Geoheritage (2021) 13: 54
https://doi.org/10.1007/s12371-021-00582-8

ORIGINAL ARTICLE

Golden Triangle Geosites: Preliminary Geoheritage Assessment in a Geologically Rich Area of Eastern Egypt

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Received: 11 November 2020 / Accepted: 7 June 2021 / Published online: 19 June 2021
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Abstract
The Golden Triangle economic zone of eastern Egypt stretching between the Nile Valley and the Red Sea coast is a historical mining area, which is vast and rich in geology. Although none single study can comprehend the entire geoheritage of this area, field investigations and literature analysis permit to identify the eight most notable localities, which are interpreted as geosites (Sukari gold mines, Al-Fawakhier gold mine, Um Greifat polymetallic ore quarry, Gebel Abu Sha'ar El-Qibli manganese quarry, White Sand quarry, Gebel Duwi (including phosphate mines), Sodmein cave, and Meatiq dome). These geosites represent broad spectrum of unique phenomena. The latter are assigned to the stratigraphical, palaeontological, palaeogeographical, tectonic, igneous, sedimentary, metamorphic, mineralogical, geomorphological, economical, and geohistorical geoheritage types. Semi-quantitative assessment of these geosites indicates on the biggest value of Gebel Duwi, the Sodmein cave, and the Al-Fawakhier gold mine. The identified geoheritage of the Golden Triangle requires geoconservation and exploitation for the purposes of science, education, and tourism (some experience has already been accumulated), and the relevant initiatives can be managed within a geopark framework. This preliminary assessment proves geoheritage richness of the study area, and it establishes frame for geoconservation activities, and, particularly, search for more geosites. The presence of similar geologically rich areas in the other parts of Egypt makes urgent development and implementation of the national approaches of geoheritage management.

Keywords Eastern Desert · Geoheritage assessment · Geotourism · Mining sites · Red Sea rift

Introduction

Territories hosting active and abandoned mining sites are often rich in geoheritage because mining focuses on geologically-specific areas, extends rock exposures, and itself may be unique. Simultaneously, mining activity can be regarded as evident threat to geoheritage. The relevant discussions and examples can be found, particularly, in the works by Wrede and Mügge-Bartolovic (2012), Fuertes-Gutiérrez et al. (2016), Pérez-Alvarez et al. (2016), Brilha et al. (2018), Prosser (2018, 2019), Ruban et al. (2018), Gioncada et al. (2019), Poblete Piedrabuena et al. (2019), and Carrión-Mero et al. (2020). A thorough inventory of geoheritage and its subsequent management on mining-affected territories are desirable. Although geoheritage studies are commonly justified to geological domains (orogenic belts, terrains, etc.) or administrative units (countries, provinces, districts, etc.), it appears to be important to focus them also on those areas that are officially designated for large-scale economic projects fuelled by mining activities.

In Egypt, a new economic zone called "the Golden Triangle" is established by the Presidential Decree No. 341 of 2017 as a perspective area for facilitation of the both regional and national socio-economic progress (http://www.riad-riad.com/en/publications/declaring-golden-trian

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gle-special-economic-zone). It is located in the eastern part of the country and stretches from the Nile valley to the Red Sea coast, i.e., it includes some parts of the Eastern Desert, the Red Sea hills, and the coastal plain (Fig. 1). This area (9200 km^2) boasts outstanding mineral resources (up to 75% of the country's resources); in addition to mining, it is planned to develop and to invest in agriculture, tourism, environmental initiatives, and transport infrastructure (https://www.egypttoday.com/Article/3/14644/Golden-Triangle-project-encourages-urbanization-investment). Solution of some social problems is also possible (AbdelMaksoud et al., 2020; Elseoud et al., 2020). This mega-project creates a valuable premise for effective management and exploitation of the rich geoheritage that exists potentially in the Golden Triangle. However, the knowledge of this geoheritage remains very limited (AbdelMaksoud 2020), and it requires significant extension and systematization. Although the geology of the area has been studied for decades and it is more or less known (Hamimi et al. 2020), specific investigations are necessary to reveal its geoheritage. In other words, the emphasis should be shifted from 'purely' geological studies to geoheritage studies.

The study area is vast, and none single research project can provide with characteristics of its entire geoheritage. This task has to be solved gradually: preliminary assessments in the course of the "purely" geological research projects and/or geoeducational excursions for university students coupled with analysis of the available literature create a frame of the local geoheritage knowledge, which is extended and deepened latter by special investigations and geoconservation inventories (Fig. 2). The present study is of such a preliminary character, and it starts filling the gap in the knowledge of the geoheritage of the Golden Triangle area. Its objective is to provide the first, pioneering characteristics of several most notable pieces of this geoheritage, which deserves attention of the international research audience due to its uniqueness and suitability to discussions of the mining-related, socio-economic contexts of geoconservation. These characteristics are essential for development of the frame for further geoheritage investigations in the Gold Triangle area. This study is derived from the geological research, but it is not geological: it employs geological information for geoheritage interpretation of some notable, already discovered, examined, and described geological features. New field investigations in this area have also allowed finding, describing, and semi-quantitative assessment of several geosites (definitely, these are not all geosites that can be found in this vast area), and these results permit preliminary judgments of geoconservation and geotourism potential of the Golden Triangle. In other words, geoheritage value is in the focus of the present study, which means reference to not only geological peculiarities, but also issues of infrastructure, attractiveness, education, tourism, and regional governance. Undoubtedly, the noted judgments are important

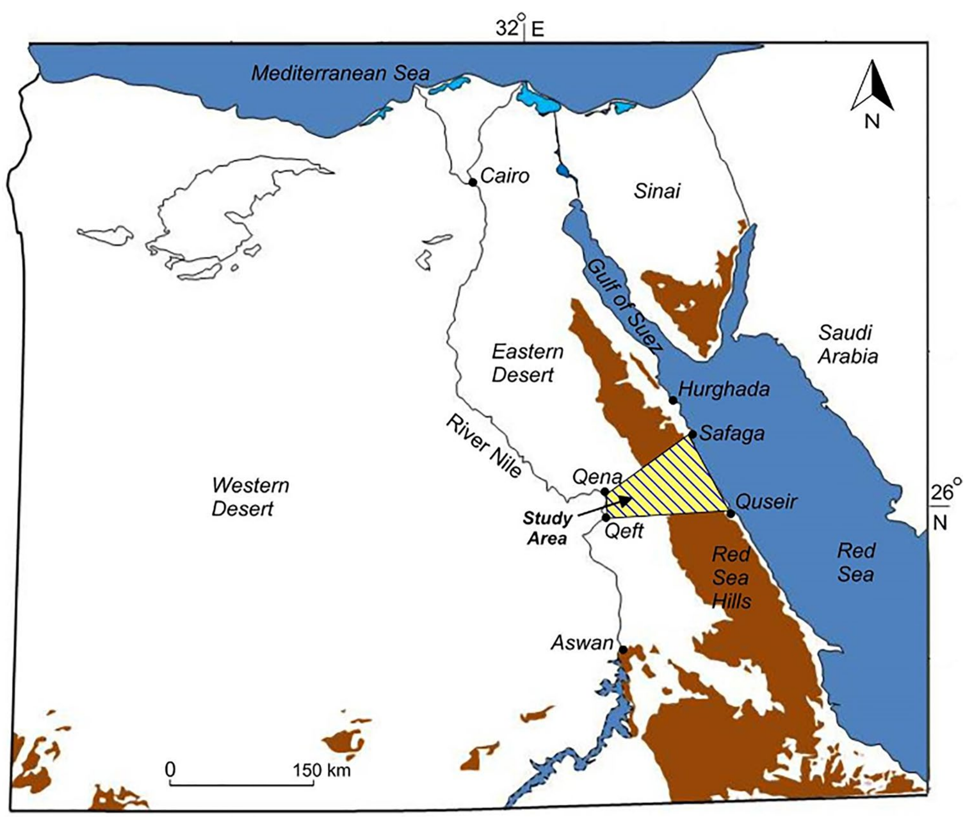

Fig. 1 Geographical location of the study area

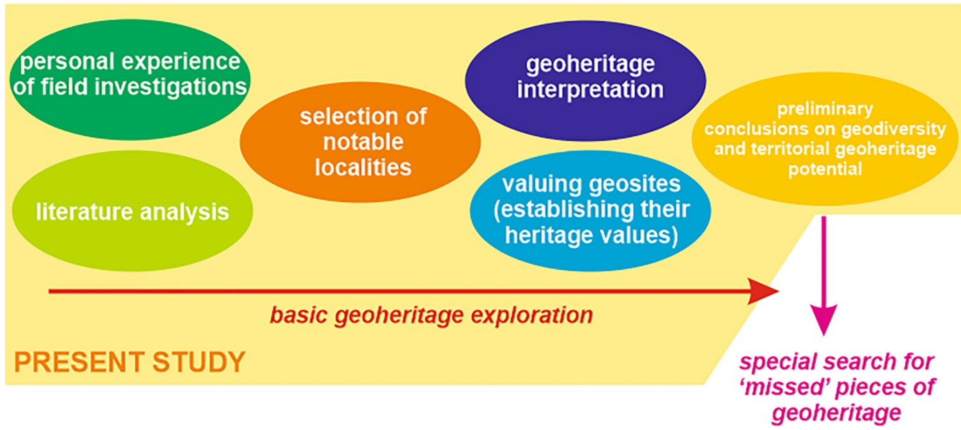

Fig. 2 The general principle of geoheritage exploration of vast territories

in regard to the above-mentioned national mega-project for this economic zone. Nonetheless, the term "Golden Triangle" is employed in this paper only to nominate the study territory. The geoheritage-related policy will be subject of further investigations.

Geological Setting

The study area is located in eastern Egypt (Fig. 1). It represents the northeastern part of the old African–Arabian continent close to where it was disrupted by the Cenozoic rift system of the Red Sea. The basic geological knowledge of this part of Egypt can be found in the synthetic works by Issawi et al. (2009), Tawadros (2011), Said (2017), and Hamimi et al. (2020). The articles by Stern (1981), Khalil and McClay (2009), El Kammar (2015), Yousif et al. (2018), and Abdelhady et al. (2020) also shed light on some issues of the local geology. The latter attracted attention already in the times of Ancient Egypt (Harrell and Brown, 1992), and, thus, the history of the regional geological exploration counts thousands of years. The present study is aimed at geoheritage interoretation of the selected objects of the area, but not at its geological re-description, and, thus, some basic geological information is summarized. The literature cited above can be used for reference for more detailed descriptions. Additionally, elementary geological outline of each given locality is provided below together with geosite characteristics.

The Precambrian basement complex exposed in the study area consists of a highly deformed Meso- and Neoproterozoic volcanosedimentary sequence, pervasively metamorphosed to lower greenschist facies and intruded by major syn- to post-tectonic granitic plutons (Stern, 1981). These rocks were formed in an active tectonic environment, and they were deformed together with the Pan-African orogeny. These occur widely on the study area. The basement rocks, which dominate the study area, are overlain with significant angular unconformity by the Upper Cretaceous–Lower Eocene sedimentary packages accumulated in the continental interiors (Fig. 3); the Lower Paleozoic sedimentary rocks also crop out locally in the northern part of the area. The syn-rift sequence is represented by sedimentary rocks of very different composition (Fig. 4), and their accumulation took place on the newly formed, faults-affected continental margin of Africa bordered by the growing Red Sea rift. One should note exceptional diversity of lithologies and facies in the study area, as well as its lengthy stratigraphical range (Figs. 3, 4). Before the Neogene, this area was located relatively far from the continental margin, although marine ingressions reached it either from the north ("Mediterranean" direction) or the east ("Arabian" direction); the Red Sea allowed for marine deposition since the Neogene (Guiraud et al. 2005).

Mineral deposits of the Golden Triangle include gold, polymetallic ores, manganese, lead–zinc, gypsum, and phosphates, and these are linked genetically to the Pan-African basement rocks, the rift-related hydrothermal fluid activity in the faulted Cenozoic carbonate rocks, and the specific depositional environment of the Upper Cretaceous Duwi Formation. The study area has remained economically important since the times of Ancient Egypt (Abdel-Maksoud 2020), and, particularly, it supplied considerable amounts of gold during the entire history of Egypt.

Material and Methods

The fundamental principles of geoheritage research are summarized by Prosser et al. (2006), Reynard and Brilha (2018), Wolniewicz (2021). Two essential tasks are finding localities exhibiting unique geological features (geosites) and their characteristics (in regard to both geology and geoheritage). In other words, these are geoheritage inventory and assessment. The materials collected in the course of the field investigations coupled with the guidance of university student excursions, as well as the information

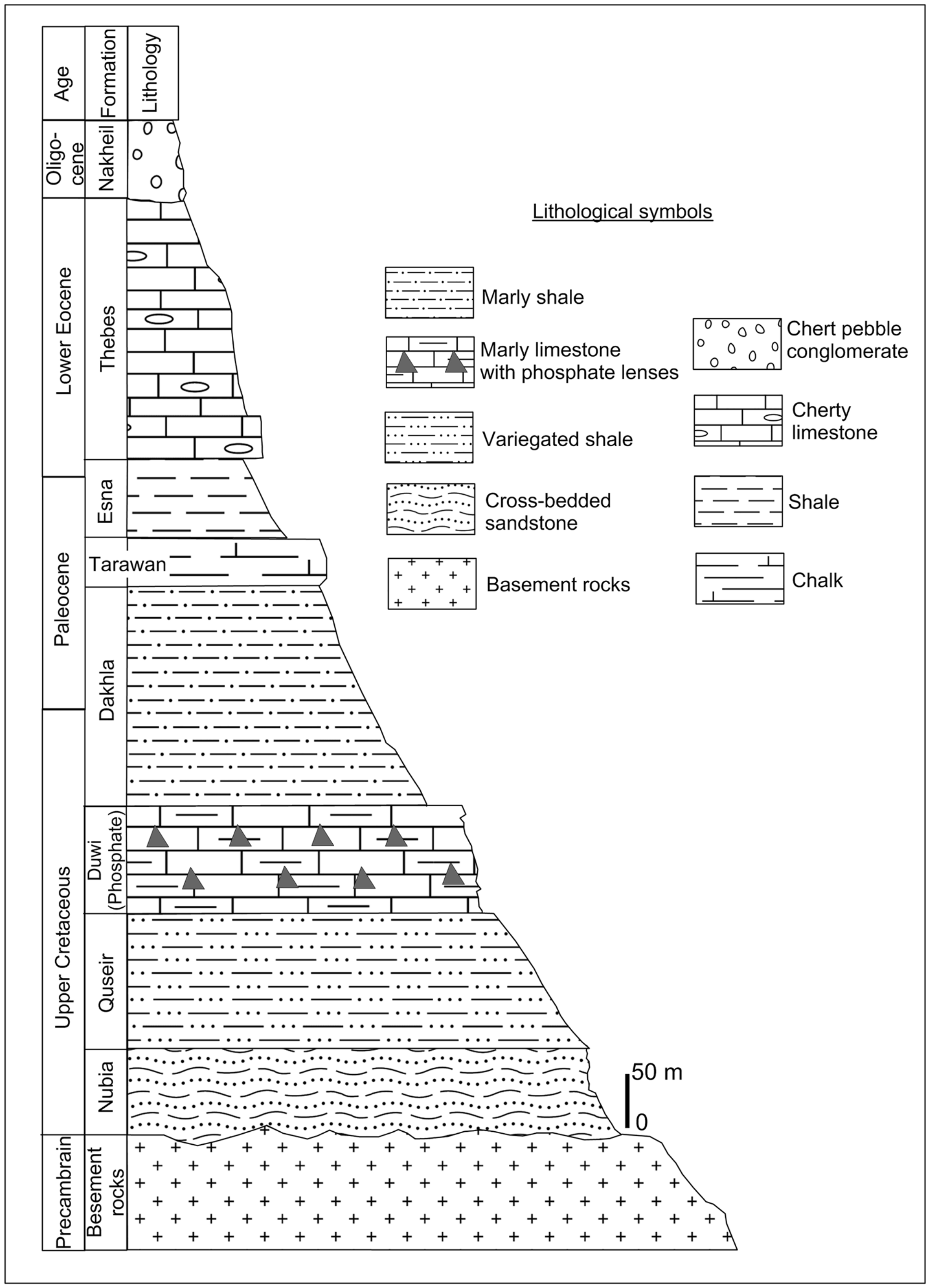

Fig. 3 Pre-Neogene composite section of the study area (partly based on Khalil and McClay 2009)

from the professional literature are used for the purposes of the present study. These materials permit to specify eight notable localities hosting unique geological features, and these localities can be proposed as geosites (Fig. 5). Each of them is characterized geologically, with special emphasis on their heritage value determined by their uniqueness. The geological characteristics are basic because the present study focuses on geoheritage interpretation, not solution of some particular tasks of "purely" geological research. It should be noted that these localities are considered depending partly on the authors' own field experience. Such an approach is suitable to the preliminary study on a vast area, which needs, first of all, some elementary knowledge of geoheritage to outline the directions for further investigations (Fig. 2). Certain subjectivity of geosite selection is totally unavoidable in such situations (vast area with rich and previously unassessed geoheritage). Nonetheless, as one can deduce from the literature (see citations provided in geosite descriptions below), the selected localities seem to be the best-known and, probably, the most unique in comparison to the other geoheritage features to be encountered in the course of further investigations in the Golden Triangle. In

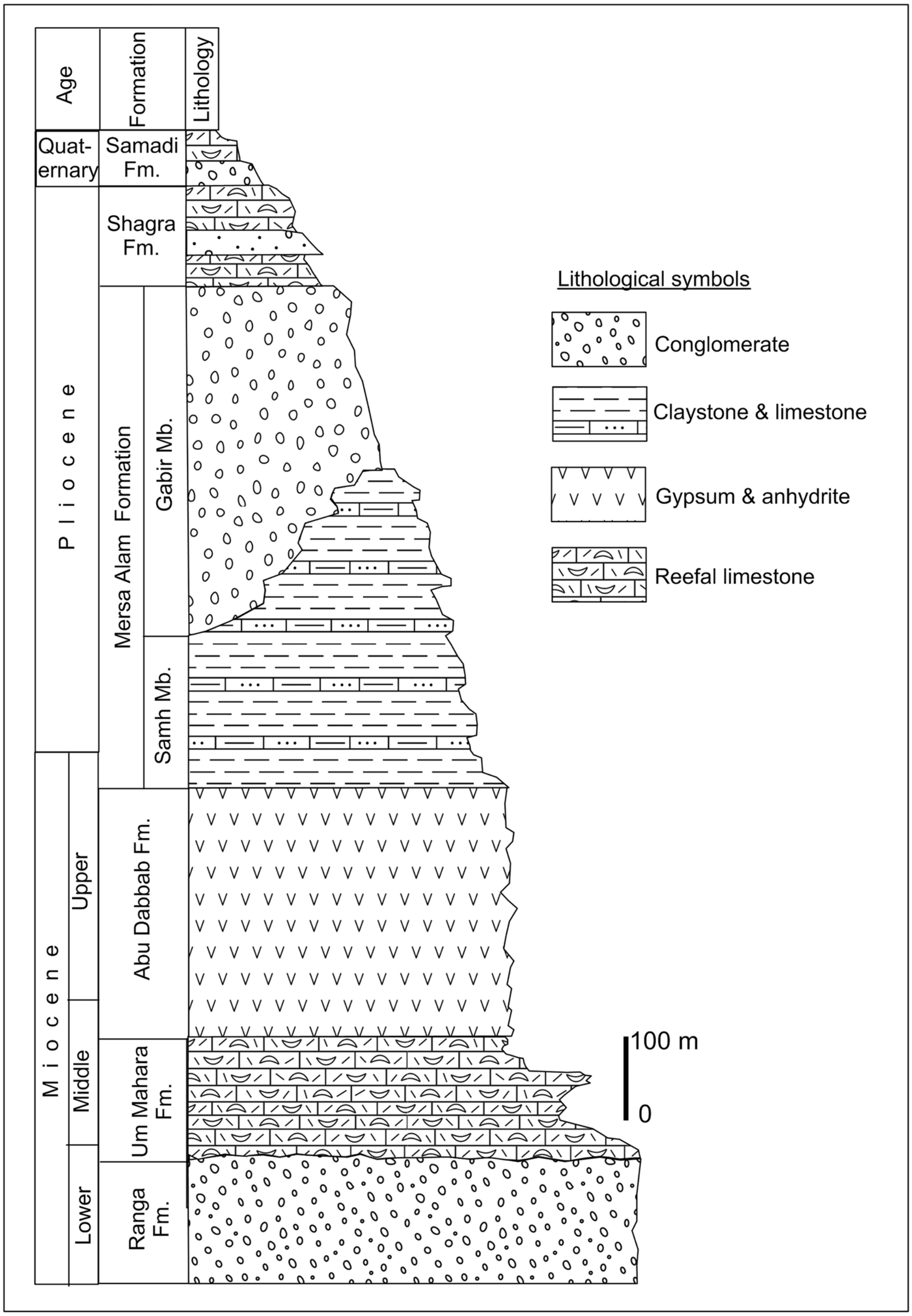

Fig. 4 Neogene–Quaternary composite section of the study area (partly based on Khalil and McClay, 2009)

other words, this paper focuses more on individual geosites than on the territorial geoheritage (comprehensive description of the latter will require many years of work of several research teams, and it will need certain frame, which is provided by the present study).

Various approaches have been proposed for geosite assessment, with the most significant progress made in the mid-2010s (Štrba et al. 2015; Warowna et al. 2016; Bollati et al. 2016; Brilha 2016; Kubalíkova et al 2021). These developments stress the utility of semi-quantitative, scoring-based assessments. The latter often deal with criteria restricted to particular loci or specific research tasks, as well as they are partly incomplete and allowing too subjective judgments (cf. Ruban 2016; Ruban and Ermolaev 2020). For instance, the state of the geoscience research in Africa (North et al., 2020) and continent-specific spatial connectivity (Righi and Gardner 2015; Porter 2016; Leitch and Chigada 2020) (probably, even

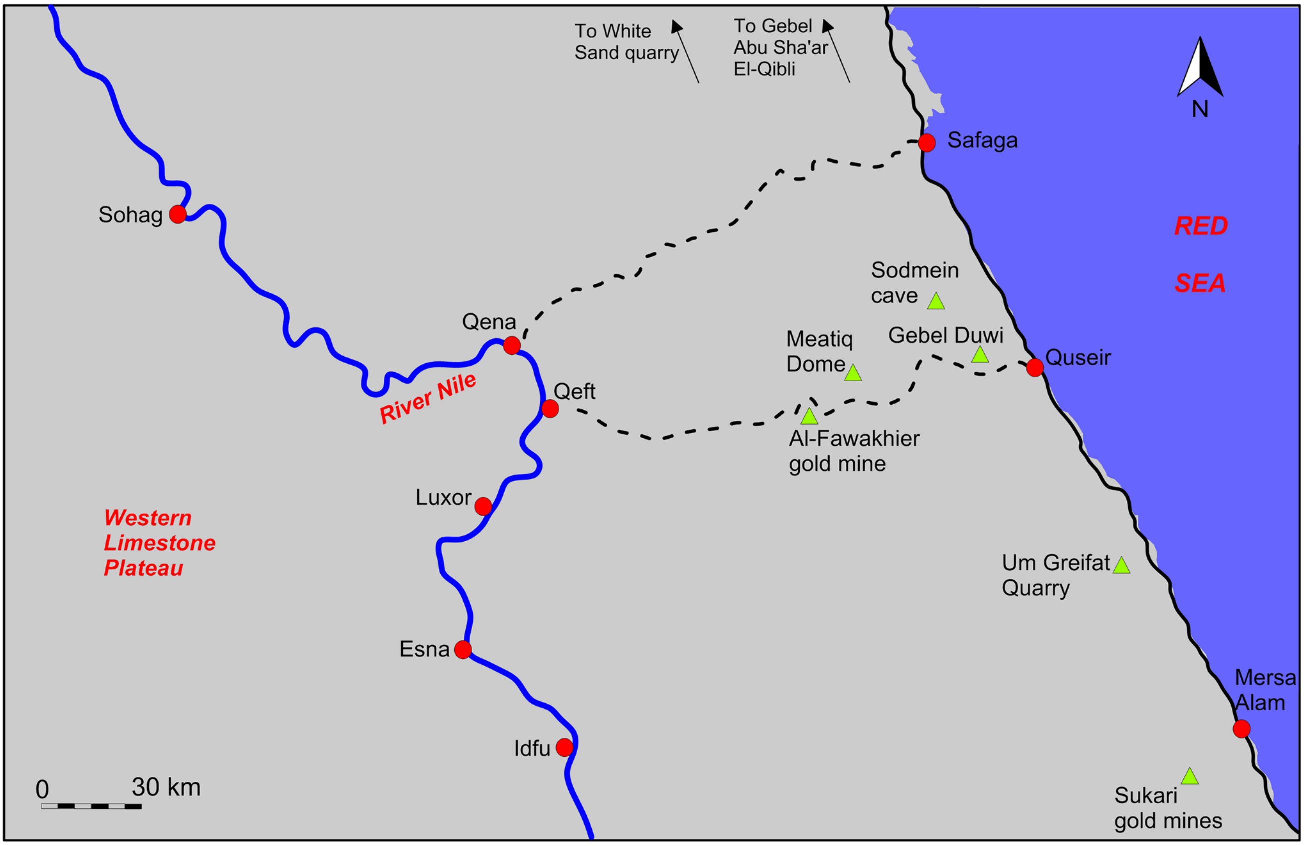

Fig. 5 Location of the geosites proposed in the present study

the other meaning of distances) do not permit to apply the same criteria and especially the same scores for judgments of scientific and tourism importance of geosites as proposed on the basis of the European experience. Anyway, the already developed approaches and criteria are of utmost importance, and these highlight the direction towards really comprehensive geosite assessment, although the latter will remain subjective to certain degree (subjective and objectively biased judgments seem to be unavoidable in the modern geoheritage research).

The present study employs a tentative system of criteria and scores (Table 1), which is based on three principles. First, geoheritage and geosites are sensible to humans, but these are objective geological features, which can be valued in regard to their natural rarity (uniqueness), whereas their utility for geoscience, geoeducation, and geotourism (Brilha 2016) affects their value. This dichotomy between rarity and utility resembles the difference between intrinsic values (Zhang et al. 2015; Sheng et al. 2019) and utility values (Costanza et al. 2017; Costanza 2020) of ecosystems. Second, some factors and conditions may increase or decrease geosite value. All proposed geosites are assessed semi-quantitatively with the system of criteria (Table 1), and the total scores are calculated for each geosite to reflect its relative value and to facilitate subsequent geosite comparison. Third, criteria and scores should not be area-specific, and they should not result from differences of geosites on the study area. In contrast, they have to be objective and not relational, i.e., based on the only properties of each given geosite.

Although some geosites are valued higher than the others, all of them are considered because of the following reasons. First, low heritage value does not mean zero value. Second, each geosite contributes to the territorial geodiversity. Third, only consideration of several geosite allows understanding of which are them are more or less valuable. Fourth, a new evaluation technique is proposed, and, thus, it needs adequate testing with geosites of different value. Fifth, only consideration of all known geosites allows understanding of which pieces of the territorial geoheritage may be "missed" to coordinate effectively further research. In other words, consideration of all these geosites is important for the purpose of not only the present, but also future investigations in the Golden Triangle, as well as for methodological developments.

Table 1 Criteria used for geosite assessment in this work

Criterion	Degree	Scores
Rank (based Ruban 2010)	Global uniqueness	+500
	National uniqueness	+250
	Regional uniqueness	+100
	Local uniqueness	+50
Number of geoheritage types (based on classification by Ruban 2020)	> 10	+50
	4–10	+25
	2–3	+10
	1	0
Accessibility	Easy (roads, trails, etc.) and location in densely-populated area	+25
	Easy (roads, trails, etc.) and location in remote area	0
	Difficult and/or location in remote area	–25
Vulnerability	No danger	+25
	In danger (potentially)	0
	Destructed (partly)	–25
	Destroyed (fully)	–50
Need for interpretation (this partly refers to the idea of specific visibility by Mikhailenko and Ruban (2019))	No special knowledge needed	+25
	Basic geological knowledge needed	0
	Professional geological knowledge needed	–10
	Scientific analysis needed	–25
Scientific importance	Potential for international research	+25
	Potential for local research	0
Educational importance	Potential for world-class educational programs	+25
	Potential for local-university educational programs	0
Touristic importance	Potential to become individual tourist attraction	+25
	Potential to be combined with local tourism offer	0
Esthetic attractiveness (various dimensions of esthetic judgments are reviewed by Kirillova et al. (2014) and Mikhailenko et al. (2017))	High	+50
	Medium	+25
	Low	0

Geological Descriptions of Geosites

Abridged geological descriptions of the eight proposed geosites are provided below. Our own observations made in the course of the fieldworks are coupled with the published characteristics when available. The unique features of each geosite are identified, which allows assigning them to geoheritage types (Table 2). The Precambrian basement dominates the study territory, and three geosites (Sukari gold mines, Al-Fawakhier gold mine, and Meatiq dome) represent the relevant peculiarities. The other geosites deal with younger features, which also occur on the study area. Moreover, the dominance of the basement decreases uniqueness of the relevant features because these are common both locally and on the country scale.

The Sukari gold mines are located ~ 15 km west of Mersa Alam city on the Red Sea coastal plain (Fig. 5). This important mining site (Fig. 6a) is related to the vein-type gold deposit hosted by the Late Neoproterozoic porphyry granite, with the vein-forming process linked to the Pan-African tectonic activity (Helmy et al. 2004). Gold is associated with sulfides in quartz veins and alteration zones. The uniqueness of this geosite is determined by its economic-geological importance and mineralogical peculiarities.

The Al-Fawakhier gold mine is located in the central Eastern Desert (Fig. 5). Presently, this mining site is abandoned (Fig. 6b), but it remained a nationally important site of gold production since the Old Kingdom of Ancient Egypt until very recently (Harrell and Brown 1992; Harrell and Storemyr 2013; Klemm and Klemm 2013). This deposit is linked to the common mechanism of metamorphic devolatization and leaching of gold from ophiolite sequences around heat anomalies produced by the Pan-African granite intrusions (Harraz 2000). Peridotites, metagabbros, and granitic rocks crop out locally (AbdelMaksoud 2010). Pluton emplacement is controlled tectonically (Zoheir et al. 2015). There are also geoarchaeological features, including Prehistoric rock art (AbdelMaksoud 2020). With regard to the above-said, the uniqueness of this geosite is determined by its importance for the understanding of the regional gold

Table 2 Distribution of geoheritage types in the proposed geosites

Geoheritage types (after Ruban, 2020)	Geosites							
	A	B	C	D	E	F	G	H
Stratigraphical						+		
Palaeontological						+		
Palaeogeographical		+			+	+	+	
Tectonic								+
Cosmogenic								
Igneous (magmatic and volcanic)		+						
Sedimentary			+	+	+	+		
Metamorphic								+
Geothermal								
Mineralogical	+	+	+	+				
Geochemical								
Geomorphological						+	+	
Engineering								
Geocryological								
Pedological								
Hydro(geo)logical								
Economical (economic-geological)	+	+	+	+	+	+		
Geohistorical (geological exploration history)		+						
Total	2	5	3	3	3	6	2	2

Geosites: A – Sukari gold mines, B – Al-Fawakhier gold mine, C – Um Greifat polymetallic ore quarry, D – Gebel Abu Sha'ar El-Qibli manganese quarry, E – White Sand quarry, F – Gebel Duwi, G – Sodmein cave, H – Meatiq dome

mineralization and the related mineralogical features, geohistorical value (historical mining site), igneous formations, and palaeogeographical elements (sensu Bruno et al. (2014) who attributed geoarchaeological features to the palaeogeographical geoheritage type).

The Um Greifat polymetallic ore quarry is situated ~ 80 km north of Mersa Alam on the Red Sea Coast (Fig. 5). The polymetallic mineralization comprises mainly Fe–Mn-Zn oxides forming a stratiform and strata-bound ore bodies overlain by lenticular and cavernous masses (Afify et al. 2020). This deposit with highly complex epigenetic-supergene origin is currently exploited (Fig. 6c). The uniqueness of this geosite is linked to its economic-geological, sedimentary, and mineralogical features.

The manganese quarry at Gebel Abu Sha'ar El-Qibli (Fig. 5) exhibits the Lower-Middle Miocene Gharmoul Formation (thickness of 50–200 m) consisting of thick-bedded, fossiliferous, dolomitic limestones (Fig. 6d). It conformably overlies the Lower Miocene Abu Gerfan Formation. The lithology and the fossil content of the Gharmoul Formation imply a shallow-marine, intertidal to subtidal mode of deposition (Issawi et al. 2009). Hypothetically, the origin of manganese ores is linked to hydrothermal solutions circulated through carbonate blocks faulted in the course of the Red Sea rifting, although further investigations are necessary for more definite judgments. The economic-geological importance of this geosite and its mineralogical and sedimentary peculiarities determine its uniqueness.

The White Sand quarry is located near the Ras Gharib–El Shiekh Fadl road (Fig. 5). There, sand is quarried from the Upper Ordovician–Silurian Naqus Formation (Fig. 6e), which consists of white, calcareous, cross-bedded sandstones of fluvial and fluvio-glacial nature. Although the noted age of this formation is broadly accepted (Wanas 2011), it was questioned by Weissbrod (2004) who attributed these sands to the Late Paleozoic. The uniqueness of this geosite is linked to its economic-geological importance, but even more to its sedimentary and palaeogeographical peculiarities.

Gebel Duwi is a conspicuous mountain with a sharp ridge, which is located in the center of the study area (Fig. 5). The Upper Cretaceous–Lower Eocene sedimentary rocks crop out there, and, particularly, this is the type locality of the Campanian–Maastrichtian Duwi Formation including phosphate lenses. This locality exhibits broad spectrum of geological phenomena, and it has become a subject of international-class geological research projects (e.g., Abdelhady et al. 2020). One should note the presence of notable natural and human-modified landforms (Fig. 7a), cross-bedding in the Nubian sandstones indicating their fluvial origin (Fig. 7b), abundant chert nodules in the Thebes Formation (Fig. 7c), phosphate-rich deposits of the Duwi Formation (Fig. 7d) that were exploited (Fig. 7e, f), and

Fig. 6 Mining-related geosites of the study area: **a** the Sukari gold mines (arrow indicates the entrance), **b** the Al-Fawakhier gold mine (arrow indicates abandoned equipment, the partly destroyed entrance is show on insert image), **c** the Um Greifat polymetallic ore quarry, **d** the Gebel Abu Sha'ar El-Qibli manganese quarry (students stand near the wall), **e** the White Sand quarry (students stand in the central part)

Fig. 7 The Gebel Duwi geosite: **a** coincidence of natural and human-modified (arrow) landforms, **b** cross-bedding in the Nubian sandstones, **c** chert nodules (arrow) of the Thebes Formation, **d** phosphate beds of the Duwi Formation, **e**, **f** abandoned phosphate mines (arrows indicate the entrances), **g** angular unconformity (dashed line) between the Lower Eocene and Miocene deposits

various elements of stratigraphic architecture like angular unconformities (Fig. 7g). Moreover, some beds with shell concentrations and biostromes are found, as well as various sedimentary structures like ripple marks. More generally, Gebel Duwi is a locality that provides textbook-like examples of various geological phenomena and information about the long-term geological evolution of the northeastern African margin. The high uniqueness of the Gebel Duwi geosite is dictated by the co-occurrence of notable geomorphological, sedimentary, stratigraphical, palaeontological, palaeogeographical, and economic-geological features.

The Sodmein cave is located in Wadi Sodmein, north of Gebel Duwi (Fig. 5). It is formed in layered carbonates of the Lower Eocene Thebes Formation (Fig. 8a), and it hosts well-developed calcareous speleothems (Fig. 8b). This has become an important site for palaeoenvironmental (Moeyersons et al. 2002; Yousif et al. 2018) and geoarchaeological (Van Peer et al. 1996; Vermeersch et al. 2015) research, which has brought outstanding discoveries. Particularly, the cave provides one of the oldest African records of domestic small livestock (Linseele et al. 2010). This geosite is unique due to representation of interesting geomorphological object (it is worth to note that caves are rare in Egypt (Sallam et al. 2020)) and palaeogeographical (sensu Bruno et al. 2014) importance.

The Meatiq dome is a metamorphic complex of the Precambrian basement of the Eastern Desert (Fig. 5). It is an antiformal structure composed of granite gneiss, and it is conformably overlain by a heterogenous, isoclinally folded, mylonitic carapace (Sturchio et al. 1983). Particularly, this locality bears amphibolite outcrops (Fig. 8c) and exhibits various types of folds (Fig. 8d, e). It serves as a place for important, international-level investigations related to the Neoproterozoic petrology and tectonics (Hamdy et al. 2017; Hassan et al. 2017; Mohammad et al. 2020). Therefore, its uniqueness is linked to metamorphic and tectonic elements.

Geoheritage Assessment

The eight proposed geosites of the Golden Triangle were assessed with criteria and scores proposed above (Table 1). The results indicate on a significant difference between these geosites (Table 3). The most valuable (> 300 scores) are Gebel Duwi, the Sodmein Cave, and the Al-Fawakhier gold mine. Three other geosites gain between 100 and 200 scores, but, nonetheless, their heritage value and, thus, importance

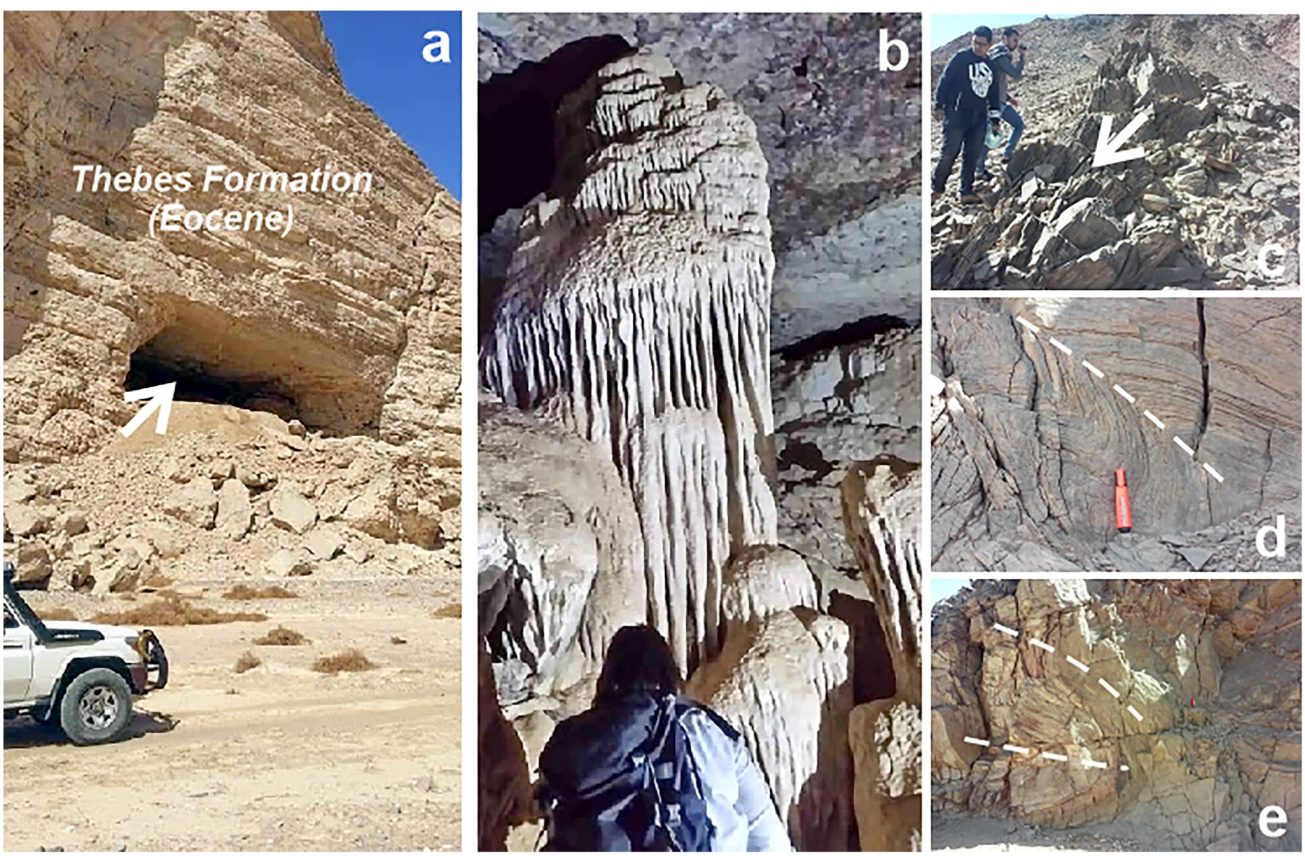

Fig. 8 The Sodmein cave (arrow indicates the entrance) (**a**) and its calcareous speleothems (**b**); Precambrian metamorphic rocks (arrow indicates outcrop) (**c**) of the Meatiq dome and their folding (dashed line traces fold axes) (**d**, **e**)

Table 3 Semi-quantitative assessment (scoring) of the proposed geosites

Criteria (see Table 1)	Geosites							
	A	B	C	D	E	F	G	H
Rank	+100	+250	+50	+50	+50	+250	+250	+50
Number of geoheritage types	+10	+25	+10	+10	+10	+25	+10	+10
Accessibility	+25	+25	0	0	+25	+25	0	0
Vulnerability	+25	–25	+25	+25	+25	+25	0	+25
Need for interpretation	0	0	–10	–25	–10	0	+25	–10
Scientific importance	0	0	0	+25	0	+25	0	0
Educational importance	0	0	0	0	0	+25	0	0
Touristic importance	0	+25	0	0	0	0	+25	0
Esthetic attractiveness	+25	+25	0	0	0	+50	+50	+50
Total scores	185	325	75	85	100	425	360	125

Geosites: A – Sukari gold mines, B – Al-Fawakhir gold mine, C – Um Greifat polymetallic ore quarry, D – Gebel Abu Sha'ar El-Qibli manganese quarry, E – White Sand quarry, F – Gebel Duwi, G – Sodmein cave, H – Meatiq dome

to the territorial geodiversity is undisputable. The particular characteristics of the geoheritage of the Golden Triangle are addressed below.

The proposed geosites are ranked locally, regionally, and nationally (Table 3) depending on the rarity of their features. Particularly, the highest rank of Gebel Duwi, the Sodmein Cave, and the Al-Fawakhier gold mine is determined by their uniqueness on the scale of entire Egypt. Gebel Duwi provides information for deciphering the geological history of the northeastern margin of Africa, the Sodmein cave is one of few caves of Egypt and boasts outstanding geoarchaeological record, and the Al-Fawakhier gold mine reflects exceptionally the millennia-long history of the geological resource exploitation in Egypt.

The number of geoheritage types differs between the geosites, but none of them comprises less than two types, and, thus, the type combination contributes to their value (Table 3). The Al-Fawakhier gold mine and Gebel Duwi boast significant diversity of unique phenomena (Table 2). The entity of geosites represents 10 geoheritage types, from which the economical, mineralogical, sedimentary, and palaeogeographical types are the most common (Table 2). This is not surprising in regard to the richest mineral resources of the Golden Triangle and wide distribution of well-exposed sedimentary sequences accumulated in different environments.

The accessibility of the proposed geosites is moderate (Table 3). Although many of them are located near roads and even in the vicinities of urbanized areas, the entire Golden Triangle area is located quite far from the well-populated areas of Egypt (Fig. 1). Moreover, some geosites can be reached by only local roads without asphaltic cover, which fact decreases their accessibility.

The majority of the proposed geosites remain in their natural state (Table 3). However, the Sodmein cave is in danger as frequent visits may easily lead to significant damage (e.g., destruction of speleothems). This piece of geoheritage needs special protection. The abandoned mining site of Al-Fawakhier is partly destroyed, and the remains of various constructions are more anthropogenic waste than mining heritage (Fig. 6b). Undoubtedly, the present state of this geosite decreases its value and requires geoconservation procedures based on a well-fixed local planning.

From the eight proposed geosites, the only Sodmein cave does not require special knowledge from its visitors, although comprehension of its palaeoenvironmental and geoarchaeological importance is impossible without interpretation. The other sites require either basic or professional geological knowledge, and additional research is necessary to understand the nature of the Gebel Abu Sha'ar El-Qibli manganese ores. The need to interpretation decreases the value of many sites (Table 3). However, installation of explanatory panels coupled with launching a special webpage focusing on the Golden Triangle geological uniqueness would solve this problem easily in the majority of cases.

The utility of the proposed geosites differs, although all of them are useful for science, education, and tourism, at least, locally (Table 3). Gebel Duwi and the Gebel Abu Sha'ar El-Qibli manganese quarry are of the greatest importance for further research due to diversity of notable phenomena or still poor knowledge, respectively. The other considered localities also provide with important information, but these were already studied adequately (see the above descriptions for citations). The diversity of the Gebel Duwi geosite with its textbook-like examples of various phenomena makes it of special importance for the world-class geoeducation. Two geosites, namely Al-Fawakhier gold mine, and the Sodmein cave can become attractions to international geotourists and other tourists. The former offers unique possibility to learn about mining in the historical times, and the latter demonstrates phenomenon (karstification) that may be judged unexpected for desert, hyper-arid conditions. The other geosites would be highly-interesting to local geotourists, and similarly or even more attractive geological localities can be found in the other parts of Egypt and many places of the world.

The esthetic attractiveness (sensu Kirillova et al. 2014; Mikhailenko et al. 2017) is significant for more than a half of the proposed geosites and increases their value (Table 3). It is determined by panoramic views of the mining site and the surrounding geological environment at the Sukari gold mines (Fig. 6a), the Prehistoric rock art and the historical significance of the Al-Fawakhier gold mine (AbdelMaksoud 2020), some spectacular geological elements visible at Gebel Duwi (Fig. 7), calcareous speleothems of the Sodmein cave (Fig. 7b), and the drawing-like folding at the Meatiq Dome (Fig. 8d, e).

Discussion and Conclusion

The results of the present study contribute to a rising awareness of the geoheritage and geotourism resources of Egypt (Ólafsdóttir and Tverijonaite 2018). They also imply that the Golden Triangle bears nationally-important geoheritage, which, therefore, deserves careful management, i.e., geoconservation and exploitation for the purposes of science, education, and tourism. Although some geosites are valued higher than the others (Table 3), these does not mean some of them are not useful. Low heritage value is not zero value, i.e., it indicates on certain importance and potential. Moreover, some lower valued geosites possess unique features that do not appear in the higher-valued geosites, and, thus, the both categories contribute to the territorial geodiversity and the overall geoheritage value of the Golden Triangle.

Currently, the proposed geosites are used chiefly for geological research (Abdelhady et al. 2020; Afify et al. 2020; Mohammad et al. 2020) and occasional, professionally guided excursions for university students (Fig. 9).

Fig. 9 Various academic geotourist activities in the study area

Nonetheless, this experience has been rather significant, and it should be taken into account in further development of geosite-related activities. Another aspect for planning is the presence of similar geologically rich territories in the other parts of Egypt, including the Bahariya and Farafra oases (Plyusnina et al. 2016), Faiyum Oasis (Sallam et al. 2018a; Al-Dhwadi and Sallam 2019; Mashaal et al. 2020), the Siwa Oasis (Sallam et al. 2018b), and the Kurkur Oasis (Sallam and Abou-Elmagd 2021). This raises the questions of the national coordination of geoheritage management, as well as of the planning of multi-destination geoconservation and geotourism programs.

The Golden Triangle mega-project of Egypt aims at sustainable development of a large territory (http://www.riad-riad.com/en/publications/declaring-golden-triangle-special-economic-zone, https://www.egypttoday.com/Article/3/14644/Golden-Triangle-project-encourages-urbanization-investment) and, if so, it is very sensible to link the geoheritage management in the study area to this mega-project. An appropriate solution would be geopark creation, with the geopark territory equal to the economic zone delineated by the Presidential Decree No. 341 of 2017. The reasons of this proposal are as follows. First, geoparks provide integrity of geoheritage conservation and exploitation and link these to the local socio-economical development (Farsani et al. 2012; Henriques and Brilha 2017; Ólafsdóttir 2019; Catana and Brilha 2020; Henriques et al. 2020). Geopark planning and creation would attract specialists and resources for really comprehensive geoheritage assessment on the study area (the present study proves the urgency of this task). Second, this mega-project itself needs additional resources and stimuli for the balanced development of the territory, and among them is the geoheritage resource that is valuable, particularly, for the rise of tourism industry (Table 3). Examples of such geoparks and the relevant initiatives can be found, particularly, in Germany (Wrede and Mügge-Bartolovic 2012) and Italy (Mossa et al. 2018; Beretic et al. 2019; Muntoni et al. 2020) where geoheritage concentrates on territories shifting in their development from mining to tourism. The main challenge for the possible geopark in the Golden Triangle is its remote position relatively to the national tourism destinations and the significant need of infrastructural development. However, it is the mega-project that can accumulate and provide the necessary resources, investments, and marketing solutions to address these challenges adequately.

Indeed, there may be concerns about the mining-related geoheritage exploration and subsequent exploitation in Egypt. However, the very fact of the mega-project launching indicates on the readiness of this country and its government to invest into development and diversification of the economy of this remote area. Such a mega-project concentrates financial and administrative resources, which can be applied successfully to really complex initiatives. This is known from the experience with mega-projects/national projects in the other countries (Lee and Jeon 2018; Meitzner Yoder 2018; Nosachevskiy et al. 2019). Moreover, the high uniqueness of the geoheritage of the Golden Triangle together with the importance of the tourism industry into the national economy make possible demand for the geopark considered above.

Conclusively, the undertaken preliminary inventory and assessment of geoheritage of the new Golden Triangle economic zone of Egypt allows for the proposal of eight geosites and to judge about the high geoheritage value of the entire study area. These geosites represent as much as ten geoheritage types. Some geosites can be of importance for the international-level development of geoscientific, geoeducational, and geotouristic initiatives in Egypt. Undoubtedly, more geosites can be found in the study area in the future, and the present preliminary findings raise the question of organization of these geoconservation initiatives. These findings indicate on the geoheritage specifics of the Golden Triangle and its potential for geoeducation and geotourism, and, thus, these can be regarded as a frame for further, years-long investigations. It is suggested to merge the geoheritage management with the mega-project realization in the Golden Triangle, and geopark creation can facilitate achievement of this ambitious task. The present study also stresses the importance of further inventory and assessment of geoheritage in Egypt and, more generally, northeastern Africa in order to explore this valuable resource for the purposes of sustainable development.

Acknowledgements The authors gratefully thank the journal editor and the reviewers for their thorough examination of this paper and helpful recommendations.

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