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ORIGINAL ARTICLE

Geomorphosite Inventory of Apollonia and Cyrene in Northeast Libya: involvement in Geotourism Promotion

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Abstract

Libya is located on the southern shore of the Mediterranean Sea in the northern part of Africa. Geomorphological landforms known as geomorphosites are those that have been seen or exploited by humans as having scientific, cultural/historical, aesthetic, or social/economic significance. Various geomorphosites transverse Libya and can be found in other parts of the world. United Nations Educational Scientific and Cultural Organization (UNESCO) geoparks need to conduct a comprehensive inventory of such geomorphosites to protect, promote, and geoconserve these sites for future generations. Geotourism promotion in Libya offers a great opportunity for the local community to grow and prosper. Additional African and developing countries with attractive geosites and landforms that can be promoted as geotourism destinations should be included in this initiative. The present study evaluates and assesses the geomorphosites in Cyrene and Apollonia. These sites are considered to possess regional importance, whose particular archeological and world heritage sites are indexed in UNESCO World Heritage, which makes the region a unique study subject. The area is highly recommended to be a geopark. Libya's substantial geological assets, notably geoheritage, are enhanced in this study. These resources can promote local, sustainable development through scientific research, educational initiatives, geotourism expansion, and diversification of Libya's isolated desert areas.

Keywords Geomorphosite · Geoheritage · Geosites · Apollonia · Cyrene · Libya

Introduction

Libya stretches along the northern coast of Africa for over 1,600,000 km^2 (Fig. 1). It has a population of approximately 6,871,000 people (as of 2020). Even though most of Libya is located in the Sahara Desert, it consists of three climatogeographic zones: the Mediterranean, a semi-arid zone, and a desert zone with some rich oases. The Mediterranean zone experiences an annual rainfall of as high as 600 mm and has a climate comparable to some parts of southern Europe. However, going southward, this zone gradually yields to intense desert conditions (Goudarzi 1970). Libya is a cratonic basin at the northern edges of the African Shield. Southcentral, southeastern, and west central Libya are home to Precambrian igneous and metamorphic rocks. Basalts and phonolites from the Tertiary and Quaternary periods straddle considerable areas in central Libya, including minor areas in southcentral and northwestern Libya. Most of southern Libya, i.e., south of latitude 28°N, comprises Paleozoic rocks and Mesozoic continental deposits. The Hamada al Hamra plateau in northwest Libya is formed by Mesozoic sedimentary rocks that are primarily covered by a thin veneer of early Tertiary sedimentary rocks. Other Tertiary rocks cover almost all the central and northeastern regions in the country, including some lesser parts in southcentral

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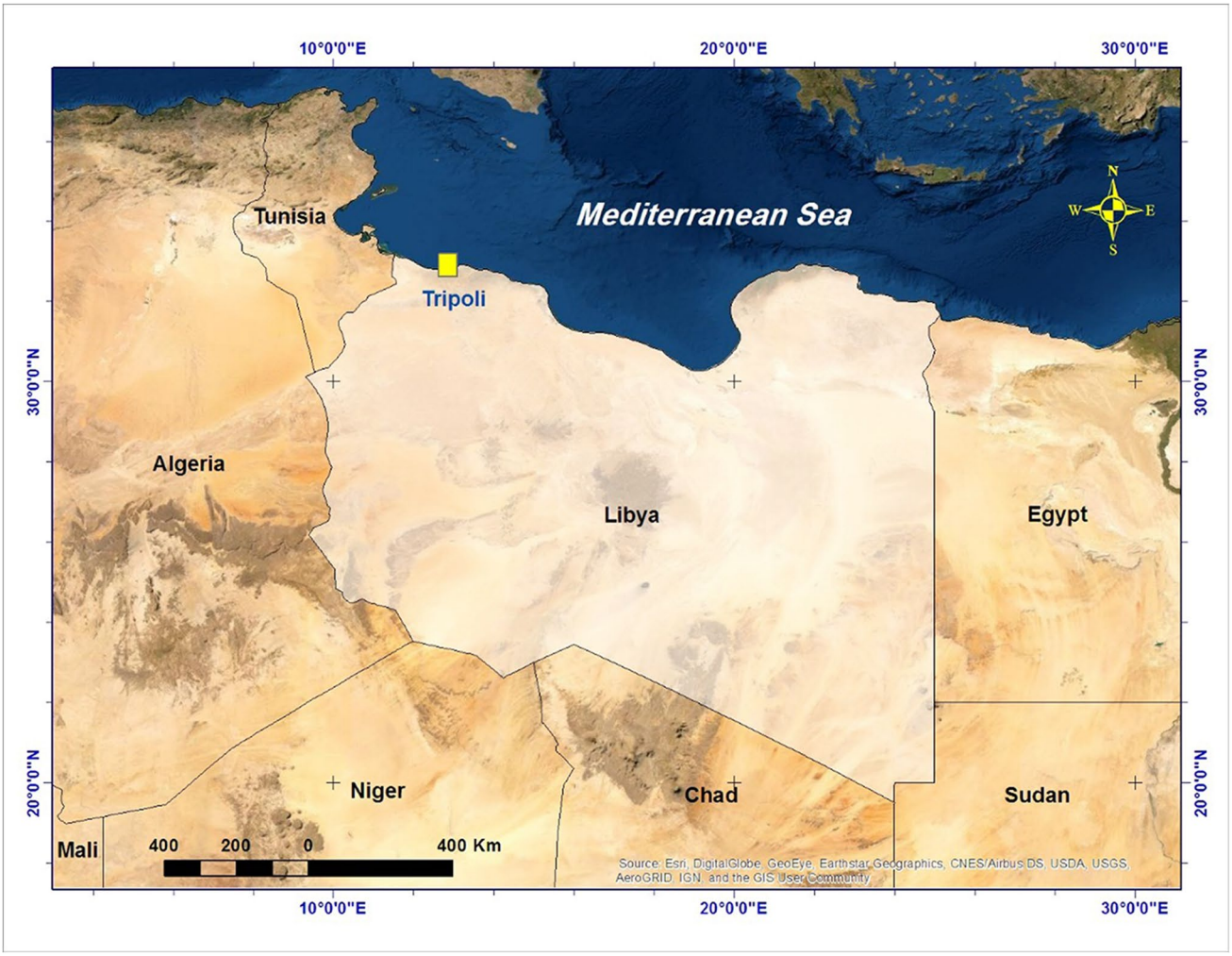

Fig. 1 Location map of Libya and neighboring countries

Libya. The narrow coastal plains are mostly covered with Quaternary deposits, and sand dunes and gravel plains cover a third of the country.

Geological legacy is a valuable resource related to the geodiversity of an area, which may be exploited for educational, scientific, and tourism purposes, similar to other geological resources (Eder and Patzak 2004; McKeever and Zouros 2005; Ruban 2017). Geotourism, as defined by Dowling (2011), is sustainable tourism that focuses on the geologic legacy of Earth in the form of distinctive features that promotes environmental and cultural awareness and conservation as well as being locally beneficial. Dowling also believed that trustworthy geotourism is based on the following five key principles: (1) it is geologically based, i.e., it is based on the Earth's heritage, (2) sustainable, i.e., it is economically viable and community-enhancing as well as promotes geoconservation, (3) instructive, which is achieved through geointerpretation, (4) locally beneficial, and (5) generates tourist satisfaction. Informal education may be considered a geotouristic activity, and formal education can adopt geoparks as an instructional resource, resulting in increased geoconservation awareness (Henriques et al. 2012).

The UNESCO Global Geoparks (UGGs) are a single undivided geographic region where international geologically significant monuments and landscapes are maintained by employing a comprehensive approach toward conservation, education, and sustainable development (UNESCO 2016; McKeever and Narbonne 2021). The UGG's goal includes geology with worldwide significance, which is objectively evaluated by scientific specialists and exploited as a sustainable economic asset for the people who live in this area, for example, through the development of responsible tourism (IGCP 2012). A sustainable development plan, which includes geoeducational programs, is required for people who live in an

area that desires to become an UGG. Here, sustainable tourism is a current method of realizing UGG through the development of walking or cycling trails, training local people to serve as guides, and creating innovative local enterprises for accommodation similar to educational activities (Dowling 2009; Henriques and Brilha 2017).

The current study investigates the geological heritage in Apollonia and Cyrene cities in northeast Libya (Fig. 2) to accomplish their role in promoting sustainable development through geotourism and education while considering people with functional diversity and establishing a geopark to geoconserve this geoheritage as stated by Panizza and Piacente (2008).

Geological Setting and Stratigraphy of the Investigated Area

Al Jabal Al Akhdar, northeast Libya, represents an uplifted tectonic element in the northeastern part of Libya, which lies south of the Mediterranean Sea (Fig. 3). The evolution of Al Jabal Al Akhdar is studied in detail, and it is considered a tectonically inverted basin (Röhlich 1980; Elwerfally et al. 2000; El Hawat and Abdulsamad 2004). Al Jabal Al Akhdar consists of two main escarpments, where the lower and upper escarpments rise up to 300 and 600 m above sea level, respectively. However, the third minor escarpment has a

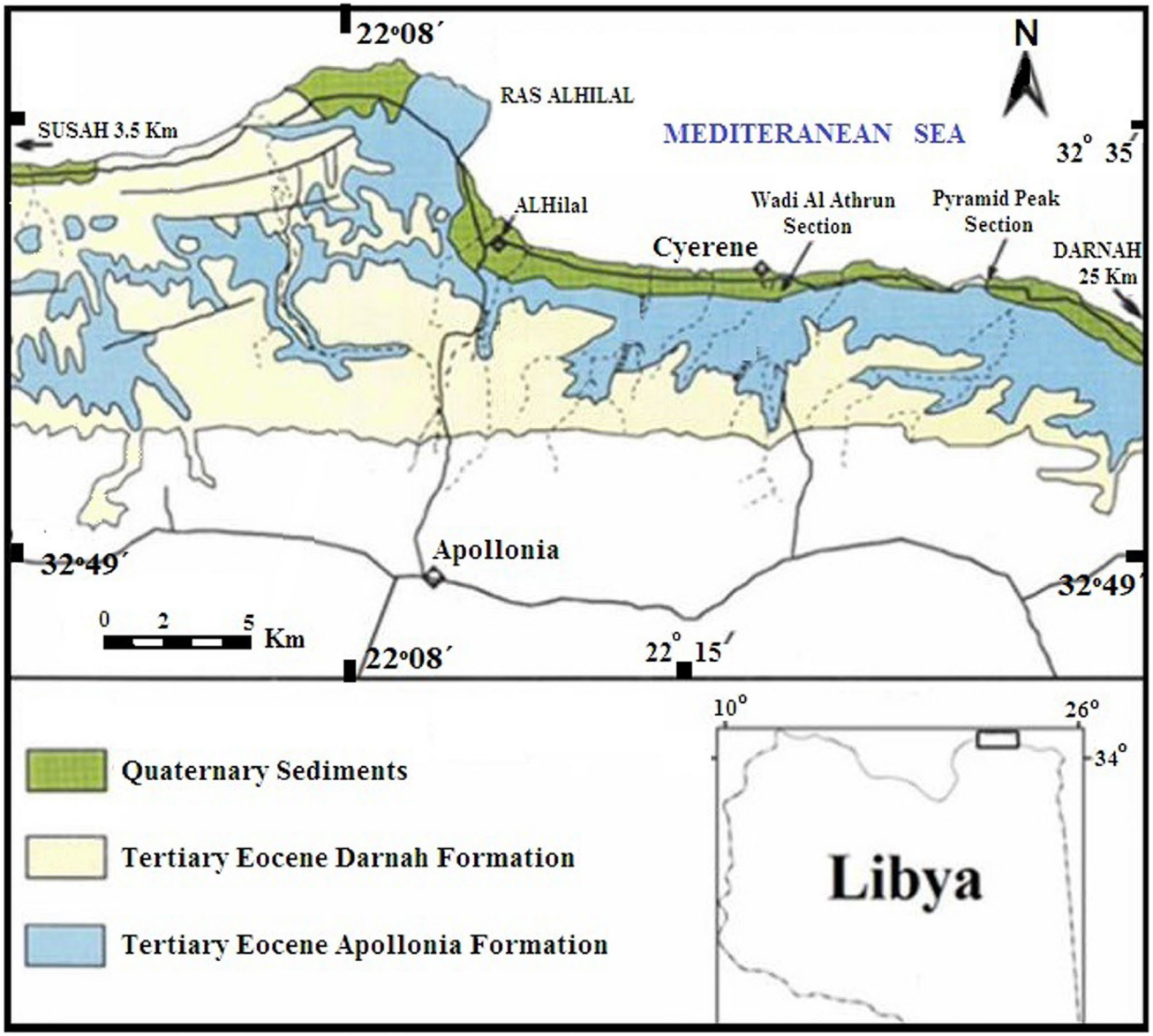

Fig. 2 Geologic map of northern Libya showing the study area (Cyrene on the Mediterranean coast and Apollonia to the south)

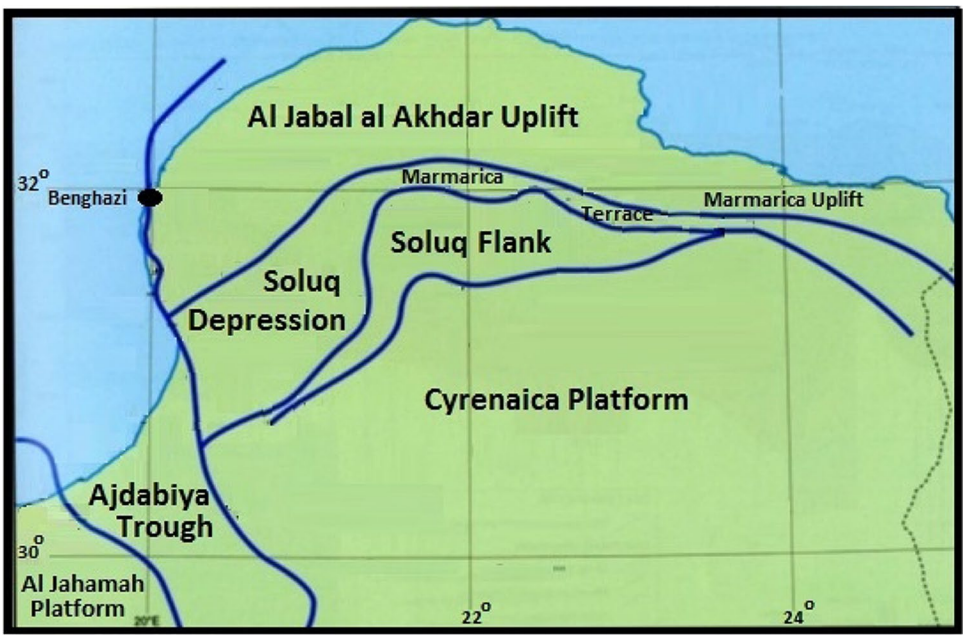

Fig. 3 Tectonic map of northeast Libya, showing the different structural elements (After El-Arnauti et al. 2008)

limited spatial extent compared with the others and rises up to 880 m above sea level. Al Jabal Al Akhdar represents a NE–SW doubly plunging anticlinorium (Röhlich 1974; Abd El-Waded and Kamh 2013). It exhibits a late Cretaceous rifting with a gentle south-vergent folding event followed by an isostatic rise, which creates a gentle unconformity between the Maastrichtian and Paleocene–Eocene successions (El-Arnauti et al. 2008).

Stratigraphically, Al Jabal Al Akhdar consists of thick sequences from upper Cretaceous to upper Miocene carbonate rocks and is divided into 14 rock units. These are identified from bottom to top as follows: Qasr al Abid Formation (late Cenomanian) overlain by Al Baniyah Formation (both are the lateral equivalents of Al Hilal Shale and the lower part of Al Athrun Formation in the coastal area); Al Majahir Formation (Campanian) overlain by Wadi Dukhan Formation (Maastrichtian) (both are the lateral equivalent of Al Athrun Formation); Tertiary, which starts at Uwayliah Formation (Paleocene), overlain by the Eocene Apollonia and Darnah Formations with an interfingering relationship; Oligocene, which starts et al. Bayda Formation (early Oligocene), overlain by Al Abraq Formation (late Oligocene); Early Miocene Al Faidiyah Formation overlain by the middle Miocene Benghazi Formation; Late Miocene Wadi al Qattarah Formation (Fig. 4). The exposed rock units (from early to middle Eocene Apollonia, middle-upper Eocene Darnah Formation, Oligocene Al Bayda Formation, and Quaternary calcarenites) are the focus of the current research.

Description of the Selected Geomorphosites

Geosites

A geosite is a natural structure, such as a group of rocks, minerals or fossils, stratum, ground formation, or geological structure, resulting from an event during the creation or evolution of the earth's crust that put a process or formation into existence that has a need for scientific documentation and, in some cases, visual attraction qualities (Wimbledon 1996; ProGeo Group 1998; www.progeo.se). Any natural legacy of a country should include its geological heritage, which is made up of several major geosites and landscapes that are profoundly shaped and determined by geology. Rocks, minerals, fossils, and geomorphological and geological characteristics are part of the natural legacy of a place, and they contribute to its geodiversity (Hagos et al. 2019). The present study is the first to consider the geosites in Cyrene, Libya, their interaction with humans, and their protection status. The following section briefly describes the most spectacular geosites in Cyrene.

Karstified Caves

Sculptured rocks can be found in many places in the world, and each of them is unique. Apollonia City, which is located in Al Jabal Al Akhdar in northeast Libya (Fig. 2), boasts of individual karstified caves in calcarenite limestone. Limestone was deposited here due to wind action during the Pleistocene period (Taboroši et al. 2013). Most of these caves

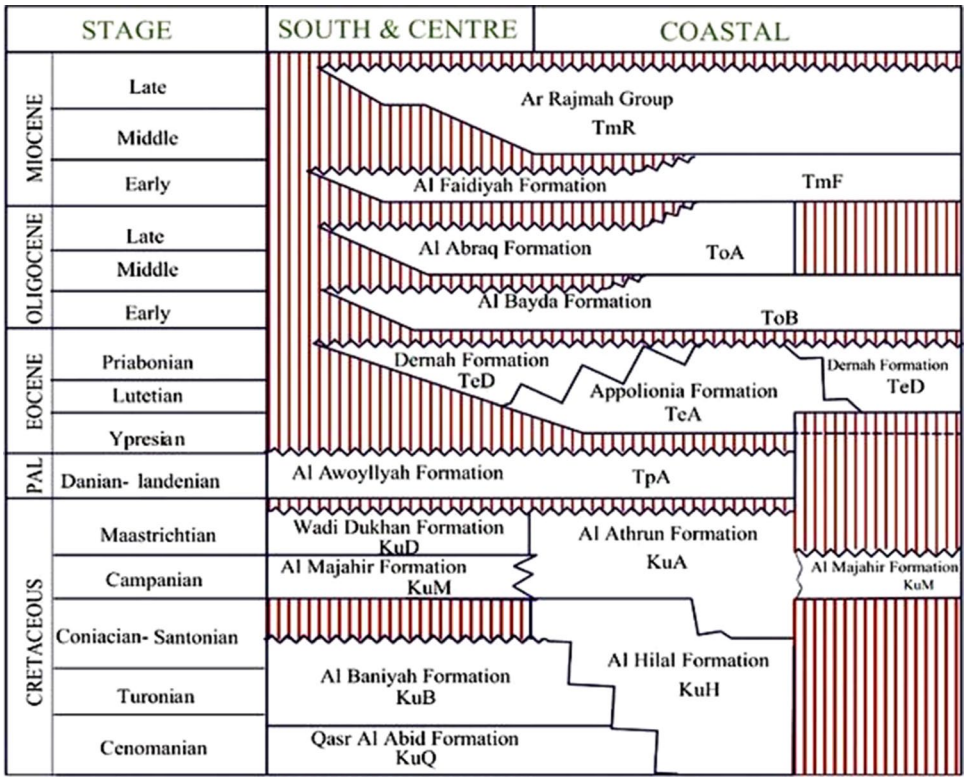

Fig. 4 Stratigraphical chart of the exposed rock units of Al Jabal al Akhdar, showing the sequence of unconformities (modified after El Hawat and Shelmani 1993)

have been used for hiding since the Roman and Greek times when they passed through the Italian colony (Fig. 5).

Goudarsi (1970) and Halliday (2003) introduced a notable overview of the karstified rocks in Libya. Cyrenaica is significant owing to the features of its Al Jabal Al Akhdar karsts. From the city of Benghazi to the Egyptian border, this well-watered collection of karsts stretches eastward. It has a diverse topography, which ranges from littoral mixing-zone

Fig. 5 Quaternary calcarenite limestones invaded by caves as karstic features. These caves are of historical importance, they revealed a deep sequence of human occupation since the Roman and Greek times

karsts and undersea springs to mountains that rise to approximately 800 m.

The superficial karstic features in Cyrenaica have attracted attention since the Greek and Roman times. Halliday (2003) mentioned that the famous Cave of Apollo, located in the ruins of the ancient Greek city of Cyrene (now Al Shahhat), is a unitary resurgence conduit that is approximately 300 m long. In addition, in Cyrenaica, several karstic caves of more than 50 m depth have been discovered. Particularly, the karstified caves represent an example of "multiple" geosites. To the best of our knowledge, no other researchers have mentioned or worked on the geoheritage value of the city. Only Errishi et al. (2020) referred to some geosites in the Libyan desert as important geosites for geotourism.

Unconformities and Sculptured Rocks

The stratigraphy of Apollonia City is characterized by a sequence of Eocene Apollonia, Darnah, and Al Bayda Formations. In addition, the Quaternary rocks contain calcarenite beds with a large diversity of karstified caves. The existence of postdepositional upper Cretaceous deformed structures and stratigraphic traces in northern Cyrenaica indicates that this region in the Mediterranean has undergone recurrent and persistent compressive episodes. These recurrent episodes are evidenced by the recurrent syndepositional mass movements of sediments and unconformities over time (El Hawat and Pawellek 2005). The gradual disappearance of deep-water marine fauna during the early Eocene (Apollonia Formation) and the gradual appearance of large nummulitids and coarsening upward of allochems during the middle Eocene (Darnah Formation) indicate a shallowing-up trend that lasted until the end of Miocene (Abdulsamad et al. 2009). One of the very interesting features in this region is the dominance of unconformity surfaces. Figure 6 shows an erosional sculptured skull of calcarenite that is cross-bedded in the Quaternary age. Almost all exposed rock units are distinguished from one another based on their unconformities (Fig. 4). The documented angular unconformities in the upper Cretaceous succession of Al Jabal Al Akhdar are strongly related to the persistent tectonic uplift of Al Jabal Al Akhdar. All other unconformities (disconformity and paraconformity) belong to the Tertiary succession.

Collapse Dolines

Collapse dolines are considered the most extensive and diverse karstic features found in the Al Jabal Al Akhdar anticlinorium in northeast Libya. Dolines are closed karst depressions with different sizes and origins (Ford and Williams 2007). Doline is a depression created by the solution of a surficial rock or subsidence collapse into an underground void (Wray 2013). They are closed depressions that are sometimes filled with water with various morphologies (cylindrical, bowl, and conical) and sizes. Normal collapse dolines are characterized by steep walls, and their formation is commonly attributed to a single collapse of a cave ceiling (Waltham et al. 2005).

Many collapse dolines, which developed from the Eocene to Miocene carbonate successions in Al Jabal Al Akhdar, were formed during the Holocene, which made them one of the most visible karst phenomena. More than 66 collapse dolines have been recorded and defined in Al Jabal Al Akhdar (Abdulsamad et al. 2010; El-Amawy

Fig. 6 Cross-bedded calcarenite of Quaternary age at Apollonia port

et al. 2010; Muftah et al. 2010; Faraj et al. 2016; Elshaafi1 et al. 2021). In plain view, these dolines are generally elliptical or slightly spherical, whose depressions range from a few meters to a few hundred meters. Their diameters range from a few meters to more than a hundred meters and are mostly water-filled depressions (Fig. 7). Elshaafi1 et al. (2021) concluded that the collapse of dolines in Al Jabal Al Akhdar frequently occurs along steep dip-slip faults consequent with the existence of several tens of meters of shallow void or cavity.

World Heritage Sites

Many sites in Cyrene have been designated as world heritage sites by UNESCO. Haua Fteah Cave and Apollo City are two of them.

Haua Fteah Cave

The 1950 excavations conducted by Charles McBurney in Haua Fteah, a large karstic cave on the coast of northeast Libya, revealed a fundamental sequence of human occupation (Fig. 8). The Haua Fteah cave (N 22°3′5″ and E 32°53′70″) is a massive semicircular rock shelter in the limestone escarpment in Al Jabal Al Akhdar with a half-circle roof diameter of approximately 80 m and a rock lip of 60 m above the ground. It is approximately 8 km east of the city of Soussa in the Cyrenaica area (northeastern Libya). In July 2020, UNESCO declared the Haua Fteah Cave a world heritage site (https://whc.unesco.org/en/tentativelists/6488). According to the criteria applied by UNESCO, "the Haua Fteah Cave contains a unique record in North Africa and the Mediterranean region of the changing adaptability of our species to climate change over the past 150,000 years, and a uniquely long cultural record of our species that is unrivaled at any current WH site."

Inglis et al. (2018) studied this cave and its importance, whose recorded ages range from the middle to the latter Stone age, along with the evolution of Homo Sapiens in North Africa. This cultural transformation entitles the cave to a great anthropogenic and archeological standing. This finding backs up the observation of Bruno et al. (2014), who claimed that distinctive geoarcheological characteristics are important to the palaeogeographical type of geological legacy. Furthermore, the sharpness of the engravings is proportional to the length of time they were exposed to erosion, which indicates the relative ages of different civilizations.

Archeological Sites

Another interesting feature of Apollonia is the archeological site in the old Cyrene City. Shahat, Cyrene (Qurina), is a Greek-founded ancient city in the district of the Al Jabal Al Akhdar anticlinorium, northeast Libya. It is located in a lush valley in the Al Jabal Al Akhdar upland. It is approximately 10 km east of Al

Fig. 7 Brak Nut Lake developed in Apollonia Formation west of Susah (Apollonia City)

Fig. 8 The Haua Fteah Cave is a large karstic cave on the coast of northeast Libya (Cyrenaica). The photograph looking south across the doline floor into the cave

Bayda. It is considered the second-largest city after Al Bayda in Al Jabal Al Akhdar. All empires that ruled northern Libya, including the Republicans in 414 BC, Alexander the Great and the Greek monarchs in 332 BC, the Romans in 96 BC, the Byzantines in 324 AD, and the Islamic invasion in 635 AD, passed through Shahat City. This city came under the Byzantine and Berber centers and finally the Arabian conquest (Goodchild 1967). Shahat City was also listed as a World Heritage Site by UNESCO in 1982. One of the spectacular features in this city is the Temple of Apollo, which was originally constructed in the early seventh century BC (Fig. 9). The Fountain of Apollo (Ain Shahat or Spring of Apollo), which was mentioned in the narrative of Herodotus on the founding of the Therean colony, continues to flow from a tunnel beneath the acropolis hill (Fig. 9). The Fountain of Apollo (Ain Shahat or Spring of Apollo) and few karstified caves that can be seen in the Oligocene limestone in Al Bayda Formation (Figs. 9 and 10).

Surface temples are not the only characteristics of old Cyrene City. In 2008 and 2009, the Archeotema Society (Venice, Italy) was contracted by the Libyan government to outline a project for the management of underwater archeological sites in Libya as places for underwater tourism (Pizzinato and Beltrame 2012). This project is part of a larger evaluation and conservation effort for the cultural heritage of Libya.

Fig. 9 The Temple of Apollo, Cyrene: main Greek settlement in Cyrenaica, the northeastern part of modern Libya, modern Shahhat. In the background, some karstified caves are seen in the Oligocene limestone (Al Bayda Formation)

Fig. 10 The Fountain of Apollo (Spring) along the contact between Shahat Marl and Algal limestone members of Al Bayda Formation at Cyrene City

Quantitative and Qualitative Methodologies for Assessing Geomorphosites

Several studies from around the world have emphasized the need for geological heritage evaluations. Geodiversity is identified as the most important geological legacy in several studies (Najwer et al. 2016; Zwolinski et al. 2018). Prosser et al. (2006), Ruban (2010), Strba et al. (2015), Brilha (2016), and Reynard and Brilha (2018) defined the fundamental concepts of geoheritage evaluation. Nonetheless, the proposed techniques are case dependent. Thus, they must consider the particular characteristics of the studied items and the idiosyncrasies of the nations where they are located (Mikhailenko et al. 2021; Ruban et al. 2021).

Furthermore, various quantitative and qualitative techniques for evaluating geomorphosites have been proposed (Reynard et al. 2016; Mucivuna et al. 2019). The technique used in this study is similar to that proposed by Reynard et al. (2016). This technique consists of two primary steps: (i) inventorying the geomorphological legacy of the research area and (ii) assessing the selected geomorphosites.

Field excursions have been conducted to extensively investigate geomorphosites. Table 1 lists the geoheritage components in the investigated region to perform the following evaluation, which is further divided into four phases (in accordance with Reynard et al. 2016). The first phase involves a two-part description of the location (general and descriptive data; see Table 2). The second phase involves the analysis of the intrinsic value, which is divided into two parts: primary and scientific values (Table 3) and supplementary values (Table 4). The supplementary values are classified into three categories: ecological, artistic, and archeological values. In the third phase, the current use and management of the site are divided into two sections: protection concerns (protection status, property, damages, and threats) and a series of variables that affects tourist usage of the site (visit conditions and educational interest). The fourth phase involves synthesis. The establishment of a geopark and promotion of geotourism in an area should be supported by UNESCO.

Table 5 lists the site-interpretation equipment and the aspects linked to the visiting conditions and educational values (Martin 2013). Because geomorphosites are regarded as a resource, data that allow for site characterization are collected in the context of management, which includes protection and valuation. The quality of the sites might be influenced by natural or human factors.

Table 1 Geoheritage constituents in the study area

Geoheritage types and subtypes	Uniqueness of the Studied area
Geomorphological	National
Sedimentological	National
Palaeogeographical	
• Paleoenviromental	Regional
• Geoarchaeological	Regional

Table 2 General and descriptive data of the geomorphosite (the table followed the classification of Reynard et al. 2016)

Data	Description	Studied area
Name	Name of the landforms or very simplified description of the geomorphosite	• Sink holes • Caves • Spring • Folds • Unconformity
Toponomy	Area where the geomorphosite is situated	➢ Apollonia City ➢ Cyrene City
Coordinates		Longitude: 22° 08′ to 22°18′N Latitude: 32° 35′ to 32° 49′E
Maximum altitude		16 m
Minimum altitude		0 (sea level)
Area		855,370 km^2
Property	PRI: Private ASS: Association PUB: Public COM: Common	Public
Protection status	Mention the protection status of the geomorphosite, if existing	No protection found in the area
Archeological findings		➢ Greek archeological sites

Table 3 Criteria used for the assessment of the scientific value of the geomorphosite (following Reynard 2006 and Reynard et al. 2016)

Criteria	Qualitative assessment	Value	Studied area
Integrity	State of conservation of the site	0 = Destroyed 0.25 = Practically destroyed 0.5 = Partly destroyed 0.5 = Slightly damaged 1 = Intact	➢ Archeological sites = 0.5 ➢ Geological features = 1
Representativeness	Concerns the site's exemplarity (region, local, and international)	0 = Null 0.25 = Weak 0.5 = Moderate 0.75 = High 1 = Very high	➢ Archeological sites = region 0.7 ➢ Geologic features = regional 0.5
Paleo geographical interest	Importance of the site for the Earth	0 = Null 0.25 = Weak 0.5 = Moderate 0.75 = High 1 = Very high	0.75
Rareness	Concerns the rarity of the site	0 = More than 7 0.25 = Between 5 and 7 0.5 = Between 3 and 4 0.75 = Between 1 and 2 1 = Unique	➢ Archeological sites = 0.25 ➢ Geological features = 0
Synthesis of scientific value	A sentence to summarize the scientific importance of the site	Average	Collective

Results and Discussion

The scientific community is relatively well aware of the assessment of geological heritage and geomorphological and geoarcheological peculiarities, which have been fairly and regularly studied in different countries (AbdelMaksoud et al. 2020, 2021).

The studied area is obviously important in terms of scientific, educational, and aesthetic values. After implementing the classification provided by Reynard

Table 4 Criteria used for the assessment of the additional values of the geomorphosite (following Reynard et al. 2016)

Ecological value		
Criteria	Qualitative assessment	Studied area
Protected site	Consideration is taken of the sites that are already protected in a national inventory or at the regional or local level for ecological reasons	Yes, one location is indexed as a world heritage
Aesthetic value		
Criteria	Qualitative assessment	Studied area
View points	Accessibility	Accessible
Contrasts, vertical development, and space structuration	Contrasting landscapes or landscapes with vertical development or landscape with individual elements	Contrasting landscapes
Culture value		
Historical importance	Role of the site in the past	Present
Geohistorical importance	Role of the site in the development of geoscience	Present
Culture value		Present

et al. (2016), we find that the area features regional ranks that can qualify it for conversion to a UNESCO geopark or a national park to provide further conservation of the geosites found in this area.

The geological heritage in the studied area features geodiversity and geological abundance such as folds, fossils, unconformities, dolines, and caves, which are identified by the inventory of the geomorphosites. These different geomorphosites are assessed in terms of the following criteria: scientific, authenticity, ecological, and cultural. The geomorphosites exhibit high integrity, very high representativeness, and high rarity values.

These decisions make this area a very valuable site for ordinary people, scientists, and the government. The investigated region possesses substantial geotouristic value owing to its geoheritage significance. It should be provided with legal protection and tourist infrastructure to enhance accessibility to its geotouristic and recreational activities. Attracting more and better visitors would be critical to expanding knowledge of its natural features to improve tourist awareness of the area and boost geotourism in the country. Libya is crisscrossed by several geomorphosites that can also be found in other parts of the world. To safeguard, promote, and geoconserve such geomorphosites for future generations, UNESCO Geoparks must conduct a comprehensive inventory of these sites. The promotion of geotourism in Libya is a great opportunity for the local community to thrive. This effort should be expanded to include additional African and developing countries that have attractive geosites and landforms that can be promoted as geotourism destinations.

Table 5 Criteria used for the documentation of the protection of the geomorphosite (following Reynard et al. 2016)

Sub criteria	Contains	Studied area
Protection status	The level of protection of the site relatively to its link with different natural reserves	Partially protected
Damages and threats	Specify the level of damage of the site by anthropogenic activities or natural processes	

Conclusions

The geoheritage analysis of Apollonia and Cyrene cities and their environs leads to the following three key conclusions.

(1) Geomorphological, sedimentological, and palaeogeographical characteristics are part of the geoheritage of the studied area, which is related to archeological heritage.
(2) The studied area features regional importance and is valuable for scientific research, education, and tourism. This conclusion is drawn after evaluating the geosites and archeological sites in the studied area.
(3) Because of its vulnerability to human and natural effects, the studied region requires official status and geoconservation measures as well as a competent assessment of its distinctive traits.

This study has contributed significant geological information to Libya, namely, its geoheritage. Through scientific research, educational programs, expansion of geotourism, and diversification of the isolated desert areas in Libya, these measures can help support sustainable local development. Further research

should focus on identifying and assessing the geoheritage in Libya to continue exploring the identified resources and to determine the most appropriate methods for their utilization.

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Declarations

Conflict of Interest The authors declare no competing interests.

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