosmogenic, 3 metamorphic, 4 igneous, 5 paleontological, 6 tectonic, 7 geomorphological, 8 stratigraphical, 9 glacial, 10 mineralogical and 11 hydrogeological); and, ε is equal to the random error.

3.2. Geodiversity Balance in Geological Sites Exposed by Mining

The geodiversity balance model that is presented is an adaptation of Reverte et al. (2020) method to assess the impact of mining on ecosystem services related to geodiversity or simply geosystem services (Gray, 2011). This method takes into account soil, geology, geomorphology and hydrology as essential geodiversity variables (Schrodt et al., 2024). The method supported the theoretical conversion of positive and negative impacts on ecosystem benefits or loss of its benefits, relating each impact to the benefits listed by Brilha et al. (2018).

Based on field data, bibliography and remote sensing, the model makes it possible to: (i) identify the abiotic ecosystem services generated or interrupted by mining; (ii) classify the significance of the changes affecting the natural environment according to the impacted area, magnitude and reversibility factors (Table 3).

Table 3. Classification significance factors used in the geodiversity balance after Reverte et al. (2020).

Parameter		**Classification**		
Name	**Description**	**Class**	**Value**	**Description**
Coverage	Impacted area range	Local	1	Localised changes
		Regional	2	Widespread changes
Magnitude	Intensity of changes	Low	1	Minor changes
		Medium	2	Significant changes
		High	3	Very significant changes
Reversibility	Restoration capacity	Fully reversible	1	Conditions appropriated to be fully restored or no restoration need
		Partially reversible	2	Restoration is possible, avoiding further damages
		Irreversible	3	It is not possible to restore the initial conditions

From these classification scores, it was possible to generate a measurer of a balance of losses (i.e., negative values) and gains (i.e., positive values) of services provided by geodiversity for each significant type of services and reaching a total balance value for the evaluated geological site – the Geosystem Services Balance, wherein the obtention of values for the services was a summatory of all three criteria and subsequently of all losses or gains registered for the respectives services.

$$GSB = \sum_{I=1}^{K}\{(S_I)\cdot[(C_I)+(M_I)+(R_I)]\}$$

Wherein GSB is the Geosystem Services Balance for the studied area; I is the quantity of identified impacts for the studied area; K is the quantity of mapped benefits or liabilities; S_I represents the geosystem services, being 1 when the service is a benefit and -1 when is a liability, C_I corresponds to the coverage attributed value; M_I corresponds to the magnitude attributed value; R_I corresponds to the reversibility attributed value; the sum of C_I, M_I and R_I cand be represented by W_I – the weights of the Table 3.

The geodiversity ecosystems benefits used in the analysis were adopted from Brilha et al. (2018), consisting of four main types of ecosystem services: 1) regulation and existence of life; 2) supporting of life and development conditions; 3) Provisioning resources for life and society; 4) Cultural contribution of the physical environment. The main benefits are expressed in Figure 2. The degradation of these benefits (gains) was considered as liabilities (losses).

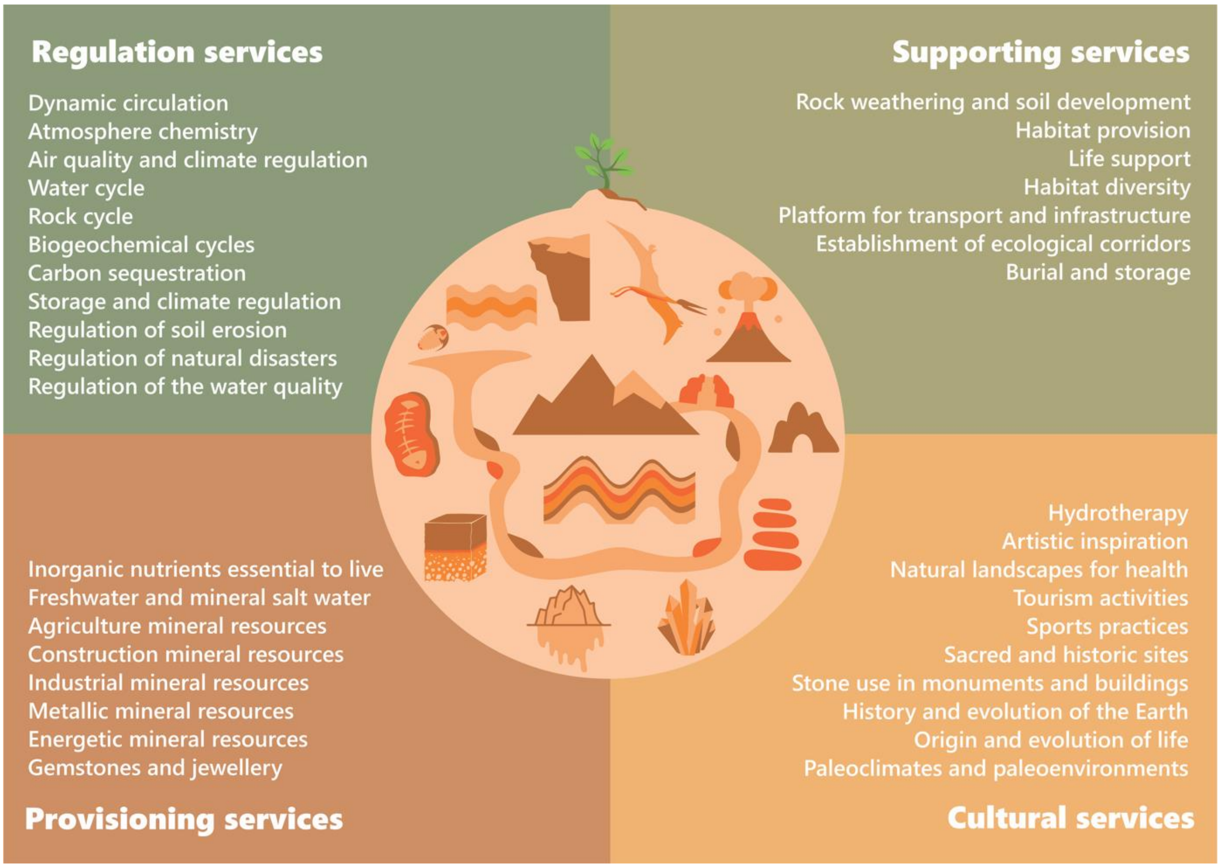

Figure 2. Benefits of geodiversity for ecosystem services after Brilha et al. (2018).

3.2.1. Study Case

The Mina Brejuí, Seridó UGGp (Figure 3) in the Northeast of Brazil was the selected geological site to apply the method of geodiversity balance, understanding the gains and losses of the ecosystem services related to the exploitation of abiotic elements. This mine has been exploited since the 1940s; it was fundamental for developing the Seridó semiarid region, turning this territory economically dependent on mining for at least 50 years. This period was sufficient to modify the nature and its services.

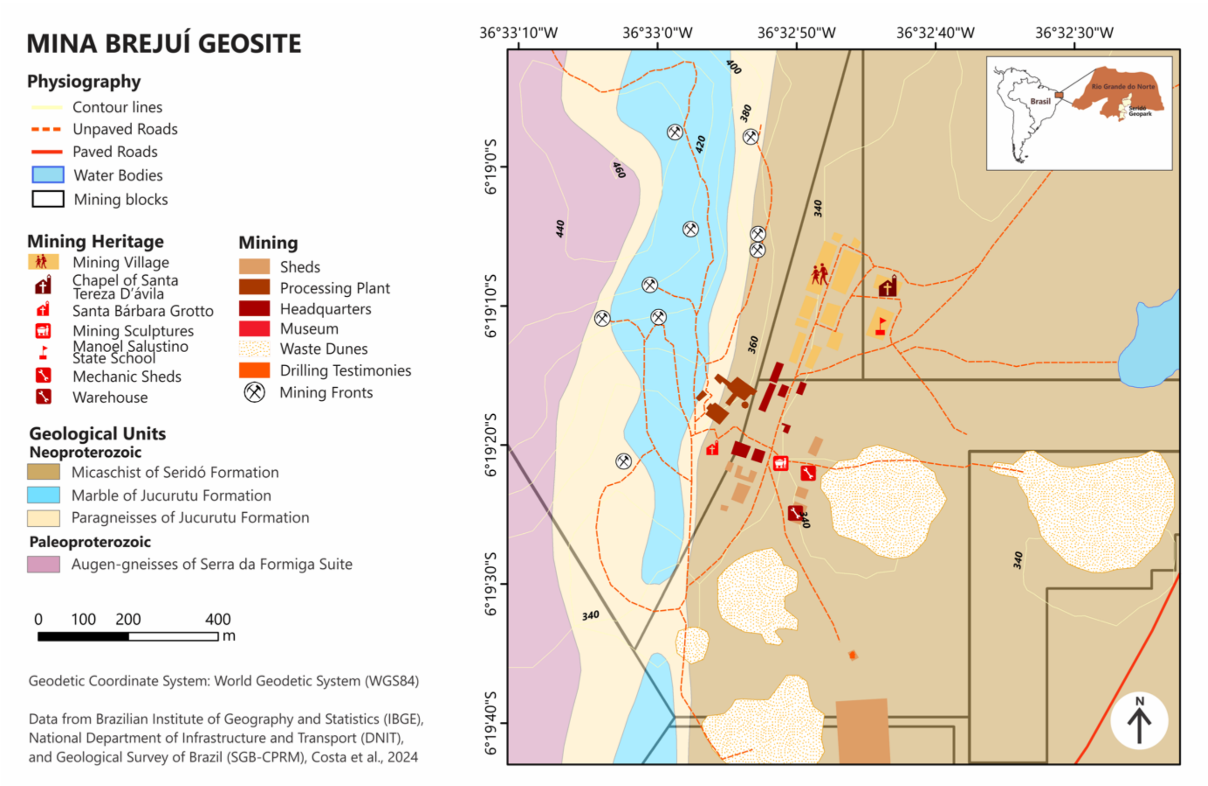

Figure 3. The Mina Brejuí geosite features and location, Seridó UNESCO Global Geopark.

The Brejuí is the main geosite of the Seridó UGGp regarding geoheritage, scientific value and geotourism attractivity. The site faces concomitant scheelite active underground mining (i.e., producing 30,000 tons per year on average) and geoconservation of good expositions of an Ediacaran-Cambrian skarn deposit formed during the Gondwana amalgamation (Costa et al., 2024a), being one of the five geosites of the geopark inserted in an active mining area (Costa et al., 2024b). The geosite also hosts a geodiversity hotspot in the geopark, registering a Very High geodiversity index because of its mineral and rock diversity, landform variations, and hydrology (Silva et al., 2019).

Multiple field stages were realised between March and August 2022, when the ecosystem benefits and liabilities were registered. The industrial installations, tailings, galleries, and saloons of exploitation, as well as museums, villages, and regions' neighbourhoods, were mapped and revisited in the bibliography to identify the impacts of mining.

4. Results

4.1. Geological Heritage and Mining in UNESCO Global Geoparks

4.1.1. UNESCO Global Geoparks: Geoheritage and Territories

The UGG has displayed a spectacular adhesion of new territory members since its origin. On average, about 11 new territories have been successfully entered yearly in this UNESCO network since the 2015 reestablishment. 51% of all territories are disposed in Europe, 39% in Asia, 8% in America, and less than 2% in Africa and Oceania. 53% of all territories are concentrated in seven countries, presenting in terms of quantity of territories: Figure 4 presents the evolution of continents nominations per year since the GGN establishment, showing the strong UGG domain of Europe and Asia. 47 in China, 17 in Spain, 11 in Italy, 10 in Japan, 10 in Indonesia, 9 in Greece and 9 in France. Asian and European continents presented the most significant values on geoparks' density area. For instance, Europe has 1.91% of their territory filled up by UGGps. The UGG-nominated areas occupied 0.4% of the global territorial area with an average of 2,420 km² per geopark.

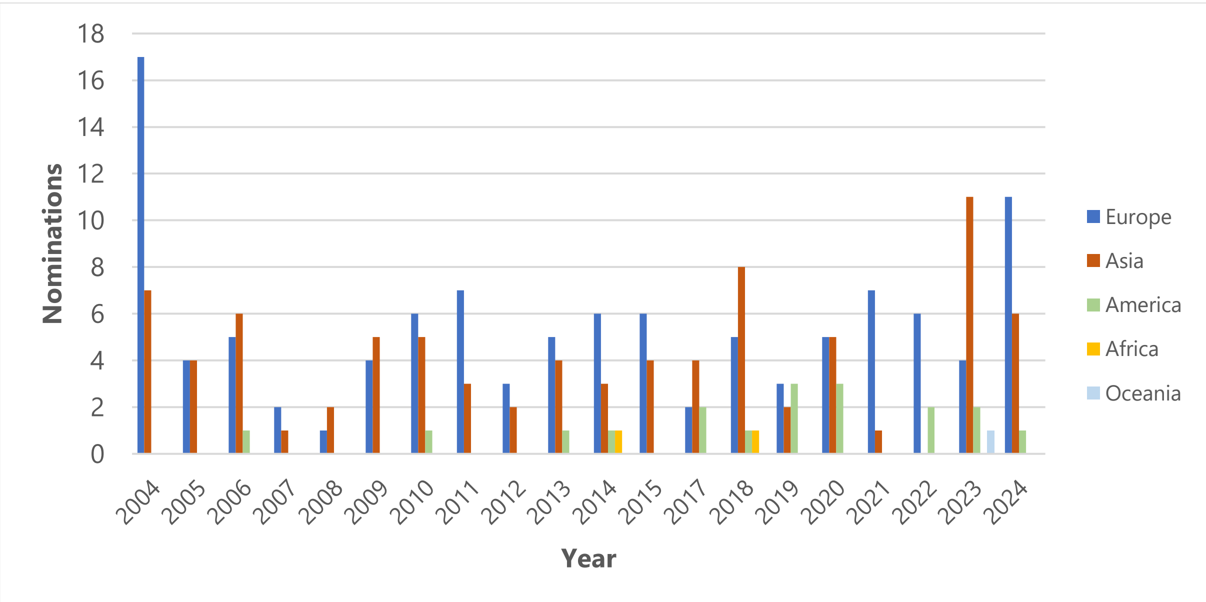

Figure 4. Nominations of UGGps per continent in the 20 years of the GGN network.

Regarding international geoheritage, each continent presented a pattern of central themes (Table 4). Europe was centred in the Alpine tectonics, geomorphology and glacier systems. Also, many European territories are the basis for formatting the Phanerozoic Eon stratigraphy and palaeontology (i.e., represented for many Global Boundary Stereotype Sections and Points – GSSPs of the International Commission on Stratigraphy - ICS) (ICS, 2024), in addition of Mediterranean carbonate rocks karst systems and volcanic islands and archipelagos. Asia has many highlights focused on the Himalayan Mountain chain, deserts and landscapes, the tectonic evolution of the Eurasian continent, tropical karst islands and arc-islands and subduction tectonomagmatic systems. The American continent presented the geoheritage registers of Gondwanan life and Earth system, Pangea breakup stratigraphy, palaeontology and tectonics, Andean tectonics and volcanism. Africa, represented by two UGGps (i.e., Ngorongoro Lengai and M'Goun), showed the Atlas Mountains, the African Rift tectonic, and the paleontological evolution of humanoids. The unique geopark of Oceania, the Waitaki Whitestone UGGp in New Zealand, offered a particular sample of the Zealandia continent tectonics and stratigraphy.

The UGGps' profile in typologies of the main geoheritage interests (Figure 5a) of each territory is expressed by: 17.4% paleontological, 17.2% igneous, 16.9% tectonic, 16.3% stratigraphical, 12.7% geomorphological, 5.3% of mineralogical, 5% of glacial, 4.7% of sedimentary, 1.9% of hydrogeological and 1.7% of metamorphic, 0.8% of cosmogenic. At the same time, the main secondary geoheritage interests (Figure 5b) are represented by: 34.2% geomorphological, 11.3% tectonic, 10.1% igneous, 9.8% paleontological, 8.6% glacial, 8.2% stratigraphical, 6.1% of sedimentary, 5.8% of mineralogical, 3.3 of hydrogeological, 2.4 of metamorphic and 0.3% of cosmogenic.

The paleontological, igneous, tectonic, and stratigraphical four classes of main geoheritage have dominated the recognitions over the network's 20 years (Figure 5c). The fewer classes recognised of main geoheritage (i.e., glacial, sedimentary, metamorphic, cosmogenic) presented a growth increase of 12.5% after 2015. For the secondary interests, the geomorphological class is a highlight. More than one-third of the geopark contains landforms as secondary geoheritage charge.

Table 4. Continental geoparks' geographical and geoheritage characteristics.

Continent	UGGps	Average area (km²)	Continental density (%)	Countries	Main geoheritage typologies	Main geoheritage topics
Europe	109	2,095	1.91	Austria, Belgium, Croatia, Cyprus, Czechia, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Luxembourg,	Stratigraphical, Tectonic, Glacial, Geomorphological, Igneous	Alpine mountain chain evolution, glaciers and landforms; Stratigraphy and palaeontology of Phanerozoic; Mediterranean karst systems;

				Netherlands, Norway, Poland, Russia, Serbia, Slovakia, Slovenia, Spain, Sweden, Turkey, United Kingdom		Volcanic islands and archipelagos
Asia	83	2,431	0.45	China, Indonesia, Iran, Japan, Malaysia, Philippines, Republic of Korea, Thailand, Vietnam	Geomorphological, Tectonic, Stratigraphical, Igneous	Himalayas mountain chain, deserts and landscapes; Evolution of the Eurasian continent since Archean; Tropical karst islands; Volcanic and tectonic systems in arc-islands and subduction zones
America	18	3,358	0.14	Brazil, Canada, Chile, Ecuador, Mexico, Nicaragua, Peru, Uruguay	Paleontological, Mineralogical, Igneous, Tectonic	Registers of Pangea breakup; Gondwana life and Earth system; Andes volcanos and tectonics
Africa	2	8,808	0.06	Morocco, Tanzania	Tectonic, Paleontological	Atlas Mountains evolution; Humanoids in the African rift
Oceania	1	7,214	0.08	New Zealand	Tectonic, Stratigraphical	Formation of the Zealandia continent
Total	213	2,420	0.4			

Additionally, based on the current industry and mining heritage of the UGGps, it was possible to identify that 79.81% of the territories have any past or current registered mineral resource exploitation, wherein the territories quantities per mineral resource classes are: 104 in ‘Construction minerals’, 92 in ‘Industrial minerals’, 81 in ‘Metallic minerals’, 42 in ‘Energetic minerals’, 17 in ‘Agriculture minerals’, 15 in ‘Gemstones’, 5 in ‘Mineral water’. Only 20.19% or 43 UGGps demonstrated the absence of mineral resource registers or data absence.

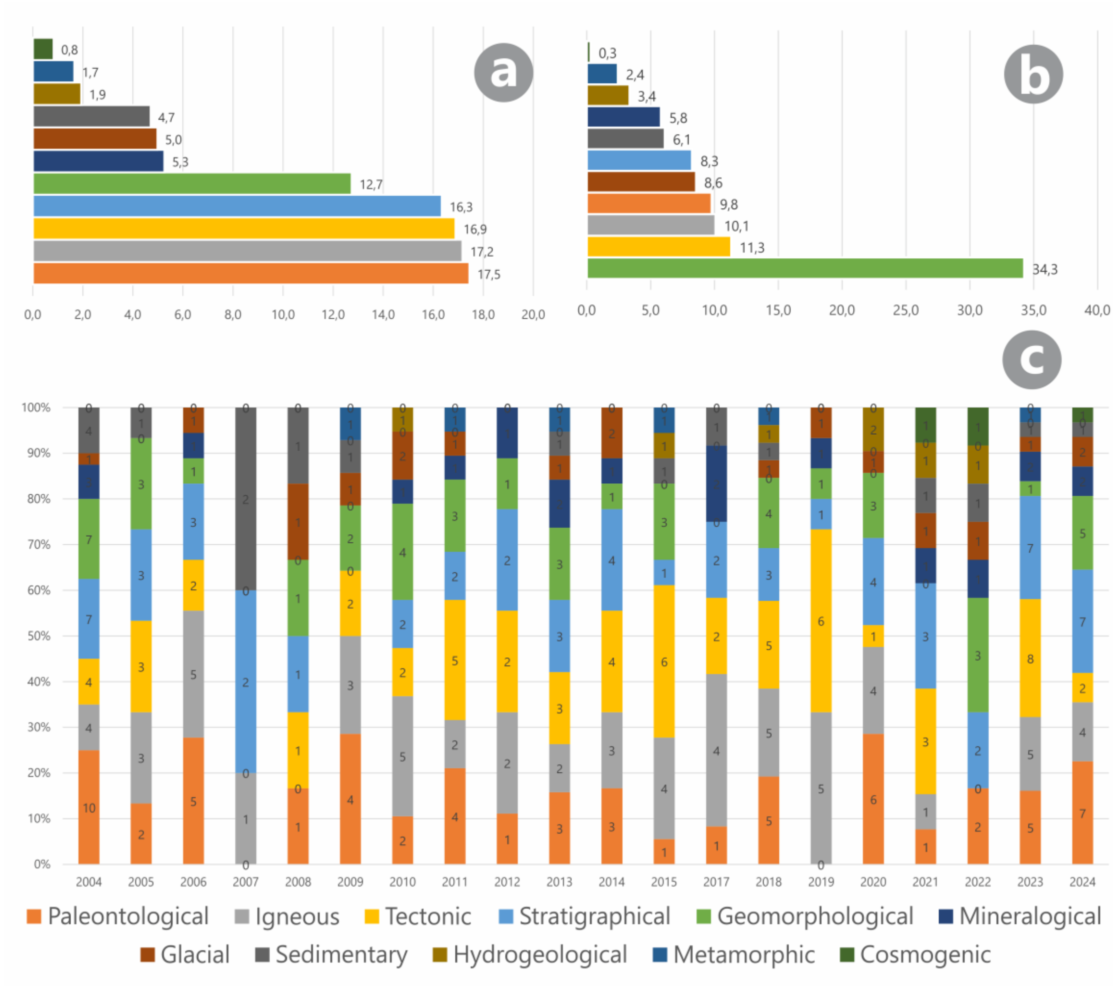

Figure 5. Geoheritage interests in the UGGps: (a) main geoheritage interests; (b) secondary geoheritage interests; (c) 2004-2024's evolution of the main geoheritage interests' types.

4.2.2. Mining Revealing Geoheritage in UNESCO Global Geoparks

The main geological heritage, and the secondary one, of 114 UGGps was, totally or partially, discovered by mining operations, representing 53.5% of all 213 UGGps. Since 2006, the influence of mining activity on the discovery of geological heritage in geoparks has been growing. The two first years of the network were exceptions to this general trend, attempting a 6.25% difference in 2005 for UGGps' geoheritage not influenced by exploitation. From 2006 to 2024, the geoparks with contributions of mining for geoheritage exposures were 7.49% more nominated than the territories not influenced by mining in its geoheritage charge. From 2010 to 2017, the UGGps' geoheritage revealed by mining increased significantly, reaching 56% of all geoparks in the network with that characteristic. After 2018, the absolute number of UGGps' geoheritage related to mining is in a crescent trend again (Figure 6), reaching 11 of 18 geoparks in the 2024's nominations. This number was lower just in the first year of the network.

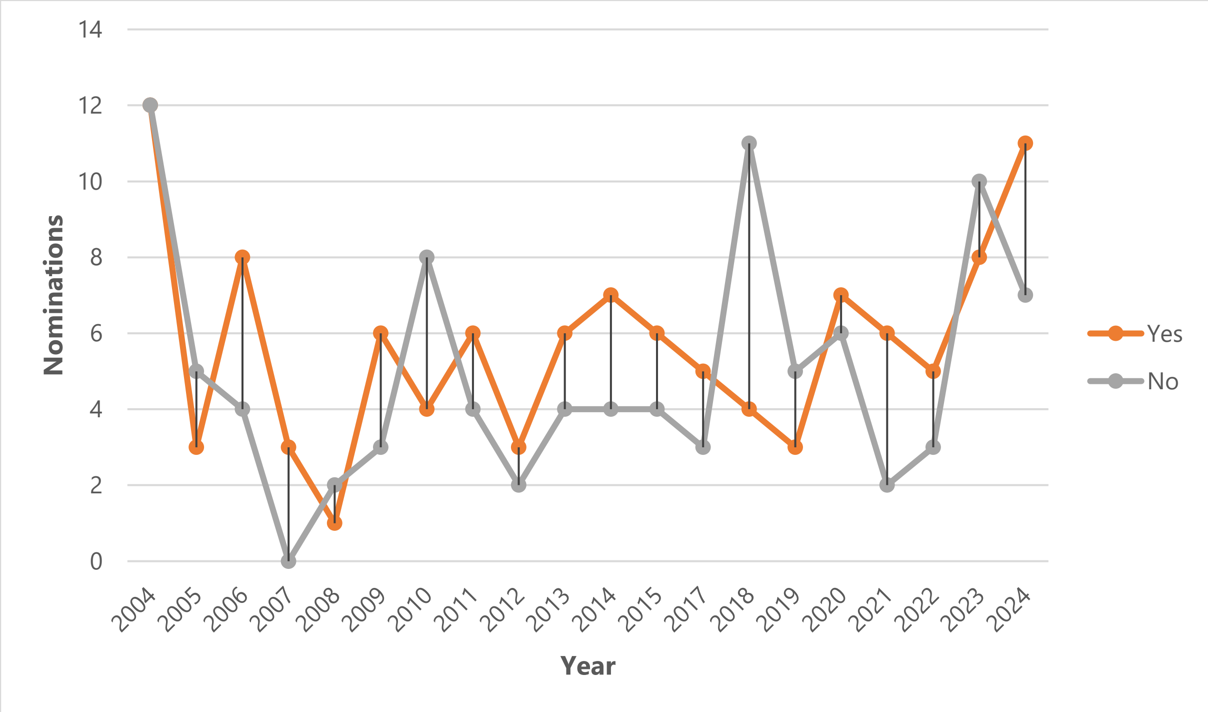

Figure 6. Timeline of mining revealing geoheritage in the UNESCO Global Geopark network: geoheritage revealed or not by mining.

There are some differences in the geographical distribution of geoparks with mining activity influencing the exposure of geological heritage (Fig. 7): Oceania have one UGGp that filled up the criterion, 71.6% in Europe, 55.5% in America, 50% in Africa., and 21% in Asia. The countries with the highest number of geoparks with mining activity revealing geoheritage are China and Spain with 12 UGGps; Italy, the United Kingdom and Germany with 7 UGGps; France with 6 UGGps; Greece and Portugal with 5 UGGps; Japan, Brazil and Norway with 4 UGGps.

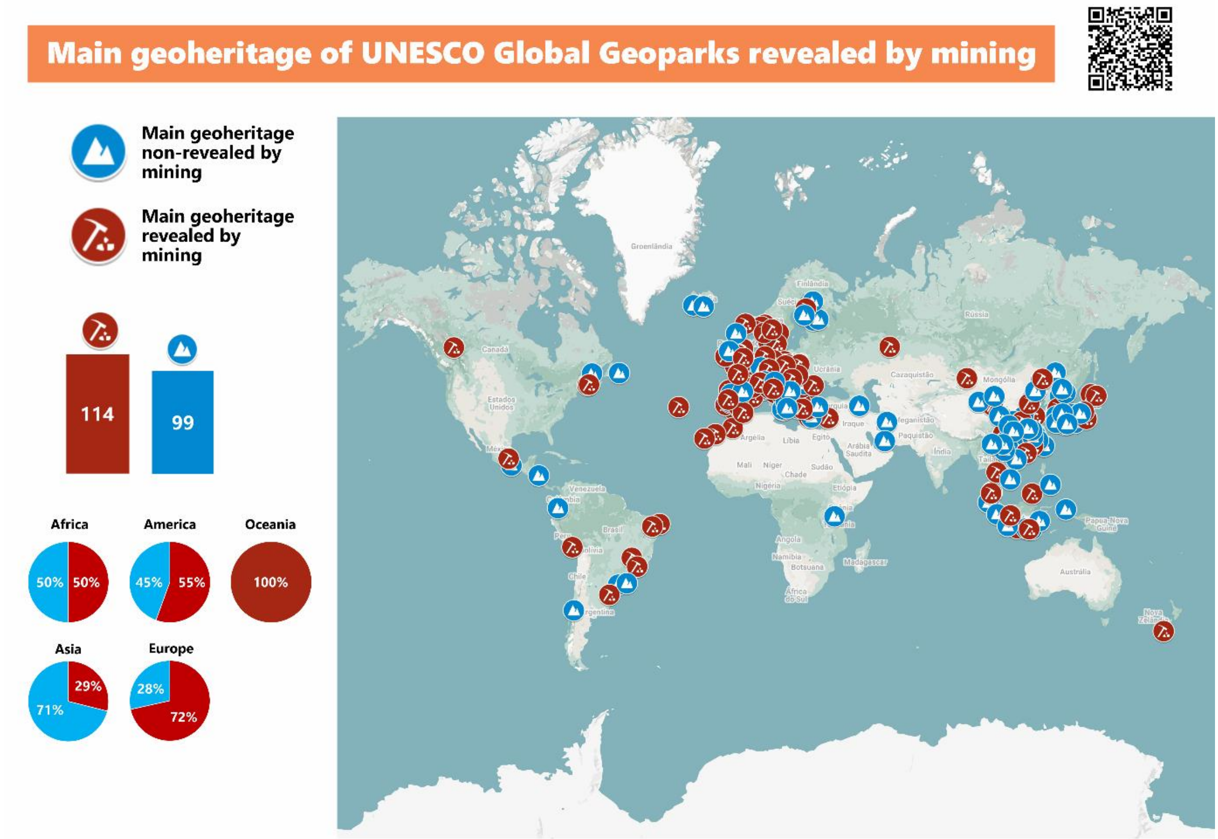

Figure 7. World map with the distribution of UNESCO Global Geoparks geoheritage revealed by mining.

The UGGps' geoheritage not related to mining has a minor area compared with the ones that present this relation, on average approximately 415.4 km^2 less for the UGGps' geoheritage revealed by mining (Table 5). From the 213 UGGps, 148 have geosites related to mining in their geoheritage inventories, wherein 113 reveals totally or partially the main geoheritage or at least partially one of the central secondaries' interests. The Tumbler Ridge UGGp is an exception of territory with geoheritage increased by mining, but the mine or quarry that generated the interest is not included in the inventory. Fifty-nine of all territories have the presence of active mining in its inventory of geosites, which represent 27.7% of the network total, being 45 of these areas are responsible for the discovery or present the geoheritage of the UGGps – in other words, 39% of the 114 territories related to mining have an active industry in its geosites. These relations can be summarised in Table 5.

Table 5. Relating area, geosites and industrial activity to mining in UNESCO Global Geoparks.

Does mining reveal geoheritage in UGGps?	UGGps quantity	Area average (km²)	Presence of mining in geosites	Active mining in the geosites	Active mining in the geosites (%)
Yes	114	2,227.06	113	45	39.82
No	99	2,642.47	35	14	40
Total	213	2,420	148	59	39.86

Regarding types of main geoheritage revealed by mining in the UGGps (Table 6), the paleontological type has the most significant number, followed by stratigraphical, igneous, tectonic, mineralogical, geomorphological, glacial, sedimentary, cosmogenic and metamorphic. Taking into account the proportion between the UGGps exposed by mining and those not exposed, the mineralogical and cosmogenic types are the ones that have the most considerable dependence on mining. Paleontological, stratigraphical, sedimentary, igneous, and tectonic geoheritage comprise most mining-exposed in geopark's territories. Hydrogeological, geomorphological, and metamorphic are the types that are less related to mining expositions.

Table 6. UNESCO Global Geoparks main geoheritage types and their relation with mining expositions.

The main geoheritage exposed by/in mining	Yes	Yes (%)	No	No (%)	Total
Igneous	33	53,22	29	46,77	62
Paleontological	45	71,43	18	28,57	63
Tectonic	31	50,82	30	49,18	61
Geomorphological	12	26,09	34	73,91	46
Stratigraphical	35	59,32	24	40,68	59
Glacial	12	66,67	6	33,33	18
Mineralogical	19	100	0	0	19
Hydrogeological	1	14,29	6	85,71	7
Sedimentary	10	58,82	7	41,18	17
Cosmogenic	3	100	0	0	3
Metamorphic	2	33,33	4	66,67	6

Correlating the presence of geoheritage in mining exposures with mineral resources in the UGGps, the 'Construction minerals' was the category with better performance – present in 64.91% of the 114 UGGps, followed in order of importance by: 'Metallic minerals' with 53.51%, 'Industrial minerals' with 52.63%, 'Energetic minerals' with 27.19%, 'Agriculture minerals' with 11.4% and 'Gemstones' with

9.65%. The class ‘Mineral water’ appeared in 5.05% of the 99 UGGps without mining relevance to the main geoheritage charge. In this category of geoparks, the most relevant classes of mineral resources were: ‘Industrial minerals’ at 32.32%, ‘Construction minerals’ at 48.83%, ‘Metallic minerals’ at 20.2%, ‘Energetic minerals’ at 11.11%, ‘Mineral water’ as mentioned, ‘Agriculture minerals’ and ‘Gemstones’ both with 4.04%.

Two significant relations were observed in analysing regressions in the geoheritage types and classes of mineral resources, both in the mining-geoheritage geoparks (Table 7). These correlations were represented by:

(1) the exposures of igneous geoheritage in exploitations of ‘Construction minerals’. Given this relationship, it is expected that for every new geopark with "construction minerals" as a mineral resource, there will be an increase of around 31% in igneous geoheritage;

(2) the relationship between mineralogical geoheritage and the exploitation of "Metallic minerals". This relationship indicates that for every new territory with "Metallic Minerals" resources, there is a 65% probability of increasing the geological heritage.

Table 7. Multiple linear regression between geoheritage types and resources classes in the UNESCO Global Geoparks, wherein β is the regression coefficient, and p represents the p-value.

Geoheritage type	Energetic minerals		Gemstones		Agriculture minerals		Construction minerals		Industrial minerals		Metallic minerals	
	β	p	β	p	β	p	β	p	β	p	β	p
Sedimentary	0,06	0,62	-0,01	0,87	-0,18	0,06	0,06	0,76	-0,11	0,47	0,20	0,27
Cosmogenic	-0,11	0,53	0,01	0,87	-0,21	0,15	0,16	0,58	0,18	0,45	-0,05	0,84
Metamorphic	-0,13	0,52	0,02	0,83	-0,17	0,31	0,18	0,60	0,35	0,20	-0,26	0,41
Igneous	-0,12	0,17	0,04	0,29	-0,20	0,00	**0,31**	**0,03**	-0,13	0,24	0,09	0,49
Paleontological	-0,01	0,92	0,03	0,51	-0,14	0,06	0,02	0,91	-0,04	0,71	0,12	0,38
Tectonic	-0,02	0,76	-0,01	0,81	-0,12	0,06	0,13	0,34	-0,13	0,23	0,16	0,19
Geomorphological	-0,05	0,61	0,01	0,81	-0,06	0,41	-0,01	0,97	0,01	0,97	0,10	0,51
Stratigraphical	0,01	0,93	0,05	0,16	-0,14	0,02	-0,02	0,90	0,12	0,23	-0,07	0,57
Glacial	-0,14	0,30	0,02	0,79	-0,05	0,68	0,05	0,84	0,27	0,15	-0,15	0,48
Mineralogical	-0,09	0,32	0,06	0,16	-0,16	0,03	-0,36	0,01	-0,11	0,37	**0,65**	**0,00**
Hydrogeological	-0,03	0,91	-0,01	0,93	-0,10	0,66	0,44	0,34	-0,10	0,80	-0,21	0,64

Investigating the UGGps’ classification according to the five classes of significance of mining to exhibit the geoheritage (Figure 8a), it was possible to verify in terms of quantity of geoparks that does not have its geoheritage charge revealed by mining: 64 or 30.04% of the UGGps for ‘None’, 35 or 16.43% for ‘Low’. On the other hand, the UGGps’ geoheritage impacted positively by mining was 48 or 22.53% for ‘Intermediate’, 29 or 13.61% for ‘High’, and 37 or 17.37% for ‘Very High’. Into these positive relations of mining and geoheritage classes, the ‘Intermediate’ one presented the best growth rate with 2.4 UGGps/year, followed by ‘Very High’ with 1.8 UGGp/year and ‘High’ with ‘1.4’ UGGp/year (Figure 8b).

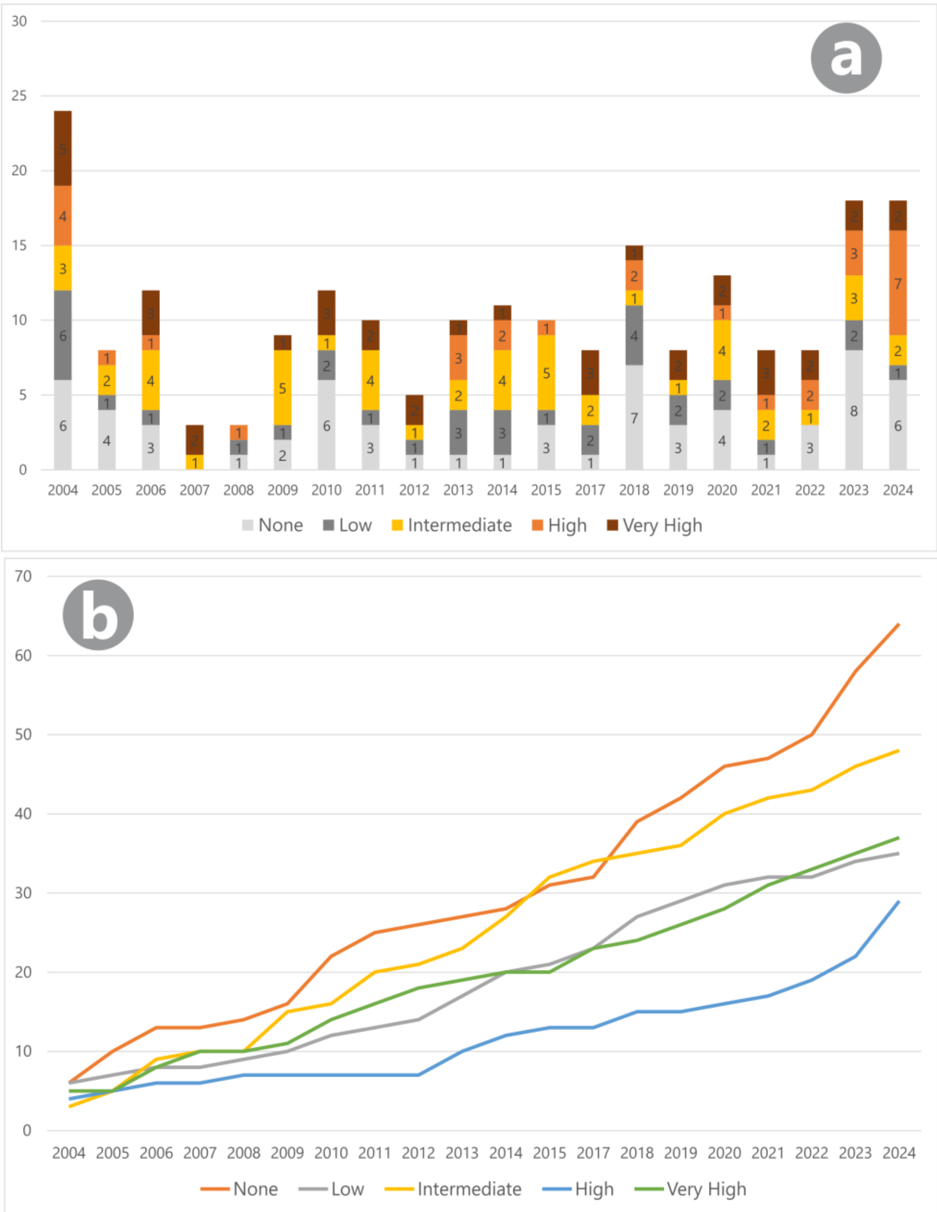

Figure 8. The expansion of UNESCO Global Geoparks was revealed by mining along the 20 years of the network. (a) Absolute quantity and (b) Accumulated quantity of geoparks for each relevant class.

The relevance classes for mining exposures obtained the highest values in the mineralogical, cosmogenic and paleontological typologies. The first case has all related territories in the 'High' or 'Very High' classes. In the second typology, two-thirds of the geoparks are 'Very High' concerning the mining dependence to exhibit the central geoheritage. Half of the territories with paleontological heritage highlights presented the two highest classes of mining outcrops. Sedimentary, igneous, stratigraphical, and tectonic typologies were also well related to the openings of the mines to reveal geoheritage. The mining exposures are less relevant in revealing hydrogeological, geomorphological, and metamorphic features. These relations can be found in the Fig. 9.

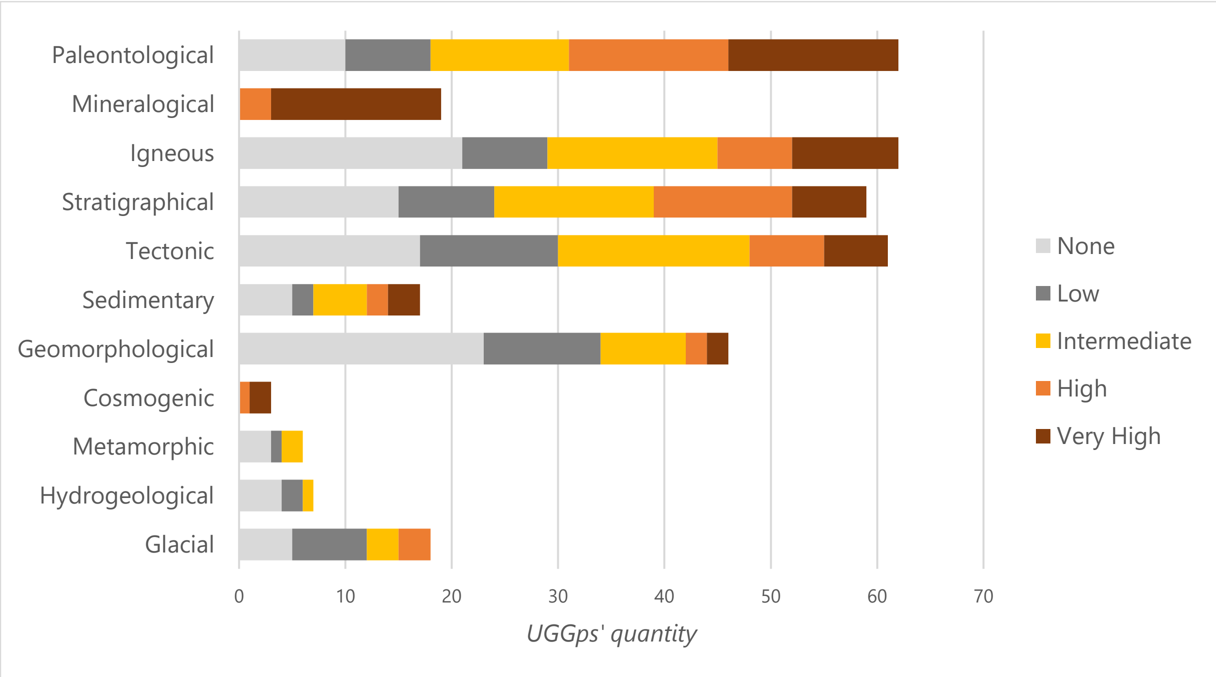

Figure 9. The relevance of mining exposures to reveal geoheritage in UNESCO Global Geoparks.

Delving into the geoparks' geoheritage revealed by mining, we find a distinct concentration in the 'Very High' UGGps. These are predominantly found in European geoparks, particularly in Germany, Italy, and the United Kingdom, with smaller quantities in America (mainly in Brazil) and Asian continents (principally in China). The most significant types of geoheritage discovered in mining are mineralogical, paleontological, and igneous, which represent 67.74% of the total geoheritage types in this class. Stratigraphical, tectonic, sedimentary, cosmogenic, and, lately, geomorphological types have also been identified as having 'Very High' relevance for mining discoveries of the UGGps' main geoheritage charge.

40.54% of the ‘Very High’ geoparks have active mining in their geoheritage inventory. The mineral resources in this class are not only abundant but also diverse, mainly based on ‘Construction minerals’ (30.34%), ‘Metallic minerals’ (23.59%), and ‘Industrial minerals’ (22.47%). This variety is further complemented by ‘Energetic minerals’, ‘Agriculture minerals’, and ‘Gemstones’.

In the class ‘High’, the same trend of European dominance is kept, increasing the proportion of Asian UGGps and decreasing the American ones. China has five territories in this class, trailed by France with three, the United Kingdom, Germany, the Netherlands and Spain with two each. Respectively, paleontological, stratigraphical, igneous and tectonic types of geoheritage are the most revealed in this class. The mineralogical, glacial, sedimentary, geomorphological and cosmogenic are in lower proportions.

For ‘High” UGGps, just 11 or 37.93% of the territories have active mining in the sites of the inventory, concentrated in China (i.e., Xiangxi, Zigong, Funiushan, Shennongjia UGGps) and France (i.e., Normandie-Maine, Monts d'Ardèche UGGps). ‘Industrial minerals’ (30%) together ‘Construction minerals’ (27.14%), and ‘Metallic minerals’ (22.86%) are the most frequent resources in these geoparks, followed by ‘Energetic minerals’, ‘Agriculture minerals’ and ‘Gemstones’.

Our research uncovers a significant global trend: at least one country from each continent hosts a geopark classified as ‘Intermediate’ in terms of mining significance. Europe leads with 32 geoparks, followed by Asia with 11, America with three, and Africa and Oceania with one each. The ‘Intermediate’ UGGps are primarily focused on territories with tectonic, igneous, stratigraphical, and paleontological interests, which make up 21.95% to 17.07% of the geoparks in this class. Geomorphological, sedimentary, glacial, metamorphic, and hydrogeological interests are also present. 39.58% of the 48 ‘Intermediate’ UGGps have active mining in their inventories. Spain (i.e., Lanzarote and Chinijo Islands, Las Loras, El Hierro UGGps) and China (i.e., Arxan, Zhangye, Wangwushan-Daimeishan UGGps) each have three geoparks containing active extractive industry in geosites.

‘Construction minerals’ (29.47%), ‘Metallic minerals’ (27.37%) and ‘Industrial minerals’ (21.05%) are the most representative categories of mined resources in the ‘Intermediate’ territories, ‘Energetic minerals’, ‘Agriculture minerals’ and ‘Gemstones’ are presented in inferior quantities. Figure 10 presents the distribution of geoheritage related to mining classes in the UGGps, a visual representation of the global impact of mining on geoheritage.

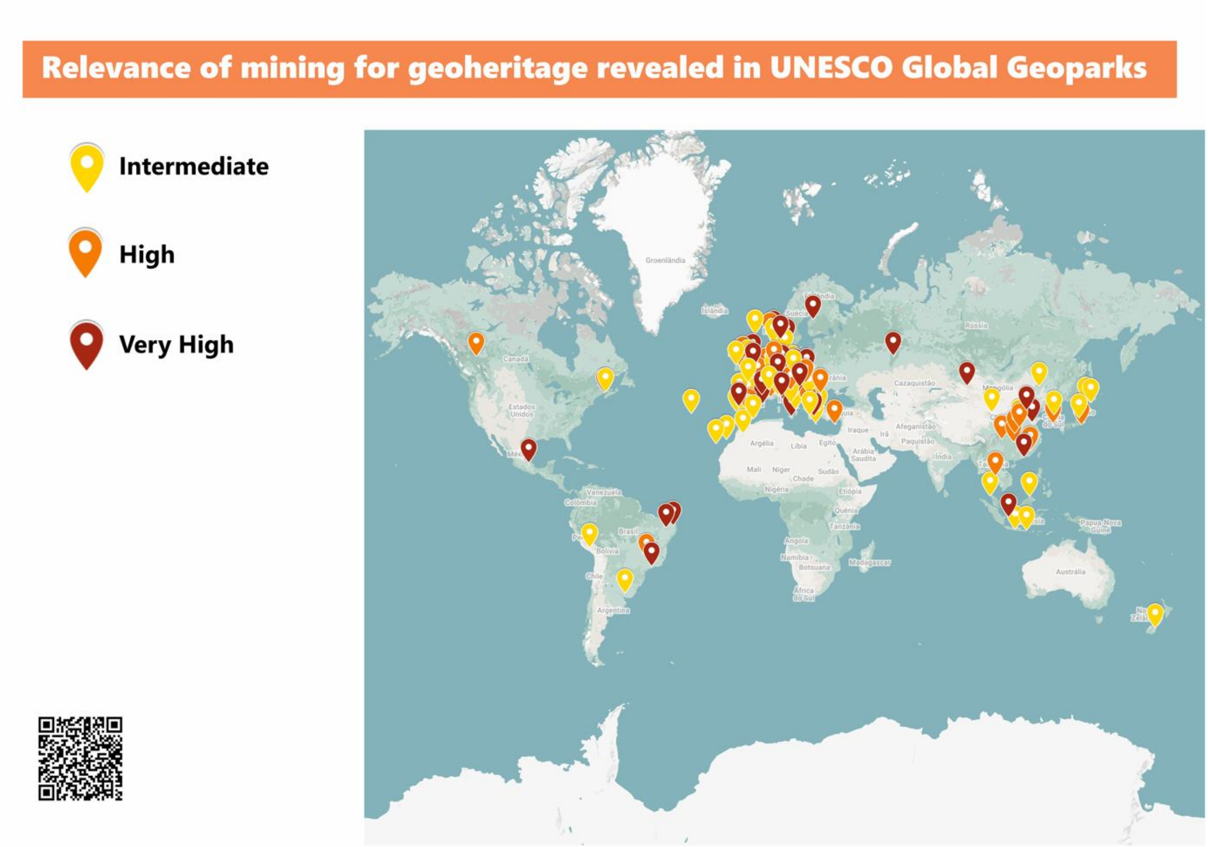

Figure 10. World map with the distribution of UNESCO Global Geoparks revealed by mining and its relevance for geoheritage.

4.2. Mining-related Actions and Infrastructure in the UNESCO Global Geoparks

At least 76 UGGps have made some contribution to mining-related infrastructures, designations or museum collections, which corresponds to 35.68% of the network. Concerning actions recorded in the geoparks' annual reports, 54 UGGp have signed up to use geological sites related to mining, mining heritage or partnerships with the extractive industry in geoconservation and sustainable development. For both infrastructure and actions, the increase of relevance of mining for geoheritage implies a significant proportional quantity of collaborations concerning mining environments. For instance, 89.19% of the 'Very High' geoparks registered the presence of some touristic, educational or conservation infrastructure related or because of mining exposing geoheritage. The same class has about 59.46% UGGps promoting measures about the mining theme. From 'Very High' to 'None', this proportion decreased to less than 5% of the territories promoting initiatives related to the theme.

There are many examples of infrastructures, recognitions, and collections generated from discoveries on the mining exploitation front. It is possible to mention as an illustration: mining communitarian and metallurgical museums; geological museums – including geodiversity, paleontological, volcanic, mineralogical, cosmogenic and mineral resources specific expositions and collections; education, interpretation and information centres; small private expositions in mining companies; rehabilitated sites (e.g., art spaces, aquatic centre in former quarries); cultural centres; mining routes and thematic parks; mining monuments (i.e., botanical garden in Kielce with the representation of historical Pb exploitations, Holy Cross Mountains UGGp; Aquatic leisure centre in the Oeste UGGp); geology amateurs clubs; mining colleges (i.e., Zijin Mining College in the Logyan UGGp). Mining in geoparks also contributed to the generation and protection of specimens for natural collections in museums; national and international recognitions for geological sites (e.g., UNESCO WHS, IUGS Geoheritage Site, IUGS Heritage Stone site, Natura 2000 site); establishment of protected areas (e.g., natural monuments, cultural mining park).

Concerning initiatives related to mining and mineral resources, a better performance was detected in terms of investment and infrastructure, with actions such as (1) improving accessibility, safety, and interpretation (e.g., rehabilitation of fences, patrol routes, inauguration of lorry rail tracks): (2) installation of renewable energy systems at mining sites; (3) construction and modernisation of exhibition centres and interpretation centres; (4) creation and expansion of geological and mining routes (e.g., cycle paths, tourist routes in former mines); (5) regional investment projects for the renovation of mining regions; (6) maintaining staff specialised in mining and geological heritage.

Education-based actions are also well documented on UGGps mining sites. Examples include public awareness activities, materials and mascots related to the mining theme; training for young technicians, 3D models and virtual tours through underground galleries; a youth camp in an open-cast mine; teacher training and tour guide training; an educational program focused on mineral resources and games related to geosites in mining environments.

Conservation initiatives and stakeholder involvement are also relevant in mining areas in UGGps. The main activities developed for conservation have involved: active mines' geological sites protection, photogrammetry of geosites in quarries, mining areas restoration (e.g., construction of mining museum, hiking areas), the inclusion of mining sites in geoconservation management planning, creation and designation of protected areas, mining and geological heritages or mineral resources inventories elaboration, geoconservation specific projects for restoring of outcrops in mines and acquisition of quarry terrains.

Parallelly, the geoparks have been developed within the community and mining industry through several joint works, for example, (1) the election of the geological site of the year, (2) the foundation of tourism and conservation associations for mining sites, (3) voluntary works for renewing and restoring abandoned mining spaces; (4) meetings of partners; (5) celebration of special days related to mining; (6) actions for the conservation of active and abandoned mines (e.g., waste removal in quarries, guided tour organisation, giving up of mining fronts to conserve geoheritage exposures); (7) regional, national and international groups for the discussion of mining and geoconservation (i.e., meeting of the partners of the Portuguese geological and mining sites, EGN mining workgroup, mining company staff participating of the scientific committee of geoparks); (8) production of documentaries and TV series about mining history.

Subsequently, tourism and policy were also promoted within mining in the UGGps. Regarding geotourism and mining: (1) practices of tourism and adventure sports (e.g., mining trails walks and hiking, guided tours); (2) recognition of industrial tourism; (3) interpretation improvement planning, development of geological, cultural and cycling routes through mines sites; (4) adaptation of mines for geotourism practices. Good practices of policies implementation: (1) governmental partnerships and collaborations (e.g., geological surveys agreements, mapping mining heritage, training of geotourism guides); (2) intervention in mining activity or rehabilitation processes (e.g., stopped landfill recovery application; (3) interruption of quarries with relevant geoheritage, closure of fossil fuels mining in the geopark); (4) establishment of protected areas and creation of legal mechanisms for mining in geological sites.

Additionally, there were recorded actions to strengthen culture and science related to mining in UGGps (Fig. 11). Art exhibitions in mining museums, events in mining spaces (e.g., national days of mining, local festivals promoted in mines), miners and geopark mining history documentation, archaeological surveys in mines ruins (i.e., prehistorical and Roman mines) are the cultural connections with mining in UGGps. The scientific realisations and uses were focused on research projects financed mainly by universities (e.g., geomorphological mapping in old quarries, sustainability in the mining industry and undergraduate final projects on mineral resources theme) and promotion of scientific conferences.

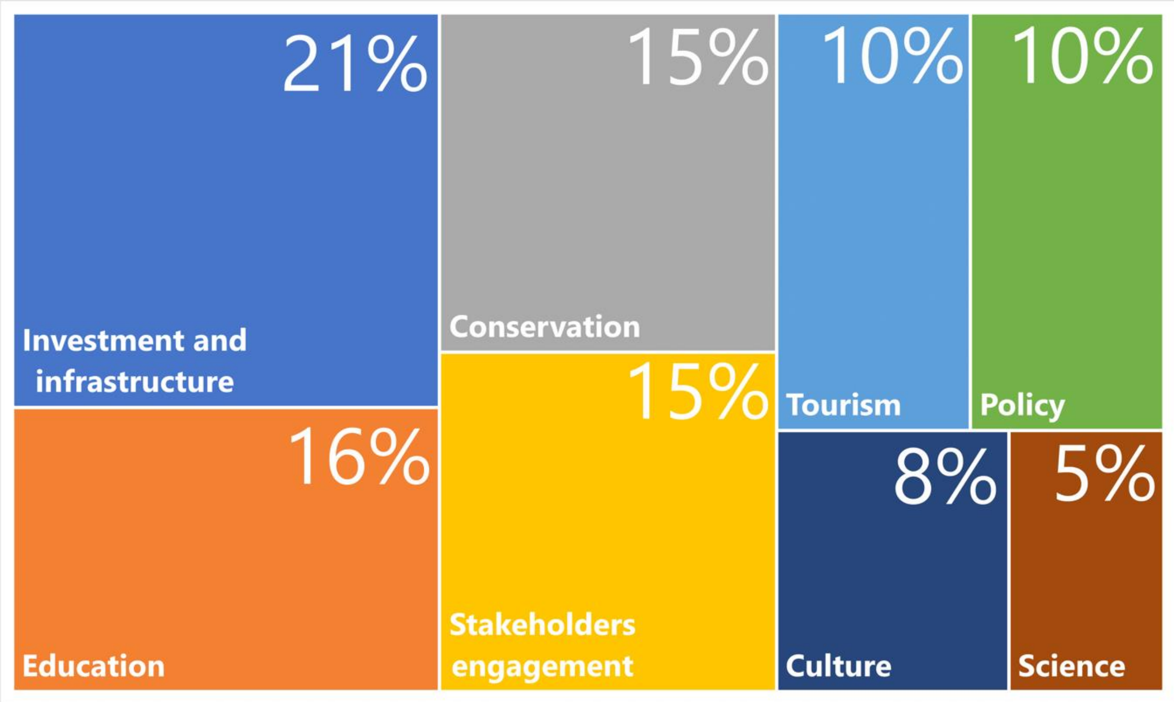

Figure 11. Quantity of sustainable actions related to mining implemented in the UNESCO Global Geoparks.

4.3. Geodiversity Balance in the Mina Brejuí, Seridó UNESCO Global Geopark

The mining response in terms of abiotic ecosystem services was defined for the Mina Brejuí geosite area – coincident with the mining concession delimitation, considering its geodiversity variables' influences, geosite scale and impact in the Seridó UGGp region (based on Costa et al., 2024). Twenty-two different impacts provided by mining were identified – 14 benefits and eight liabilities, divided into six regarding regulation services, six attributed to supporting services, four to provisioning services, and six to cultural services.

Three benefits were mapped to regulation services. The active mining proportionated three abiotic benefits. The formation of anthropogenic minerals and karst features in the underground galleries and old open pits is related principally to carbon sequestration and secondarily to rock and water cycles. The second benefit is the accumulation of water in the underground saloons and galleries, which is connected with the water cycle of that semiarid region. The last regulation benefit was the reduction of mountain slopes' declivity and control of natural disasters in the Serra Branca surroundings. Three losses of benefits were recognised for regulation services. The stream degradation and construction of artificial reservoirs and the generation and accumulation of anthropic sediments impacted the water cycle, soil erosion regulation, water quality and biogeochemical cycles (Petta et al., 2014). Lastly, the emission of pollutant gases resulting from the mineral transformation impacts the air quality, climate regulation and atmosphere chemistry.

For the supporting benefits, generating carbonate-rich tailings (Fig. 12a) enabled the development of caatinga and invasive vegetation in an anthropised soil (Bernardino et al., 2023). The underground galleries excavated in schist, gneiss, calc-silicate and marble rocks are a new habitat platform for endemic species living, mainly bats, lizards, insects and other photophobic fauna, similar to caves' environment support. The artificial reservoirs in the mining area support the avifauna's water supply. On the other hand, the liabilities are stream siltation, modifications on the mountain range habitats (Fig. 12b) and waste storage. The first service damage impacts the water life support. The second interferes with the habitat provision of surface rocks and landforms, and the third impacts the presence of natural soil as a provider of habitats.

Regarding provisioning, the primary material related to the mine is the scheelite concentrated, but also subproducts such as pyrite, molybdenite, copper and other metals. The high carbonate content in the waste made these materials sources of agriculture and construction commodities (Ramos Filho et al., 2021). Cement and cattle food supply companies have acquired these residues as industrial inputs. The consumption of resources was considered one of the two liabilities for Provisioning services. Water usage on an industrial scale affects the water provisioning for the region (Dantas, 2015), adding to the destruction of good exemplars of mineral specimens and rock outcrops (Fig. 12c) in the mining fronts and processing.

The cultural aspects were the only ones, among all the services listed, with only benefits recorded. Five general benefits could be listed: (1) monuments and arts related to mining and geological heritages (wellness and health); (2) mining community use of the tailing dunes for sports trail and events (wellness and health); (3) geotourism activities in the mining theme park (recreation); (4) spirituality related to the miner's protection (human history); (5) international geoheritage revealing (knowledge) (Fig.12d); and (6) mine's rocks used in plazas and monuments constructions (human history).

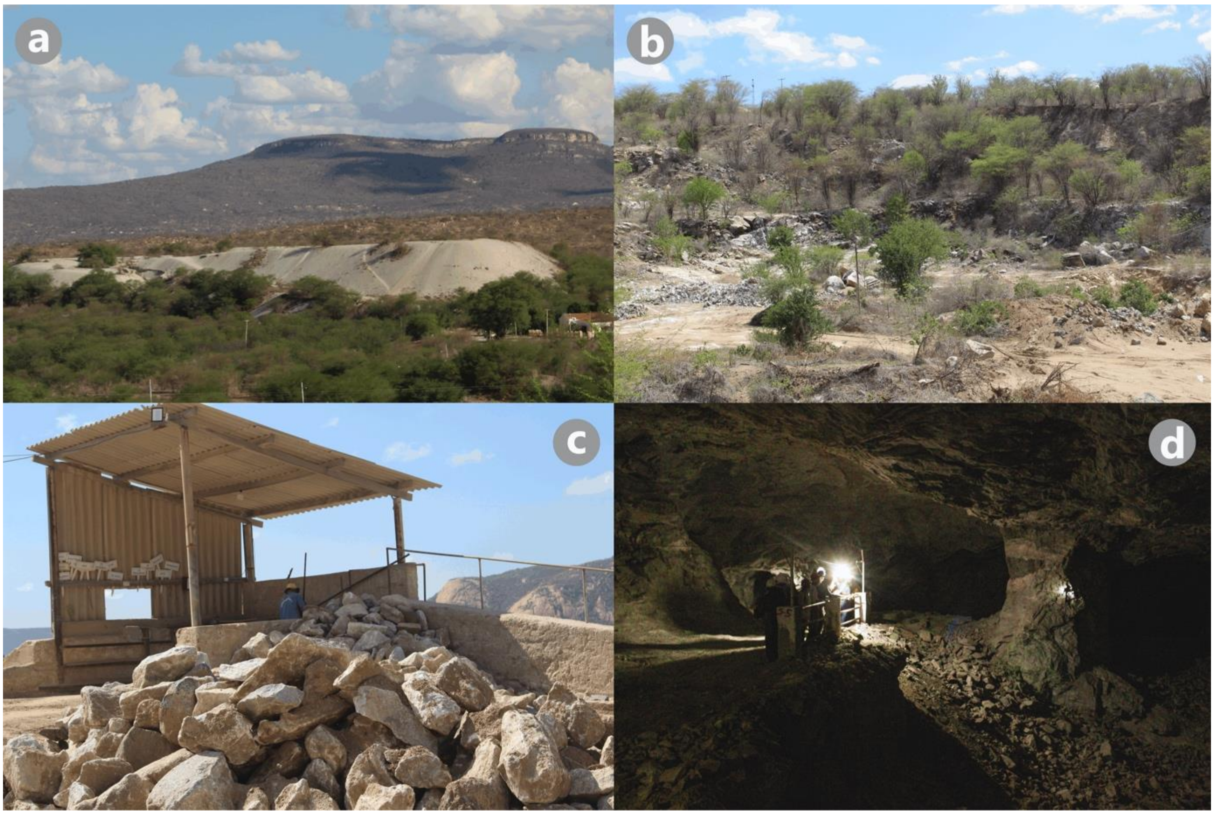

Figure 12. Abiotic ecosystem benefits and liabilities generated by mining in the Mina Brejuí geosite. (a) tailing dunes and soil generation; (b) mountain slopes control and mountain habitat disturbance; (c) destruction of rocks and minerals specimens in the mineral processing; (d) scheelite mineralisation tourism, science and conservation usages.

The mining in the Mina Brejuí geosite contributed positively to the total geodiversity balance scheme. The sum of all criteria weights or the Geosystem Services Balance considering the benefits and liabilities was positive, having a value of “17”. The positive values of the Cultural services benefits maximised this contribution. This group of services identified a value of “24” for the analysed geosite. Provisioning was also another positive contribution with a value of “1”. The Regulation services obtained a “-5” value and the Supporting services a “-3”, with the same quantity of benefits and liabilities, highlighting the significant magnitude values related to the negative impacts. The mining provided a geodiversity gain of “56” for the geosite, whereas it produced “-39” in geodiversity losses. These relations are represented in Figure 13, showing the geodiversity balance provided by mining in the Mina Brejuí geosite.

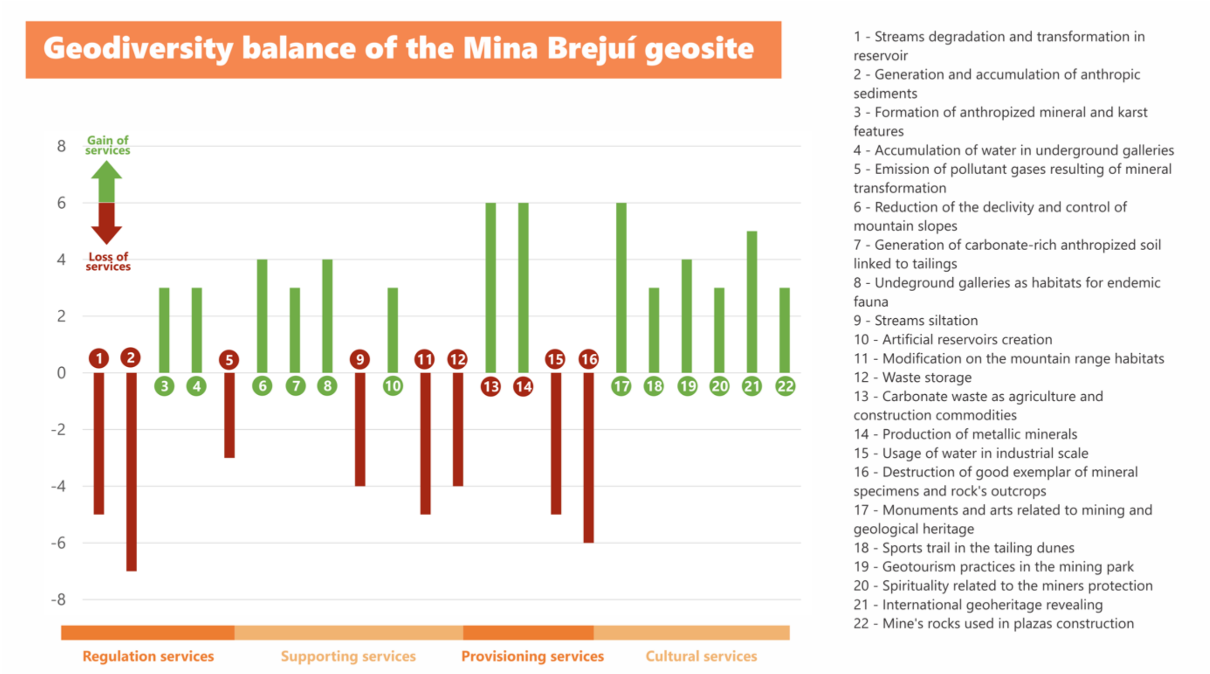

Figure 13. Geodiversity balance of mining influencing geosystem services in the Mina Brejuí geosite.

The most significant values identified for the coverage criteria were associated with the generation and accumulation of anthropic sediments, usage of water on an industrial scale, monuments and arts related to mining and geological heritage, production of metallic minerals and carbonate waste as agriculture and construction commodities – all these found in regional level. For magnitude values, the stream's degradation and transformation in reservoir, generation and accumulation of anthropic sediments, carbonate waste as agriculture and construction commodities, production of metallic minerals, monuments and arts related to mining and geological heritages and international geoheritage registered significant changes. The destruction of good examples of mineral specimens and rock outcrops had a unique impact, and it was reported that it was impossible to restore initial conditions.

5. Discussions

5.1. Contributions of Mining in the UNESCO Global Geoparks' Geoheritage

Mining has contributed significantly to scientific advances regarding the global geoheritage, especially the UGGps. The most considerable quantity of geoparks in the UGG network expressed the relation 'geoheritage-mining', disclosing an unexpected formula for the success of geoconservation strategies and geoheritage valuing strictly connected with mining exposures. This information could represent a milestone for a new understanding of revealing geoheritage's international significance and its positive relation with mining. Facts indicate that the exploitation of mineral resources is a constant and non-renewable source of the Earth's natural history, leading to the urgent need to propose legislation and collaborative mechanisms to geoheritage's safeguard for this industry context. This is consistent with IUCN Resolution WCC 88/2020, which considers mining activities often exposing geoheritage with rich natural environments (Monge-Ganuzas et al., 2024).

Two critical steps for protecting geoheritage in mining environments are the recognition of geological sites and the designation of protected areas. An exceptional step was taken by including five geological sites revealed by mining in UGGps, in IUGS "The First 100 IUGS geological heritage sites" (IUGS, 2022), namely: (1) the giant trilobites of Canelas quarry in Arouca; (2) the first appearance of Devonian tetrapods of Zachelmie quarry in the Holy Cross Mountains; (3) the giant mercury deposit of Almadén mine in Calatrava Volcanoes; (4) the Eocene lagerstatten of Messel Pit in Bergstraße-Odenwald; (5) the Cretaceous rhyolitic columnar disjunctions revealed by High Island dam quarries in Hong Kong).

Other recognitions were identified for mines and quarries in the UGGps, reaffirming the significance of these sites for establishing sustainable territories. Various GSSPs (e.g., Salzgitter-Salder limestone quarry of the Harz, Braunschweiger Land UGGp as Turonian- Coniacian stratotype), WHS (e.g., Hwasun Dolmen Welded Tuff with Bronze Age quarries for tombs constructions in the Mudeungsan UGGp; or the first natural WHS Messel Pit), IUGS Heritage Stone (e.g., the Tezoantla tuff quarry in Comarca Minera UGGp) and national scientific interest sites - SSSIs (e.g., Parys Mountain copper mine in GeoMôn UGGp as Wales' SSSI) highlighted the importance of mining for international geoheritage content in geoparks (Conway and Wood, 2016; Kim and Lim, 2019; Frey et al., 2021; Walaszczyk et al., 2022; González-León et al., 2024).

Along the network expansion, the results showed the crescent contribution of the geoparks' geoheritage revealed in mining, showing that international geoheritage recognition is not necessarily dependent on non-modified natural landscapes. The higher demand for geoconservation strategies is moving toward the strongly anthropised areas recovering, mainly in rural regions (Conlin & Jolliffe, 2010). This gradual change, mainly after the first two years of the network, could represent a change of the conceptual understanding not only in the acceptance criteria and GGN management for new territories. It equally shows the stakeholders' willingness of the applicant territories to accept its geoheritage exposed by mining as relevant and sufficient to propose geoconservation strategies for international recognition.

Geographically, the territories with geoheritage most influenced by mining are concentrated in Europe, in absolute and proportional numbers, which different possible reasons could explain:

(1) the historical geoscientific pioneer progress (Hansen, 2009);

(2) the medieval Europe industrial development (Wrigley et al., 2017);

(3) network evaluation bias on the recognition of more anthropised areas in Europe (Tiess and Ruban, 2013);

(4) the tradition or legal facilities to approach mining rehabilitated areas for geoconservation purposes;

(5) the Asian geoparks understanding of natural relics and cultural appreciation of less anthropised landscapes (Yang et al., 2011);

(6) geomorphological or hydrogeological heritage features significant frequency as highlights in non-European geoparks;

(7) the lack of data regarding the geological sites, mainly on the Chinese geoparks;

(8) geoparks have opted to hide information regarding the presence of the geological sites and geoheritage related to active mining (Figure 14) (e.g., Galve clay and Peace Rivel Coal mines where several dinosaur holotypes were discovered in the Maestrazgo and Tumbler Ridge UGGps, not presenting these sites on the inventory; active quarries in the Azores UGGp exposing volcanic strata) (Broatch, 1987);

(9) presence of own geoheritage conservation programs (e.g., the cases of the United States of America and Australia) (Ren and Simonson, 2013);

(10) More resources are needed to recognise and invest in geoscience programs in Latin American and African countries (North et al., 2020).

On the other hand, the results accentuated the opportunity to develop UGGps' projects with international geoheritage in active or abandoned environments, especially in the south hemisphere, supported by the mining industry. Knowing that the American, African and Asian continents registered a sort of conflict with the extractive sector (Dietz & Engels, 2018), the geoparks could be powerful tools to improve social responsibility and cleaner production mechanisms within mining regions. Encouraging projects of geoparks together mining industry in the American and African continents can represent hereafter a better distribution of territories through the continents (Wang et al., 2022). Another critical point in this discussion is the numerous contributions of the 'invisibles' of the geosciences – community locals, miners and enthusiasts – to discover geoheritage in mining environments (Carvalho & Leonardi, 2022), wherein geoparks' are potential tools to give the deserved visibility to these actors.

Figure 14. Active mining sites exhibiting the main geoheritage are not included in the geoparks' inventories. (a) active clay open-pit in Galve, Maestrazgo UNESCO Global Geopark; (b) tuff quarrying in the Faial Island, Azores UGGp.

The significance of mining for the geopark's geoheritage was further augmented with (1) the existence of geological sites in active or closed mining environments in almost 70% of the UGGps; (2) the occurrence of quarries and mines sites in UGGps without geoheritage-mining relation; (3) almost one-third of the geoparks having active mining in its geoheritage sites' inventories; (4) approximately the same proportion of active mining in inventories in geoparks with presence or absence of the relation mining-main geoheritage; and (5) presence of a significant proportional concentration of geoheritage charge – the UGGps' where the geoheritage was revealed by mining needed less territorial area to present its geoheritage charge; (6) dependence of geoheritage types to be revealed in mining environments. These are six complementary proofs of the permanent and active collaboration of the extractive industry for the UGGps' territorial construction boosted by geoscientific knowledge.

Mining contributed differently to geoheritage exposition, sometimes just composing complementarily of the principal geoheritage content as in the Estrela, Famenne-Ardenne, Ngorongoro Lengai or Imbabura UGGps where the main geoheritage interests were not generated by mining, but significative or some presence of traditional mines or quarries are composing the cultural heritage of the territories principally (Imbabura, 2017; Fernandes et al., 2021; Scoon, 2021; Quiniff et al., 2024).

The intermediate relations represented territories wherein mining generated good expositions but was not the main highlight of geoheritage content. The Terra de Cavaleiros UGGp is an instance of this occasion. Some parts of the ophiolitic sequence and Rheic paleocean registers are exposed in the Vale da Porca and Salselas quarry (Pereira & Pereira, 2020).

In cases such as Ries UGGp, mining has increased the scientific value of the features, increasing the knowledge about geological processes and their products. Through its expositions, the Amerdinger, Lindley, Kalvarienberg and other quarries significantly expanded the understanding of the Ries' impact crater (Bringemeier, 1994).

The very high relations mean the significant geological discoveries triggered by mining fronts. Without these expositions, features such as the trilobites of the Arouca UGGp or the scheelite skarn deposit of the Seridó and many others in geoparks would never have been discovered and studied (Sá et al., 2007; Côrrea et al., 2020).

The concomitant active extraction and conservation cases are proof of the possibility of extraction and geoparks harmonious convivence. Multiple times exhausted galleries, wells or pits are used to conserve outcrops or sections (Shenhaijing salt well in Zigong UGGp), protecting the sites from biodiversity-based restoration or alternative social uses (i.e., Messel Pit in Bergstraße-Odenwald UGGp in protecting the fossils instead of a trash dump installation), extraction areas are interrupted to preserve an exposition (i.e., Brejuí mine in Seridó UGGp) or created museums to safeguard ex situ geoheritage (i.e., Valério quarry in Arouca UGGp) (Yuning et al., 2013; Henriques & Carvalho, 2022; Costa et al., 2024a).

The fact that UGGps' geoheritage related to mining displayed minor delimitated areas could be explained by localised occurrences of the main geoheritage interest within mineral deposits localised expressions in fewer municipalities or districts. The Copper Coast, English Riviera and Black Country UGGps are examples of small mining districts with concentrated main geological sites in quarries and mines (Maugh, 1975; Hurley, 2005; Hart & Smart, 2021; Worton et al., 2021).

The UGGps' geoheritage types of interest most dependent on mining discoveries were mineralogical, cosmogenic and paleontological. About the main mineralogical heritage highlights dependent on mining expositions: (1) mineralisation styles linked to tectonic, igneous or stratigraphy (e.g., five different styles of mineralisations and discovery of 33 minerals' species in the Lavreotiki UGGp, Fig. 15a); (2) ultra-diverse mineral assemblies (e.g., copper mineral diversity in the Copper Coast UGGp), rare mineralisations (e.g., cinnabar in the Idrija UGGp); (3) world-class deposits (e.g., gold and silver deposits in the Comarca Minera UGGp; (4) REE's deposits in a pegmatite in the Keketuohai UGGp), continental most important deposits (e.g., scheelite deposits in the Seridó UGGp); and (5) type-localities for minerals (e.g., Karawanken UGGp as dravite type-locality) (Moreton, 2007; Kavcic & Peljhan, 2010; Liu et al., 2014; Bedjanic et al., 2017; Voudouris et al., 2021; García-Sánchez et al., 2021; Costa et al., 2024a).

Also, meteorite impact craters and impactites (i.e., Ries, Lappajärvi and Belitong UGGps) presented a total influence of mining to be revealed or increased significantly in terms of scientific values (Tagle et al., 2007; Bhinekawati et al., 2020; Lambert & Reimold, 2023).

The UGG's paleontological records (Fig. 15b and 15c) discovered in mining sites presented milestones on: (1) taphonomy (e.g., giant fossils of trilobites of Arouca UGGp; lagerstatten deposits of Araripe or Black Country UGGps); (2) biostratigraphy (e.g., first occurrence of terrestrial species in Thuringia Inselsberg-Drei Gleichen UGGp, the last European dinosaurs of Origens UGGp); (3) palaeoanthropological discoveries (e.g., the Peking Man in the Fangshan UGGp); (4) ichnofossils (e.g., dinosaur footprints in the Terra.Vita UGGp and Maestrazgo UGGp), holotypes discoveries (e.g., new dinosaurs specimens in the Maestrazgo UGGp) and (5) other fossils interests (Yu & Liu, 2009; Fohlert & Brauner, 2010; Gascón & Pérez-Lorente, 2012; Dias & Carvalho, 2020; Sá et al., 2021; Fischer et al., 2021; Worton et al., 2021).

Other interests, such as glacial, stratigraphical, sedimentary, igneous, and tectonic, have obtained the majority of expositions related to mining. Despite the unexpected mining relation among the glacial interest, the De Hondsrug UGGp presented an excellent example of a sand pit exhibiting stratigraphical registers of the Last Glaciation (Fig. 15d). For the same interest, the Sunnhordland UGGp has an outstanding example of a quarry exposing glacial erratic boulders (Koopman, 2013; Uleberg & Pederson, 2013). The Mechetlino's Kungurian stage of the Permian section in the Yangan-Tau UGGp was exposed in a limestone quarry. Another relevant stratigraphical heritage highlight is the Gyllene GSSP in the Platåbergens UGGp, which was exposed in an old shale quarry (Chernykh et al., 2020; Samani, 2021). Sedimentary international registers are presented in the gypsum quarries with shallow-marine sedimentation structures in the Maiella UGGp (Agostini & Colecchia, 2019).

Many examples on igneous heritage (Fig. 15e) were revealed or better exposed in quarries, such the columnar disjunctions in the Hong Kong and Papuk UGGps (McFeat-Smith et al., 1989; Balen et al., 2023), maar volcanic deposits in the Bakony-Balaton and Calatrava Volcanoes UGGps, Precambrian igneous complexes in the Yimengshan UGGp (Cai et al., 2019) and recent volcanoes systems in El Hierro, Colca y Volcanes de Andagua and Azores UGGps (Lima et al., 2014; Galas et al., 2018; Dóniz-Páez & Pérez, 2023). Regarding tectonic features (Fig. 15f), the Paleozoic greenschists' tectonic window of the Alpi Apuane UGGp is a classic example of geoscientific knowledge improvement after mineral deposit exploration and subsequent exploitation in underground mines (Amorfini et al., 2015). The Troodos ophiolite in the homonymous UGGp is another illustration of mining contributing to increasing a region's scientific value (Bukala et al., 2016).

Figure 15. Multiple geoheritage types uncovered by mining in UNESCO Global Geoparks: (a) Metalliferous skarn deposit in the Plaka former mines geosite, Lavreotiki UGGp; (b) Giant trilobites of Valério active quarry geosite, Arouca UGGp; (c) Ababuj sauropods and theropods footprints in a former quarry for road construction, Maestrazgo UGGp; (d) Three Ice Ages registers in the Donderen former sand pit, De Hondsrug UGGp (Koopman, 2013); (e) Rhyolitic columnar disjunctions in the Rupnica former quarry, Papuk UGGp (Balen et al., 2023); (f) Marbles of Salselas former quarry as part of a Variscan deformed ophiolitic sequence, Terra de Cavaleiros UGGp.

Concerning metamorphic and geomorphological main interests, there are rare examples where mining has revealed geoheritage. The GeoMôn UGGp has internationally relevant sites with Precambrian blueschist rocks revealed in copper mines or quartzite quarries (Conway & Wood, 2016). The Gunung Sewu UGGp showed an example of karst landform interest amplified after the exploitation of calcite and phosphates (Gunung Sewu, 2024). The hydrogeological typology was unique to geoheritage typology without a strong relation with mining to increase the scientific value of its features in the UGGps.

5.1.1. Mining methods, mineral resources and geological heritage

Mining methods are crucial factors influencing the discovery or exposure of geoheritage of international value in UGGps. The exploitation techniques can significantly enhance the visibility of geoheritage features. The methods are adapted to maximise the feasibility of the mineral deposits; sometimes, the geoheritage features align with the ore geological conditions, but occasionally not precisely when related to wall rock characteristics. Furthermore, some mineral resources categories are mined in well-defined methods because of deposit scale or geometry characteristics, such as metallic and energetic minerals in large open-pit or underground mines, non-metallic minerals in small quarries and surface mining methods (Hartman & Mutmansky, 2002; Corke et al., 2008).

Many geoparks have been developed thanks to the scientific contributions of previous intensive prospection of mineral resources, opening windows to geoheritage directly or indirectly linked to the mined ore (Prosser, 2018). When compared to other artificial expositions in civil construction (e.g., tunnels, railroads, roads, dams, bridges), energy production (e.g., geothermal, wind, hydroelectric plants), agriculture, etc., the extractive industry has significantly contributed to the exposition of UGGps' geoheritage. Figure 16 illustrates different mining methods patterns' in revealing distinct geoheritage types based on the UGGps'.

The mining of construction minerals resources, mainly stones extraction, could be interpreted as the foremost expositor of UGGps' geoheritage due to its characteristics, avoiding the use of destructive explosives, opening large walls and 3D mining benches and preserving good visibility of the slope faces (Yarahmadi et al., 2015; Bustillo, 2021). The exploitation of ornamental foliated or well-stratified rocks has the potential to preserve geological records of detailed scale as fossils, minerals and structures – as shown in the cases of Permian fossils found in the Plattenbruch ornamental sandstones in the Thuringia Inselsberg UGGp (Voigt & Haubold, 2000).

The strong correlation between the igneous features and the construction resources can be explained in several examples of quarries of basalts, rhyolites, tuffs and granitoids revealing relevant and rare igneous intrusion or cooling structures. In the Mourne Gullion Strangford UGGp, the main geosite exhibiting a ring-dyke was found in a granodiorite quarry (Baxter, 2008). At least three geoparks have their main sites exposing hexagonal rock columns after quarry activities (e.g., Hong Kong, Papuk, Novohrad-Nógrád UGGps) (McFeat-Smith et al., 1989; Balen et al., 2023; Harangi et al., 2023).

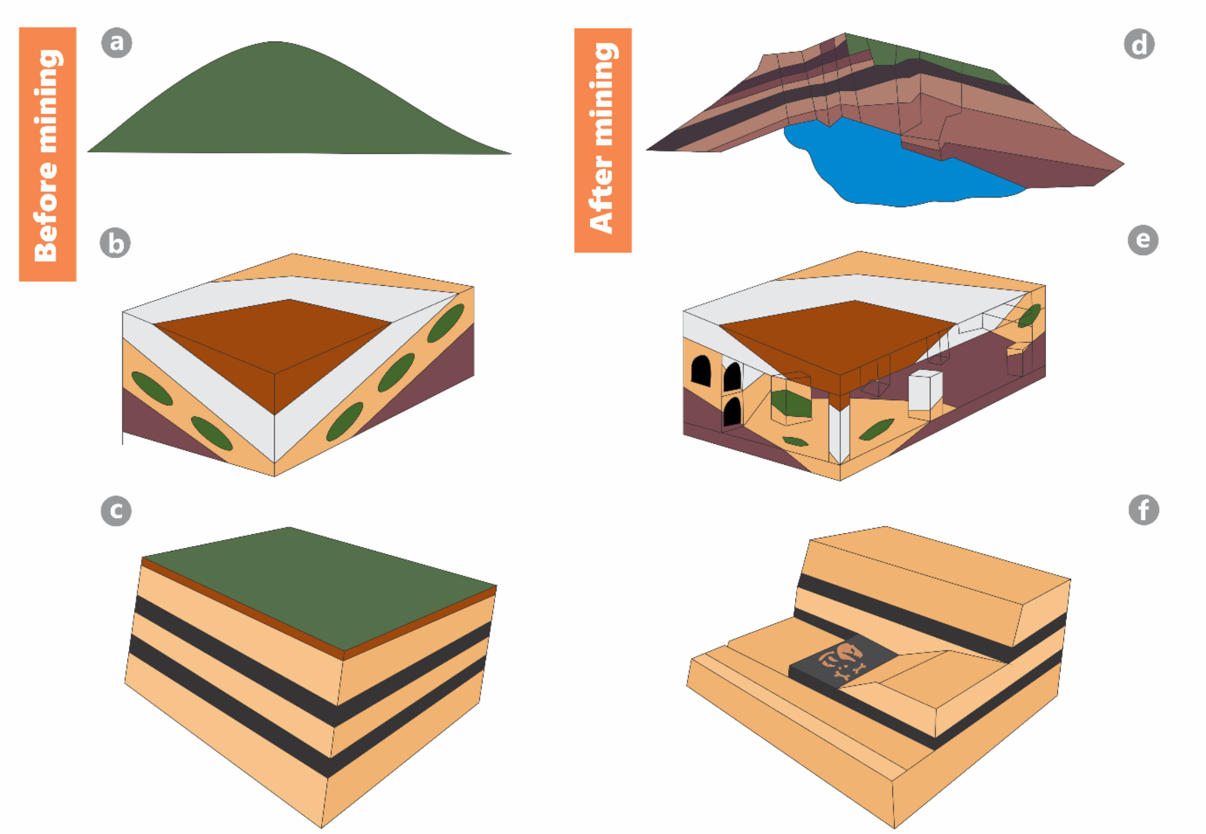

Figure 16. Mining methods influencing the geoheritage discovery according to the UNESCO Global Geoparks' patterns: (a) and (d) exposure of strata in open pits or dimensional stone quarrying; (b) and (e) opening of underground accesses and keeping lithological and mineralogical registers in pillars, saloons, floor, ceiling etc.; (c) and (f) strip mining exposing strata tops and fossiliferous records.

The metallic minerals are similarly strongly correlated with geoheritage, especially to mineralogical type discoveries. For these raw materials, the principal methods of mining that contributed to mineralogical heritage discoveries were the underground techniques. The extensive and spread underground galleries' levels allow discoveries due to a series of technical and environmental factors: (1) the underground accesses follow the whole orebodies geometry in different topographical levels, conditions of mineralisation (i.e., host and wall rocks interactions and diversity), observation sections; (2) natural rocky structures of geomechanical or infrastructure support (e.g., pillars, rooms, walls, ramps, ventilation tubes, shafts) preserves mineral occurrences even into ore mineralised boundaries; (3) isolation to weathering and erosion on the surface, allowing the discovery of fresh rock and reducing the rhythm of rock alterations when compared to open pit mining; (4) formation of new rare mineral specimens due the interaction of water, fluids and gases, during or after mining, with uncovered minerals (Hamrin et al., 2001; Hazen et al., 2017). Lavreotiki, Ore of the Alps, Tuscan Mining Park, Comarca Minera, Gea Norvegica, Caçapava, North Pennines AONB, Seridó, Copper Coast and Longyan are examples of metallic assemblies hosting an important mineralogical highlight found in underground mines.

Gemstones mining is directly linked to mineralogical heritage added to some cases of cosmogenic, tectonic and paleontological heritages, such as the case of the Buzău Land UGGp amber fossils mined as gems in the past (Buzau Land, 2020). Active metallic and gems mining in the geoparks are the main font of polemics concerning the lousy relationship between geoconservation, exploitation and sale of geological heritage. The UGG network recommends avoiding official partnerships or the image association of the brand with these mining activities in the geoparks because of the imprecision of the geological objects' commercialisation guidelines (Geoparks Secretariat, 2006), even taking into account the national legitimacy of these industries and recognising the geological heritage relevance and related efforts of the companies to conserve the Earth’s memory.

Such contradiction led the companies to avoid the geoparks’ initiatives. Policies and practices to engage the mining industry in the sustainable development strategies of UGGps are two tasks that GGN could propose in the following years of the network, as well as the criteria present in the aspiring’s evaluation of the actions against illegal mining. Except in cases of extreme need of conservation, when the extractive activity represents a significant threat to keep the geoheritage significance or occurrence, the geopark should take actions through dialogue and actioning the legally responsible institutions to interrupt the mining activity, taking measures to protect that Earth memory (e.g., delimitation of core protection areas in geological sites limiting industrial expansion in the Huanggang Dabieshan UGGp). (Deng and Zou, 2021).

Industrial, energetic, and agricultural mining methods displayed a positive relation in uncovering stratigraphical, paleontological, sedimentary, and less often tectonic heritage features. The mining fronts developed to extract horizontal or following strata trends in an open pit, strip surface methods or room and pillar underground mining (Nelson, 2011) have the potential to uncover stratigraphical boundaries, sequences, top and bottom with ichnofossils, fossil deposits and salt tectonics structures. Rocca di Cerere, Central Catalonia and Causses du Quercy UGGp are robust cases where sulphates, phosphates and salt mining revealed spectacular evaporitic sections (Fíguis et al., 2013; Versaci & Cardaci, 2019; Pélissié et al., 2021). Table 8 summarises the relations between mining and geoheritage regarding their different techniques and typologies, mainly in 'Very High' geoparks related to mining exposures.

Table 8. Best examples of mining revealing geoheritage in UNESCO Global Geoparks.

Geoheritage typology	Geosite and Geopark	Mining activity	Geoheritage highlight revealed
Igneous	High Island Reservoir, Hong Kong UGGp	Rhyolite as aggregate quarries for the construction of the East Dam	Globally rare Cretaceous rhyolitic hexagonal columns
	Camlough Quarry, Mourne Gullion Strangford UGGp	Granodiorite aggregate disused quarry	Cross-section through the Slieve Gullion Paleogene ring-dyke system
Paleontological	Pedra Cariri, Araripe UGGp	Laminated dimensional limestone active quarry	Lagerstätte Cretaceous invertebrates and vertebrates
	Messel Pit, Bergstraße-Odenwald UGGp	Former open-cast bituminous oil shale mine	Richest fossil site with registers of the Eocene exceptional mammal fossils
	Valério Quarry, Arouca UGGp	Dimensional slate active quarry	Ordovician giant trilobites
Tectonic	"Ślichowice" nature reserve, Holy Cross Mountains UGGp	Disused quarries of industrial limestone	Spectacular Variscan tectonic folds
	Levigliani's mine, Alpi Apuane UGGp	Cinnabar former underground mine	Ore following the basement's axial plane in the Apuane Alps tectonic window context
Geomorphological	Gua Potro Bunder caverns, Gunung Sewu UGGp	Guano phosphate and lime old artisanal quarrying	Tropical karst landforms affected by neotectonics
Stratigraphical	Gyllene golden spike, Platåbergens UGGp	Abandoned shale quarry	Reference site for the first appearance of the Tetragraptus graptolite in the Floian Stage
	Lummaton Quarry, English Riviera UGGp	Former dimensional limestone quarry	Shell beds of the Givetian age that led to the naming of the Devonian Period
Glacial	Donderen Section, De Hondsrug UGGp	Former sandpit	Saalian glaciations sedimentation register
	Siggjo Quarry, Sunnhordland UGGp	Prehistoric rhyolite quarry for arrowhead fabrication	Glacial erratic blocks
Mineralogical	Plaka Geosite, Lavreotiki UGGp	Zinc, iron, arsenic and lead underground galleries and small open-pit fronts	Five different styles of mineralisation (porphyry, skarn, carbonate replacement, vein, breccia)

	Boqueirão Geosite, Seridó UGGp	Active Paraíba-tourmaline gemstone underground galleries	World rarest gemmological Paraíba blue-indicolite variety in Gondwanan pegmatites
Sedimentary	Nieuw-Namen, Schelde Delta UGGp	Meester Van der Heijden clay and sand aggregate former quarry	Neogene shallow sea and glacial sedimentary facies deposition and Quaternary fluvial facies showing the sea-level evolution in the Netherlands
Cosmogenic	Kannanlahti and Kannanlahti quarries, Lappajärvi UGGp	Sand and gravel former aggregate quarry and karnaite active quarry	Impact diamonds and impactite sediments transported by glaciers and suevite layers in karnaite as meteorite impact evidence
	Amerdinger Quarry, Ries UGGp	Suevite former quarry	Diamonds of impact as proof of the Miocene asteroid impact
Metamorphic	Parys Mountain mine and Llanlleiana Geosite, GeoMôn UGGp	Formers copper open-pit mine and dimensional quartzite quarry	Different registers of metamorphic facies and grades related to the Caledonian orogeny

5.2. Mining and UNESCO Global Geoparks for Implementing Sustainable Development

The actions promoted by UGGps involving mining are mainly related to eight of the 17 Sustainable Development Goals (SDGs) of the UN's 2030 Agenda. The territories within the mining theme performed better, in frequency order, the SDGs: 11 (Sustainable cities and communities), 4 (Quality education), 17 (Partnerships for the goals), 12 (Responsible consumption and production), 3 (Good health and well-being), 7 (Affordable and clean energy) and 8 (Decent work and economic growth). Good practices already adopted by the geoparks (Fig. 17) could serve as guidelines for future application in other territories. It is essential to mention the significant impact of the geoparks' infrastructures related to mining on implementing these SDGs. Museums and interpretative centres boosted SDG 4. Mining routes and thematic parks are essential to the SDGs 3, 11 and 8. SDGs 7, 12 and 17 are correlated with the presence of rehabilitated sites and SDG 16 is linked with national and international recognitions.

The same references noted the importance of these infrastructures for carrying out the initiatives. The Casa da Pedra, Araripe UGGp, was built with Cariri limestones from active quarry fronts, and it is a reference to the promotion of culture, tourism and education (Henriques et al., 2020). An entire city was re-created from the paleontological discoveries in the Galve city, Maestrazgo UGGp. This traditional village now has an identity totally (Fig. 18a) associated with the *Iguanodon galvensis* found in the clay open pit nearby, containing a paleontological museum, graffiti panel, real-size models of dinosaurs and dinosaur trails (Alcalá et al., 2018). The Currais Novos city, Seridó UGGp, is an example of a theme city (Fig. 18b) of the scheelite mineral. The historical mine produced a material legacy with themed plazas, streets, hotels and museums supporting the geotourism practised in the geopark (Costa et al., 2024a).

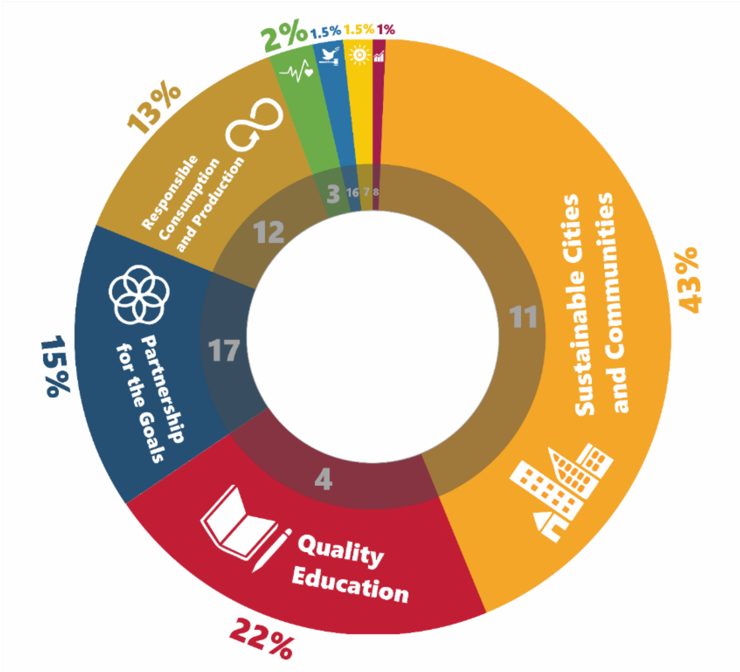

Figure 16. UNESCO Global Geoparks' performance in implementing the 2030 Agenda goals with actions related to mining.

Similar mining cities and related infrastructures with strong mining culture appeal are also presented in many 'Very High' UGGps, for instance: Bakony-Balaton, Belitong; Black Country (Fig. 18c); Caçapava; Comarca Minera; Harz, Braunschweiger Land; Holy Cross Mountains; Karawanken, Keketuohai, Lavreotiki, North Pennines AONB, Novohrad-Nógrád, Ore of the Alps, Rocca di Cerere, TERRA.vita and Tuscan Mining Park.

When comparing the SDGs most effectively promoted in mining with those identified by UNESCO (2015) as best implemented by the geoparks, goals 3, 4, 8, 11, 12, and 17 are common to both. Conversely, when comparing the mining industry's role (Monteiro et al., 2019) with the role of geoparks in mining, the primary shared goal is SDG 8. Additionally, SDG 4 is strongly developed in mining when associated with geoparks.

The geoparks, in partnership with the mining sector could improve its sustainable development performances, redirecting the attention to proposing initiatives to implement the SDGs 1, 2, 5, 6, 9, 10, 13, 14 and 15 through geotourism (e.g., geoproducts with mining identity), community engagement, solutions to reduce water and soil pollution, environmental projects to reuse waste (e.g., possible association with local handicraft), incentivising the participation of the traditional communities, cooperating with other UNESCO designation programs, qualification of stakeholders on nature conservation (López, 2020; Vafadari & Cooper, 2020; Rodrigues et al., 2021).

Among the studied initiatives, it is possible to suggest the best practice for each SDG mapped for the UGGps. Table 9 linked the UGGps' initiatives to the principal correspondent SDG implemented. Starting with SDG 3, the Ore of the Alps UGGp developed a joint program with Thuringia Inselsberg-Drei Gleichen UGGp, structuring an adventure sports route through historical mining sites (Fig. 18d). This is an exciting application for multiple geographically close geoparks containing mining sites to offer integrated geotouristic routes.

Table 9. UNESCO Global Geoparks' practices regarding mining in the 2030 Agenda implementation.

Goal	Action	Geoparks
SDG 3 – Good health and well-being	Development of routes of adventure sports through mines (i.e., hiking, mountain biking, climbing)	Ore of the Alps, Thuringia Inselsberg-Drei Gleichen, Troodos, Muskauer Faltenbogen
SDG 4 – Quality education	Events, expositions and exhibitions about mining	Bergstraße-Odenwald, Tuscan Mining Park, Villuercas Ibores Jara
	Mining in games and educational interactive strategies (i.e., mascots, books, competitions, camps, virtual tours, videos)	Bergstraße-Odenwald, Keketuohai, Seridó, TERRA.vita, Buzău Land, Zigong, Copper Coast, Cabo de Gata-Níjar, Ries, Muskauer Faltenbogen, Naturtejo, Terras de Cavaleiros, Vulkaneifel
	Scholar and touristic excursions to geosites in mining environments	Harz, Braunschweiger Land, Keketuohai, Land of Extinct Volcanoes, De Hondsrug, Naturtejo
	Training and capacitation about mining, including technical education	North Pennines AONB, Tuscan Mining Park, Origens, Rocca di Cerere, Zigong
SDG 7 – Affordable and clean energy	Implementing clean energy sources in mining environments or districts	TERRA.vita UGGp, Bükk Region
SDG 8 – Decent work and economic growth	Geopark staff responsible for geoconservation and geology of mining heritage	Troodos
SDG 11 – Sustainable cities and communities	Structuration, restoration, recognition or promotion of mining geosites, trails, museums, interpretation centres and routes	Central Catalonia, Bakony-Balaton, Caçapava, Causses du Quercy, Harz, Braunschweiger Land, Lavreotiki, North Pennines AONB, Rocca di Cerere, Thuringia Inselsberg-Drei Gleichen, TERRA.vita, Izu Peninsula, Zigong, Ries, Copper Coast, Muskauer Faltenbogen, Magma, Sierras Subbéticas
	Inventory of sites related to mines, mineral resources, mining heritage and outcrops	Yangan-Tau UGGp, Origens, Zigong, Chelmos Vouraikos, Naturtejo, Sesia Val Grande
	Festivals and events promoted in mining environments	Thuringia Inselsberg-Drei Gleichen, Swabian Alb, Armorique, Magma, Sesia Val Grande
SDG 12 – Responsible consumption and production	Interrupting or prohibiting mining activities for geoconservation purposes	Bakony-Balaton, Chelmos Vouraikos, Mt. Apoi
	Active convivence between mining and geoconservation	Seridó, Calatrava Volcanoes, Maestrazgo, Normandie-Maine

	Rehabilitation of closed mining environments	Keketuohai, Bakony-Balaton, Batur, Beaujolais, Vulkaneifel
SDG 16 – Peace, justice and strong institutions	Law promulgation for geoconservation in mining environments	Comarca Minera
	The mining industry's active participation in the geopark's committees	M'Goun
SDG 17 – Partnerships for the goals	Cooperations and partnerships to promote geoconservation in mining environments and districts within governmental, non-governmental, academic communities and other geoparks	Alpi Apuane, Araripe, Central Catalonia, Bergstraße-Odenwald, Tuscan Mining Park, Thuringia Inselsberg-Drei Gleichen, Fforest Fawr, Izu Peninsula, Zigong, Batur, Itoigawa, Armorique, Magma, Naturtejo, Terras de Cavaleiros, Muskauer Faltenbogen

The SDG 4 have many actions that could be highlighted since the training and educational programs (i.e., oil and gas mineral resources educational program of the De Hondsrug UGGp; mining heritage training program of the North Pennines AONB UGGp; teachers' qualification in nature and mining of the Tuscan Mining Park UGGp; technical training of young talents with salt drilling technology in the Zigong UGGp) to new technologies applied to education (i.e., Tankardstown 3D Tour in the Copper Coast UGGp, Figure 18e; Piesberg quarry photogrammetry in the TERRA.vita UGGp) and geosciences interactive events (i.e., the geological games in the Brejuí mine promoted by the Seridó UGGp).

The replacement of fossil fuels for green energy sources in the Silbersee mining tunnels used for geotourism and Bükk Region UGGp are among the best actions to implement SDG 5. With a professional dedicated to geology and geoconservation of mining heritage, the Troodos UGGp is an example of a direct generation of SDG 8 relating to mining and geoconservation in the UGGps.

The actions regarding SDG 11 are mostly projects of restructuration of former quarries or mines to promote geotourism and geoconservation added to mining sites inventories and events in mining environments. The Thuringia Inselsberg-Drei Gleichen and Lavreotiki UGGps (Fig. 18f) have a regular programme on maintaining mining sites' safety and renovation, which is crucial to developing geotourism securely. The Bakony-Balaton UGGp has a voluntary programme with local people and non-governmental organisation members to valorise abandoned quarries and mining trails.

Figure 18. Mining-related infrastructures and initiatives in UNESCO Global Geoparks: (a) panel thematised with dinosaurs found in the Galve mine, Maestrazgo UGGp; (b) Mining wagons as a frequent symbol of the Currais Novos municipality, Seridó UGGp; (c) Ammonite houses in the Fossil View street close to the Wren's Nest former quarry and geosite, Black Country UGGp; (d) GeoEnjoyRelaxProgramme program of the Ore of the Alps UGGp along mining traces (Geopark Erz der Alpen, 2017); (e) Virtual tour in the Tankardstown mine, Copper Coast UGGp (Copper Coast Geopark, 2013); (f) Protection fences installed in the Lavriou-Kumarizas Mining centre, Lavreotiki UGGp.

The collaborative and voluntary engagement of private companies in the geoheritage conservation in two UGGps' examples are the best cleaner production initiatives related to SDG 12. The Seridó and Calatrava Volcanoes UGGp benefited from the efforts of mining companies to protect expositions, donate land for infrastructure construction and open for geotourism promotion. In other cases, the government within the geopark's management intervened in stopping operations to protect the geological heritage, such as the cases of Bakony-Balaton, Chelmos Vouraikos, Beaujolais and Mt. Apoi UGGps.

The Comarca Minera and M'Goun UGGps bring valorous initiatives concerning democracy and justice for geoconservation related to mining sites. The environmental law promoted in the Hidalgo Mexican state to protect the geoheritage associated with mining sites and the participation of mining stakeholders in the M'Goun's scientific committee is related to SDG 16. SDG 17 provides a good example of how the other continental networks of geoparks could quickly adapt. The EGN has a collaborative thematic workgroup to discuss mining in the geoparks. In national terms, the partnerships with universities, mining institutes, government and companies were fundamental examples observed in the UGGps (e.g., partnership between Araripe UGGp and the Brazilian National Mining Agency for the observation of paleontological heritage; mining sites inventorying in partnership with the Italian Ministry of Culture in the Tuscan Mining Park UGGp).

5.3. Mining Proportionating Geodiversity Gain

From a biodiversity perspective, rehabilitating mined areas is not solely about restoring the original ecosystem. It is about regenerating the ecosystem with a beneficial purpose, leading to social and ecological benefits. The concept of biodiversity net gain, where the re-creation of a degraded environment aims to exceed its potential biodiversity, is a critical trend in biotic restoration. In essence, the biodiversity gains should more than compensate for the losses.

The ecosystem services are already used as metrics for biodiversity gain evaluation, including the service's spatialisation and monetarisation values (McVittie et al., 2020); This is still a step forward for geodiversity (Puzey & Matthews, 2023). The geodiversity gain or balance is relevant for the total environmental quality assessment of active or degraded mining areas because of the strong correlation between geodiversity hotspots, mineral deposits, and affluent biodiversity areas (Dushin et al., 2020).

The proposed model of geodiversity balance, considering the ecosystem services generated by mining, offered an impact assessment of the abiotic perspective. The Mina Brejuí geosite's results presented benefits and liabilities that could be the basis for improving positive impacts and reducing negatives in a current or future mining rehabilitation planned for geodiversity-based uses. A solid current geoconservation in the mine closure plan for Mina Brejuí should consider the re-establishment of the stream's health and morphology (Stefanidis et al., 2023). It should also consider the maximum reutilization of the tailing dunes (Metsaranta et al., 2018), considering nature-based solutions to solving the principal quantity of liabilities related to regulation and supporting services. It is essential to highlight the necessity of keeping the cultural services (Erikstad et al., 2023) and mainly the geoheritage features with international scientific value, where the benefits contributed to the significant values for the total geosystem services of the site.

Regarding the hostile relations between mining and ecosystem services, mining in the Mina Brejuí geosite followed the global scientific literacy trend (Boldy et al., 2021), in which active mines produced more liabilities for regulating and supporting services. Despite its negative performance in generating liabilities, the provisioning services in the geosite registered a positive balance from the perspective of geodiversity – the opposite of the relation found in the trends. The cultural services have been matched for the active mineral extractive industry, producing significant benefits during mining production. After closure, large contributions were expected for regulating, provisioning, and supporting, reaffirming that these variables should be included in geoconservation-based plans of post-mining areas.

Depending on the techniques of mine development, distinct ecosystem services could be generated or influenced (Seki, 2023). The underground accesses of extraction allowed knowledge and recreation benefits (cultural), positive interferences in the water cycle and carbon sequestration (regulation), and habitat platforms for endemic photophobic fauna (supporting). These benefits reduced the destruction of specimens on production fronts (provisioning liability) in the geodiversity balance assessment.

The highest values found in this evaluation proposed for mining and other industries impacting the geosystem services could represent a positive argument for the implementation of geoconservation uses strategies for a mining restoration project, being in multiple times the leading geological sites or inventories to develop a regional plan of sustainability such the geoparks, specifically as happened in the case of Seridó UNESCO Global Geopark with an equilibrated balance scheme for geosystem services in a regional scale (Costa et al., 2024b).

6. Conclusions

Following the detailed analysis of the relationship between geological heritage and mining activity in UGGps, several conclusions were reached, listed below.

(1) Relevant geoheritage associated with mining exposures has been growing over the 20 years of UGG;
(2) Presence of global geoheritage components in mining exposures;
(3) Geoparks in which there is or has been mining required less territory to find relevant geological heritage;
(4) Mining heritage as a relevant part of cultural legacy in geoparks;
(5) New comprehension of geoheritage commerce in UGGps' active mines;
(6) Establishing a better relationship between geoparks and the mining industry could help increase the number of geoparks outside Europe and reduce global mining conflicts.
(7) Mineralogical, cosmogenic and paleontological heritages showed an extreme dependence on mining to be exposed;

(8) Mineralogical, paleontological, and igneous were the geoheritage types most exposed by mining in terms of relevance. Additionally, stratigraphical and tectonic also presented High and Intermediate significances;
(9) Hydrogeological, geomorphological, and metamorphic types of geoheritage presented their features mainly in natural expositions.

Mining is the lead artificial source for geoheritage expositions, and different mining methods are relevant variables for geoheritage discoveries. The extraction of construction, metallic, and industrial minerals is the main source of exposing geoheritage in the UGGps, with construction and metallic minerals leading to the discovery of igneous and mineralogical types of geoheritage.

Several territories presented educational, touristic or conservation infrastructures related to mining. These infrastructures are essential for promoting initiatives regarding mining environment enhancement. The increase in the mining-geoheritage relationship implied a significant engagement in promoting actions or built infrastructure related to mining. The mining heritage and geological-themes museums were the main contributors to infrastructures for geoparks, supported by ex situ collections found in mining environments.

Several identified mining-related initiatives developed improvements in accessibility, safety, and interpretation infrastructure, contributing to the development of geotourism, education, and community engagement. Other actions in mining environments involved policies for conservation, effective conservation measures, scientific research and events. UGGps mining activities contributed directly to implementing mainly eight SDGs (3, 4, 7, 8, 11, 12, 16 and 17), demonstrating the potentiality of integrating mining and geoparks in advancing multiple sustainable development features.

The successful practices observed in UGGps serve as valuable guidelines for other territories aiming to implement similar initiatives. The main suggestion for the network is the creation of global and continental workgroups or brands on the mining-geoheritage relationship, similar to other projects, likewise GeoFood. Moreover, propositions of UNESCO IGGP's projects framing mining and geoheritage (i.e., IGCP project 637 - HERitage STONES Recognition), spaces in the GGN editorials, and recognising the mining stakeholders' collaborations in geoparks.

The overall geodiversity balance in the Mina Brejuí geosite in the Seridó UGGp was positive for the 22 abiotic ecosystem services promoted by scheelite mining. The study showed that an active mine in a geopark could coexist well with geoconservation and sustainable development in a UGGp, contributing positively to nature and society. Cultural services mainly influence a positive geodiversity net gain, diminishing regulation and supporting net losses. Mitigating the losses means having ideals and equilibrated geosystem services.

The geodiversity balance or net gain approach adapted from Reverte et al. (2020) could support spatialised analysis in multiple scales involving mining temporal studies, complementing Environmental Impact Assessment studies, rehabilitation and geoconservation action plans. This method permitted identifying the main impact's fragilities and strengths as essential perspectives to the mining social and environmental planning. It is recommended that national legal measures be implemented to adopt conservation actions in mine closure situations.

These approaches draw attention to the need to establish guidelines in legislation regarding geoconservation and the recovery of geodiversity in degraded mining areas, protecting vital geological features and developing protocols for scientific, educational and tourist use to enhance communities, following the conclusions of Prosser (2018).

References

Agostini, S., & Colecchia, A. (2019). Scenari di ricerca, innovazione, pianificazione, valorizzazione del patrimonio culturale, produttivo e identitario nella Majella settentrionale. Dai territorio di resistenza alle comunità di patrimonio: percorsi di autorganizzazione e autogoverno, 24.

Alcalá, L., Espílez, E., & Mampel, L. (2018). Ariño: La mina de los dinosaurios. In Fósiles: Nuevos Hallazgos Paleontológicos En Aragón (pp. 111-141). Institución «Fernando el Católico».

Amorfini, A., Bartelletti, A., & Ottria, G. (2015). Enhancing the Geological Heritage of the Apuan Alps Geopark (Italy) Valorisation du géopatrimoine du Géoparc des Alpes Apuanes (Italie). From geoheritage to geoparks, 199.

Balen, D., Schneider, P., Petrinec, Z., Radonić, G., & Pavić, G. (2023). Cretaceous volcanic rock geosites of the Papuk UNESCO Global Geopark (Croatia): scientific aspect of geoheritage in geoeducation, geotourism and geoconservation. Geoconservation research, 6(1), 1-17.

Baxter S (2008). A geological feld guide to Cooley, Gullion, Mourne & Slieve Croob. Geological Survey Ireland, Ireland

Bedjanič, M., & Lenka, R. (2017). "Geo-interpretation": The interpretation of the geological heritage of Karavanke Geopark. in Primošten and Kraków (2014 and 2015), 31.

Bernardino, D. S. D. M., de Menezes, E. H. S., dos Santos, J. Y. G., Diniz, M. T. M., & do Nascimento, M. A. L. (2023). Land Use and Land Cover in the Territory of Seridó UNESCO Global Geopark, Northeast Brazil. Geoheritage, 15(2), 62.

Bhinekawati, R., Nelloh, L. A. M., & Abdurahman, O. (2020). The analysis of entrepreneurial intention in rural area: A case study of bukit peramun geosite in Indonesia. Geo Journal of Tourism and Geosites, 28(1), 80-94.

Boldy, R., Santini, T., Annandale, M., Erskine, P. D., & Sonter, L. J. (2021). Understanding the impacts of mining on ecosystem services through a systematic review. The Extractive Industries and Society, 8(1), 457-466.

Brilha, J. (2016). Inventory and quantitative assessment of geosites and geodiversity sites: a review. *Geoheritage*, 8(2), 119–134.

Brilha, J., Gray, M., Pereira, D. I., & Pereira, P. (2018). Geodiversity: An integrative review as a contribution to the sustainable management of the whole of nature. *Environmental Science & Policy*, *86*, 19-28.

Bringemeier, D. (1994). Petrofabric examination of the main suevite of the Otting Quarry, Nördlinger Ries, Germany.

Broatch, J. C. (1987). Palynologic zonation and correlation of the Peace River coalfield, northeastern British Columbia (Doctoral dissertation, University of British Columbia).

Bukała, M., Zboińska, K., & Szadkowski, M. (2016). Troodos ophiolite mantle section exposed along Atalante Geo-Trail, Troodos Geopark, Cyprus. Geoscience Records, 3(1), 1-6.

Bustillo, R. M. (2021). Dimension Stone. In Construction Materials Springer, Cham. pp. 55–90.

Buzau Land UNESCO Global Geopark. (2020). *UNESCO application dossier*. Retrieved June 5, 2024, from https://buzauland.org/

Cai, Y., Wu, F., Han, J., & Chu, H. (2019). Geoheritage and sustainable development in Yimengshan Geopark. Geoheritage, 11, 991-1003.

Carvalho, I. D. S., & Leonardi, G. (2022). The invisibles of science and the paleontological heritage: the Brazilian study case. Geoheritage, 14(4), 107.

Chakraborty, A., Cooper, M., & Chakraborty, S. (2015). Geosystems as a framework for geoconservation: the case of Japan's Izu Peninsula Geopark. Geoheritage, 7(4), 351–363.

Chernykh, V. V., Kotlyar, G. V., Chuvashov, B. I., Kutygin, R. V., Filimonova, T. V., Sungatullina, G. M., ... & Batalin, G. A. (2020). Multidisciplinary study of the Mechetlino Quarry section (Southern Urals, Russia)—the GSSP candidate for the base of the Kungurian Stage (Lower Permian). Palaeoworld, 29(2), 325-352.

Coglianese, C. (1999). The limits of consensus: The environmental protection system in transition: Toward a more desirable future. Environment: Science and Policy for Sustainable Development, 41(3), 28-33.

Conlin, M., & Jolliffe, L. (2010). What happens when mining leaves?. In *Mining Heritage and Tourism* (pp. 25–32). Routledge.

Conway, J., & Wood, M. (2016). A Geoheritage Case Study: GeoMôn in Wales. Geoheritage and Geotourism A European Perspective. The Boydell Press, Woodbridge, pp. 219–231.

Corrêa, R. S., Oliveira, C. G., Dantas, E. L., & Botelho, N. F. (2020). Hydrothermal footprint related to regional-scale shear zone-controlled scheelite mineralization, Seridó W-skarn system, northeastern Brazil. Journal of South American Earth Sciences, 103, 102755.

Corke, P., Roberts, J., Cunningham, J., & Hainsworth, D. (2008). Mining robotics. Springer handbook of robotics, 1127–1150.

Costa, S. S. S., do Nascimento, M. A. L., & da Silva, M. L. N. (2024a). Geological and mining heritages in the Seridó UNESCO Global Geopark: Ediacaran to Cambrian mineral deposits revealed by historical mines in Northeast Brazil. International Journal of Geoheritage and Parks, 12(2), 311-332.

Costa, S. S. S., do Nascimento, M. A. L., & da Silva, M. L. N. (2024b). Correlating geodiversity and mining in the seridó UNESCO Global Geopark: Spatial and impact analysis in brazilian northeast. Resources Policy, 95, 105196.

Dantas, F. M. (2015). Os direitos constitucionais a água e ao desenvolvimento em um contexto de escassez: o caso de Currais Novos/RN (Master's thesis, Brasil).

Deng, L., & Zou, F. (2021). Orogenic belt landforms of Huanggang Dabieshan UNESCO Global Geopark (China) from geoheritage, geoconservation, geotourism, and sustainable development perspectives. Environmental Earth Sciences, 80(19), 662.

Dias, J. J., & de Souza Carvalho, I. (2020). Remarkable fossil crickets preserved in the Crato Formation (Aptian, Araripe Basin), a Lagerstätten from Brazil. Journal of South American Earth Sciences, 98, 102443.

Dietz, K., & Engels, B. (2018). Contested extractivism: actors and strategies in conflicts over mining. In The Routledge Handbook of Transregional Studies (pp. 275-282). Routledge.

Dóniz-Páez, J., & Pérez, N. M. (2023). El Hierro Island Global Geopark: Diversity of Volcanic Heritage for Geotourism (p. 123). Springer Nature.

Du, Y., & Girault, Y. (2018). A genealogy of UNESCO global geopark: Emergence and evolution. *International Journal of Geoheritage and Parks*, *6*(2), 1-17.

Dushin, A. V., Ignatyeva, M. N., Yurak, V. V., & Ivanov, A. N. (2020). Economic evaluation of environmental impact of mining: Ecosystem approach. Eurasian Mining, pp. 1, 30–36.

Eder, F. W., & Patzak, M. (2004). Geoparks—geological attractions: a tool for public education, recreation and sustainable economic development. *Episodes Journal of International Geoscience, 27*(3), 162-164.

Erikstad, L., Hagen, D., & Simensen, T. (2023). Working with Natural Processes: Restoring a Mining Landscape in the High Arctic, Svalbard, Norway. Geoheritage, 15(3), 87.

Fernandes, G., Tracana, R. B., Castro, E., & Fernandes, M. (2021). Geoeducation and tourism in Estrela UNESCO Global Geopark (Portugal) and its contributions to the construction of a sustainable destination. Mediterranean Protected Areas in the Era of Overtourism: Challenges and Solutions, 137-152.

Fíguls, A., Weller, O., Grandia, F., Bonache, J., González, J., & Lanaspa, R. M. (2013). La primera explotación minera de la sal gema: La Vall Salina de Cardona (Cataluña, España). Chungará (Arica), 45(1), 177-195.

Fischer, T., Chellouche, P., Lockley, M. G., & Meyer, C. A. (2021). The Dinosaur Tracks of Bad Essen-Barkhausen in the UNESCO Global Geopark TERRA. vita (NW Germany): 100 Years of Development from an Industrial Quarry to an Open-air Museum. Geoconservation Research, 4(2), 378–388.

Fohlert, K., & Brauner, S. (2010). The Cabarz locality-an active quarry, a natural monument and an outstanding Lower Permian fossil site in the National GeoPark Thuringia Inselsberg-Drei Gleichen. Series of the German Society for Geosciences , 38-39.

Franks, D. M., Keenan, J., & Hailu, D. (2023). Mineral security essential to achieving the Sustainable Development Goals. *Nature Sustainability*, 6(1), 21-27.

Frey, M. L., Schmitz, P., & Weber, J. (2021). Messel Pit UNESCO World Heritage fossil site in the UNESCO Global Geopark Bergstrasse-Odenwald, Germany–challenges of geoscience popularisation in a complex geoheritage context. Geoconservation Research, 4(2), 524-546.

Gałaś, A., Paulo, A., Gaidzik, K., Zavala, B., Kalicki, T., Churata, D., ... & Mariño, J. (2018). Geosites and geotouristic attractions proposed for the project Geopark Colca and volcanoes of Andagua, Peru. Geoheritage, 10, 707-729.

García-Sánchez, L., Canet, C., Cruz-Pérez, M. Á., Morelos-Rodríguez, L., Salgado-Martínez, E., & Corona-Chávez, P. (2021). A comparison between local sustainable development strategies based on the geoheritage of two post-mining areas of Central Mexico. International Journal of Geoheritage and Parks, 9(4), 391-404.

Gascón, J. H., & Pérez-Lorente, F. (2012). El Rompido (Aguilar del Alfambra). Icnitas de dinosaurios en la Formación Villar del Arzobispo. Teruel. Geogaceta, 51, 39-42.

Geoparks Secretariat. (2006). Guidelines and criteria for national geoparks seeking UNESCO's assistance to join the Global Geoparks Network. Episodes, 29(2), 115–118.

Global Geoparks Network. (2024). Home. http://www.globalgeopark.org/ (Accessed April 2024).

González-León, L. I., Canet, C., Lozada-Amador, E., Alvarado-Sizzo, I., Lagarda-García, F. O., Cruz-Pérez, M. Á., ... & Salgado-Martínez, E. (2024). Tezoantla Tuff («Cantera de Tezoantla», Hidalgo state): the first Mexican "Heritage Stone". Episodes Journal of International Geoscience, 47(1), 109-119.

Gonzalez-Tejada, C., Du, Y., Read, M., & Girault, Y. (2017). From nature conservation to geotourism development: Examining ambivalent attitudes towards UNESCO directives with the global geopark network. *International Journal of Geoheritage and Parks*, 1-20.

Gray, M. (2011). Other nature: geodiversity and geosystem services. Environmental Conservation, 38(3), 271-274.

Gunung Sewu UNESCO Global Geopark. (2024). Gunungsewu Wonogiri. Retrieved June 5, 2024, from https://geoparkgunungsewu.com/gunungsewu-wonogiri/

Hamrin, H., Hustrulid, W., & Bullock, R. (2001). Underground mining methods and applications. Underground mining methods: Engineering fundamentals and international case studies, pp. 3–14.

Hansen, J. M. (2009). On the origin of natural history: Steno's modern, but forgotten philosophy of science. Rosenberg, Gary D. The Revolution in Geology from the Renaissance to the Enlightenment, 159-178.

Harangi, S., Szarvas, I., & Lukács, R. (2023). Wide-ranging and violent volcanic history of a quiet transborder area: volcanic geoheritage of the Novohrad–Nógrád UNESCO Global Geopark. Geoconservation Research, 6(1), 178-206.

Hart, M., & Smart, C. (2021). The Coral-Rich Devonian Limestones of the English Riviera UNESCO Global Geopark. Geoconservation Research, 4(1), 170–195.

Hartman, H. L., & Mutmansky, J. M. (2002). Introductory mining engineering. John Wiley & Sons.

Hazen, R. M., Grew, E. S., Origlieri, M. J., & Downs, R. T. (2017). On the mineralogy of the "Anthropocene Epoch". American Mineralogist, 102(3), 595-611.

Henriques, M. H., Castro, A. R. S. F., Félix, Y. R., & Carvalho, I. S. (2020). Promoting sustainability in a low density territory through geoheritage: Casa da Pedra case-study (Araripe Geopark, NE Brazil). Resources Policy, 67, 101684.

Henriques, M. H. P., & de Souza Carvalho, I. (2022). Culturally differentiated paths towards the conservation of the paleontological heritage at Araripe (NE Brazil) and Arouca (N Portugal) UNESCO Global Geoparks. Geoheritage, 14(2), 68.

Hurley, F. (2005). A preliminary account of an archaeological excavation at Tankardstown (Knockmahon) copper mine, Bunmahon, Co. Waterford. Journal of the Mining Heritage Trust of Ireland, 5(2005), 11–14.

Imbabura Provincial Government. (2017). *Nomination dossier for the designation "UNESCO Global Geopark"*. Imbabura, Ecuador.

International Commission on Stratigraphy. (2024). Global Boundary Stratotype Section and Point (GSSP). Retrieved May 19, 2024, from https://stratigraphy.org/gssps/

International Union for Conservation of Nature. (2020). Resolution 88: Conservation of the natural diversity and natural heritage in mining environments. IUCN. Retrieved June 06, 2024, from https://portals.iucn.org/library/sites/library/files/resrecfiles/WCC_2020_RES_088_EN.pdf

International Union of Geological Sciences. (2022). The first 100 IUGS geologicalheritage sites IUGS, 299 p.

Jones, J. P. G., Bull, J. W., Roe, D., Baker, J., Griffiths, V. F., Starkey, M., ... & Milner-Gulland, E. J. (2019). Net gain: seeking better outcomes for local people when mitigating biodiversity loss from development. One Earth, 1(2), 195–201.

Kim, H. S., & Lim, C. (2019). Developing a geologic 3D panoramic virtual geological field trip for Mudeung UNESCO global geopark, South Korea. Episodes Journal of International Geoscience, 42(3), 235-244.

Kavčič, M., & Peljhan, M. (2010). Geological heritage as an integral part of natural heritage conservation through its sustainable use in the Idrija region (Slovenia). Geoheritage, 2(3), 137-154.

Koopman, G. (2013). Pleistocene steilrand in Donderen, het tweede aardkundig moment van Drenthe. Gea, 46(1), 16–18.

Lambert, P., & Reimold, W. U. (2023). Terrestrial impact sites as field analogs for planetary exploration. Frontiers in Astronomy and Space Sciences, 10, 1186173.

Liu, F., Zhang, Z. X., Li, Q., Zhang, C., & Li, C. (2014). New precise timing constraint for the Keketuohai No. 3 pegmatite in Xinjiang, China, and identification of its parental pluton. Ore Geology Reviews, pp. 56, 209–219.

López, E. O. (2020). Apropiación territorial y construcción de identidad colectiva frente al despojo de recursos. El caso del Geoparque Mundial Mixteca Alta, Oaxaca, México. EMPIRIA. Revista de Metodología de las Ciencias Sociales, (48), 67-93.

Lima, E. A., Nunes, J. C., Costa, M. P., & Machado, M. (2014). Basis for the geological heritage management in the Azores Archipelago (Portugal). RGCI-Revista de Gestão Costeira Integrada, 14(2).

Maugh, T. H. (1975). Paleontology: Facing a Choice Between Fossils and Trash. Science, 189(4207), 985–986.

McFeat-Smith, I., Workman, D. R., Burnett, A. D., & Chau, E. P. Y. (1989). Geology of Hong Kong. Environmental & Engineering Geoscience, 26(1), 17–107.

McKeever, P. J., Zouros, N. C., & Patzak, M. (2010, January). The UNESCO global network of national geoparks. In *The George Wright Forum* (Vol. 27, No. 1, pp. 14–18). George Wright Society.

Mairesse, F. (2019). The Evolution of the Economics of Culture and its Influence on the Development of Geoparks. *UNESCO Global Geoparks: Tension Between Territorial Development and Heritage Enhancement*, pp. 91-107

McVittie, A., & Faccioli, M. (2020). Biodiversity and ecosystem services net gain assessment: A comparison of metrics. Ecosystem services, 44, 101145.

Metsaranta, J. M., Beauchemin, S., Langley, S., Tisch, B., & Dale, P. (2018). Assessing the long-term ecosystem productivity benefits and potential impacts of forests re-established on a mine tailings site. Forests, 9(11), 707.

Monge-Ganuzas, M., Guillén-Mondéjar, F., Díaz-Martínez, E., Herrero, N., & Brilha, J. (2024). Geoconservation at the International Union for Conservation of Nature (IUCN). Philosophical Transactions of the Royal Society A, 382(2269), 20230053.

Monteiro, N. B. R., da Silva, E. A., & Neto, J. M. M. (2019). Sustainable development goals in mining. *Journal of Cleaner Production*, *228*, 509-520.

Moreton, S. (2007). Copper-bearing silica gel from the walls of Tankardstown mine, Co. Waterford, Ireland. Journal of the Russell Society, pp. 10, 10–17.

Nelson, M. G. (2011). Evaluation of mining methods and systems. SME mining engineering handbook, pp. 1, 341.

Neves, A. C. O., Nunes, F. P., de Carvalho, F. A., & Fernandes, G. W. (2016). Neglect of ecosystems services by mining, and the worst environmental disaster in Brazil. Natureza & Conservação, 14(1), 24-27.

North, M. A., Hastie, W. W., & Hoyer, L. (2020). Out of Africa: The underrepresentation of African authors in high-impact geoscience literature. Earth-Science Reviews, 208, 103262.

Pélissié, T., Orliac, M. J., Antoine, P. O., Biot, V., & Escarguel, G. (2021). Beyond Eocene and Oligocene epochs: the causses du Quercy geopark and the Grande Coupure. Geoconservation Research, 4(2), 573-585.

Pereira, D. I., & Pereira, P. (2020). Terras de cavaleiros geopark: a UNESCO global geopark. Landscapes and Landforms of Portugal, 315-327.

Petta, R. A., Sindern, S., Souza, R. F., & Campos, T. F. (2014). Influence of mining activity on the downstream sediments of scheelite mines in Currais Novos (NE Brazil). Environmental earth sciences, 72, 1843-1852.

Prach, K., & Tolvanen, A. (2016). How can we restore biodiversity and ecosystem services in mining and industrial sites?. Environmental Science and Pollution Research, 23, 13587-13590.

Poblete Piedrabuena, M. Á., Martí Molist, J., Beato Bergua, S., & Marino Alfonso, J. L. (2019). The deterioration of geoheritage in the Central Spanish Volcanic Region by open-pit mining. Geoheritage, 11, 1903-1917.

Prosser, C. D. (2018). Geoconservation, quarrying and mining: opportunities and challenges illustrated through working in partnership with the mineral extraction industry in England. Geoheritage, 10(2), 259-270.

Puzey, J. C., Matthews, J. J. (2023). Geodiversity net gain: The next step in geoconservation? In XIth International PROGEO Symposium, Charnwood Forest, UK, Abstract Volume 2.

Quiniff, Y., Delaby, S., Frebutte, C., Hallet, V., Petit, A., Thys, G., ... & Verheyden, S. (2024). Les géosites karstiques, fondements du Geopark Famenne-Ardenne. Physio-Géo. Géographie physique et environnement, (Volume 20), 35-59.

Ramos Filho, R. E. B., de Souza, J. M., Duarte, J. B., da Silva, V. M., & Acchar, W. (2021). Compósito de resíduos de mineração com cimento e cal para materiais de construção sustentáveis. Revista Principia-Divulgação Científica e Tecnológica do IFPB, (54), 193-205.

Ren, F., Simonson, L., & Pan, Z. (2013). Interpretation of geoheritage for geotourism–a comparison of Chinese geoparks and national parks in the United States. Czech Journal of Tourism, 2(2), 105–125.

Reverte, F. C., Garcia, M. D. G. M., Brilha, J., & Pellejero, A. U. (2020). Assessment of impacts on ecosystem services provided by geodiversity in highly urbanised areas: A case study of the Taubaté Basin, Brazil. *Environmental Science & Policy*, *112*, 91-106.

Rodrigues, J., de Carvalho, C. N., Ramos, M., Ramos, R., Vinagre, A., & Vinagre, H. (2021). Geoproducts–Innovative development strategies in UNESCO Geoparks: Concept, implementation methodology, and case studies from Naturtejo Global Geopark, Portugal. *International Journal of Geoheritage and Parks*, *9*(1), 108-128.

Rosado-González, E. M., Lourenço, J. M. M., Palacio-Prieto, J. L., & Sá, A. A. (2023). Collaborative mapping on sustainable development goals in Latin America UNESCO global geoparks: A methodological discussion. *International Journal of Geoheritage and Parks*, *11*(2), 203-220.

Ruban, D. A. (2017). Geodiversity as a precious national resource: A note on the role of geoparks. *Resources Policy*, pp. 53, 103–108.

Ruban, D. A., Mikhailenko, A. V., Yashalova, N. N., & Scherbina, A. V. (2023). Global geoparks: Opportunity for developing or “toy” for developed?. *International Journal of Geoheritage and Parks*, *11*(1), 54-63.

Samani, B. B. (2021). Geoproducts in Unesco Global Geoparks: A Study Applied to Platåbergens Aspiring Geopark (Sweden) (Master’s thesis, Universidade do Minho, Portugal).

Sá, A. A., Gutiérrez-Marco, J. C., Rábano, I., & Valério, M. (2007). Palaeontology and stratigraphy of the Ordovician in the Arouca region (central Portugal). Acta Palaeontologica Sinica, 46, 434.

Sá, A. A., Pereira, S., Rábano, I., & Gutiérrez-Marco, J. C. (2021). Giant trilobites and Other Middle Ordovician Invertebrate Fossils from the Arouca UNESCO Global Geopark, Portugal. Geoconservation Research, 4(1), 121-130.

Schrodt, F., Vernham, G., Bailey, J., Field, R., Gordon, J. E., Gray, M., ... & Daniel Kissling, W. (2024). The status and future of essential geodiversity variables. Philosophical Transactions of the Royal Society A, 382(2269), 20230052.

Scoon, R. N. (2021). Lake Natron and the Ngorongoro Conservation Area, Northern Tanzania: Alkaline Lakes, Gregory Rift, Ngorongoro Caldera, Oldoinyo Lengai Volcano, Oldupai Gorge, and Serengeti Migration. The Geotraveller: Geology of Famous Geosites and Areas of Historical Interest, 117-137.

Seki, H. (2023). Environmental impacts of mining on biodiversity and ecosystem services (Doctoral dissertation, University of York).

Silva, M. L. N., Nascimento, M. A. L., & Mansur, K. L. (2019). Quantitative assessments of geodiversity in the area of the Seridó Geopark Project, Northeast Brazil: Grid and centroid analysis. Geoheritage, 11, 1177-1186.

Szakács, A., & Chiriță, V. (2017). Protected natural values of geoheritage interest in the Călimani National Park, Eastern Carpathians, Romania. Geoheritage, 9(3), 421-434.

Tagle, R., Öhman, T., Schmitt, R. T., Erzinger, J., & Claeys, P. (2007). Traces of an H chondrite in the impact-melt rocks from the Lappajärvi impact structure, Finland. Meteoritics & Planetary Science, 42(10), 1841-1854.

Tiess, G., & Ruban, D. A. (2013). Geological heritage and mining legislation: a brief conceptual assessment of the principal legal acts of selected EU countries. Proceedings of the Geologists' Association, 124(3), 411-416.

Uleberg, E., & Pedersen, E. A. (2013). Ecological and social space in the high mountains in South Norway 8500–2000 BP. Archaeology in the Digital Era, 2, 617-623.

UNESCO (2015) UNESCO Global Geoparks contributing to the Sustainable Development Goals. Retrieved June 05, 2024, from: http://unesdoc.unesco.org/images/0024/002477/247741E.pdf

UNESCO. (2020). *Mineral resources in UNESCO Global Geoparks in Latin America and the Caribbean*. UNESCO. Retrieved May 19, 2024, from https://unesdoc.unesco.org/ark:/48223/pf0000373617_eng

UNESCO. (2024). About UNESCO Global Geoparks. UNESCO. Retrieved May 19, 2024, from https://www.unesco.org/en/iggp/geoparks/about

Vafadari, K., & Cooper, M. J. (2020). Community engagement in Japanese geoparks. In The Geotourism Industry in the 21st Century (pp. 357-373). Apple Academic Press.

Versaci, A., & Cardaci, A. (2019). The drawing of the sulphur landscape in Sicily: the mining site of Floristella-Grottacalda. DISEGNARECON, 12(22), 29-1.

Voigt, S., Haubold, H., 2000. Analyse zur Variabilität der Tetrapodenfährte Ichniotherium cottae aus dem Tambacher Sandstein (Rotliegend, Unterperm, Thüringen). Hallesches Jahrbuch für Geowissenschaften B22, 17–58.

Voudouris, P., Melfos, V., Mavrogonatos, C., Photiades, A., Moraiti, E., Rieck, B., ... & Zaimis, S. (2021). The Lavrion mines: a unique site of geological and mineralogical heritage. Minerals, 11(1), 76.

Walaszczyk, I., Čech, S., Crampton, J. S., Dubicka, Z., Ifrim, C., Jarvis, I., ... & Toshimitsu, S. (2022). The Global Boundary Stratotype Section and Point (GSSP) for the base of the Coniacian Stage (Salzgitter-Salder, Germany) and its auxiliary sections (Słupia Nadbrzeżna, central Poland; Střeleč, Czech Republic; and El Rosario, NE Mexico). Episodes Journal of International Geoscience, 45(2), 181-220.

Wang, J., Liu, S., Li, X., Xiao, Y., Scheuer, B., & Zhao, P. (2022). Analysis on temporal and spatial evolution of UNESCO Global Geoparks and impact factors. Geoheritage, 14(4), 105.

Worton, G. J., Prosser, C. D., & Larwood, J. G. (2021). Palaeontological And Geological Highlights Of The Black Country UNESCO Global Geopark. Geoconservation Research, 4(1), 144-157.

Wrigley, E. A. (2017). The supply of raw materials in the industrial revolution. In The causes of the industrial revolution in England (pp. 97-120). Routledge.

Wu, L., Jiang, H., Chen, W., & Peng, W. (2021). Geodiversity, geotourism, geoconservation, and sustainable development in xiangxi UNESCO global geopark—a case study in ethnic minority areas. Geoheritage, 13(4), 99.

Yang, G., Chen, Z., Tian, M., Wu, F., Wray, R. A., & Ping, Y. (2011). On the growth of national geoparks in China: distribution, interpretation, and regional comparison. Episodes Journal of International Geoscience, 34(3), 157-176.

Yarahmadi, R., Bagherpour, R., Sousa, L. M., & Taherian, S. G. (2015). How to determine the appropriate methods to identify the geometry of in situ rock blocks in dimension stones. Environmental Earth Sciences, 74, 6779-6790.

Yu, Z., & Liu, Y. (2009). Characteristics and evaluation of geological heritage landscape resources in Fangshan Global Geopark. Resources and Industry, 2, 5.

Yuning, Y., Mingzhong, T., & Lujun, G. (2013). Geological Settings and Significance of Zigong Global Geopark. Journal of Landscape Research, 5(9), 37.

Zouros, N. (2004). The European Geoparks Network-Geological heritage protection and local development. *Episodes Journal of International Geoscience*, *27*(3), 165-171.