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A quantitative study of the geosites in the hinterland of Agadir Ida-Outanane (Western High Atlas, Morocco)

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ABSTRACT

The Ida-Outanane hinterland of Agadir, in the Western High Atlas, harbours remarkable geodiversity – karst caves, travertine waterfalls, paleontological sites and tectonic structures – which has so far received little systematic documentation. This study presents an inventory and quantitative assessment of ten geosites using Brilha's (2016) methodology, analysed according to four criteria: scientific value (SV), educational potential (PUE), tourism potential (PUT) and risk of degradation (RD). The results indicate high to very high scientific values (average 3.51), with the Win Timdwin cave leading the way (SV = 3.8), followed by the Alma Ammonites and the Imouzzer Idaoutanane Fault (SV =3.7). The educational potential (PUE = 3.52) and tourism potential (PUT = 3.415)confirm the multifaceted value of these sites. However, the risk of degradation (average RD = 2.1) remains a cause for concern, particularly for the MoulayAbd Allah Dam (RD = 2.5) and the Alma Ammonites (RD = 2.45), due to theiraccessibility and the lack of appropriate protective measures. A 224 km georoute over three days is proposed tostructure sustainable geotourism combining heritage promotion andthe involvement of local communities. Thereby contributing to initiatives of national and geoheritage importance. This study constitutes the first quantitative inventory of geosites in the hinterland of Agadir Ida-Outanane, a region where only descriptive or purely geological studies existed previously.

Keywords: Western High Atlas, Agadir Ida-Outanane, geodiversity, geosites, quantitative assessment, georoute, geoconservation.

INTRODUCTION

The conservation and management of geological heritage have become fundamental elements of international strategies for sustainable development and environmental protection (Brilha, 2016; Reynard et al., 2016, etc.) This global trend is leading to increased scientific research and structuring initiatives, such as UNESCO Global Geoparks, whose approach is based on the balanced integration of geological conservation, educational activities, and tourism to ensure sustainable development and the involvement of local communities (UNESCO, 2015; Aoulad-Sidi-Mhend et al., 2026).

A crucial preliminary stage in any geoconservation initiative requires a careful inventory and quantitative assessment of geosites. This methodological framework allows for an objective classification of sites, based on their scientific interest and their vulnerability to disturbances (Wimbledon, 1996; Pereira and Brilha, 2010). Based on this insight, standardized protocols have been developed and evaluated in diverse geographical locations, including Spain (Fuertes-Gutiérrez and Fernández-Martínez, 2010), Portugal (Rocha et al., 2014), France (Poiraud et al., 2016), Brazil (Mucivuna et al., 2017), and Italy (Ferrando et al., 2021), which provides a reliable reference frame for comparative studies.

In the Moroccan context, the recognition of exceptional geodiversity has led, over the last years, to a significant development of research focused on the inventory and valuation of the geological heritage. Innovative projects have been initiated in several regions throughout the country, notably in the Central Jbilet (Kaid Rassou et al., 2019), the Middle Atlas (Oukassou et al., 2019), the Rif (Aoulad-Sidi-Mhend et al., 2019, 2020; Ben Ali et al., 2023, 2025), Khnifes (Mirari et al., 2020), the Meseta (Mehdioui et al., 2020, 2022), (Ouardaras et al., 2025), and the Western High Atlas (Boukfaoui et al., 2026). These investigations have successfully used quantitative methods to describe and characterize the geosites, laying the foundation for a national strategy for geoconservation.

Nevertheless, a significant geographical disparity persists. Although, the northern and central regions of Morocco have benefited from considerable attention, the southwestern Atlantic territories, particularly the hinterland of Agadir Ida-Outanane remain largely unexplored in terms of a systematic investigation of geological heritage. This continental area, located in the vicinity of the coastline, which is already well known for its natural riches (Boukfaoui et al., 2026), extends into the centre of the Western High Atlas, that forms a mountain range characterized by notable structural complexity.

The Agadir Ida-Outanane hinterland region is distinguished by its remarkable geological diversity, featuring geological formations dating from the Mesozoic to the Cenozoic, comprising diverse sedimentary sequences, complex tectonic structures, inherited relief forms, and well-developed karst features. This territory includes sites of considerable interest, notably deep gorges, limestone platforms, perennial water sources, natural cavities, and outcrops displaying remarkable sedimentary patterns. A significant portion of this area has been designated as having high ecological value, highlighting its close interactions between the geological bedrock, climate, and biological diversity. Furthermore, this potential heritage is supported by a particularly favorable logistical and infrastructural framework, giving this region an obvious capacity to host educational, scientific, and tourism activities. The Agadir Ida-Outanane area and its vicinity offer a wide range of accommodations, including thousands of facilities from high-end hotels to rural inns and traditional homestays within mountain villages. This capacity is enhanced by well-developed and interconnected infrastructure, including Agadir-Al Massira International Airport and other logistical facilities. In addition, security, which guarantees a peaceful tourism experience, remains a significant advantage for Morocco as a travel destination. This hospitality, transportation, and infrastructure network serves as an operational platform ready to organize geotourism itineraries in the Agadir Ida-Outanane hinterland, making the systematic inventory of its geological heritage fully relevant and beneficial.

Despite this obvious abundance, scientific knowledge regarding this region remains limited and focused on specific topics of study, without a comprehensive assessment of its potential heritage. The lack of an integrated assessment represents a significant scientific gap, which contributes to the ongoing vulnerability of these geosites facing increased pressures related to urban development, the spread of agricultural activities, and the development of an insufficiently regulated tourism. This study was conducted in response to the above mentioned observation. Its primary objective is to perform an initial comprehensive inventory and a multi-criteria quantitative assessment of the main geosites in the hinterland of Agadir Ida-Outanane. This aim is manifested through three specific objectives: (i) To systematically identify and characterize a set of representative geosites reflecting the geodiversity of the study area; (ii) To quantitatively evaluate each geosite using an adapted methodology based on previous studies by Brilha (2016), by calculating scores for scientific value (SV), educational use potential (EUP), tourism use potential (TUP), and risk of degradation (RD), according to a rating scale ranging from 1 to 4; (iii) synthesize the obtained results to propose scientific geotourism itineraries that combine the imperatives of promotion with the requirements of preservation.

The present study is guided by two basic hypotheses: (1) Hinterland geosites demonstrate significant scientific and educational values, justified by their diversity, preservation status, and their representativeness of regional geological processes; (2) It should be noted that their degree of vulnerability is correlated with their accessibility and proximity to human activities. Some isolated sites benefit from relative natural protection, while others, located near transportation networks or populated areas, are more exposed to the risk of degradation.

This research is expected to yield a variety of benefits: It aims to provide government officials and regional planners with data-driven decision-making tools, to deepen the scientific analysis of continental geological heritage assessment in a semi-arid mountainous environment, and to propose practical guidelines for the sustainable geotourism development of the hinterland. This will contribute to the potential creation of a geopark encompassing the complementary geological resources of both the coast and the hinterland in the Agadir Ida-Outanane region.

MATERIALS AND METHODS

Study area: Geographic and geological context

The Agadir Ida-Outanane hinterland, located on the southern flank of the Western High Atlas (Figure 1a), is characterized by complex geological outcrops resulted from the Alpine orogenic deformation (Ambroggi, 1963; Hafid, 2006). This area features a succession of formations which are mainly sedimentary, dating from the Jurassic to the present, with a predominance of carbonate rocks and evidence of shallow marine environments.

Structurally, the study area is characterized by various major tectonic features that reflect its complex geodynamic history. The South Atlas Fault (SAF) is the most famous feature in the region; it consists of a regional reverse fault trending WSW-ENE and forms the northern border of the Souss Plain (Fig Anti-Atlas). This fault was reactivated as a reverse fault during the Alpine orogeny and played a major role in the devastating 1960 Agadir earthquake (Meghraoui et al., 1998; Sébrier et al., 2006). The Agadir-Tagragra Fault, a segment of the SAF with a northward dip, represents the tectonic inversion of an ancient Triassic rift (Mustaphi et al., 1997). Furthermore, NW-SE-trending transverse faults have segmented the area into individual blocks characterized by intense fracturing of the Jurassic limestones. This has played an important role in the evolution of the karst systems of Imouzzer and Timdouine (Belfoul et al., 2001; Tixeront, 1974).

From a lithological point of view, the Jurassic formations, dominated by massive limestones and dolomites (Figure 1b), are widely present in the Imouzzer and Timdouine areas. These formations constitute a substrate where spectacular karst systems have developed, such as those observed in the Win Timdouine cave, witch is one of the largest in North Africa (Angelova et al., 2005). This cave was developed within intensely fractured Kimmeridgian limestones influenced by the SAF as a major tectonic structure (Belfoul et al., 2001). Jurassic limestones are also behind the travertines clearly visible at the Imouzzer Ida-Outanane Waterfalls (Fig), where carbonate precipitation associated with algae mats forms stratified deposits of domes and laminations, and providing important paleoclimatic indicators of alternating humid and arid periods during the Quaternary (Rousseau et al., 2008). In the Aourir area, the Alma site features marl and dolomite dating Early Cretaceous. These beds are rich in well-preserved ammonites, providing accurate dating of the Hauterivian to Albian periods and offering a window into the paleoenvironment of the Agadir-Essaouira basin (Duffaud et al., 1971; Hafid, 2006).

In terms of hydrology, the province's river system is structurally influenced by Atlantic tectonic trends. The Tamri and Tamraght rivers are the main waterways on the Atlantic side; they exhibit a semi-arid torrential regime, characterized by seasonal floods mainly from October to March and low flows during the summer (Ambroggi, 1963; Irifi et al., 2020). The Imouzzer Gorges, carved withing Jurassic limestones, provide evidence of the progressive erosion of river channels following the Quaternary tectonic uplift (Weisrock et al., 2006). Many karst sources emerged at the contact between Jurassic limestones and dolomites, supplying local irrigation and contributing to the replenishment of the deep Lias aquifer in the Souss Basin (Ambroggi, 1963).

The whole region illustrates a major influence of the Atlas tectonic phases and differential erosion on the establishment of the current relief, which alternates between karst systems, deep gorges, and travertine domes, forming a veritable natural laboratory for geological and climatic research in the Western High Atlas.

Approach for the inventory and quantitative assessment of geosites

This study applied a multi-criteria quantitative assessment approach, based on the internationally recognized methodology of Brilha

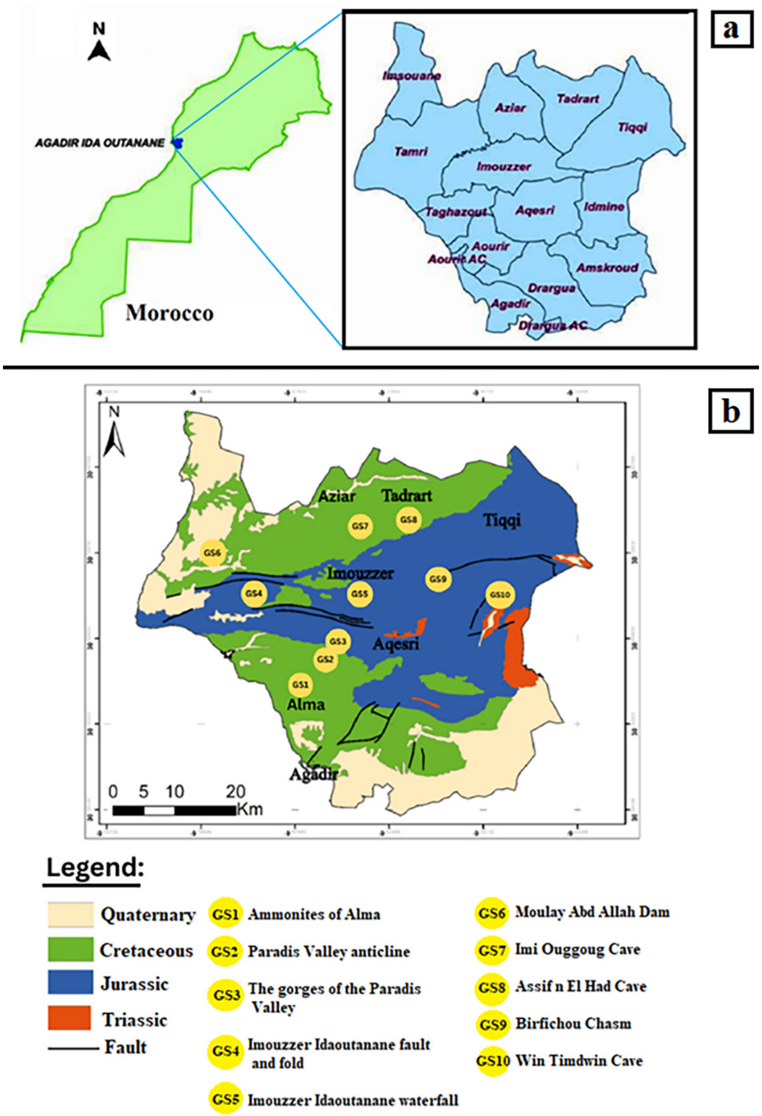

Figure 1. (a) Geographical location and (b) geological components of the study area (Agadir Ida-Outanane hinterland)

(2016). This has been successfully adapted to the Moroccan context in previous studies (e.g., Aoulad-Sidi-Mhend et al., 2019, 2020, 2023; Ben Ali et al., 2023, 2025; Boukfaoui et al., 2026). The overall methodological process, as presented in Figure 2, was implemented in three sequential and interconnected phases, with the aim of ensuring a systematic and reproducible approach.

Phase 1: Literature review and preliminary inventory

A detailed analysis of the existing scientific literature, geological maps (e.g., Michard, 1976), topographic maps, and previous specific studies was conducted. This preliminary analysis focused on identifying and listing areas of potential geological interest in the hinterland of Agadir Ida-Outanane. The aim is to compile an initial comprehensive list of suitable sites.

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

Fieldwork was carried out to validate the preliminary inventory. During these investigations, each site was systematically characterized using standardized assessment forms (adapted from Aoulad-Sidi-Mhend et al., 2019, 2020; Ben Ali et al., 2023, 2025; Boukfaoui et al., 2026). Data collection included registering GPS coordinates, producing exhaustive photographic documentation, and making precise observations regarding geological properties, structural integrity, accessibility, and contemporary anthropogenic pressures. Meetings with local experts and community members allowed for the collection of relevant contextual information. The final selection of the ten geosites presented in this study was based on the applicability of three essential selection criteria in the field, specifically: representativeness (i.e., the degree in which the site illustrates a geological process or feature), integrity (i.e., the degree of preservation against deterioration) and rarity (i.e., the unique nature of a feature at the regional or national scale), etc., as defined by Brilha (2016).

Phase 3: Multi-criteria quantitative assessment

Each selected geosite has been evaluated using a quantitative analysis based on four key criteria: Scientific value (SV), educational use potential (PUE), tourism use potential (PUT), and risk of degradation (RD). The evaluation was conducted in accordance with the structured system of criteria and weightings proposed by Brilha (2016) and presented in Table 1.

Expert-based assessment procedure

The evaluation of geosites followed the methodology proposed by Brilha (2016). The assessment was conducted by five experts with complementary experience in geology, geomorphology, geoheritage assessment, and geotourism. Each expert independently scored the geosites according to the criteria established in the assessment framework. Subsequently, the scores were reviewed during a consensus meeting, where discrepancies were discussed and resolved collectively. Final scores were assigned based on expert agreement. The detailed scores for each criterion and geosite are presented transparently in Tables 2–5 of the main manuscript. Field verification surveys were conducted during February 2025, June 2025, and October 2025, covering all inventoried geosites. Geographic coordinates of each site are provided directly in the description of each geosite (see GS1 to GS10).

Scoring process

Each criteria related to a specific geological site was evaluated by the research team on a scale of 1 to 4, based on a consensus derived from field data, photographic evidence, and literature review. The evaluation scale was defined as follows: 1 (low), 2 (moderate), 3 (high), and 4 (very high).

Calculation of final scores

The detailed scores for each criteria by geological site, the weighted intermediate scores, and the final aggregate scores are presented transparently in Tables 2 to 5. The final results for all geological sites are summarized in Table 6, which provides a clear overview of their assessed values and their risk of degradation.

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

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

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

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

RESULTS

The first results of this study were obtained from several field trips, detailed analysis of documentation, and meetings with local partners. This approach led to the identification of ten major geological sites in the hinterland of Agadir Ida Outanane. These sites, selected for their scientific relevance, educational potential, and touristic value, are located in relatively accessible areas. They are characterised by a variety of geological contexts, including geological formations, structures, fossil deposits, and the actions of water on limestone (karst, travertine deposits). The identification of the ten geosites provides a solid base for developing a strategy for promoting heritage and developing geotourism inside the territory.

GS1: Ammonites from Alma: (30°30’37.5”N 9°35’25.5”W)

The palaeontological site of Alma (Figure 1) (Figure 3a) is located approximately 2.5 km northeast of the village of Alma. It features the Alma geological cross-section (Figure 3b), which is a

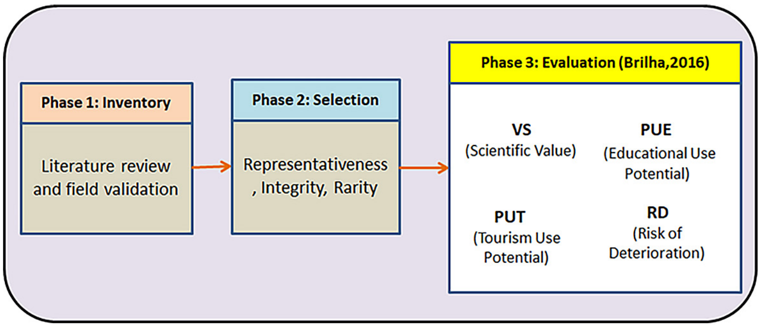

Figure 2. Methodology used for the inventory, selection and assessment of geosites (according to Brilha, 2016)

reference site for studying the Lower Cretaceous era along the Moroccan Atlantic coast (Ferry et al., 2007). This site belongs to the Essaouira-Agadir sedimentary basin, formed during the Mesozoic period. It is one of the Northwest African regions where the Cretaceous stratigraphic sequence is best preserved.The ammonites are well preserved within alternating layers of marl and limestone, dating from the Hauterivian to the Albian (Ferry et al., 2007). This lithological succession forms an oblique monoclinal serie as a result of alpine tectonic. Thus, this site is of triple interest: paleontological (the fossils), stratigraphic (the lithological sequence), and structural (the oblique succession).

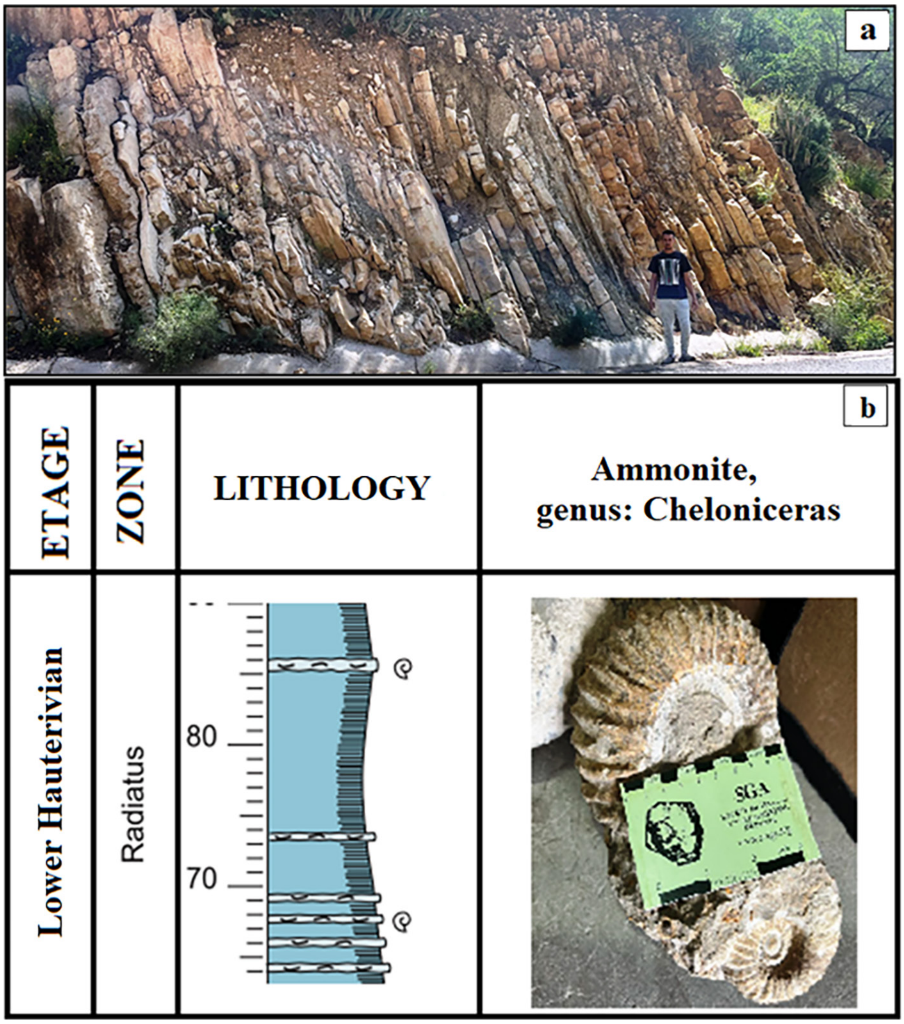

Figure 3. (a) Alternating layers of limestone and marl from the fossil-bearing Cretaceous strata at Alma, (b) cross-section of Alma, adapted from (Ferry, 2007)

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

The genus Cheloniceras represents the most abundant ammonites at the site (Figure 3b). These fossils can be used to precisely date the stratigraphic units according to international stratigraphic scales. A small local bazaar located near the village of Alma (Figure 4a) showcases a range of geological specimens and traditional artisanal products. The mineral collection includes geodes (Figure 4b), whereas traditional pottery (Figure 4c) reflects the local cultural heritage. Fossils collected from nearby outcrops are also available, notably brachiopods (Figure 4d), echinids (Figure 4e), and ammonites (Figure 4f).

GS 2: The anticlinal fold of the Paradis Valley (30°35′16.0″N 9°31′41.1″W)

The anticlinal fold of the Paradis Valley (Figures 1; 5) (also known as the Ouankrim Valley) is a major tectonic structure formed by Mesozoic sedimentary sequences. These are dominated by limestones and sandstones, deformed by the Alpine orogeny linked to the collision of the African and Eurasian plates during the Cenozoic (Frizon de Lamotte et al., 2009; Lanari et al., 2020). The Jurassic is represented by a thick sequence of sandstones, limestones, and marls (Medina et al., 2011). The uplift of the High Atlas was mainly during the Cenozoic, caused by a NW-SE compression related to the Africa-Eurasia convergence, exhibiting an open geometry typical of weak deformation.

GS 3: The gorges of the Paradise Valley (30°35′20.7″N 9°31′28.6″W)

Located about 30 kilometres northeast of Agadir (Figure 1), the gorges of the Paradise Valley (Figure 6) are of significant geological interest. This spectacular canyon was shaped by the continuous erosive action of the Oued Tamraght, which progressively carved its channel across the sedimentary strata. The current topography of this site, characterized by abrupt escarpments and deep gorges, results from the ongoing interaction between two main processes: on the one hand, the Tertiary tectonic activity, known as the Atlas orogeny, which caused the uplift and fracturing of the massif, and, on the other hand, the hydraulic erosion, which benefited from these areas of structural weakness (Michard et al., 2008; Frizon de Lamotte et al., 2009). Along these fracture patterns, the river has consequently carved out narrow channels dominated by high escarpments. Areas where the limestone was more resistant, the erosive action of sediment led to the development of erosion cavities and distinctive morphologies.

Figure 4. (a) Alma Bazaar, (b) geodes, (c) traditional pottery, (d) brachiopods, (e) echinids, (f) ammonites.

GS 4: Imouzzer Ida-Outanane faults and fold (30°41′28.4″N 9°37′17.4″W)

The Imouzzer Ida-Outanane folds and faults site (Figure 1), located around 30 km south of Imouzzer Ida-Outanane in the Douar of Timsal. The site exhibits highly deformed Jurassic limestone strata (Figure 7), providing evidence of the compressional processes linked to the major north-Atlas fault system (Medina et al., 2011).

Geologically, sedimentary layers that were originally horizontal underwent plastic deformation under compressive stress. This stress generated a regular alternation of anticlines and synclines separated by large tabular plateaus (Teixell et al., 2003; Arboleya et al., 2004). The entire structure is cut by a reverse fault, inherited from the Triassic-Lias rift and reactivated during the tectonic inversion since the Upper Eocene (Medina et al., 2011; Teixell et al., 2003; Frizon de Lamotte et al., 2009). Regional paleostress shows two successive compressional regimes: N20–30°E from the Maastrichtian to the Oligocene, then N120–160°E in the Miocene–Pliocene, both linked to the Africo-Eurasian collision (Aït Brahim et al., 2002; Medina, 1985). Due to the clear visibility and accessibility of its structures, this site is a reference example for structural geology and the tectonics of intracontinental mountain ranges.

GS 5: Imouzzer Ida-Outanane waterfalls (30°40′38.7″N 9°28′48.4″W)

The hydrogeological geosite of the Imouzzer Ida-Outanane waterfalls, located approximately 50 km northeast of Agadir (Figure 1). It correpends to a geological site of great importance, and characterized by extensive Quaternary travertine formations (Figure 8a) (Weisrock et al., 2008). The bedrock consists of Upper Jurassic

Figure 5. Anticlinal fold observed in the Paradis Valley

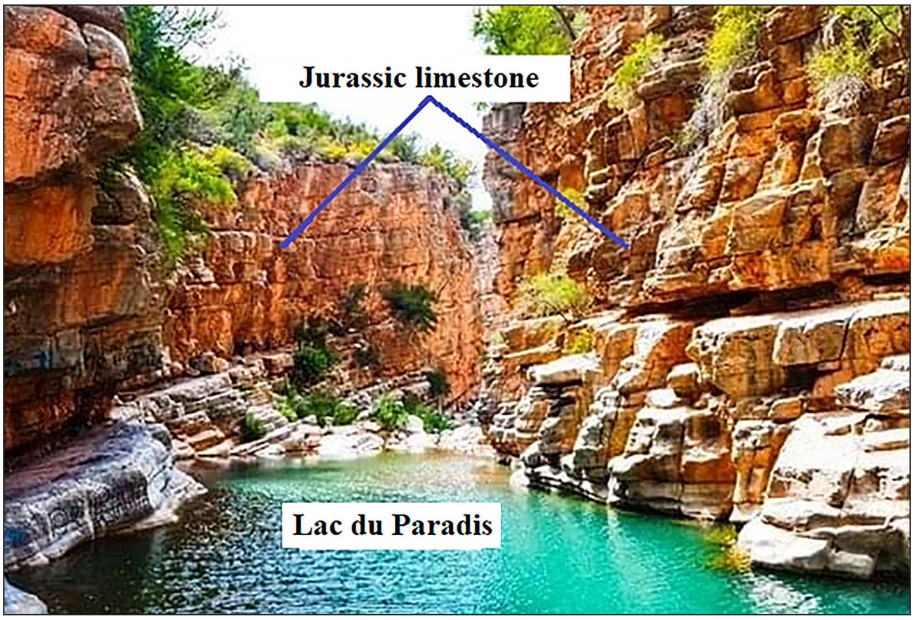

Figure 6. Gorge in the Paradis Valley

Figure 7. Panoramic view of folded Jurassic limestone strata with a reverse fault in the Douar de Timsal, Imouzzer Ida-Outanane

limestones and dolomites, deformed into folded structures, notably southwest-northeast trending anticlines (Ambroggi, 1963; Michard et al., 2008). The waterfalls are not supplied by a permanent, individualised flow of water, but by karst resurgence sources, locally known as the Imouzzer sources. these are originate from the circulation of water within the regional Jurassic carbonate aquifer. These resurgences give rise to temporary flows that form cascades, which are particularly active during the humid season.

As it flows, the water precipitates calcium carbonates (travertine) onto algae (Rousseau et al., 2008). The accumulation of multiple generations of travertine highlights an alternation between humid climatic phases, characterized by periods of travertine formation, and arid phases, marked by erosion and fluvial incision (Rousseau et al., 2008; Weisrock et al., 2008). Therefore, these formations represent exceptional paleoclimatic archives, enabling the reconstruction of Quaternary hydrological and environmental variations on the northern border of the Moroccan Sahara, linked to regional and Atlantic climate fluctuations (Weisrock et al., 2008). This site of international importance is currently situated in a semi-arid climate (average annual precipitation of 422 mm), but suffers significant anthropogenic impact.

GS 6: The Moulay Abd Allah dam (30°46′21.1″N 9°40′33.3″W)

The Moulay Abd Allah dam is located on the Ouggar River, a branch of the Tamri River (Figures 1; 9). It is a double-curved structure that was put into service in 2002, primarily designed to supply drinking water to Agadir city (ABHSM, 2002). It is 65 m high and 166 m in length at the crest, and holds a volume of 110 Mm³ at normal level with a regulated inflow of 27.5 Mm³/year. Indeed, it constitutes an essential component of regional water security. The site stands on highly fractured Mesozoic carbonate formations of the Western High

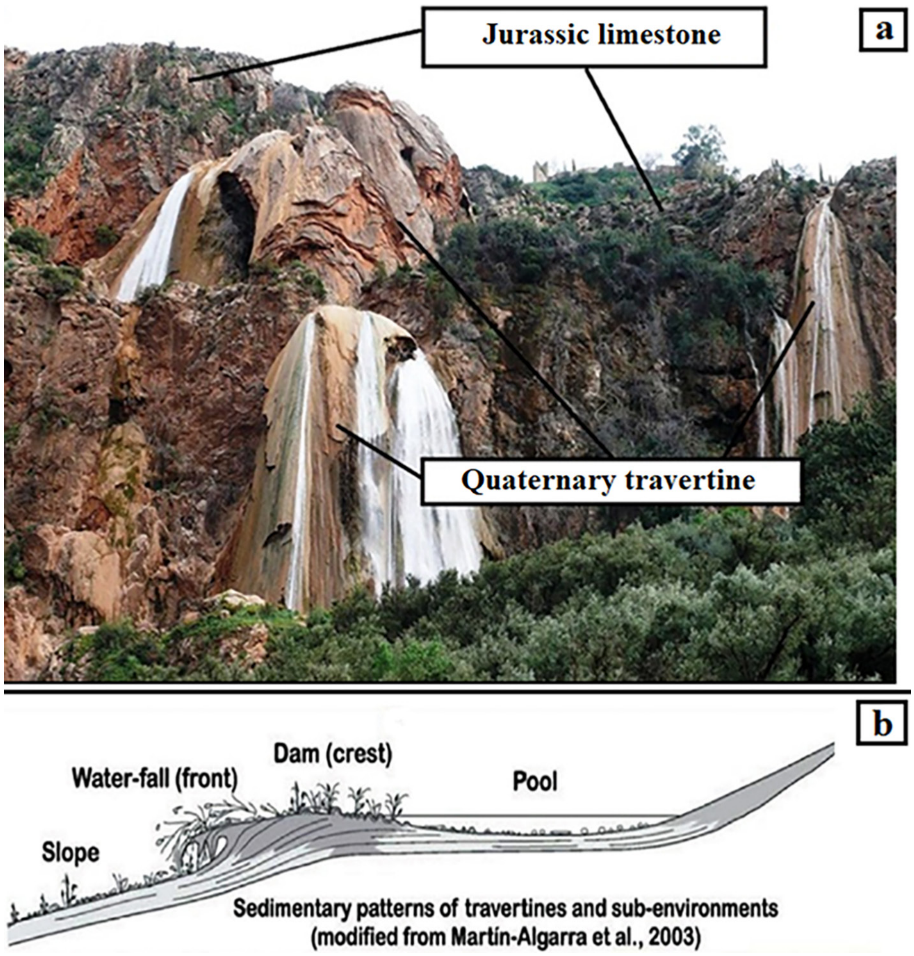

Figure 8. (a) Imouzzer Ida-Outanane waterfalls, (b) travertine sedimentation, model (Martin-Algarra et al., 2003)

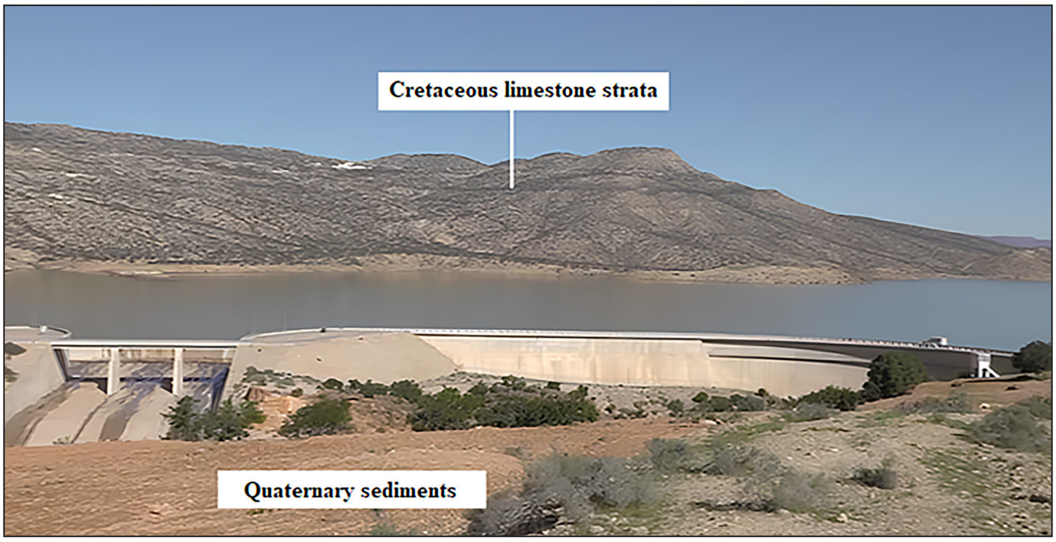

Figure 9. Moulay Abd Allah dam

Atlas, which are favorable to karstification (Michard, 1976; Akdim, 2015). marly interbeds control hydraulic separation (Qurtobi, 1996), while Atlas tectonics control drainage directions and the vulnerability of the aquifers of the watershed (Frizon de Lamotte et al., 2000; Hafid, 2006). These interactions between geology, karstification, and water management make this barrage a hydrogeological site of considerable scientific value in the semi-arid context of the Western High Atlas.

GS7: Imi Ouggoug cave (30°36′53″N 9°28′7.2″W)

The Imi Ouggoug cave (Figures 1; 10–14) is located in the village of Aqsri, on a cliff above the Assif n'Talmat. To reach this site, visitors should take the road leading to Imouzzer Ida-Outanane; upon arriving at the village of Ait Chleuh, they must descend toward the Oued Talmat. This natural site, known for its natural beauty, attracts both speleologists and hiking enthusiasts. According to the 1981 inventory (Camus and Lamouroux, 1981), this cave is geologically part of Morocco's third speleological zone and ranks fourth within that zone. It is largely carved into lithographic limestones dating from the Oxfordian period, which overlie older sedimentary formations (Ambroggi, 1963). Discovered in the 1950s and 1960s by French speleologists, this cave had only one exit: the bat exit (Figure 11). Furthermore, recent investigations have identified a new access to the cave, known as the "Spider Entrance" (Figure 12). This discovery revealed a previously unknown connection to a different cave in the area, further enhancing its geological and speleological significance. In terms of speleology, the Imi Ouggoug cave possesses an impressive variety of speleothems that bear evidence of past hydrogeology, notably giant potholes shaped by erosion (Figure 13a,b), superimposed layers of calcareous sediments (Figure 13c), microgours formed by the slow flow of calcareous water (Fig. 13d), an ancient eroded stalagmite indicating a period of severe flooding (Figure 13e). Microconcrements resulting from carbonate precipitation (Figure 13f), as well as a colony of harvestmen (Figure 14a) and colonies of bats (Figure 14b), which illustrate the biological diversity characteristic of the underground environment. The Imi Ouggoug cave holds great scientific, educational, and aesthetic importance.

GS 8: Assif n'El Had cave (30°44′49.1″N 9°28′36.0″W)

Located in the village of Tadrart, which is part of the Imouzzer Ida-Outanane region, the Assif n'El Had cave (Figures 1; 15) is an interesting speleological site that is easily accessible from Imouzzer. This site provides a unique opportunity for visitors to explore a remarkable underground environment characterized by a permanent water flow within the cave. Geologically, this underground cavity is developed within lithological formations of Jurassic age, specifically in Sequanian lithographic limestones (Ambroggi, 1963). The area exhibits typical karst features, created

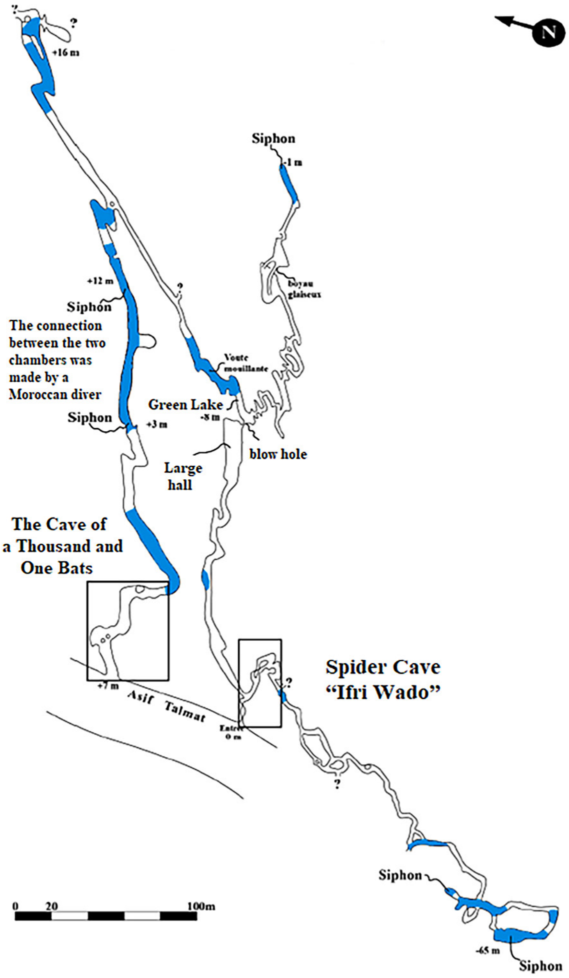

Figure 10. A plan of the Imi Ouggoug cave (adapted from B and J Lips 1980)

by erosion processes that have generated multiple cavities such as the Assif n El Had cave.

The internal morphology of this cave is characterized by several distinctive features: an entrance (Figure 15a) acting as a point of infiltration

Figure 12. Imi Ouggoug cave; the spider's entrance

for the river. a chimney (Figure 15b) attesting to the presence of previous vertical conduits. An internal source (Figure 15c) supplied by infiltration, and an exit (Figure 15d) which corresponds to the downstream resurgence, where the water reappears. This hydrological dynamic, which illustrates the phenomenon of a watercourse disappearing and reappearing, is fundamental to the evolution of the karst system and contributes to the enriching of the cave with remarkable geological features. The presence of alluvial sediments within the cave attests to previous hydrological activity, which has significantly modified its internal structure.

GS 9: The Birfichou chasm (30°41′41.2″N 9°24′09.2″W)

The Birfichou chasm (Figures 1; 16) is defined as a collapse sinkhole located near the village of

Figure 11. Imi Ouggoug cave; the bats' entrance

Bou-Tara, north of Agadir. It is easily accessible from the road linking Imouzzer to the village of Tamgalt. This feature is a significant example of potential karst collapse risk in proximity to populated areas (Boudhair, 2023). This sinkhole is developed within the massive limestones of the Upper Portlandian (Late Jurassic); it consists of a carbonate formation of marine origin that is characterized by its hardness, while still being susceptible to dissolution (Ambroggi, 1963). These limestones, locally covered by Quaternary alluvium, belong to the Western High Atlas Series. The lithology serie is characterized, in its upper part, by Portlandian-age dolomitic limestones overlying gypsum-rich marls, forming a stratigraphic sequence that provides favorable conditions for differential dissolution and collapse (Ambroggi, 1963).

GS 10: The Win Timdwin cave (30°40'49.6"N 9°20'41.4"W)

The Win Timdouine cave geosite (cave of the lakes in Amazigh) (Figures 17a) is located in the Western High Atlas, approximately 70 km northeast of Agadir, at an altitude of 1,400 m. This karst system, one of the largest in Africa, comprises 19 km of explored caves, including the 8.5-km-long main gallery characterized by a succession of underground stream channels (Bouchaou et al., 2002).

Lithologically, it consists of Jurassic-age carbonate formations, represented by Upper Callovian dolomitic limestones and Rauracian-Sequanian marly dolomites, over a thickness of 42 to 50 m. These layers are superimposed on an impermeable Oxfordian marl substrate that isolates the aquifer (Bouchaou et al., 2002). Precipitation infiltration is facilitated by the development of surface karst features (Qurtobi et al., 2001). The cave network is also a remarkable underground ecosystem, with endemic species such as the isopod Castellanethes ougougensis (Figure 17b) (Moutaouakil et al., 2023). The hydrological regime shows a perennial flow, with varying discharge rates, reflecting a high sensitivity to precipitation, a characteristic of karst systems (Ait Brahim et al., 2019). The calcium bicarbonate-type waters exhibit mineralization indicative of active water-rock interaction. This dissolution is evident in the galleries through the abundance of speleothems

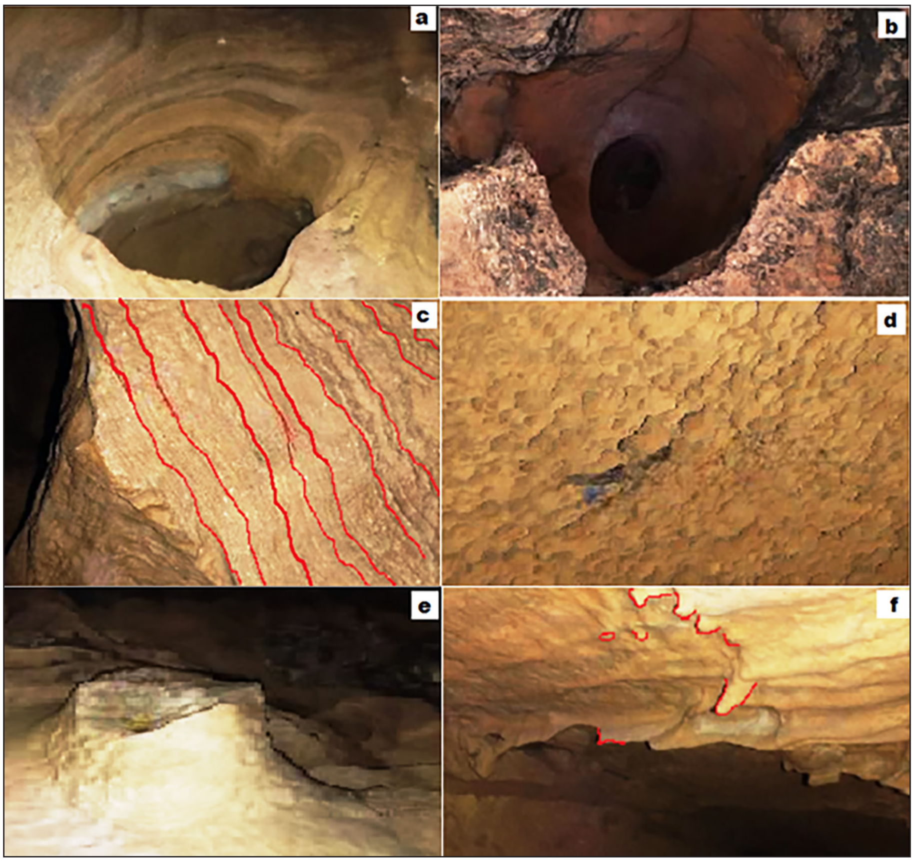

Figure 13. Speleothems in the Imi Ougoug cave: (a, b) a giant's kettle; (c) the superimposition of several layers of calcite sediment; (d) microcavities; (e) an ancient eroded and polished stalagmite; (f) microconcrements

Figure 14. (a) A colony of harvestmen, (b) a colony of bats

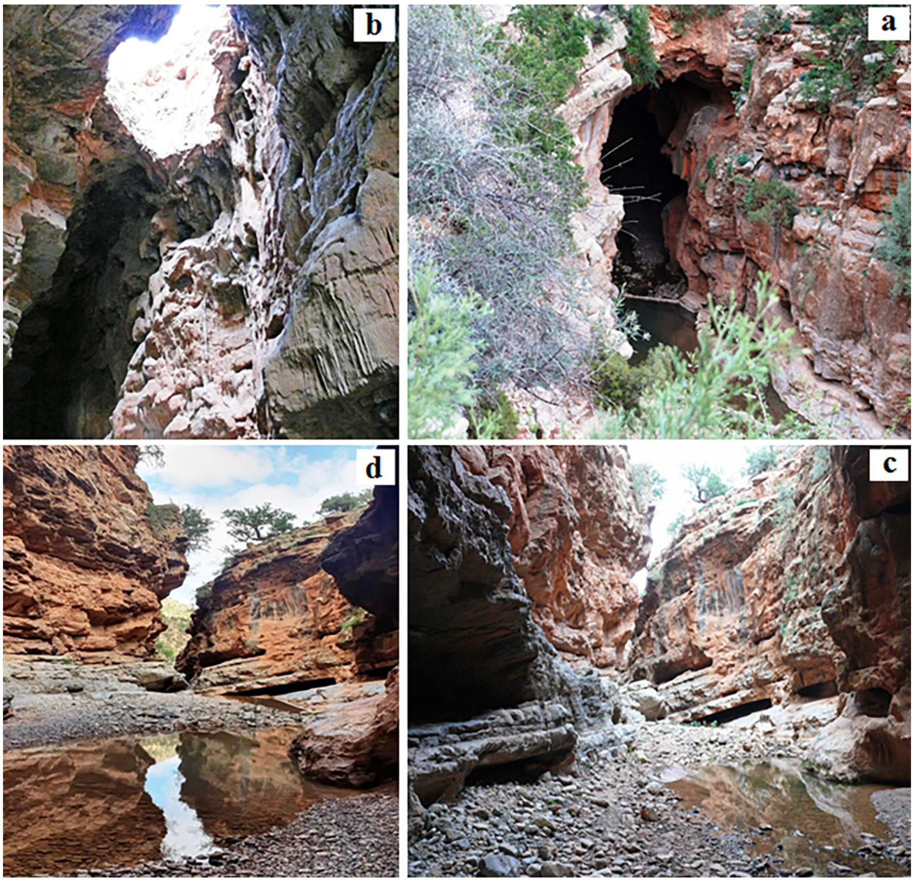

Figure 15. Assif n El Had cave, (a) the entrance, (b) the chimney, (c) the water source, (d) the exit

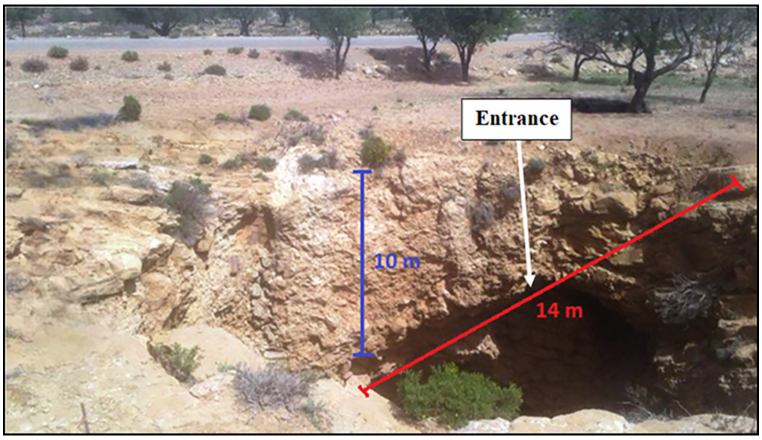

Figure 16. The Birfichou chasm, Agadir Ida-Outanane province

(Figure 17c) and, at the surface, through tufa deposits (Bouchaou et al., 2002).

DISCUSSION

Geosites in the Agadir hinterland

Based on a qualitative analysis of the ten geosites within the Agadir hinterland, a quantitative assessment was conducted to evaluate their scientific value (SV), educational use potential (PUE) and touristic use potential (PUT), as well as their degradation risk (DR). These values were derived using standardized and balanced assessment grids.

Scientific value

The scientific value (SV) of the ten geosites was assessed based on several criteria (Table 2). The entire group of sites exhibits a diversity of geological characteristics, including paleontological, structural, geomorphological, and hydrogeological attributes. The results range from 3.3 to 3.8, with an average weighted score of 3.51, indicating high to very high scientific value for all inventoried sites.

The relatively limited variability observed in several assessment criteria (e.g., integrity and representativeness) is related to the preliminary site-selection process. Only geosites considered representative of the geological and geomorphological heritage of the study area were included in the inventory. Consequently, the evaluated sites already possessed relatively high geoheritage value prior to the quantitative assessment, which explains the concentration of final scores within the upper range of the classification system. Similar patterns have been reported in other geoheritage assessment studies applying the Brilha (2016) methodology, where inventories are intentionally focused on sites with recognized scientific and educational relevance.

Geosites of very high scientific value (SV ≥ 3.5)

- The Win Timdwin vave (SV = 3.8) is the most outstanding site in the inventory. A significant karst geomorphological site, it is distinguished by its status as an exceptional Key Locality (KL = 0.8), attested by international scientific publications, as well as by its notable Rarity (Rar = 0.6) and remarkable geological diversity.
- The Alma Ammonites (SV = 3.7) represent a paleontological deposit of international interest to studying the Early Cretaceous. Their score is explained by their status as a Key Locality (KL = 0.8), which allows for global-scale stratigraphic correlations, maximum representativeness (Rpt = 1.2), and excellent state of preservation (Int = 0.6).
- The Imouzzer Idaoutanane faulted fold (VS = 3.7) is internationally recognized in scientific studies (KL = 0.8). The combination of reverse faults and folds, along with the record of paleostress, gives it remarkable geological diversity (DG = 0.2). The Paradise Valley Anticline (SV = 3.6) perfectly illustrates the shortening processes linked to the Africa–Eurasia collision. Its maximum representativeness (Rpt = 1.2) and its recognition as a reference site (KL = 0.8) justify this high score.
- The Imouzzer Ida Outanane waterfalls (VS = 3.6) stand out for their rarity (Rar = 0.6) and provide a striking illustration of travertine

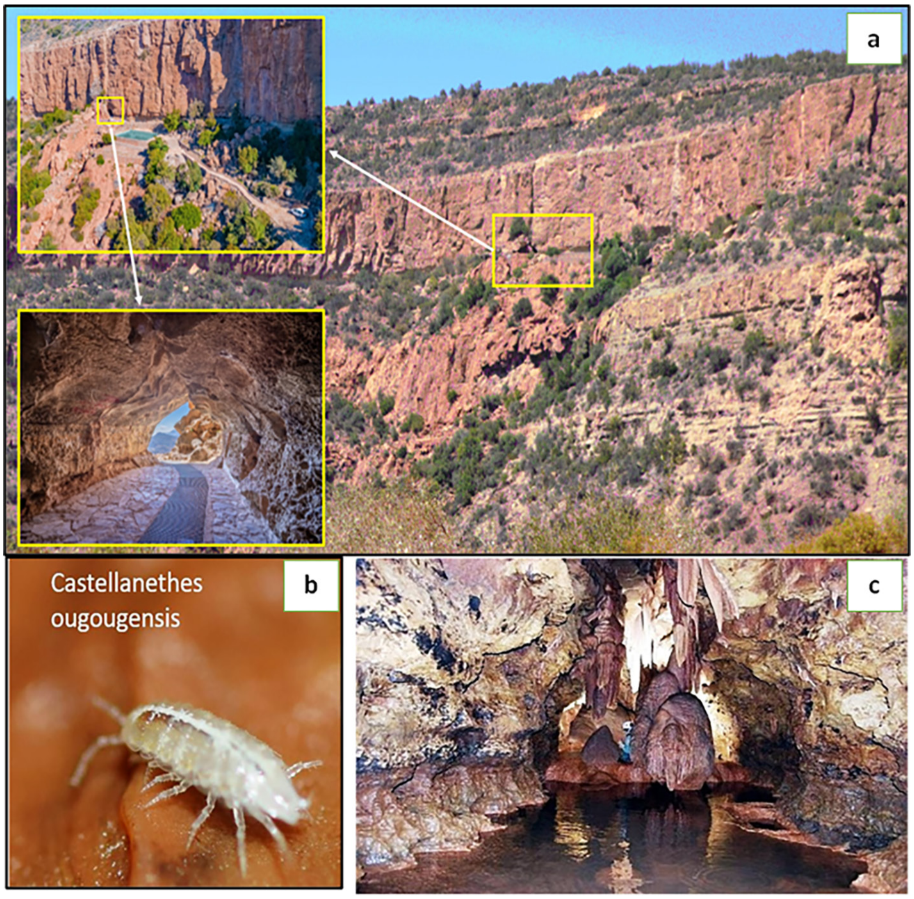

Figure 17. (a) The Win Timdouine cave, (b) Castellanethes ougougensis (Moutaouakil et al., 2023), (c) speleothems (stalactites, stalagmites, draperies, etc.)

formation processes and associated hydrogeological dynamics

Geosites of high scientific value (3.3 ≤ SV < 3.5)

- The Moulay Abd Allah dam (SV = 3.4) is a reference hydrogeological site illustrating the interaction between geology and anthropogenic development. Its notable rarity (Rar = 0.6) is slightly balanced by limitations of use (UL = 0.2) due to its developed state.
- The Birfichou chasm (VS = 3.4) is representative of vertical karst formations, with notable rarity (Rar = 0.6). Its limited accessibility (UL = 0.2) explains its classification in this category.
- The Paradise River gorge (VS = 3.3), the Imi Ouggoug cave (VS = 3.3), and the Assif n El Had cave (VS = 3.3) have comparable scores, reflecting their strong scientific interest and their representativeness of the regional karst, despite not being as exceptional as the previous sites.
- The overall weighted average of 3.51 attests to the exceptional quality of the geological heritage of the Agadir hinterland. The consistency of the integrity (Int = 0.6) and representativeness (Rpt = 1.2) criteria, which reach their maximum values at almost all sites, confirms how remarkably well-preserved and geologically relevant this inventory.

Education use potential

The ten geosites in the Agadir Ida-Outanane province demonstrate very high overall educational potential (PUE) (Table 3), with scores ranging from 3.3 to 3.8 and an overall average of 3.52. This illustrates their considerable suitability to serve as teaching supports in disciplines such as structural geology, geomorphology, hydrogeology, karstology, and paleontology. Detailed analysis of various criteria reveals that the main features of these sites consist of their exceptional educational potential, their geological diversity (0.4), and favorable observation conditions. The main challenges relate to safety (0.23), logistics (0.19), and population density (0.135), particularly for the most remote sites in rural areas.

Geosites with very high educational use potential (PUE ≥ 3.5)

Five geosites have a score of 3.5 or higher, representing the main educational sites in the province:

- The anticline folds and the gorge of the Paradise Valley (3.8) are excellent sites for studying structural geology, as they provide a clear illustration of folding and faulting phenomena, as well as the interactions between tectonics and erosion. Their accessibility and optimized educational potential (0.8) make them natural laboratories particularly adaptable to all educational levels.
- The Win Timdwin cave (3.8) is an essential site to study karstology, speleothems, and underground ecosystems. Safety (0.4) and accessibility (0.4) are optimal, allowing for regular use of the site for university field investigations and High school field excursions in the Agadir region.
- Alma Ammonites (3.5): This paleontological site serves as an important reference for studying the biostratigraphy of the Cretaceous period and ancient marine environments.
- High educational potential (0.8) balances moderate singularity (0.1).
- The Assif n' El Had cave (3.5) is a complex karst system characterized by a remarkable diversity of formations, including stalactites and stalagmites and underground channels, as well as notable geological features. It is particularly well-suited for field trips for geoscience students from Ibn Zohr University of Agadir and other institutions.

Geosites with high educational use potential (3.3 ≤ PUE < 3.5)

Five additional sites within the province demonstrate considerable educational potential, characterized by scores ranging from 3.3 to 3.4 (Table 2):

- The Imouzzer Ida Outanane faulted fold (3.4) represent an important structural feature, allowing for the observation of tectonic deformations (faults, folds) within a passive margin setting. This site is particularly well-suited for practical field exercises in structural geology, as it is located in the town centre.
- Imouzzer Ida Outanane waterfalls (3.4): This site, remarkable from both geomorphological and hydrological perspectives, highlights the interrelationships between lithology, geological structure, and hydrographic networks. Easily accessible and offering an attractive landscape, this site is an essential part of the local heritage.
- Moulay Abd Allah dam (3.4). This site has been included in this study because of its complementarity. It is perfectly suited to a multidisciplinary approach combining geology (rock formations, erosion), hydrology (watershed, reservoir), and ecology (lacustrine ecosystem).
- The Imi Ouggoug cave (3.3) is a karst site offering insights into the study of underground flows and speleological landforms. Limited accessibility (0.1) restricts its use to specialized and strictly supervised groups in outlying areas.

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

N°	GS Name	Typology	Int	Rpt	Rar	KL	SK	DG	UL	SV
1	Ammonites from Alma	Paleontological	0.6	1.2	0.3	0.8	0.2	0.2	0.4	3.7
2	The anticlinal fold of the Paradis Valley	Structural	0.6	1.2	0.3	0.8	0.2	0.1	0.4	3.6
3	The Gorges of the Paradise Valley	Geomorphological	0.6	1.2	0.3	0.4	0.2	0.2	0.4	3.3
4	Imouzzer Idaoutanane Faults and Fold	Structural	0.6	1.2	0.3	0.8	0.2	0.2	0.4	3.7
5	Imouzzer Ida-Outanane Waterfalls	Geomorphological	0.6	1.2	0.6	0.4	0.2	0.2	0.4	3.6
6	The Moulay Abd Allah Dam	Hydrologique	0.6	1.2	0.6	0.4	0.2	0.2	0.2	3.4
7	Imi Ouggoug Cave	Geomorphological	0.6	1.2	0.3	0.4	0.2	0.2	0.4	3.3
8	Assif n'El Had Cave	Geomorphological	0.6	1.2	0.3	0.4	0.2	0.2	0.4	3.3
9	The Birfichou chasm	Geomorphological	0.6	1.2	0.6	0.4	0.2	0.2	0.2	3.4
10	The Win Timdwin Cave	Geomorphological	0.6	1.2	0.6	0.8	0.2	0.2	0.2	3.8
	Weighted average		0.60	1.20	0.42	0.56	0.20	0.19	0.34	3.51

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

N°	GS name	Vul	Acc	UL	Saf	Log	DP	AV	Sce	Uni	OC	DP	GD	PUE
1	Ammonites from Alma	0.3	0.4	0.2	0.3	0.2	0.1	0.2	0.2	0.1	0.3	0.8	0.4	3.5
2	The anticlinal fold of the Paradis Valley	0.4	0.3	0.2	0.3	0.2	0.2	0.2	0.2	0.2	0.4	0.8	0.4	3.8
3	The Gorges of the Paradise Valley	0.4	0.3	0.2	0.3	0.2	0.2	0.2	0.2	0.2	0.4	0.8	0.4	3.8
4	Imouzzer Idaoutanane Faults and Fold	0.4	0.3	0.2	0.1	0.2	0.1	0.2	0.2	0.1	0.4	0.8	0.4	3.4
5	Imouzzer Ida-Outanane Waterfalls	0.4	0.3	0.2	0.1	0.2	0.1	0.2	0.2	0.1	0.4	0.8	0.4	3.4
6	The Moulay Abd Allah Dam	0.4	0.3	0.2	0.2	0.2	0.2	0.2	0.15	0.15	0.4	0.6	0.4	3.4
7	Imi Ouggoug Cave	0.4	0.1	0.2	0.2	0.2	0.1	0.2	0.2	0.1	0.4	0.8	0.4	3.3
8	Assif n'El Had Cave	0.4	0.3	0.2	0.2	0.2	0.1	0.2	0.2	0.1	0.4	0.8	0.4	3.5
9	The Birfichou chasm	0.3	0.3	0.2	0.2	0.15	0.1	0.2	0.15	0.2	0.3	0.8	0.4	3.3
10	The Win Timdwin Cave	0.4	0.4	0.15	0.4	0.15	0.15	0.2	0.2	0.15	0.4	0.8	0.4	3.8
	Weighted average	0.38	0.30	0.195	0.23	0.19	0.135	0.2	0.19	0.14	0.38	0.78	0.4	3.52

- The Birfichou chasm (3.3) is distinguished by its unique character (0.2) and high educational potential (0.8). Its location near the town of Imouzzer Ida-Outanane, combined with the lack of safety facilities and partially restricted observation conditions, makes it more suitable for guided field trips for high school and college students.

Tourism use potential

The assessment of the tourism use potential (TUP) of the ten geosites in the Agadir Ida Outanane province reveals a globally high tourism value (Table 4), scores ranging from 3.05 to 3.75, with an overall average of 3.415 out of 4. The results presented indicate a significant potential for geotourism and scientific ecotourism development in the region, as a supplement to pre-existing natural features such as waterfalls, valleys, and the coastline. A detailed examination of criteria reveals that the main tourist assets of these sites reside in their outstanding landscape (average of 0.585), their interpretation potential (0.39), and their geological distinctiveness (0.3). The predominant constraints are the proximity of areas of leisure (0.14), population density (0.125), and logistical challenges (0.185), particularly for the most isolated sites in the hinterland.

Geosites with very high tourism use potential (PUT ≥ 3.4)

Five geosites stand out with a score of 3.4 or higher, constituting the main attractions of the provincial geotourism network:

- The anticline of the Paradis Valley (3.75) and Paradis Valley gorge (3.75) is a landmark site, characterized by an exceptional landscape (0.6) and remarkable uniqueness (0.4). Their significant interpretation potential (0.4) makes them accessible to a wide audience. These locations are essential stops on any geotourism itinerary in the region.
- Birfichou chasm (3.6): This site, accessible directly from the road, offers immediately apparent geological interest. Its landscape (0.6), uniqueness (0.4), and interpretation potential (0.4) give it significant tourist attraction, making it ideal for a quick and remarkable stop on the Imouzzer waterfalls itinerary.
- The Win Timdwin cave (3.55), which has already been developed as part of some tourism initiatives, stands out for its adequate accessibility (0.4), safety (0.4), and a karst landscape of notable interest. The accessibility of its interpretation for a broad public makes it a great location for guided visits.
- The "Ammonites of Alma" site (3.4), a paleontological reference site, stands out for its easy accessibility (0.4) and clear interpretation. The site's rich fossil record makes it of major interest for paleontological geotourism, making it particularly suitable for families and school groups.

Geosites with high touristic use potential (3.2 ≤ PUT < 3.4)

Four sites stand out for their high touristic use potential, with scores ranging from 3.2 to 3.3:

- The Imouzzer Ida Outanane waterfalls (3.3), a site already included in national tourist itineraries, feature a remarkable natural environment characterized by travertine formations and waterfalls. Although the site's popularity is well-established, its geological aspect remains relatively inexploited in the existing tourist offerings.
- The Assif n'El Had cave (3.3) represents an esthetic and spectacular karst system. Although its development is limited, it offers high potential for the development of adventure tourism and guided visits. Its landscape features (0.6) and interpretation potential (0.4) are its main advantages.
- The Moulay Abd Allah dam (3.25) is characterized by a unique synergy between a lacustrine landscape, karst geology, and proximity to populated areas. Its uniqueness (0.4) and accessibility (0.4) make it a relevant site for diversifying tourism opportunities.
- The Imouzzer Idaoutanane faulted fold (3.2) constitute a remarkable structural site, closely linked to an exceptional mountainous landscape. Although this site is valued for its esthetic value, it would be appropriate to further highlight its geological significance to a broader public.

Geosites with moderate touristic use potential (PUT < 3.2).

A site has more limited potential, primarily due to access difficulties.

- Imi Ouggoug Cave (3.05): This site, which is remarkable for speleology and studying underground water flows, has limited accessibility (0.1) and lacks safety equipment. Access is restricted to experienced visitors or specialized groups, such as speleologists, researchers, and advanced graduate students.

Risk of degradation

The risks of degradation (RD) facing the ten geosites in the Agadir Ida Outanane province are generally moderate to high. Scores range from 1.6 to 2.5 out of 4, with an average of 2.1/4. In other word, while these sites have strong touristic and educational use potential, they deserve special attention to ensure their protection in the long term. The analysis reveals that the main risks come from three factors:

- The fragility of geological features (average of 0.735), particularly for caves and fossil sites,
- The lack of legal protection (0.68) for most sites,
- The accessibility (0.405) of some of them, which exposes them to more visitors.

Other factors such as population density (0.26) or proximity to human activities (0.38) also contribute, but remain secondary.

The most vulnerable sites (RD ≥ 2.3)

Four sites deserve particular attention (Table 5):

- Moulay Abd Allah dam (2.5): This is the site with the highest risk. Its easy access (0.6) and lack of protection (0.8) make it vulnerable, especially if visitor numbers increase. The fragility of its geological features (0.7) is also worrying. Regular monitoring is essential, alongside consideration of appropriate management measures.
- Alma Ammonites (2.45) and Birfichou chasm (2.45): Same rating, same risk profile. Both are easily accessible (0.6) and located along the main road, which makes them particularly vulnerable:
- For Alma, there is a real risk of illegal fossil collection.
- For Birfichou, the main danger comes from visitors walking everywhere without guidance, which risks destroying the ground and the rock formations.
- Quick protection measures (awareness signs, signage, or even a temporary enclosure) would be welcome.
- Assif n El Had cave (2.3): This karst system is highly fragile (1.05), relatively easy to access (0.45), and lacks protection (0.4). It is therefore vulnerable to graffiti, unauthorized sampling, and unregulated visitation. A better approach would be to implement protective measures and organize visits more strictly.

Sites with moderate risk (2.0 ≤ RD < 2.3)

Four other sites present a more limited risk, but this should not be overlooked:

- Imi Ouggoug cave (2.0): Isolated and difficult to access (0.15), it does not appear to be at risk in the short term. But caution is advised: its fragility is high (1.05). If a decision is ever made to open it to tourism or develop its surroundings, extreme care will be required.
- Imouzzer faulted fold (2.05) and Imouzzer waterfalls (2.05): Same score for these two

sites. They benefit from legal protection (0.8), which limits the risks. But tourist traffic, especially at the waterfalls, can lead to damage.

- Paradise Valley anticline (1.8) and Paradise Valley gorge (1.8): These two twin sites fare better, due to legal protection (0.4) and a slightly higher population density (0.4), which promotes natural surveillance. Their intrinsic fragility is also lower (0.35).
- The good example: a model to be followed (RD < 2.0)
- Win Timdwin cave (1.6): This is clearly the best-protected site in the area. It benefits from maximum legal protection (2), distance from degrading activities (2), and lower fragility (0.35). Existing facilities and visitor management are doing their job. A model to follow for the management of other sites.

During three days in the field, we kept discovering new places. Each morning we visited three or four geosites, and in the evening we went back to the Atlantic Camping in Imourane (Figure 19), a quiet spot in the coastal village of Tamraght. After a whole day of walking and observing, it felt really good to return there.

Overall, the scores we gave to the ten geosites were quite satisfying (Table 6, Figure 18). Scientific value averaged 3.51, educational potential 3.52, and touristic potential 3.42. In plain words, these places are not only geologically interesting – they are also easy for a curious hiker to understand and genuinely enjoyable to explore.

What worried us, though, was the degradation score: only 2.1 on average. This tells us that some sites are already showing signs of wear and becoming fragile. If we want to keep enjoying them in the future, we really have to be careful and take concrete steps to protect them.

We also looked at practical feasibility. Here is what we found:

- Transport – the route starts and ends near Agadir, only 30 km from Agadir-Al Massira International Airport. Eight out of ten geosites are reachable with a normal car; only GS7 (Imi Ouggoug) and GS8 (Assif n'El Had) require a 4WD.
- Visitor capacity – the most fragile sites (GS1, GS7, GS8, GS9) can handle about 20 to 30 visitors per day without serious impact, while more open sites like GS2, GS3 and GS5 can take larger groups.
- Cost – for a three-day independent tour, budget around 150–250 euros per person, covering transport, accommodation and meals, based on current local prices.

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

N°	GS Name	Vul	Acc	UL	Saf	Log	DP	AV	Sce	Uni	OC	IP	EL	RA	PUT
1	Ammonites from Alma	0.3	0.4	0.2	0.3	0.2	0.1	0.2	0.6	0.2	0.15	0.4	0.15	0.2	3.4
2	The anticlinal fold of the Paradis Valley	0.4	0.3	0.2	0.3	0.2	0.2	0.2	0.6	0.4	0.2	0.4	0.15	0.2	3.75
3	The Gorges of the Paradise Valley	0.4	0.3	0.2	0.3	0.2	0.2	0.2	0.6	0.4	0.2	0.4	0.15	0.2	3.75
4	Imouzzer Idaoutanane Faults and Fold	0.4	0.3	0.2	0.2	0.2	0.1	0.2	0.6	0.2	0.2	0.4	0.15	0.05	3.20
5	Imouzzer Ida-Outanane Waterfalls	0.4	0.3	0.2	0.2	0.2	0.1	0.2	0.6	0.3	0.2	0.4	0.15	0.05	3.3
6	The Moulay Abd Allah Dam	0.3	0.4	0.2	0.2	0.15	0.1	0.2	0.45	0.4	0.2	0.3	0.15	0.2	3.25
7	Imi Ouggoug Cave	0.4	0.1	0.2	0.2	0.2	0.1	0.2	0.6	0.2	0.2	0.4	0.15	0.1	3.05
8	Assif n'El Had Cave	0.4	0.3	0.2	0.2	0.2	0.1	0.2	0.6	0.2	0.2	0.4	0.15	0.15	3.3
9	The Birfichou chasm	0.3	0.4	0.2	0.3	0.15	0.1	0.2	0.6	0.4	0.2	0.4	0.15	0.2	3.6
10	The Win Timdwin Cave	0.4	0.4	0.15	0.4	0.15	0.15	0.2	0.6	0.3	0.2	0.4	0.15	0.05	3.55
	Weighted average	0.37	0.32	0.195	0.26	0.185	0.125	0.2	0.585	0.3	0.2	0.39	0.15	0.14	3.415

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	Ammonites from Alma	1.05	0.2	0.4	0.6	0.2	2.45
2	The anticlinal fold of the Paradis Valley	0.35	0.2	0.4	0.45	0.4	1.8
3	The Gorges of the Paradise Valley	0.35	0.2	0.4	0.45	0.4	1.8
4	Imouzzer Idaoutanane Faults and Fold	0.7	0.2	0.8	0.15	0.2	2.05
5	Imouzzer Ida-Outanane Waterfalls	0.7	0.2	0.8	0.15	0.2	2.05
6	The Moulay Abd Allah Dam	0.7	0.2	0.8	0.6	0.2	2.5
7	Imi Ouggoug Cave	1.05	0.2	0.4	0.15	0.2	2
8	Assif n'El Had Cave	1.05	0.2	0.4	0.45	0.2	2.3
9	The Birfichou chasm	1.05	0.2	0.4	0.6	0.2	2.45
10	The Win Timdwin Cave	0.35	2	2	0.45	0.4	1.6
	Weighted average	0.735	0.38	0.68	0.405	0.26	2.1

Table 6. Detailed scoring of selected geological interest sites (SV, PUE, PUT, RD)

N°	GS Name	SV	PUE	PUT	RD
1	Ammonites from Alma	3.7	3.5	3.4	2.45
2	The anticlinal fold of the Paradis Valley	3.6	3.8	3.75	1.8
3	The Gorges of the Paradise Valley	3.3	3.8	3.75	1.8
4	Imouzzer Idaoutanane Faults and Fold	3.7	3.4	3.20	2.05
5	Imouzzer Ida-Outanane Waterfalls	3.6	3.4	3.3	2.05
6	The Moulay Abd Allah Dam	3.4	3.4	3.25	2.5
7	Imi Ouggoug Cave	3.3	3.3	3.05	2
8	Assif n'El Had Cave	3.3	3.5	3.3	2.3
9	The Birfichou chasm	3.4	3.3	3.6	2.45
10	The Win Timdwin Cave	3.8	3.8	3.55	1.6
	Weighted average	3.51	3.52	3.415	2.1

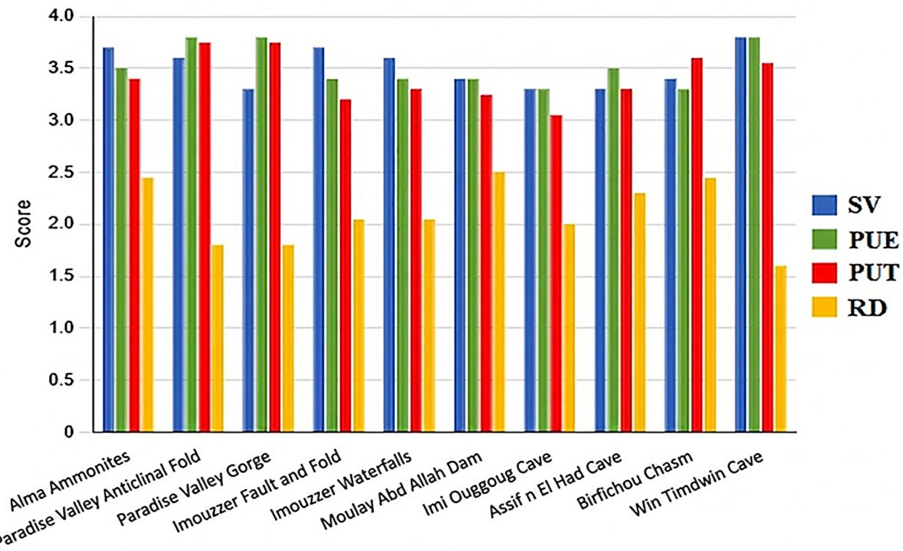

Figure 18. Comparison of ratings (SV, PUE, PUT, RD) for the ten geosites in the Agadir hinterland

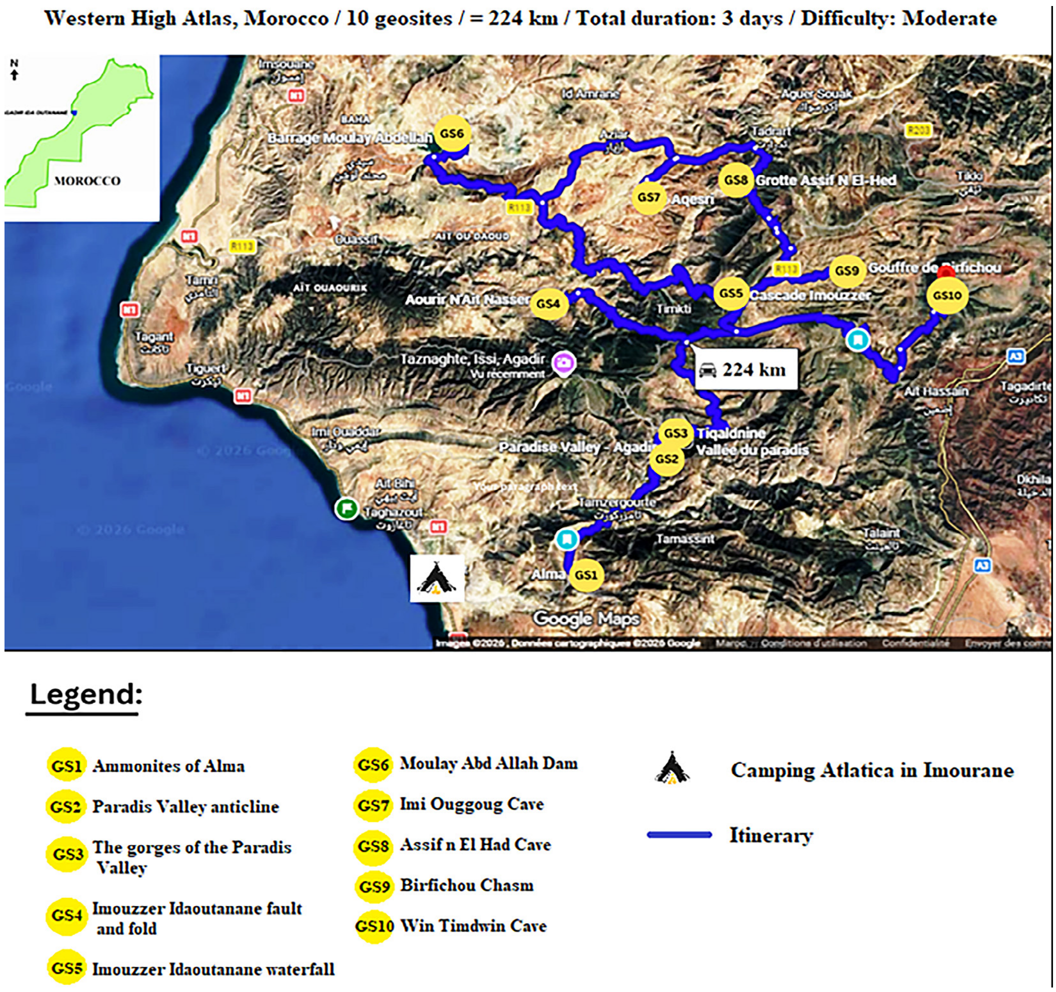

Figure 19. Map of the scenic route on a satellite image (Google Maps), the blue line – the recommended route

Limitations of the study

The present assessment is based on the Brilha (2016) framework, which inevitably involves expert judgment despite the use of standardized criteria. Although efforts were made to ensure consistency during the evaluation process, some degree of subjectivity cannot be entirely eliminated. Future studies could strengthen the robustness of the assessment through larger expert panels, inter-rater agreement analyses, and sensitivity testing of weighting schemes. Economic feasibility, visitor carrying capacity, and tourism demand were beyond the scope of the present study and should be addressed in future geotourism planning initiatives.

Perspectives

This study's findings offer interesting perspectives, both in terms of scientific research and the implementation of effective regional initiatives. In immediately practical terms, it is crucial to further characterize certain geosites, particularly those that are most vulnerable. Detailed geophysical and topographic studies would provide a better understanding of the internal structure of the partially explored karst networks, particularly the Imi Ouggoug cave and its recently identified connections. Furthermore, additional analyses of the travertine deposits at the Imouzzer Ida Outanane waterfalls could enhance our understanding of Quaternary paleoclimatic variations in this region of the High Atlas. At the same time, establishing a programme for the regular monitoring of the most vulnerable sites is required: a monitoring system based on simple and consistent indicators (visitor numbers, human impact, state of speleothems, fossil sampling) would help to anticipate critical limits of degradation before it becomes irreversible. The Win Timdwin cave, which is already subject to structured management, represents a relevant model in this regard, and its adaptation to the specific characteristics of each site should be considered.

It appears necessary to proceed with the operational phase of the proposed cycling itinerary, which involves precisely defining the locations of the stop sites, developing the necessary interpretation supports for the intended audiences (school groups, families, and researchers) and implementing minor infrastructure improvements to ensure safety and manage visitor flow. Close collaboration with local partners, including provincial authorities, rural municipalities, development associations, and tourist guides, will be crucial to ensuring that the communities involved take ownership of this initiative and to ensuring its long-term sustainability. Over the next few years, expanding the inventory to unexplored areas of the region, such as the limestone highlands to the east or the transition zones toward the Souss Plain to the south, is likely to reveal new interesting geosites, which would gradually expand the existing geotrail and improve the territorial integrity of the project. From an academic perspective, the methodology employed could be extended to other areas of the Western High Atlas, thereby facilitating the establishment of a unified national database on Morocco's geological heritage. The results indicate that several geosites possess high scientific, educational, and touristic value within the regional and national context. While the study highlights favourable conditions for future geoheritage development and geotourism planning, additional comparative, institutional, and management assessments would be required before considering potential UNESCO Global Geopark designation.

CONCLUSIONS

This study represents an original contribution to the validation of knowledge regarding the continental geological heritage of the Agadir Ida-Outanane hinterland, a region that has not yet been the subject of systematic surveys. A multi-criteria quantitative analysis of ten representative geosites, conducted according to Brilha's (2016) methodology, revealed that this portion of the Western High Atlas exhibits geodiversity of high to very high scientific value, with a weighted average of 3.51. Sites such as the Win Timdwin cave (SV = 3.8), the Alma Ammonites, and the Imouzzer Idaoutanane fault (SV = 3.7) stand out for their exceptional heritage value, while all sites demonstrate notable geological representativeness and landscape integrity. In addition to their inherent scientific value, the results highlight considerable educational (PUE = 3.52) and touristic (PUT = 3.415) potential, confirming the multiple roles of these geosites. Nevertheless, the analysis of the degradation risk (average RD = 2.1) reveals a real vulnerability for various sites, particularly the Moulay Abd Allah dam (RD = 2.5) and the Alma Ammonites (RD = 2.45), which requires the implementation of appropriate and immediate protective measures.

The main contribution of this study lies in the creation of a quantified, comparable, and operational database that goes beyond traditional descriptive inventories to provide practical indicators capable of guiding priorities in conserving and developing the territory. The proposed geo-itinerary, extending over 224 kilometres and connecting the ten sites from Alma to the Win Timdwin cave along a three-day trip, offers a structured framework for sustainable geotourism, integrating heritage promotion, the involvement of local communities, and respect for natural balances. Finally, these geosites represent an essential component of the geological and landscape heritage of the Western High Atlas, and their preservation is both an ethical and scientific imperative for future generations.

REFERENCES

1. Ait Brahim, Y., Bouchaou, L., Sifeddine, A., Beraaouz, E. H., Wanaim, A., Cheng, H. (2019). Hydro-climate characteristics of the karst system of Wintimdouine cave (Western High Atlas, Morocco): monitoring and implications for paleoclimate research. *Environmental Earth Sciences, 78*(16), 508.
2. Aït Brahim, L., Chotin, P., Hinaj, S., Abdelouafi, A., El Adraoui, A., Nakcha, C., Dhont, D., Charroud, M., Sossey Alaoui, F., Amrhar, M. (2002).Paleostress evolution in the Moroccan African margin from Triassic to present.*Tectonophysics, 357*(1–4), 187–205.
3. ABHSM. (2002). *Monographie technique du barrage Moulay Abd Allah*. Agence du Bassin Hydraulique du Souss-Massa, Agadir.
4. Akdim, B. (2015). Karst landscape and hydrology in Morocco: research trends and perspectives. *Environmental Earth Sciences, 74*(1), 251–265.
5. Ambroggi, R. (1963). Étude géologique du versant méridional du Haut Atlas occidental et de la plaine du Souss. *Notes et Mémoires du Service Géologique du Maroc, 157*, 1–160.
6. Andreu-Boussut, B. (1992). Distribution stratigraphique des ostracodes du Barrémien au Turonien, le long d'une transversale Agadir-Nador (Maroc).

Géologie Méditerranéenne, 19(3), 165–187.

7. Aoulad-Sidi-Mhend, A., et al. (2019). The geological heritage of the Talassemtane National Park and the Ghomara coast natural area (NW of Morocco). *Geoheritage, 11*, 1005–1025.
8. Aoulad-Sidi-Mhend, A., et al. (2020). A quantitative approach to geosites assessment of the Talassemtane National Park (NW of Morocco). *Estudios Geológicos, 76*(1).
9. Aoulad-Sidi-Mhend, A., Martín-Martín, M., Hlila, R., Maaté, A., Chakiri, S., Achab, M., Aziz, A., Slimani, H., Maaté, S., Mohammadi, M. (2023). Methodology for a Moroccan inventory and assessment of geological sites: A proposal to be applied in other African regions. *Revista de la Sociedad Geológica de España, 36*(1), 16–37.
10. Arboleya, M. L., Teixell, A., Charroud, M., Julivert, M. (2004). A structural transect through the High and Middle Atlas of Morocco. *Journal of African Earth Sciences, 39*(3–5), 319–327.
11. Belfoul, M. A., Faik, F., Belfoul, A. (2001). Les grandes structures tectoniques atlasiques et leur rôle dans le développement karstique de la grotte de Win Timdouine. *Karstologia, 38*, 11–20.
12. Belfoul, M. A., Qurtobi, M., Faik, F. (2001). Impact de la structuration atlasique sur l'architecture interne de la grotte de Win-Timdouine (Haut-Atlas Occidental Marocain). *Revue d'Analyse Spatiale*, 47–50.
13. Ben Ali, S., Aoulad-Sidi-Mhend, A., Bejjaji, Z., Maâté, A., Mehdioui, S., Mohammadi, M., Tayebi, M., Mirari, S. (2023). Inventory and quantitative assessment of Belyounech commune geosites (east of the site of biological and ecological interest of Jbel Moussa, northern Moroccan Rif). *Ecological Engineering & Environmental Technology, 24*(7), 105–128.
14. Ben Ali, S. B., Aoulad-Sidi-Mhend, A., Maaté, A., Tayebi, M., Mohammadi, M., Mehdioui, S., Eddifai, I., Bejjaji, Z. (2025). From inventory and quantitative assessment of geosites to sustainable development: Case study of the Flyshs georoad of the Tangier Peninsula. *Ecological Engineering & Environmental Technology, 26*(5), 237–256.
15. Boualla, O. (2016). *Etude des risques de mouvements de terrain dans la région de Safi (Maroc): Approche géomatique, géophysique et géostatistique* (Thèse de doctorat). Université Chouaïb Doukkali, El Jadida, Maroc.
16. Bouchaou, L., Qurtobi, M., Hsissou, Y., Boutaleb, S. (2002). The underground river of Win Timdouine (Agadir region, High Atlas): a contribution to the inventory of the geological heritage in Morocco. In *Karst and environment. 2nd Nerja Cave Geological Symposium* (pp. 273–279). Nerja, Málaga, Spain.
17. Boudhair, F. (2023). *La cartographie spéléologique et géophysique des grottes de la région d'Inouzzer Ida Ou Tanane* (Mémoire de master). Université Ibn Zohr, Agadir, Maroc.
18. Boukfaoui, Z., Aoulad-Sidi-Mhend, A., Chakiri, S., El Ouad, Z., Moussaoui, R. (2026). Contribution to the inventory of Morocco's geological heritage: The coastal geosites of Agadir Ida-Outanane (western High Atlas, Morocco). *Ecological Engineering & Environmental Technology, 27*(2), 89–108.
19. Brilha, J. (2016). Inventory and quantitative assessment of geosites and geodiversity sites.*Geoheritage, 8*, 119–134.
20. Camus, J., Lamouroux, C. (1981). *Inventaire spéléologique du Maroc*. Ministère de l'équipement, Rabat.
21. Duffaud, F., Cochet, E., Guy, M., Issenmann, O., Taussac, R. (1971). Carte géologique du Maroc au 1/100 000, feuille Taghazoute. *Notes et Mémoires du Service Géologique du Maroc, 204*.
22. Ettachfini, E. M. (1992). *Le Vraconien, Cénomanien et Turonien du bassin d'Essaouira (Haut Atlas occidental, Maroc): Analyse lithologique, biostratigraphique et sédimentologique, stratigraphie séquentielle* (Thèse de doctorat). Université Toulouse 3, Toulouse, France.
23. Ferry, S., Masrour, M., Grosheny, D. (2007). *Excursion Le Crétacé de la marge atlantique marocaine (région d'Agadir)*. Excursion du Groupe Français du Crétacé, 75 p.
24. Frizon de Lamotte, D., Leturmy, P., Missenard, Y., Khomsi, S., Ruiz, G., Saddiqi, O., Guillocheau, F., Michard, A. (2009). Mesozoic and Cenozoic vertical movements in the Atlas system (Algeria, Morocco, Tunisia): An overview. *Tectonophysics, 475*(1–2), 9–28.
25. Frizon de Lamotte, D., Saint Bezar, B., Bracène, R., Mercier, E. (2000). The two main steps of the Atlas building and geodynamics of the western Mediterranean. *Tectonics, 19*(4), 740–761.
26. Frizon de Lamotte, D., Zizi, M., Missenard, Y., Hafid, M., Azzouzi, M. E., Maury, R. C., Michard, A. (2008). The Atlas system. In A. Michard et al. (Éds.), *Continental Evolution: The Geology of Morocco* (pp. 133–202). Springer, Berlin, Heidelberg.
27. Fuertes-Gutiérrez, I., Fernández-Martínez, E. (2010). Geosites inventory in the Leon Province (Northwestern Spain): a tool to introduce geoheritage into regional environmental management. *Geoheritage, 2*(1–2), 57–75.
28. Hafid, M. (2006). Styles structuraux du Haut Atlas de Cap Tafelney et de la partie septentrionale du Haut Atlas occidental. *Notes et Mémoires du Service Géologique du Maroc, 465*, 172.
29. Hafid, M., Ait Salem, A., Bally, A. W. (2000). The western termination of the Jebilet–High Atlas system (offshore Essaouira Basin, Morocco). *Marine and Petroleum Geology, 17*(3), 431–443.
30. Irifi, H., Tribak, A., Achour, A. (2020). Diversité floristique et paysagère du cours d'eau de la basse

vallée de l'oued Tamri. *Geomaghreb, 17*, 13–30.

31. Lanari, R., Fellin, M. G., Faccenna, C., Balestrieri, M. L., Piana Agostinetti, N., Piromallo, C. (2020). Tectonic evolution of the Western High Atlas of Morocco: Oblique convergence, reactivation, and transpression. *Tectonics, 39*(3), e2019TC005563.
32. Luber, T. L., Bulot, L. G., Redfern, J., Frau, C., Arantegui, A., Masrour, M. (2017). A revised ammonoid biostratigraphy for the Aptian of NW Africa: Essaouira-Agadir Basin, Morocco. *Cretaceous Research, 79*, 12–34.
33. Martín-Algarra, A., et al. (2003). Sedimentary patterns in perched spring travertines near Granada (Spain) as indicators of the paleohydrological and paleoclimatological evolution of a karst massif. *Sedimentary Geology, 161*(3–4), 217–228.
34. Medina, F. (1985). Chronologie des phases et style tectonique dans le Haut Atlas occidental (Maroc). *Garcia de Orta, Série Géologie, 7*(1–2), 7–15.
35. Medina, F., Cherkaoui, T. E. (1991). Mécanismes au foyer des séismes du Maroc et des régions voisines (1959–1986). *Geodinamica Acta, 5*(3), 151–161.
36. Medina, F., Chalouan, A., Soto, J. I. (2011). *Nouveaux guides géologiques et miniers du Maroc — Volume 7 : Haut Atlas occidental, Haut Atlas central nord-ouest*. Notes et Mémoires du Service Géologique du Maroc, n° 564.
37. Mehdioui, S., et al. (2020). Inventory and quantitative assessment of geosites in Rabat-Tiflet region (North-Western Morocco): Preliminary study to evaluate the potential of the area to become a Geopark. *Geoheritage, 12*, 1–17.
38. Mehdioui, S., et al. (2022). The geoheritage of Northwestern Central Morocco area: Inventory and quantitative assessment of geosites for geoconservation, geotourism, geopark purpose and the support of sustainable development. *Geoheritage, 14*, 86.
39. Meghraoui, M., Outtani, F., Choukri, A., Frizon de Lamotte, D. (1998). Coastal tectonics across the South Atlas Thrust Front and the Agadir Active Zone, Morocco. *Geological Society, London, Special Publications, 146*(1), 239–253.
40. Michard, A. (1976). *Éléments de géologie marocaine*. Notes et Mémoires du Service Géologique du Maroc, 252.
41. Michard, A., Frizon de Lamotte, D., Saddiqi, O., Chalouan, A. (2008). An outline of the geology of Morocco. In A. Michard et al. (Éds.), *Continental Evolution: The Geology of Morocco* (pp. 1–31). Springer, Berlin, Heidelberg.
42. Moutaouakil, S., Boulanouar, M., Ghamizi, M., Lips, J., Ferreira, R. L. (2023). Two new sympatric cave species of Castellanethes (Isopoda, Oniscidea, Olibrinidae) from Western High Atlas of Morocco. *Subterranean Biology, 45*, 17–37.
43. Mustaphi, H., Medina, F., Jabour, H., Hoepffner, C. (1997). Le bassin du Souss : résultat d'une inversion tectonique contrôlée par une faille de détachement profonde. *Journal of African Earth Sciences, 24*(1–2), 153–168.
44. Oukassou, M., Boumir, K., Benshili, K., Ouarhache, D., Lagnaoui, A., Charrière, A. (2019). The Tichoukt Massif: A geotouristic play in the folded Middle Atlas (Morocco). *Geoheritage, 11*(2), 371–379.
45. Pereira, P., Pereira, D., Brilha, J. (2010). Geoformas e depósitos glaciários e periglaciários, uma das categorias temáticas para a inventariação do património geológico português. *e-Terra, 18*(2), 4.
46. Piqué, A., Ait Brahim, L., Ait Ouali, R., Amrhar, M., Charroud, M., Gourmelen, C., Laville, E., Rekhiss, F., Tricart, P. (2002). The Mesozoic-Cenozoic Atlas belt (North Africa): An overview. *Geodinamica Acta, 15*(4), 185–208.
47. Poiraud, A., Chevalier, M., Claeyssen, B., Biron, P. E., Joly, B. (2016). From geoheritage inventory to territorial planning tool in the Vercors massif (French Alps): Contribution of statistical and expert cross approaches.*Applied Geography, 71*, 69–82.
48. Qurtobi, M. (1996). *Reconnaissance hydrogéologique de la région d'Immouzzar des Ida-Ou-Tanane* (Thèse de doctorat). Université Ibn Zohr, Faculté des Sciences, Agadir, Maroc.
49. Qurtobi, M., Boutaleb, S., Bouchaou, L., Chauve, P., Mudry, J. (2001). Apport de la géologie et de l'hydrochimie à la connaissance des circulations karstiques dans le Haut-Atlas occidental d'Agadir (Maroc). *Sciences et techniques de l'environnement. Mémoire hors-série*, 305–311.
50. Rassou, K. K., Razoki, B., Yazidi, M., Chakiri, S., El Hadi, H., Bejjaji, Z., Allouza, M. (2019). The vulgarization for the patrimonialization of the Kettara geodiversity (Central Jbilet) Morocco. *International Journal of Civil Engineering and Technology, 10*(6), 194–214.
51. Reboulet, S., Jaillard, E., Shmeit, M., Giraud, F., Masrour, M., Spangenberg, J. E. (2022). Biostratigraphy, carbon isotope and sequence stratigraphy of South Tethyan Valanginian successions in the Essaouira-Agadir Basin (Morocco). *Cretaceous Research, 140*, 105341.
52. Reynard, E., et al. (2007). A method for assessing scientific and additional values of geomorphosites. *Geographica Helvetica, 62*(3), 148–158.
53. Reynard, E., et al. (2016). Integrated approach for the inventory and management of geomorphological heritage at the regional scale. *Geoheritage, 8*, 43–60.
54. Rousseau, L., Weisrock, A., Falguères, C., Bahain, J. J., Beauchamp, J., Pozzi, J. P., Ouammou, A. (2008). Premières datations de travertins d'Imouzzer Ida Ou Tanane, Maroc (pp. 209–221).

55. Sébrier, M., Siame, L., Zouine, E. M., Winter, T., Missenard, Y., Leturmy, P. (2006). Active tectonics in the Moroccan High Atlas.*Comptes Rendus Geoscience*, *338*(1–2), 65–79.
56. Teixell, A., Arboleya, M.-L., Julivert, M., Charroud, M. (2003). Tectonic shortening and topography in the central High Atlas (Morocco). *Tectonics*, *22*(5), 1051.
57. Tixeront, M. (1974). Lithostratigraphie et minéralisations des formations permo-triasiques de la côte atlantique marocaine. *Notes et Mémoires du Service Géologique du Maroc*, *263*, 1–175.
58. UNESCO. (2015). *UNESCO Global Geoparks: Celebrating Earth Heritage, Sustaining Local Communities*. UNESCO, Paris.
59. Weisrock, A., Rousseau, L., Ouammou, A., Lefèvre, D., Hoang, C. T., Ghaleb, B. (2006). Datations U/Th de travertins et évolution morphoclimatique quaternaire dans le Haut Atlas occidental. *Géomorphologie: Relief, Processus, Environnement*, *12*(3), 203–214.
60. Weisrock, A., Rousseau, L., Reyss, J. L., Falgueres, C., Ghaleb, B., Bahain, J. J., Ouammou, A. (2008). Travertines of the Moroccan Sahara northern border: Morphological settings, U-series datings and palaeoclimatic indications. *Géomorphologie: Relief, Processus, Environnement,* (3), 153–168.
61. Wimbledon, W. A. (1995). The development of a methodology for the selection of British geological sites for conservation: Part 1. *Modern Geology, 20,* 159–202.