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Degradation risk of geosites analysis in the Rehamna region (Morocco): Inventory and quantitative assessment

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ABSTRACT

The geological heritage of the Rehamna region (Morocco) is rich and diverse, but is highly exposed to natural and anthropogenic pressures. Despite numerous geosite inventories in Morocco, no specific quantitative study had yet assessed the risk of degradation in this region, which constitutes a major gap in the implementation of a geoconservation strategy. The objective of this work is to fill this gap by proposing a hierarchy of degradation risk for ten representative geosites in Rehamna. The methodology is based on the analytic hierarchy process (AHP), a multi-criteria approach combining seven vulnerability factors: anthropogenic activity, uncontrolled tourism, proximity to roads, lack of protection, lithology, natural erosion, and climate change. The relative weights of the criteria were established using a pairwise comparison matrix (CR = 0.044), and each geosite was evaluated using field scores, which were then converted into weighted scores.The numerical results show that three geosites – the Sidi Bou Othmane pegmatites (3.48/5), the Paradoxides schists (3.31/5) and the Kettara pyrrhotite (3.29/5) – present a high to moderate-high risk, while the Sebt Brikiine granite (1.77/5) and the Kef El Mounib conglomerates (1.97/5) appear to be low vulnerability.The practical value of this research lies in the development of a decision-making tool for geological heritage managers, enabling them to define conservation priorities and integrate geosites into land-use planning. The originality of the study lies in the first-time application of the AHP method to the Rehamna, accompanied by innovative graphical visualizations (proportional circles and comparative diagrams).The limitations of this work concern the partially subjective nature of the weighting of criteria and the lack of quantitative data on tourist numbers. Nevertheless, the approach can be extended to other regions of Morocco and enriched by the integration of GIS tools and temporal monitoring, thus contributing to the development of a national geoconservation strategy.

Keywords: geosites, AHP method, degradation risk, geoconservation, Rehamna, Morocco.

INTRODUCTION

Geological heritage is an essential component of the Earth's natural diversity. It includes rock outcrops, tectonic structures, fossils, geomorphological formations, and exceptional landscapes that bear witness to our planet's geodynamic, biological, and climatic history (Brilha, 2002; Gray, 2004). Beyond its scientific value, this heritage also has educational and cultural significance and is increasingly recognized as a lever for sustainable development (Reynard et al., 2007).

Internationally, several initiatives have been implemented to inventory and protect geosites. UNESCO programs, the creation of global geoparks, and the standardized methodologies proposed by Brilha (2016) have helped to structure this field of research. In Europe and Latin America, these approaches have resulted in the creation of national databases and the integration of geological heritage into regional conservation and development policies (Gordon et al., 2017; García-Cortés and Carcavilla, 2009).

In Morocco, geological history spans from the Precambrian to the Quaternary, offering remarkable diversity (Hollard et al., 1985; Oukassou et al., 2018). Several recent studies have inventoried and evaluated geosites in different regions, including the meseta, (Akhlidej et al., 2024; Mehdioui et al. 2020; 2022) Middle Atlas (Lahlou et al., 2021; El Machkour et al., 2023; Oukassou et al., 2019), Anti-Atlas (Si Mhamdi et al., 2023), and Rif (Aoulad-Sidi- Mhend et al., 2019; Ben Ali et al. 2023; 2025). This research has contributed to the scientific and geotouristic promotion of the national geological heritage. However, it remains essentially descriptive and focused on heritage characterization, without any real quantitative analysis of the risks of degradation.

The Rehamna region, located in central Morocco between the High Atlas Mountains and the Meseta, is an open-air geological laboratory characterized by great lithological and structural diversity (Hoepffner et al., 2011). Despite its scientific, educational, and tourist potential, this region has not benefited from any concrete protection or management measures, exposing its geosites to various factors of degradation such as erosion, uncontrolled sampling, and urbanization.

Thus, despite the geological richness and heritage interest of the Rehamna region, no quantitative tool has yet been applied to assess and prioritize the risk of degradation of geosites. This gap is a major obstacle to the development of effective geoconservation strategies.

This study aims to fill this gap by applying the analytic hierarchy process (AHP) method to ten representative geosites in the region. The approach is based on the assumption that the most accessible and unprotected geosites are at greater risk of degradation than those that are isolated and lithologically resistant.

The main objective is to develop a quantitative and reproducible ranking of geosites according to their vulnerability. This work will not only identify priority sites for conservation, but also propose a methodological tool that can be transferred to other regions of Morocco. The originality of this research lies in the first-ever application of AHP to the Rehamna geosites, with the aim of strengthening the scientific basis for management decisions and contributing to the integration of geological heritage into sustainable development policies.

LOCATION AND GEOLOGICAL CONTEXT

The Rehamna region is located in central Morocco, between the Jebilet Mountains to the west and the High Atlas Mountains to the southeast. Administratively, it is part of the Marrakech–Safi region (Figure 1). It is characterized by relatively flat to hilly landscapes, alternating between well-exposed rocky outcrops and eroded surfaces.

Geologically, the Rehamna region belongs to the western Meseta, an area that is part of the Moroccan Hercynian foreland (Hoepffner et al., 2011) (Figure 2).

It is a true open-air geological laboratory, illustrating a wide variety of sedimentary, magmatic, metamorphic, and volcano-sedimentary formations the span from the Precambrian to the Mesozoic (Oukassou et al., 2018; Hervé, 1989; Hollard et al., 1985).

Sedimentary formations are represented by a wide range of facies: Middle Cambrian paradoxid shales, Cambrian quartzite sandstones, Stephanian red conglomerates, and discordant Paleozoic deposits deformed by tectonic activity. These different units reflect a wide range of ancient environments, ranging from shallow marine basins to fluvial systems and alluvial cones (Oukassou et al., 2018).

Magmatic formations are dominated by the Granite of Sebt Brikiinepluton, a late Hercynian intrusion with alkaline affinity dated between 260 and 300 Ma (Hervé, 1989; Hoepffner, 1982). Numerous post-magmatic pegmatite veins, rich in rare accessory minerals (beryl, garnet, tourmaline, cassiterite), are also present, particularly around Sidi Bouathmane.

Metamorphic formations are visible in the mica schists and amphibolites of Lala Titaf, evidence of moderate to high-grade regional metamorphism attributed to Hercynian orogenesis, which is well documented in the Rehamna region (Hoepffner et al., 2005). Ductile deformations (shears, P2 folds) and metamorphic minerals such as kyanite and chlorite-phengite are also observed (El Mahi et al., 2000).

Finally, volcanic-sedimentary formations, such as those of Kettara pyrrhotites, are the result of ancient hydrothermal processes, with sulfide mineralization characteristic of VMS (Volcanogenic Massive Sulfides) deposit environments, interpreted as linked to ridge or back-arc basin environments (Essaifi et al., 2019).

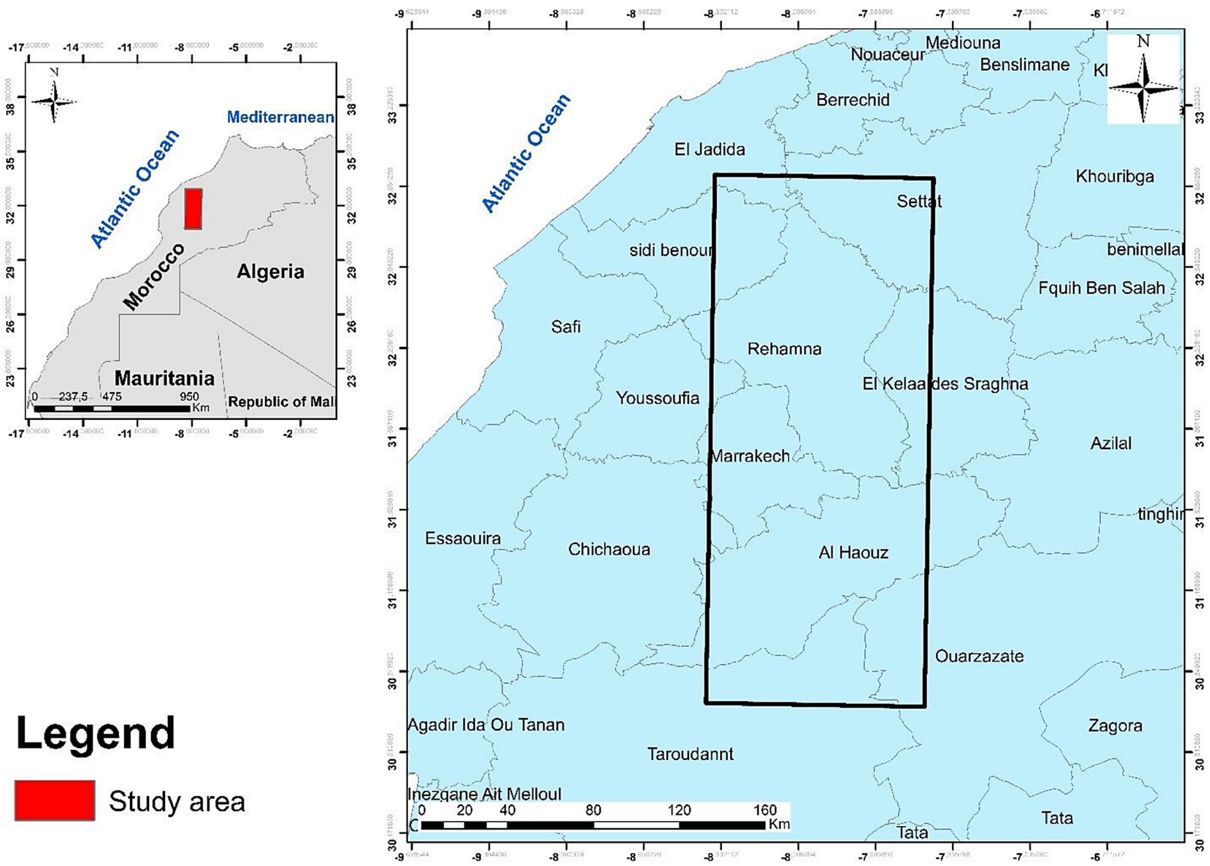

Figure 1. Geographical and administrative position of the study area

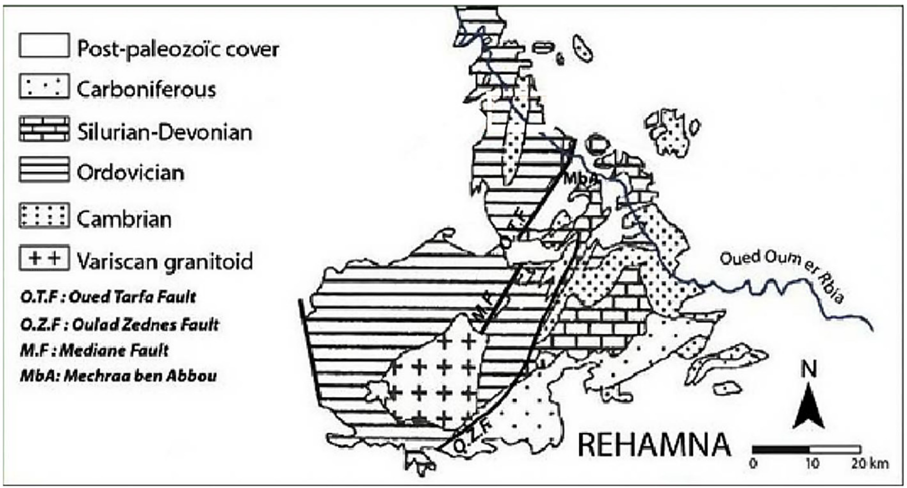

Figure 2. Geological map of the study area (Piqué, 1981, modified)

This geological richness is further enhanced by a complextectonic history, marked by numerous angular unconformities, reverse faults, thrust structures, and post-orogenic movements. thus represents an exceptional natural laboratory for understandingthe sedimentary, tectonic, and magmatic cycles that have affected central Morocco.

METHODS AND MATERIALS

Data collection

The information used to evaluate the geosites comes from two main sources: the first is the field observations: state of conservation of the sites, accessibility, proximity to roads, presence

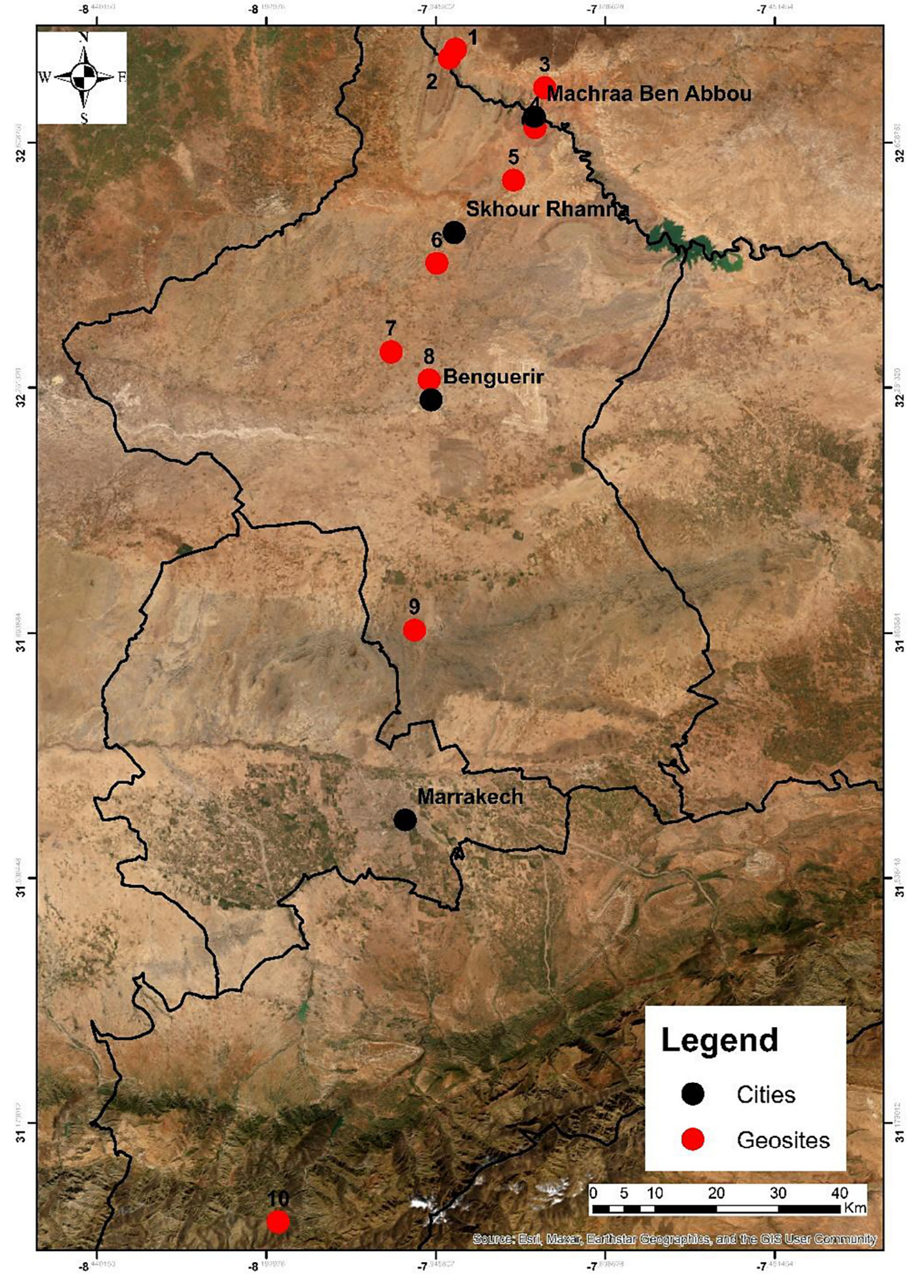

Figure 3. Geosite location map
1: Paradoxid Shale; 2: Cambrian Gres-Quartzitic Facies; 3: Angular unconformity of Cambrian-Cretaceous; 4: Conglomerates of Machraâ Ben Abbou; 5: Conglomerates of Sidi Abdelah; 6: Conglomerates of Kef El Mounib ; 7: Granite of Sebt Brikiine; 8: Micashiste of Lalla Titaf ; 9: Pegmatite of Sidi Bouathmane; 10: Pyrrhotites of Kettara

of human activity or signs of visitor traffic, the second is the bibliographic sources: stratigraphic, lithological, and structural data from previous studies. Each geosite was assessed according to seven risk factors, rated on a scale of 1 to 5: 1 – very low or non-existent risk, 2 – low, limited or occasional risk, 3 – moderate risk, influential but partially controlled factor, 4 – high risk, significantly impacting vulnerability, 5 – very high risk, direct, constant or uncontrolled impact.

Climate change has been incorporated as a vulnerability criterion in a qualitative and contextual manner, rather than on the basis of direct local measurements. The Rehamna region, located in central Morocco, is characterized by a semi-arid to arid climate, with low rainfall (often less than 350 mm/year), highly irregular rainfall patterns, and frequent episodes of drought. Several studies conducted in Morocco (Driouech, 2010) highlight a gradual decrease in precipitation and an increase in climate variability, confirming a trend towards more intense droughts and a resurgence of extreme events. These results are consistent with IPCC projections (IPCC, 2021) for North Africa and the Mediterranean. These climatic changes, known to accentuate physical alteration and erosion phenomena, justify the inclusion of climate change as a long-term risk factor in the assessment of geosite vulnerability.

Choice of method

to assess the risk of degradation of geosites, we adopted the AHP method, developed by Saaty (1980) and widely used in complex decision-making contexts (Saaty, 2008).

This is a multi-criteria decision-making model based on pairwise comparisons of factors at the same hierarchical level (Jiang et al., 2014). This method is recognized for its ability to quantify qualitative criteria through structured weighting, thereby facilitating decision-making in complex contexts (Ramos et al., 2014; Saaty, 1991; Yalcin et al., 2011). Some authors have even claimed that AHP has revolutionized the way multidimensional problems are handled (Grandmont, 2013; Saaty and Sodenkamp, 2010): Structure the problem by ranking risk factors,,Compare these factors in pairs according to their relative importance,And determine weighted scores reflecting the contribution of each factor.

Pairwise comparison matrix

Sevenriskfactorswereselected:Anthropogenic activity, Uncontrolled tourism, Proximity to roads, Lack of protection, Lithology, Natural erosion, Climate change

The seven vulnerability criteria selected (anthropogenic activity, uncontrolled tourism, proximity to roads, lack of protection, lithology, natural erosion, climate change) were compared in pairs using Saaty's scale (1–9). The pairwise comparison matrix used is shown in Table 1.

The pairwise comparison matrix (Table 1) was constructed according to AHP logic: each value reflects the relative importance of one criterion compared to another, based on field observations, scientific literature, and the authors' expertise. When two criteria have the same importance, the value assigned is 1. If one criterion is judged to be moderately, strongly, or extremely more important than another, the values 3, 5, or 9 are used, with the intermediate values 2, 4, 6, and 8 to nuance the assessment. Conversely, when the row criterion is less important than the column criterion, the value assigned is the inverse of the comparison (1/2, 1/3, 1/5, etc.).

For example, if anthropogenic activity is considered three times more important than proximity to roads, the value 3 is assigned to the corresponding cell (anthropogenic activity row, proximity to roads column), and the value 1/3 is assigned to the symmetrical cell (proximity to roads row, anthropogenic activity column). This principle of symmetry ensures the consistency of the matrix. The judgments therefore reflect the risk hierarchy based on the authors' expertise, field observations, and available scientific references.

The seven criteria used to assess the risk of degradation (anthropogenic activity, uncontrolled tourism, proximity to roads, lack of protection, lithology, natural erosion, and climate change) were selected on the basis of previous scientific references (Brilha, 2015; Reynard, 2007; Pereira and Pereira, 2010), which identify them as determinants of geosite vulnerability.

Table 1. Pairwise comparison matrix of degradation factors according to the AHP method used for the assessment of geosites in the Rehamna region

Factors ↓ vs →	Anthropogenic activity	Uncontrolled tourism	Proximity to roads	Lack of protection	Lithology	Natural erosion	Climate change
Anthropogenic activity	1	2	3	3	4	2	2
Uncontrolled tourism	1/2	1	2	2	3	2	2
Proximity to roads	1/3	1/2	1	2	2	3	3
Lack of protection	1/3	1/2	1/2	1	2/3	2/3	2/3
Lithology	1/4	1/3	1/2	1.5	1	2/3	2/3
Natural erosion	1/2	1/2	1/3	1.5	1.5	1	2
Climate change	1/2	1/2	1/3	1.5	1.5	1/2	1

The relative weighting of these criteria was not decided arbitrarily by the authors alone. It was established through consultation with experts (geology professors and researchers and natural heritage specialists in Morocco), supplemented by field observations made by the authors. Each criterion was compared in pairs according to the Saaty scale (1–9), and the values entered in the matrix (Table 1) are the result of a consensus validated within the research team.

This procedure ensures that the matrix is based on both sound scientific principles and contextualized local expertise, thereby guaranteeing the relevance and validity of the coefficients applied.

Weight calculation and consistency

The normalized weights Wi of the criteria were calculated from the matrix using the eigenvalue method.

The consistency index (CI) is given by:

$$CI = \lambda_{max} - n/(n-1) \quad (1)$$

where: λ_{max} – maximum eigenvalue of each factor in the matrix table and n the size of the matrix.

The consistency ratio (CR) equation is:

$$CR = CI/RI \quad (2)$$

where: CR – onsistency ratio, RI – random index, CI – consistency index.

The value of random index developed by Saaty (1977) was RI = 1.32 for n = 7 factors.

Calculation of the overall risk score

For each geosite, the scores assigned (1–5) were multiplied by the corresponding AHP weights. The sum of the weighted scores provides an overall degradation risk index. The results were then classified into five risk categories: low, low to moderate, moderate, moderate to high, and high. This classification makes it possible to identify the most vulnerable geosites and establish conservation priorities in the Rehamna region.

Visualization and classification

Finally, a graphical visualization was created using proportional circles representing the contribution of each factor to the overall risk per geosite, a comparative diagram ranking geosites according to their level of risk.

RESULTS

Inventory of geosites

Ten geosites located along the route (Figure 3) have been selected for study from among the region's geological potential. The selection of these sites was based on their scientific, educational, and touristic. They illustrate the region's lithological and geodynamic richness and diversity, with outcrops ranging from the Cambrian to the Permian periods. These sites represent different geological contexts: sedimentary, magmatic, metamorphic, tectonic, and paleontological. Each geosite has its own characteristics in terms of lithological nature (shale, sandstone, conglomerate, granite, pegmatite, etc.) and associated geological processes. The Table 2 provides a summary of each site, indicating its name, geological age, type of geosite, main lithology, and bibliographic references. This overview provides the foundation for the subsequent degradation risk analysis carried out in this study.

The results obtained are based on a two-step approach. First, the pairwise comparison matrix was used to compare the seven risk factors in pairs according to their relative importance. Using the AHP method, these comparisons were translated into numerical values and normalized to calculate the final weights for each factor. Thus, anthropogenic activity appears to be the most decisive factor (0.2816), followed by uncontrolled tourism (0.1934) and proximity to roads (0.1711), while the absence of protection, lithology, natural erosion, and climate change have more moderate weights. The consistency ratio obtained (CR = 0.044) (Table 3) confirms that the judgments made are reliable and consistent. In a second step, each geosite was rated from 1 (very low risk) to 5 (very high risk) for each of the criteria, based on field observations and the literature. These scores were multiplied by the corresponding AHP weights to obtain weighted scores. The sum of the weighted scores provides an overall vulnerability index for each geosite. This process, carried out and validated with the support of experts in geosciences and geoconservation, guarantees the robustness and reproducibility of the results.

Detailed interpretation of each geosite

A detailed assessment of the ten geosites in the Rehamna region justified the identified risk

Table 2. General characteristics of the ten geosites studied in the Rehamna region (age, type, lithological nature, and references)

No.	Name of geosite	Age / Period	Type of geosite	Main lithological nature	References
1	Paradoxides shales	Middle cambrian	Paleontological and stratigraphic	Shales, fine siltstones, greenish sandstones	Piqué, 1979; Oukassou et al., 2018
2	Cambrian Gres-Quartzitic Facies	Cambrian	Sedimentological and Paleontological	Quartzitic sandstones, biomats, seismites, dendrites, brachiopods	Oukassou, 2018; Baidder, 2007
3	Angular uniconformity of Cretaceous-Cambrian	Cretaceous / Cambrian	Structural and Stratigraphic	Breccias, red conglomerates, greywackes, faults	Hoepffner, 2011
4	Conglomerates of Machraâ Ben Abbou	Stephanian–Autunian	Sedimentological and Tectonic	Red conglomerates, sandstones	Hoepffner, 2011; Termier, 1936; Muller et al., 1991
5	Conglomerates of Sidi Ben Abdellah	Lower–middle Devonian	Tectonic and Metamorphic	Deformed conglomerates, green schist facies metamorphism	Michard et al., 1982
6	Conglomerates of Kef El Mounib	Lower Devonian	Tectonic and Metamorphic	Coarseconglomerates, sandstones, kyanite	Hoepffner, 2011
7	Granite of Sebt Brikiine	Permian (260–300 Ma)	Magmatic	Alkaline granite, quartz, feldspar, biotite, muscovite	Hervé, 1989; Hoepffner, 1982
8	Micaschists of Lalla Titaf	Upper Viséan	Metamorphic	Micaschists, amphibolites	Benacer El Mahi, 1991; Hoepffner and Saddiqi, 2011
9	Pegmatites of Sidi Bou Othmane	Upper Viséan–Namurian	Magmatic and Mineralogical	Pegmatites: orthoclase, quartz, muscovite, rare minerals	Huvelin, 1975; Permingeat, 1952
10	Pyrrhotite of Kettara	Hercynian	Mineralogical and Metallogenic	Sulfide masses, pyrrhotite, metapelites	Essaifi, 2011

levels, taking into account lithological characteristics, accessibility, protection status, and natural degradation factors.

Geosite 1: Paradoxides Shales

The Paradoxides Shalesgeosite, located right next to the road, is characterized by a lithology composed mainly of siltstones and finely micaceous schists, with clearly marked stratification.

The AHP method was used to assess the various risk factors for degradation of this site, with scores ranging from 1 to 5. The justifications associated with each factor are presented in Table 4, while the AHP weights and weighted scores are shown in Table 5.

After calculation, the final score of 3.31/5 indicates that the risk of degradation is moderate to high. In fact, the proximity of the road and the fragile lithology are the main factors contributing to the risk of degradation of this site, as shown in the graphical distribution (Figure 4). The absence of any protective measures or scientific enhancement exacerbates the situation, making this site vulnerable to progressive degradation. The combination of lithological fragility and immediate accessibility justifies its classification as high risk.

Geosite 2: Cambrian Gres-Quartzitic Facies

The geosite consists mainly of quartzite sandstone containing traces of brachiopods and dendrites, evidence of its paleontological and sedimentological interest. It is located approximately 20 meters from the road, making it moderately accessible, but it is not regularly visited by humans.

Analysis of the risk factors for degradation reveals scores ranging from 1 to 5, accompanied by their justifications (Table 6). The AHP weights assigned to each factor and the corresponding weighted scores are presented in Table 7.

Table 3. Weighting of degradation factors obtained using the AHP method for the assessment of geosites in the Rehamna region

Factors	AHP weight
Anthropogenic activity	0.2816
Uncontrolledtourism	0.1934
Proximity to roads	0.1711
Lack of protection	0.0731
Lithology	0.0744
Natural erosion	0.1098
Climate change	0.0966
CR = 0.044	

Table 4. Evaluation of AHP factors

Factors	Score (1–5)	Justifications
Anthropogenic activity	2	The site is visited occasionally, but no exploitation or direct damage has been reported. Low risk but present due to its visibility
Uncontrolled tourism	2	Although the site is easily accessible, it is not developed, and visitor numbers appear to be very low. Limited risk but should be monitored.
Proximity to roads	4	The site is located approximately 20 meters from a road, which facilitates access and increases the immediate risk of damage
Lack of protection	5	There are no protective measures, no markings, and no official recognition → high risk in the event of unexpected use or visitation.
Lithology	2	Quartzite sandstones are very hard, highly resistant to weathering, and therefore very resistant to mechanical and natural damage. Very low risk.
Natural erosion	1	The facies is extremely resistant to erosion. No degradation linked to climate or runoff has been observed → very low vulnerability
Climate change	2	Even though the site is in a semi-arid climate, the quartzite rock is highly resistant to weathering. Low to very low risk

Table 5. AHP weights and weighted scores

Factor	AHP weight	Weighted score
Anthropogenic activity	0.2816	0.8448
Uncontrolled tourism	0.1934	0.3868
Proximity to roads	0.1711	0.6844
Lack of protection	0.0731	0.3655
Lithology	0.0744	0.2976
Natural erosion	0.1098	0.4392
Climate change	0.0966	0.2898

Table 7. AHP weights and weighted scores

Factors	AHP weight	Weighted score
Anthropogenic activity	0.2816	0.5632
Uncontrolled tourism	0.1934	0.3868
Proximity to roads	0.1711	0.6844
Lack of protection	0.0731	0.3655
Lithology	0.0744	0.1488
Natural erosion	0.1098	0.1098
Climate change	0.0966	0.1932

The calculation results in a final score of 2.45/5, indicating that the risk of degradation remains low to moderate. This can be explained by the presence of highly resistant rocks such as quartzite sandstone, which naturally limits physical degradation. Located approximately 20 meters from the road, its accessibility remains moderate. The absence of regular human traffic and the solid nature of the geological formations explain its classification as low to moderate risk. However, without official protection, the site could be affected in the long term by occasional collection or degradation. This site also features dendrites and brachiopods, reinforcing its scientific and heritage value and further justifying the need for its conservation.

The proximity to the road and the lack of protection are the main risk factors, although the lithology remainsgenerally resistant (Figure 4).

Table 6. Evaluation of AHP factors

Factors	Score (1–5)	Justifications
Anthropogenic activity	2	The site is visited occasionally, but no exploitation or direct damage has been reported. Low risk but present due to itsvisibility
Uncontrolled tourism	2	Although the site is easily accessible, it is not developed, and visitor numbers appear to be very low. Limited risk but worth monitoring
Proximity to roads	4	The site is located approximately 20 meters from a road, which facilitates access and increases the immediate risk of damage
Lack of protection	5	There are no protective measures, no markings, and no official recognition → high risk in the event of unexpected use or visitation
Lithology	2	Quartzite sandstones are very hard, highly resistant to weathering, and therefore highly resistant to mechanical and natural damage. Very lowrisk
Natural erosion	1	The facies is extremely resistant to erosion. No climate- or runoff-related degradation has been reported → very low vulnerability
Climate change	2	Even though the site is in a semi-arid climate, the quartzite rock is highly resistant to weathering. Low to verylowrisk

Geosite 3: Angular unconformity of Cambrian-Cretaceous

The angular unconformity of Cambrian-Cretaceousgeosite is characterized by heterogeneous lithology composed of breccias, conglomerates, and greywackes, affected by faults and various tectonic structures. The assessment of degradation risk factors, accompanied by their justifications (scores from 1 to 5), is presented in Table 8. The weights assigned by the AHP method and the corresponding weighted scores are shown in Table 9. The final score is 2.84/5, indicating that the risk of degradation is moderate.

Although these formations are relatively resistant (breccias, conglomerates, and greywackes), the presence of faults and tectonic structures makes the site susceptible to localized erosion. The site's high scientific value contrasts with its lack of formal protection. Its proximity to the road makes it easily accessible, but the lack of tourist traffic currently limits direct pressures. This context explains a moderate but growing risk in the event of unregulated tourist development.

Table 9. Poids AHP et scores pondérés

Factors	AHP weight	Weighted score
Anthropogenic activity	0.2816	0.2816
Uncontrolled tourism	0.1934	0.3868
Proximity to roads	0.1711	0.8555
Lack of protection	0.0731	0.3655
Lithology	0.0744	0.2232
Natural erosion	0.1098	0.4392
Climate change	0.0966	0.2898

Natural factors, in particular natural erosion and heterogeneous lithology, are predominant in the risk of degradation (Figure 4).

Geosite 4: Conglomerates of Machraâ Ben Abbou

Geosite 4, located in Machraâ Ben Abbou in the immediate vicinity of the road, consists of detrital sedimentary rocks, notably red conglomerates and coarse-grained sandstones. These formations have a marked and regular dip towards the NNW. The assessment of degradation risk factors, accompanied by the corresponding justifications,

Table 8. Evaluation of AHP factors

Factors	Score (1–5)	Justifications
Anthropogenic activity	1	The site is completely natural, with no exploitation, construction, or direct human activity → no current anthropogenic risk
Uncontrolled tourism	2	The discrepancy is spectacular and potentially attractive, but little known and rarely visited, so the risk remains low, but not zero
Proximity to roads	5	The site is located along the roadside, making it extremely accessible, which increases the immediate risk of accidental or intentional damage
Lack of protection	5	There are no management or protection measures, no marking, and no official recognition → high risk
Lithology	3	The site shows heterogeneous lithology: breccias, conglomerates, greywackes, faults. Some rocks are resistant, others more sensitive → medium risk
Natural erosion	4	Slopes, visible faults, and natural weathering are observed → high risk of uncontrolled morphological change
Climate change	3	The arid climate of the region, combined with the exposure of faults, can lead to slow but real alteration over the long term → moderate risk

Table 10. Evaluation of AHP factors

Factors	Score (/5)	Justifications
Anthropogenic activity	2	There is no evidence of direct exploitation or human disturbance, but its proximity to the road may expose the site to occasional indirect risk
Uncontrolled tourism	2	The site is little known and rarely visited, with no tourist facilities. The risk associated with tourism is very limited, but not zero due to its accessibility
Proximity to roads	5	The geosite is located right next to the road, which greatly increases its accessibility and the risk of immediate damage (littering, sampling, etc.)
Lack of protection	5	No protective measures, no formal status or signage: this leaves the site completely vulnerable to any form of disruption
Lithology	4	Coarse-grained, cohesive rocks, but conglomerates and sandstones can be susceptible to mechanical erosion, especially on slopes
Natural erosion	4	Presence of slopes and exposed outcrops → mechanical erosion by runoff and gravity is clearly present
Climate change	3	The semi-arid climate, combined with coarse materials, could cause slow differential erosion, particularly with seasonal rains → moderate risk

is presented in Table 10. The AHP weights and weighted scores associated with this geosite are detailed in Table 11.

Based on the final score of 3.2/5, we can conclude that the risk of degradation is moderate to high. This is due to the proximity of the Machraâ Ben Abbou Conglomerates to the road and the lack of protection; these two factors could be responsible for the potential degradation of this site (Figure 4). In addition, the coarse texture of its facies could cause mechanical erosion of the geosite, particularly by water and wind; the strong and regular dip towards the NNW is also a factor that could accentuate the structural vulnerability of the site. The lack of protection, combined with total accessibility and the absence of tourist management, exposes the site to a risk of degradation that could intensify in the event of increased human pressure.

Geosite5: Conglomerates ofKef El Mounib

The Conglomerates of Kef El Mounibgeosite consists of detrital rocks, notably conglomerates with elongated pebbles and interbedded lenses of kyanite. The assessment of the risk factors for degradation of this site is presented in Table 12, while the AHP weights and corresponding weighted scores are shown in Table 13.

Based on the final score of 1.97/5, we conclude that the risk level of degradation of the Conglomerates ofKef El Mounibgeosite is low. The lithology is a low risk factor. Although composed of poorly sorted conglomerates and kyanite lenses, the outcrop observed in the field has a generally solid and resistant structure, limiting its immediate vulnerability to erosion. In addition, the isolated nature of the site, located more than 700 meters from the road and difficult to access, considerably reduces anthropogenic pressures. This combination of factors explains the low overall risk level, as reflected in the graphical distribution of degradation factors (Figure 4).

Geosite6 :Conglomerates of Sidi Abdelah

Geosite 6, located in Sidi Ben Abdellah approximately 80 meters from the road, is distinguished by the presence of deformed and metamorphosed conglomerates. The assessment of degradation risk factors (with scores ranging from 1 to 5) is presented in Table 13, while the AHP weights and corresponding weighted scores are shown in Table 14.

Table 11. AHP weights and weighted scores

Factors	AHP weight	Weighted score
Anthropogenic activity	0.2816	0.5632
Uncontrolled tourism	0.1934	0.3868
Proximity to roads	0.1711	0.8555
Lack of protection	0.0731	0.3655
Lithology	0.0744	0.2976
Natural erosion	0.1098	0.4392

Table 13. AHP weights and weighted scores

Factors	AHP weight	Weighted score
Anthropogenic activity	0.2816	0.5632
Uncontrolled tourism	0.1934	0.3868
Proximity to roads	0.1711	0.1711
Lack of protection	0.0731	0.3655
Lithology	0.0744	0.0744
Natural erosion	0.1098	0.2196
Climate change	0.0966	0.1932

Table 12. Evaluation of AHP factors

Factors	Score (/5)	Justifications
Anthropogenic activity	2	There is no direct human activity or evidence of exploitation. The site is remote and difficult to access, which limits the impact, but pressure remains possible in the long term
Uncontrolled tourism	2	The site is virtually unknown to the public, unmarked, and without significant tourist traffic. However, its scientific interest could attract attention in the future if it is promoted
Proximity to roads	1	The geosite is located more than 700 meters from the road, with no direct access route → very low accessibility, therefore very low risk
Lack of protection	5	No protection status, no signage, and no site management → maximum vulnerability at the institutional level
Lithology	1	The conglomerates of Kef El Mounib are massive, very coherent, and difficult to alter or break, as observed in the field → very low risk
Natural erosion	2	Natural erosion is present locally due to the slope and poorly sorted materials, but is generally very limited
Climate change	2	The site is located in a semi-arid area, but the materials are resistant. The climate may promote slow deterioration over the long term → low to moderate risk

The final score of 2.03/5 indicates a low to moderate risk of degradation, which can be explained by the absence of human activity or immediate tourist pressure (Figure 4). In fact, although this site is composed of deformed and metamorphosed conglomerates, it is difficult to access, little known, and rarely visited. Its relative solidity, as observed in the field, and its isolation make it a naturally protected site.

Geosite 7: Granite of Sebt Brikiine

Geosite 7 corresponds to the pink alkaline granite of Sebt Brikiine, accessible via a track located approximately 5 km from the main road. The assessment of degradation risk factors (with scores ranging from 1 to 5), the associated justifications, as well as the AHP weights and weighted scores are presented in Tables 16 and 17, respectively.

Granite of Sebt Brikiinehas a low final score of 1.77/5, indicating a low risk of degradation. It is formed of very resistant rock that is virtually impervious to erosion. Its location 5 km from the road and access only by track reduces anthropogenic pressures. This site has no tourist activity, mining, or other significant human use, making it the best-preserved geosite in the region (Figure 4).

Geosite 8: Pegmatite of Sidi Bouathmane

The Sidi Bou Othmane site is notable for the presence of pegmatite veins intruded into andalusite schists, a host rock altered by hydrothermal circulation. Rich in rare minerals, this geosite is located along a road and was once the site of mining operations that have now been abandoned. However, it remains exposed to individual mineral collection and unregulated prospecting activities. The assessment of degradation risk factors (Table 18), supplemented by AHP weights and weighted scores (Table 19), reveals vulnerability levels ranging from moderate to high.

Pegmatites of Sidi Bou Othmanegeosite has the highest score of 3.48/5 due to several cumulative factors. The lithology, composed of pegmatite veins rich in rare minerals but susceptible to hydrothermal alteration, is a factor of fragility. The immediate proximity of the road facilitates access to the site, exposing it to illegal unauthorized extraction. The site's mining history, with an abandoned mine, has already altered the integrity of the site. The total absence of institutional protection or signage leaves the geosite exposed to moderate to high direct and indirect threats of degradation, despite limited tourist traffic (Figure 4).

Table 14. Evaluation of AHP factors

Factors	Score(/5)	Justifications
Anthropogenic activity	1	This geosite is little known, undeveloped, and shows no signs of human activity or direct exploitation. It istherefore not particularlyexposed to anthropogenic pressure
Uncontrolled tourism	2	No known tourist traffic. The site is not promoted or developed. Low risk, but the total absence of surveillance makes accidental or future damage possible
Proximity to roads	3	The geosite is located approximately 80 meters from the road, making it fairly accessible on foot but not immediately exposed. The riskisthereforemoderate
Lack of protection	5	No official protection measures, no markings, no recognized status → high risk, especially in the event of future activity in the area
Lithology	1	In the field, the site is very solid and difficult to break (despite tectonic deformation). This indicatessignificantresistance to mechanical and climatic stress
Lack of protection	2	Although the rock is resistant, weathering is possible in some areas due to metamorphism (shearing) and tectonic structure → low risk
Climate change	2	The semi-arid climate can accelerate certain alterations locally, but the impact remains low overall for this type of metamorphosed conglomerate

Table 15. AHP weights and weighted scores

Factors	AHP weight	Weighted score
Anthropogenic activity	0.2816	0.2816
Uncontrolled tourism	0.1934	0.3868
Proximity to roads	0.1711	0.5133
Lack of protection	0.0731	0.3655
Lithology	0.0744	0.0744
Natural erosion	0.1098	0.2196
Climate change	0.0966	0.1932

Table 17. AHP weights and weighted scores

Factors	AHP weight	Weighted score
Anthropogenic activity	0.2816	0.2816
Uncontrolled tourism	0.1934	0.3868
Proximity to roads	0.1711	0.1711
Lack of protection	0.0731	0.3655
Lithology	0.0744	0.0744
Natural erosion	0.1098	0.1098
Climate change	0.0966	0.0966

Table 16. Evaluation of AHP factors

Factors	Score (1–5)	Justifications
Anthropogenic activity	2	The site is remote from any human activity, with no exploitation or development. There are no signs of current use. However, a very low indirect risk can never be ruled out
Uncontrolled tourism	2	The site is very isolated and difficult to access, so there is currently no tourist pressure. However, the granite could be of interest in the future if it is developed
Proximity to roads	1	The granite is located about 5 km from the road, accessible only by trail → very difficult to access, therefore low risk
Lack of protection	5	No legal protection or signage in place → maximum administrative vulnerability in the event of future pressure
Lithology	1	Very hard, relatively unalterable, highly consistent granite: it is extremely resistant to mechanical and chemical erosion → very low risk
Natural erosion	1	Granite is not very susceptible to weathering, even in semi-arid climatic conditions → low natural erosion
Climate change	1	This type of rock is highly resistant to climate change (no dissolution, no fragile materials) → low risk

Table 18. Evaluation of AHP factors

Factors	Score (/5)	Justifications
Anthropogenic activity	3	Former abandoned mining operation, with occasional human activity (hunting) currently taking place. Although the site is no longer in operation, it remains exposed to irregular human pressures
Uncontrolled tourism	2	No known tourist traffic, no facilities, but the site is accessible and contains rare minerals that may attract unregulated collectors
Proximity to roads	5	The geosite is located 10 m from the road, making it extremely accessible → increased risk of spontaneous visits, littering, and mineral collection
Lack of protection	5	No protective measures are in place. This leaves the site completely vulnerable to any form of damage
Lithology	4	Pegmatites are often massive, but in this case, they show local hydrothermal alteration → friable areas. In addition, the host rock (andalusiteschists) is fragile
Natural erosion	4	Hydrothermally altered zones are susceptible to degradation. Natural exposure and semi-arid conditions promotedifferentialerosion
Climate change	3	The semi-arid climate can promote the oxidation of certain minerals (e.g., cassiterite) and accelerate weathering processes, but less so than direct human activity

Table 19. AHP weights and weighted scores

Factors	AHP weight	Weighted score
Anthropogenic activity	0.2816	0.8448
Uncontrolled tourism	0.1934	0.3868
Proximity to roads	0.1711	0.8555
Lack of protection	0.0731	0.3655
Lithology	0.0744	0.2976
Natural erosion	0.1098	0.4392
Climate change	0.0966	0.2898

Geosite 9: Pyrrhotites of Kettara

Pyrrhotite of Kettarageosite is characterized by complex lithology dominated by sulfide deposits associated with former mining operations. Its immediate proximity to the road increases its vulnerability. The assessment of degradation risk factors using the AHP method reveals scores ranging from 2 to 5, accompanied by specific justifications presented in Table 20. The AHP weights and corresponding weighted scores are shown in Table 21.

Pyrrhotite of Kettarahas been given a final score of 3.29/5, indicating a moderate to high risk of degradation. This is due to the presence of complex lithology, including sulfide deposits that are particularly vulnerable to chemical alteration, especially oxidation in a semi-arid environment. The site is very close to the road and shows signs of former mining activity. This ease of access and the absence of protective measures expose the site to a risk of increased chemical degradation. In addition, the exposed sulfides react strongly to climatic conditions and water infiltration, accelerating the mineral degradation process (Figure 4).

Geosite10: Micashiste of Lalla Titaf

The Lala Titaf site, characterized by dark mica schists to amphibolites, is located in close proximity to the road and railway line. The AHP factor evaluation table, with scores ranging from 2 to 5 (Table 22), is followed by the AHP weights and weighted scores table (Table 23).

Table 20. Evaluation of AHP factors

Factors	Score (/5)	Justifications
Anthropogenic activity	2	No recent exploitation, but historical traces of mining activities and occasional human presence (e.g., hunting). The site remainsrelativelyundisturbedtoday
Uncontrolled tourism	2	The site is little known, undeveloped, and rarely visited, but its accessibility could spark curiosity in the future
Proximity to roads	5	The site is extremely close to the road (less than 1 meter), with visible outcrops → highly exposed to potential external pressures
Lack of protection	5	No formal protective measures, no signage or markings → the geosite is completely vulnerable to any type of damage
Lithology	4	Presence of sulfides (pyrrhotite, pyrite, etc.), which are susceptible to chemical alteration (oxidation, dissolution), even though the metamorphic host rock (metapelite) is more resistant
Natural erosion	4	Exposure of sulfides to climatic conditions can lead to gradual chemical alteration (oxidation, acid formation). Natural degradationisthereforesignificant
Climate change	4	The semi-arid climate promotes the oxidation of sulfide minerals, accelerating the chemical degradation of the site. The riskissignificant in the long term

Table 21. AHP weights and weighted scores

Factors	AHP weight	Weighted score
Anthropogenic activity	0.2816	0.5632
Uncontrolled tourism	0.1934	0.3868
Proximity to roads	0.1711	0.8555
Lack of protection	0.0731	0.3655
Lithology	0.0744	0.2976
Natural erosion	0.1098	0.4392
Climate change	0.0966	0.3864

Table 23. AHP weights and weighted scores

Factors	AHP weight	Weighted score
Anthropogenic activity	0.2816	0.5632
Uncontrolled tourism	0.1934	0.3868
Proximity to roads	0.1711	0.8555
Lack of protection	0.0731	0.3655
Lithology	0.0744	0.2976
Natural erosion	0.1098	0.3294
Climate change	0.0966	0.2898

Table 22. Evaluation of AHP factors

Factors	Score (/5)	Justifications
Anthropogenic activity	2	The geosite is close to the road and railway line, but no significant direct human activity has been observed on the site. Low but possible risks associated with the proximity of infrastructure
Uncontrolledtourism	2	There are no tourist facilities or development of the site. Low or no tourist traffic, therefore low risk
Proximity to roads	5	The site is very accessible, located along the road and in close proximity to the railway line. This greatly increases the risk of accidental or deliberate exposure
Lack of protection	5	The geosite has no official protection status or any form of management → high risk
Lithology	4	Mica schists are layered metamorphic rocks that are susceptible to physical weathering. Amphibolite intercalations are present, but the rock is relatively fragile overall
Natural erosion	3	Moderate risk of mechanical erosion due to the layered structure and direct exposure to weathering agents. The rocks are not extremely friable, but wear is visible
Climate change	3	The semi-arid climate promotes the physical alteration of mica schists (dehydration, cracking), especially on the surface. The riskismoderate in the long term

This geosite received a final score of 3.09/5. Its mica schists are susceptible to physical weathering, with a risk of surface layers becoming detached, particularly in the region's semi-arid climate. The immediate proximity of the road and railway increases its exposure to pollution and vibrations. Although the site is not heavily frequented, the lack of protection and the intrinsic fragility of the rocks explain its moderate to high risk of degradation. This site thus presents a combination of natural vulnerabilities and exposure to anthropogenic disturbances (Figure 4).

Final scores and risk level of geosites in the Rehamna region

Applying the AHP method to the ten geosites in the Rehamna region made it possible to calculate weighted scores for each of the seven degradation factors. The overall results – detailed weighted scores and final scores on a scale of 1 to

5 – make it possible to classify geosites according to their level of risk of degradation (Table 24).

This ranking reveals that the pegmatites of Sidi Bou Othmane, the paradoxid schists, and the pyrrhotite of Kettara are the most vulnerable geosites, with moderate to high risk levels. On the other hand, the granite of Sebt Brikiine and Conglomerates ofKef El Mounib present a low risk.

Table 24. Final weighted scores for geosites in the Rehamna region

Geosites	Final score (/5)	Risk level
Pegmatites of Sidi Bou Othmane	3.48	High
Paradoxides Shales	3.31	High
Pyrrhotite of Kettara	3.29	Moderate to high
Conglomerates of Machraâ Ben Abbou	3.20	Moderate to high
Micaschiste of Lala Titaf	3.09	Moderate to high
Angular uniconformity of Cretaceous-Cambrian	2.84	Moderate
CambrianGres-Quartzitic Facies	2.45	Low to moderate
Conglomerates of Sidi Ben Abdellah	2.03	Low to moderate
Conglomerates of Kef El Mounib	1.97	Low
Granite of Sebt Brikiine	1.77	Low

Graphical visualizations: proportional circles and ranking diagram

To supplement the quantitative analysis, two graphical representations were developed. Segmented proportional circles for each geosite (Figure 4), representing the relative contribution of each degradation factor to the overall score. These graphs allow the dominant factors specific to each site to be visualized:

- For the pegmatite of Sidi Bouathmane, the circle reveals a predominance of anthropogenic activity, proximity to roads, and lack of protection, reflecting historical mining pressure and immediate accessibility.
- In the case of the Paradoxid Shale, the circle shows the importance of proximity to the road and fragile lithology, coupled with a strong contribution from natural erosion.
- The Granite of Sebt Brikiine and Conglomerates of Kef El Mounib have circles dominated by very weak segments, reflecting a low contribution from all factors, which corresponds to their low overall risk.

In general, the most accessible or unprotected sites have significantly more developed segments, particularly for the factors of proximity to roads, human activity, and lack of protection.

The final comparative diagram (Figure 5) ranks the ten geosites in the Rehamna region according to their overall degradation risk score, from lowest to highest. This summary visualization allows for the rapid identification of priority sites for conservation actions: the pegmatites of Sidi Bou Othmane and Paradoxid Shale stand out with scores above 3.30, corresponding to a high risk level, while the Granite of Sebt Brikiineand-Conglomerates of Kef El Mouniboccupy the last positions with scores below 2, confirming their low risk level.

These graphical representations facilitate overall understanding of the pressures exerted on each geosite and enable effective guidance for conservation and management strategies for the geological heritage of the Rehamna region.

DISCUSSIONS

The quantitative assessment carried out on the ten geosites in the Rehamna region made it possible to rank the risks of degradation according to natural and anthropogenic factors. The application of the AHP method thus provided a rigorous framework for cross-referencing various criteria weighted according to their importance.

The results show that the most exposed geosites are those that are easily accessible, lack official protection, and consist of lithologies that are sensitive to weathering or human exploitation. This is particularly the case for pegmatite of Sidi Bouathmane and the Paradoxid Shale, which have the highest risk scores. On the other hand, geosites that are difficult to access and composed of resistant rocks, such as the Granite of Sebt Brikiine or Conglomerates of Kef El Mounib, present low levels of risk.

These results confirm that accessibility, lack of protection, and lithological fragility are major determinants of geosite vulnerability.

The originality of this study lies in the use of the AHP method (Saaty, 1980) to produce a precise and quantitative ranking of degradation risks, incorporating field observations and multidimensional criteria. In addition, graphical visualization using proportional circles and comparative

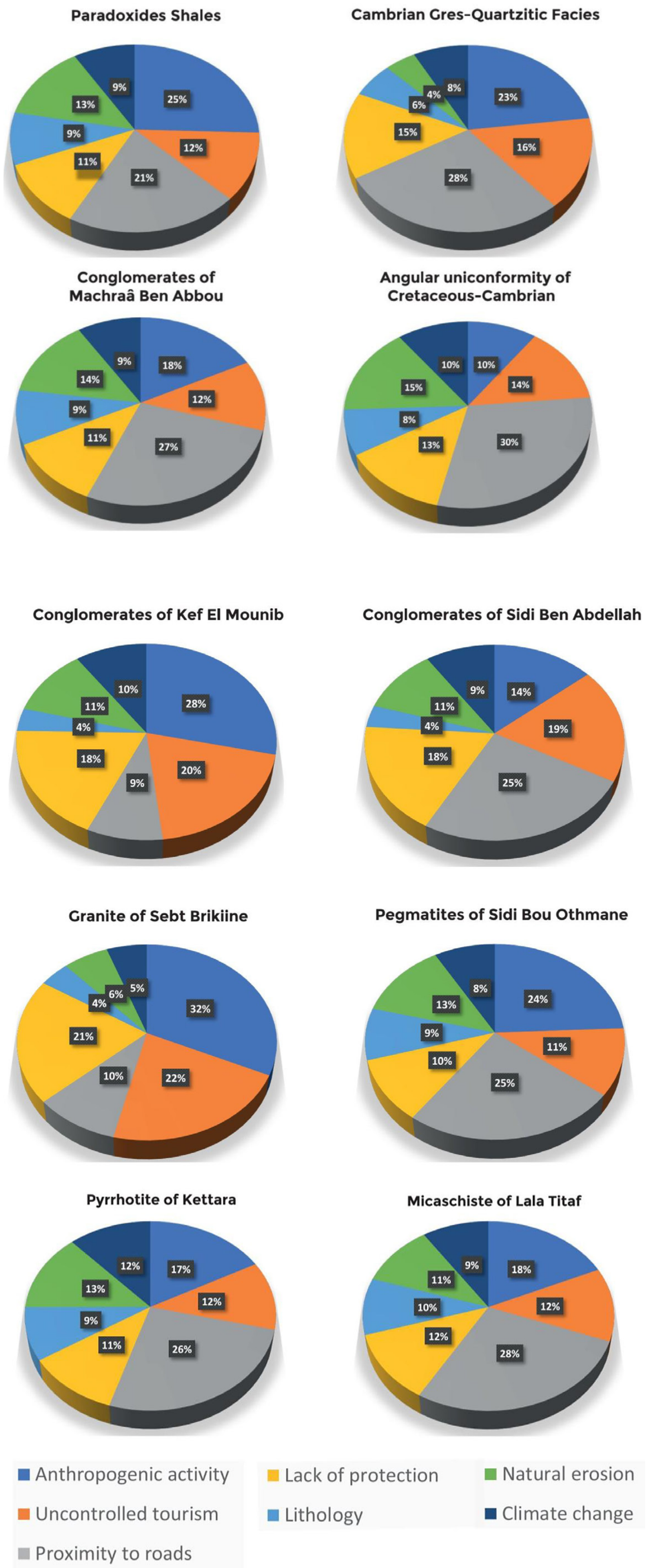

Figure 4. Comparative representation of degradation factors by geosite in the form of proportional circles

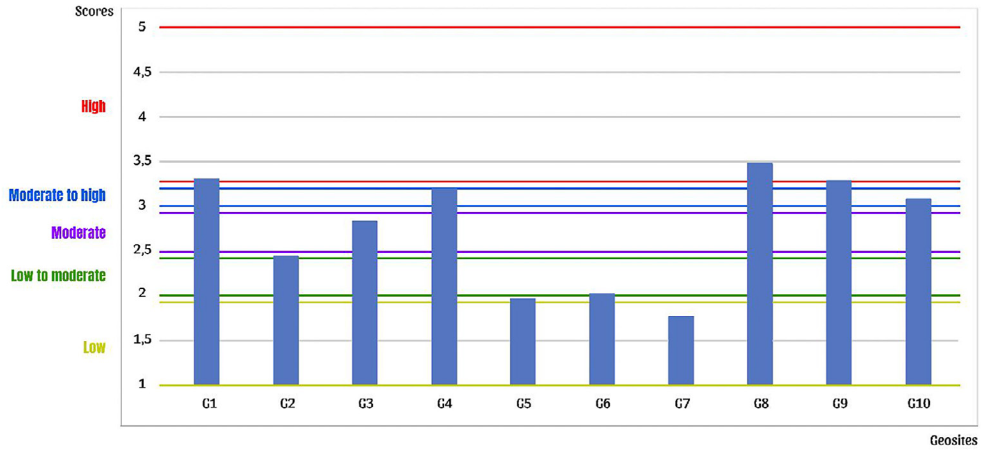

Figure 5. The final comparative diagram ranks the ten geosites in the Rehamna region according to their overall degradation risk score: G1 – Paradoxid Shale; G2 – Cambrian Gres-Quartzitic Facies; G3 – Angular unconformity of Cambrian-Cretaceous; G4 – conglomerates of Machraâ Ben Abbou; G5 – Conglomerates of Kef El Mounib ; G6 – Conglomerates of Sidi Abdelah; G7 – Granite of Sebt Brikiine; G8 – Pegmatite of Sidi Bouathmane; G9 – Pyrrhotites of Kettara; G10 – Micashiste of Lalla Titaf

diagrams adds methodological value, facilitating the communication of results to decision-makers and heritage managers.

However, it should be noted that the choice of factors and their weighting are based in part on expert judgment. Although this approach is methodologically sound, a certain degree of subjectivity may remain, which is inherent in this type of multi-criteria assessment. For future prospects,this method could be applied to other regions of Morocco, integrated with GIS tools for risk mapping, and include more detailed data such as actual visitor numbers or topographical conditions.

In the specific context of the Rehamna region, the results of this study can serve as a basis for reflection on a regional geoconservation strategy. Several avenues can be explored: Implementation of priority protection measures for the most exposed geosites, such as the Sidi Bou Othmane pegmatites and the paradoxid schists, through awareness-raising, signage, and restrictions on destructive practices (exploitation, illegal collection), development of supervised geotourism for accessible sites with high scientific and educational potential. Controlled development would raise awareness among local populations and visitors, while ensuring the preservation of the sites. Integration of geosites into territorial planning documents, so that geological heritage is taken into account in development projects, roads, or potential mining operations. Creation of a georeferenced database of geosites in the region, combined with regular monitoring of their state of conservation, and finally, involvement of local authorities and academic institutions in action research projects to further analyze risks and implement long-term monitoring tools.

CONCLUSIONS

This study enabled the AHP method to be applied for the first time to assess the risk of degradation of geosites in the Rehamna region. The results show that factors related to accessibility and the lack of institutional protection are the main sources of vulnerability, while lithological and climatic parameters play a secondary role. The overall risk index calculated highlights significant contrasts between sites, with some showing high exposure to degradation while others appear more stable and less threatened.

The study thus fills a significant gap in Moroccan research, where approaches have thus far been primarily qualitative and descriptive. It provides a quantitative and reproducible framework for prioritizing conservation efforts, strengthening the scientific basis for management decisions.

Beyond the case of Rehamna, the applied methodology is a tool that can be transferred to other regions of Morocco and similar geological contexts. It opens up prospects for the development of national geoconservation strategies based on objective and comparable indicators. With this in mind, future research could refine certain criteria, in particular by incorporating more detailed climate and tourism data, in order to further strengthen the robustness of the model.

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