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ORIGINAL ARTICLE

Enhancing the Geological Heritage of the Errachidia Area in the High Atlas, Morocco: Inventory and a Proposal for a Pedagogic and Geotouristic Trail

Hicham Si Mhamdi[1] · Ali Charroud[2] · Mostafa Oukassou[3] · Amar Alali[1] · Lahssen Baidder[4] · Mohammed Raji[3] · Abdelhak Ijaajaane[3,1] · Souad Elfaiz[5] · Salem Elouariti[6]

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Abstract

Geological heritage is now a main component in the current patterns of socio-economic and sustainable development and is becoming essential in the educational process. Morocco is among the countries with the most fascinating geological diversity in the world. This work presents a result of the proposal for a pedagogical and geotouristic trail in the Errachidia province. The latter is known for its fabulous geological and oasis landscapes as well as its mining wealth. Through this study, we will describe the pedagogical geosites in this region, which is part of the Preafrican Trough between the High Atlas and the Anti-Atlas. The fieldwork and assessment of values demonstrate that the studied geosites have substantial scientific significance and remarkable educational and tourism potential. The study area offers pedagogical geosites of different types: structural, stratigraphical, paleontological, geomorphological, hydrological, and ecological. These geosites, which reflect the geological, geomorphological, and environmental history of the region, are doubled with an additional aesthetic value, which provides them with a particular scientific and geotouristic interest. The present approach will be used in the educational process and the promotional activities for tourism, by offering well-illustrated hikes and in situ panels describing the main characteristics of the locations. Accordingly, a total of nine geosites have been selected to serve as a basis for this educational and geotouristic trail. Furthermore, geoconservation through geoeducation, such as fieldwork or museum exhibitions, is discussed along with its role in fostering local socio-economic development through geotourism.

Keywords Geotourism · Geosite · Geoheritage · High Atlas · Morocco

Introduction

Morocco is located at the northwest corner of the Saharan platform of the African continent. It is surrounded by the mobile Alboran Plate to the north and the Atlantic Ocean to the west. Morocco's geology is considered a geologists' paradise and a pedagogical area to study all geological aspects (Frizon De Lamotte et al. 2008; Michard et al. 2008, 2011; El Hadi et al. 2015). It constitutes a set of structural domains that show strong similarities with their Euramerican and African counterparts. Morocco presents pronounced reliefs at the High Atlas within the Jbel Toubkal which is the highest peak in North Africa (4167 m), as well as a wide Saharan platform and plains.

✉ Hicham Si Mhamdi
hicham.simhamdi@gmail.com; h.simhamdi@umi.ac.ma

1 Laboratory of Applied Geology, Department of Geosciences, Faculty of Sciences and Techniques Errachidia, Moulay Ismail University of Meknes, Errachidia, Morocco

2 Laboratory of Engineering Sciences and Techniques, Faculty of Sciences and Techniques Errachidia, Moulay Ismail University of Meknes, Errachidia, Morocco

3 Laboratory of Applied Geology, Geoinformatics and Environment, Department of Geology, Faculty of Sciences Ben M'Sick, Hassan II University of Casablanca, Casablanca, Morocco

4 Laboratory of Geosciences, Department of Geology, Faculty of Sciences Ain Chock, Hassan II University of Casablanca, Casablanca, Morocco

5 Laboratory of Geosciences, Faculty of Sciences Kenitra, Ibn Tofail University, Kenitra, Morocco

6 Laboratory of Geosciences and Applications, Department of Geology, Faculty of Sciences Ben M'Sick, Hassan II University of Casablanca, Casablanca, Morocco

The diversity of the relief is a reflection of the diversity of the geological structures and geometry, linked to the succession of four geological events, which are the Eburnian, Panafrican, Variscan, and Alpine orogenies.

In the last decade, a focus has been given to the geological heritage across the Kingdom of Morocco. The geological heritage or geoheritage refers to earth science objects that can be in situ and called "geosites", such as Earth's geology, geomorphology, and landscapes. It also includes the exitu geoheritage elements available in the museum (El Hadi et al. 2015; Brilha 2016).

The most important publication of Moroccan geoheritage is the geological and mining guides of Morocco (Michard et al. 2011), which have tried to cover the whole country through geological tours (nine volumes). Another book was recently published where this heritage culture has been widely discussed, in particular the Moroccan geological heritage as wealth and prospects for inventory, valorisation, and preservation (El Hassani 2022). Other works have handled geological heritage as an example in different structural domains: in the Rif (Tahouri et al. 2017; Aoulad Sidi Mhend et al. 2019, 2022), in the Middle Atlas (De Waele et al. 2008; Oukassou et al. 2019; Baadi et al. 2021), in the Meseta domain (Tahiri et al. 2010; Enniouar et al. 2015; Hili 2020; Mehdioui et al. 2020, 2022), in the High Atlas (Enniouar et al. 2014; Errami et al. 2015; Bouzekraoui et al. 2017, 2018; Arrad et al. 2020; Rais et al. 2021; Louz et al. 2022), in the Anti-Atlas (El Hadi et al. 2011; Druguet et al. 2015; El Hassani et al. 2017; Beraaouz et al. 2019; Berred et al. 2019, 2022; Lahmidi et al. 2020, 2021, 2022; Karmaoui 2022) and in the Sahara (Saddiqi et al. 2015). These works have focused on the inventory of geosites, including their identification, assessment, and vulnerability. This inventory takes into account many parameters by which we distinguish between scientific, touristic, educational, and degradation risk values. After the inventory, the promotion and the protection of geoheritage are highly recommended, which in turn will contribute to the socio-economic development by proposing geotrails integrating variable characteristics of the relevant regions.

The present work aims at elaborating an inventory of important geosites in the study area. This inventory is supported by a description of each geosite using several methods and approaches in order to highlight their scientific and educational values and their potential for geotourism.

In addition to the enhancement of scientific, socio-economic, and aesthetic potentialities, the elaboration of tour guidebooks constitutes an important tool in education. Technical sheets will be suggested for educational geosites with easy access and well documented, which will facilitate the transmission of information to future generations by creating repositories in the document centres of high schools, universities, and the different ministries.

The northern zone of Errachidia city shows a geological heritage of scientific, educational, and geotouristic relevance. However, the only study that has attempted to describe the geosites, through a few stops, has been carried out within the framework of the geological guides of Morocco by Saddiqi et al. (2011).

Presentation of the Study Area

Geographic Setting

The study area is located in the southern part of the central High Atlas Mountains in the north of the Errachidia province, which belongs to the administrative region of Draa Tafilalet (Fig. 1). It is the north side of the Saharan space, consisting of a set of oases over several kilometres along the Ziz Valley. The area's natural environment is marked by an arid climate with low rainfall and high levels of evapotranspiration that can reach 4000 mm/year. The study area presents altitudes up to 1029 m within the valleys carved by the Oued Ziz. The last reliefs of the Atlassic chain constituted a favourable zone on which the dam of El Hassan Addakhil was built for approximately 6 km (Fig. 1b). It is one of the largest dams in Morocco, with a significant retention capacity of about 312.8 million m^3.

Geological Framework

The Atlas Mountains are a major morphological feature in the North African area. They extend along a subequatorial direction for nearly 2000 km, from the Moroccan Atlantic margin to Tunisia on the Mediterranean fringe, and they represent the highest topography in Western Africa. The Moroccan Atlas Mountains domain is considered the only African orogenic system resulting from the convergence of African and European plates (Michard 1976; Beauchamp et al. 1999). This Atlas System is represented in the Maghreb from east to west by the Tunisian Atlas, the Algerian Atlas, and the Moroccan Atlas, respectively (Fig. 2a). The High Atlas is an intracontinental chain that extends over 700 km in length and was progressively structured during the succession of extensive and compressive events that mark the Mesozoic and Cenozoic history of Morocco (Michard 1976; Mattauer et al. 1977; Beauchamp et al. 1999; Laville et al. 2004). It is subdivided into three main zones, the Saharan High Atlas (Eastern High Atlas), the Central High Atlas, and the Western High Atlas (Fig. 2b).

The study area belongs to the south-eastern part of Morocco and is within the structural unit referred to the Preafrican Trough (eastern part of the Preafrican Trough) (Fig. 2b). It straddles the High Atlas and the Anti-Atlas in the form of a vast asymmetrical syncline with a high

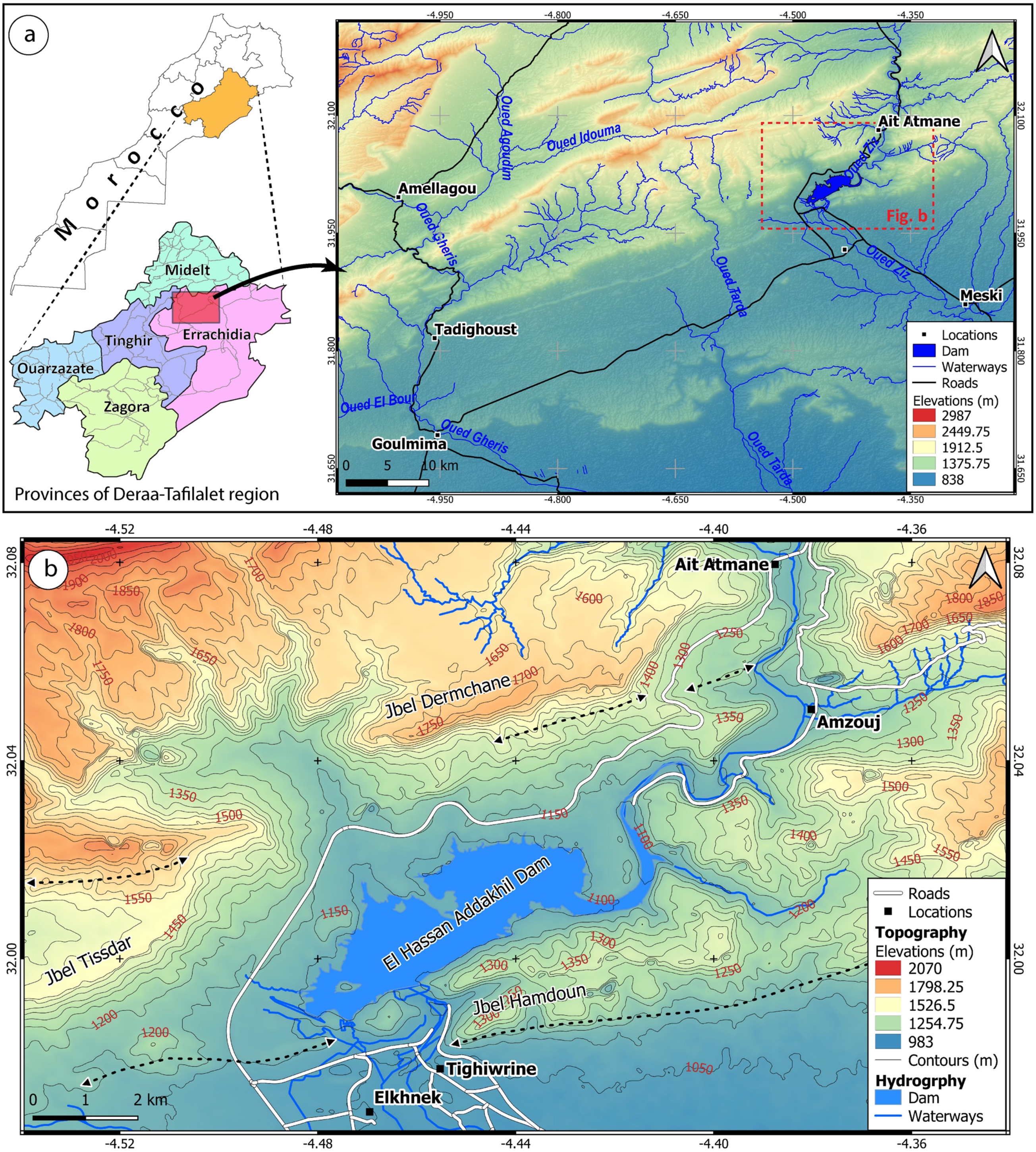


Fig. 1 **a** Geographic location of the study area in Morocco. **b** Topographic map of the study area

variety of geological facies of the Meso-Cenozoic age that have been slightly deformed by the Alpine Orogeny. The geological mapping of the study area showed the lithological succession of the Jurassic, Cretaceous, and Quaternary facies (Fig. 3a).

The lithostratigraphic column of the north part of Errachidia shows the succession of the following geological formations (Fig. 3b). At the base, the Pliensbachian is represented by limestones with thinly intercalated marls, on which lie marls and marlstones with ammonites of the

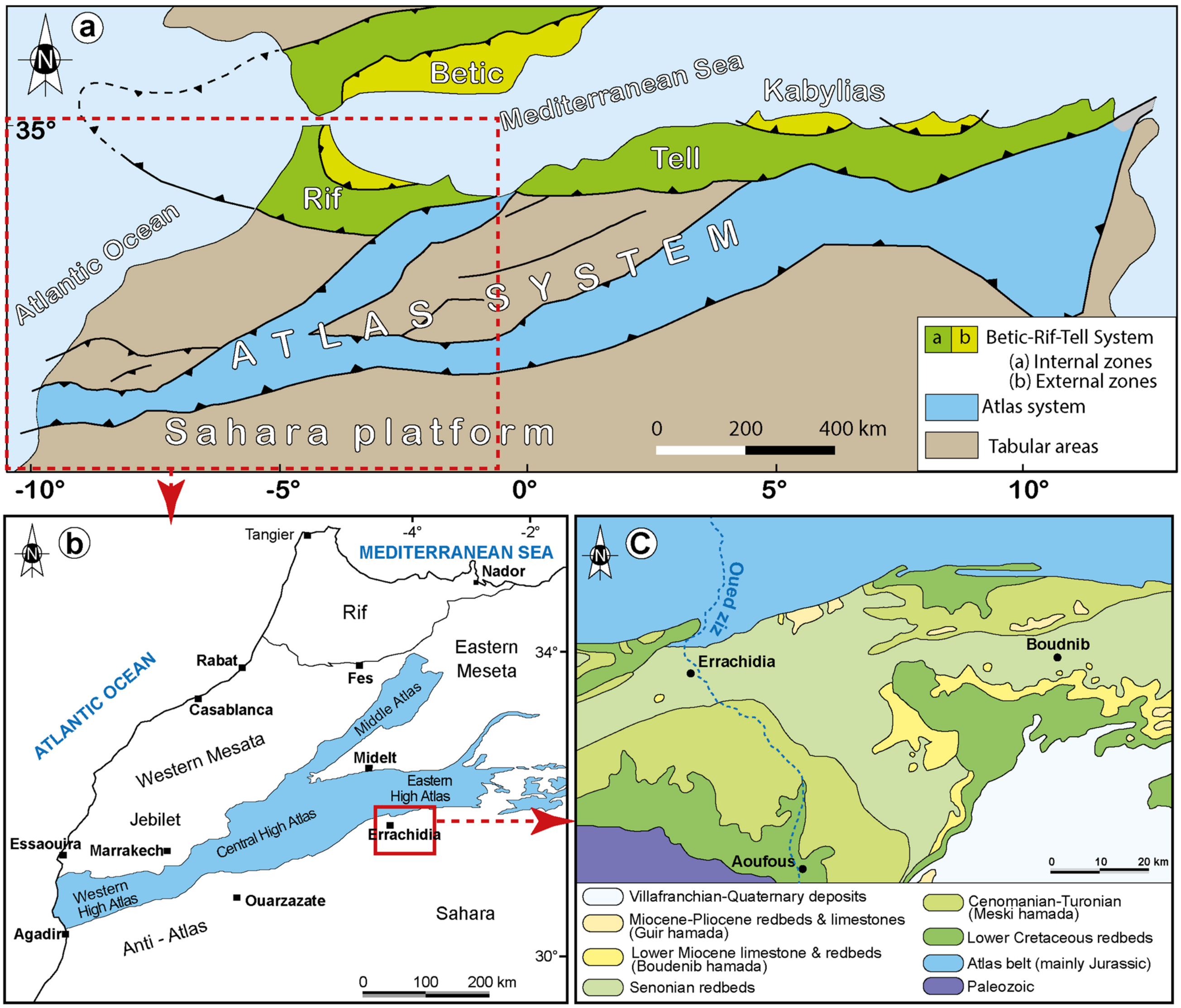


Fig. 2 **a** The Atlas System of North Africa (after Frizon De Lamotte et al. 2008; Escosa et al. 2021). **b** Location of the High Atlas within the Atlas system in the northern part of Morocco. **c** Geological location of the study area (after Zouhri et al. 2008)

Toarcian and then dolomitic limestones with marly intercalation of the Aalenian. The Bajocian is represented by bioclastic limestones with oblique stratification surmounted by versicoloured marls, siltstones, and fossiliferous limestones. The Bathonian records a change of facies, which becomes rather conglomerate with polygenic elements, sandstone, and siltstone of red colour.

The Cretaceous sequences begin with the Albian formations of Ifezouane including sandstones within cross-stratification, pink and white sands, mudstones, and marls with gypsum layers, on which rests the Cenomanian formation of Aoufous, represented by clayey sandstones and marls with gypsum layers. Then, the Akrabou formation of the Cenomanian–Turonian is characterized by limestones with lamellibranchs and ammonites and the appearance of some rich levels of organic matter. The Cretaceous ends with the Iflilt formation, dating from the Senonian period and formed by argillites and siltstones with sandstone layers. In the end, the Quaternary is largely represented by scree and alluvial deposits in the form of conglomerates with polygenic elements of large size.

The study area is presented as a large flat-bottomed syncline bordered by two Atlassic faults that develop anticline structures at their extremities and whose vergence is towards the south (Fig. 3c).

Regarding mineral resources, this area belongs to the territory under the management of the Purchasing and Development Centre of the Tafilalet and Figuig mining region (CADETAF), which is a public socio-economic institution deriving from the development of the Purchasing and

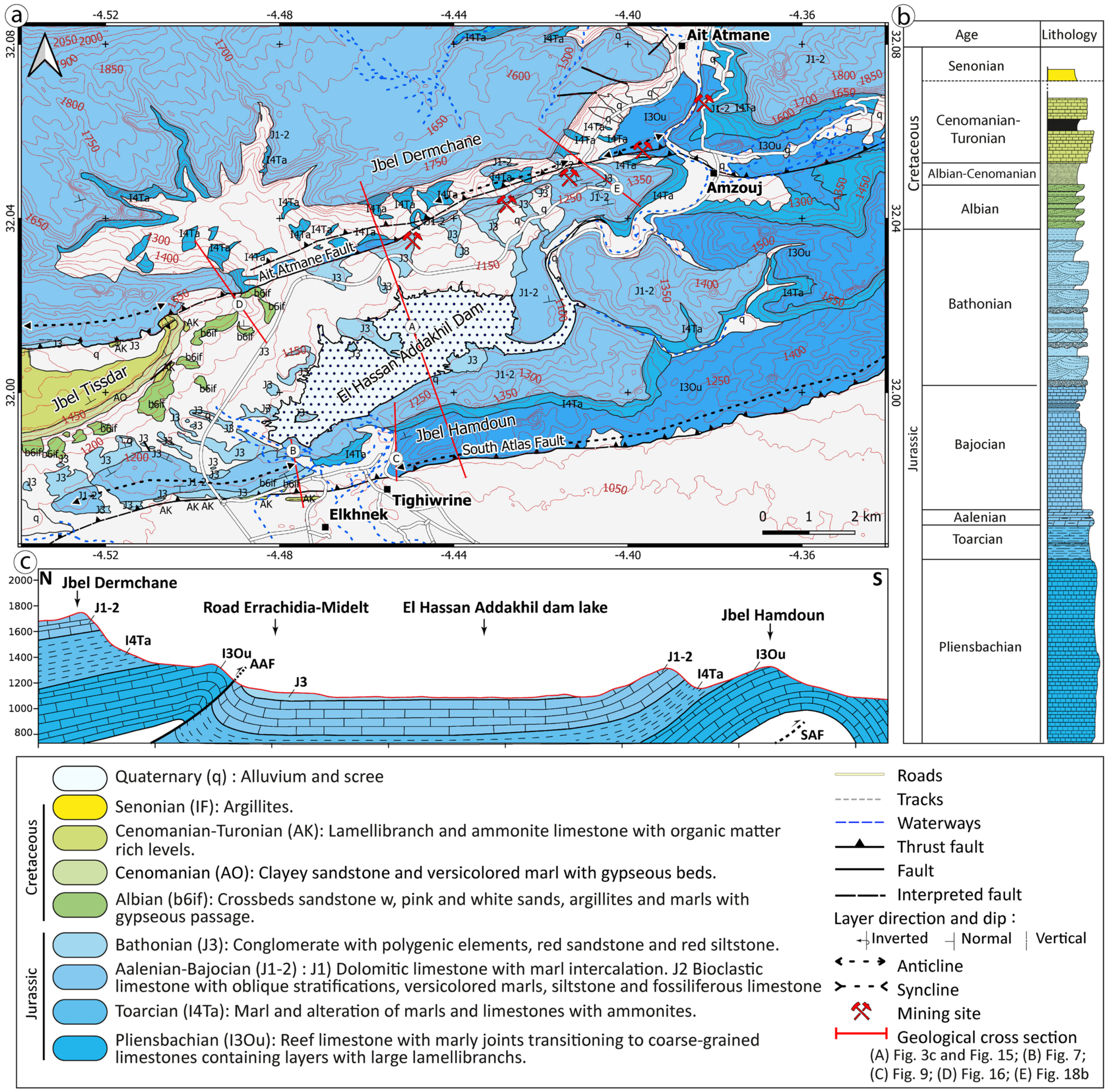


Fig. 3 **a** Geological map of the study area (modified and completed after Baidder et al. (2020)). **b**, **c** Lithostratigraphic record and cross sections of the study area

Development Centre of the Tafilalet mining region (CADET) created and governed by Law n°74–15 repealing the Dahir of December 1st, 1960. This structure, placed under the supervision of the Ministry of Energy and Mines, is in charge of collecting and purchasing the ores from artisanal mining operations as well as the commercialisation of lead, zinc, and barite ores from the area. Most ore deposits are mined by artisanal miners, while the CADETAF provides technical assistance, research, execution of the work, and development of the operations to the industrial stage.

In the study area, the predominant minerals being extracted are lead and zinc. These ore deposits are aligned along the Ait Atmane Fault Zone (structural metallotect), in particular in the Early Jurassic formations (lithological metallotect) (Fig. 3a).

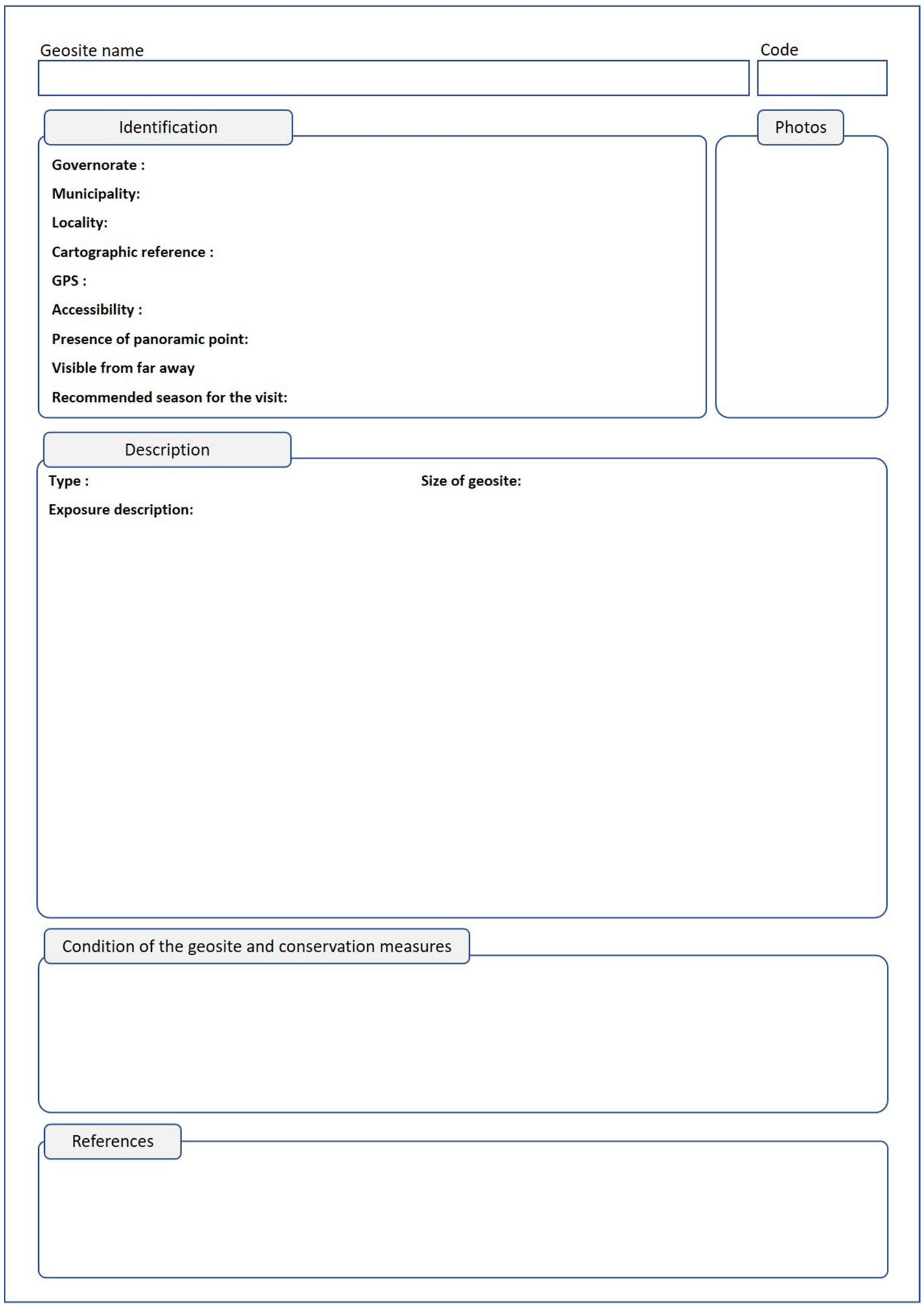
Methodology

The characterisation of the geological heritage of any given area is subject to a particular methodology.

First, a list of possible geosites was compiled. The inventory of natural resources and selection of representative geosites of the geological heritage in the area were carried out based on a literature review and fieldwork. A descriptive sheet of geosite was created to collect information about these places, in which the site's identifying data (e.g. locality and coordinates) was given along with information on accessibility, visibility, geology, and geomorphology (Fig. 4). It is nevertheless necessary to report on the use and state of conservation. The establishment of a grid to identify geosites will enable the selection of geosites of interest for the suggested trail.

Subsequently, a quantitative assessment of the geosites was carried out. In fact, several works have tried to propose grids that are based on inventory and quantification through several parameters (Coratza et al. 2005; Serrano and González-Trueba 2005; Pereira et al. 2007; Reynard et al. 2007, 2015; Ruban 2010; De Lima et al. 2010; Brilha 2016; Zwoliński et al. 2018; Brilha et al. 2018). These works were based on case studies and, in some instances, require adaptation to the relevant regions of the survey. Indeed, in our case,

Fig. 4 Descriptive sheet of geosite


Geosite name
Code
Identification
Photos
Governorate :
Municipality:
Locality:
Cartographic reference :
GPS :
Accessibility :
Presence of panoramic point:
Visible from far away
Recommended season for the visit:
Description
Type :
Size of geosite:
Exposure description:
Condition of the geosite and conservation measures
References

we adopted the methodology proposed by Brilha (2016), where we estimated based on various criteria scored 0 to 4 (Table 1). The author divided the evaluation criteria into four parts, each reflecting a different goal of the study. The first part focuses on scientific values and includes 7 criteria, while the second part assesses the potential educational use using 12 criteria. The third part evaluates the potential tourist use using 13 criteria, 8 of which are similar to those used in the PEU. Finally, the fourth part assesses the management and conservation of geosites using 5 criteria.

These geosites were chosen based on their scientific value, educational or aesthetic features, and, most importantly, their accessibility. However, because of their educational and geotourism potential, several panoramic views were included as trail stations.

Overall, the inventory criteria will be described based on the identification and description, followed by a quantitative assessment and conservation measures.

Table 1 Weights for the different criteria used for the assessment of scientific value, potential educational use, potential touristic use and degradation risk (Brilha 2016)

	Criteria (scored 0 to 4)	Weight (%)
Scientific value (SV)	A. Representativeness (R)	30
	B. Key locality (Kl)	20
	C. Scientific knowledge (Sn)	5
	D. Integrity (I)	15
	E. Geological diversity (Gd)	5
	F. Rarity (R)	15
	G. Use limitations (Ul)	10
Potential educational use (PEU)	A. Vulnerability (V)	10
	B. Accessibility (A)	10
	C. Use limitations (Ul)	5
	D. Safety (S)	10
	E. Logistics (L)	5
	F. Density of population (Dp)	5
	G. Associations with other values (Av)	5
	H. Scenery (Sc)	5
	I. Uniqueness (U)	5
	G. Observation conditions (Oc)	10
	K. Didactic potential (Dp)	20
	L. Geological diversity (Gd)	10
Potential touristic use (PTU)	A. Vulnerability (V)	10
	B. Accessibility (A)	10
	C. Use limitations (Ul)	5
	D. Safety (S)	10
	E. Logistics (L)	5
	F. Density of population (Dp)	5
	G. Associations with other values (Av)	5
	H. Scenery (Sc)	15
	I. Uniqueness (U)	10
	G. Observation conditions (Oc)	5
	K. Interpretative potential (Ip)	10
	L. Economic level (El)	5
	M. Proximity recreational areas (Pr)	5
Degradation risk (DR)	A. Deterioration geological elements (Dg)	35
	B. Proximity activities cause of degradation (Pa)	20
	C. Legal protection (Lp)	20
	D. Accessibility (Ac)	15
	E. Density of population (Dpp)	10

Geosite Inventory

In the proposed itinerary for the northern zone of Errachidia, nine geosites were inventoried. The concept of "secondary geosite" was introduced to refer to complex geosite. It encompasses a part of the primary geosite, which highlights various themes or distinct geosites that focus on a similar theme. This categorisation has been used previously by Arrad et al. (2020).

The main aspects of the nine geosites included in the tour are summarised in Table 2. The block diagram in Fig. 5 shows their locations as well as the geometry of geological structures in the study area. In the following section, we will describe each geosite starting from Errachidia 1 (ER1) and going north.

Geosite ER1: Panorama of the Atlas Front

Geosite ER1 serves as an ideal introduction to the geological and geomorphological background of the region, showcasing its history, evolution, and diversity. It is located at the northern exit of Errachidia city. It allows visualising the whole of the Jurassic and Cretaceous rocks, which outcrops all along a panoramic view from Jbel Hamdoun in the East to Jbel Tissdar (Fig. 6). Furthermore, this geosite allows having an idea of geosites' positions on both sides of the first relief. This geomorphological relief results from geological processes including erosion, tectonic activity, and climate change. This area encompasses features such as mountains, valleys, rivers, and oasis. It will help us understand how the Earth's surface has been shaped over time and the processes that continue to shape it.

Geosite ER2: South Atlas Fault

This geosite is located near the South Atlassic Fault that was described as a blind fault (not observed on the surface); its existence is indicated by anticline bulges affecting the Jurassic formations. The most representative examples are the Jbel Tissdar anticline in the West and the Jbel Hamdoun anticline in the East (Fig. 7).

The South Atlas Fault is a structural feature at the border between the Cretaceous Errachidia-Boudnib Basin and the south front of the central High Atlas. This fault was first described by Russo and Russo (1934). It is a fault that extends for about 1900 km from the city of Agadir in Morocco until the Gulf of Gabes in Tunisia (Jacobshagen 1992). In the study area, many authors have described this fault (Jossen and Filali-Moutei 1992; Ibouh 2004). It is a thrust fault oriented broadly at N75° with a southward thrusting component. This fault has nearly the same dip as the neighbouring layers (Fig. 7). At the outcrop scale, the Jurassic bedrocks are folded, with the bedding showing a change of dip according to an anticline structure (fold-thrust). This folding shows a southward overturned fold with an axis plunging to the west. The extrados of the hinge has been eroded, resulting in a structure formed by Bajocian limestones enveloped by the red continental layers (sandstones, mudstones, and siltstones) of the Middle Jurassic (Bathonian).

Table 2 Surveyed geosites constituting the educational and geotouristic trail to the north of Errachidia city

Primary geosite	Code	Secondary geosite		
		Code	GPS coordinates (X;Y)	Main illustrated theme
Panorama of the Atlas front	ER1	ER1	−4.4761;31.9569	Geomorphological
South Atlas Fault	ER2	ER2	−4.4835;31.9760	Structural and stratigraphic
Jbel Hamdoun anticline	ER3	ER3.1	−4.4580;31.9846	Structural and geomorphological
		ER3.2	−4.4555;31.9828	Structural
		ER3.3	−4.4545;31.9852	Geomorphological
		ER3.4	−4.4535;31.9896	Structural
		ER3.5	−4.4537;31.9913	Stratigraphic and paleontological
Jurassic/Cretaceous contact	ER4	ER4	−4.4978;31.9815	Stratigraphic and paleontological
Perched syncline between two Atlassic faults	ER5	ER5	−4.4967;31.9896	Structural and geomorphological
Ait Atmane Fault	ER6	ER6.1	−4.4652;32.0252	Structural
		ER6.2	−4.4577;32.0279	Structural
		ER6.3	−4.4052;32.0509	Structural and stratigraphic
Ait Atmane biostromes and reef mounds	ER7	ER7	−4.3954;32.0663	Stratigraphic and paleontological
Panorama of El Hassan Addakhil Dam	ER8	ER8	−4.4101;32.0466	Hydrological and geomorphological
Dermchane waterfall	ER9	ER9	−4.4851;32.0552	Geomorphological and hydrological

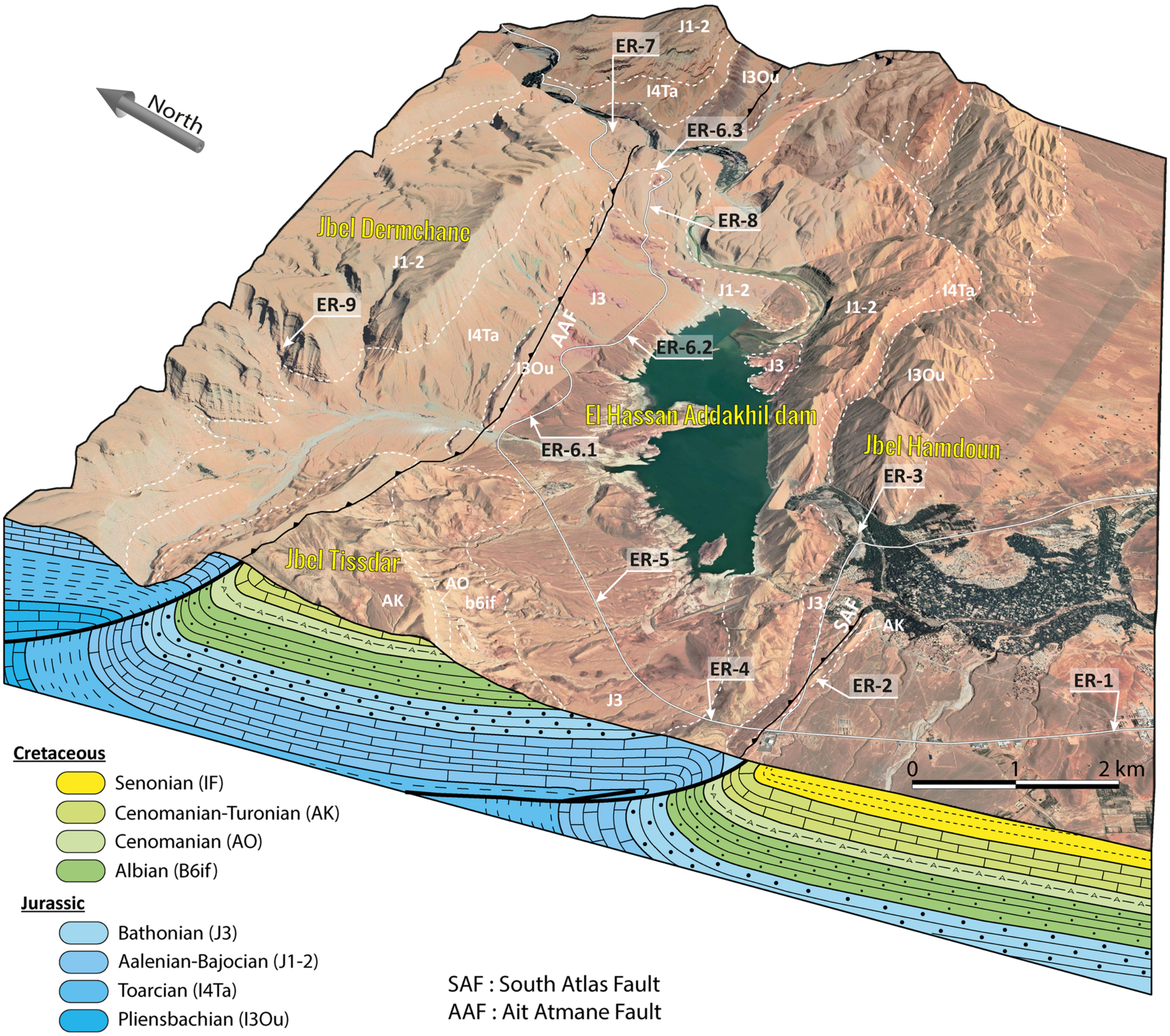


Fig. 5 Block diagram illustrating the geological structure of the outcrops crossed by the trail with location of proposed geosites

In this area, the facies and geometry of the Cretaceous formations can be observed, which are vertical or even overturned, and where the tectonic control of certain strike-slip faults that produced shifts within these formations (Fig. 8a, b). These are the fossiliferous limestones of the Akrabou Formation of the Cenomanian–Turonian age, which are rich in lamellibranchs, gastropods, and brachiopods (Fig. 8c–e). The facies and their fossil contents and sedimentary patterns characterise a proximal platform deposit (Ettachfini and Andreu 2004; Wang et al. 2021).

The South Atlas Fault can be considered a valuable geosite because it is one of the major features of Moroccan geology. It represents the presence of tectonic activity and can provide important information about the geological and geomorphological history of the foreland basin and tectonic activities resulting in earthquakes along this major fault zone. Hence, this geosite is of scientific, educational, and potential interest in tourism and environmental education.

Geosite ER3: Jbel Hamdoun Anticline Structure

The Errachidia area is situated in front of the High Atlas Mountains and is recognised as a foreland basin. Foreland basins such as Errachidia are marked by the occurrence of anticlines, with the Jbel Hamdoun Anticline being a notable example. The examination of anticlines in foreland

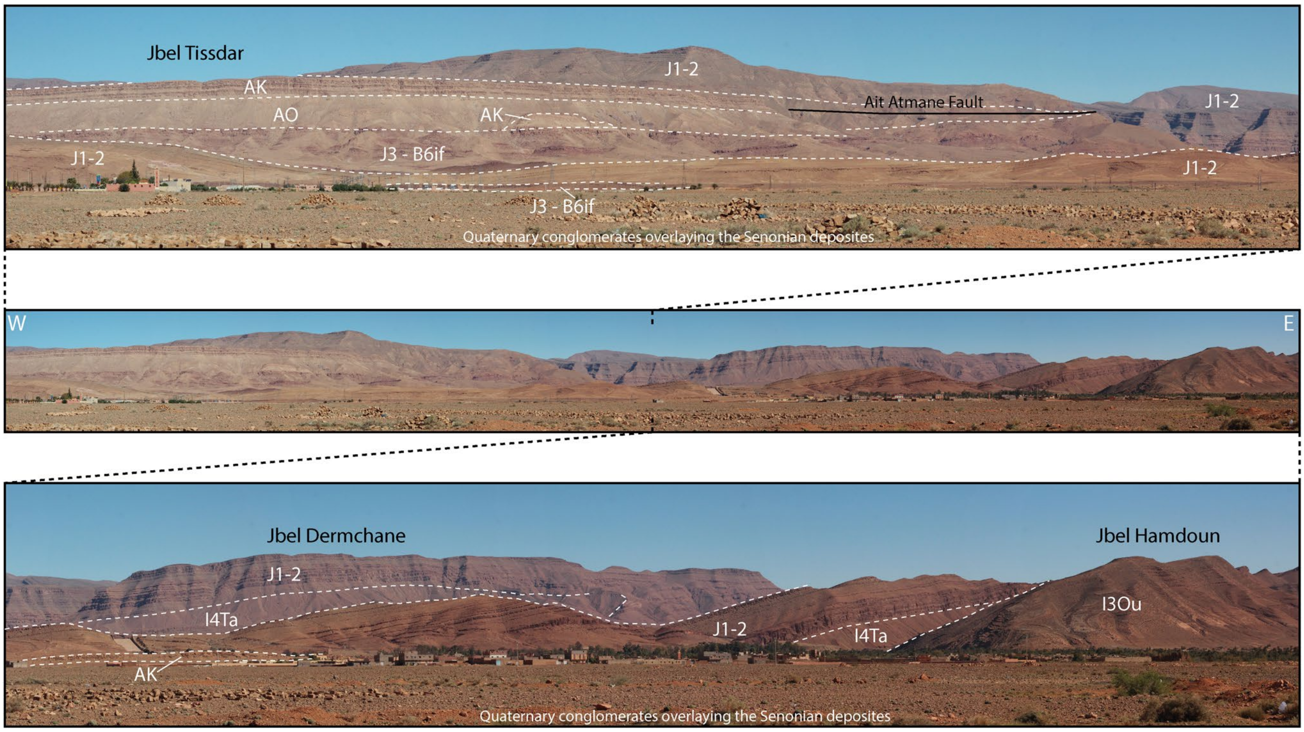


Fig. 6 Panoramic view of geosite ER1; AK: Cenomano-Turonian; AO: Cenomanian; B6if: Albian; J3: Bathonian; J1-2: Aalenian-Bajocian; I4Ta: Toarician; I4Ou: Pliensbachian

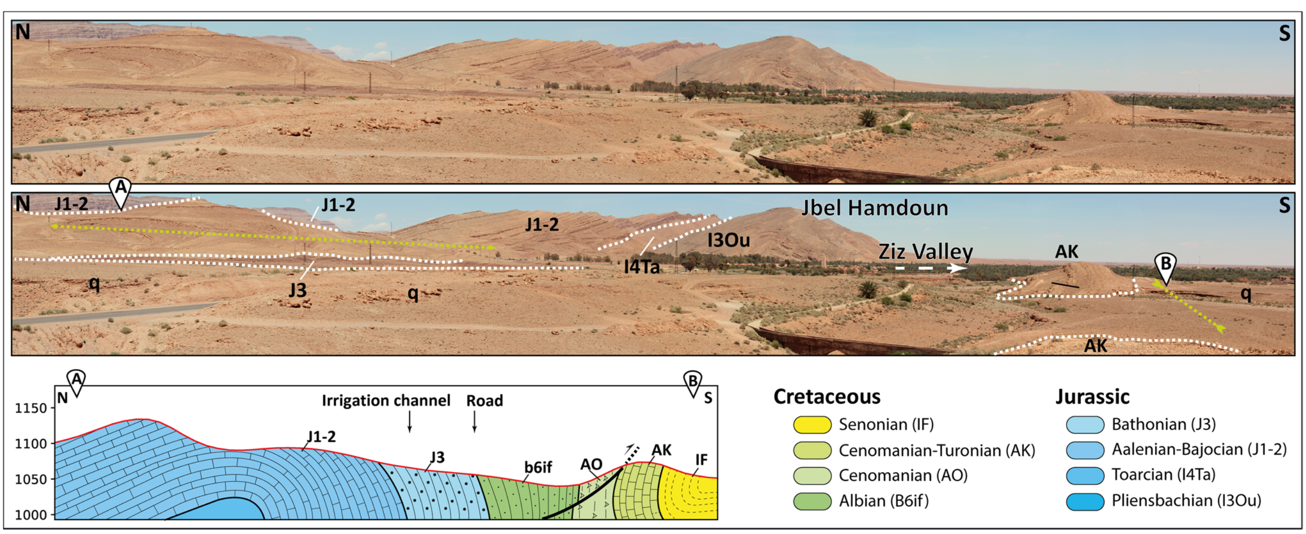


Fig. 7 Panoramic view and geological section illustrating the anticline related to the South Atlas Fault in geosite ER2

basins has important scientific and educational value. In addition, the Ziz Valley offers a beautiful landscape that adds to the overall aesthetic appeal of this geosite. This geosite has been divided into various sublocations, considered as secondary geosites.

Geosite ER3.1 is a panoramic view that allows us to see the anticline structure closely formed by folds with southern vergence (Fig. 9). The folded terrains are of Early and Middle Jurassic age (Kaoukaya et al. 2001). Their deformations are related to the different branches of the southern

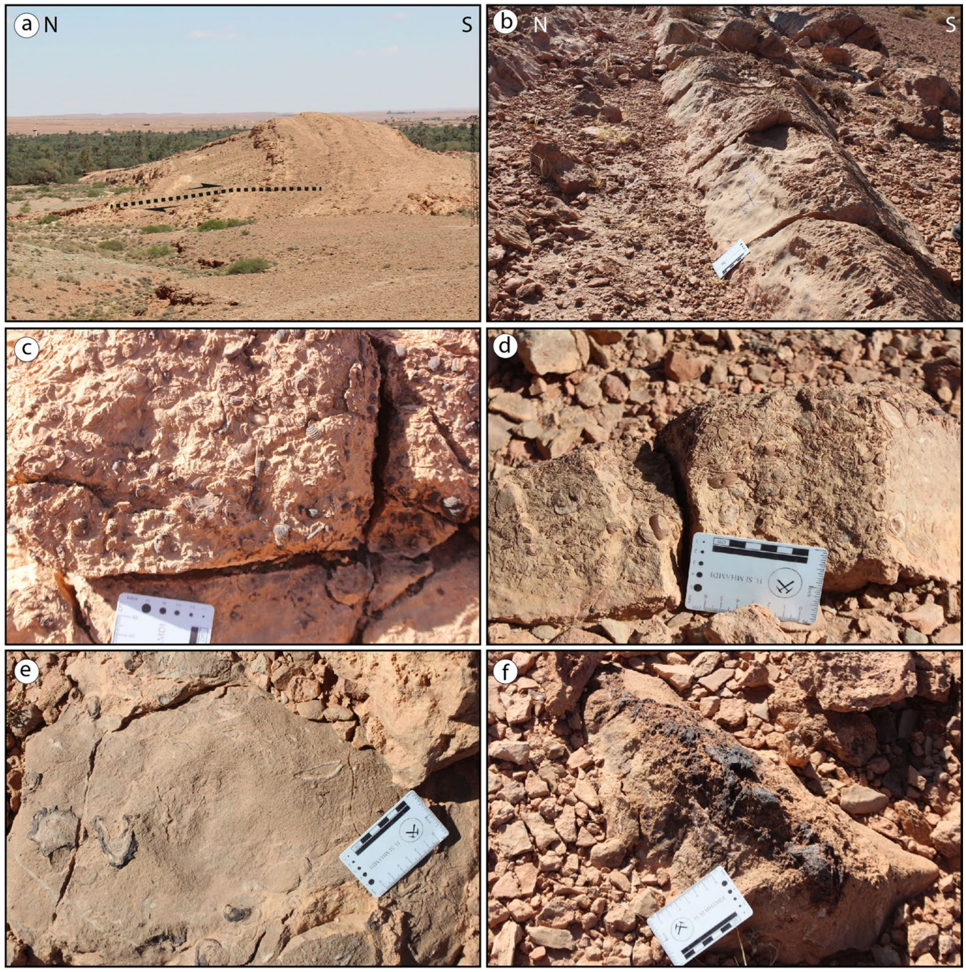


Fig. 8 Aspect of the Akrabou Formation of Cenomanian–Turonian age at the outcrop at geosite ER2: **a** north–south sinister break affecting the Akrabou Formation; **b** overturned limestone layers of the Akrabou Formation; **c–e** fossiliferous limestone layers; **f** limestone layers showing a ferruginous condensed surface

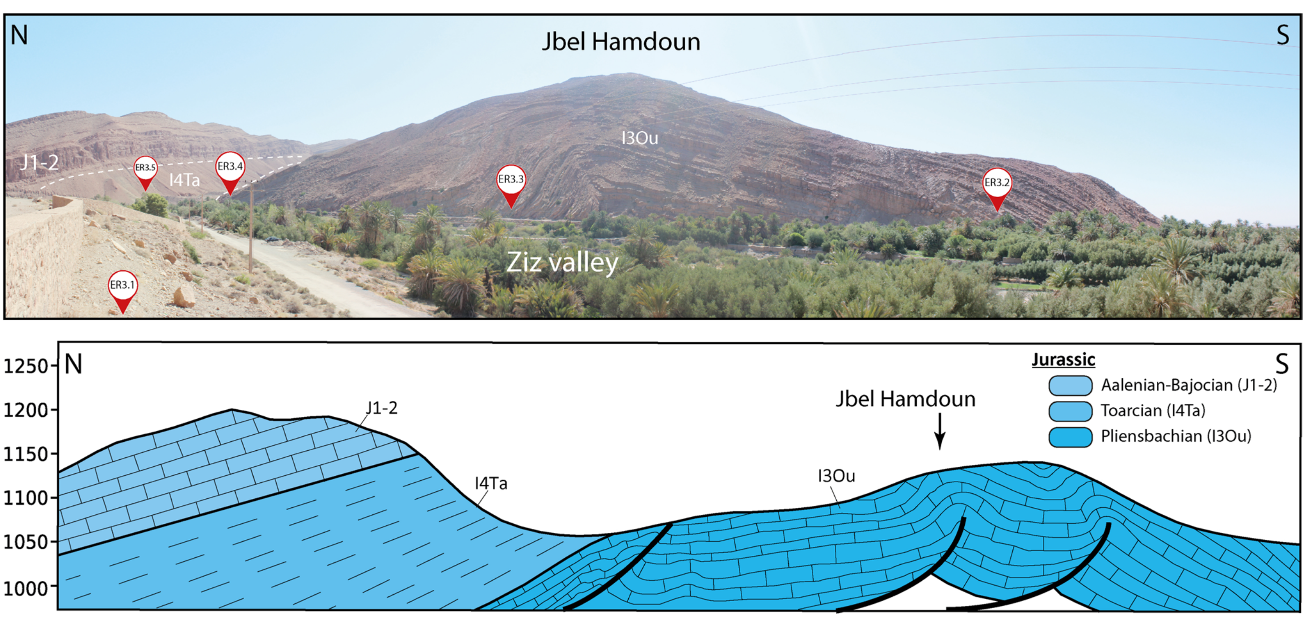


Fig. 9 Panoramic view and geological section illustrating the Jbel Hamdoun anticline (geosite ER3.1)

Atlassic blind fault (c.f. Paragraph 4.2). Other stops are pointed out in Fig. 9a.

Geosite ER3.2 shows one of the hinges of the anticline structures and several faults. We can also see the phenomenon of the sliding of layers resulting in the striated plane (Fig. 10a–c). On the limestone beds, we can see the stylolitic joints with their two modes of formation under lithostatic pressure or tectonic pressure (Fig. 10d, e). The first ones are parallel to the stratification planes and have a "U" shape, while the second ones are perpendicular to the stratification planes and have a "V" shape.

Geosite ER3.3 depicts various karst occurrences on a smaller scale (Fig. 10e, g, h). This occurrence is common in carbonate rocks, which are created by chemical dissolution in the presence of water that infiltrates between layers and through fractured zones.

Geosite ER3.4 displays a faulted zone with a generally east–west direction in harmony with the Atlas features (Fig. 11a, b). We also note the occurrence of Quaternary travertine in the form of encrustations (Fig. 11c).

Geosite ER3.5 shows highly fossiliferous marls (Fig. 11d–f), with the occurrence of brachiopods and lamellibranchs of the Jurassic age.

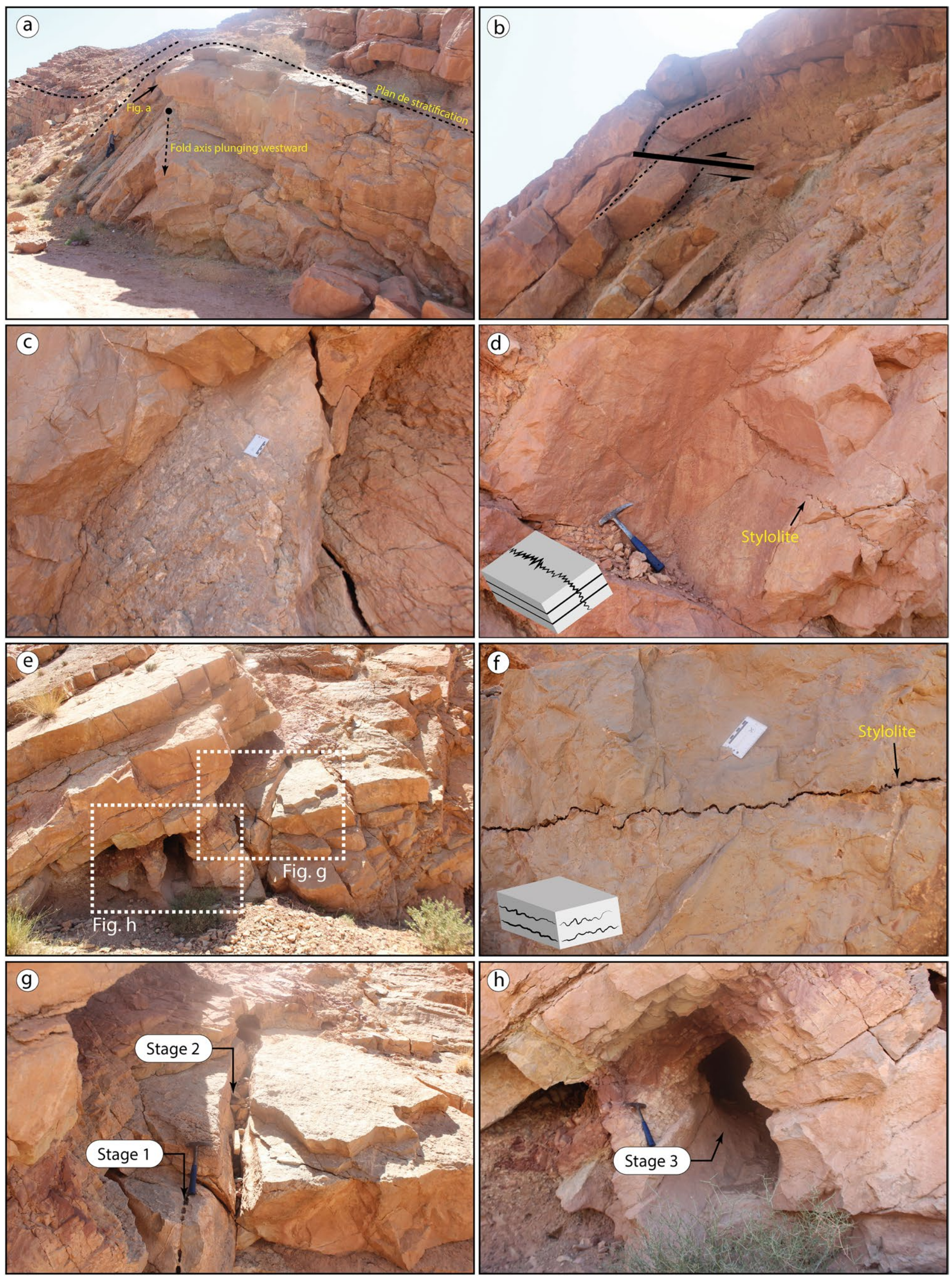


Fig. 10 *Geosite ER3.2*: **a** folding within the main Jbel Hamdoun anticline; **b** fault developed in the fold limb; **c** striated plane related to layers sliding; **d** lithostatic pressure stylolite; **e** tectonic pressure stylolite. *Geosite ER3.3*: **f–h** illustration of the karstification phenomenon development in the carbonates

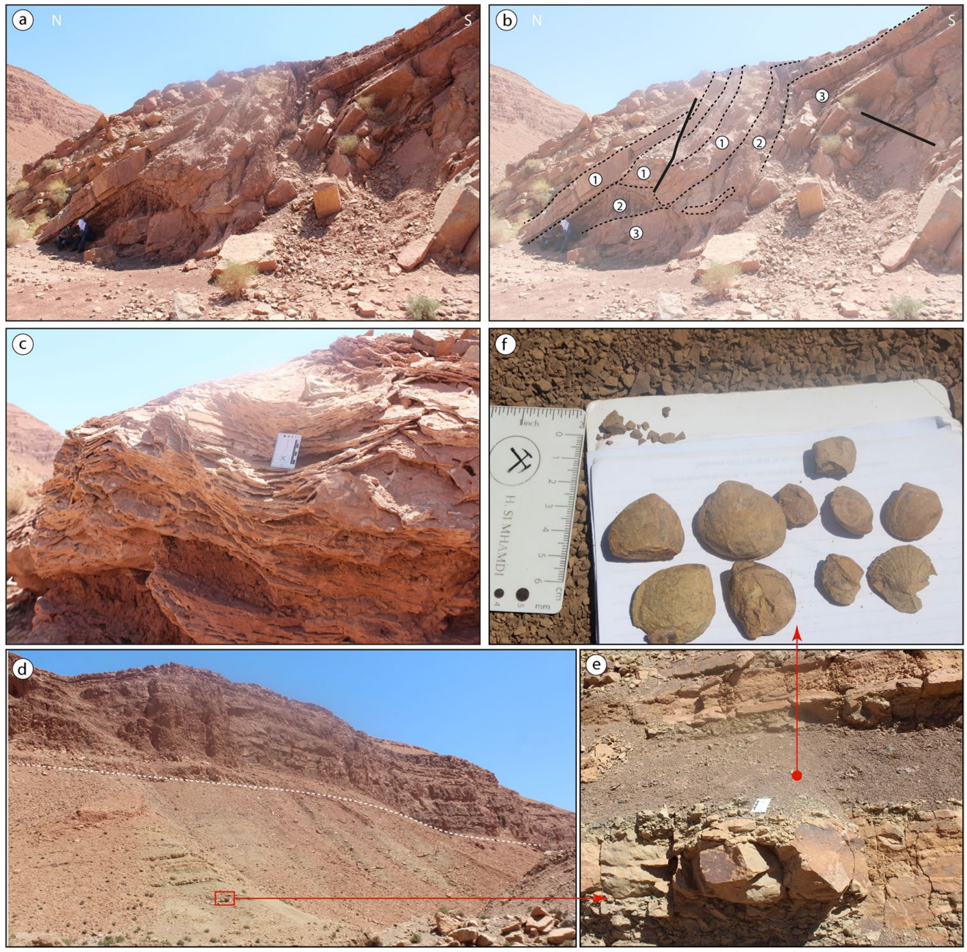


Fig. 11 *Geosite ER3.4*: **a**, **b** fault zone and its interpretation; **c** Quaternary travertine. *Geosite ER3.5*: **d** panoramic view showing the contact between the Toarcian and Aalenian-Bajocian outcrops; **e**, **f** marly limestones and fossiliferous marls of Toarcian

Geosite ER4: Jurassic/Cretaceous Contact

The Jurassic/Cretaceous contact is a very interesting topic in the Errachidia-Boudnib basin. On the one hand, it illustrates, with its facies diversification, a variation of depositional environments. On the other hand, this limit constitutes a debatable topic due to the lack of fossil records in order to place precisely this limit between the Jurassic and the Cretaceous (Haddoumi et al. 2010; Adardor et al. 2021; El Ouali et al. 2021). To follow this facies variation and depositional environment, we propose the stops described in the northern zone of the Tissdar Anticline (Fig. 12), to avoid any perturbation related to the work of the South Atlas Fault (geosite 2).

The panoramic view (Fig. 13) shows the contact between the Jurassic and Cretaceous formations. This sequence illustrates very well that the deposits are controlled by constantly changing sea levels. The last relief in this panorama depicts Bajocian strata that are thrust up by the Ait Atmane Fault (see Sect. 4.6).

Bajocian formations are formed by limestones and versicoloured marls with aligned and isolated reef structures called “patch reefs” in the summit part, indicating very particular conditions about an environment within the marine platform with high energy and good circulation. In the reef level shown in Fig. 14a, b, these reefs are prominent, plainly visible, and oriented heading eastward.

The Bajocian age rocks are overlain by red continental rocks of the Bathonian age. The latter are made up of conglomerates containing polygenic elements with a base marked by erosive surfaces. Subsequently, an alternation of conglomerate, sandstone and mudstone illustrate a continental environment attested by the occurrence of cross-stratified sandstones and channel deposits (Fig. 14c, d). Towards the top, the passage is not clear between the Jurassic and the Cretaceous. The Cretaceous is formed at its base by alternating clayey sandstones and siltstones with some very oxidized levels (Fig. 14f). These facies indicate a transition zone between the continental and marine environment, which is confirmed by gypsum marls

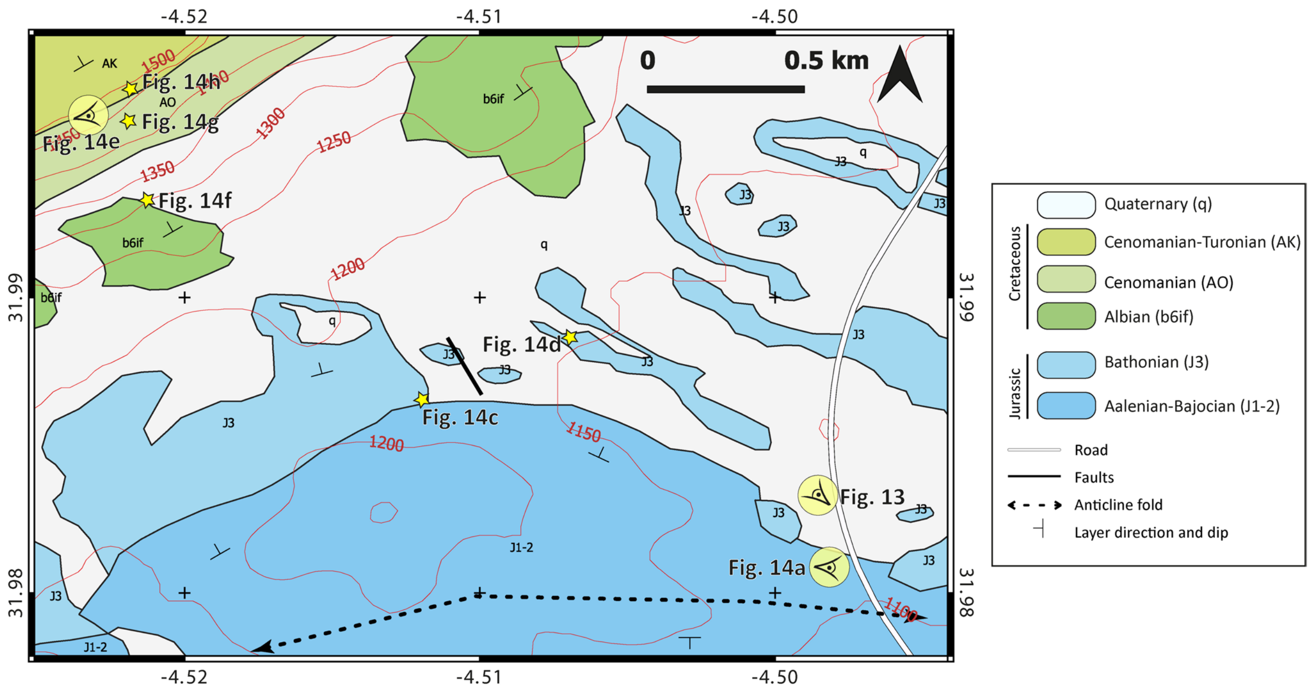


Fig. 12 Geological map with the location of the spots to follow the succession of the Jurassic and Cretaceous sequences

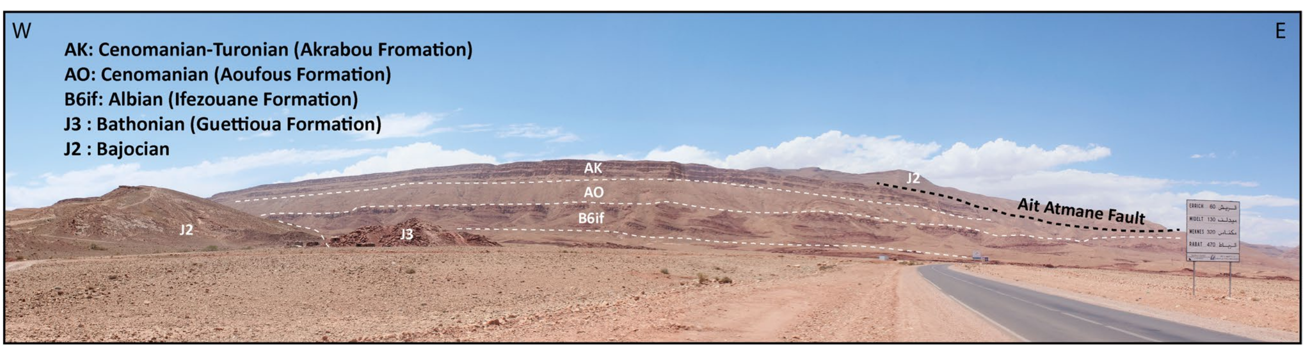


Fig. 13 Panoramic view illustrating Jurassic/Cretaceous formation contact in ER4

of the Cenomanian age, indicating a lagoon environment (Fig. 14g). This is followed by a marine platform on which carbonate sedimentation was deposited in the form of limestone bars of the Cenomanian–Turonian age. This level is described as a benchmark for the whole Boudnib basin (Fig. 14h).

Geosite ER5: Perched Syncline Between Two Atlassic Faults

This syncline is the result of the Atlassic tectonic uplift. It is bounded by anticlines related to the working of the Ait Atman Fault in the northeast and the South Atlas Fault in the south (Fig. 15). This structure between the two faults reflects all the structures that are located along the transverse between Errachidia and Midelt, corresponding to an alternation of tight anticlines (ridge anticlines) and flat-bottomed synclines. In the study area, this syncline has constituted a suitable area for the capture of the waters of Oued Ziz River into El Hassan Addakhil dam.

Geosite ER6: Ait Atmane Fault (Amzouj Fault)

The Ait Atmane Fault is located in the northern part of the study area (Ibouh 2004; Saddiqi et al. 2011). This fault was previously described by Baidder (1991) as the Amzouj Fault. It extends parallel to Jbel Dremchane

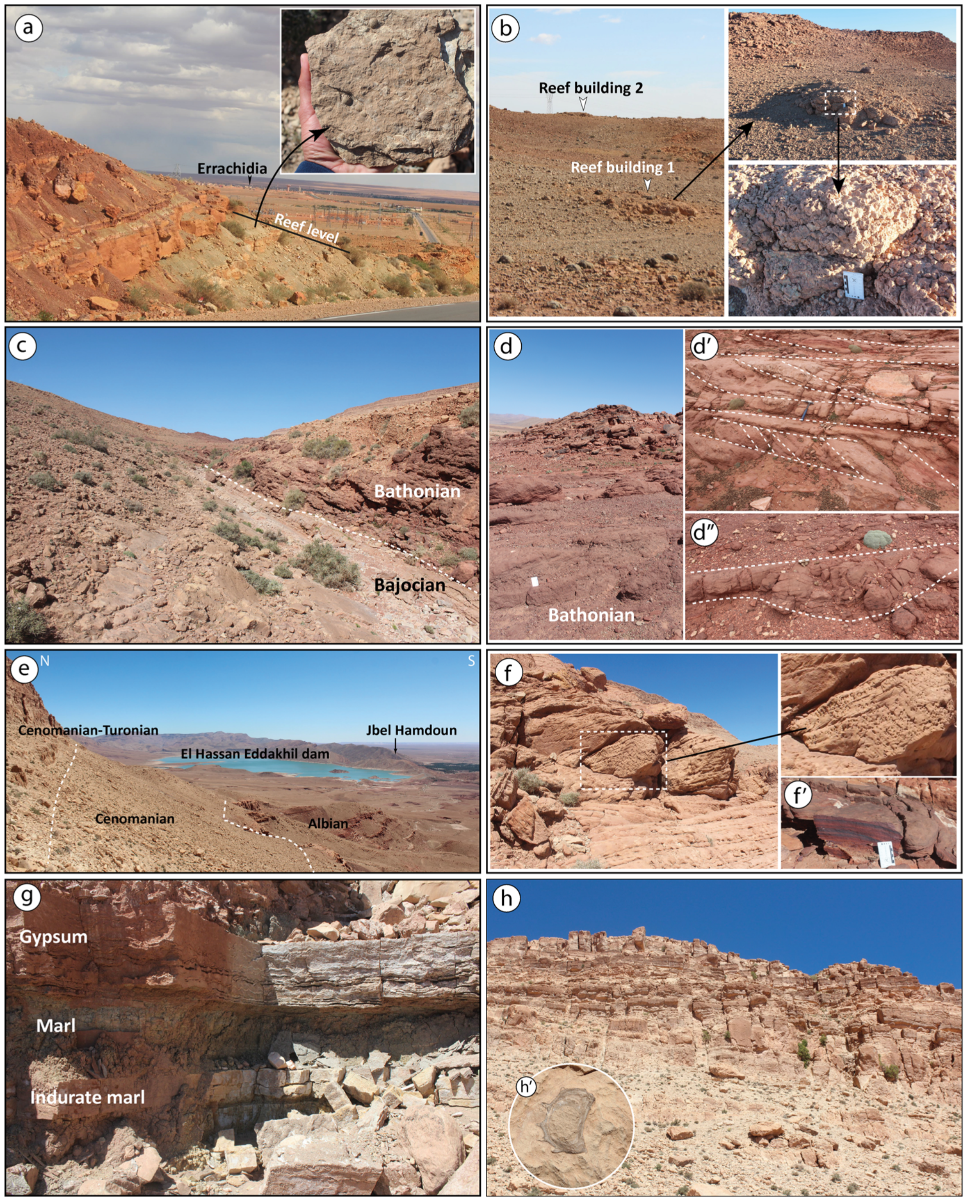


Fig. 14 Jurassic/Cretaceous contact at the geosite ER4: **a**, **b** fossiliferous limestones and marls of Bajocian age with reef edifices at the top; **c** Bajocian/Bathonian contact marked by erosive base conglomerates with polygenic elements; **d** sandstone and mudstone of Bathonian age showing fluvial deposit structures and cross-stratification and bioturbations; **e** panoramic view from Jbel Tissdar; **f** cross-stratified sandstone of Albian age containing *skolithos*-type bioturbations; **g** aspect of gypsum marls of Cenomanian age; **h** fossiliferous limestone of Cenomanian–Turonian age

in a mean direction N70° (Ibouh 2004; Saddiqi et al. 2011). This fault is a joint contact of many terrains of different ages (Fig. 5). To the southwest of the study area, this fault brings Jurassic and Cretaceous strata into contact, with a significant displacement, and develops an anticline structure at its end (Fig. 16; ER6.1). Moving westward, the fault joins Jurassic rocks in abnormal contact (Figs. 17 and 18; ER6.2 and ER6.3). This fault corresponds to a southward thrust, as attested by tectonic markers, the most visible of which are the folds showing a southward dip. To the northwest, in addition to the thrust, the Ait Atmane Fault shows a dextral component marked by folds with dipping axes.

Geosite ER7: Panorama of El Hassan Addakhil Dam

The structure to be observed at this geosite is similar to the structure observed at geosite 5 (Figs. 15 and 19). It corresponds to a large syncline whose centre is occupied by subhorizontal formations of the Jurassic age and whose limits are the South Atlassic fault in the South and the Ait Atmane Fault in the North.

Geosite ER8: Ait Atmane Biostromes and Reef Mounds

This stop offers the opportunity to explore a variety of different interests, as it encompasses a wide range of

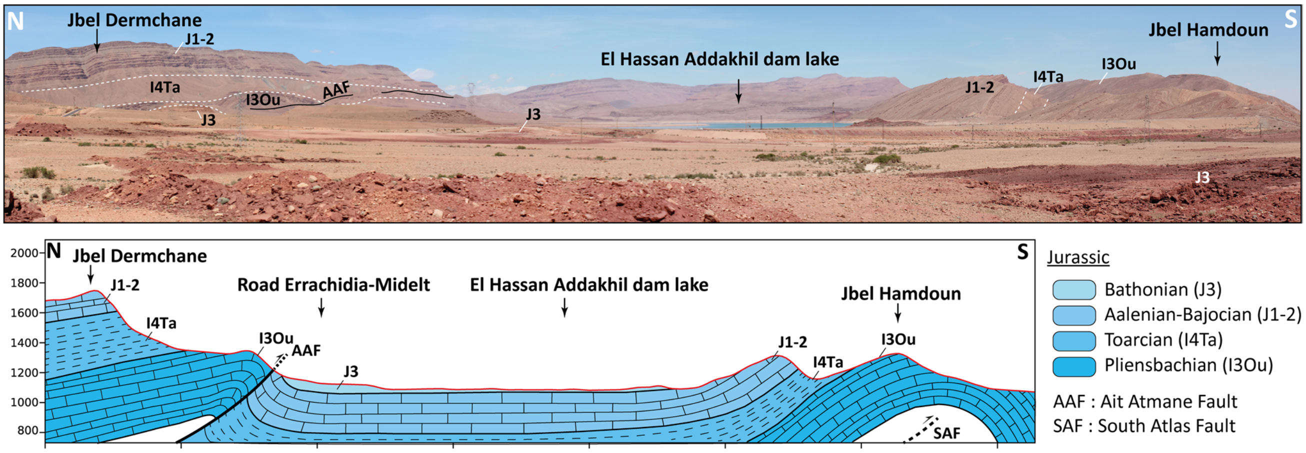


Fig. 15 Panoramic view and cross section illustrating the perched syncline structure (geosite ER5) between the South Atlas Fault and the Ait Atmane Fault

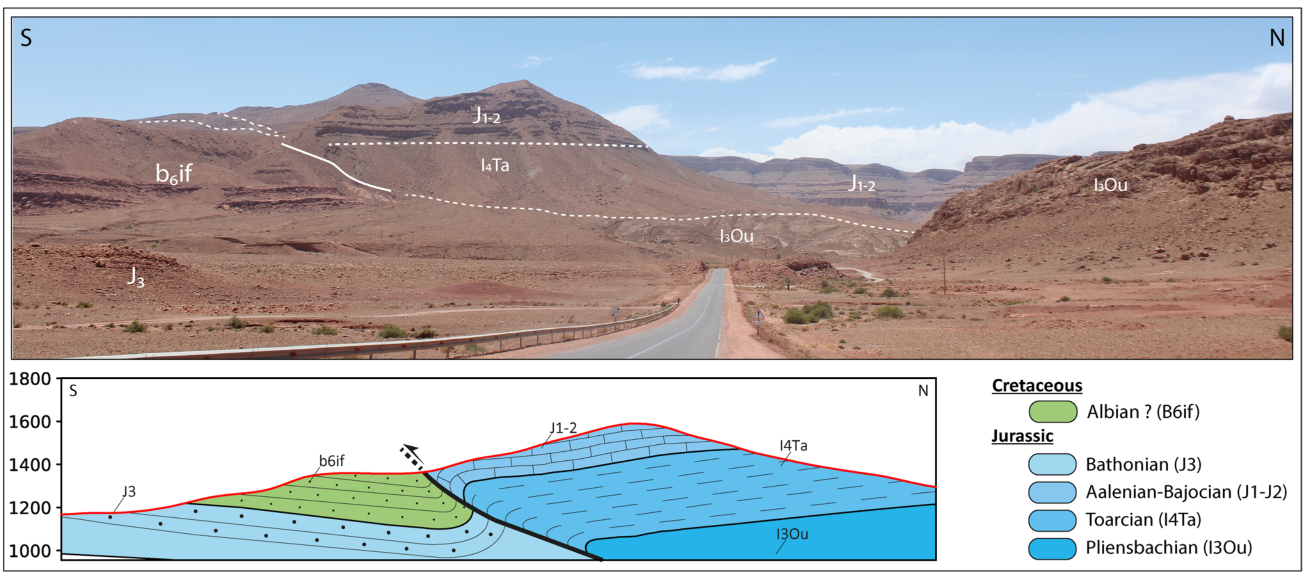


Fig. 16 Panoramic view and geological section illustrating the Ait Atmane Fault in geosite ER6.1

information about structural, lithostratigraphy, and geomorphology, but it has been specifically designed to present the fossil contents of biostromes and reef mounds from Ait Atmane of Pliensbachian age (Fig. 20).

Besides ordinary fossils of the marine limestones, the latter are distinguished by the occurrence of giant lamellibranchs (litiotidae) associated with gastropods and brachiopods (Kaoukaya et al. 2001; Brame et al. 2019). Some limestone layers show fossil remains, such as corals and sedimentary structures such, as pisolites. The latter are sedimentary rocks made up of concretionary grains (pisoids), mainly calcium carbonate, which look like ooids but are larger, between 2 and 10 mm in diameter. These grains are approximately spherical, with concentric laminated layers (Scholle and Ulmer-Scholle 2003). These structures (pisoids and reef structures) indicate the conditions of the rock formation in a very high-energy setting and are often found in the Pliensbachian.

Geosite ER9: Dermchane Waterfall

The waterfall of Dermchane is a geomorphological relief formed by the considerable fall of an abrupt watercourse with a height of about 8 m, on the plateau of Jbel Dermchane, downstream of the meandering structures. Precisely on the northern flank of the synclinal structure constituted by Jurassic age formations (Fig. 21). This geosite is very rich in ornamentation formed by calcites and travertine of variable shape and size (Fig. 21d). On

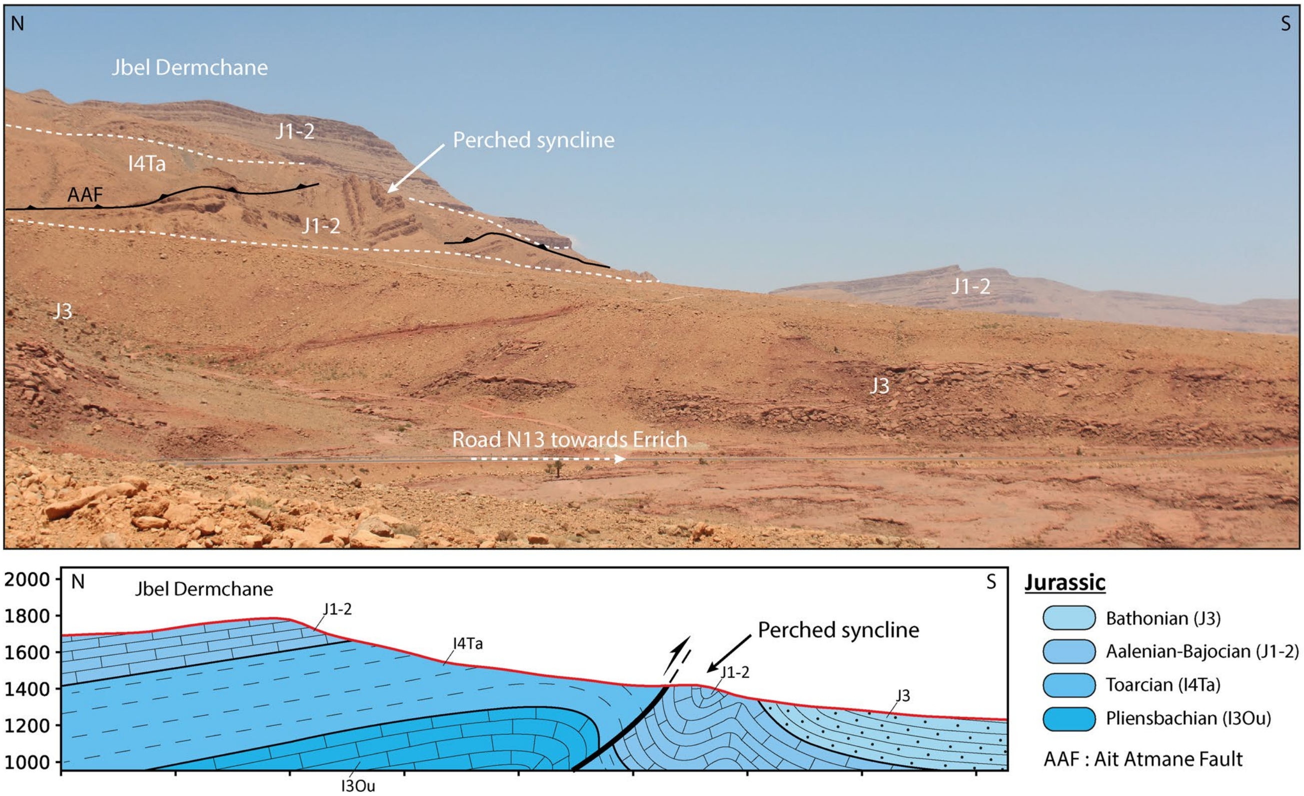


Fig. 17 Panoramic view and geological section illustrating the Ait Atmane Fault in geosite ER6.2

the one hand, in the cave, which corresponds to a zone of soft eroded material, speleothems develop by precipitation of calcite resulting from the solution of carbonates by CO_2-rich water. These structures are called "columns". They are stalactites and stalagmites that have become connected (Fig. 21e). On the other hand, the abrupt surfaces show draperies in the form of "Moroccan Bournous" (Fig. 21f).

Generally, the waterfalls occur in areas of abrupt geomorphology "cliffs" shaped by a difference in the competence of the rocks or by the existence of faults. In the literature, few works have tried to explain how waterfalls are formed, of which the best-known models are the following:

(i) The "headwall undercutting" model proposed by Gilbert (1890), which proposes a mechanism linked to the heterogeneity of the rocks where lateral mechanical erosion is ensured at the level of the soft rocks which are overlapped by hard rocks. In this case, the upstream retreat is favoured by a failure and fall of the hard rocks.

(ii) The "vertical drilling" model proposed by Howard et al. (1994) and Lamb et al. (2007). This model is also applicable in homogeneous terrains with an alignment of vertical drilling assimilated to small spaced waterfalls where successive vertical erosion allows the retreat of the upstream escarpment.

Besides these two models, more factors are controlling the mode of formation and development of waterfalls, such as water-current velocity parameters and sedimentation in the basin (Scheingross and Lamb 2017).

Based on our field observations, the most appropriate model of formation for the Dermchane waterfall is the "headwall undercutting" model (Gilbert 1890), where the hard formations correspond to limestones and dolomitic limestones of the Aaleno-Bajocian age and the soft formations correspond to marls of the Toarcian age (Fig. 21g).

Quantitative Assessment of Geosites

The inventory of the geological heritage of the northern part of the Errachidia area was carried out taking into account the quantitative assessment of the scientific values (SV), the

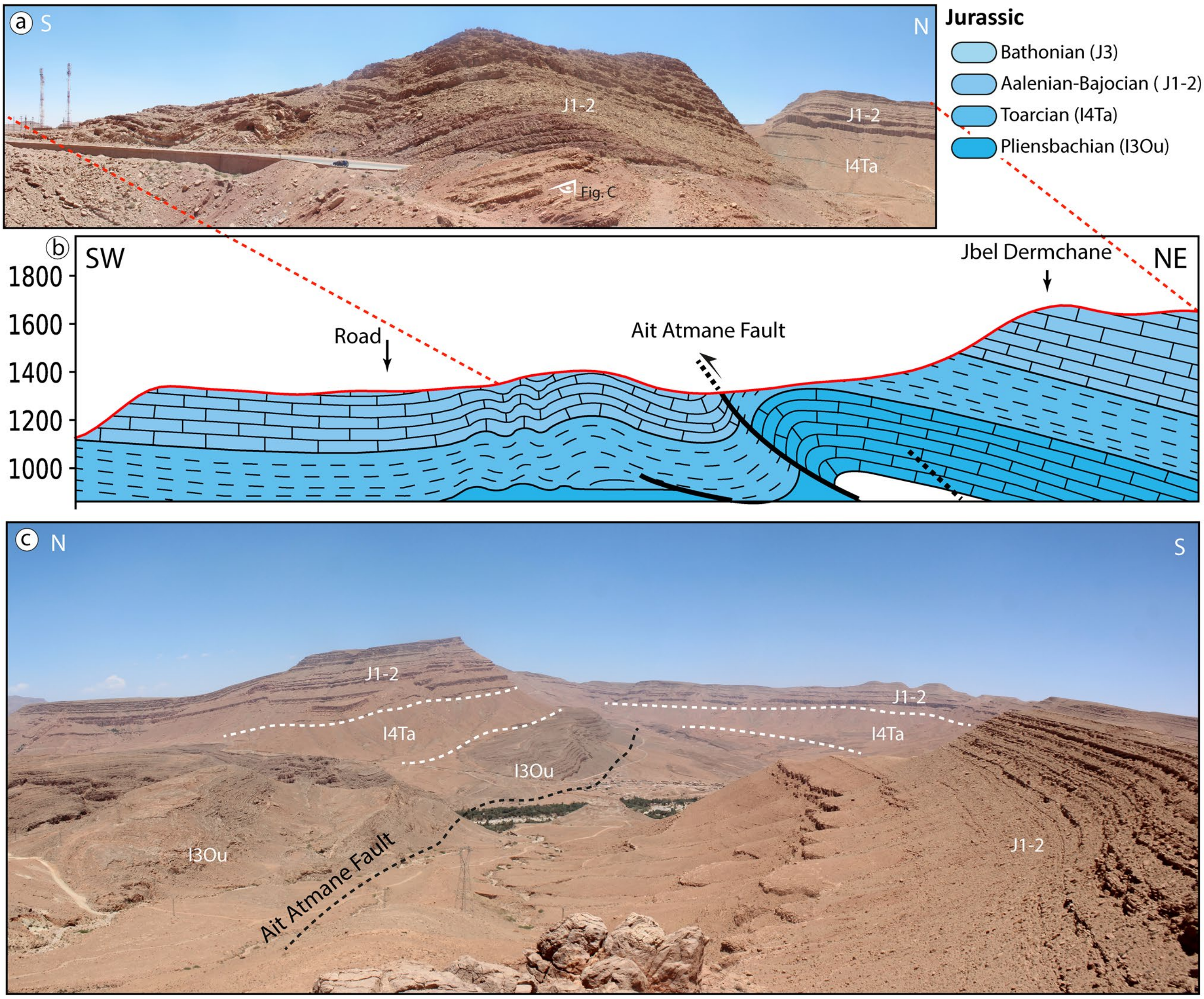


Fig. 18 Geosite ER6.3: **a**, **b** panoramic view and a geological section illustrating the geometry of the tectonic structures; **c** panoramic view showing Jurassic age facies and the Ait Atmane Fault

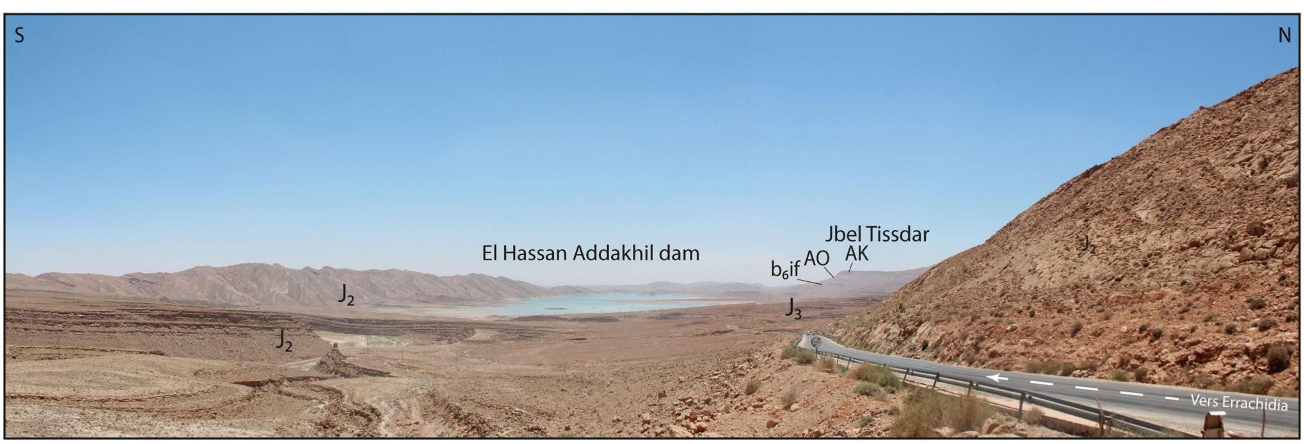


Fig. 19 Panoramic view in front of El Hassan Addakhil dam (looking east); AK: Cenomano-Turonian; AO: Cenomanian; B_6if: Albian; J3: Bathonian; J2: Bajocian

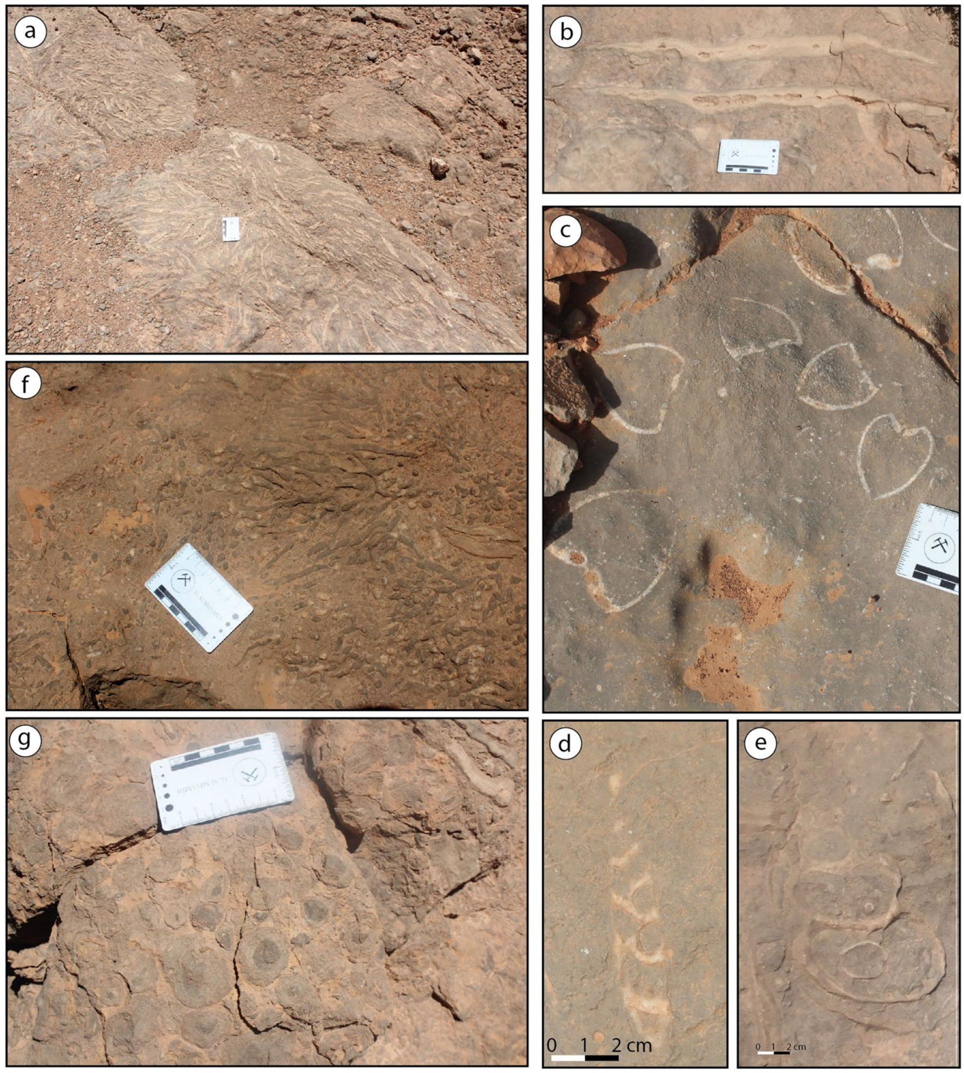


Fig. 20 Fossils from Ait Atmane biostromes and reef mounds: **a** limestones with giant lamellibranchs (litiotidae); **b** two valves of litiotidae; **c** megalodontid bivalve; **d**, **e** fusiform and turriculated gastropods; **f** coral reef; **g** pisolites (oncoids)

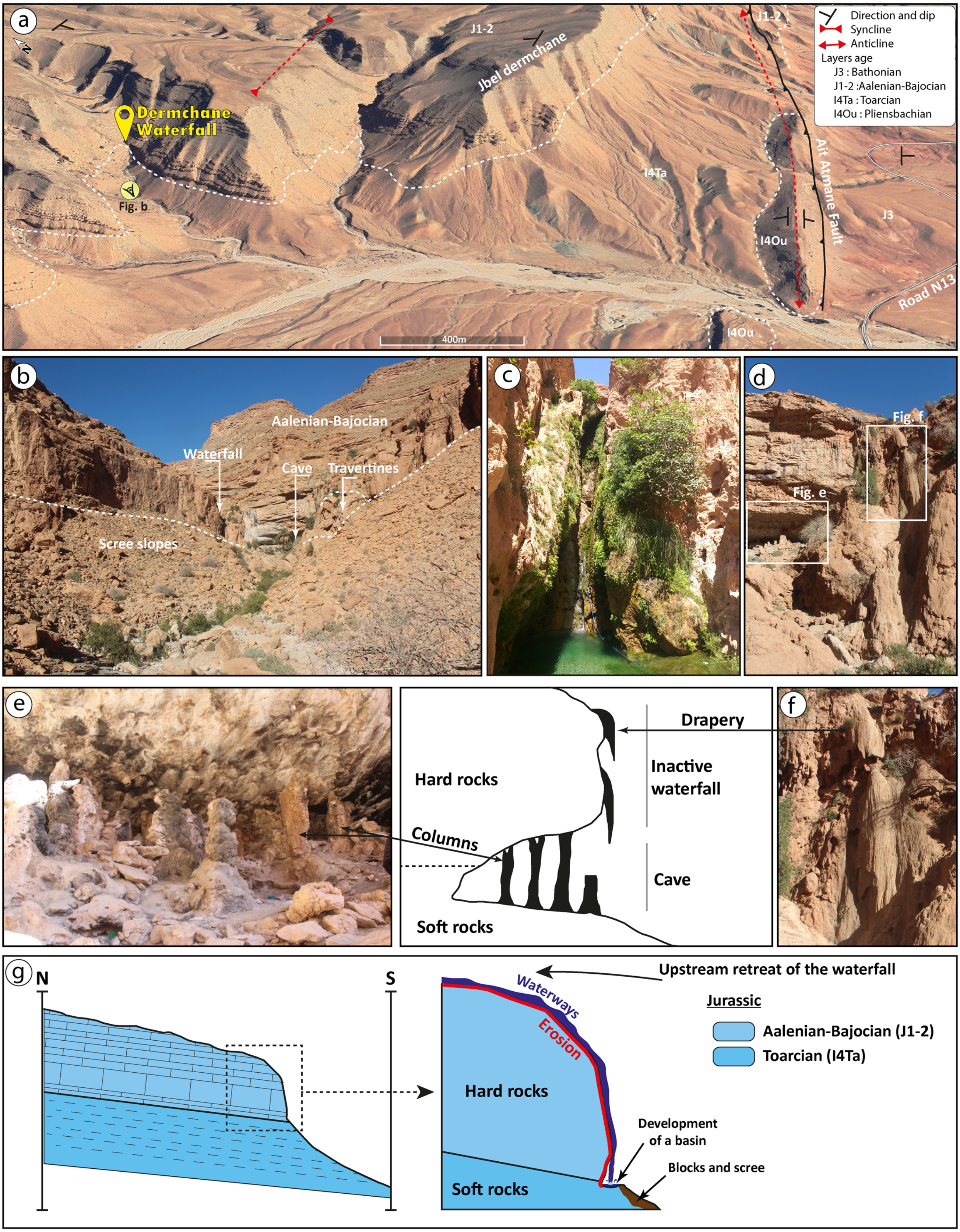
potential for educational use (PEU), the potential for tourism use (PTU) and the degradation risk (DR) of geosites (Table 3).

- *Scientific Values*

The assessment results show that the majority of the studied geosites have a highly scientific value of between 60 and 90%, except for the panoramic view ER1, which has a score of 43.75% (Table 3). Despite this value, geosite ER1 is of great importance since it offers a landscape view that encompasses most of the geosites proposed in the present trail. The high scientific values reflect a geological history of more than 200 Ma that will be described in this area, which involves a diversity of illustrative themes for a transdisciplinary application. The scientific values of geosites are greatly improved by several factors, including their significance for the advancement of geoscience knowledge and the preservation of the sites for future research. The selected geosites are representative and constitute key localities that will serve as important international references in various fields of study, such as structural geology (e.g. ER1, ER2, ER3, ER5 and ER6 for studying the tectonic of the foreland basin and the transition between the High Atlas and Anti-Atlas mountains), stratigraphy (e.g. ER4 to study the paleoenvironment and the sequence stratigraphy of Jurassic and Cretaceous strata), and paleontology (e.g. ER2, ER3, ER4 and ER7 that focuses on the fossils and ichnofacies of the Cretaceous and Jurassic periods).

- *Educational Values*

Across this assessment, all geosites have high educational values, ranging from 77.5% to 88.75% (Table 3). These scores are so high due to the many criteria, including the geological diversity that provides the opportunity to discuss several themes. Moreover, the geological elements are observed in good conditions and present favourable accessibility and



a
J1-2
Jbel dermchane
Dermchane Waterfall
Fig. b
I4Ta
I4Ou
J3
Ait Atmane Fault
Road N13
400m
Direction and dip
Syncline
Anticline
Layers age
J3 : Bathonian
J1-2 :Aalenian-Bajocian
I4Ta : Toarcian
I4Ou : Pliensbachian
b
Aalenian-Bajocian
Waterfall
Cave
Travertines
Scree slopes
c
d
Fig. f
Fig. e
e
Drapery
Hard rocks
Inactive waterfall
Columns
Cave
Soft rocks
f
g
N
S
Upstream retreat of the waterfall
Waterways
Erosion
Jurassic
Aalenian-Bajocian (J1-2)
Toarcian (I4Ta)
Hard rocks
Development of a basin
Blocks and scree
Soft rocks

◂**Fig. 21** **a** Google Earth panoramic view showing the geology and the access to Dermchane waterfall. **b** Panoramic view near Dermchane waterfall. **c** Dermchane waterfall. **d–f** Speleothems. **g** Cross section in Dermchane waterfall areas and the illustration of its model of formation "headwall undercutting"

safety parameters as the majority of geosite are located near the road except for the geosite ER9. Consequently, we note the copulation of both educational and scientific. Incorporating these geosites into the education process at all educational levels provides a unique opportunity for students and researchers to study geological features and processes in their natural environment (Fig. 22), which is not possible in a traditional classroom setting. Additionally, geosites can serve as a valuable resource for environmental education, raising awareness about issues such as climate change and conservation.

- *Touristic Values*

The geosites on this trail show a high tourism potential, with percentages between 75% and 86.25% (Table 3). These values are not consistent with educational values. Indeed, the geosites show low tourist values compared to the educational values, but overall, the differences between 2.5% and 5% remain of less importance. The high score of tourism values in this area is due to the aesthetic appeal of geological mountains, canyons, oasis, waterfall, and lake dam, which make the area attractive and easy to understand with low risk.

- *Degradation Risk*

The majority of geosites exhibit degradation risk values between 205 (51.25%) and 265 (66.25%) (Table 3). According to the classification of Brilha (2016), these values denote moderate degradation. Only the ER4 geosite shows a low degradation value of 190 (%). The majority of geosites currently show no signs of degradation. However, we must point out the geosites that are likely to eventually be damaged by the risk of landslides or pollution caused by waste left on site by temporary visitors to this natural environment, especially the geosites of Jbel Dermchane (ER9) and Jbel Hamdoun (ER3) (Fig. 23). Other geosites may be the result of future degradation, as is the case for the secondary geosite (ER6.3) relating to the fault of Ait Atmane. Any future development of the road between Ait Atmane and Errachidia could have direct consequences for the destruction and loss of visibility of the fault. It is recommended that consultations must be held before working on land development projects so as not to lose the scientific, educational and geotouristic heritage of the region in an inattentive manner.

The northern itinerary of Errachidia offers a wide range of features. The quantitative assessment showed mainly the proposed geosites as having a high potential for scientific, educational, and tourist use. However, the panoramic views have more educational and touristic values than scientific ones.

Conclusion and Recommendations

In the light of the assessment and evaluation of the inventoried geosites, the methodology was considered appropriate for this context, thus providing a basis for further surveys and assessments that will be conducted on other geosites of regional importance. This methodological approach that we are developing for the trail in Errachidia area fits into our strategic vision of the preservation and enhancement of natural areas and landscapes of the Draa Tafilalet region.

Beyond the characterisation of their scientific, educational, and tourist interests, this will have an additional socio-economic impact on the area. Hence, geoheritage is significant for several reasons.

Table 3 Quantitative assessment of SV, PEU, PTU and DR of geosites

Code	Geosite	SV		PEU		PTU		DR	
		Value	%value	Value	%value	Value	%value	Value	%value
ER1	Panorama of the Atlas front	175	43,75	325	81,25	315	78,75	205	51,25
ER2	South Atlas Fault	330	82,5	345	86,25	335	83,75	205	51,25
ER3	Jbel Hamdoun anticline	360	90	350	87,5	330	82,5	205	51,25
ER4	Jurassic/Cretaceous contact	330	82,5	345	86,25	325	81,25	190	47,5
ER5	Perched syncline between two Atlassic faults	280	70	355	88,75	345	86,25	205	51,25
ER6	Ait Atmane Fault	330	82,5	350	87,5	340	85	240	60
ER7	Ait Atmane biostromes and reef mounds	270	67,5	350	87,5	340	85	205	51,25
ER8	Panorama of El Hassan Addakhil Dam	240	60	355	88,75	345	86,25	205	51,25
ER9	Dermchane waterfall	295	73,75	310	77,5	300	75	265	66,25

Fig. 22 Photos from fieldwork in the southern front of the central High Atlas. **a**, **b** Errachidia area. **c** Goulmima area

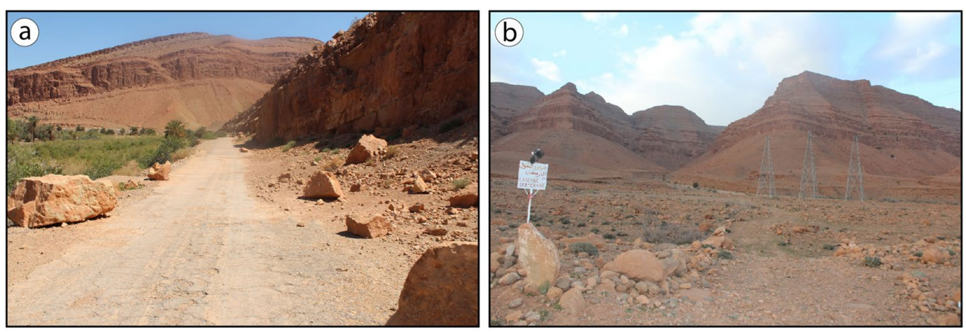


Fig. 23 **a** Landslide at the Jbel Hamdoun geosite. **b** Undeveloped access to the Dermchane waterfall geosite

Fig. 24 Example of a proposed panel

Fig. 25 Example of a geological exhibition at the Faculty of Science and Techniques Errachidia (FSTE)

Scientific Value Geoheritage provides valuable insights into the Earth's history, geology, and evolution of life. Such information is crucial for understanding the planet and its natural processes. Through geoheritage, researchers will interact easily with the public and share their scientific findings.

Educational Value Geoheritage can be used as an educational resource for students in geology and earth science. Moreover, it can be important to educate visitors about preserving biodiversity and ecological processes.

Touristic and Economic Value Geoheritage will participate in supporting local economies by attracting visitors and creating jobs in the tourism, valorisation and conservation sectors.

Studying geoheritage typically involves a multidisciplinary approach, from inventory to geoconservation. The latter implies a clear strategy for the identification, protection, and management of valuable elements of geodiversity. In this context, we intend to proceed with the realisation of a database of the trails, as well as the connection of these trails with other trails in the region or outside the region.

As researchers, we have proceeded to the realisation of the necessary documentation for the organisation of educational field trips (universities, high schools, etc.), as well as the promotion with tourist agencies and the media by producing geotrail maps, guide books and the proposal of panels of geosites (Fig. 24). We are also considering the installation and enhancement of a university museum, likewise the geological exhibition in the Department of Geosciences of the Faculty of Science and Techniques of Errachidia (Fig. 25). This exhibition is a valuable resource for visitors of all ages and backgrounds. It can support research by offering geological collections that can be used by students for research purposes or as supplementary educational resources to enhance learning. Moreover, the exhibition constitutes an area to connect with the public (school groups, families, and the general public) and share researchers' results.

Another aspect could be developed in order to make geosites popular tourist destinations in this area, such as hiking, rock climbing, and nature observation.

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Author Contribution H. Si Mhamdi: writing original draft, conception and design. H. Si Mhamdi, A. Charroud and A. Alali: acquisition of data. H. Si Mhamdi and M. Oukassou: analysis, interpretation. A. Charroud, M. Oukassou, L. Baidder and M. Raji: reviewing, validation. A. Ijaajaane, S. lfaiz, S. Elouariti: quantitative assessment.

Data Availability The authors confirm that the data supporting the findings of this study are available within the article. Supplementary data are available on request from the corresponding author.

Declarations

Conflict of Interest The authors declare no competing interests.

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