

Article

Geodiversity of Skyros Island (Aegean Sea, Greece): Linking Geological Heritage, Cultural Landscapes, and Sustainable Development

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Abstract

Skyros Island, the largest island of the Sporades Complex (NW Aegean Sea, Greece), preserves a geologically diverse record spanning from the Upper Permian to the Quaternary, including crystalline and non-metamorphosed carbonate rocks, ophiolitic rocks and mélanges, medium-grade metamorphic units, rare Miocene volcanic rocks, and impressive fossil-bearing sediments and tufa deposits, together with historically significant quarry and mining landscapes. Through a comprehensive evaluation of the geological heritage of Skyros, this study proposes a transferable, results-based framework for geoconservation, geoeducation, and tourism space management within a geopark context. A systematic inventory of twenty (20) geosites, including six (6) flagship case studies, was established based on scientific value, dominant geodiversity type, risk of degradation, accessibility, educational and tourism potential. The assessment integrates the Scientific Value and Risk of Degradation criteria with complementary management and sustainability indicators. The results demonstrate consistently high scientific value across the selected geosites, with several reaching maximum or near-maximum scores due to their rarity, integrity, and reference character at a regional to international scale. Although some geosites exhibit elevated degradation risk, overall vulnerability is considered manageable through targeted conservation measures and spatially explicit visitor management. Based on the assessment results, a network of thematic georoutes was developed and evaluated using route-level indicators, including number of geosites, route length, educational potential, tourism suitability, accessibility, and contribution to responsible geotourism. The study demonstrates how integrated geosite and georoute assessment can support sustainable land management and confirms that Skyros Island meets key criteria for inclusion in the Hellenic Geoparks Network, providing a robust scientific basis for future UNESCO Global Geopark designation.



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1. Introduction

In recent decades, the concepts of geoheritage and geodiversity have evolved from purely scientific discussions to central components of global debates on sustainable development, conservation policy, and landscape management. As environmental pressures intensify and public awareness grows, geoheritage is increasingly recognized not only

as a scientific asset but also as a key driver of education, regional identity, and sustainable tourism [1–6]. Geoheritage encompasses geological features, sites, and landscapes of significant scientific, educational, cultural, or aesthetic value [5–9], while geodiversity represents the abiotic foundation of biodiversity and human civilization, comprising the natural range of geological, geomorphological, and hydrological features, as well as other types of geodiversity not listed here. Despite its fundamental role in ecosystem stability and climate regulation, geodiversity has historically received less attention than biodiversity in conservation strategies. Recent research, however, shows that the conservation of abiotic diversity is a prerequisite for effective ecological protection and long-term biodiversity maintenance [1,10,11].

This growing recognition has led to the development of geoconservation as a formal management discipline, aiming to safeguard significant geological sites from threats such as urbanization and infrastructure development while promoting public access, education, and appreciation. Within this framework, geotourism has emerged as an important tool for sustainable development, transforming scientific knowledge into cultural experience and economic opportunity and fostering a balanced relationship between conservation, tourism, and local communities [9–14]. Geotourism, when implemented according to principles of responsible tourism, promotes low-impact visitor experiences, enhances environmental awareness, supports local economies, and contributes to the long-term protection of geoheritage resources. As such, it is increasingly recognized as a key component of sustainable tourism space management, particularly within geopark territories.

Closely linked to these developments is the concept of geoethics, which addresses the ethical responsibility of humans in their interactions with the Earth system. Within a geoheritage context, Geoethical Relevance refers to the capacity of a geosite to raise awareness of responsible human–Earth relationships, encourage respect for geological resources, and promote ethically informed decision-making in land use, tourism development, and resource exploitation [7,15–17]. Geosites with high geoethical relevance not only illustrate geological processes but also communicate the consequences of human actions on the geological environment, thereby supporting environmental responsibility, social awareness, and sustainable governance.

The most structured institutional expression of these principles is found in UNESCO Global Geoparks (UGGs), which are unified geographical areas containing sites of international geological significance managed through an integrated approach to protection, education, and sustainable development. As of 2025, the Global Geoparks Network comprises 229 geoparks in 50 countries. In Greece, these initiatives are coordinated through the Hellenic Geoparks Network (HGN) (Figure 1), which currently includes seven territories with UGGp status, such as Lesvos, Psiloritis, and Vikos-Aoos, illustrating the capacity of geoheritage to enhance local resilience, responsible tourism, and sustainable land-use planning [12]. Nevertheless, despite Greece's exceptional geodiversity, several regions of high geological and cultural value, including the Sporades complex, remain outside this formal framework and face challenges related to limited funding, fragmented management, and low public engagement.

Within this context, Skyros Island (Figure 1) represents a distinctive geo-cultural landscape in the Aegean Sea, where geology, biodiversity, and human history are deeply interconnected. Situated between Euboea and the Northern Sporades, Skyros constitutes a natural archive of Alpine orogenic evolution, characterized by ophiolitic mélanges, high-pressure metamorphic units, Miocene volcanic outcrops, extensive karst systems, Quaternary deposits, and other geodiversity elements that reflect the island's complex geological evolution. Beyond its geological complexity, the island is distinguished by the long-standing entanglement of lithology with cultural practices and ecological systems. An-

cient marble quarries producing the renowned Skyrian breccia supplied building material for Roman and Byzantine monuments, while tuffaceous and schistose formations strongly influenced vernacular architecture and settlement patterns. Mythological narratives associated with figures such as Achilles and Theseus, together with archaeological sites like the prehistoric settlement of Palamari, further illustrate the influence of geology and topography on human occupation. This relationship extends to ecological processes, as Skyros hosts unique biodiversity, including the endemic Skyrian horse and extensive Natura 2000 areas whose development is closely linked to the island's geomorphological conditions.



Figure 1. Location of Skyros Island within the national context of Greek UNESCO Global Geoparks. Stars indicate the existing UNESCO Global Geoparks in Greece (Lesvos, Psiloritis, Chelmos–Vouraikos, Vikos–Aoos, Sitia, Grevena–Kozani, Kefalonia–Ithaca, Lavreotiki, Nisyros, and Meteora–Pyli), while the red box highlights the position of Skyros Island in the central Aegean Sea. The map situates the study area within the Hellenic Geoparks Network and illustrates its spatial relationship to established geopark territories (modified from ref. [12]).

Despite these attributes, Skyros lacks a comprehensive and systematic geoconservation and tourism management strategy, highlighting the need for an integrated inventory, assessment, and evaluation of risk of degradation related to its geoheritage assets. The absence of a formal geopark framework in the Sporades further limits the structured development of responsible geotourism initiatives and coherent tourism space management.

In response to this gap, the present study aims to contribute to the ongoing dialogue on geoheritage valorization, responsible tourism, and geopark development through a systematic, interdisciplinary, and locally grounded assessment of Skyros Island's geosites. Based on an initial inventory of twenty (20) potential geosites identified across the island, this study focuses on the detailed assessment of six (6) representative sites. These sites were selected according to their scientific value, representativeness of different geodiversity types, state of preservation, accessibility, educational and tourism potential, and relevance for geopark zoning and sustainable land management.

Unlike traditional inventories that emphasize scientific description alone, this research adopts a holistic assessment approach tailored to the principles of sustainable land management.

To achieve this objective, two complementary methodological frameworks are integrated. The assessment applies the criteria proposed by Brilha [18,19] to evaluate the Scientific Value (SV) and Degradation Risk (DR) of the selected sites, while the Use Value (UV) component is enhanced using criteria from the GEOAM methodology of Zafeiropoulos & Drinia [7]. This combined approach allows for the explicit evaluation of geoeucational relevance, interpretative potential, geoethical value, economic contribution, and accessibility, while maintaining consistency with internationally established geosite assessment standards. Ultimately, the study aims to establish the scientific and management foundation necessary for Skyros to join the Hellenic Geoparks Network, with the long-term objective of achieving UNESCO Global Geopark status. Through the design and evaluation of thematic georoutes oriented toward education and tourism, the paper proposes a strategic framework for transforming Skyros's geoheritage into a central pillar of responsible tourism and sustainable regional development

2. Study Area

2.1. Geomorphological and Geological Setting

Skyros is the southernmost and largest island of the Northern Sporades Complex (209 km²), located in the NW Aegean Sea (38°53' N, 24°31' E), (Figure 2). Morphologically, the island exhibits a striking dichotomy, effectively bisected along its central axis by a narrow isthmus. This creates two contrasting landscapes: the northwestern part, locally known as Meroi (an anagram of the Greek word 'iremo', meaning peaceful), features gentle topography with low hills and dense pine forests. In sharp contrast, the southeastern region, referred to as Vouno ('Mountain'), is dominated by the arid, rugged carbonate massif of Mount Kochylas (792 m).

Geotectonically, the island belongs to the Internal Hellenides domain, presents a remarkable geological structure bisected by a major NE-SW strike-slip fault zone, which separates the island into two distinct neotectonic blocks with contrasting stratigraphy (Figure 2) [20–25]. The southeastern block is structurally simpler and is composed of the relatively autochthonous Sub-Pelagonian Unit, comprising slightly crystal-line and intensely deformed Triassic–Jurassic platform carbonates, overlain by transgressive Upper Cretaceous limestones [20]. In contrast, the northwestern block exhibits a complex nappe-pile structure. At its base lies a Permian–Lower Triassic low-grade metamorphosed volcano-sedimentary sequence, locally including Upper Permian carbonate lenses rich in fossilized reef structures (mostly of calcisponges and sclerosponges) [20,26]. These are overlain by thick Middle Triassic–Jurassic crystalline carbonates of the Sub-Pelagonian Unit. Tectonically emplaced upon these platform carbonates are ophiolitic rocks derived from the Vardar/Axios Ocean, appearing as imbricated wedges within the nappe stack [25]. The stratigraphic column continues with undeformed transgressive Upper Cretaceous carbonates and a flysch sequence, structurally overlain by allochthonous metamorphic units: the

Lower Metamorphic Unit (LMU), consisting of metavolcanics, metasediments and marbles, imbricated with ophiolites [25], and the Upper Metamorphic Unit (UMU), also referred to as the “Skyros Unit” [20,21,25,27–31]. The UMU, forming the summit of the Skyrian Olympus Mountain, comprises silicate marbles and gneiss-schist intercalations, resting above sheared ultramafic rocks with a chaotic structure [21,32]. Notably, these higher-grade metamorphic nappes document a Late Cretaceous tectono-metamorphic event [25], of significant contribution in tectonic evolution of the Hellenides.

The geological framework is completed by Neogene to Quaternary deposits, including Upper Miocene–Pliocene shallow-water marine sediments (mainly marls and sandstones) [20], as well as a few distinct Middle Miocene volcanic outcrops (adakitite andesites) [33] in the central area of the northern block. Holocene alluvial deposits, coastal dunes, and extensive aeolianites and tufa deposits shape the island’s present-day coastal geomorphology.

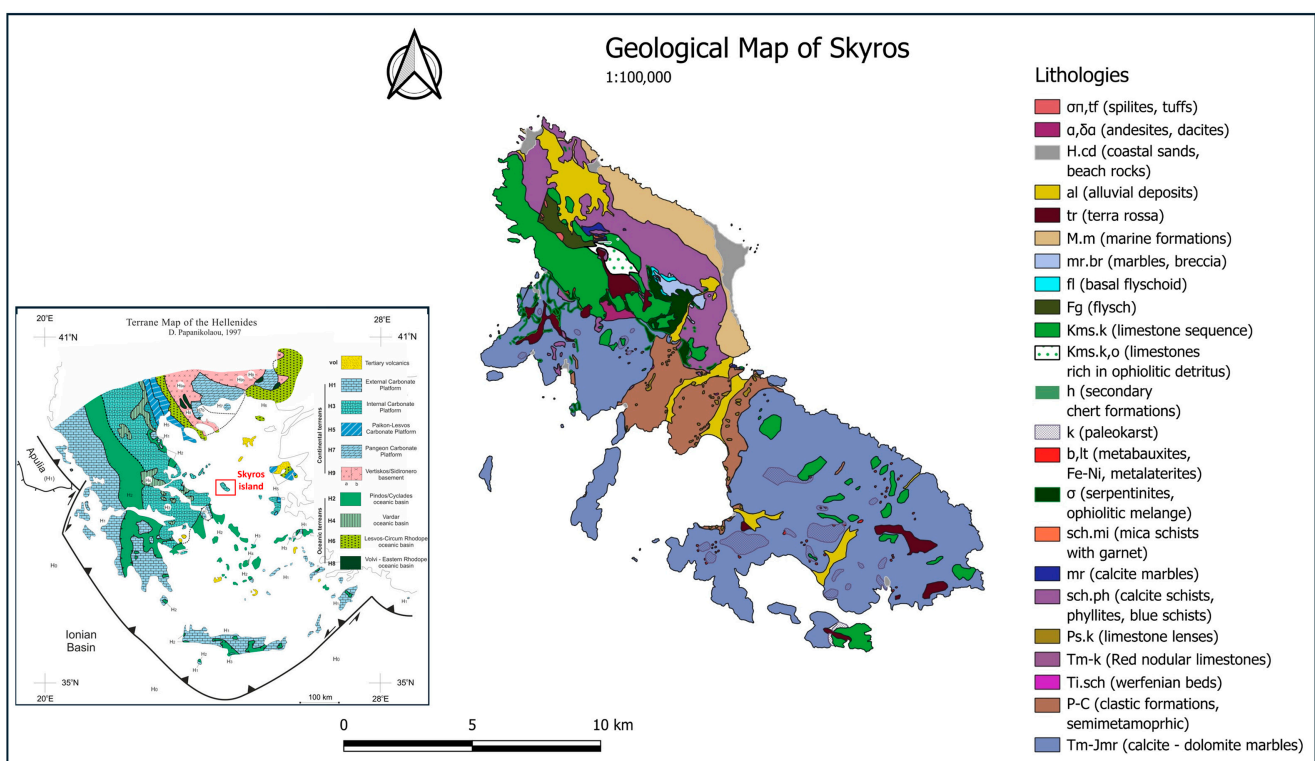


Figure 2. Geological Map of Skyros Island modified from refs. [20,21].

2.2. Geo-Cultural Heritage

The geological diversity of Skyros has profoundly dictated its settlement patterns, architecture, and economic history, creating a distinct “geo-cultural landscape.” The island is historically renowned for the Skyrian Marble, particularly the polychrome tectonic breccias (Breccia di Settebasi and Breccia di Sciuro). These stones, characterized by clasts of red, white, and purple carbonates, were extensively quarried during the Roman period and exported to decorate monumental structures across the empire, such as the Baths of Diocletian (Figure 3) [34–38].

Beyond decorative stone, the daily life and vernacular architecture of Skyros were shaped by local lithology (Figure 4). The prevalence of phyllitic schists led to the use of “Melagi,” a local impermeable clay material derived from weathered schist, traditionally used for roofing and insulation. Similarly, the easily quarried Quaternary tufa formations in northern Skyros provided the primary masonry material for local settlements. In more recent history, the ophiolitic landscape drove industrial land use, with the systematic

mining of iron–nickel laterites and chromitites in the 19th and 20th centuries leaving behind significant industrial heritage sites at Atsitsa and Achladones.



Figure 3. Leptis Magna, the baths of the so-called palace of Diocletian [38].



Figure 4. Integration of local geomaterials in Chora Castle's masonry, featuring ancient marble spolia, porous Quaternary tufa, and traditional schist-based 'melagi' mortar.

2.3. Ecological Context and Biodiversity

The geomorphological dichotomy of Skyros, green and pine-covered in the north (sedimentary/schistose substrate) versus rugged and rocky in the south (carbonate/karstic substrate), supports a rich mosaic of habitats included in the Natura 2000 network (GR2420006). The southern massif of Mt. Kochylas (792 m), dominated by karstified marbles and steep coastal cliffs, serves as a critical biological refuge (Figure 5a,b).

This inaccessible karstic terrain hosts the world's largest breeding colony of Eleonora's falcon (*Falco eleonora*) and other rare raptors (Figure 5). Furthermore, this rugged landscape is the ancestral habitat of the Skyrian Horse (*Equus caballus skyriano*) [39], a globally unique dwarf breed. The horse's morphology and survival strategies have evolved in direct response to the harsh, semi-arid conditions of the southern geological zone, making it a powerful symbol of the island's biocultural heritage.

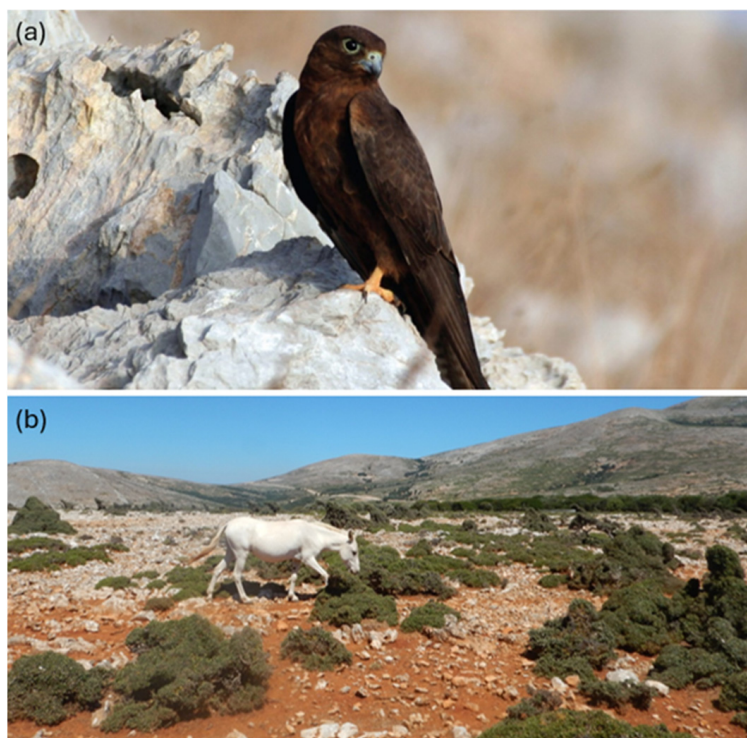


Figure 5. Emblematic fauna within their geological habitats. (a) *Falco eleonora* nesting on steep limestone cliff; (b) Endemic Skyrian Horse grazing on the karstic Ari Plateau (G12).

3. Methodology

3.1. A “Systemic” Approach to Geosite Identification

In many geopark initiatives, geosites are commonly identified and evaluated as isolated points of geological interest. In the case of Skyros Island, this study adopts a systemic approach, recognizing that several geosites correspond to spatially extended areas or geocultural clusters rather than discrete outcrops. This approach is based on the premise that geological features on Skyros are inseparably linked to cultural practices, ecological systems, and land-use patterns.

Consequently, geosites are interpreted as interconnected systems, where a single geological feature (e.g., a limestone or marble outcrop) may simultaneously function as a natural monument, a habitat supporting endemic biodiversity, and a historical resource related to quarrying, construction, or local traditions.

The systemic perspective does not replace quantitative assessment but informs the identification and contextual interpretation of geosites, allowing geological value to be analysed together with cultural and environmental dimensions relevant to geopark planning and tourism space management.

3.2. Quantitative Assessment Methodology

To ensure a transparent and reproducible evaluation aligned with the principles of Sustainable Land Management, geoeducation, and responsible tourism, this study applies a dual quantitative assessment methodology that integrates internationally recognized geosite evaluation standards with complementary indicators addressing management, ethics, and sustainability.

The quantitative assessment was applied to the entire inventory of twenty (20) identified geosites, documented through extensive fieldwork, literature review, and cartographic analysis. The evaluation process consisted of two clearly distinct but complementary phases.

The first phase focused on the evaluation of Scientific Value (SV) and Risk of Degradation (DR), following the methodology proposed by Brilha [18,19], which is widely adopted in international geoheritage and geopark studies. Scientific Value was assessed using criteria that measure the intrinsic geological importance of each site, including Representativeness (how well the site illustrates geological processes or stages of geological evolution), Key Locality value, Scientific Knowledge (extent of peer-reviewed research and documentation), Integrity (state of preservation of geological features), Geological Diversity, and rarity at local, national, or international scale. Risk of Degradation was evaluated independently, using criteria related to deterioration of geological elements, proximity to degrading activities, legal protection status, accessibility, and population pressure. This separation ensures that high scientific value does not mask high vulnerability, which is essential for management prioritisation.

The second phase addressed Use Value, management potential, and sustainability, responding directly to the requirements of geopark development and tourism space management. Importantly, the criteria for Potential Use in Education and Tourism proposed by Brilha [18,19] were fully applied in this study and constitute the primary framework for evaluating educational and tourism suitability. These criteria include Accessibility and safety, Interpretative potential, Visibility and aesthetic appeal, and Suitability for educational activities and guided visits. To complement this evaluation, selected criteria from the GEOAM (Geoeducational Assessment Method) [7] were incorporated in a complementary (not substitutive) manner. GEOAM was used specifically to address dimensions not explicitly covered by Brilha [18,19], particularly those related to sustainability and social engagement, including Geoeducational Relevance (capacity to support structured learning), Cultural Connection (links between geology and local history/traditions), Interpretative Potential, Geoethical Value (potential to raise environmental responsibility awareness), Economic Contribution (support for local sustainable development), and Accessibility. This combined framework ensures that tourism and education values are explicitly assessed using internationally established criteria, while sustainability, ethics, and cultural embeddedness are systematically incorporated.

Table 1 summarizes the quantitative assessment criteria and weighting scheme applied in this study. Scientific Value and Risk of Degradation follow the weighting proposed by Brilha [18,19], ensuring comparability with international geoheritage assessments. Management and Use Value criteria derived from GEOAM were weighted equally, reflecting the balanced importance of education, ethics, culture, accessibility, and economic contribution within a geopark context.

Table 1. Description of the quantitative assessment criteria used in this study. The methodology integrates the Brilha [18,19] framework for Scientific Value and Degradation Risk, with the GEOAM method [7] for Management and Use Value. The values in column 3 represent weights assigned according to the original Brilha [18,19] framework and the GEOAM methodology [7], and where “equal weight” is applied, all criteria contribute equally to the final score, calculated as an arithmetic mean.

Category	Main Criteria/Indicators	Weights
Scientific Value (SV) (Based on refs. [18,19])	Representativeness	30%
	Key Locality	20%
	Scientific Knowledge	5%
	Integrity	15%
	Geological Diversity	5%
	Rarity	15%
	Use Limitations	10%
	Total SV Score:	Sum of weighted criteria (Max 4.0)

Table 1. Cont.

Category	Main Criteria/Indicators	Weights
Risk of Degradation (DR) (Based on refs. [18,19])	Deterioration of Geological Elements	Equal Weight (20%)
	Proximity to Degrading Activities	Equal Weight (20%)
	Legal Protection	Equal Weight (20%)
	Accessibility	Equal Weight (20%)
	Density of Population	Equal Weight (20%)
	Total DR Score:	Arithmetic Mean (Average) (Max 4.0)
Management Value (GEOAM) (Based on ref. [7])	Geoeducational Relevance	Equal Weight (~16.7%)
	Cultural Connection	Equal Weight (~16.7%)
	Interpretative Potential	Equal Weight (~16.7%)
	Geoethical Value	Equal Weight (~16.7%)
	Economic Contribution	Equal Weight (~16.7%)
	Accessibility	Equal Weight (~16.7%)
	Total GEOAM Score:	Arithmetic Mean (Average) (Max 5.0)

3.3. Geosite Inventory and Selection of Representative Case Studies

Based on the field research, twenty (20) geosites were identified, documented, and quantitatively assessed (Table 2) (Figure 6). These sites collectively represent the full spectrum of the island's geodiversity, from the Paleozoic formations to the Quaternary coastal outcrops (e.g., stratigraphic, tectonic, petrological, geomorphological, karstic, and mining-related features), as well as sites of cultural and historical relevance linked to geological resources.

Table 2. List of the 20 identified geosites on Skyros Island.

No.	Geosite Name	Primary Geological Value	Coordinates
1	Palamari	Archaeological/Coastal Geomorphology	38°57'54" N, 24°30'37" E
2	Pouria—Ancient Quarry	Petrological/Cultural	38°55'28" N, 24°34'56" E
3	Ancient Marble Quarry	Petrological/Cultural	38°51'57" N, 24°30'14" E
4	Atsitsa	Ophiolitic/Mining History	38°55'03" N, 24°28'04" E
5	Bares—Kalogeratsi	Volcanic/Mining	38°54'13" N, 24°30'07" E 38°53'50" N, 24°30'53" E
6	Linaria—Kalamitsa—Nyfi	Tectonics/Coastal	38°50'19" N, 24°32'23" E 38°49'16" N, 24°34'03" E
7	Lino	Petrological/Geomorphology	38°53'19" N, 24°34'27" E 38°53'25" N, 24°34'22" E
8	Chora—Skyros Castle Town	Geomorphology/Cultural	38°54'20" N, 24°34'04" E
9	Anavalsa	Hydrogeological	38°54'21" N, 24°33'18" E
10	Panagia Lympiani	Cultural/Petrological	38°55'15" N, 24°31'19" E
11	Markesi	Petrological/Cultural	38°58'31" N, 24°28'27" E
12	Ari Plateau	Karstic landscape/Horse Habitat	38°48'02" N, 24°38'35" E
13	Agios Artemios	Cultural/Petrological	38°51'07" N, 24°35'41" E
14	Kyra Panagia	Coastal/Petrological	38°55'36" N, 24°27'59" E
15	Panagia Spiliotissa	Karstic Cave/Cultural	38°51'46" N, 24°34'33" E
16	Agios Petros Beach—Agalipa	Coastal/Petrological	38°58'04" N, 24°28'06" E
17	Dam	Ophiolitic/Hydrological	38°54'05" N, 24°32'47" E
18	Achilli Beach—Agnos Beach	Coastal/Petrological	38°52'17" N, 24°34'51" E
19	Agios Fokas Beach	Coastal/Petrological	38°52'27" N, 24°28'38" E
20	Acherounes	Metamorphic Basement/Petrological	38°51'00" N, 24°32'13" E

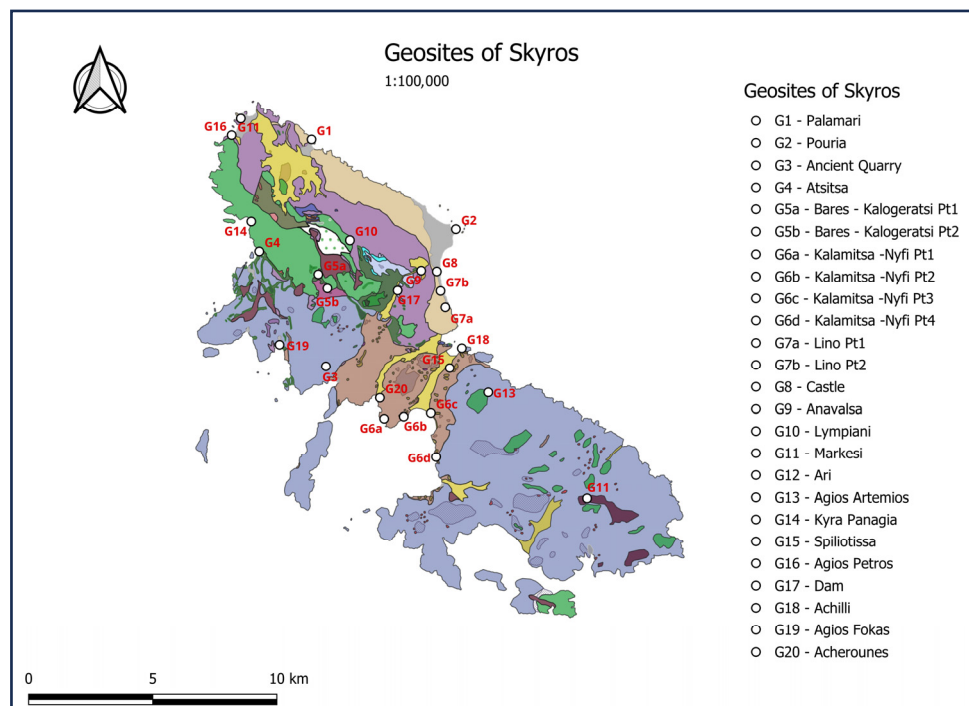


Figure 6. Map of Geosites on Skyros Island. The geological background corresponds to the lithologies detailed in Figure 2. The map depicts the complete inventory of 20 sites; the 6 sites selected for detailed assessment in Table 2 are highlighted in bold.

From this inventory, six (6) representative geosites were selected for detailed assessment. The selection was informed by, but not limited to, the quantitative ranking results based on a set of predefined criteria, including: high scientific value and representativeness of distinct geodiversity types, relevance for illustrating human–geology interactions, state of preservation and varying levels of risk of degradation, accessibility and safety conditions and potential contribution to geoeducation, geotourism, and geopark zoning.

This holistic selection strategy ensures that the assessed sites collectively reflect the geological diversity of Skyros Island while also addressing management and tourism-related considerations.

4. Results

This section presents the detailed analysis of the six (6) flagship geosites selected based on the assessment methodology described in Section 2. The selection of these six sites was guided by a combination of quantitative results and qualitative criteria, ensuring representativeness rather than simple ranking. Specifically, the sites were chosen because they (i) exhibit high Scientific Value according to Brilha [18,19], (ii) represent different dominant geodiversity types, (iii) display varying levels of Risk of Degradation, and (iv) are suitable for education, tourism, and geopark zoning. Although these sites achieved among the highest combined scores in Scientific Value (SV) and Use/Management Value, the final selection did not rely solely on numerical ranking, but followed a holistic approach aligned with UNESCO Global Geopark guidelines. The final scores for the Scientific Value (SV), Risk of Degradation (DR), and Management Value (GEOAM) were calculated and rounded to two decimal places for reporting consistency.

4.1. Detailed Description of Selected Geosites

For each geosite, a dominant value category has been identified, following the typologies recommended by UNESCO for the selection of territories and key sites in future

Geoparks. Secondary values are considered complementary and support interpretation and management.

4.1.1. Geosite 1: Palamari (Coastal Geomorphology & Archaeology)

Location: Northeastern Skyros | Primary Value: Geoarchaeological/Coastal Geomorphology.

Geological Description: The Palamari geosite is situated on a coastal promontory at the northeast end of the Trachi valley. Geologically, it rests upon the Eohellenic Nappe, comprising calcitic schists, phyllites, and blueschists, locally overlain by Neogene marine deposits (marls, sandstones) and Quaternary aeolianites (Figure 7). Its Scientific Value, following Brilha [18,19], is particularly high due to its representativeness, integrity, and reference value for Holocene coastal evolution in the Aegean. The site features extensive beachrocks at two distinct levels (0 to −1.7 m and −1.5 to −3.8 m), correlated with Holocene sea-level stands. The presence of submerged abrasion platforms and archaeological remains at depths up to −4 m indicates relative sea-level rise and tectonic subsidence [40]. Sedimentary sequences in the adjacent coastal plain preserve tsunami and tephra deposits related to the Minoan eruption of Santorini, providing key paleogeographic and paleoenvironmental markers [40–42].

Cultural & Management Value: Palamari is the most significant Early–Middle Bronze Age settlement on Skyros (2800–1700 BCE) [43], featuring a unique fortification system. The site demonstrates a profound geo-cultural synergy: the ancient settlement was built directly on the geological formations that offered strategic defense, while its eventual decline was likely driven by geo-environmental changes (coastal retreat, volcanic events). From a management perspective, Palamari offers a unique opportunity for underwater geotourism. A structured diving route could allow visitors to observe the submerged prehistoric ruins alongside the geological indicators of sea-level change (beachrocks, notches), offering an immersive lesson on climate change and coastal dynamics.



Figure 7. Geoarchaeological site of Palamari (G1). (a) Bronze Age fortifications founded on coastal deposits; (b) Bay view including the wetland; (c) Submerged beachrocks indicating relative sea-level rise; (d) Reconstruction model showing settlement extent prior to coastal erosion.

4.1.2. Geosite 2: Pouria—Ancient Quarry (Tufa Formations)

Location: Northern Coast (Gyrismata); Primary Value: Petrological/Industrial (Quarry Landscape).

Geological Description: This geosite is dominated by extensive Quaternary Tufa deposits (Figure 8). Unlike travertine, these porous, calcareous rocks formed by the precipi-

tation of calcium carbonate from cool, mineral-rich waters emerging from karstic springs. The deposits at Pouria contain fossilized plant material and create a distinct coastal landscape of weathering forms. The site also includes coastal sands and beachrocks, showcasing dynamic sedimentary processes.

Cultural & Management Value: Pouria represents a prime example of an Ancient Quarry landscape. The soft, workable tufa was the principal building stone for Skyros from antiquity to the 19th century. The site preserves visible extraction fronts and rock-cut structures, most notably the Chapel of Agios Nikolaos, which is carved entirely into a monolith of tufa. The site's Scientific Value is linked to rarity, representativeness, and integrity, as coastal tufa quarry landscapes are uncommon in the Aegean. In terms of Geoethics and Conservation (GEOAM criteria), the site is highly sensitive. The porous nature of tufa makes it vulnerable to mechanical damage from trampling and over-tourism [42,44]. Therefore, the management proposal focuses on defined walking paths to protect the formations while highlighting the connection between local geology and vernacular architecture.



Figure 8. Pouria (G2) ancient quarry in Quaternary tufa. (a) Agios Nikolaos chapel carved into a tufa monolith within the extraction site; (b) Characteristic tufa development; (c,d) Traces of ancient extraction techniques on quarry faces.

4.1.3. Geosite 3: Ancient Marble Quarry—Agios Panteleimon

Location: Mt. Marmara; **Primary Value:** Petrological/Historical.

Geological Description: Located on the southern slopes of the “Marmara” mountain, this geosite comprises a complex of quarries extracting the renowned Skyrian Marble (Figure 9). The dominant lithologies are the polychrome carbonate breccias (Breccia di Settebasi and Breccia di Sciro) [34–38,43]. These are tectonic breccias formed during Alpine orogenesis, consisting of angular clasts of varicolored crystalline carbonates cemented by a hematitic matrix, indicating karstic weathering processes [45]. The Scientific Value is high due to rarity, key locality character, and extensive scientific documentation, fulfilling multiple Brilha [18,19] criteria.

Cultural & Management Value: This site is of global cultural significance. It was a major extraction center during the Roman Imperial period, supplying decorative stone for monuments across the Mediterranean (e.g., Rome, Constantinople). The site preserves industrial heritage features, including ancient cutting faces, unfinished monoliths, and a Roman cistern used for quarrying operations. The area was reactivated in the late 19th century by the British company Marmor Ltd., adding a layer of modern industrial heritage

(stone loading docks at Pefkos Bay). The management potential lies in establishing a “Marble Route,” linking the quarries with the loading bays, narrating the story of stone from extraction to export.



Figure 9. Ancient Roman Marble Quarry at Mt. Marmara (G3). (a) Entrance signage; (b,c) Extraction fronts showing tool marks and polychrome “Skyrian Breccia” blocks.

4.1.4. Geosite 4: Atsitsa (Ophiolites & Mining Heritage)

Location: Western Coas; Primary Value: Economic Geology/Industrial.

Geological Description: Atsitsa is situated on the Ophiolitic Mélange of the Eohellenic Nappe. The dominant rocks are serpentinites, peridotites, and chromitites (Figure 10). These ultramafic rocks are scientifically important for understanding the oceanic crust evolution of the Neotethys [21–25,32]. The area also hosts iron–nickel laterite deposits formed by the chemical weathering of the ophiolitic substrate [45–47]. Scientific Value is derived from representativeness, rarity, and reference value, as defined by Brilha [18,19].



Figure 10. Atsitsa (G4) industrial landscape on ophiolitic mélange. (a) Pine forest extending to the coast; (b) Stone pylons of the ore-loading railway; (c,d) Ruins of 19th-century mining infrastructure.

Cultural & Management Value: Atsitsa is the landmark of Skyros' Mining History. In the early 20th century, the Skyros Mining Company exploited the iron-chromite ores. The site preserves impressive industrial ruins, including stone pylons of the old railway system, loading bridges, and the administrative mansion (now a cultural center). This geosite scores exceptionally high in Economic Contribution and Historical Value. It demonstrates how geological resources (ores) drove the local economy and social change. A proposed geotrail here would focus on "Industrial Archaeology," explaining the link between the oceanic rocks (ophiolites) and the modern steel industry.

4.1.5. Geosite 5: Bares—Kalogeratsi (Volcanic Petrology)

Location: Central–North Skyros; **Primary Value:** Petrological/Volcanological.

Geological Description: This area represents a unique geological window in the Aegean, hosting Miocene volcanic rocks (andesites and dacites) of adakitic affinity (Figure 11) [23–25,27–33]. These rare high-Mg magmatic rocks are chemically distinct from typical Aegean arc volcanism, offering evidence of slab detachment and asthenospheric upwelling. The site allows for the observation of sharp contacts between the volcanic intrusions, the surrounding ophiolites, and the metamorphic basement. The site achieves maximum Scientific Value (SV = 4.0) due to exceptional rarity, integrity, and key reference status, fully aligned with Brilha [18,19].



Figure 11. Bares-Kalogeratsi (G5) geological features. (a) Oxidized iron-ore deposits; (b) Serpentinized rocks; (c) Miocene andesitic outcrop.

Cultural & Management Value: While less culturally modified than other sites, Bares-Kalogeratsi has very high Ecological and Educational Value. The nutrient-rich soils derived from volcanic and ophiolitic weathering support dense pine forests and unique micro-habitats. From a management perspective, this geosite is ideal for scientific tourism and educational cycling routes. It serves as an open-air laboratory for geology students to study magmatic processes and tectonic contacts within a protected forest environment.

4.1.6. Geosite 6: Linaria—Kalamitsa—Nyfi (Tectonics & Hydrology)

Location: Southwestern Skyros; **Primary Value:** Tectonic/Hydrogeological.

Geological Description: This is a complex geosite rather than a single point, defined by the major NE–SW strike-slip fault zone that bisects the island (Figure 12). The fault activity has shaped the coastal geomorphology and the port of Linaria. For instance, the Nyfi Spring

is a major karstic spring emerging at the contact between the permeable carbonates and the impermeable underlying schists/phyllites, a clear hydrogeological manifestation of the tectonic discontinuity [25,32]. Scientific Value is particularly high due to representativeness and educational clarity, satisfying Brilha [18,19] criteria.



Figure 12. Tectonic and hydrological system of Linaria–Kalamitsa–Nyfi (G6). (a) Kalamitsa landscape shaped by the major NE-SW strike-slip fault; (b) Nyfi karstic spring at the marble–schist contact; (c) Foliated Permian schists.

Cultural & Management Value: The fault zone is a tangible lesson in Tectonics, visible to the naked eye. The Nyfi spring has high Biocultural Value; historically, it was the watering point for the semi-wild Skyrian Horses before they ascended to Mt. Kochylas. The “Gate of Nyfi” physically and symbolically separated the inhabited northern part from the wild southern “Mountain” (Vouno). Integrating this system into a geopark highlights the interdependence of tectonics (faults creating aquifers), ecology (horse habitat), and tradition (pastoralism).

4.2. Overview of Complementary Geosites

Beyond the six flagship sites, the inventory includes fourteen (14) complementary geosites that enrich the thematic diversity of the proposed Skyros Geopark (Figure 13). Although not analyzed in detail in this section, they play a crucial role in the proposed georoute network (see Section 5).

These sites include Cultural–Geomorphological Sites such as the Castle of Chora (G8) and Lino (G7), where geomorphology dictated fortification and settlement. Additionally, Coastal & Paleontological Sites including Markesi (G11) with its fossiliferous Neogene deposits, and the pristine beaches of Agios Petros (G16) and Agios Fokas (G19), showcase coastal sedimentary dynamics. Finally, Karstic Features such as the Ari Plateau (G12) and Panagia Spiliotissa Cave (G15) are essential for understanding the karst evolution and the hydrogeological regime of southern Skyros.

Collectively, these 20 sites create a comprehensive grid of points of interest, ensuring that the geopark narrative covers the entirety of the island’s geological, ecolog-

ical, and cultural history (Full assessment data for all 20 geosites is provided in the Supplementary Materials).



Figure 13. Complementary geosites of Skyros. (a) Chora Castle (G8) on a limestone exposure; (b) Agios Nikolaos coastal chapel at Achilli (G18); (c) Weathered formations at Acherounes (G20); (d) Lino site (G7) Quaternary sediments.

4.3. Integrated Geosite Assessment: Scientific, Risk, and Management Value

The 20 identified geosites underwent a detailed, two-tiered assessment to determine both their intrinsic scientific worth and their potential for sustainable management. The final calculated scores are summarized in Table 3, with the six (6) flagship geosites serving as the cornerstone of the Geopark proposal.

Table 3. Quantitative assessment results for the six flagship geosites. SV: Scientific Value (Brilha), DR: Risk of Degradation (Brilha), GEOAM: Average of Management/Educational criteria.

ID	Geosite Name	Scientific Value (SV) (Max 4.0)	Risk of Degradation (DR) (Max 4.0)	GEOAM Avg (Max 5.0)
G1	Palamari	3.75	3	4.83
G2	Pouria—Ancient Quarry	3.55	3.8	5
G3	Ancient Marble Quarry	3.55	2.6	4.83
G4	Atsitsa	2.65	3.2	4.33
G5	Bares—Kalogeratsi	4	3	4.5
G6	Linaria—Kalamitsa—Nyfi	4	3.6	4.83

The integrated assessment confirms that the geoheritage of Skyros is not only scientifically significant but also possesses exceptional potential for educational and sustainable economic development:

1. Scientific Value (SV): Strong Geodiversity Base

The quantitative assessment of Scientific Value (SV) provides compelling evidence of a strong geodiversity base. The flagship geosites consistently demonstrate high ratings, with Palamari (G1) and the Ancient Marble Quarry (G3) scoring between 3.55 and 3.75, while Mpares (G5) and Linaria–Kalamitsa (G6) achieved the maximum possible score of 4.00. These results substantiate the premise that the island’s unique petrological assem-

blage, ranging from adakitic volcanism and ophiolitic sequences to fossiliferous Permian formations, represents a scientifically robust foundation for the Geopark proposal. The perfect scores of G5 and G6, in particular, underscore their international significance as pivotal localities for understanding the geodynamic evolution of the Aegean.

2. Management and Use Value (GEOAM): Exceptional Potential

The application of the GEOAM assessment confirms that the identified geological sites possess exceptional potential to serve as powerful drivers of local development. Notably, the site of Pouria (G2) achieved the maximum possible score of 5.00, validating the study's focus on 'Geo-Cultural Synergy.' High sub-scores in Cultural Connection, Economic Potential, and Geoeducational Value demonstrate that integrating geological features, such as tufa formations, with cultural landmarks creates a highly effective model for Geopark development. Similarly, Palamari (G1) and the Ancient Marble Quarry (G3) recorded extremely high values (4.83), driven by the strong correlation between their historical significance (e.g., ancient marble exports) and their modern economic prospects, such as geoarchaeological diving tourism. Furthermore, the impressive average score of 4.49 across the entire inventory of 20 geosites indicates that the proposed network is not only scientifically significant but also manageable and eminently suitable for sustainable territorial development.

3. Risk of Degradation (DR): Manageable Threats and Overall Synthesis

Regarding Risk of Degradation (DR), the analysis reveals generally moderate scores across the inventory, ranging from 2.6 to 3.8. The highest vulnerability is observed at Pouria (G2) which scored 3.8. This elevated risk is attributed to the combined effects of geological fragility, specifically regarding the tufa and coastal formations, and anthropogenic pressure from high visitor volumes; consequently, these sites require the implementation of immediate and targeted conservation measures. Conversely, sites such as the Ancient Marble Quarry (G3) and the Ari Plateau exhibit lower risk levels (2.6), indicating a high degree of intrinsic preservation. This stability allows management strategies for these locations to prioritize interpretation infrastructure and improved visitor access, rather than focusing exclusively on protective interventions.

Collectively, this integrated assessment validates that the geoheritage of Skyros is characterized by both scientific robustness and manageable resilience, possessing optimal potential to serve as the foundation for the proposed National and, ultimately, UNESCO Global Geopark.

5. Discussion

5.1. Feasibility and Institutional Framework for the Skyros Geopark

The results of the integrated geosite assessment confirm that Skyros Island represents a strong and feasible candidate for designation as a National Geopark and, in the longer term, for inclusion in the UNESCO Global Geoparks Network [48–52]. Specifically, the island conforms to the guidance on international status outlined in the [51]. The presence of geosites with high Scientific Value—including Upper Permian fossiliferous formations, rare Miocene adakitic volcanism, ophiolitic complexes, and historically significant marble quarries—fulfils the core geological criteria required by recent UNESCO assessment evaluation guidelines [50,52]. At the same time, the coexistence of significant geodiversity with protected biodiversity (Natura 2000 areas, Skyrian Horse habitats) and cultural heritage demonstrates the holistic geo-bio-cultural synergy expected of contemporary geoparks.

From a legal and administrative perspective, the proposed Geopark framework is compatible with the Greek National Law on Protected Areas (N. 3937/2011) and the UNESCO Statutes. The establishment of a dedicated Management Body—potentially

involving the Municipality of Skyros, local stakeholders, and scientific advisors—emerges as a necessary next step. Importantly, the quantitative results of this study provide a concrete evidence base for such a body to prioritize actions across the three geopark pillars: (i) Conservation, by identifying sites with elevated risk of degradation (e.g., tufa deposits at Pouria) that require controlled access and targeted protection; (ii) Education, by highlighting geosites and georoutes with high scientific and geoeducational value; and (iii) Geotourism, by selecting routes and activities that balance visitor experience with environmental resilience.

5.2. From Geosite Assessment to a Results-Driven Georoute Network

The transformation of the geosite inventory into a functional tourism and land-management tool is achieved through the development of a structured network of thematic georoutes [53]. Unlike purely conceptual route proposals, the georoute network presented here is directly derived from the quantitative assessment results. Each georoute aggregates geosites with compatible Scientific Value (SV), Management Value (GEOAM), and Risk of Degradation (DR) profiles, and is further characterized by its spatial parameters, notably the number of geosites and total route length (Table 4). These parameters allow georoutes to be evaluated as planning units rather than abstract narratives.

Table 4. Thematic georoutes proposed for Skyros Island and their main characteristics.

ID	Georoute Name	Main Mode	Length (km)	Geosites Included	Primary Theme
GR1	Skyros Circuit	Car	49	G6-G18-G7-G8-G2-G1-G16-G14-G4-G19-G3	Island Overview
GR2	Via Volcanica	Cycling	14.9	G8-G17-G5-G4	Petrology/Volcanic & Ophiolitic landscapes
GR3	Holy Spring	Walking	1.3	G8-G9	Hydrogeology/Springs
GR4	Water Hunting	Walking	2.2	G8-G9-G17	Hydrology/Water pathways
GR5	Marble Hunting	Cycling	9.3	G6-G3	Ancient stone trade
GR6	Tectonic Panorama	Cycling	8.6	G6	Tectonics/Fault zones
GR7	Wild Skyros	Car	19.3	G6-G12	Ecology/Geomorphology/Horse habitat
GR8	Olympian Hike	Walking	7.4	G8-G10	Cultural/Panoramic Views
GR9	Olympian Bike	Cycling	9.9	G8-G10	Cultural/Panoramic Views
GR10	Skyrian Sediments	Walking	2.3	G8-G7	Stratigraphy/Sedimentary contacts
GR11	Tufa Road	Walking	3.7	G8-G2	Geomorphology/Tufa deposits
GR12	Shipwreck	Walking	4.4	G16	Karstic landscape/
GR13	Roman Forest	Walking	3.8	G16-G11	Coastal Dynamics/Petrology
GR14	Roman Trail	Cycling	5.7	G3-G19	Archaeology/Roman transport route
GR15	Holy Cave	Walking	4.7	G18-G15-G18	Karst & Culture/Cave-chapel
GR16	Pilgrim's Trail	Walking	5.4	G18-G13	Cultural/Religious heritage
GR17	Roman Fields	Walking	8.4	G19	Archaeology/Roman port facilities

Short routes incorporating a limited number of highly legible geosites and low total length (e.g., stratigraphy- or hydrogeology-focused walking routes) are particularly suitable for educational use, including school excursions and university field courses. In contrast,

longer routes integrating multiple geosites with strong cultural and economic connections (e.g., mining and marble heritage routes) exhibit higher tourism suitability, supporting cycling-based and slow-tourism experiences. In this way, route length, number of sites, and geosite scores function together as measurable indicators of route performance [54].

The inclusion of the number of geosites and total length for each georoute (Table 4) provides a practical planning tool for education- and tourism-oriented route design, supporting visitor management and accessibility assessment.

5.2.1. Methodology of Route Design

The proposed routes (Figure 14) were designed using GIS data and field mapping. The proposed routes were digitized and visualized using accessible platforms (Bikemap), leveraging the potential of smart mobile applications to enhance the visitor experience and promote self-guided exploration. This approach aligns with modern trends in geopark management, where digital technologies facilitate the interpretation of geoheritage [55–58]. The design criteria for the network emphasize Thematic Cohesion (linking sites with a shared narrative, e.g., ‘Via Volcanica’), Carrying Capacity (directing heavy traffic to accessible hubs while reserving sensitive areas for low-impact hiking), to avoid exceeding the ecological limits of the Sporades ecosystem [58–60] and intermodality (combining driving to hubs like Chora and Linaria with hiking or cycling for the final approach). The proposed network comprises 17 distinct routes categorized by their primary mode of transport (Table 4).

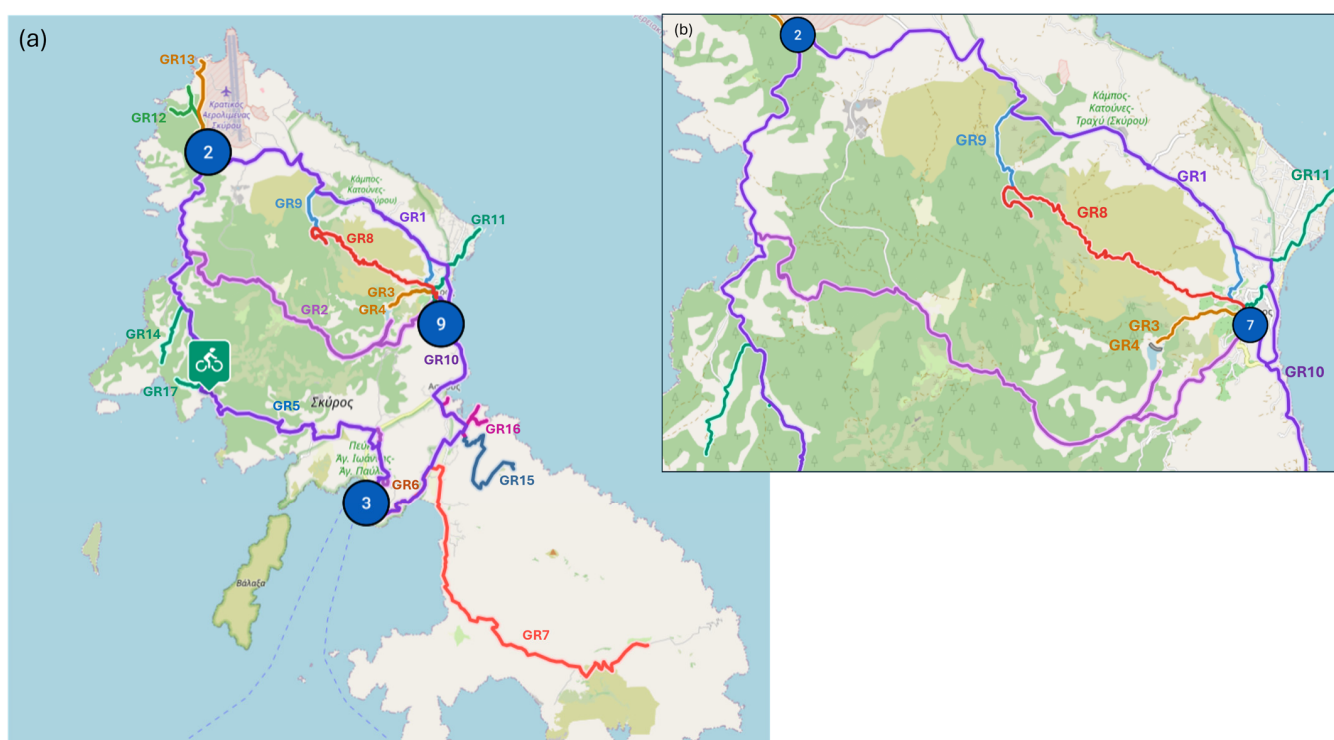


Figure 14. Visualization of the proposed Georoute Network. (a) Overview of the 17 thematic routes covering the entire island; (b) Detail of the hiking and cycling routes originating from the main hub of Chora. (Routes digitized using the Bikemap platform).

5.2.2. Innovation: E-Biking and Marine Geotourism

A key innovation of this proposal is the emphasis on Electric Biking (E-bike) for the cycling routes (e.g., GR2, GR9). Given Skyros’s topography, e-bikes democratize access to higher elevations, allowing visitors of varying fitness levels to reach geologically significant

sites like the volcanic outcrops of Bares without the carbon footprint of a car. Additionally, while not listed as a numbered route in the terrestrial network, Scuba Diving at sites like Palamari (G1) aligns with the emerging trend of “Blue Geotourism.” Diving ecotourism can serve as a powerful tool for environmental education in Skyros, expanding the Geopark’s narrative to the underwater domain [54].

5.3. Socio-Economic Impact and Sustainability

The establishment of a UNESCO Global Geopark in Skyros is expected to have a profound positive impact on the local community, aligning with the United Nations Sustainable Development Goals (SDGs), particularly Quality Education (SDG 4), Decent Work and Economic Growth (SDG 8), and Responsible Consumption and Production (SDG 12).

Firstly, the Geopark model targets the extension of the tourism season shifting visitor interest beyond the summer peak toward hiking, cycling, educational activities, and guided georoute experiences during the spring and autumn “shoulder seasons”. This temporal redistribution of tourism demand reduces seasonal dependency, enhances income stability for local businesses, and contributes to more resilient local livelihoods throughout the year. Educational tourism linked to schools, universities, and lifelong learning initiatives further strengthens this seasonal diversification.

Secondly, geopark development fosters economic diversification by activating new, place-based micro-economies. The creation and management of georoutes generate employment opportunities in local guiding services, geo-interpretation, e-bike rental operations, diving tourism, and small-scale transport services. At the same time, the “Geopark Brand” enhances the added value of local products from the primary and secondary sectors, such as honey, ceramics, and traditional crafts, by associating them with certified quality, sustainability, and cultural authenticity. This integration strengthens short value chains and encourages responsible consumption patterns consistent with SDG 12. Furthermore, existing initiatives, such as the environmental awareness center at Linaria port, demonstrate the island’s capacity to host education-oriented tourism, including interpretative activities focused on geology, biodiversity, and climate change awareness. Such initiatives contribute directly to SDG 4 by promoting inclusive, place-based education and strengthening environmental literacy among visitors and residents alike [61].

The proposed geopark framework also promotes biocultural resilience by explicitly linking geological landscapes with endemic biodiversity and living traditions. The integration of emblematic species such as the Skyrian Horse and *Falco eleonora* into georoute narratives (e.g., the “Wild Skyros” route) enhances awareness of the interdependence between geodiversity, ecosystems, and cultural practices, thereby incentivising conservation through sustainable ecotourism income [61].

While the proposed development model draws inspiration from successful strategies in established Greek UNESCO Global Geoparks, such as the agrotourism integration in Sitia and Psiloritis [62,63], karst management in Kefalonia–Ithaca [64], as well as the promotion of mineralogical heritage in Lavreotiki [65], it also aligns with the holistic management approaches of aspiring territories like Nisyros [66] and Meteora–Pyli [67]. Skyros possesses a distinct comparative advantage derived from its compact insular setting. Unlike larger continental parks (e.g., Vikos–Aoos [68]), Skyros offers an exceptionally high density of interconnected values geological, archaeological, ecological, and cultural values within a limited spatial extent.

This configuration enables the development of a “Total Heritage” narrative where geological evolution is inseparable from archaeological landmarks (e.g., the prehistoric settlement of Palamari on a subsiding coastline, the cave cut chapels, the quarries) and from con-

temporary social practices. This strong Geo-Cultural synergy positions Skyros not merely as a geological reserve, but as a holistic biocultural landscape of international significance.

The Skyros Geopark proposal represents a conservation initiative but a comprehensive Land Management Strategy. By transforming geological features from passive scenery into active assets for education, tourism space management, and local entrepreneurship, the geopark framework provides a robust pathway for sustainable regional development that balances environmental protection, socio-economic vitality, and cultural continuity.

6. Conclusions

This study contributes to the literature on island geoconservation by demonstrating how quantitative assessment can serve as a decision-making tool for zonation and route planning, rather than remaining a static inventory. Building on this premise, the paper provides a comprehensive evaluation of the geoheritage of Skyros Island, demonstrating that it possesses the necessary geological, ecological, and cultural assets to establish a UNESCO Global Geopark. Through a holistic assessment framework combining scientific criteria [18,19] with management and geoethical indicators (GEOAM [7]), the research validates Skyros as a distinct ‘geo-cultural landscape’ within the Aegean.

The geological inventory of twenty (20) geosites confirms that Skyros functions as a natural laboratory for the Hellenide orogenic system. The identification of six (6) flagship geosites highlights the island’s unique “geo-cultural synergy,” where geological features are inextricably linked to human history. This synergy is evident in the island’s petrological uniqueness, spanning from Paleozoic reefs to rare Miocene adakitic volcanics; its history of resource exploitation, exemplified by the ancient extraction of Skyrian Marble and historic mining; and its biocultural continuity, most notably seen in the adaptation of the Skyrian Horse to the karst landscape and the diverse habitats of the Natura 2000 network.

Moving beyond scientific documentation, this work proposes a concrete Sustainable Land Management Strategy. The design of 17 thematic georoutes creates a multi-modal network (Hiking, Cycling, Driving) that promotes low-impact mobility and extends the tourism season. This strategy aligns with the United Nations Sustainable Development Goals (SDGs), fostering local entrepreneurship while ensuring the conservation of fragile sites like the tufa formations at Pouria and the coastal prehistoric settlement of Palamari.

In conclusion, Skyros is not merely an island of aesthetic beauty but a dynamic territory where hundreds of millions of years of geological history coexist with living tradition. The potential designation as a National and eventually UNESCO Global Geopark represents a strategic tool for resilience. It offers a framework to safeguard this wealth against environmental pressures, empower the local community through education and green tourism, and position Skyros as a model for sustainable insular development in the Mediterranean.

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