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Degradation Risk Assessment: Understanding the Impacts of Climate Change on Geoheritage

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Abstract: Several factors and processes, both natural and anthropogenic, can threaten the integrity of any geosite, leading to their degradation. For this reason, geoheritage degradation risks should be considered a fundamental step in any geoconservation strategy, all the more when the aim is to tackle the effects of climate change. The present work proposes a quantitative methodology for the degradation risk assessment of geosites by considering the extrinsic factors that can damage the geoheritage. The methodology has been tested on the Maltese Islands, where considerable previous research has been undertaken in order to highlight the international significance of the Maltese landscapes. Three criteria to assess the degradation risk are proposed: natural vulnerability, anthropogenic vulnerability and public use. For each criterion, several parameters have been identified in order to propose a detailed numerical evaluation. The results show that the degradation risk of geosites is mainly related to negligence and lack of knowledge of its inherent geological heritage, and which leads to public misuse and mismanagement of the geosites. The results give an overview of the condition of the geosites and provide information for the design and management of suitable protection measures, especially in the light of future threats related to climate change.

Keywords: degradation risk; geoheritage; geosites; Malta

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1. Introduction

The last 25 years have been significant in the growth of geoconservation studies and comprehensive interest in geoheritage. To date, investigations carried out on geosites have mostly focused on their identification, classification and assessment, and recently, new attention has been paid to geosites mapping as well (cf. [1] and reference therein). A high number of methodologies, both qualitative and quantitative, were developed for the assessment of geosites values (scientific and additional) and of their potential educational and touristic uses (cf. [2–5] and references therein). A much less explored topic in this domain has been the degradation risk assessment of geosites, which, nevertheless, is of paramount importance, providing key information for their management and conservation. In fact, geoheritage is constantly under pressure from natural or anthropogenic factors and processes. In many countries, geosites are at risk of degradation or even total loss due to the lack of a systematic inventory and the resultant inadequate management [6]. A number of studies have dealt with the concept of geosites degradation risk, leading to the use of ambiguous terminology and with some of the terms being used interchangeably [6–12] the recognition and prevention of threats affecting geosites still lack a common investigation schemes and approaches. One of the first comprehensive works on the assessment of geoheritage degradation risk has been conducted by Garcia-Ortiz et al. [13] with the intent to establish a common framework for specialists working on geoconservation. The authors present the degradation risk as a combination of three main criteria [13]: fragility, vulnerability and public use. More recently, Brilha [14] considered the degradation risk as part of the geosites' assessment and proposes five risk parameters that indistinctly comprise both natural and anthropogenic factors.

Regarding the natural factors that may affect geosites, it is important to consider their direct connection with climate change. According to the Intergovernmental Panel on Climate Change [15,16], future climate change will affect the frequency and intensity of extreme weather, resulting in greater losses [17], and will be the cause of intensive geodiversity and landscape modification [18]. A direct consequence of global temperature increase is sea level rise, which has a range of potential impacts including coastal erosion, flooding events, the salinization of surface and ground waters and the degradation of coastal habitats with wetlands loss [19].

In the Mediterranean region, the problem of possible sea level rise as an effect of climate change is particularly felt since the coastal zones are highly vulnerable to environmental events, such as floods, which can directly or indirectly affect the coastal community. Several national assessments, expert assessments and recent model-based studies have forecasted an upper bound global mean sea level rise in the range of 1.5–2.0 m for the 21st century [20]. The rise in sea level along most European coasts is projected to be similar to the global average, and according to Galassi and Spada [21], sea level will increase from 10.7 cm (min) to 25.8 cm (max)—excluding additional effects from tectonics and coastal processes—by 2050 on the south-central Mediterranean area, where the Maltese Islands are located. The Maltese archipelago is a European country located in the centre of the Mediterranean with a rich and internationally recognized natural and cultural heritage [22]. Despite the small size of the archipelago, with a surface area of 316 km^2, it encompasses a high number of sites with geological interest and presents a considerable geodiversity [23]. In a recent study comprising the islands of Gozo, Comino and north-western Malta, 27 geosites were inventoried and assessed for a potential recognition of the area as a UNESCO Global Geopark [23]. The geosites are known by the scientific community due to specific research on local geoheritage [24–27]. However, the legal framework that protects the local natural heritage is still more focused on biodiversity and ecological conservation. Therefore, a potential risk of degradation of this geoheritage, due to both the steadily increasing population and number of tourists on the archipelago (the latter standing at 2.7 million in 2019) [28,29] must be assessed and managed. As a small-island state, the Maltese archipelago is considered as being prone to increased vulnerability to the impacts of climate change [20]. The Maltese Islands are in fact exposed and vulnerable to a variety of natural hazards related to tectonic, geological/geomorphological and climatic processes [17,30]. As reported by the European Environmental Agency extreme events such as flooding and drought costed the Maltese Islands EUR 62 million between 1980 and 2013 [31]. The future costs of extreme weather and other hazards (e.g., earthquakes and other tectonic related phenomena, extreme geomorphological events) will depend on several factors including the presence and effectiveness of policies of disaster risk reduction (DRR) designed to boost resilience [17,30].

In the present study, the degradation risk of 27 Maltese geosites have been quantitatively assessed by applying a methodology initially proposed by Garcia Ortiz et al. [13] and specifically based on the following three criteria: natural vulnerability, anthropogenic vulnerability and public use. The proposed methodology is meant to be a useful tool for nature conservation and management in the framework of territorial management planning, identifying areas that can be more negatively affected by both public use and climate- and marine-related processes.

2. Study Area

The study area is located on the Maltese Islands, central Mediterranean Sea, and comprises the entire islands of Gozo and Comino and approximately half the main island, Malta. Despite the archipelago reaches one of the highest numbers of population density in

EU, i.e., over 1500 habitants per km^2 for a total population almost 516,100 as of December 2020 [32], the study area is sparsely inhabited since it does not include the most urban sector situated in the Northern Harbour and Southern Harbour of Malta [33]. However, the population is projected to increase further to 706,915 persons by 2070 [20], and the archipelago also attracts a high number of tourists, currently standing at 2,771,888 in 2019 [34,35], thanks to its mild Mediterranean climate and rich historical heritage. The study area is composed of a marine sedimentary rock sequence ranging in age from Upper Oligocene to Upper Miocene that consists of limestones, marls and clays, which are ca. 250 m thick (Figure 1). In addition, a discontinuous layer of quaternary deposits is found on the archipelago [36,37].

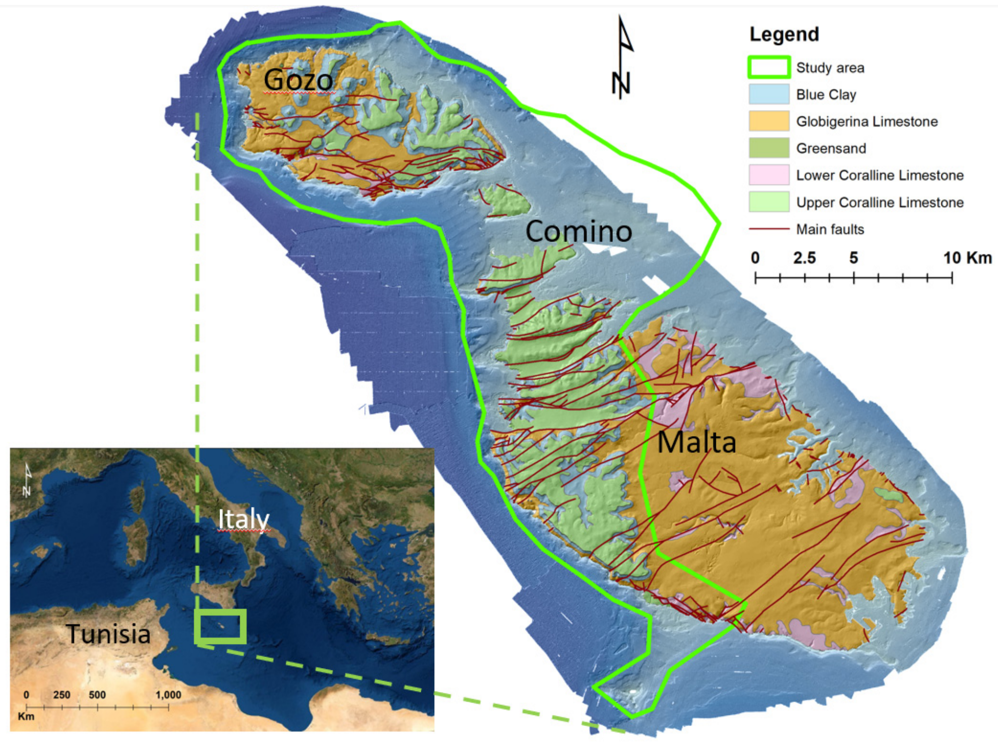

Figure 1. Location of the Maltese Islands in the Mediterranean and detailed map of the study area and its lithology; the background image is courtesy of ERSI.

The geological formations lie almost horizontally, although they are displaced by tectonic structures [38–40]: the archipelago is in fact dominated by two rift systems with different orientation and intersecting each other at an angle of 30 to 60°. This brings the intersection of two trending faults, which are different in age. The fault systems also contributed to the landscape evolution allowing the juxtaposition of lithological strata with different physical and mechanical properties [41]. The close link between geological formations and geomorphological processes has led to the creation of a rich variety of contrasting landscapes [40]. The geomorphology of the archipelago has been investigated by several authors [24,27,38,42–49]. Some researchers have focused on specific sections of the islands, such as coastal areas [50–52], or on specific topics such as dissolution processes and landslides [25,53–57]. Gravity-induced slope landforms and processes are widespread over the Maltese Islands, especially along the northwestern coast of Malta and eastern Gozo, both characterized by Upper Coralline Limestone karst plateaus. Karst processes play a significant role in the Maltese archipelago due to the extensive presence of limestones. A considerable number of circular or elliptic sinkholes of different size can be found all around the study area, usually caused by the collapse of cave roofs: the most spectacular are Il-Maqluba (Malta) and Dwejra (Gozo) [58]. Submarine sinkholes have recently been recognised on the offshore eastern coast of Malta [59–61]. Karst pavements, solution holes, solution pans, sea caves, arches and shore platforms are also common on the islands. The archipelago exhibits a rich and complex coastline that displays a myriad of structural, gravitational, aeolian, fluvial, marine and karstic landforms [40]. In addition, there is a deep relationship between island geomorphology and society. All the archipelago has been significantly influenced over time by human activities, especially in recent years due to its high population density. Another notable human impact are the numerous quarries carved in the Globigerina Limestone, with the Lower Globigerina Limestone recognized at Global Heritage Stone Resource in view of its historic use in the archaeological and architectural legacy of the islands [62]. In fact, the coast is endowed with a rich archaeological and military heritage such as megalithic temples [63], extensive fortification networks dating back to the Order of St John (1530–1800) [64] and the British period (1800–1964) [65]. However, some of the historical use of the coast by the military has also led to irreversible damages to coastal features, such as Filfla and the surrounding islets, when they were used as military target practice for bombings by the British and American forces until 1970s. In 1988, the islet was declared a Natural Reserve via the Filfla Nature Reserve Act [57].

The rich diversity of the Maltese physical landscapes is the focus of several scientific studies in recent years. Specific studies on geoheritage recognition and geosites inventory have been carried out in the northwest coast of Malta, especially in the area of the Il-Majjistral Nature and History Park and environs [23,24,66,67]. Other studies on geoheritage assessment were conducted on the island of Gozo [26,58], in particular on the Dwejra area that comprises outstanding sinkholes having highly scientific, ecological, aesthetic, cultural and use values as geomorphosites. In addition, a first geomorphology monograph about Maltese landforms and landscapes was recently published in 2019, collecting several contributions and edited by Gauci and Schembri [27]. On the contrary, on a legal framework, the importance of geoheritage protection and conservation remains however diluted. The main act governing environmental protection is the Environmental Protection Act (EPA, Chap. 549), adopted in 1991 and last amended in 2018 together with its subsidiary legislation Flora, Fauna and Natural Habitats Protection Regulations (SL 549.44). As a member of the European Union since 2004, Malta adopted two important European environmental directives on the conservation of natural habitats and of wild fauna and flora: the Habitat Directive (Council Directive 92/43/EEC) which aims to promote the maintenance of biodiversity and the Bird Directive (Directive 2009/147/EC) for the protection of the wild bird species naturally occurring in Europe. To date, 13.8% of the total land area of the Maltese Islands (43.7 km2) is composed of Natura 2000 sites [68]. Despite the high number of legislations and acts on natural heritage, there is still no legislation created ad hoc to exclusively protect the geological heritage.

With regard to geoheritage, 27 geosites were inventoried and assessed in a previous work (Figure 2) [23]. The geosites have high scientific relevance and are the most representative and rare geological elements and landforms of the sector. Most of the geosites are situated along the coast where impressive lateral spreading phenomena dominate the landscape and where wave action and lithological-structural processes shape cliffs and bays, sea caves, arches and shore platforms. In total, 85% of the geosites are characterized by primary geomorphological interest and consist of Upper Coralline Limestone plateaus affected by lateral spreading, Globigerina Limestone shore platforms rich in fossils, karstic features such as sinkholes and dissolution subsidence structures and badland topography on Blue Clay slopes. A total of 11% of the geosites have structural main interests: two examples are the Magħlaq fault in S Malta and the Great Fault across St. Paul's Islands and N Malta that are characterized by the juxtaposition of different lithologies. The last 4% have mainly stratigraphic interest, represented by the GSSP which define the boundary between Langhian and Serravallian stages and an outcrop showing all the geological formations.

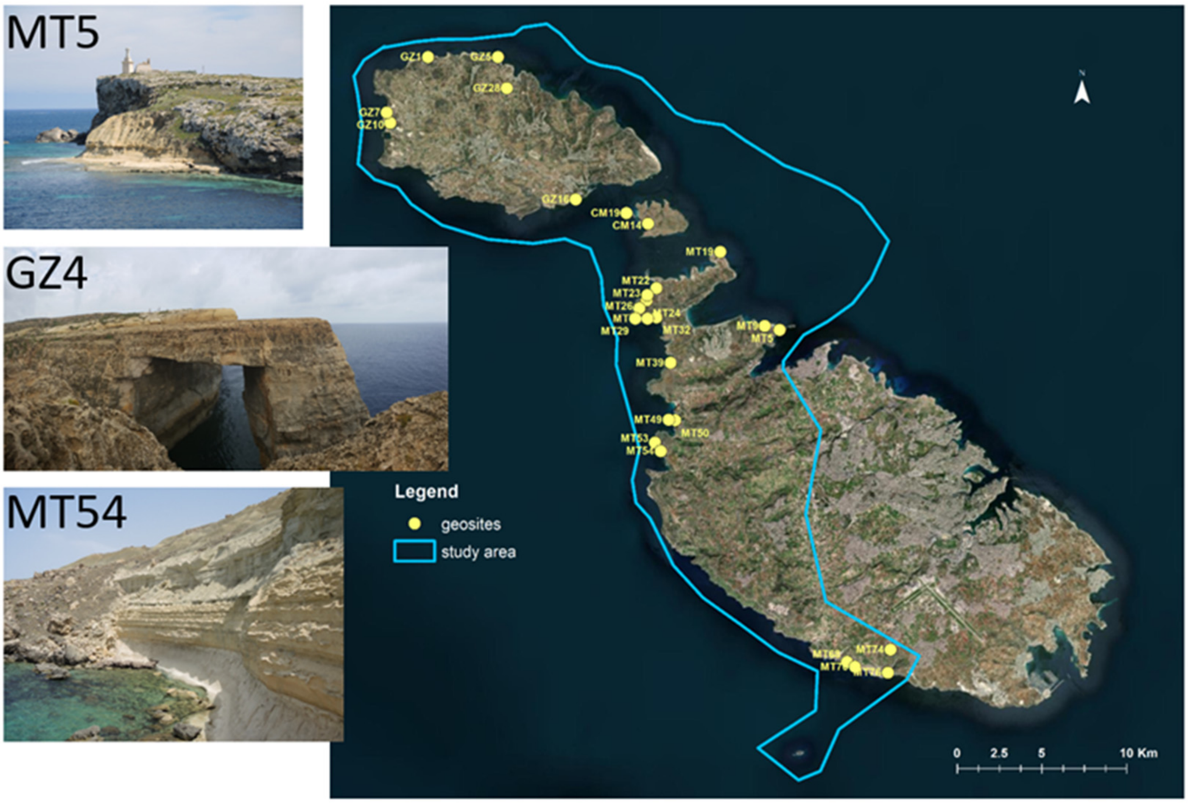

Figure 2. Location of the 27 geosites within the study area. In detail, pictures of 3 geosites: MT5 St. Paul's Islands, structural main interest; GZ4 Wied il-Mielaħ arch, geomorphological main interest: MT54 GSSP, stratigraphical main interest; the background image is courtesy of ERSI.

3. Principles and Methods

Given the range of possible conceptual interpretations of terms related to degradation risk, it is deemed essential to clarify which definitions were adopted for the development of the degradation risk methodology presented in this work. The concepts of fragility, natural vulnerability, anthropogenic vulnerability and public use proposed by Garcia et al. [13] were adopted and are summarized in Table 1.

Table 1. Terms and definitions related with the degradation of geosites, according to Garcia et al. [13].

Term	Definition
Natural vulnerability	The sensitivity of a geosite to be damaged or destroyed by natural processes not involved in its creation.
Anthropogenic vulnerability	The sensitivity of a geosite to be damaged or destroyed by human activities related to its economic value due to its geological characteristics (mining, quarrying, collection, etc.).
Public use	The susceptibility of a geosite to damage due to its location and its current or possible use (vandalism, no control of access, no physical protection, etc.).
Fragility	The sensibility of a geosite to damage by processes involved in its creation and directly related to its geological characteristics.

The degradation risk methodology proposed in this study is based on other previous method-focused research (e.g., [6,7,10,11,13,14,69,70]).

In 2005, Brilha introduced the concept of fragility and the need of geosites protection, considering exclusively the human threats. Other works have been conducted subsequently by Pereira et al. [8], Carcavilla et al. [9], Fuertes-Gutierrez and Fernandez-Martinez [10], Fassoulas et al. [11] and Garcia-Cortes and Carcavilla Urqui [71], although always presenting different terminology and partially considering the aspects that contribute to the degradation risk. De Lima et al. [6] used the term vulnerability to define the natural and human processes that might affect the geosites. Fuertes-Gutiérrez and Fernández-Martínez [10] introduced the concept of vulnerability as being the risk of destruction only due to human activity. The same authors in a later work [72] presented the degradation risk as a combination of vulnerability, which involves the intervention of human activities, and fragility, which involves the natural conditions. According to Fassoulas et al. [11], the risk of degradation can be estimated considering the geosite's value and its need for protection. The first comprehensive work on degradation risk assessment has been conducted by Garcia-Ortiz et al. [13] with the intent to establish a common framework for specialists working on geoconservation. The researchers conducted a detailed analysis of the risk of degradation of the geosites in La Rioja (Spain) but only considering the natural criteria: fragility and natural vulnerability. More recent research [14] considers the degradation risk as part of the geosites' assessment. In this work, the author recognizes the importance of an assessment of the degradation risk in parallel with the scientific assessment of the geosites but does not distinguish anthropogenic threats from natural ones.

Quantitative Assessment of Geosites Degradation Risk

The quantitative methodology proposed in this research for the geosites degradation risk assessment is based on the identification and assessment of three set of criteria, i.e., (i) natural vulnerability, (ii) anthropogenic vulnerability and (iii) public use. The fragility arises from natural intrinsic factors, and it is important to measure them in order to have a knowledge of the state of the site, its dynamic condition and integrity. However, they are also generally impossible to prevent due to their unavoidable natural origin. In some cases, geosites are important due to the evidence of the natural process involved in their creation. The constant activity of geosites may lead to them evolving more complex features and increase their value until the construction of new landforms. It is also an ethical issue to stop the activity of natural processes and interrupt the natural evolution of the sites. For this reason, it was not considered to contribute to the total degradation risk score.

Parameters to describe each criterion and the respective indicators used to measure them have been defined and are reported in Table 2. Scores between 0 and 3, representing low risk and high risk, respectively, were assigned to each parameter, and the degradation risk of a geosite was estimated by summing the scores of each criterion. The lower the score obtained, the lower the level of degradation risk of the geosite.

In particular, the assessment of the *natural vulnerability* of geosites is based on two parameters:

- *Active processes*. This parameter considers the active processes which are not involved in the creation of the geosite, but the latter may be affected by such processes. The processes that can cause damage could have different origins such as geological, climatic and biological. Thus, it is important to identify the active natural processes in the study area that can cause degradation [13]. The processes of geological origin comprise gravity induced movements, water erosion and weathering. It is important to consider biological active processes related both to the animal world, such as trampling or burrowing, and the vegetation world, such as roots developments and surface growth by plants. The processes with climatic origin need a long-term collection of data and comprise temperature, humidity, precipitation, wind, flooding and meteo-marine factors. Moreover, it is important to assess if the natural extrinsic processes are operating as continuous or episodic. Active sites are in turn classified as active-continuous or active-episodic, considering that some processes are acting throughout the year and others just for short recurrent periods [73]. The value of 0 is given to the sites affected by no one extrinsic natural process, 1 and 2 respectively to the sites that are affected by episodic or constant natural processes; 3 is given to the sites that are affected by two or more extrinsic natural processes.
- *Proximity.* This parameter considers the proximity of the site to an area of possible degradation due to active natural processes. It is important to identify the conditions

that make the geosite and its surrounding area at risk of degradation (e.g., coastal area with coastal erosion, volcanic area, slopes/landslides, etc.). The value of 0 is given to the sites in proximity to no area of possible degradation, 1 and 2 to the sites that are affected by 1 or 2 active processes in proximity of the sites, respectively; and 3 is given to the sites that are in proximity to an area with more than 2 possible processes of degradation.

The assessment of *anthropogenic vulnerability* of geosites is based on two parameters:

- *Economic interest*. This parameter expresses the presence of geological elements having economic value. This parameter considers whether the geosites are actually or potentially of interest for economic exploitation (e.g., elements valuable for quarrying and mining).
- *Private interest*. The parameter considers the presence of geological collectibles, such as fossils and minerals, for private use through illegal collection or misappropriation, comprising damages undertaken in the name of scientific advancement by irresponsible scientist [74,75].

A value from 0 to 3 has been assigned to each parameter, with 0 representing no economic interest and 3 for more than 2 elements of economic value. Both parameters are directly linked with the geosite's geological characteristics.

The *public use* criterion fundamentally depends on pressure from urban development, susceptibility to pillaging or vandalism and lack of protection. It includes the following seven parameters:

- *Legal protection*. It evaluates the presence of legal protection instruments for the geosite. This parameter assesses whether the geosite is legally protected due to its geological value, if it is situated within a natural area or an area protected for other value such as a cultural or historical one.
- *Human proximity*. This parameter considers the proximity of the geosite to an area with human activities that can cause degradation. It measures the distance in meters to human activities that can potentially damage the site.
- *Accessibility*. Good accessibility to a site is a risk because the more people visit the site, the higher the risk that the site will be damaged.
- *Population Density*. The concentration of people living near a site increases the probability of human-induced deterioration.
- *Physical protection*. It evaluates the presence of physical barriers and structure to protect the sites. The protection limits the direct contact with the public that can deteriorate the site. Examples of physical protection are fences, stairs or walking paths.
- *Degrading use*. It refers to the incorrect public use of the geosite. Examples are the presence of waste (plastic battles, papers, cans) and vandalism.
- *Control of access*. This parameter evaluates the presence of physical barriers, direct controls—such as patrols surveillance—or indirect controls—such as cameras.

The total degradation risk score can range from 0 to 33 points (Table 3). Once the total degradation risk score is obtained, it is possible to identify the degradation risk level of a geosite (Table 3): The geosites that reach a score lower than 7 points are considered at low risk of degradation, whereas the higher degradation risk level is attributed to sites that reach a total score higher than 25 points. Details concerning the scores and the degradation risk levels related to each range are shown in Table 3. The assessment conducted is based on qualitative data, mainly collected through analysis of photos and past observation conducted in the fieldworks. The risk levels are based on expert estimation.

Table 2. Criteria, parameters, indicators and points used for the quantitative assessment of the degradation risk of geosites.

Criteria	Parameters	Indicators	Points
Natural Vulnerability	Active processes	no active processes affect the geosite	0
		one active process affects the geosite episodically	1
		one active process affects the geosite continuously or seasonally	2
		two or more active processes affect the geosite	3
	Proximity	no possibility of degradation	0
		one possible active process in proximity of the geosite	1
		two possible active processes in proximity of the geosite	2
		more than two active processes in proximity of the geosite	3
Anthropogenic Vulnerability	Economic interest	no geological elements with economic interest	0
		the geosite has one geological element with economic interest	1
		the geosite has two geological elements with economic interest	2
		the geosite has more than two geological elements with economic interest	3
	Private interest	no geological elements of private interest	0
		the geosite has one geological element collectable for private interest	1
		the geosite has two geological elements collectable for private interest	2
		the geosite has more than two geological elements collectable for private interest	3
Public Use	Legal protection	the geosite is protected for its geological heritage	0
		the geosite is inside a protected natural area	1
		the geosite is inside an area protected for other values (historical, cultural, etc.)	2
		the geosite is not in a protected area	3
	Human proximity	the geosite is located less than 100 m from a potential degradation activity	3
		the geosite is located less than 500 m from a potential degradation activity	2
		the geosite is located less than 1 km from a potential degradation activity	1
		the geosite is located more than 1 km from a potential degradation activity	0
	Accessibility	the geosite is located less than 100 m from a paved road and bus parking space	3
		the geosite is located less than 100 m from a paved road	2
		the geosite is located less than 100 m from a gravel road or between 100 and 500 m from a paved road	1
		the geosite is located more than 100 m from a gravel road or more than 500 m from a paved road/no direct access	0
	Density of population	the geosite is located in a municipality with less than 100 inhabitants/km^2	0
		the geosite is located in a municipality with 100–250 inhabitants/km^2	1
		the geosite is located in a municipality with 250–1000 inhabitants/km^2	2
		the geosite is located in a municipality with more than 1000 inhabitants/km^2	3
	Physical protection	the geosite is not protected at all	3
		geosite with structure for tourists but without physical protection of the geoheritage	2
		geosite with physical protection but without structure for tourists	1
		geosite with physical protection of geoheritage features and structure for tourists	0
	Degrading use	no degradation from public use	0
		one element of degradation	1
		two elements of degradation	2
		more than two elements of degradation	3
	Control of access	no control at all	3
		the geosite is monitored by one method of control	2
		the geosite is monitored by two method of control	1
		the geosite is monitored by more than two methods of control	0

Table 3. Classification of the degradation risk of geosites: partial and total scores; risk level.

Criteria	Partial Score	Total Score		Total Score on Degradation Risk	Risk Level
Natural Vulnerability	0–6	0–33		0–7	low
Anthropogenic Vulnerability	0–6			>7 ≤ 15	medium
Public Use	0–21			>15 ≤ 25	high
				>25	very high

4. Results and Discussion

The 27 geosites identified in the Maltese Archipelago have been assessed through the methodology described in paragraph 3.1 (Table 4) in order to define their degradation risk, and the results are presented in Figure 3.

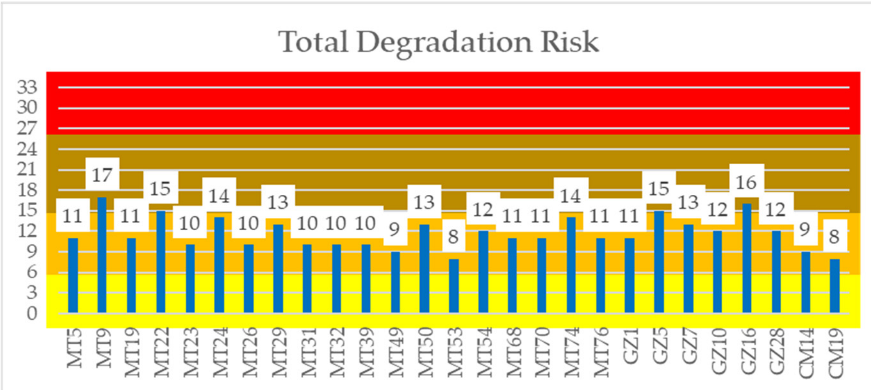

Figure 3. Total degradation risk of the 27 geosites surveyed in the Maltese Archipelago: bar chart representation; X-axis: geosites; Y-axis degradation risk score.

Almost all the geosites have a medium risk of degradation, with only four geosites that reach the score equal or higher than 15 which corresponds to high risk of degradation.

The four geosites with high risk of degradation are as follows: MT9 and GZ16, badland topography in Blue Clay slopes, located at Blata l–Bajda and southeast, respectively Gozo; GZ5, mesa in Globigerina Limestone located at il-Qolla l-Bajda; and MT22, area affected by rock spreading at Paradise Bay (Figure 4). The three first mentioned geosites, which are fragile due to the inherent soft and erodible lithological properties, are under anthropogenic pressure due to the areas being highly visited and often subject to uncontrolled and illegal recreational activities.

Regarding the last geosite, MT22, the risk of degradation is entirely given by the high human pressure, with no recognition and attention to its geological value. Analyzing the different factors that contribute to the obtained scores, the degradation risk of the geosites is mainly influenced by public accessibility (Figure 5). In five geosites, the risk of degradation is influenced by natural vulnerability, resulting in more than 30% of the total score. In detail, the geosites that reach a high score on natural vulnerability are MT29, MT50 and GZ16, which are characterized by badland topography on steep Blue Clay slopes. The geosites are easily eroded at the bottom by marine wave action and rendered unstable at the top by gravity-induced movements. Blue Clay is the most erodible and softest formation of the limestone lithological sequence and as seismic waves are known to have triggered historic slope failures [76]. This lithology, cropping out below UCL, defines a particularly problematic situation, confirmed by several studies carried out in different coastal areas: Għajn Tuffieħa and Mistra Bays [77] Xemxija Bay [78]; the coastline between Paradise Bay and Ras il-Pellegrin [17,79–82]. Geosite MT54, GSSP point for the Serravallian stage, reports a 40% score in natural vulnerability due to its characteristics of being a cliff in Globigerina Limestone and Blue Clay exposed to water erosion on the west coast of Malta.

Table 4. Quantitative assessment of the degradation risk of the 27 geosites inventoried in the Maltese Archipelago.

	Vulnerability						Public Use								
	Natural Vulnerability			Anthropogenic Vulnerability											
Geosite	Active Processes	Proximity	Total Natural Vulnerability 0–6	Economic Interest	Illegal Collecting	Total Anthropogenic Vulnerability 0–6	Legal Protection	Human Proximity	Accessibility	Density of Population	Physical Protection	Degradation Public use	Control of Access	Total Public Use 0–21	Total Degradation Risk 0–33
MT5	3	1	4	0	0	0	1	0	0	0	3	0	3	7	11
MT9	3	1	4	0	0	0	1	0	2	2	3	2	3	13	17
MT19	0	0	0	0	0	0	1	0	2	2	3	0	3	11	11
MT22	0	0	0	0	0	0	1	3	3	2	3	0	3	15	15
MT23	0	0	0	0	0	0	1	0	1	2	3	0	3	10	10
MT24	2	1	3	0	0	0	1	0	1	2	3	1	3	11	14
MT26	0	0	0	0	0	0	1	0	1	2	3	0	3	10	10
MT29	3	1	4	0	0	0	1	0	0	2	3	0	3	9	13
MT31	0	0	0	0	1	1	1	0	0	2	3	0	3	9	10
MT32	0	1	1	0	0	0	1	0	0	2	3	0	3	9	10
MT39	0	1	1	0	0	0	1	0	0	2	3	0	3	9	10
MT49	0	0	0	0	0	0	1	0	0	1	3	1	3	9	9
MT50	3	1	4	0	0	0	1	0	0	1	3	1	3	9	13
MT53	0	0	0	0	0	0	1	0	0	1	3	0	3	8	8
MT54	3	1	4	0	0	0	1	0	0	1	3	0	3	8	12
MT68	0	1	1	0	0	0	1	0	0	2	3	1	3	10	11
MT70	0	1	1	0	0	0	1	0	0	2	3	1	3	10	11
MT74	3	0	3	0	0	0	1	0	3	2	2	1	2	11	14
MT76	0	0	0	0	0	0	1	0	3	2	2	0	3	11	11
GZ1	0	0	0	0	0	0	3	0	1	2	2	1	2	11	11
GZ5	0	1	1	0	0	0	3	0	3	2	3	1	2	14	15
GZ7	1	0	1	0	0	0	1	0	3	1	3	1	3	12	13
GZ10	0	0	0	0	0	0	1	0	3	1	3	1	3	12	12
GZ16	3	1	4	0	0	0	3	0	1	2	3	0	3	12	16
GZ28	0	0	0	0	0	0	3	0	0	2	3	1	3	12	12
CM14	1	0	1	0	0	0	1	0	1	0	3	0	3	8	9
CM19	1	0	1	0	0	0	1	0	0	0	3	0	3	7	8

Figure 4. Geosites in the Maltese Archipelago assessed with high risk of degradation.

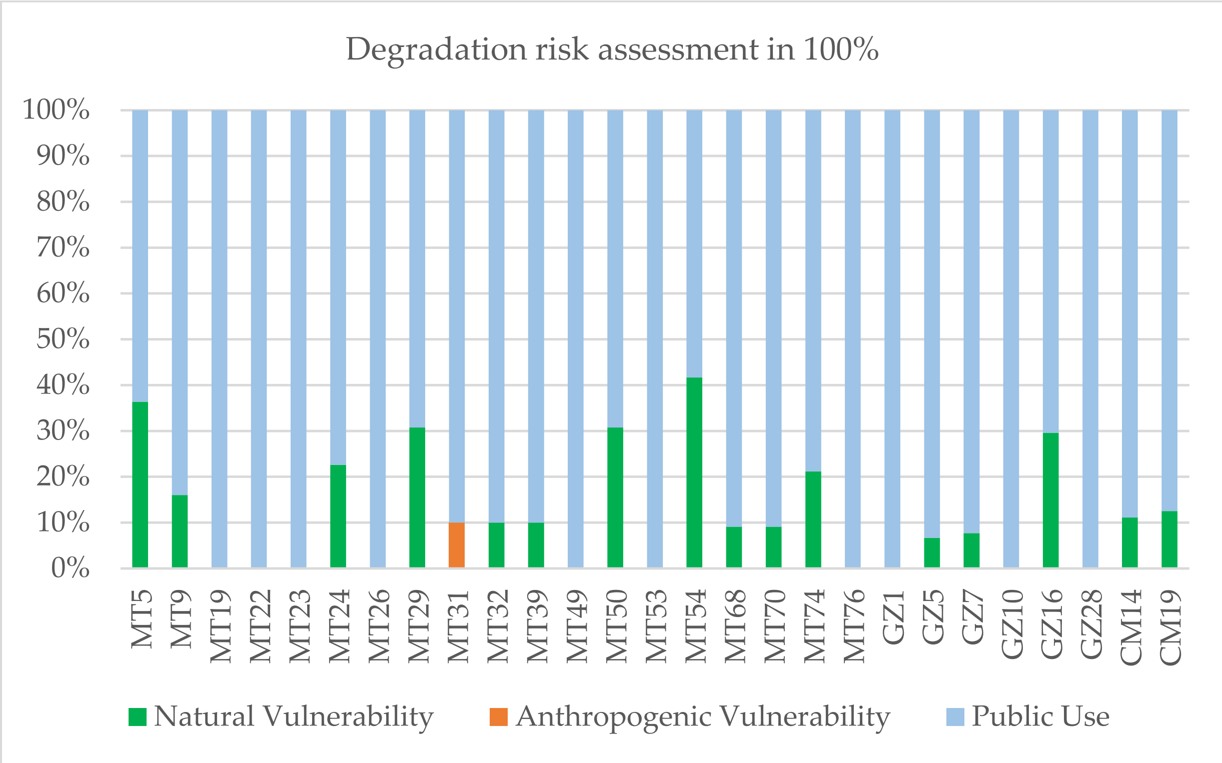

Figure 5. Results of the quantitative assessment of the degradation risk of the 27 geosites surveyed in the Maltese Archipelago, with relative weights of natural vulnerability, anthropogenic vulnerability and public use in each geosite.

The anthropogenic vulnerability is almost absent except for MT31, the Lower Globigerina Limestone terrace, where fossils of echinoderms in perfect condition can be illegally collected by private individuals. Fossil hunting in Malta is strictly regulated and retrieving and excavating them without permission is in breach of the country's 2002 Cultural Heritage Act (Chap. 445). All palaeontological elements are considered a 'movable or immovable object of geological importance' and form part of the country's cultural heritage.

Humans are just one agent that causes degradation, but their activities are very varied and cause a range of modifications similar or even more degrading than natural processes at various spatial and temporal scales. The risk of degradation by public use usually progresses faster than natural ones, and sometimes, may have a sudden component [83] (Figure 6). The high score in public use is in most cases related to negligence and lack of knowledge of the geological heritage that leads to incorrect public use of the geosites areas. Threats from public use include conflicts with other territorial uses as infrastructure construction and possible conflicts with other types of natural or cultural heritages. It also includes threats raised from incorrect educational and recreational uses of the geosites, as well as misappropriation and vandalism.

The critical point is the low awareness of the geological importance of the geosites by locals and tourists. Most of the geosites are in fact located along the coast, where the pressure of tourism and infrastructures are concentrated. Tourism could be a resource, but only if managed in a sustainable and responsible way.

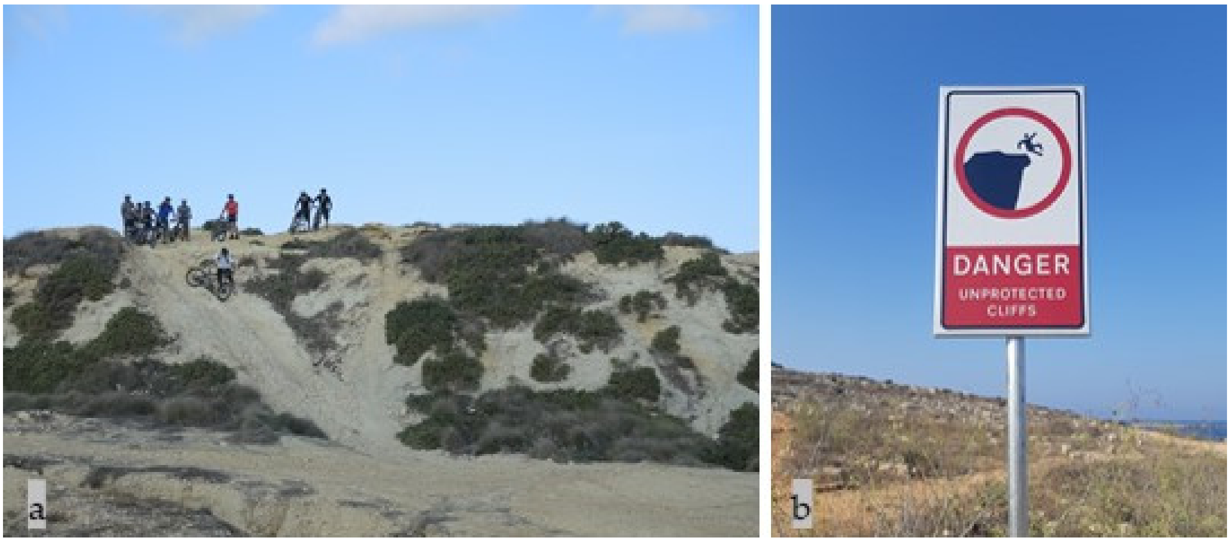

Figure 6. Examples of incorrect public use in the Maltese coastal geosites: (**a**) cycling activity on Blue Clay slopes; (**b**) absence of physical protection and control of access along the geosites on the coast.

Regarding the natural threats, the proximity of the geosites to the coast makes them more vulnerable to water and wind processes. Coastal erosion threatens the degradation of geosites and the connected environments, with the resultant reduction of coastal biodiversity. Coastal erosion also has its socio-economical aspects, including loss of land with economic value and damage of coastal infrastructure and tourism, the latter two considered as sectors that play a key role in the economy [84]. Coastal areas are in fact complex environments in view of their exposure to natural hazards and are therefore more affected by effect of climate change (sea level rise, changes in coastal deposition and erosion, increase in violent marine storms and tsunamis from near-field and far-field sources) [29,85,86].

Almost all the geosites are along the coast and hence exposed to natural hazards, but the different lithologies made some geosites at a higher risk of natural deterioration than other, such as those made up of soft and erodible Globigerina Limestone and Blue Clay. On the contrary, geosites in Lower and Upper Coralline Limestone located along the coast report usually low or non-existent natural vulnerability.

Several studies (e.g., [87–89]) emphasized how possible sea level rise may threaten coastlines and high wave-energy beach zones. Beaches will be particularly affected as they might be obliterated or reduced in size. The predicted sea level rise and increase in extreme weather events is a serious threat to coastal environment and coastal population, particularly high-density ones. Measurements in the last 40 years of sea surface temperature at Delimara, southeast Malta, show a steady increase at a hefty average rate of close to +0.05 °C/year. The rise is most evident during hot summer months and is comparable to Mediterranean averages, the latter considered well above the global average of +0.01 °C/year. The warming of the sea has a direct influence on the marine ecosystems that respond both physically and biologically to changes in climate [90].

The impacts range from inundation, coastal erosion and damage caused by storm surges, waves and high winds [20]. The loss of beaches and the creation of new beaches with replenishment will be very expensive, with short-term benefits. In particular, extreme weather events will impact part of Malta's coast made up of Blue Clay at sea level. In the study area, as located in the Mediterranean region, the problem of future sea level rise is particularly felt. According to the estimation of Galassi and Spada [21], the sea level of the Mediterranean sub-basin is going to rise from min 10.7 cm and max 25.8 cm. Low-elevation coastal zones, especially on the island of Comino and eastern region of the island of Malta, southwest of Gozo, are highly vulnerable to environmental events, like floods, which can directly or indirectly affect the economic activities and coastal communities. For this reason, it is important to monitor the natural vulnerability due to the continuing active natural evolution of the coast which may affect the value of such landforms classified as geosites [91]. The Maltese National Risk Assessment [92] identifies a list of natural and weather-related hazards as earthquake, tsunami, landslides, coastal erosion, sea currents, flood and weather-related hazards. The main three factors that make the islands susceptible to extreme natural events are as follows: (i) regional tectonics, as earthquakes are not only associated with ground shaking but are also capable of generating tsunamis and triggering slope failure; (ii) geology and geomorphology, such as karstic features, landslides and cliff collapse; and (iii) weather and climate, such as flash flooding, groundwater flooding and that resulting from a combination of high tides, storm waves and heavy rainfall [17]. Whereas catalogues of earthquakes and volcanic eruptions that have impacted the Maltese Islands are largely incomplete, those for geological and geomorphological features and weather and climate are almost non-existent [17]. For the present research, we considered the last two categories of events together with biological activity. The events connected with regional tectonics were not considered in the present research since they are difficult to assess in a short period of time and without a complete database. An incomplete historical catalogue is present only regarding earthquakes, earthquake-related phenomena and volcanic phenomena. There is no historical catalogue on extreme geomorphological events, such as karstic collapse and landslides and thus there can be no progress in their assessment. However, some attentions are reported after recent events, such as a cliff face collapse in November 2011 at Għar Lapsi on the southern coast, that led to the first cliff protection measures set up in 2013 by the Ministry of Infrastructure, using a combination of rock nets (i.e., gabions) at the base of the cliff and rock bolts on exposed faces [17,93]. More often than not, protection measures are implemented in areas important for tourism and following a dangerous event.

Despite this, in the present state, the natural vulnerability is low in most of the geosites. Most of the natural processes acting on the geosites are involved in their construction and evolution, and thus are considered in their fragility. The natural processes which are not involved in the creation and evolution of the geosites but which do affect them are usually of minor importance. The extrinsic natural processes considered are the biological activity, geological activity and climate factors. The biological activity has no negative effect on the geosites. The activity by animals such as trampling or burrowing is almost non-existent. The biological activity by plants related to root development or surface growth was recorded, but the level of activity and the area involved do not lead to measurable impacts. The climate factors, such as humidity, precipitation, wind, floods and freeze thaw cycle may exacerbate natural vulnerability. In this case, the result of the assessment was based on the consideration that climate factors did not contribute to visible or substantial changes to the geosites during the three period of this research. A constant monitoring activity is required to collect more data about the influence of climatic factors over time and to identify changes that are continuously occurring. Modeling such changes would contribute to better informed decisions at all levels and across all sectors and allow the Maltese Islands to adapt and become resilient to climate change [20].

Malta already has early warning systems in place, in particular for heat waves/high temperatures and flooding events, but it is imperative that these systems are maintained, developed and strengthened [94].

5. Conclusions

Human activities and natural processes may cause negative impacts that act directly or indirectly on geosites. In this regard, a methodology to assess the degradation risk related to the geosites was developed. The methodology includes the assessment of three main factors: natural vulnerability, anthropogenic vulnerability and public use.

The methodology was applied on 27 geosites located on the Maltese Islands, a small-island state that counts 271 km of shoreline. Given its geographical location in the Central Mediterranean Sea, the archipelago is exposed to several hazards and threats, with a generally low to medium risk level [92].

The degradation risk assessment gave an overview of the condition of the geosites and provided precious information for a correct protection of the geological heritage and its management, with attention given to the effects of climate change. The results in the study area show that most of the geosites are at medium risk of degradation, mainly due to the lack of recognition by locals and tourists and by the absence of more tangible protection measures in situ. Most of the geosites are located along the coast, which is associated with a very sensitive environment. It is particularly vulnerable to disturbance and prone to change, and with climate change impacts considered as very acute [23]. The issue of changing climatic conditions and the consequential threats is not a new phenomenon; however, political recognition worldwide of this problem is a relatively recent occurrence and mostly given a strong impetus over 25 years ago by a singular initiative that Malta took within the framework of the United Nations Organization [20].

Scientific evidence suggests that climate change will impact the ecosystem through the loss of biodiversity, habitat destruction, increased salinization, changes in species composition, reduction in groundwater resources, increased desertification and fires and a potential fertilizing effect. The competition between the conservation of natural heritage and land use for anthropogenic needs has left an indelible mark on the Maltese natural landscape and ecosystems [20]. The Maltese Islands have taken preventive and precautionary measures to address this challenge by adopting policy and legal measures that promote sustainable development. However, the small scale of the country also amplifies the impact of such changes, and thus, addressing climate change is an urgent need in order to ensure resilience in one of the zones predicted to be the worst-affected by climate change [20].

The application of the methodology in the study area is meant to be the first attempt to identify and evaluate the main natural and anthropogenic processes that currently affect the geosites. Malta is an ideal meeting avenue for researching climate studies, both for the relevant academic expertise in these sectors and its island setting that makes it a living laboratory to investigate [20]. The assessment conducted is based on qualitative data, mainly collected through analysis of photos and past observation conducted in the fieldworks. Projections of negative natural and anthropogenic impacts are still subject to large uncertainties, owing to a lack of direct observation and inadequate schemes in numerical climate models. For a complete degradation risk analysis of the geosites, it is important to compare and monitor their evolution over time and assess their degradation risk regularly to ensure the implementation of proper and effective protection strategies.

The results are extremely important to inform stakeholders about the risk connected with geoheritage and to decide in which sites their resources should be applied. In the study area the main threat seems related to the lack of awareness of geoheritage. It is necessary to adopt a comprehensive communication and education strategy. As mentioned on the National Climate Change Adaptation report [95], communication and education are essential elements to decrease natural and anthropogenic vulnerability in response to climate change. The implementation of a sustained education and communications campaign are fundamental long term and should target simultaneously different cohorts of the public [95]. Communication and education are fundamental to share common understanding and awareness of natural and anthropogenic threats, so that the community will be aware and resilient. As also highlighted on the NRA [92], this will support the development of collaborative thinking on strategic needs across prevention, mitigation and recovery requirements.

The low knowledge and recognition of geological heritage, also on the legal framework, means that the geosites are not protected. The absence of protection, physical barriers or infrastructures that can reach the visitors, leads to the consequent absence of control of access and the increase of degradation risk. The uncontrolled access to the geosites, the lack of knowledge on their geoheritage value and the absence of any preservation and safeguarding actions led to a high risk of degradation of the geological heritage, with consequent deterioration of biodiversity and irreversible loss of certain components of the entire ecosystem. In fact, the degradation risk on geosites may also present threats to important habitats (flora and fauna). For this reason, care must be taken to prevent any disturbance that could, in the long term, affect the geoheritage and its biological and heritage quality. The conservation of biodiversity and thus restoring habitats to favour conservation status, is considered one of the pillars of adaptation strategies addressed by Climate Change Committee for Adaptation [95], but the importance of education of the risk is still missing.

For this, the degradation risk analysis is meant to be a tool to prioritize the management of geosites, stressing the importance of constant monitoring and measurements of natural and anthropogenic vulnerability in order to prevent and avoid future degradation and destruction of geoheritage.

To conclude, despite Malta being proactive on adaptation to climate change and several measures have already been adopted, more needs to be done, particularly for legislation and research to integrate climate change considerations into environmental policies, in order to ensure a higher protection of its rich geoheritage.

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