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Contribution to the inventory of Morocco's geological heritage: The coastal geosites of Agadir Ida-Outanane (western High Atlas, Morocco)

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ABSTRACT

This study examines ten geosites distributed along the coastline of the Agadir Ida Outanane area, southwestern Morocco. A significant part of the study area is located within the Cap Ghir-Taghazout site of biological and ecological interest (SIBE). The selected sites display exceptional geological diversity in terms of stratigraphy, sedimentology, palaeontology, hydrogeology and geomorphology. Some also have significant cultural and ecological value. The geosites were evaluated using a methodology that allows for identification, characterisation and appropriate quantitative assessment. This assessment covers scientific value (SV), potential for educational use (PUE), potential for tourist use (PUT) and risk of degradation (RD). This is done by assigning scores from 1 to 4. The results indicate high scientific value (average SV = 3.67), with five geosites scoring ≥ 3.5, including the caves of Cap Ghir (3.95) and the cliffs of Taghazout (3.80). The educational use potential (PUE) and the touristic use potential (PUT) show respectively very high and high values, with respective averages around 3.56 and 3.50. However, the risk of degradation was moderate (average risk of degradation = 2.61), particularly for accessible sites such as the Anza dinosaur footprints (risk of degradation = 2.90) and the Tiguert travertines (risk of degradation = 2.55). These results highlight the need for sustainable management to reconcile conservation and the development of geotourism. The proposed geological itinerary joins these geosites, promoting local economic growth while preserving Morocco's geological heritage. This work provides the first integrated quantitative assessment of coastal geosites in the Agadir Ida Outanane region, offering a replicable model for promoting geological heritage in Morocco and similar coastal contexts.

Keywords: Agadir coastline, geodiversity, geological heritage, valorization, geosites, Anza dinosaur tracks, site of biological and ecological interest, georoute.

INTRODUCTION

The preservation and promotion of geological heritage (geoheritage) have emerged as essential components of sustainable development and environmental management on a global scale (Brilha, 2016; Reynard et al., 2016). This international recognition is reflected in the proliferation of scientific publications and the creation of initiatives such as UNESCO Global Geoparks, which integrate geoconservation with education, tourism and community involvement (UNESCO, 2015). Fundamentally, the initial and most crucial step in any geoconservation strategy is the systematic inventory and quantitative assessment of geosites, allowing for scientific prioritisation based on their value and vulnerability (Wimbledon, 1996; Pereira and Brilha, 2010). As a result, standardised methodologies have been developed and applied in various geographical contexts, notably in Portugal (Rocha et al., 2014), Spain (Fuertes-Gutiérrez and Fernández-Martínez, 2010), France (Poiraud et al., 2016), Italy (Ferrando et al., 2021) and Brazil (Mucivuna et al., 2017), providing a robust framework for comparative analysis.

In Morocco, the recognition of the country's remarkable geodiversity has fostered a significant increase in scientific contributions focused on the inventory and evaluation of geopatrimony. Several precursory studies have been conducted in different regions, including the Rif (Mhend et al., 2019, 2020; Ben Ali et al., 2023; 2025), the Meseta (Mehdioui et al., 2020, 2022), the Middle Atlas (Oukassou et al., 2019) and the Central Jbilet (Kaid Rassou et al., 2019). These studies have successfully applied quantitative assessment methods to document and evaluate geosites, providing a framework for national geoconservation strategies. However, a significant geographical and thematic gap remains. While northern and central Morocco have received considerable attention, the southwestern Atlantic coastal region, and particularly the Agadir Ida-Outanane area, remains largely unexplored using a systematic approach to geoheritage.

The Agadir Ida-Outanane coastline, extending approximately 68 km in the western High Atlas Mountains, is a region characterized by geological complexity and marked ecological sensitivity. Its stratigraphic units date from the Jurassic to the Quaternary periods, including famous sites such as the Cretaceous dinosaur footprints at Anza, the Upper Jurassic coral reefs at Cap Ghir, Quaternary travertine formations and active geomorphological features. A substantial portion of this coastline is included in the Cap Ghir-Taghazout site of biological and ecological interest (SIBE), highlighting the intrinsic interconnection between its geological foundations and its unique biodiversity. Despite this richness, previous research in the area has often been limited, focusing on isolated geological units (e.g., Masrour et al., 2017 on dinosaur tracks; Martin-Garin et al., 2007 on reefs) without providing a holistic and quantitative assessment of its overall geopatrimonial potential within a framework of geoconservation and sustainable tourism. This lack of integrated assessment constitutes a major scientific and managerial gap, leaving the region's geological assets misvalued and vulnerable to uncontrolled impacts of tourism and development.

Consequently, this study aims to fill this identified gap. The main objective is to carry out the first comprehensive and quantitative inventory and multi-criteria assessment of the major geosites on the Agadir Ida-Outanane coastline. To achieve this, we are focusing on three specific objectives: (i) identify and systematically characterize ten representative geosites that represent the geodiversity of the area; (ii) evaluate each geosite quantitatively using an adapted methodology based on Brilha (2016), by calculating scores for scientific value (SV), educational use potential (PUE), tourism use potential (PUT), and degradation risk (DR). and (iii) summarise the results to propose scientific geotourism itineraries that provide a balance between promotion and conservation requirements. We are making the following hypothesis: (1) the geosites in this region will have very high scientific and educational value due to their rarity and representativeness, while (2) their degradation risk will be significantly correlated with their accessibility and proximity to human activities. The results of this research should provide an essential database for regional planners, contribute to the scientific discourse on the evaluation of coastal geoheritage, and offer a concrete path towards sustainable geotourism development and the possible creation of a geopark in south-western Morocco.

MATERIALS AND METHODS

Study area – geographical and geological setting

Located in the Souss-Massa region in Morocco, The Agadir Ida Outanane coastline (Figure 1), is an exceptional geological and ecological area, distinguished by its remarkable geological heritage and significant biodiversity. Bounded by the Atlantic Ocean, this region extends for approximately 67.2 kilometres, from the Agadir's coast (30°23'59.99 'N, 9°35'59.99 "W) to Timlalin (30°35'00 "N, 9°25'00 'W). It is important to note that a large part of this territory forms the biological and ecological interest site of Cap Ghir-Taghazout. It consists of a protected area known for its ecosystems and exceptional species.. The study area comprises seven emblematic localities – Agadir, Anza, Taghazout, Tiguert, Cap

Ghir, Tamri and Timlalin. Each locality hostsat least one remarkable geosite. These sites feature not only diverse geological formations formed by complex processes over millions of years (such as Jurassic limestone cliffs, Quaternary travertines, and paleontological deposits), but also provide remarkable habitats for endemic flora and fauna. The interaction between geological diversity (stratigraphic, geomorphological and palaeontological) and ecological value (coastal, marine and terrestrial ecosystems) highlights the imperative need for integrated conservation strategies to preserve this valuable heritage from human pressures and environmental degradation.

Geologically, the Agadir-Ida-Outanane coastline is dominated by geological formations dating from the Mesozoic to the Quaternary periods. The marine and coastal formations consist mainly of Quaternary sands and gravels (Michard, 1976). Alluvial sediments from the Souss River, which flows into the ocean south of the Gulf of Agadir, contribute to the sedimentary diversity of the region (Michard, 1976). In addition, limestone and shale outcrops are visible in the mountains, particularly in the western High Atlas (Michard, 1976). Located north of Agadir, the Anza region is particularly well known for its fossilised dinosaur footprints, which bear witness to the presence of theropods and pterosaurs in this region (Smith, 2018). Several studies have revealed that these fossils date back to the Cretaceous period, offering a fascinating glimpse into the region's prehistoric fauna (Smith, 2018), while Taghazout is renowned for its oil shales containing organic matter dating back to the Jurassic period (Johnson, 2019). Further north, Cap Ghir is renowned for its Upper Jurassic coral reefs.

These reefs, composed mainly of corals of the genera Dimorpharaea, Microsolena and Stylina, formed on a tilted Jurassic block (Martin-Garin et al., 2007).

Structurally, the Agadir-Ida-Outanane region is characterised by complex tectonic structures. Tectonic movements linked to Alpine orogenesis shaped the surrounding mountains, generating faults and folds that are visible in the landscape (Frizon de Lamotte et al., 2009). For example, the Gulf of Agadir is located near active faults, which explains the frequent earthquakes in the region, including the devastating earthquake of 1960. These tectonic structures reflect the ongoing dynamics between the African plate and the Iberian microplate (Cherkaoui et al., 2007).

Methodology for geosites inventory and quantitative assessment

This study used a quantitative multi-criteria evaluation framework, following the internationally recognised methodology of Brilha (2016), which has been successfully adapted to the Moroccan context in previous work (e.g., Aoulad-Sidi-Mhend et al., 2019, 2023). The overall methodological process, summarised in Figure 2, was conducted in three sequential and interconnected phases to ensure a systematic and reproducible approach.

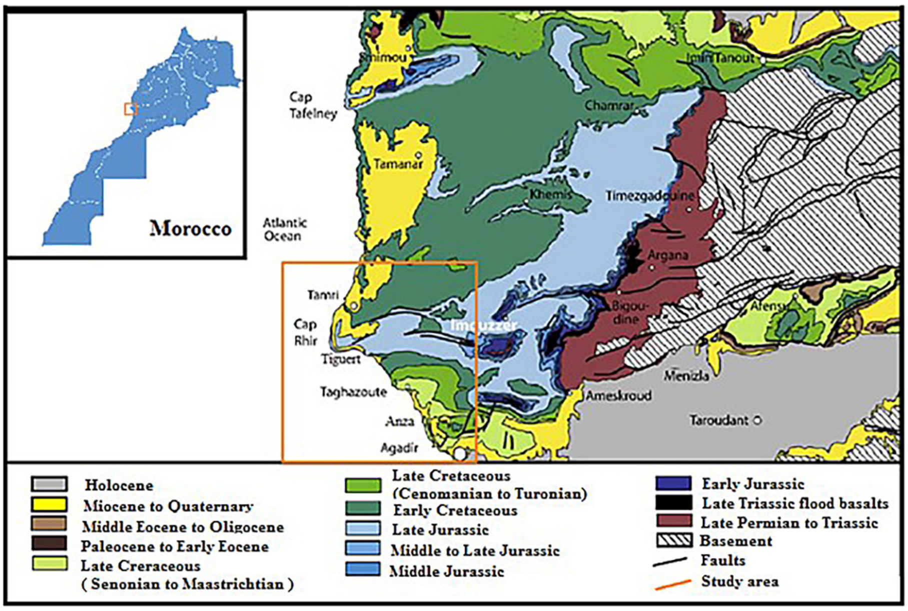


Figure 1. Geological map of the study area and geographical location (Agadir Ida Outanane coastline)

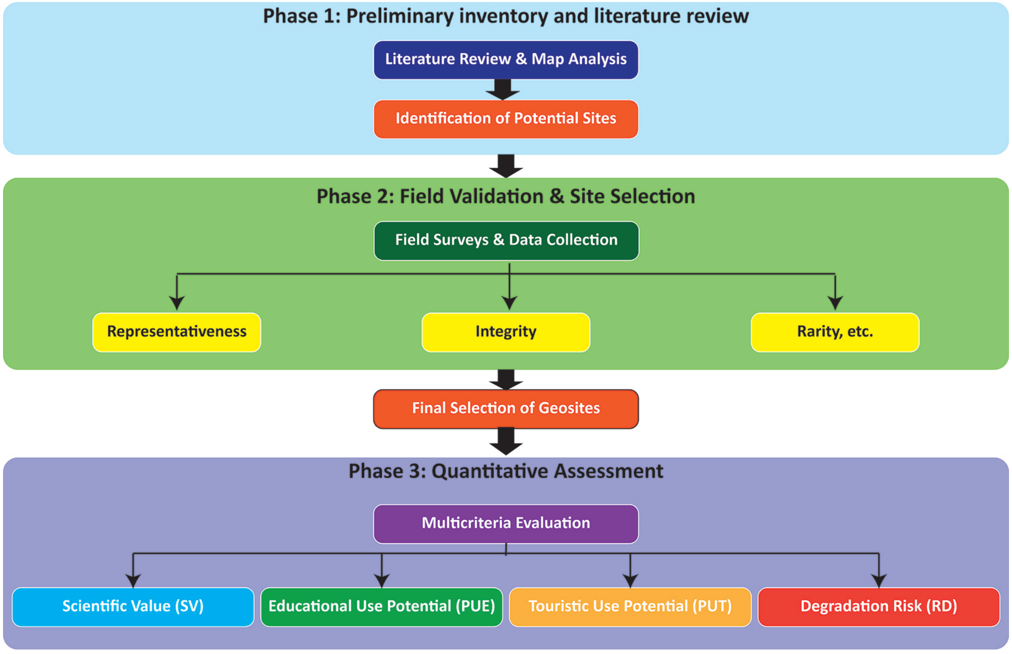


Figure 2. Methodological process followed for the inventory, selection, and evaluation of geosites (After Brilha 2016)

Phase 1: Preliminary inventory and literature review

A comprehensive review of existing scientific literature, geological maps (e.g., Michard, 1976), topographical maps and previous specific studies was carried out. This desk analysis aimed to identify and document areas of potential geological interest along the Agadir Ida-Outanane coastline, forming an initial long list of candidate sites.

Phase 2: Field validation, characterisation and final selection of sites

Field campaigns were undertaken to verify the preliminary inventory. During these surveys, each site was systematically characterised using standardised field assessment forms (adapted from Aoulad-Sidi-Mhend et al., 2019). Data collection included recording precise GPS coordinates, taking comprehensive photographic documentation and making detailed observations on geological characteristics, integrity, accessibility and current anthropogenic pressures. Consultations with local experts and community members provided valuable contextual information. The final selection of the ten geosites presented in this study was based on the application of three key selection criteria in the field: representativeness (the extent to which the site illustrates a geological process or feature), integrity (the degree of preservation from deterioration), and rarity (the uniqueness of the feature on a regional or national scale),etc. as defined by Brilha (2016).

Phase 3: Multi-criteria quantitative assessment

Each selected geosite underwent a quantitative assessment based on four fundamental values: scientific value, educational use potential, tourist use potential and risk of degradation. The assessment followed the structured system of criteria and weightings proposed by Brilha (2016), as detailed in Table 1.

Scoring process

Each criterion for a given geosite was assigned a score of 1 to 4 by the research team, based on a consensus derived from field data, photographic evidence, and literature review. The rating scale was defined as follows: 1 (low), 2 (moderate), 3 (high), and 4 (very high). For example, a score of 4 for 'rarity' was assigned to features that are unique on a global or national scale (e.g., the Anza pterosaur tracks), while a score of 1 indicated a common feature.

Calculation of final values

The final score for each value (*SV, PUE, PUT, RD*) was calculated by summing the weighted scores of its constituent criteria. The weights

Table 1. The criteria for scientific value, educational use potential, touristic use potential, and degradation risk, as well as their scores and weighting

Values	Criteria (scores 1 to 4)*	Weight (%)
Scientific value (SV)	Representativeness (Rpt)	30
	Integrity (Int)	20
	Rarity (Rar)	5
	Key Locality (KL)	15
	Scientific Knowledge (SK)	5
	Geological Diversity (DG)	15
	Use Limitations (UL)	10
Educational use potential (PUE)	Vulnerability (Vul)	10
	Accessibility (Acc)	10
	Use Limitations (UL)	5
	Safety (Saf)	10
	Logistics (Log)	5
	Population Density (DP)	5
	Association with Other Values (Av)	5
	Scenery (Sce)	5
	Uniqueness (Uni)	5
	Observation Conditions (OC)	10
	Didactic Potential (DP)	20
	Geological Diversity (GD)	10
Touristic use potential (PUT)	Vulnerability (Vul)	10
	Accessibility (Acc)	10
	Use Limitations (UL)	05
	Safety (Saf)	10
	Logistics (Log)	05
	Population Density (DP)	05
	Association with Other Values (Av)	05
	Scenery (Sce)	15
	Uniqueness (Uni)	10
	Observation Conditions (OC)	05
	Interpretation Potential (IP)	10
	Economic Level (EL)	05
	Proximity to Recreational Areas (RA)	05
Degradation risk (RD)	Deterioration of Geological Elements (Dg)	35
	Proximity to Degrading Activities (PD)	20
	Legal Protection (LP)	20
	Accessibility (Acc)	15
	Population Density (DP)	10

(expressed as percentages) reflect the relative importance of each criterion within the overall value, as established by Brilha (2016). The calculation formulas are:

$$SV = (0.30 \times Rpt + 0.20 \times Int + 0.05 \times Rar + + 0.15 \times KL + 0.05 \times SK + + 0.15 \times DG + 0.10 \times UL) \quad (1)$$

$$PUE = (0.10 \times Vul + 0.10 \times Acc + 0.05 \times UL + + 0.10 \times Saf + 0.05 \times Log + 0.05 \times DP + + 0.05 \times Av + 0.05 \times See + 0.05 \times Uni + + 0.10 \times OC + 0.20 \times DP + 0.10 \times GD) \quad (2)$$

$$PUT = (0.10 \times Vul + 0.10 \times Acc + 0.05 \times UL + 0.10 \times Saf + 0.05 \times Log + 0.05 \times DP + 0.05 \times Av + 0.15 \times See + 0.10 \times Uni + 0.05 \times OC + 0.10 \times IP + 0.05 \times EL + 0.05 \times RA) \quad (3)$$

$$RD = (0.35 \times Dg + 0.20 \times PD + + 0.20 \times LP + 0.15 \times Acc + 0.10 \times DP) \quad (4)$$

Compilation of results

Detailed scores for each criterion by geosite, weighted intermediate scores, and final aggregate values are compiled transparently in Tables 2 to 5. The final results for all geosites are summarised in Table 6, providing a clear overview of their assessed values and risk of degradation.

RESULTS

The first result was obtained after several field trips, a litterature review and contacts with the owners and partners such as the Moroccan Association for Scientific Orientation and Research (AMORS: https://www.assohelp.org/asso-632-l-association-marocaine-d-oriention-et-la-recherche-scientifique) present in the area. The identification of the GS that represent the geodiversity of the Agadir Idaoutanane coastline has facilitated the establishment of a list of 10 significant, rare, and included GS, in addition to being located in the most easily accessible sector of the study area.

GS1: Coast of Agadir

The Agadir Bay (30°25‘, 14’‘N - 09°36’,36‘’W) (Figure 3a) and Agadir Oufella Hill (30°25,46‘N - 09°37,25’W) (Figure 3b), form a highly valuable geological and historical site. Agadir Bay, with its exceptional landscape combining sea, mountains and plains, is a site of major sedimentological interest. It is characterized by well-classified medium-sized sediments, formed by the influence of waves and marine flows. (Aouiche et al., 2016). Throughout geological periods, the bay has played a key role in hydrosedimentary processes, operating as a natural regulator of sediments and water flows.

The Agadir Oufella hill, overlooking the bay, constitutes a geocultural site. Geologically, the hill is dominated by sedimentary rocks dating Cretaceous and Paleogene, including limestone, marl, and sandstone, indicating a shallow marine environment (Michard, 1976; Ettachfini and Andreu, 2004). It contains well-preserved marine fossils, which provide valuable evidence of environmental conditions (Benzaggagh, 2016; El Albani et al., 1999). The hill's structure, marked by faults and folds resulting from tectonic activity linked to the Moroccan Atlas Mountains' evolution (Frizon de Lamotte et al., 2008; Teixell et al., 2003). Built in 1540 by Saadian Sultan Mohammed ech-Cheikh in order to protect the city from Portuguese invasions, the Kasbah of Agadir Oufella (Figure 3 c) is an outstanding example of resilience despite the destruction it suffered during the 1960 earthquake (Boudhan, Agadir and its past; Sabir, Histoire d'Agadir).

These two closely linked sites offer a unique combination of landscapes, geological diversity, and history, while confronting conservation challenges linked to erosion and human activities.

GS 2: Dinosaurs of Anza

The Anza site (30°26‘,43’‘N - 09°39’,39‘’W) (Figure 4 a), located near the Agadir city, is an exceptional palaeontological site dating Upper Cretaceous (Coniacian-Santonian). It is situated on

Figure 3. (a) Agadir Bay, (b) Agadir Oufella Hill and (c) Agadir Oufella Kasbah after restoration

the north-western flank of the Kasbah d'Agadir oufella anticline, in the western High Atlas range, this site is easily accessible along the N1 national road linking Agadir to Essaouira. It is mainly known for its pterosaur and carnivorous theropod footprints (Figure 4 a), which constitute the third deposit of this type discovered in Africa, after those of Tagragra (Maastrichtian) and Mibladen (Jurassic). The Anza footprints, showing the first pterosaur track identified in Africa offer valuable informations on the behaviour and locomotion of these flying reptiles (Masrour et al., 2017).

This site is distinguished by the quality and density of its footprints, with approximately 323 identified tracks, revealing a remarkable diversity of dinosaurs. These footprints are preserved in calcareous sandstone of up to 10 meters thick, which is characteristic of a Coniacian-Santonian coastal environment.. The pterosaur footprints, concentrated in a specific layer, they consist of a complete trackway of seven handprints (manus) that are tridactyl and asymmetrical, with no footprints (pes). These prints have an average length of 8.7 cm and 4.9 cm in Width, with a morphology suggesting that they belong to a small to medium-sized pterosaur, probably of the Ornithocheiroidea or Azhdarchoidea superfamilies, which have been found in Upper Cretaceous layers in Morocco. (Masrour et al., 2017).

In spite of being protected due to its scientific value, this site remains vulnerable to marine erosion and human activities. Its study could contribute to a better understanding of the environmental conditions and sedimentary dynamics of that geological period. (Masrour et al., 2017).

The Anza Dinosaur Museum officially opened on January 31, 2022, near the Anza paleontological site. it is famous for its dinosaur footprints. This museum contains remarkable fossils, including a reconstructed theropod skull (Figure 4b) and a pterosaur leg (Figure 4c).

The site is distinguished by its exceptional geological features, and the Museum's mission is to promote it among the general public and students, in order to communicate scientific knowledge related to this unique heritage.

GS3: Cliffs of Taghazoute

The Taghazoute cliffs (30°33'12''N - 9°44'22''W) (Figure 5a) are located along the Moroccan Atlantic coast northwest of Agadir. it consists of a geological and natural landscape of major importance.. Characterized by striking linear formations of Tertiary limestones and sandstones, these cliffs reveal a complex geological history marked by sedimentary processes, and erosion over millions of years. (Benkaddour, 2020; Benyahia et al., 2020). The bituminous shales (Figure 5b) embedded in the bedrock layers are particularly interesting as they provide not only an insight into the ancient sedimentary environments of the region, but also hold significant unexploited energy potential due to their organic matter. (Benyahia et al., 2021; Khamlichi and Tazi, 2019). In addition to this geological mosaic, the surrounding strata preserve fossils such as clams (Figure 5c) and other paleoenvironmental indicators, enabling researchers to reconstruct the ecological and climatic past of the region. (El Azzouzi and El Boukhari, 2019; El-Idrissi and Tazi, 2022). However, the driving forces which expose these treasures to marine erosion have also created spectacular shapes, such as arches and cavities, making the site both visually stunning and becoming increasingly fragile. This vulnerability

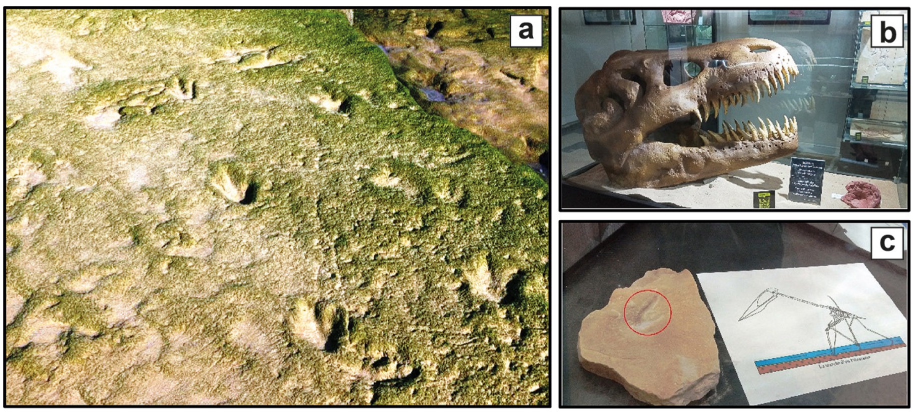


Figure 4. (a) Dinosaur footprints found at Anza, mainly those of carnivorous theropods and pterosaurs, (b) a reconstruction of a theropod skull and (c) a pterosaur leg

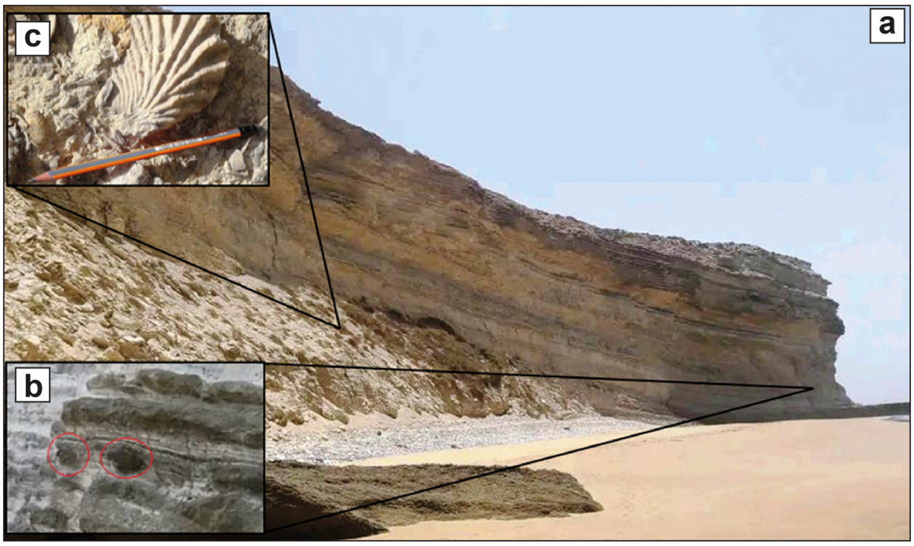


Figure 5. (a) Taghazoute cliffs, (b) Taghazoute bituminous shale, (c) clam fossil (photo Z. Boukfaoui, 2024)

is increased by human activities like uncontrolled tourism and urban expansion, which have accelerated erosion, emphasizing the urgent need for conservation measures. (Aït Hssaine, 2021; Bouzekraoui et al., 2019).

The Taghazoute cliffs play a key role in geotourism, combining spectacular landscapes and scientific value. Their preservation is essential to maintain their geological integrity, educational value, and economic potential (El Azzouzi and El Boukhari, 2020).

GS 4: Tiguert Travertines

Located near the RN1 national highway joining Agadir and Essaouira cities, the Tiguert Travertines (Figure 6a, N30°33'12" W09°44'22") constitute a geological park offering excellent accessibility for visitors and researchers. This site comprises three distinctive areas of limestone formations, providing a truly panoramic view of the region's geological history.

The first sector, dominated by stratified gray limestone from the Upper Jurassic (160–145 million years ago), preserves evidence of an ancient marine environment, where sedimentary layers reveal variations of sea levels and sedimentation processes (El Kadiri, 2006).

The second area is characterized by ocre-colored travertines deposits featuring globular structures commonly named "Patates." These formations, dating for the Quaternary period (approximately 2.6 million years ago to the present), resulted from the precipitation of calcium carbonates ($CaCO_3$) in mineral-rich waters associated with hydrothermal sources. They provide valuable informations on past hydrological and climatic conditions (Ford and Pedley, 1996).

The third zone consists of a whitish limestone powder of Quaternary age, resulting from the mechanical and chemical erosion of limestones from the above-mentioned zones. This zone shows the dynamics of erosion and sedimentation, providing a better understanding of the environmental influence, such as climate and water activity on the formation of coastal landscapes. (Aït Hssaine, 2003). While protected for its ecological and geological interest, this site remains vulnerable to erosion and human activities, requiring vigilant conservation efforts to safeguard its scientific and educational legacy.

GS 5: Tiguert angular unconformity

The Tiguert angular unconformity site (Figure 7), (30°37'43 'N 9°50'20 'W is in a coastal area that's exposed to the tides, influencing both its preservation and accessibility. This site highlights a stratigraphic break between geological units dating of different ages and revealing ancient tectonic activity. The angular discordance observed here occurs between a Quaternary fluvial sediment formed by the rivers' action and Upper Jurassic limestone strata, indicating shallow marine environments (Miall, 2016). This geological pattern reveals an uplift and erosion period between two geological sediments, showing a complex and rich geological history. According to Tucker (2001), this type of unconformity is crucial for reconstructing past tectonic events

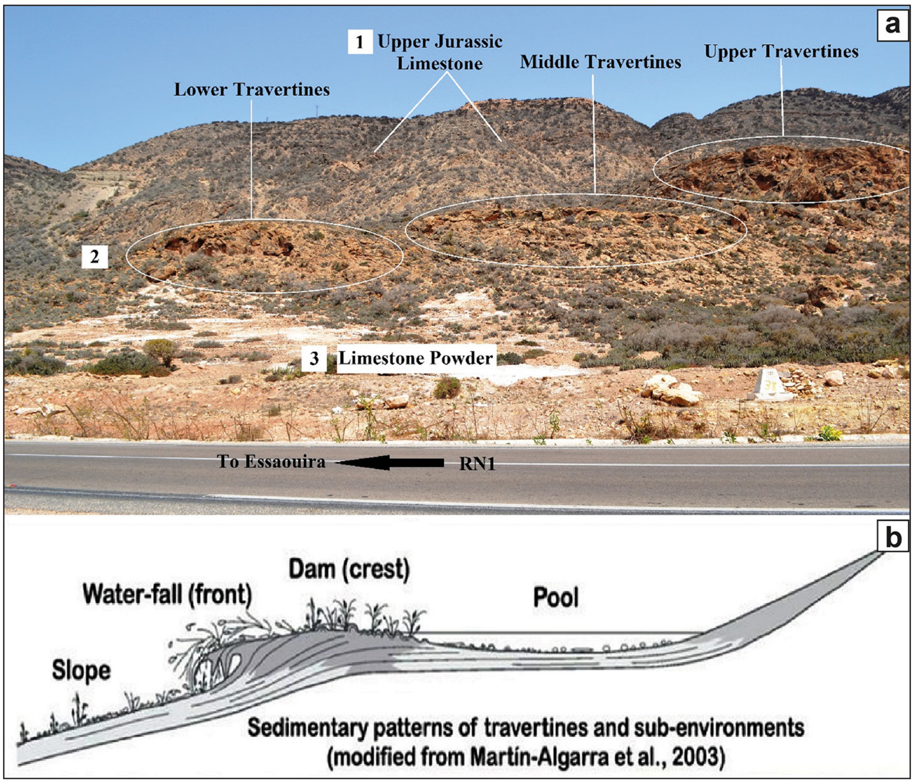


Figure 6. (a) Panoramic view showing the three types of limestone (1- limestone of Upper Jurassic age, 2- travertines of Quaternary age, 3- limestone powder of Quaternary age) (photo Z. Boukfaoui., 2023); (b) Travertine sedimentation model (Martin-Algarra et al., 2003)

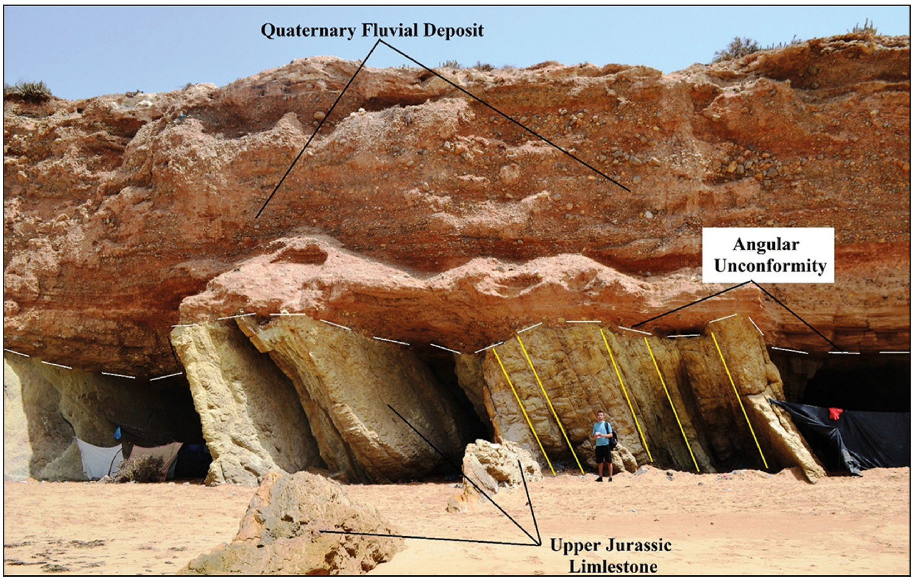


Figure 7. Tiguert angular unconformity (photo Z. Boukfaoui, 2023)

and environmental changes. Geomorphological studies have been carried out on these formations to understand the landscape evolution and environmental processes that influenced the creation of these formations (Davis and Reynolds, 1996). Prothero and Schwab (2013) emphasize that angular unconformities are geological archives detailing the tectonic movements, sea level variations, and erosion processes over Million years.

GS 6: Caves of Cap Ghir

The Cap Ghir caves (Figure 8 a) (N30°37’51’‘ W09°51’41’’) are marine cavities developed in the

Upper Jurassic limestones (Weisrock, 1980/93). they were created by the waves and tides actions during Quaternary marine transgressions, particularly the Harounian transgression and/or probably the Anfati transgression, which sculpted the coastal rock formations (Plaziat et al., 2008; Meghraoui et al., 1998). These formations consist of dolomitic and reef limestones offering an important geological evidence of erosional and sedimentary processes that formed the Moroccan Atlantic coast.

The site has major archaeological significance, highlighted by a mound of excavated material bearing numerous flint tools, indicating a prehistoric occupation. In 2005, archaeological investigations conducted by researchers from the National Institute of Archaeological Sciences and Heritage (INSAP) and the Faculty of Letters and Human Sciences (FLSH) of Agadir revealed a lithic industry consisting mainly of blunt-edged flakes, bone awls, and red ochre fragments. These findings suggest an Upper Palaeolithic human activity (Occhietti et al., 1999).

Beyond geology and archaeology, the caves host ecologically important bat species, including Rhinolophus ferrumequinum (Figure 8 b), commonly founded in Moroccan karst systems (Aulagnier andThévenot, 2020). These bats play a vital role in nocturnal insect control, supporting local ecosystem balance (Sevilla, 2019). However, unregulated tourism threatens their colonies, especially during breeding periods (Benda et al., 2021).

The caves' multidisciplinary value attracts researchers and visitors alike, but their preservation is critical to mitigate environmental and human impacts, necessitating targeted conservation efforts (Plaziat et al., 2008).

GS7: Kimmeridgian Reef of Cap Ghir

The Upper Jurassic Cap Ghir's reefs (30°37'33"N 9°51'54"W), constitute a major geological site to study the evolution of coral reefs and environmental changes over geological periods. This easily accessible site testifies to the geological and biological history of the region, offering a unique sight into the ancient marine environments of the Moroccan Atlantic basin (Ourribane et al., 1999). This reef of Jurassic age has developed through several phases: an initial fluvial detrital sedimentation, followed by shallow lagoonal and marine deposits, then by open marine sedimentation and fossiliferous marls. (Bouaouda 1987). The reef development occurred in several stages: (i) a stabilization stage (Figure 9b), with bioclastic fragments and encrusting organisms (algae and Stromatoporids), (ii) a colonization stage (Figure 9c), characterized by the appearance of branching polyps, (iii) a diversification stage (Figure 9d), marked by the flourishing of branching and massive polyps, and (iv) a domination stage (Figure 9e), where massive polyps predominate, accompanied by a variety of fossils (Lamellibranchs, Gastropods, Brachiopods, etc.). These phases illustrate the complex dynamics of reef's ecosystems and their adaptation to environmental changes.

GS 8: Reef of the main fossils at Cap Ghir

This area is marked by a lighthouse and is home to exceptional geological formations (30°37'59 'N 9°53'16 'W), including fossilised coral reefs and marine deposits dating from the Upper Jurassic. The Cape Ghir fossil reef of palaeontological

Figure 8. (a) The caves of Cap Ghir (photo Z. Boukfaoui, 2023), (b) Rhinolophus ferrumequinum

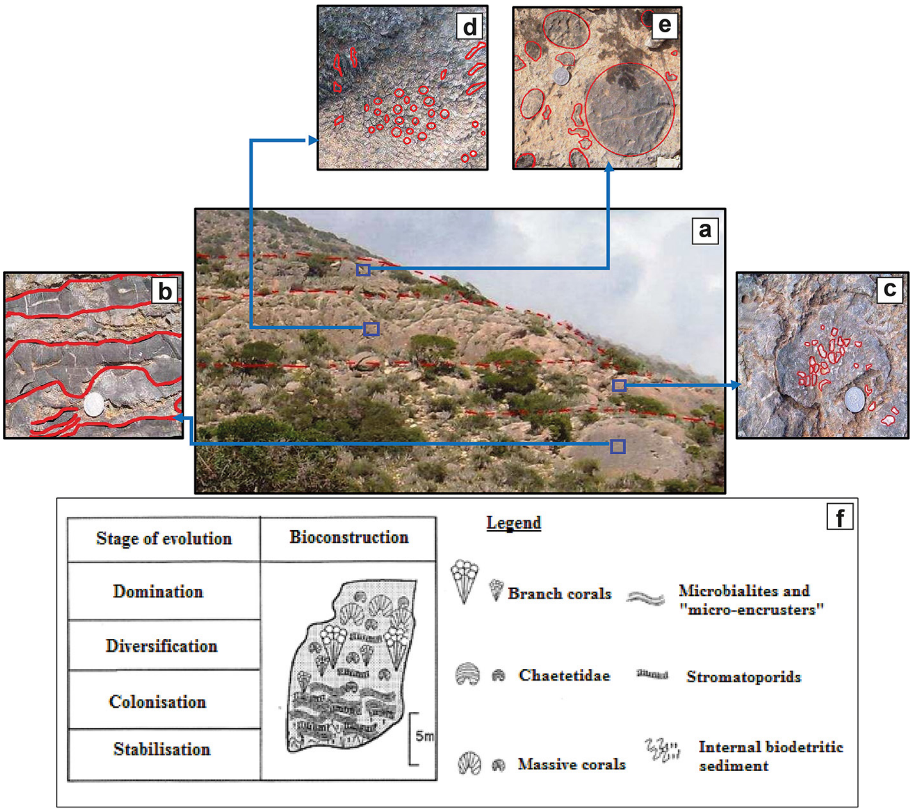


Figure 9. (a) The main formation stages of the Cap Ghir reef, (b) stabilisation stage, (c) colonisation stage, (d) diversification stage, (e) domination stage, (f) vertical evolution stages of the biological sequence of the Kimmeridgian reef lens (Cap Guir); Ourribane, et al., (1999)

interest, studied by Amborggi (1963), has a well exposed stratigraphic succession, comprising (Figure 10a) recent dunes (D) formed by the accumulation of sand, very hard light grey to dark limestones containing a diversity of marine fossils such as Lamellibranchs (Diceras) (Figure 10b), Gastropods (Nerinea) (Figure 10c), branching Cnidaria (Calamophylliopsis) (Figure 10d) and massive Cnidaria (Stylocoenia) (Figure 10e) and algae (Figure 10f). These fossils bear witness to

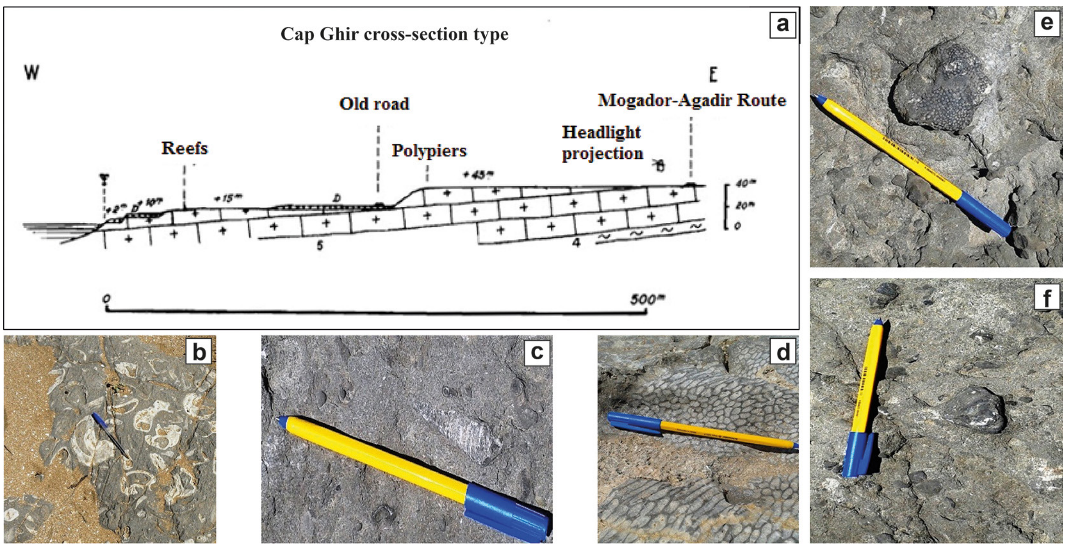


Figure 10. (a) Cap Ghir cross-section type; Amborggi (1963), (b) Diciras, (c) Stylocoenia, (d) Calamophylliopsis, (c) Nirene, (d) Stylocoenia and (e) algae, (photo Z. Boukfaoui., 2023)

environmental variations, with high-energy environments near the wave breaking zone (Stylocoenia) and calmer, shallower environments (Calamophylliopsis). This site is of major scientific interest, providing a better understanding of Upper Jurassic reef ecosystems and fossilisation processes in the context of a carbonate platform.carbonatée.

GS 9: The Tamri estuary

The Tamri estuary (Figure 11a), located around 50 km north of Agadir on Morocco's Atlantic coast (30°42'40 'N 9°51'17 'W), is an emblematic ecosystem in a semi-arid region. Flowing via the Tamri River, it consists of lagoons, sandy plains and coastal dunes, providing a vital habitat for threatened species such as the Northern Bald Ibis (Geronticus eremita) (Figure 11 b) and serving as an important area for migratory birds. due to its proximity to theN1 coastal road, the site attracts researchers, tourists and educators. Geologically, the estuary is marked by Cretaceous and Tertiary formations, dominated by limestone, marl and marine sediments, bearing marine transgressions and fluvial deposits. The beaches and coastal dunes, composed of fine sands and aeolian materials, reflect the influence of desertification and wind erosion. The marine fossils found in the region are evidence of ancient marine transgressions and tectonic processes that have shaped the landscape, as shown by Weisrock (1980/93) and Plaziat et al (2008). These complex geological dynamics make the Tamri estuary a site of major interest for the study of sedimentary formations and coastal evolution.

GS 10: The Timlaline gorges

The Timlaline gorges (Figure 12a) (30°46'00 'N 9°49'39 'W), located near Tamri area, are a

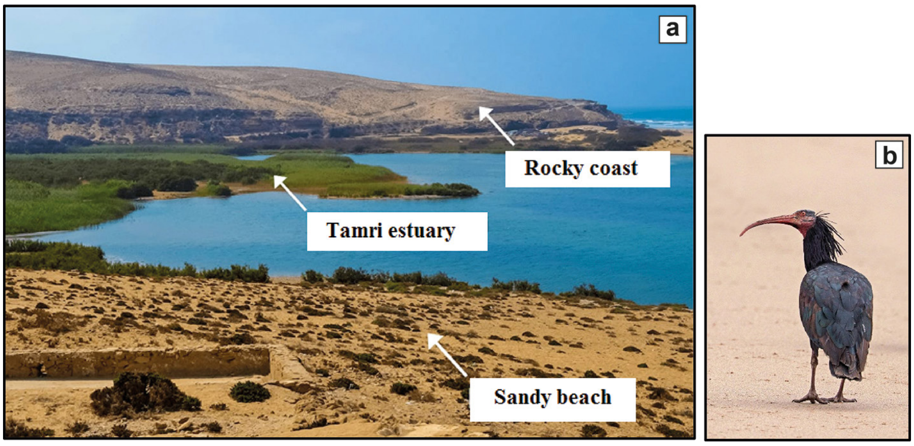


Figure 11. (a) The Oued Tamri estuary. (b) the Northern Bald Ibis (Geronticus eremita)

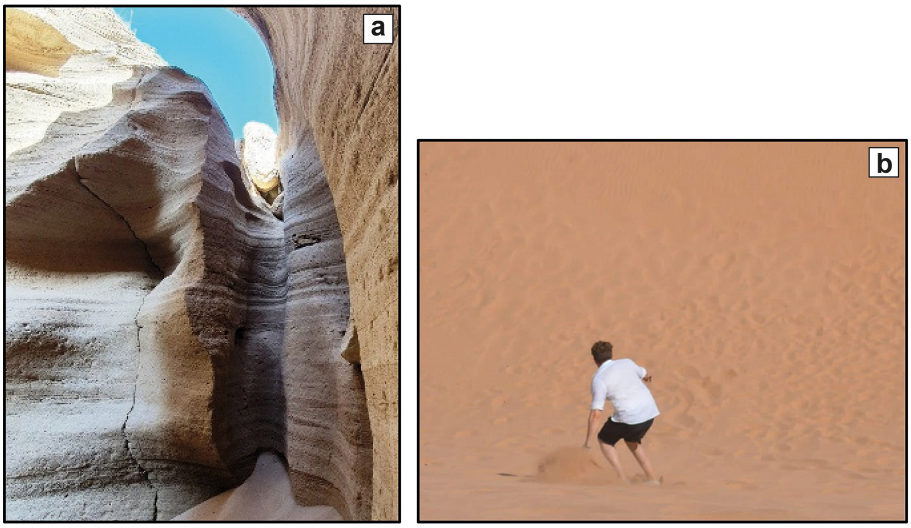


Figure 12. (a) Timlaline gorge, (b) Sandboard

remarkable geological and landscape site, sculpted by the fluvial erosion of the Tamri river over millions of years. These gorges feature impressive rock walls and a spectacular landscape, attracting local and international hikers and tourists. Nearby the gorges, the sand dunes are ideal for activities such as sandboarding (Figure 12b). Geologically, the Timlaline Gorges are characterised by Jurassic and Cretaceous sedimentary formations, including limestone, marl and sandstone, reflecting a variety of depositional environments, from open marine to continental (Michard, 1976; Frizon de Lamotte et al., 2008). The massive limestones indicate sedimentation in open marine environments, while the marls suggest periods of finer sedimentation in calm, deep environments. The sandstones, on the other hand, reflect detrital deposits resulting from erosion of the relief during the Alpine orogeny (Charrière, 1990). Differential erosion played a key role in the formation of today's landscape, with resistant limestones forming imposing cliffs and softer marls eroding more rapidly (Michard, 1976).

DISCUSSION

Quantitative study of the geological sites

Once the 10 geological sites had been identified and described qualitatively, a quantitative study was carried out to assess their scientific value (SV), their potential for educational use (PUE), their potential for tourist use (PUT) and their risk of degradation (RD). These assessments were carried out by applying the criteria and weightings proposed by Brilha (2016) and adapted by Aoulad-Sidi-Mhend et al, (2019, 2023). (Figure 13).

Scientific value (SV)

The scientific value of the geosites has been evaluated according to seven criteria (Table 2): Integrity (Int), Representativity (Rpt), Rarity (Rar), key locality (KL), Scientific Knowledge (SK), Geological Diversity (DG) and Use Limitations (UL). The scores range from 3.35 to 3.95, indicating an overall high average scientific value for the studied sites.

- Geosites of very high scientific value (SV > 3.5):
  - Cap Ghir caves (3.95): Exceptional archaeological and geological site, rich in fossils and limestone formations.
  - Taghazout cliffs (3.80): Complex stratigraphic formation, revealing ancient marine environments.
  - Kimmeridgian reefs and fossils at Cap Ghir (3.75): Remarkable palaeontological and sedimentological sites.
  - Anza Dinosaur footprints (3.75): A unique palaeontological site providing valuable information on prehistoric fauna.

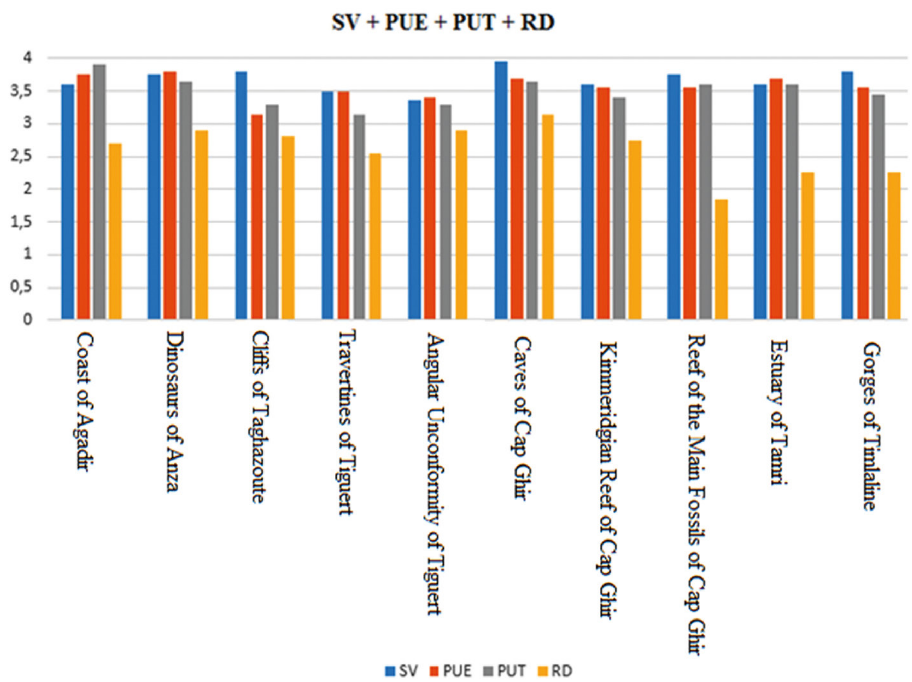


Figure 13. Histogram representation of SV, PUE, PUT, and RD

Table 2. Typology and evaluation of the scientific value criteria of the GS studied and their weighted average

No.	GS Name	Typology	Int	Rpt	Rar	KL	SK	DG	UL	SV
1	Agadir Coast	Sedimentological	0.6	1.2	0.6	0.4	0.2	0.2	0.4	**3.60**
2	Anza Dinosaur footprints	Paleontological	0.6	1.2	0.6	0.8	0.2	0.15	0.20	**3.75**
3	Taghazoute Cliffs	Stratigraphic	0.6	1.2	0.6	0.8	0.2	0.2	0.2	**3.80**
4	Tiguert Travertines	Hydrogeological	0.6	1.2	0.6	0.4	0.2	0.1	0.4	**3.50**
5	Tiguert angular unconformity	Geomorphological	0.45	1.2	0.6	0.4	0.2	0.2	0.3	**3.35**
6	Caves of Cap Ghir	Geocultural	0.6	1.2	0.6	0.6	0.4	0.15	0.4	**3.95**
7	Kimmeridgian Reef of Cap Ghir	Paleontological	0.6	1.2	0.45	0.8	0.2	0.15	0.2	**3.6**
8	Reef of the Main Fossils of Cap Ghir	Paleontological	0.6	1.2	0.6	0.8	0.2	0.15	0.2	**3.75**
9	Estuary of Tamri	Hydrogeological	0.6	1.2	0.6	0.4	0.2	0.2	0.4	**3.6**
10	Gorges of Timlaline	Geomorphological	0.6	1.2	0.4	0.8	0.2	0.2	0.4	**3.8**
	Weighted Average		0.58	1.2	0.56	0.62	0.22	0.17	0.31	**3.67**
	Weight		15%	30%	15%	20%	5%	5%	10%	**100%**

  - Agadir Coast (3.60): Major sedimentological site showing coastal dynamics..
- Geosites of high scientific value (3.0 ≤ SV ≤ 3.5):
  - Tiguert Travertines (3.50): Important hydrogeological site demonstrating carbonate precipitation processes.
  - Tiguert angular unconformity (3.35): Geomorphological site, providing educational interest by demonstrating the interaction between tectonic and erosive processes, helping to visualize geological processes over long periods of the Earth's history.

Potential of educational use (PUE)

The educational potential of the geosites has been assessed according to 12 criteria (Table 3), including vulnerability (Vul), accessibility (Acc), safety (Saf), logistics (Log), landscape (Sce), unicity (Uni), and didactic potential (DP). The scores ranged from 3.15 to 3.80, showing a high educational potential for most of the sites.

- Sites with very high educational potential (PUE > 3.5):
  - Dinosaurs of Anza (3.80): An ideal site for illustrating palaeontological and geological concepts.
  - Agadir Coast (3.75): Accessible site providing a rich source of information on coastal sedimentary processes.
  - Cap Ghir's caves (3.70): An archaeological and geological site offering a variety of educational opportunities.
  - Tamri estuary (3.70): Hydrogeological and ecological site, suitable for environmental education.
  - Cap Ghir main fossil reef (3.55): Palaeontological site, used to study past biodiversity.
  - Timlaline gorges (3.55): Geomorphological site, offers an ideal model for understanding the combined action of tectonics and erosion on landscapes.
- Sites with high educational potential (3.1 ≤ PUE ≤ 3.5)
  - Tiguert Travertines (3.50): Site illustrating hydrogeological and sedimentary processes.
  - Tiguert angular unconformity (3.40): Geomorphological site, useful for teaching stratigraphy and tectonics.
  - Taghazout cliffs (3.15): Stratigraphic site, although less accessible, offering lessons on ancient marine environments.

Potential for tourism use (PUT)

The tourism potential of the geosites has been evaluated against 13 criteria (Table 4), including vulnerability (Vul), accessibility (Acc), landscape (Sce), unicity (Uni), interpretation potential (IP), and proximity to recreation areas (RA). The scores range from 3.15 to 3.90, indicating moderate to high tourism potential.

- Sites with very high tourism potential (PUT > 3.5)
  - Agadir Coast (3.90): Accessible and attractive site, combining coastal landscapes and geological interest.

Table 3. Assessment of educational value criteria and their weighted average for each GS

No.	GS Name	Vul	Acc	UL	Saf	Log	DP	AV	Sce	Uni	OC	DP	GD	PUE
1	Agadir coast	0.40	0.40	0.20	0.30	0.20	0.15	0.20	0.20	0.10	0.40	0.50	0.40	**3.75**
2	Anza Dinosaur footprints	0.30	0.40	0.20	0.30	0.20	0.20	0.20	0.20	0.20	0.40	0.80	0.40	**3.80**
3	Cliffs of Taghazoute	0.20	0.30	0.10	0.30	0.15	0.15	0.15	0.20	0.20	0.30	0.80	0.30	**3.15**
4	Tiguert Travertines	0.40	0.30	0.20	0.20	0.15	0.20	0.20	0.15	0.10	0.40	0.80	0.40	**3.50**
5	Angular Unconformity of Tiguert	0.30	0.30	0.20	0.20	0.15	0.20	0.20	0.20	0.15	0.40	0.80	0.30	**3.40**
6	Cap Ghir’s caves	0.40	0.40	0.20	0.40	0.10	0.15	0.15	0.20	0.20	0.40	0.80	0.30	**3.70**
7	Kimmeridgian Reef of Cap Ghir	0.30	0.40	0.10	0.40	0.20	0.10	0.20	0.20	0.15	0.40	0.80	0.30	**3.55**
8	Reef of the Main Fossils of Cap Ghir	0.30	0.40	0.15	0.20	0.20	0.10	0.20	0.20	0.20	0.40	0.80	0.40	**3.55**
9	Estuary of Tamri	0.40	0.40	0.20	0.30	0.20	0.15	0.20	0.20	0.10	0.40	0.80	0.40	**3.70**
10	Gorges of Timlaline	0.30	0.40	0.20	0.30	0.20	0.15	0.20	0.20	0.20	0.40	0.60	0.40	**3.55**
	Weighted Average	0.33	0.37	0.17	0.29	0.17	0.15	0.19	0.19	0.16	0.39	0.75	0.36	**3.56**
	Weight	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	**100%**

Table 4. Assessment of tourism value criteria and their weighted average for each GS

No.	GS Name	Vul	Acc	UL	Saf	Log	DP	AV	Sce	Uni	OC	IP	EL	RA	PUT
1	Coast of Agadir	0.40	0.40	0.20	0.40	0.20	0.20	0.20	0.60	0.30	0.20	0.40	0.20	0.20	**3.90**
2	Dinosaurs of Anza	0.40	0.30	0.20	0.30	0.20	0.20	0.15	0.60	0.40	0.20	0.40	0.10	0.20	**3.65**
3	Cliffs of Taghazoute	0.20	0.30	0.10	0.30	0.20	0.15	0.15	0.60	0.40	0.15	0.40	0.15	0.20	**3.30**
4	Travertines of Tiguert	0.40	0.30	0.20	0.20	0.15	0.20	0.20	0.45	0.20	0.20	0.40	0.15	0.10	**3.15**
5	Angular Unconformity of Tiguert	0.30	0.30	0.20	0.20	0.15	0.20	0.20	0.60	0.30	0.20	0.40	0.15	0.10	**3.30**
6	Caves of Cap Ghir	0.40	0.40	0.20	0.40	0.10	0.15	0.15	0.60	0.40	0.40	0.40	0.15	0.10	**3.65**
7	Kimmeridgian Reef of Cap Ghir	0.40	0.40	0.20	0.40	0.10	0.15	0.15	0.60	0.40	0.40	0.40	0.15	0.10	**3.40**
8	Reef of the Main Fossils of Cap Ghir	0.30	0.40	0.15	0.30	0.20	0.10	0.20	0.60	0.40	0.20	0.40	0.15	0.20	**3.60**
9	Estuary of Tamri	0.40	0.40	0.20	0.40	0.20	0.15	0.20	0.60	0.20	0.20	0.40	0.10	0.20	**3.60**
10	Gorges of Timlaline	0.30	0.40	0.20	0.30	0.20	0.15	0.20	0.60	0.20	0.20	0.40	0.10	0.20	**3.45**
	Weighted Average	0.35	0.36	0.185	0.32	0.17	0.165	0.18	0.585	0.32	0.235	0.4	0.14	0.16	**3.5**
	Weight	10%	10%	5%	10%	5%	5%	5%	15%	10%	5%	10%	5%	5%	100%

- Caves of Cap Ghir (3.65): Spectacular site, attracting nature and history lovers.
- Anza Dinosaur footprints (3.65): A unique site, captivating visitors interested in palaeontology.
- Reef of the main fossils at Cap Ghir (3.60): A site that attracts scientific tourists and the curious, combining geological discovery with scenic appeal.
- Tamri estuary (3.60): An exceptional wetland combining unique biodiversity and striking landscapes, attracting ecotourists and nature lovers.

- Sites with high tourism potential (3.0 ≤ PUT ≤ 3.5)
  - Taghazout cliffs (3.30): Landscaped site, although less accessible, offering spectacular views.
  - Travertines of Tiguert (3.15): An interesting site for geology enthusiasts, but in need of development for tourism.
  - Tiguert Angular Discordance (3.30): Geomorphological site, attracting visitors curious about tectonic processes.

Risk of degradation (RD)

- Sites with a moderate risk of degradation (2 ≤ RD < 3.0)
  - Dinosaurs of Anza (2.90): This site is vulnerable to degradation due to human activities and its proximity to degrading areas (Table 5). its accessibility and dense population increase the risks.
  - Tiguert angular discordance (2.90): The site is similar to the dinosaur footprints, presenting high risks due to human activities and its proximity to degrading areas.
  - Taghazout cliffs (2.80): This site is exposed to moderate to high risks due to human activities and its accessibility.
  - Agadir coast (2.70): Moderate risk due to its high accessibility and proximity to degrading areas. Legal protection and population density contribute to a moderate risk.
  - Cap Ghir Kimmeridgean Reef (2.75): Although relatively preserved, this site presents a moderate risk due to its vulnerability to human activities and its easy access.
  - Travertines of Tiguert (2.55): This site is exposed to moderate risk due to its vulnerability to human activity and its proximity to degrading areas. Legal protection and accessibility are additional risk factors.
- Sites with low risk of degradation (RD < 2.0)
  - Reef of the main fossils of Cap Ghir (1.85): This site has a low risk due to its distance from degraded areas and very low population density. Although, it is legally well protected, it remains moderately vulnerable.
  - Tamri estuary (2.25): The site is considered relatively low risk due to its low vulnerability and moderate population density, despite its proximity to degraded areas.
  - Gorges of Timlaline (2.25): The risk is similar to the Tamri estuary, with low vulnerability and moderate population density. Its legal protection and accessibility help to limit the risks

In this context, we propose integrating the study area and other areas to be studied into the worldwide geoparks network as a better management strategy that integrates all components of sustainable development (Table 6).

Additional considerations: Agadir's tourism potential

Agadir possesses significant tourism assets, making it a key destination within the Souss-Massa region and across Morocco. The area hosts numerous cultural initiatives, including museums such as the Anza Dinosaur Museum, the Meteorite Museum, and various art museums, along with major attractions under development, such as Crocopark and the forthcoming Lion Park. In addition, the region benefits from remarkable biodiversity, particularly due to the Arganeraie Biosphere Reserve as an UNESCO designated site that safeguards the endemic argan tree and its unique ecosystem.

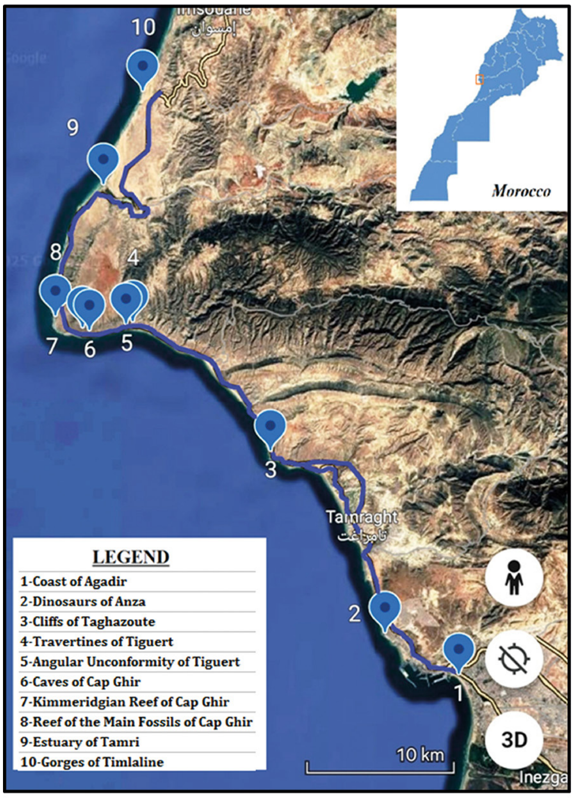
These assets, combined with the region's geological wealth, provide a strong foundation for the establishment of a geopark, promoting sustainable tourism, environmental conservation, and socio-economic development (Figure 14).

Table 5. Assessment of the risk of degradation value criteria for the geosites studied and their weighted average

N°	GS Name	DG	PD	LP	Acc	DP	**RD**
1	Agadir coast	0.70	0.60	0.40	0.60	0.40	**2.7**
2	Dinosaurs of Anza	1.05	0.60	0.40	0.45	0.40	**2.90**
3	Cliffs of Taghazoute	1.05	0.60	0.40	0.45	0.30	**2.80**
4	Travertines of Tiguert	0.70	0.60	0.40	0.45	0.40	**2.55**
5	Angular Unconformity of Tiguert	1.05	0.60	0.40	0.45	0.40	**2.90**
6	Caves of Cap Ghir	1.05	0.40	0.80	0.60	0.30	**3.15**
7	Kimmeridgian Reef of Cap Ghir	1.05	0.40	0.40	0.60	0.30	**2.75**
8	Reef of the Main Fossils of Cap Ghir	0.70	0.20	0.40	0.45	0.10	**1.85**
9	Estuary of Tamri	0.35	0.60	0.40	0.60	0.30	**2.25**
10	Gorges of Timlaline	0.35	0.60	0.40	0.60	0.30	**2.25**
	Weighted Average	0.805	0.52	0.44	0.525	0.32	**2.61**
	Weight	35%	20%	20%	15%	10%	**100%**

Table 6. Detailed scoring of selected geological interest sites (SV, EP, TP, and DR)

No.	GS Name	SV	PUE	PUT	RD
1	Coast of Agadir	3.60	3.75	3.90	2.7
2	Dinosaurs of Anza	3.75	3.80	3.65	2.90
3	Cliffs of Taghazoute	3.80	3.15	3.30	2.80
4	Travertines of Tiguert	3.50	3.50	3.15	2.55
5	Angular Unconformity of Tiguert	3.35	3.40	3.30	2.90
6	Caves of Cap Ghir	3.95	3.70	3.65	3.15
7	Kimmeridgian Reef of Cap Ghir	3.6	3.55	3.40	2.75
8	Reef of the Main Fossils of Cap Ghir	3.75	3.55	3.60	1.85
9	Estuary of Tamri	3.6	3.70	3.60	2.25
10	Gorges of Timlaline	3.8	3.55	3.45	2.25
	Weighted Average	3.67	3.56	3.5	2.61



Length	67,2 km
Difficulty	Low
Start point	Agadir coastline
End point	Timlaline Gorges
Total duration	5h30min

Figure 14. Location of stops on the Agadir Ida Outanane coastal geo-route, shown on a Google Earth satellite image

CONCLUSION

This study demonstrates that the Agadir Ida-Outanane coastline contains a geopatrimony of high scientific value, characterized by remarkable coastal geodiversity that has been insufficiently documented until now. The quantitative multi-criteria analysis reveals significant contrasts between geosites, both in terms of scientific value and vulnerability, highlighting differentiated exposure to anthropogenic pressures. These results provide an objective and hierarchical interpretation of conservation issues, which was lacking in previous studies devoted to the southwestern Atlantic coast of Morocco.

The major scientific contribution of this work lies in the creation of a new, quantified, and comparable dataset, making it possible for the first time to integrate heritage value, development potential, and risk level for a coherent set of coastal geosites. This approach goes beyond traditional descriptive inventories by providing operational indicators that can guide management and protection priorities.

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