

Article

Geoheritage as a Tool for Environmental Management: A Case Study in Northern Malta (Central Mediterranean Sea)

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Abstract: The recognition, selection and quantitative assessment of sites of geological and geomorphological interest are fundamental steps in any environmental management focused on geoconservation and geotourism promotion. The island of Malta, in the central Mediterranean Sea, despite having a steadily increasing growth in population and tourism, still conserves geological and geomorphological features of great relevance and interest, both for their contribution to the understanding of the geological processes acting through time on landscape and for their aesthetic importance. The present work proposes an inventory for northern Malta, through three main stages, with the outcome of a final list of geosites that have the potential to be recognized as both natural heritage and tourist resources with potential economic benefits. In particular, the assessment methodology applied combines scientific value and additional and use-values, showing the links existing between geoheritage and other aspects of nature and culture of the sites. The results provide useful knowledge for the definition of strategies aimed at the development of a sustainable and responsible tourism.

Keywords: geoheritage; geosites; quantitative assessment; Malta

1. Introduction

Recent global trends have shown heightened appreciation of the variety of abiotic natural resources, known as geodiversity. This variety of non-living natural resources is defined by Gray [1] as the natural range (diversity) of geological, geomorphological and soil features. It describes the diversity of physical processes operating on Earth and the resultant rocks, minerals, fossils, sediments, soils, landforms, landscapes and habitats found on the world's surface today [1–3]. Geodiversity, a resource still little known and which can create potential economic growth that has been largely untapped, allows for the definition of geosites, that together form the geological heritage. In this regard, geoheritage is considered as a natural resource and can be used in local and regional development, especially for promoting a territory for geotouristic purposes [4,5].

The Maltese archipelago, which lies at the center of the Mediterranean Sea, is a European country with a rich cultural heritage endowed with a great variety of natural features of international significance. Indeed, the small geographic scale of the islands is inversely proportional to the richness and frequency of places and artefacts of major importance, and it encompasses, as well, a large number of sites of geoscientific interest, showing a considerable geodiversity. This applies in particular to northern Malta, a sector of the island moderately populated, but which still conserves landscapes of great relevance and interest from a scenic and scientific point of view. These sites are mainly located

along coastal areas, and have to co-exist with the island's main economic activity of tourism. This industry has in fact been capitalizing on some of the most impressive coastal sceneries of the Maltese archipelago for over half a century. However, there is still remarkable potential on how the rich natural and cultural heritage of the archipelago is valued and promoted especially with regard to its geological and geomorphological heritage.

It is a widely shared opinion that any action aiming to promote or protect geoheritage implies a good knowledge of the resource in terms of its location and characteristics. For this reason, an inventory, based on the analysis and assessment of the most valuable elements that define the geoheritage of a territory, represents the first necessary step towards its effective management. A number of European countries have already carried out a similar national inventory, such as Czech Republic, Denmark, Estonia, Finland, France, Iceland, Ireland, Italy, Lithuania, Netherlands, Poland, Portugal, Slovakia, Spain, Switzerland and United Kingdom [6]. More work is, however, required on a global scale.

Recently in Malta, considerable geological and geomorphological research, especially in the north of the archipelago, has been undertaken by scientists in order to showcase the international geological and geomorphological significance of Maltese landscapes [7–13]. Nevertheless, the Maltese Islands still lack an official inventory of sites of geological interest and the government has not yet assigned geological heritage as a specific (or separate) legal provision related to the conservation and management of natural sites. Though the Maltese natural landscapes are governed by a comprehensive legal framework, such instrument mainly (but not only) sustains the importance of biodiversity and ecological conservation at local and international levels. Recently, efforts to recognize elements of geological heritage of the Maltese Islands were primarily channeled to urban landscapes, through the historical and cultural use of the Maltese Lower Globigerina Limestone over the centuries for heritage buildings. These efforts resulted in this limestone unit receiving the status of Global Heritage Stone Resource (GHSR) by the International Union of Geological Sciences in 2019.

In this context, a study for the inventory and assessment of sites of geological interest, highlighting their location and characteristics (e.g., integrity, state of activity, attractiveness and accessibility) in the northern part of the island of Malta has been conducted and the results are here presented. This work aims at providing a better understanding of the geological and geomorphological characteristics of the study area and facilitating the recognition of the opportunities and threats, in order to strengthen the argument for the setting-up an effective environmental management plan, which would directly include both geoconservation and geotourism actions.

2. Maltese Context

Despite the small geographic size of the archipelago, the protection of the natural heritage of the Maltese Islands is governed by a fair number of main legislative acts, related legal chapters and subsidiary legislation (Table 1). These legal instruments are regularly updated in order to transpose European and international laws, mainly from the United Nations (including the Mediterranean Action Plan), the Council of Europe and the European Union [14]. A number of subsidiary legislations are also in force (Table 1), a few of which have replaced earlier legal notices, in order to also transpose international legal obligations into national law.

The Environment Protection Act is the main legal instrument that safeguards the protection of the 'landscape and its features' under the relatively broad umbrella term of 'environment'. A number of natural landscape features are classified as areas of high landscape value (AHLV) under the Development and Planning Act, mainly coastal cliffs, valley systems, karstic plateaus, escarpments, woodland and agricultural settings. Most of these natural features intrinsically incorporate geological and geomorphological properties; however, the value of these features is primarily recognized for its support function to biodiversity and ecological systems, rather than specifically (or exclusively) for their geological properties in their own right. Under the Cultural Heritage Act, the definition of cultural heritage also includes 'geological sites and deposits' and 'landscapes'; however, the act has no specific provisions related to their geoheritage value. The Fertile Soil (Preservation) Act primarily

addresses the maintenance of terraced landscapes, so typical in Malta’s rural setting, by offering direct protection to soil as a resource. A number of islets around the Maltese Islands, such as Filfla and St. Paul’s Islands have been legally established as nature reserves and limiting human access only for scientific purposes. In addition to that, 13.1% of terrestrial areas of the Maltese Islands and 35% of their territorial waters form part of the EU Natura 2000 Network as protected areas under various designations (Table 2, [15]).

Table 1. Maltese legal instruments related to the natural landscape management and protection.

Type of Legal Instruments	Designations
Acts	Environment Protection Act (Chapter 549)
	Development Planning Act (Chapter 552)
	Cultural Heritage Act (Chapter 445)
	Fertile Soil (Preservation) Act (Chapter 236)
	Filfla Nature Reserve Act (Chapter 323)
Subsidiary Legislations	Flora, Fauna and Natural Habitats Protection Regulations (SL 549.44)
	Trees and Woodland Protection Regulations (SL 549.64)
	Selmunett Islands (St. Paul’s Islands) Nature Reserve Regulations (SL 549.03)
	Fungus Rock (il-Ġebbla tal-General) Nature Reserve Regulations (SL 549.01)
	Motor Vehicles Off-roading Regulations (SL 552.01)
	Rubble Walls and Rural Structures (Conservation and Maintenance) Regulations (SL 552.02).
	Conservation of Wild Birds Regulations (SL 549.42)
	Establishment of the Majjistral, Nature and History Park Regulations (SL 549.48)
	Establishment of the Park Nazzjonali tal-Inwadar Regulations (SL 549.109)
Protected Beaches (SL 549.42)	
Tree Protection Areas (SL 549.123)	

Table 2. The number of protected sites according to designation type (Source: Compiled from the Environment and Resource Authority (ERA) [15]).

Designation Type	Number of Sites
Tree Protection Areas	60
Area of Ecological Importance and Site of Scientific Importance	41
Special Areas of Conservation - International Importance	35
Bird Sanctuary	26
Area of Ecological Importance	22
Special Protection Areas	21
Area of High Landscape Value	13
Protected Beaches	11
Site of Scientific Importance	10
Special Areas of Conservation—National Importance	7
List of Historical Trees Having an Antiquarian Importance	6
Nature Reserve	3

The legal framework of natural heritage protection of the Maltese Islands is thus a mosaic of different provisions, with a number of sites protected by more than one designation (Table 2). Within this legal context, the importance of geoheritage as a conservation rationale remains, however, diluted, when compared with that for ecological and biodiversity protection. Despite this, the interest of the scientific community in geoheritage and geotourism has been growing over a number of years. With respect to the Maltese archipelago, the importance of developing studies to investigate the linkage between environment and cultural heritage and the relationship between geoheritage and tourism was initially explored in April 2007 during the International Workshop on the ‘Integration of the geomorphological environment and cultural heritage for tourism promotion and hazard prevention’

held in Malta [16,17]. The papers presented dealt with different aspects of the integration of the physical environment and cultural heritage through case studies from different parts of the world including Malta (e.g., [18]). More recently, Gauci et al. [11] and Gauci and Inkpen [19] have highlighted the geoheritage value of shore platforms in Malta by examining the close relationship between the physical landscape of the foreshore and human cultural development. The significance of Maltese coastal landforms for societal wellbeing was also investigated by Satariano and Gauci [20] who examined the intense reactions experienced by both the Maltese and international community following the sudden loss of an iconic sea arch at Dwejra (Gozo) in March 2017. This latter work forms part of a collection of contributions recently edited by Gauci and Schembri [13] and which illustrate the rich diversity of the Maltese physical landscapes under the World Geomorphological Landscapes series (Springer). Specific studies on geoheritage and geosites inventory and assessment have been carried out on the north-west coast of Malta, especially in the area of Il-Majjistral Nature and History Park and environs [7,12]. With respect to the island of Gozo, this theme was explored by Coratza et al. [8] who examined spectacular sinkholes having highly scientific, ecological, aesthetic, cultural and use-values as geomorphosites. Specific research on Dwejra area, on the western coast of Gozo [9,21], has highlighted how the integration of environmental and cultural heritage aspects makes this area a site of remarkable value to be promoted for a more holistic and varied tourism.

3. Study Area

The study area is located in the north of Malta, the largest island of the Maltese archipelago (Figure 1). It is sparsely inhabited and characterized by a high tourism vocation. According to the National Tourism Policy 2015–2020, northern Malta is defined as a ‘tourism zone’ due to its tourism infrastructures, hosting a further 42% of tourist accommodation [22].

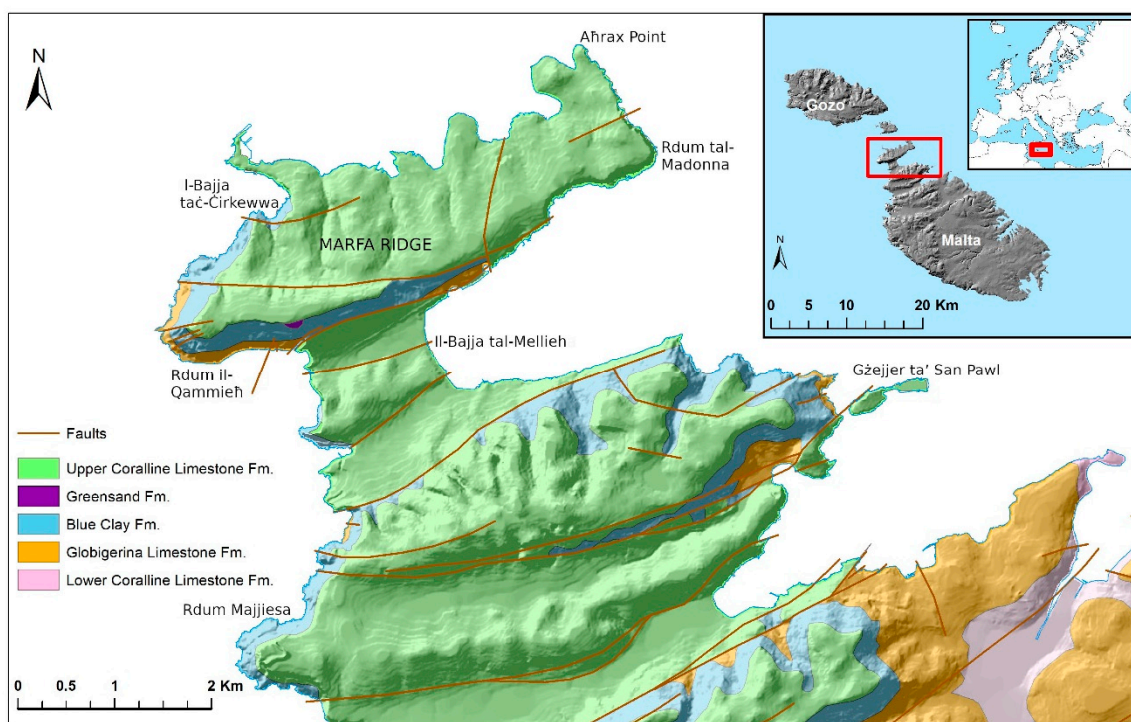


Figure 1. Location and geological setting of the study area.

The island attracts many tourists, also thanks to its mild Mediterranean climate characterized by an average rainfall of 530 mm per year and mean temperatures ranging from 12 to 27 °C.

The rocks exposed in the island comprise a marine sedimentary succession, mostly composed of limestones and marls and deposited in a period between Upper Oligocene and Miocene [23,24]. In the

study area, all five geological formations constituting the Maltese archipelago outcrop (Figure 1). From the oldest to the youngest the formations are Lower Coralline Limestone Fm., Globigerina Limestone Fm., Blue Clay Fm., Greensand Fm. and Upper Coralline Limestone Fm. (Figure 2).

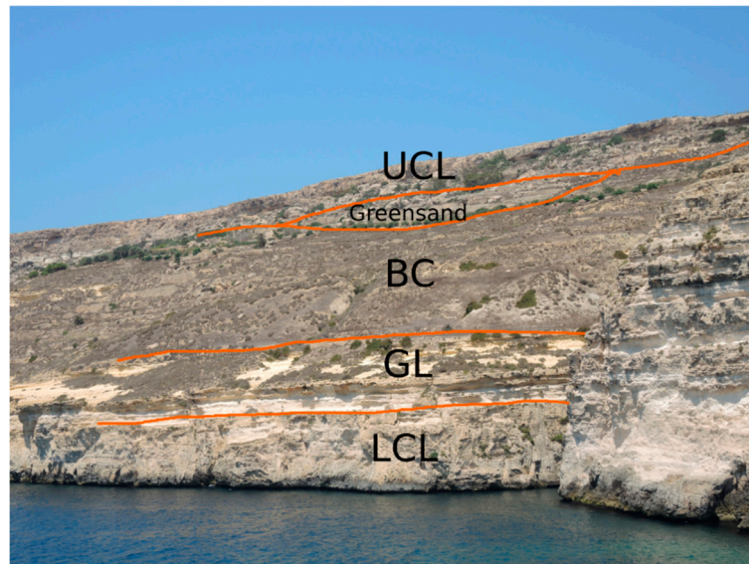


Figure 2. View of Il-Qammieħ, showing the entire geological/stratigraphic sequence. From the bottom: Lower Coralline Limestone Fm. (LCL), Globigerina Limestone Fm. (GL), Blue Clay Fm. (BC), Greensand and Upper Coralline Limestone Fm. (UCL).

The Lower Coralline Limestone Fm., composed of pale grey, hard, shallow marine biomicrites and biospartites [23,25], outcrops in a restricted coastal stretch between Rdum il-Qammieħ and Iċ-Ċumnija, in the eastern part of the study area. The sequence continues with the soft and yellowish Globigerina Limestone Fm., named on account of the high percentage of planktonic foraminifera present in the unit (Figure 3a). The usual color of the formation is pale-yellow, although a pale-grey subdivision bounded both above and below by phosphorite conglomerate horizons, occurs in the middle of the sequence [25,26]. It outcrops on the Ras il-Qammieħ coast and in Selmun Bay, in proximity of St. Paul's Islands.



Figure 3. Landscape features of the study area: (a) Terrace in Lower Globigerina Limestone at Il-Qammieħ with typical honey pots dissolution structures; (b) badland topography in Blue Clay slopes overlain by Upper Coralline Limestone cliffs at Il-Qammieħ.

It is followed by the Blue Clay Fm., formed in a deep-sea depositional setting and is made up of fine-grained sediments with a large component of organic material derived from planktonic organisms.

It consists of sequences of alternating pale-grey and dark-grey banded marls (Figure 3b), with lighter bands containing a higher proportion of carbonate [27]. The uppermost part of the Blue Clay Fm. Shows an increase in brown phosphatic sand grains and green grains of glauconite, together with abundant fossil fragments, often separated by an erosional surface. This level is known as Greensand Fm. and underlines the passage to the overlying Upper Coralline Limestone Fm. The fossiliferous content is mostly represented by mollusks, gastropods, brachiopods, echinoids, bryozoans, algae, shark teeth, and remains of marine mammals [23,24,28]. It shows its maximum thickness of 11 m in Gozo, but the formation is rarely thicker than one meter in the area under study at Il-Qammieħ point. The upper part of the sequence is made up of the Upper Coralline Limestone Fm., a hard, pale grey limestone unit, very similar to the Lower Coralline Limestone especially in color and coralline algal content, of shallow water environment. It usually makes up plateaus and steep cliffs affected by weathering and mass movements [26]. It is often affected by a dense network of tectonic discontinuities which provide the rock masses with a brittle behavior (Figure 3b) [29,30]. This formation largely covers the study area, with a thickness even higher than 100 m.

The geological formations lie almost horizontally across the islands, although they are displaced by tectonic structures [25,31,32]. From a tectonic viewpoint, the archipelago is crossed by two fault systems, the NW-SE trending Pantelleria Rift and the WSW-ENE graben system [23]. The latter is the most ancient and is responsible for a horst and graben structure that characterizes the northern sector of the island of Malta [33,34]. Indeed, the study area is part of the North Malta Graben, one of the three main structural regions of the Maltese Islands. The North Malta Graben is characterized by typical ridge-trough morphology and bounded by the Great Fault to the south [32].

The geomorphological landscape is largely controlled by the different physical and mechanical properties of the lithostratigraphic units and by tectonic features.

The coastal landscape is mainly shaped by marine processes, that produce inlets and bays with small pocket beaches [35–37]. Due to the presence of resistant conglomerate beds and hardgrounds within the stratigraphy of Globigerina Limestone, a number of shore platforms have developed at sea level as a result of differential erosion [19]. On the contrary, plunging cliffs are the dominating features in Upper Coralline Limestone, at times shaped in sea caves. Mass movements are widespread all along the northwestern part of the study area, due to the fragile behavior of limestones, which cap Blue Clay Fm. characterized by visco-plastic properties. Rock falls and topples are abundant along the coastline and mainly affect the Upper Coralline Limestone plateaus which are characterized by persistent fissures and cracks of tectonic origin [29,37–41]. Evidence of rock spreading and block sliding phenomena characterize the stretch of coast at Rdum il-Qammieħ and Rdum il-Qawwi, in the northwestern part of the Marfa Ridge Peninsula, and at Rdum il-Majjiesa, located inside the Il-Majjistral Park boundaries. The lateral extension of rock masses tends to evolve into block sliding whose onset is extensively witnessed by scattered blocks of variable size lying on the Blue Clay slopes which gently slide toward the sea and protect the shoreline from the marine erosion (Figure 4a) [29,42–44].

Karstic features are well developed on the surface topography of plateaus, characterized by highly irregular and rugged surface morphology, resulting from solution processes. Karst pavements, solution holes and solution pans are also particularly relevant. Sinkholes have been found in the area, usually caused by the collapse of cave roofs (Figure 4b). They are characterized by a flat bottom and may reach a few hundreds of meters in diameter and stratigraphic throw [45,46].

The area under study is relatively less urbanized compared with the rest of the island, but has been significantly influenced over time by human activity for agricultural and tourism purposes [47]. Coastal and inland slopes have been remodeled into terraced fields retained by dry stone walls and utilized as terraced agricultural land [48,49]. The terraced fields and agricultural land are usually installed on V-shaped dry valleys, relict of former pluvial conditions and extensive groundwater sapping. The presence of archaeological features and British military architecture can also be encountered.

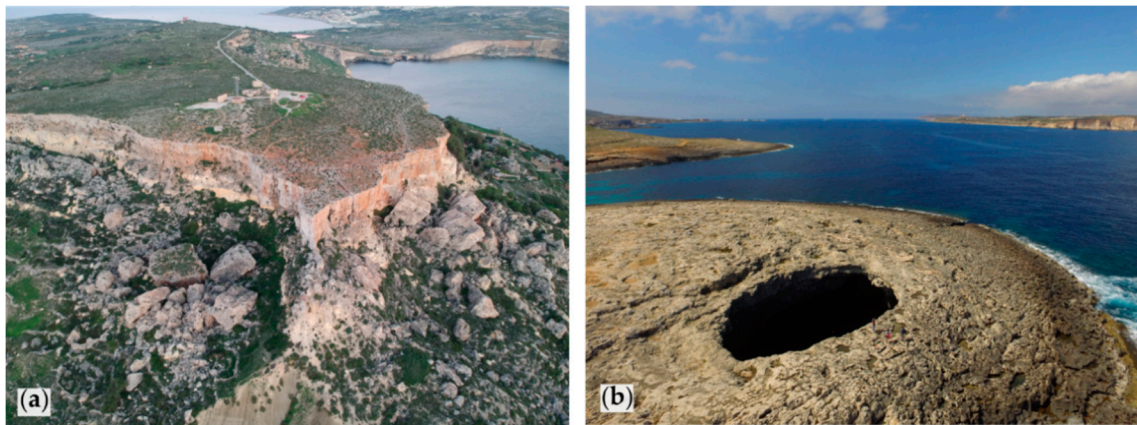


Figure 4. Landscape views of the study area: (a) Aerial photo of Rdum il-Qammieh, showing the impressive rock fall and block slides, typical of the area; (b) remarkable example of karstic feature in Upper Coralline Limestone Fm. at Ahrax point.

4. Materials and Methods

During the last 30 years, the increasing interest in geoheritage has led to the development of methodologies for its inventory and assessment [50,51] and references therein. In fact, the scientific literature is rich in examples of geosite inventories both at national (e.g., [52–56], regional (e.g., [51,57–59]) and local scale (e.g., [60–62]). Numerous methods are described in literature for the qualitative and quantitative assessment of geoheritage and geosites in various contexts (cf. [63,64]): Environmental Impact Assessment and territorial planning (e.g., [65–68]); inventory of natural heritage sites (e.g., [53,58,69–71]); tourist promotion (e.g., [72–76]); management of nature parks and geoheritage (e.g., [77–81]). A complete review of methods for the assessment of geosites has been recently published by Brilha [82]. In general, it should be emphasized that all methods inevitably imply a degree of subjectivity since their intrinsic value cannot be measured. In order to reduce subjectivity and properly evaluate the various components of a geosite, it is necessary to define clear and transparent criteria, which can vary according to the aim, working scale and subject of the assessment. Even though there is no generally accepted method for the numerical assessment of geosites, recurrent criteria are used in literature, such as rarity, representativeness and integrity, ecological value, paleogeographic importance, educational value etc. [64].

Based on published literature, as well as on knowledge achieved in previous research on geoheritage in various morphoclimatic contexts, the methodological approach adopted for the identification of geosites in northern Malta comprises the following operational phases (Figure 5): (i) Recognition and selection of sites of geological and geomorphological interest (i.e., potential geosites), based on their representativeness in terms of geohistory and geo(morpho)diversity [51,79]; (ii) analysis and characterization of potential geosites; (iii) quantitative assessment of potential geosites and final selection of geosites.

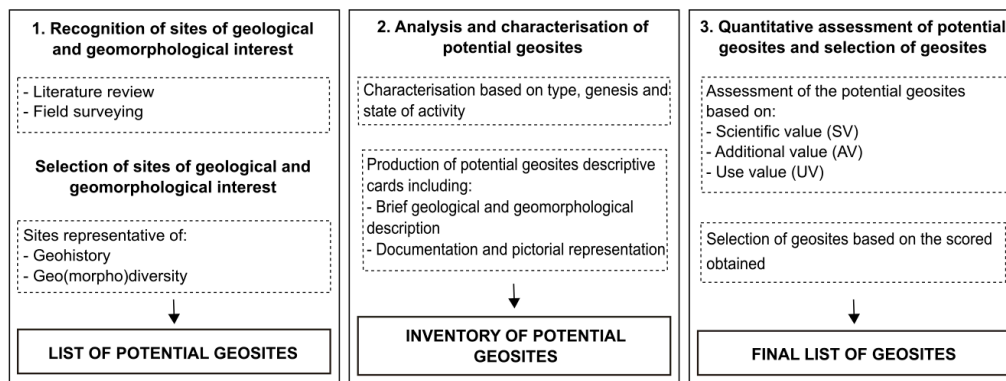


Figure 5. The three stages of the methodological approach.

4.1. Recognition and Selection of Sites of Geological and Geomorphological Interest

In order to recognize sites of geological and geomorphological interest, the first phase consists of a literature review of papers and maps of the area under study and field surveys. A number of papers dealing with the geological and geomorphological features of the Maltese archipelago compiled in the last decades are available, some of which specifically devoted to the geoheritage of the northwestern sector of the island.

Literature review and field survey are fundamental for the recognition of sites of geological and geomorphological interest to be qualitatively assessed, considering the different morphoclimatic conditions, geomorphological processes and lithological and structural constraints that controlled their development. This enables us to account for a variety of features that can finally be considered as geosites. Two main criteria have been taken into account in the assessment procedure (cf. [51]):

- The sites have to be representative of the geo-history and geomorphological evolution of the study area at a regional scale. Both active and inherited geological and geomorphological features can be considered as potential geosites.
- The sites have to represent the regional geo(morpho)diversity, i.e., a complete set of geomorphological processes that acted over time in the study area. Unique or rare landforms, as well as more common and abundant ones, can be useful to provide an overview of the landforms visible in the area (cf. [12]).

4.2. Analysis and Characterisation of Potential Geosites

The second phase foresees the analysis and characterization of potential geosites to be selected among the sites of geological and geomorphological interest previously identified. The analysis provides for the identification of a series of parameters characterizing each potential geosites. These parameters are collected in a descriptive card including elements of textual description and pictorial data. In particular, each descriptive card collects the following headings:

- (1) Feature: name of the potential geosite;
- (2) Location: as precise as possible;
- (3) Coordinates: international system;
- (4) Type (according to [51,58,60,83,84], distinguished on its geometrical characters in: (i) punctiform, small-size isolated single form or object (e.g., a sinkhole or a spring); (ii) linear, one or more simple forms developed preferentially in a single direction (e.g., a canyon, or a paleo riverbed) and/or stratigraphical sequences; (iii) areal: a set of large simple landforms related to just one type of genetic process (e.g., a karren field);
- (5) Lithology;

- (6) Genesis/main interest: e.g., tectonic, geomorphological, stratigraphic; regarding the geomorphological interest, a morphogenetic division related to a group of processes (coastal, fluvial, karstic, gravity-induced etc.) can be applied;
- (7) State of activity (e.g., [85–93]): active sites, those that allow the visualization of geological and geomorphological processes in action (e.g., fluvial systems); inherited sites defined as inherited landforms, which testify to past processes and have a particular heritage value since they are symbols of Earth's history and evolution (e.g., stack);
- (8) Brief geological and geomorphological description based on field observations and literature survey;
- (9) Documents, archive material and pictorial representations: e.g., photographs, sketches.

4.3. Quantitative Assessment of Potential Geosites and Selection of Geosites

The employment of a quantitative assessment is considered necessary in order to decrease the subjectivity associated with any evaluation. The methodology adopted by Coratza et al. [8], already applied with positive results on the northwestern coast of the island of Malta, in a similar geological and geomorphological context [12], has been considered as the most suitable for the assessment of potential geosites. This methodology is inspired by methods previously proposed by Serrano and González Trueba [69], Bruschi and Cendrero [68], Pererira et al. [77] and Reynard et al. [70]. The geosite value assessment is based on 16 criteria divided into three main groups of value, i.e., scientific value (SV), additional value (AV) and use-value (UV), each one producing a final score for its category (Table 3). The scientific value aims to reveal the value of the site for the geosciences and it is assessed according to four criteria (paleogeomorphological model, rareness, representativeness and integrity) scored on a scale from 0 to 1. The additional value is linked to the importance that a geosite assumes owing to non-geological aspects which increase its overall value and is made up of three independent sub-values: ecological, aesthetic and cultural. The use-value refers to the possible utilisation of geosites by society. The scores given for each criterion are reported in Table 3.

Table 3. Values and criteria of geosite assessment methodology and related scores.

Value	Criteria	Score	
Scientific value (SV)	Paleogeomorphological model	0–1	
	Rareness	0–1	
	Representativeness	0–1	
	Integrity	0–1	
Additional value (AV)	Ecological value	Ecological role support 0–1	
	Aesthetical value	Panoramic quality	0–0.25
		Color diversity	0–0.25
		Vertical development	0–0.25
		Naturalness	0–0.25
	Cultural value	Religious importance	0–0.33
		Historical importance	0–0.33
Artistic importance		0–0.33	
Use value (UV)	Accessibility	0–0.75	
	Visibility	0–0.75	
	Services	0–0.75	
	Importance for education	0–0.75	

The value of a geosite results from the total of the scores obtained from all criteria, with 10 being the highest score possible. Once completed, the assessment will provide a set of total scores for each of the three observed values (scientific, additional and use-value). On the basis of both the range and the total of these scores, a series of score-defined thresholds were established in order to allow also the

inclusion of sites, which though they may have limited scientific value, they nonetheless may hold potential for geotourism and educational activities. The score thresholds were established on both the basis of the highest scores and the scope of the study. The sites that reach such thresholds can be finally considered as geosites.

5. Results

5.1. Recognition and Selection of Sites of Geological and Geomorphological Interest

As a first stage, a literature review has been carried out referred to more than 50 scientific references comprising 13 theses, ca. 40 national and international papers, 5 geological and geomorphological maps and several reports of Maltese environmental agencies (Planning Authority, Environmental and Resources Authority, Malta Environment and Planning Authority). In particular, the scientific papers analyzed (Figure 6) deal with various geological aspects including geomorphology (33%), structural geology (19%), stratigraphy (10%), paleontology (7%), geoheritage (6%) and miscellaneous geological topics (25%).

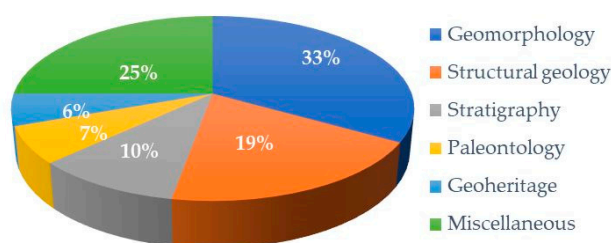


Figure 6. Distribution of geological literature according to the main topics of the scientific papers analyzed. The item miscellaneous comprises papers on geology l.s.

This detailed literature review combined with several field surveys led to the identification of sites in the study area with geological and geomorphological interest. The field surveys were essential to integrate the list of sites previously identified with new sites not mentioned in literature. In addition, field surveys were also fundamental to collect site-specific updated information—i.e., state of conservation, state of activity, accessibility, visibility and presence of services—relevant to the completion of the descriptive cards and the quantitative assessment of potential geosites.

Through literature review and field surveys, sites with geological and geomorphological interest were recognized and 31 were selected as potential geosites considering the two criteria mentioned in paragraph 4.1, i.e., geohistory and geo(morpho)diversity. The sites selected are representative evidence of the main geological and geomorphological processes acting through time in the study area (Figure 7).


5.2. Analysis and Characterization of Potential Geosites

The 31 potential geosites selected were analyzed and for each site a descriptive card has been compiled including the information reported in paragraph 4.2 and Figure 8. The data collected in this phase were stored in a GIS database.



Figure 7. Location of the 31 sites selected within the study area. The numbers correspond to the ID of the sites.

ID3 Sinkhole	
Municipality	Mellieha
Location	Il-Latnija
Coordinates	35°58'38.68"N 14°19'43.10"E
Type	punctiform
Lithology	Upper Coralline Limestone
Main interest	geomorphology
State of activity	inherited



Brief description
Sinkhole, probably Quaternary in age, represents a collapse of the limestone surface which formed the roof of a cave. The roof area has not collapsed entirely resulting in the formation of a cave within the sheltered area. This sinkhole is situated at an altitude of 65 metres above sea level.

Source: Saliba, 2008; Soldati et al. 2013.

Figure 8. Example of a descriptive card of a potential geosite.

Regarding the type of sites (Figure 9a), 19 sites were classified as areal (61%), 10 sites as punctiform (31%) and 2 sites as linear (7%). It can be stated that the selected sites refer to the three main lithological formations of the area under study (Upper Coralline Limestone Fm., Blue Clay Fm. and Globigerina Limestone Fm.) and most of the sites consist of two or more different lithologies (Figure 9b). Regarding the main scientific interest, 26 of the selected sites have mainly geomorphological interest (84%), 3 sites display evidence of anthropogenic activity (10%) and the last 2 sites have tectonic origin (6%). As

reported in Figure 9c, almost half of the geomorphological sites (45%, 14 sites) feature gravitational movements, followed by 7 sites (23%) shaped by sea action and 3 sites (16%) by karstic processes. Most of them are located along the coast (Figure 9d), where impressive lateral spreading phenomena dominate the landscape and where wave action and litho-structural processes shape cliffs and bays. For their representativeness, karst morphologies have also been selected, such as the surface topography on limestone plateaus that present small irregular rock pools colonized by typical Mediterranean vegetation and a large number of endemic communities [94]. Other selected sites in the area are two sinkholes at the eastern and western ends of the Marfa Ridge peninsula.

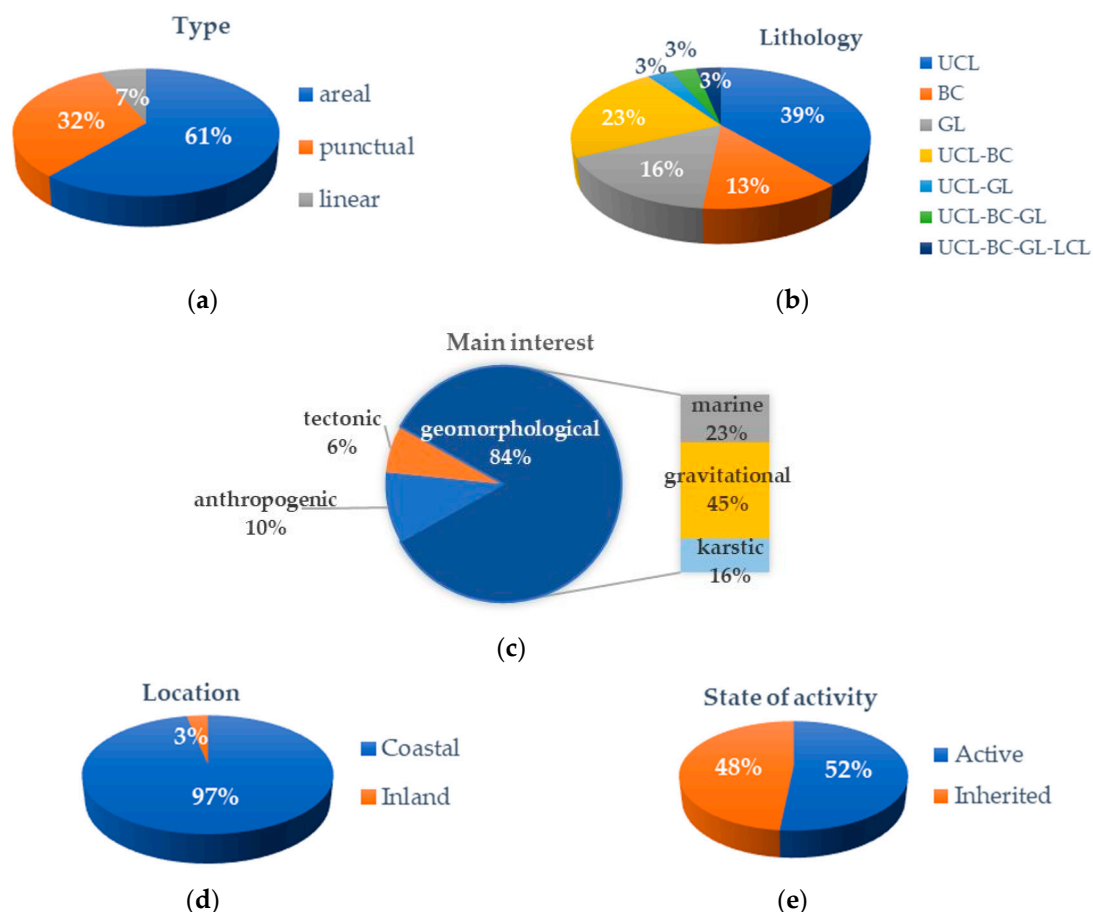


Figure 9. Distribution of potential geosites according to (a) type; (b) lithology; (c) main interest; (d) location; (e) state of activity.

Besides the sites with entirely natural origin, sites of geological and geomorphological interest strictly linked with the anthropogenic activity were selected. In fact, the geology has greatly influenced the location of settlement and activity of human civilization. The term ‘anthropogenic site’ was then used to differentiate these types of sites from the pristine ones. The best example is the large area of industrial salinas (ID26, ID27), not in use anymore, that covers approximately 1 km along the shore platforms of Blata l-Bajda in Selmun [95]. The rocky shore platforms in soft Globigerina Limestone developed the ideal coastal landscape for the formation of natural pools filled with seawater. This natural feature was extended and built from humans in order to collect seawater for the production of salt [11,19]. This site shows how geological features influence traditional practices and how sites with geological and geomorphological interest can be considered as part of the cultural heritage. Another example of anthropogenic site is the presence of cart ruts (ID12), on Wied Musa battery. This site is evidence of ancient agricultural civilizations that hewn the rock below the field, using a slide-car or wheeled cart.

Two sites have been chosen mainly for the geological/geotectonic interest such as St. Paul's Islands that are crossed by one of the major SW-NE faults in the island and which affected the horizontal transition between Upper Coralline Limestone and Upper Globigerina Limestone. The 52% of the sites (16 sites) are active landforms which provide clear evidence of geological and geomorphological processes in action. The remaining 48% (15 sites) consist of inherited landforms, that testify to inactive processes which are evidence of past geological and geomorphological processes (Figure 9e).

5.3. Quantitative Assessment and Selection of Geosites

The 31 potential geosites have been assessed through the methodology described in paragraph 4.3 in order to establish the final selection of geosites.

Once the potential geosites have been evaluated, the total scores for each value (scientific, additional and use-value) were plotted on a graph plane according to the cartesian coordinate system. The total scores of the scientific value plus additional and use values (combined) were plotted on the cartesian plane as x-axis and y-axis respectively (Figure 10). A score value of ≥ 4.5 was established for the total value, along which to define the potential geosites as (final) geosites, provided that the scientific value was ≥ 2.0 .

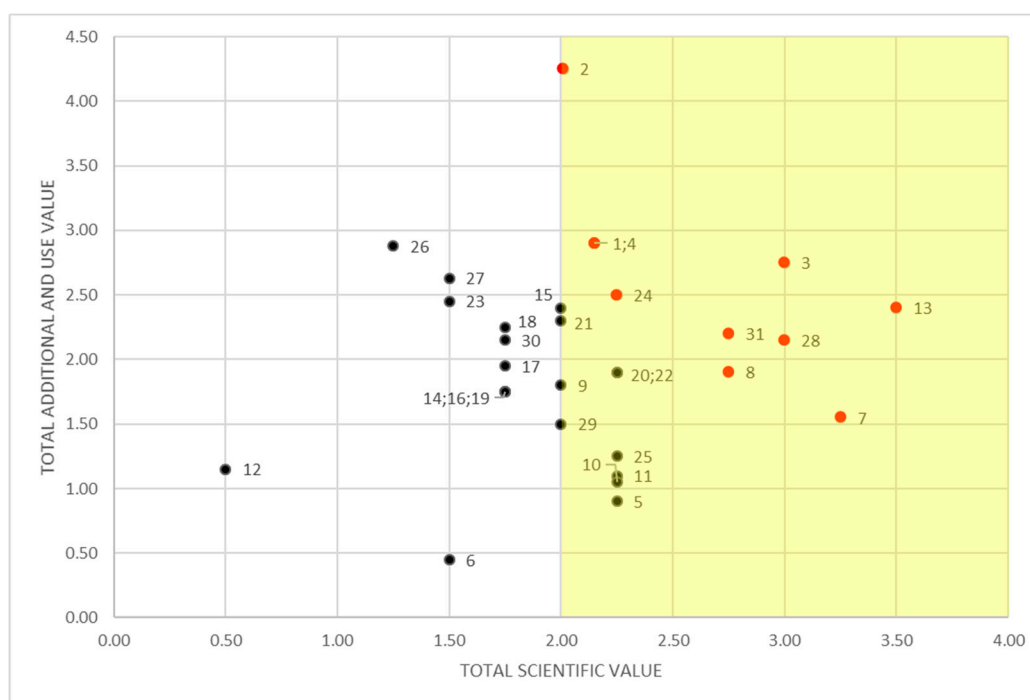


Figure 10. Total scientific value vs total additional and use-value of potential geosites. Sites finally selected as geosites are those displaying a scientific value of ≥ 2.0 and a total value of ≥ 4.5 (red dots).

The results are presented in Table 4 where the values of each geosite are shown. 10 sites have been selected as geosites for the high score in scientific interest and total additional and use-value. Not only sites with high scientific value were selected, but also sites with potential as geotourist destination and ideal for educational activities, according to the aim of the present research. As shown in Figure 10, two salinas at Blata l-Bajda (ID26 and ID27), despite the high potential as tourist attractions, were not selected as geosite due to the lack of relevant scientific importance. Instead, areas affected by rock spreading (ID1 and ID4) and rock topple (ID2), even though the low relevance as scientific site, are selected as geosite due to their important score in additional and use-value. All the identified geosites are examples that well represent geohistory and geo(morpho)diversity of the study area and are capable of being exploited as geotourist resources. The sinkhole at Il-Ponta tal-Aħrax (ID 13) is considered the only occurrence of this type in the island of Malta and the fault at Il-Qammieh (ID31) is

the only spot where all the Maltese geological formations outcrop in the study area. Considering the use-value, the rock topple at Il-Bajja taċ-Ċirkewwa (ID2) is the only site presenting a complete range of services and facilities, thus having the possibility to host geotourism activities. Almost all the sites are accessible without obstacles, except ID24 that is located on St. Paul's Islands, a protected nature reserve with limited access. All the sites have educational potential at different levels. All the geosites show a high total aesthetic value, making them attractive also to a public of non-specialists.

Table 4. Final quantitative assessment of potential geosites (sites finally selected as geosites are highlighted in yellow).

ID	Feature	Location	Geosite Values				
			SV	AV	UV	AV+UV	SV+AV+UV
1	Area affected by rock spreading	Ta' Qassisu	2.15	1.15	1.75	2.90	5.05
2	Rock topple	Il-Bajja taċ-Ċirkewwa	2.00	1.25	3.00	4.25	6.25
3	Sinkhole	Ċirkewwa	3.00	1.10	1.65	2.75	5.75
4	Area affected by rock spreading	Rdum il-Qawwi	2.15	1.40	1.50	2.90	5.05
5	Rock window	Ta' Qassisu	2.25	0.65	0.25	0.90	3.15
6	Marine cave	Ġebel Imbark	1.50	0.30	0.15	0.45	1.95
7	Lower Globigerina Limestone terrace	Rdum il-Qammieh	3.25	1.15	0.40	1.55	4.80
8	Badland topography in Blue Clay slopes	Rdum il-Qammieh	2.75	1.00	0.90	1.90	4.65
9	Dissolution structure (Globigerina pavement)	Rdum il-Qammieh	2.00	1.30	0.50	1.80	3.80
10	Shore platform	Ras il-Qammieh	2.25	1.10	0.00	1.10	3.35
11	Badland topography in Blue Clay slopes	Ras il-Qammieh	2.25	0.80	0.25	1.05	3.30
12	Cart ruts	Il-Palazz tal-Marfa	0.50	0.25	0.90	1.15	1.65
13	Sinkhole	Il-Pontal-Ahrax	3.50	1.00	1.50	2.40	6.00
14	Marine Cave	Rdum l-Ahmar	1.75	0.60	1.15	1.75	3.50
15	Karst landform (limestone pavement)	Ahrax Point	2.00	1.15	1.25	2.40	4.40
16	Rock topple	Rdum l-Ahmar	1.75	0.25	1.50	1.75	3.50
17	Rock topple	Rdum tal-Madonna	1.75	0.45	1.50	1.95	3.70

Table 4. Cont.

18	Area affected by rock spreading	Il-Marbat	1.75	0.75	1.50	2.25	4.00
19	Rock topple	Rdum il-Ħmar	1.75	0.50	1.25	1.75	3.50
20	Badland topography in Blue Clay slopes	Rdum il-Ħmar	2.25	0.75	1.15	1.90	4.15
21	Area affected by rock spreading	Il-Parsott	2.00	0.80	1.50	2.30	4.30
22	Sinkhole	Ta' L-Imgharrqa	2.25	0.65	1.25	1.90	4.15
23	Area affected by rock spreading	Rdum il-Bies	1.50	0.95	1.50	2.45	3.95
24	Fault	Gżejjer ta' San Pawl	2.25	1.00	1.50	2.50	4.65
25	Marine cave	Gżejjer ta' San Pawl	2.25	0.25	1.00	1.25	3.50
26	Salinas	Blata l-Bajda	1.25	0.88	2.00	2.88	4.13
27	Salinas	Blata l-Bajda	1.50	0.88	1.75	2.63	4.13
28	Badland topography in Blue Clay slopes	Tal-Blata	3.00	0.90	1.25	2.15	5.15
29	Tsunami deposit	Il-Ponta tal-Ahrax	2.00	0.25	1.25	1.50	3.50
30	Area affected by rock spreading	Għajn Ħadid	1.75	1.15	1.00	2.15	3.90
31	Fault	Il-Qammieħ	2.75	2.20	1.25	2.20	6.20

Description of the Geosites

The geosites finally selected are reported in descending order, considering the total score value achieved.

ID31: Il-Qammieħ Fault

Il-Qammieħ, on the south side of the Marfa Ridge, is one of the most striking geological features which exposes the entire Oligo-Miocene Maltese lithological sequence, including the Greensand Fm. The place is already designated under the Flora, Fauna and Natural Habitats Protection Regulations (SL 549.44) in view of its diverse and endemic ecology. Upper beds of the Lower Coralline Limestone are well exposed along the base of an elevated platform. The top of this formation is marked by the abundance of the echinoid *Scutella subrotunda* and constitutes the important marker Scutella Bed. The succession continues with the exposure of Globigerina Limestone Fm., all the three members, and passes transitionally up into the banded Blue Clay deposit. Overlying the Blue Clay Fm. there is approximately 1 m of the Greensand Fm., occurring as a friable, green and brown colored glauconitic micrite. On the top of this stratigraphic section, the Upper Coralline Limestone Fm. outcrops, typically cream colored by fossiliferous algal limestones (Mtarfa Member) containing abundant spherical rhodoliths [23,96]. The site is one of the most accessible and clear spots showing the intact transition of the five formations, suitable for educational activities (Figure 2).

ID13: Id-Dragonara Sinkhole

The site is a subsidence structure found at Il-Ponta tal-Aħrax. This structure is created as a result of the corrosive action of rainwater with limestone which enlarges a cave to an extent where the cave's roof becomes unstable and collapses. This unique site is connected with the sea and it is a place of interest for diving and kayaking. It lies 10 m above sea level; for this reason, it is regarded as a panoramic lookout point from where it is possible to view all Marfa peninsula, Gozo and Comino. The site has already considered as a site with aesthetical value frequented by recreational activities, but it has also scientific relevance being a unique sinkhole in Malta connected with the sea (Figure 4b). It is known by the locals as Id-Dragonara.

ID3: Ċirkewwa Sinkhole

A semi-circular sinkhole is found in Ċirkewwa, northwest of Malta, known from the locals as Latnija, or as Ghajn Tuta, the latter being the name of the local area in which it is situated. It is probably Quaternary in age [46,97] and represents the collapse of a limestone roof of a small cave. It shows a semi-circular shape and has a diameter of 35 m, on the ground level and it is surrounded by a rocky pavement with soil infills on its karstic surface. Partly obscured by typical Mediterranean scrubland, the site is highly affected by human activities such as rock climbing, camping and recreation such as barbeque. The geodiversity content of the site can be linked with other subjects as ecology and biology, due to the presence of Mediterranean vegetation. The site is a unique example of inland sinkhole in the area under study and the second in all Malta (consequent only by Il-Maqluba in the south of Malta). It is a perfect spot to appreciate the karst processes that acted and act nowadays on the archipelago (Figure 11a).



Figure 11. Views of the selected geosites: (a) Latinija sinkhole (ID3); (b) Il-Bajja taċ-Ċirkewwa where mass movements affect Upper Coralline Limestone overlying Blue Clays (ID2); (c,d) badland topography in Blue Clay slopes (ID28 and ID8); (e) Lower Globigerina terrace (ID7); (f) lateral spreading affecting Upper Coralline Limestone overlying Blue Clays (ID1).

ID2: Il-Bajja Taċ-Ċirkewwa Rock Topple

A spectacular site with lateral spreading and rock topple in Upper Coralline Limestone Fm., this embayment represents a highly-sought-after bay on the island with a pocket sandy beach. The site is called Il-Bajja taċ-Ċirkewwa, better known as Paradise Bay due to the clear sea waters that fringe the white sandy beach. The high score is assigned not only from a scientific point of view for its landslide

features, but also for the presence of recreational facilities. Services as bars, hotels, car parks and a bus station are found within the site. The bay is also popular for shore diving. The whole area is easily accessible via public services and directly connected with the national road that could favor educational activities (Figure 11b).

ID28 and ID8: Badland Topography on Blue Clay Slopes

Both sites have a high visual impact and make up exemplary cases that help to understand the geomorphological evolution of coastal areas. ID28 (Figure 11c) is located at Blata l-Bajda, between the salinas in Globigerina Limestone and the fragmented plateau of Upper Coralline Limestone. The site is easily accessible and it could be the destination of a number of activities related to other subjects, such as history, ecology and biology due to the presence of salinas, military fortifications and green areas. Despite the fragility of the environment, this site is widely used by locals for recreational activities such as hiking, cycling, motorcycling and hunting. These recreational activities are a potential threat to the exposed Blue Clay slopes. The second site, ID8 (Figure 11d), has high scenic impact and remarkable educational value. The Blue Clay slopes outcrop, gently corrugated, between the Upper Coralline Limestone plateau and a unique terrace (ID7) in Globigerina Limestone. In this site it is possible to understand how detached blocks of Upper Coralline Limestone move on the underlying Blue Clays slopes and how badland topography develops.

ID7: Rdum Il-Qammieh Terrace

A 1 km terrace in Lower Globigerina Limestone Fm. extends along the coast of Rdum il-Qammieh, featuring with typical examples of karst terrain. Chemical weathering is the main process shaping the surface of the platform and forming small solution pools, also known as honeycomb structures. High scientific value and high aesthetic value are assigned to this unique terrace in northern Malta, which is spectacularly flat and yellow-colored. In addition, it conserves a substantial number of fossils. The intensive network of fossilized burrowing channels over the surface of the Lower Globigerina Limestone scallop shells especially within the Lower Conglomerate bed, and the fossils of Echinoids species exposed at the surface. It can be considered an unspoiled outbound site, without services nearby. The Upper Coralline Limestone forms a plateau at the top of the slope profile and is the source of numerous boulders that are deposited on the Blue Clay slopes and the terrace. These boulders, different in size, are used by climbers for boulder activity (Figure 11e).

ID1 and ID4: Areas Affected by Lateral Spreading

Located on the west coast, respectively in Ta' Qassisu (Figure 11f) and Rdum il-Qawwi (Figure 12a), these two sites are representative of gravity-induced processes active on the coast. In particular, it is possible to appreciate deep fissures on the carbonatic plateau, block sliding and lateral spreading, constantly expanding towards the sea. The geodiversity content of the area can be combined with two other subjects: biology and history. Indeed, as additional value, the plateau hosts a variety of endemic flowers and plants and offers a spectacular view of Gozo. Rich also from the cultural-historical point of view, both sites host remains of old villages and pillboxes of the Second World War. ID4 presents a higher number of blocks located on the coast and a small rock window shaped by sea action.



Figure 12. Views of the selected geosites: (a) Lateral spreading affecting Upper Coralline Limestone overlying Blue Clays (ID4); (b) St. Paul's Islands fault (ID24).

ID24: St. Paul's Islands Fault

The islets of St. Paul, protected as Nature Reserve, lie 800 m from Selmunett Bay. A direct fault across the island has brought the Upper Coralline Limestone in juxtaposition with Upper Globigerina Limestone [95]. The Upper Coralline Limestone is predominant on the surface and represents the entire surface morphology of the islets; the Upper Globigerina Limestone outcrops as a small cliff with a narrow shore platform at the base. The coast of islets also features a number of marine caves. The islets are a Level 2 Site of Scientific Importance (SSI) for its geomorphology (GN 827 of 2002). Access to the islets is only permissible between sunrise and sunset and then only against an entry permit obtainable from the Environment and Resource Authority (ERA) (Figure 12b).

6. Conclusions

This work aims to increase the knowledge of the rich geological heritage of northern Malta, providing a better understanding of the geological and geomorphological characteristics of the study area and facilitating the recognition of the opportunities, in order to strengthen the argument for the setting-up an effective environmental management plan, taking into full account the geological component as well. The present research shows that, considering the small geographic scale of the island, there is a high level of geodiversity of features primarily controlled by the interaction between geomorphological processes, structure and stratified geology. An assessment of geosites has been carried out based on a set of criteria that links geological and geomorphological importance with additional values of the sites, as aesthetic, cultural, ecological and economic. The accurate description and characterization of potential geosites and their inventory aim to help the government administration become more aware of the sites of geological interest in the area, giving useful information for their effective management which includes both geoconservation and geotourism actions. As found in the result (Section 5.1), we classified the sites in active or inherited, not only to note their state of activity, but to take into consideration their vulnerability and fragility. Active geosites, in fact, are fragile and may necessitate management and protection measures. Similar to most geosites, they are exposed to natural and man-made processes that threaten their integrity and may compromise their value. Therefore, their conservation is a complex issue since it should address the problem of both possible destruction by natural active processes and man-induced damage. In addition, very often dynamic sites are highly sensitive features, susceptible to modifications due to processes' changes in time, frequency and intensity. Many coastal environments are very sensitive areas, particularly vulnerable to disturbance and prone to change, where climate change impacts are very acute. Changes are visible at very short time scales and may generate active processes, very evident to observe. The same consideration can be done to the size of the sites. The limited study area comprises small isolated

features that are usually more vulnerable due to their dimension and can stand a lower tourist pressure compared to extensive areal geosites [58]. Geoheritage inventory and assessment are therefore the first steps in the process of effective conservation and promotion. Some degree of legal protection already exists in a few sites. A wide part of the study area falls under Natura 2000 management as Special Areas of Conservation (SAC) or Special Protected Areas (SPA). In addition, some sites, such as Gżejjer ta' San Pawl, are scheduled as Nature Reserves and so protected under the Nature Reserve legislation (Table 1) or established as nature parks, such as the Majjistral Nature and History Park. The integration of the geoheritage character of the area would mean both strengthening the landscape value for its geological and geomorphological component and unifying the whole study area under geoheritage conservation rather than leaving it as an area with single components of conservation.

Geoheritage, combined with the rich cultural heritage, could be considered as the heart of tourism and educational activities, with Malta's tourism direct contribution to GDP being among the highest in the EU. Data from the World Travel and Tourism Council (WTTC) show that the travel and tourism industry's total contribution to Malta's GDP stood at 27.1% in 2017. This was the highest share recorded within the Mediterranean region by a notable margin and was also well above the Mediterranean, European Union and World averages, which ranged between 10% and 12%. The total contribution of travel and tourism industries to employment including indirect and induced impacts was estimated to reach 55,000 jobs in 2017 (28.3% of total employment) [98,99]. Concerning the kind of tourism, leisure tourism remains the main purpose of visit for the vast majority of tourist arrivals to the Maltese Islands, with a share of 85.3% of total inbound tourists in 2017. The number of visitors for business purposes stood at 7.9% (2017), whilst "other" tourist segments, such as for educational, religious and health-related purposes, stood at 6.8%. Most importantly, there has also been some evidence of diversification within the Maltese holiday product itself, which departs from the stereotypical image of the islands as a 'sun and sea' destination. The Market Profile Survey (for 2017) undertaken by the Malta Tourism Authority's [100] has in fact shown that only 15.7% of inbound tourists chose Malta based on traditional 'sun and sea' destinations. The largest share of tourists (42.9%) chose Malta for its culture and heritage. Moreover, the tourism industry in Malta has gradually also shifted from package to non-package holidaymakers. This reflects the emergence of a more independent type of tourist who wishes to experience the Maltese Islands in a more autonomous and dynamic way.

Given the increasing number of tourists (currently standing at 2.6 million tourists in 2018), geotourism, as a form of sustainable tourism, is the best solution that sustains and enhances the identity of the territory, especially rural areas, taking in consideration its geology, environment, culture, aesthetics, heritage and the well-being of its residents [101]. Geotourism will ensure benefits for traveler that will discover the geoheritage, cultural heritage and traditions of the archipelago in an innovative and green way, respecting the environment and ensuring a sustainable economic growth. At the same time, geotourism may offers to locals a high-quality standard of life, helping to build a local identity and promote the unique and authentic heritage in their territory, being involved and architects of geotourism activities. In addition, the need to establish geoheritage recognition of these sites is also paramount to provide long-term sustainable measures [102], especially in view of the recent trends of construction boom on the islands to meet the demands of a growing population. The latter is primarily driven by the influx economic migrant workers (EU and non-EU) to support the current growing economy of the Maltese Islands, with 14.1% of the population in 2017 being foreign citizens.

The establishment of a geopark could align well with the recent vision announced by the Maltese government to improve not only the quality of the tourists' experiences but also increase high expenditure and demand-oriented tourists [103,104], over and above the already high annual number of tourists reaching the islands (2.6 million in 2018). Geoparks have the strong potential to maximize the quality of these experiences expected by such higher-expenditure tourists and it would directly inject further policy actions in both geoconservation and geotourism strategies for the islands. In this framework, the recognition of viewpoint geosites, intended as "a specific locality which allows for unobstructed observation of the surrounding landscape and comprehension of Earth history recorded

in rocks, structures and landforms visible from this locality” [105], would be crucial for geo-education and outreach activities, and future research will be addressed to this.

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