Human Utilization of Paleo Karst Caves in the Western Desert of Egypt: An Applied Geomorphological Study

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HUMAN UTILIZATION OF PALEO KARST CAVES IN THE WESTERN DESERT OF EGYPT: AN APPLIED GEOMORPHOLOGICAL STUDY

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Abstract

The paleo-karsts in the Western Desert of Egypt hold significant scientific, cultural, historical, and touristic value. These rarely known features could be used in various aspects of life, including geology, architecture, archaeology, paleontology, and tourism. Deserts have played a significant role in Earth's development, with nomadic tribes and civilizations interested in history, geography, and ecology. Recent discoveries of Stone Age tools in some caves have further fueled interest in ancient human habitation in arid desert caverns in the southern portion of the Western Desert of Egypt. Geomorphology studies earth surface-process relationships to improve land and water resource management. It aids in understanding caves in Egypt's western desert and evaluates tourism prospects near historical paleo karst caves. Landforms record past and present processes, making their form and pattern crucial in geomorphological studies. This paper is intended to identify the geomorphological characteristics of the caves of the Egyptian Western Desert and the extent of their use for human purposes.

Keywords: Paleo karst caves; human utilization; the Western Desert; Egypt

1. Introduction

The importance of paleo karst caves as a long-term resource has prompted their study on global scales (Moulana et al., 2022). Their characteristics, which include a long forming and developing history, well-preserved morphologies, and moderate size, allow for the identification of abundant vignettes of human interaction

Paleo karst caves are common in the Western Desert of Egypt, yet the extent of their human utilization remains poorly understood. Karst features are widespread there, carved into a series of uplifted carbonate, gypsum, and anhydrite rock layers (Shields, 2018). These caves were an important focus of study on an applied geomorphology field course with the Egyptian Society of Environmental Change during February 2025. Several of these caves are known to have been used by local people for a diverse range of purposes: agricultural, military, and tourism (Stewart et al., 2024). We conducted two field visits to study them. This paper focuses on the micro-scale landforms and processes in the paleo karst caves of the Western Desert in Egypt and the anthropological influences on this diversity of use.

1.1. Study Area Description

Egypt's Western Desert remains little studied geomorphologically. Remnants of infilled caves are widely distributed in the karst terrain (Figure 1). The original caves and cave sediments formed during multi-cycles of humid karstification of Cretaceous-Paleocene age were exposed during tectonic uplift followed by paleo-karst denudation. The site is very popular within the White Desert National Park and is easily accessible. It has a very high level of geomorphological interest. The site is in satisfactory conservation condition without natural or anthropogenic threats. The area significantly contributes to job opportunities and local ecotourism activities (El Aref et al., 2017).

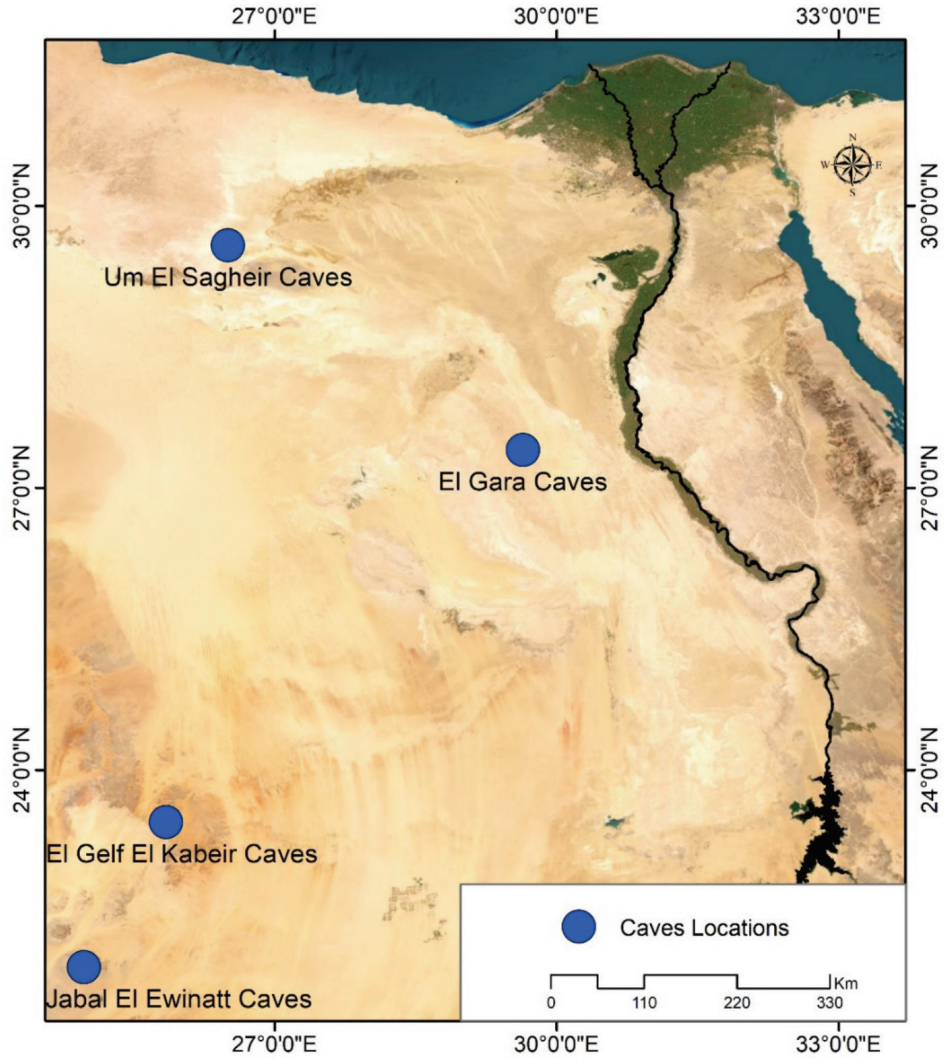

Figure (1): The locations of Paleo Karst Caves in the Western Desert of Egypt

1.2. Literature Review

Information concerning the geological and geomorphological settings of many caves and their significance with respect to human occupation or use is limited or lacking. Karst processes are widely recognized in the Western Desert as a significant geomorphological feature and are particularly relevant to paleoenvironmental and archaeological investigations (Moulana et al., 2022). Cave sites in many parts of the world were popular places of birth, burial, religious practice, and refuge for early people, while many modern visitors use Western Desert caves for camping, recreational, and other purposes. However, the potential geomorphological impact of these different types of human interaction with caves has yet to be properly assessed.

Paleo karst caves figure prominently as unique geomorphological features in arid terrain, where many regions are devoid of surface drainage networks (Shields, 2018). These caves serve as stand-alone sites, stripped barren of sediment and organic matter due to extensive erosion over multiple parts of the stratigraphic sequence. The majority of caves are developed within the Upper Cretaceous limestone, with a few prominent examples hosted in the lower Nubian Sandstone (Figure 2). Within a few dune-filled basins, large depressions harbor

rock shelter caves in the Nubian Sandstone, which provide more limited geomorphological insights. Caves exhibit a complex interplay between solution and collapse mechanisms during their development; at times, solution processes dominate, resulting in passage enlargement and the formation of plenum-like cave morphologies resembling labyrinths. At other times, collapse processes prevail, producing sediment-filled chambers accessible through partially missing vadose canyons, often distorting cave shapes such that the original speleogenetic fabric becomes unrecognizable.

The geomorphological characteristics of the Western Desert provide the framework for understanding the distribution of National Geoparks and the occurrence of human occupation. Defined as the area between the Nile Valley and the Libyan borders, the Western Desert is subdivided into five geomorphological regions: the Eastern Desert, the Nile Oases, the Western Desert Oases, the Western Desert Highlands, and the Great Sand Sea (El Aref et al., 2017). These broad divisions do not encompass the full diversity in landscape that characterizes the region; nevertheless, the dominant geomorphological processes in each area bring about distinct landforms. Consequently, the Western Desert is extremely rich in geomorphological and geological sites. A well-designed geomorphological study of the region, therefore, not only can assist in the selection of new sites but also is vitally important for the understanding of caves and their role in the long-term human occupation of the desert.

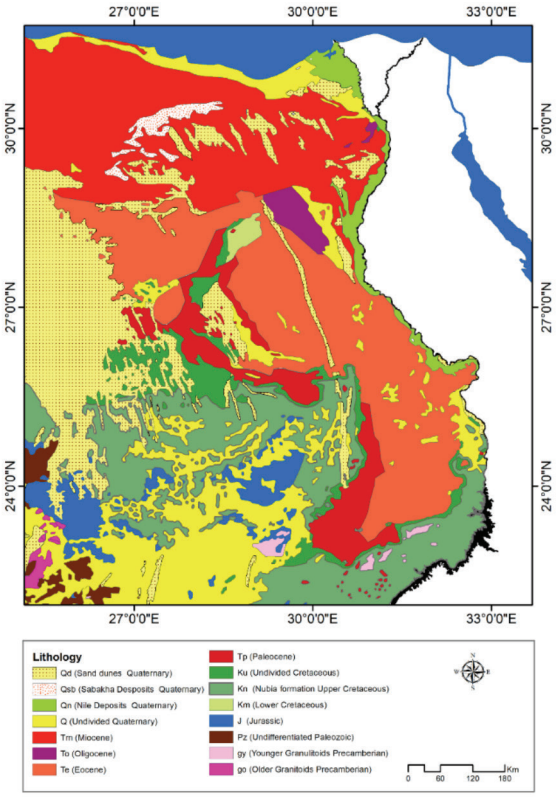

Figure (2): The lithology of the Western Desert of Egypt

In the Western Desert, the widespread occurrence of limestone has led to extensive karstification, yet the study of karst is in its infancy. A major obstacle that requires crossing is the great complexity of karst in the region. Climate, lithology, tectonics, and fluvial processes, all of which vary from place to place, have resulted in geomorphological systems, including karst landforms and caves, that have variable character. Understanding these geomorphological characteristics is essential, as it enables the precise study of karst features, helps to decipher their formation mechanisms, and clarifies their role within the broader landscape and human occupation (Moulana et al., 2022).

1.3. Objective

This paper aims to identify the geomorphological characteristics of the caves of the Egyptian Western Desert and the extent of their use for human purposes, whether at the present time or in ancient historical exploitation.

1.4. Methodology

For the purpose of this study, datasets on caves attributes were first acquired through a variety of secondary and primary data sources. In the context, literature on cases in the Western Desert of Egypt were reviewed. Also, additional data on anthropological and archaeological cave use were collected. Due the significance of geology in understanding of processes occurring near caves in the western desert of Egypt, the lithology of the Western Desert of was delineated from the geologic map scale 1:2000000. As an arbitrary data source, a field visit to Gara Um El Sagheir Oasis caves was conducted during the period 22 – 25 April 2025. During the field visit, true cave surveys were undertaken for the caves displaying substantial paleo-environmental, archaeological or anthropological potential. The data acquired on the field visit provided valuable information on unknown cave locations, human use, and access.

3. Results and Discussion

3.1.Geomorphological Features of Paleo Karst Caves

Underground cavern systems arise through multiple speleogenetic mechanisms, including tectonic activity, chemical weathering, and solely by groundwater processes (Shields, 2018). In particular, diapiric gypsum deposits harbor subsurface fissures, which are vulnerable to karstic widening and consequent cave formation. Caves developed exclusively during earlier geological epochs, such as the Tertiary or Mesozoic, are identified as paleo-karst cavities. Such limestone cavities dating back to the Upper Cretaceous remain widespread in the southwestern desert of Egypt. These cavities often contain extensive fill deposits varying from thin remnants to over 20 m thick accumulations. This morphometric pattern resembles scenarios in northern Sudan where caves originated under Pleistocene pluvial climates, remaining largely unmodified since the Pliocene. A labyrinthic, maze-like morphology predominates in proto-karst caves with original enclosures less than 2 m, whereas those exceeding 2.5 m tend to develop along dendritic, anastomotic, or somewhat linear schemes.

3.2. Formation Processes

Paleo karst caves maintain significant importance for human communities in Egypt's Western Desert, in separated locations in some Oases, such as Gara Umm El Saghir NE of Siwa Oasis, Kharga and Dakhla Oases, and El Galph El Kebir historical caves. Ancient water wells and bronze artifacts found in the 'Potenki' cave near Bahariya Oasis demonstrate the enduring utilization of caves by local populations. Although remote sensing clearly reveals these caves, their scientific investigation remains scant. The study aims to elucidate the geomorphological characteristics of paleo karst caves—with a focus on their formation and the morphology of their interiors—alongside the sedimentary environment of the enclosing basin. Additionally, it explores their utilization by local communities from an applied geomorphological perspective.

Paleo karst caves arise from the chemical dissolution of carbonate rocks, frequently whey-colored, in low hills that form plateaux on the Western Desert's fringes. Located at the

upper parts of valleys occupied by dry, steep alluvial wadis with extensive scree deposits, the caves are composed of gypsum, marl, and limestone. Their ceiling morphologies include network and polygonal patterns; the former results from the reactivation and later enlargement of pre-existing conduit systems, whereas the latter indicates local stress states. Based on the materials present in the enclosing basin, the associated sediments are interpreted to be Early Pleistocene and Holocene (Moulana et al., 2022). The evolution of speleogenesis in these gypsum plateaux, as demonstrated by remote-sensing analysis, is controlled by a complex interplay of tectonic, stratigraphic, hydrogeologic, and climatic factors (Shields, 2018).

3.3. Morphological Analysis

Twenty caves in the Western Desert of Egypt were analyzed to establish a systematic approach for studying their geomorphological and archaeological attributes. These caves, which currently appear morphologically mature, were carefully surveyed to document their form and orientation (Figure 3). Each cave was measured for height, entrance width, in-cave length between key bends, and width at key points, in line with protocols adapted from New Mexico's Gypsum Plain caves (Shields, 2018). Photographs of each cave and the surrounding terrain were also captured for reference.

A substantial data set was collected, facilitating a comprehensive morphological interpretation within the broader cave environment. Deepening the study, extensive geomorphological and geomorphometric research was conducted to characterize nine caves rather than solely at the entrance points. The selected caves exhibited distinctive morphological and geological traits representative of the region.

(a)

(b)

Figure (3): Morphological pattern of Djara Cave

3.4. Sedimentology of Cave Deposits

The geomorphology of caves and karst systems, relating to their tectonic and structural setting, influences sediment accumulation and types of sediments prior to extensive atmospheric weathering (Farrand, 2001). Sedimentological characteristics indicate geological evolution and contribute to interpreting human utilization. A study of Eastern Desert paleo karst caves examines human use, focusing on geomorphology and sedimentology, employing field surveys and satellite image analysis. Sedimentological aspects are central to assessing human habitation and paleoenvironmental conditions. Sediments inside palaeocaves and open-air archaeological sites differ significantly, but caves nonetheless provide an archive of paleoenvironmental change. These deposits

potentially inform regional archaeological interpretations and permit direct sampling of stable cave facies from earlier epochs of human evolution. Sedimentological analysis of cave fills, integrated with taphonomic and archaeological studies, enhances understanding of human impact on cave environments. Describing sedimentological characteristics and their palaeoclimatic and palaeoenvironmental implications contributes to interpreting human use of paleo-karst caves.

3.5. Human Interaction with Paleo Karst Caves

Caves have served numerous functions for human beings, ranging from shelter to religious ceremonies. Especially in the Western Desert of Egypt, kites placed near caves have been linked to the hunting of migratory herds that sought respite within these refuges. Wadi Sura paintings near Gilf Kebir, Egypt, document prehistoric activities inside a 70 m-deep granite cave at known water collection points (Stewart et al., 2024). Rock art within basalt entrances of hamada caves illustrates diverse human interactions from Neolithic to historical periods. These characteristics make such caves attractive sites for ongoing occupation.

The West Nile Delta hosts approximately sixty caves that demonstrate the geological and geomorphological aspects of karst development, accompanied by archaeological, geological, and palaeo-geographical theses from the Holocene period. Investigations of cultural heritage within these caves provide key information on the environment and human interaction. Archaeological investigations combined with monitoring activities, including mapping, sampling, and sediment analysis, identify the presence of fossils and anthropogenic influence in caves. Throughout historical times, such caves have captured human imagination due to their small, intimate chambers compared to the expansive deserts.

Interaction with caves involves transit, periodic, or prolonged occupations, exemplified by the archaeological study of Umm Jirsan—a recently documented human occupation of a lava tube in northern Saudi Arabia during the Neolithic and Chalcolithic/Bronze Age periods. Caves naturally serve as significant points for travelers by providing shelter (Damm & Young, 2013). In Egypt's Western Desert, historically under-explored caves have recently been identified as suitable water sources, prompting their search and study. Beyond the provision of water, caves offer shelter from the harsh desert environment through their limited openings and often shallow depths.

3.6. Cultural Significance

The abundant yet largely unstudied cave systems carved from carbonate bedrock offer a cultural and archaeological record whose artifacts and loci represent a long history of multi-context occupation and use (Damm & Young, 2013). From their earliest conceptualization, natural caves "...have long occupied an important role in human culture, remaining credible factors in the creative arts and natural sciences to the present." Occupation of natural caves during lateral-phase human movement therefore constitutes a strong hypothesis and an initial point at which to contextualize the data. Cultural evidence may be categorized into archaeological remains, with cave walls serving as a canvas for artistic expression; paleontological specimens, including faunal and human remains that feasibly correlate with patterns of use; place-names and local urban legends; and contemporary utilization, ranging from deep cave installations to more casual fishing expeditions.

3.7. Archaeological Findings

Paleo karst caves in Egypt's Western Desert have attracted human interest for millennia. Early studies already reflected these observations by emphasizing the caves' potential significance for human activity throughout the ages. However, the archaeological utilization of these caves does not receive a great deal of attention within research, a conclusion supported by the assessments presented here.

The Western Desert is a particularly hostile environment. Human use of the caves found there explains one aspect, even if only briefly and in applied form. Doing so requires considering the cave geomorphology in more detail—not only the manner of formation, morphology, and sediment fill, but also the actual effect of the cave on contemporary society. Historical archaeological evidence, combined with current use, follows logically—a complementary approach rather than compartmentalized function-specific investigations. Three caves exemplify this. The common setting is Egypt's Western Desert, which embodies the outstanding conditions in substratum, lithology, and climate.

3.8. Impact of Tourism

Caves open to tourism require management plans for sustainability (Augusto Santos Lobo et al., 2014). Unregulated visitor influx has caused accelerated degradation of caves worldwide. Djara Cave, with its remarkable natural and cultural attributes, is a viable candidate for epigeal ecotourism east of the Farafra Oasis area.

3.9. Gara Umm El Saghir Oasis Cave: A Case Studies

Several caves in the Western Desert of Egypt, such as Djara Cave and the El Galf El Kabir caves, provide examples of the type of information that can be readily accessed with geomorphological approaches. Also, some small caves of Gara Umm El Saghir Oasis rank among the largest paleo karst caves in the Western Desert of Egypt and is situated near the administrative center of Siwa Oasis. They involve 18 caves that are located in seven sites to the south-west of Gara Um El Sagheir Oasis (Figure 4). This hypogene gypsum cave is positioned at the lower extremity of the Marmarica cliff, exhibiting wide dimensions with a substantial volume estimated at 33 m^3.

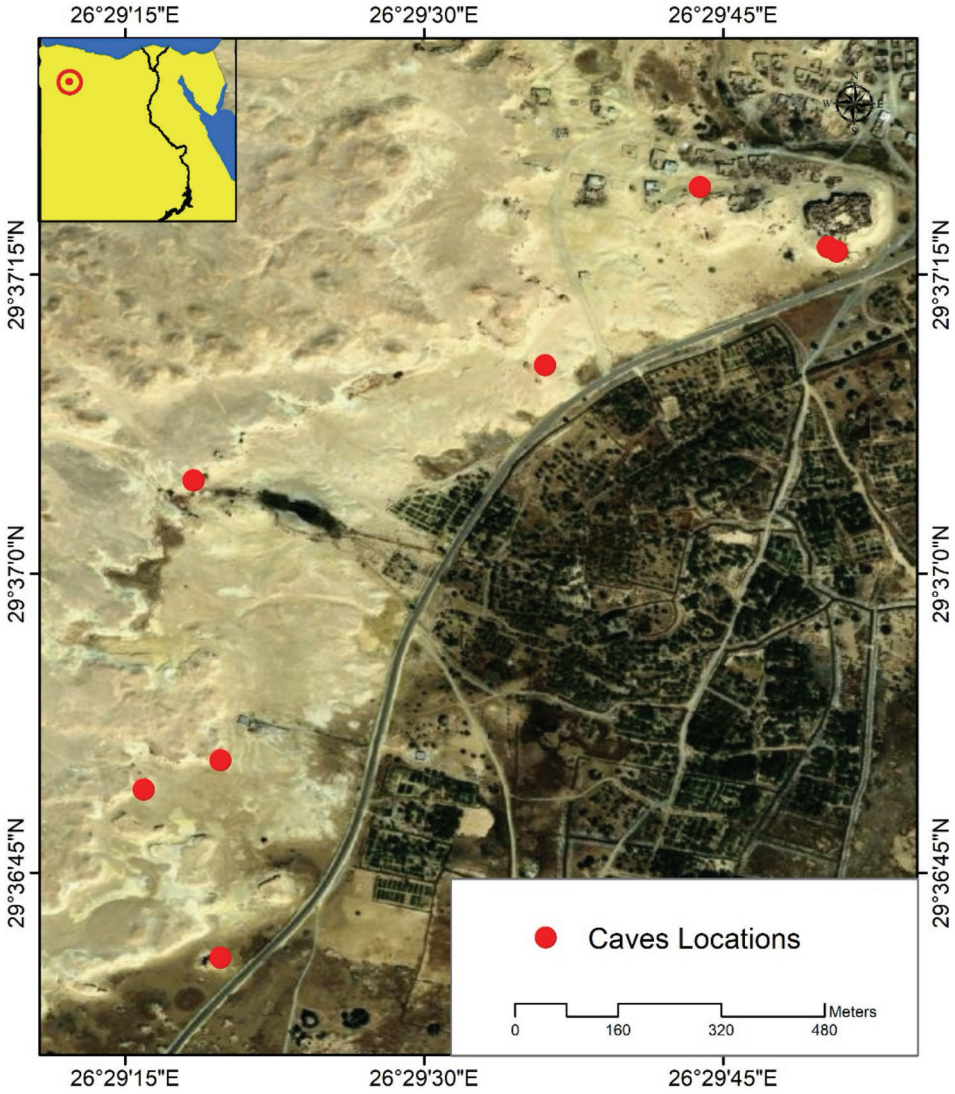

Figure (4): Locations of Gara Um El Sagheir Oasis caves

It was found that Gara Um El Sagheir Oasis caves have varied width ranging between 0.9 and 10.10 m with an average of 2.51 m. Meanwhile, they were found to have less varied depths ranging between 1.00 and 3.73 m with an average of 2.02 m. Similarly, no significant differences were noticed among these caves in terms of their height that range between 0.70 and 2.00 m with an average of 1.21 m (Table 1).

Such a relatively low varied depth and height compared to width of these caves (Figure 5) can be attributed to the geological structure of the area which is dominated by faults and joints that accelerate the action of erosion and weathering leading to widening these caves

Table (1): Summary Statistics of Gara Um El Sagheir Oasis caves dimension

Parameters	Depth (m)	Height (m)	Width (m)
Min	1.00	0.70	0.90
Max	3.73	2.00	10.10
Average	2.02	1.21	2.51

Source: field visit measurements

(a) (b)

Figure (5): Varied dimensions of Gara Um El Sagheir Oasis caves

Human utilization of some of these caves is evident via structural modifications that have been established by local residents to use them as shelters (Figure 6).

(a) (b)

Figure (6): Structural modifications by local residents of Gara Um El Sagheir Oasis caves

4. Discussion

The investigation of human utilization of paleo karst caves in Egypt's Western Desert represents an important component of the broader environmental and archaeological reconstruction of the region (Stewart et al., 2024). Accordingly, the selected caves fall within an applied geomorphological framework and constitute a representative sample of the principal types of karst caves. Four main requirements informed the choice of study sites: accessibility for observation and recording; the presence of datable archaeological remains; association with known archaeological localities; and representation of all major cave types or features. The final assemblage comprises seven caves.

Preliminary observations concerning the environment within the caves reveal large water bodies, extensive paleo-karst features and archaeologically significant sediments in some cases, and evidence of disturbance in others.

Archaeological materials within the sediment include a distinctive pottery assemblage, lithic tools, grinding stones, and human remains. In contrast, earlier work in Qatar concluded that caves occur mainly along the central axis of the limestone outcrop and are accessible to a wide range of visitors, with no evidence for human occupation or cave-related activities prior to the Middle Islamic period (Shields, 2018).

4.1. Sustainable Tourism Practices

In the development of ecotourism, safeguards governing the use of natural sites such as paleo karst caves assume critical importance. Case studies in Nigeria and Brazil illustrate guiding principles for sustainable tourist activity. The government and private sector must conform to established ecotourism regulations to accommodate local concerns and prevent community opposition to site development. Conversely, community participation in the establishment of management policies and decision-making accelerates efforts to balance the interests of visitor inflow and conservation objectives. Education programs can orient local populations in the benefits of ecotourism potential and cultivate a positive engagement with site development (Eja & Judipat, 2017).

Landmarks with sensitive geomorphological or archaeological features, including many paleo karst caves, require careful calibration of carrying capacity. The degree of potential impact and ensuing environmental resilience cannot be predicted from gross visitor numbers alone but depends strongly on the duration of exposure at specific locations where critical points occur. Carrying capacity consequently must function as a space- and time-dependent parameter, with dynamic limits established for both seasonal cycles and the specific environmental context. These scientifically informed, long-term provisions are essential for equilibrating public access with site conservation and must therefore be integrated into any advance proposal relating to the tectono-geomorphology of a region (Augusto Santos Lobo et al., 2014).

5. Conclusion

- This study provides an integrated approach for geomorphological and archaeological assessment of paleo-karst caves in Egypt's Western Desert. The results revealed the complex origins of these caves, diverse morphologies, and long-standing human significance. The caves were shaped through a combination of tectonic, stratigraphic, hydrogeologic, and climatic processes, and later served as shelters, cultural sites, and potential water sources for human communities across various historical periods.

- The morphological analysis of the caves, particularly of the Gara Umm El Saghir Oasis caves as a case study, shows that structural controls such as faults and joints have played a decisive role in their widening, while their relatively consistent height and depth reflect lithological constraints.

- However, many cave systems in the western desert of Egypt are under-documented, with restricted accessibility due to remoteness, harsh climatic conditions, and logistical constraints. Due to small dimensions of the caves, remote sensing could be hardly employed for identifying and mapping these caves. This is due to the course spatial resolution of remotely sensed data. Additionally, increasing tourism, if unmanaged, poses threats to the preservation of fragile geomorphological and cultural features.

- Future research work is needed in the field of using geomatics techniques integrated with speleological surveys to document both accessible and concealed cave networks.

Ultimately, sustained, systematic investigation of these paleo-karst systems promises to illuminate not only the geological evolution of Egypt's deserts but also the resilience and adaptability of past human populations in extreme environments.

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