Re-geomorphic Mapping of Unroofed Cave of Crystal Mountain Area, Bahariya – Farafra Depressions, Western Desert of Egypt

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RE-GEOMORPHIC MAPPING OF UNROOFED CAVE OF CRYSTAL MOUNTAIN AREA, BAHARIYA – FARAFRA DEPRESSIONS, WESTERN DESERT OF EGYPT

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Abstract

The Bahariya and Farafra depressions lie in the heart of Egypt's Western Desert, between the Dakhla and Qattara depressions. The depressions called Bahariya and Farafra, which separate the plateau, are mostly made up of carbonate rocks from the Late Cretaceous and Late Tertiary periods. These rocks are broken up by a number of paleokarst or karstified breaks and classic interval rocks. Layers of shallow and deep marine sediments, fluctuating sea levels, and varying rates of sedimentation, particularly in the Paleocene and Eocene periods east of the Great Sand Sea, comprise the Farafra depression. Karstic processes of limestone solution formed the Upper Cretaceous snow-white chalk that covers it. In the late Quaternary, the study area, located in the heart of the Western desert, experienced limited surface runoff activities during humid periods and wind-induced deposition activities during dry periods. We recognized an eroded, unroofed cave system between the Bahariya and Farafra depressions. The northern and southern cavern parts are located in a hilly area on the plateau, about 17 km south of the Naqb El-Sellem area and 4 km southeast of Qaret Sheihk Abdalla Muhammed. Fluvial erosion of a Wadi, filled with windblown sand due to climate change, separates these two parts of the cavern system. A recent buildup of Aeolian sand and a sand prominence above the surface with calcite and quartz crystals entangled in it are geomorphological signs of activity in the past few thousand years. The cave system's karst remains are characterized by the existence of several solution features, such as karst hills, karren, caverns, stalactites, cave columns, cones, and other palaeo-karstic deposits. This work aims to create a detailed geomorphological map of the eroded cave, detailing the features of the karst remains. It also aims to define the stages of its exposure to erosion factors as well as the stages of erosion itself while studying the types of its epikarstic deposits. This study primarily focuses on the geomorphological evidence of the paleo-cavern system. It does this by using a total station to perform detailed field surveys and field topographic profiling, as well as interpret satellite images, analyze DEMs, and create geomorphic maps.

Keywords

Farafra Depression, Bahariya Depression, Unroofed Cave, Paleocave, PaleoKarst, Eroded Cave, Egypt.

1. INTRODUCTION

Recent erosion factors have caused the unroofed caves, which are ancient caves, to collapse, split, or become uncovered due to the karst surface's lowering or dissection (Knez and Slabe, 2002).

1.1. Location

The studied area is located in the central Western Desert of Egypt, east of the Great Sand Sea, on the plateau between two large depressions: the El-Bahariya and El-Farafra Depressions, where the rocks exposed are sedimentary layers that range in age from Upper

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Cretaceous to Recent. We classify the geological layers into two types: carbonate rocks and non-carbonate rocks. Carbonate rocks cover most of the area. Some of the rocks in the area are non-carbonate, such as clay, loam, sand sheets, dunes, and Cenominean clastic rocks from the Bahariya formation. There are also clastic rocks from the Wadi Hennis formation in the northern part of the Farafra depression, as well as Dakhla shales, interbedded loams, clay, and carbonate layers from the Esna formation. There are many karst hills, depressions, carbonate pavements, sinkholes, towers, mushrooms, and other degraded karstic features around the studied cavern system. Most of them are separated by networks of semi-arid wadi basins.

1.2. Background and significance

It is well known that the Western Desert of Egypt is an important location for scientists in various fields of study, such as geology, geomorphology, hydrogeology, and environmental sciences. Egypt is also known for its unique caves amongst the structural depressions of the Western Desert. The calcareous rocky plateau of the Western Desert depressions forms the caves. Many research groups have been interested in delineating and elaborating the origin and evolution of these caves. The researchers conducted numerous field trips within the Bahariya Depression to study the caves' genesis, magnificence, and geomorphological significance. They persistently pursued and searched for new caves in various regions of the Bahariya Depression. In 2009, one of the authors discovered a big

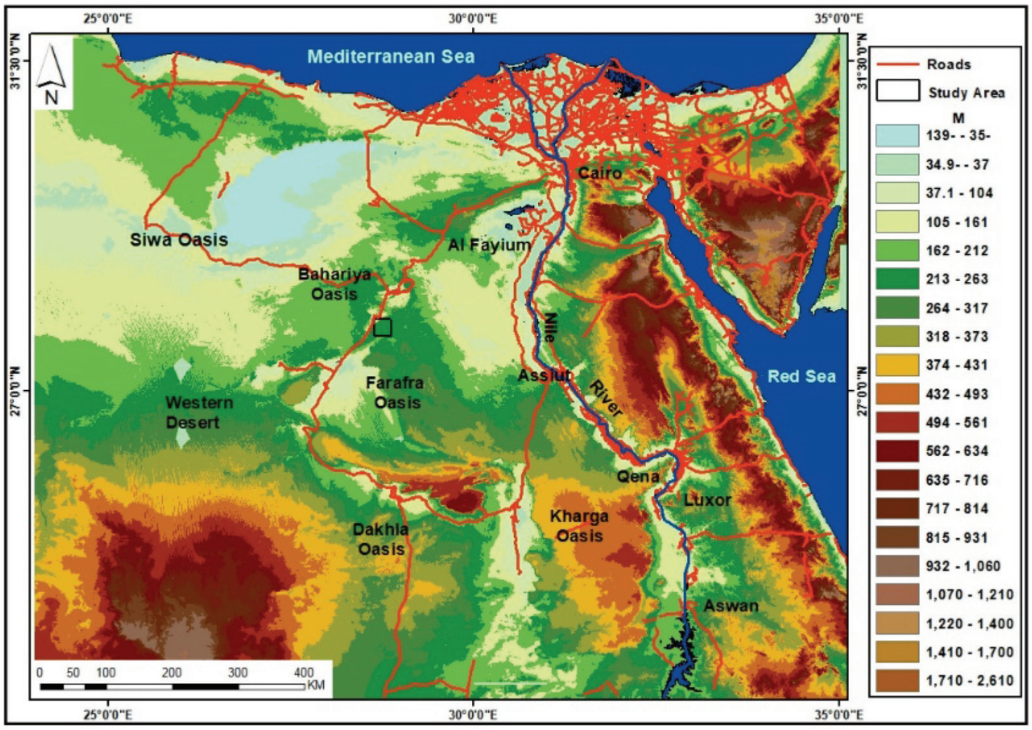

Fig.1: Location map of the study area on a relief map of Egypt

limestone hill of unroofed cave in the Crystal Mountain area in the Western Desert between Bahariya and Farafra Depressions right on the asphaltic road (between km 40 and km 41). The cave has a clear karstic development and emerges into Crystal Mountain's limestone outcrop caves. Therefore, the significance of this area stems not from the cave itself but rather from its existence. In this context, the present work aimed to illustrate the geomorphological activities that led to the formation of the huge unroofed cave in the study area.It is well known that the Western Desert of Egypt is an important location for scientists in various fields of study, such as geology, geomorphology, hydrogeology, and environmental sciences. Egypt is also known for its unique caves amongst the structural depressions of the Western Desert. The calcareous rocky plateau of the Western Desert depressions forms the caves. Many research groups have been interested in delineating and elaborating the origin and evolution of these caves. The researchers conducted numerous field trips within the Bahariya Depression to study the caves' genesis, magnificence, and geomorphological significance. They persistently pursued and searched for new caves in various regions of the Bahariya Depression. In 2009, one of the authors discovered a big limestone hill of unroofed cave in the Crystal Mountain area in the Western Desert between Bahariya and Farafra Depressions right on the asphaltic road (between km 40 and km 41) . The cave has a clear karstic development and emerges into Crystal Mountain's limestone outcrop caves. Therefore, the significance of this area stems not from the cave itself but rather from its existence. In this context, the present work aimed to illustrate the geomorphological activities that led to the formation of the huge unroofed cave in the study area.

1.3. Objective

To protect and show off the geomorphological development and check how well it can handle surface runoff, it was important to find the natural depression (sinkhole) that was made when the karstic activity caused the roof of the underground cave to partially collapse, leaving an opening to the surface. After dissecting the geomorphic landforms, reapplying larger-scale mapping to the area may reveal new features on the ground surface. In order to conduct further analysis with greater accuracy using modern space technologies, this study proposes reapplying mapping of some parts not completed during the current first preliminary geomorphic studies.

To do this project, we need to make a new geomorphological map of the Crystal Mountain area's eroded, unroofed cave system. We also need to investigate the various types of epikarstic deposits and determine the duration of the cave system's exposure to erosion factors. We achieve this through detailed geomorphological surveying using a total station, field topographic profiling, satellite image interpretation, DEM analysis, and geomorphic mapping.

The research aims also to update the geomorphologic features that have undergone changes due to the elevation of the entire land surface following the dissection of the major cave system in the study area. The goal is to identify the primary drainage route that shapes the surface Wadi course of the Upper Bahariya depression. We also aim to understand the absorption of the smaller surface drainage by excavating a long, straight surface channel that connects to the southwest El Qasr depression in a sub-surveillance direction. The goal is to chart the region surrounding the unroofed eastern section of the main chamber, utilizing the most accurate scale accessible during the geomorphic investigation.

1.4. Previous work

Scientists like El-Aref et al. (1987), El-Sayed (1995), Mostafa (2007), El-Aref & Hammed (2007), Wanas (2009), and El Aref et al. (2017) have written about the paleokarst features and how they relate to the palaeoenvironment of the Bahariya and Farafra depressions, which includes the area under study here. These articles have studied karst topography in the Eocene plateau in the Bahriya-Farafra area in general, but this article reconstructs a detailed geomorphological map of the remains of the cave and the stages of its removal by weathering processes and erosion factors during the Quaternary.

The Bahariya Oasis was the focus of a wide range of geological research works intended at structural geology, stratigraphy, iron ore deposits, sedimentology, paleontology, geoarchaeology, etc. These studies include Ball and Beadnell, 1903; Stromer, 1914, 1936; Lebling, 1919; Weiler, 1935; El-Akkad and Issawi, 1963; Said and Issawi, 1964; Soliman et al., 1970; Slaughter and Thurmond, 1974; Khalifa, 1977; El-Aref et al., 2006; Catuneanu et al., 2006; Khalifa and Catuneanu, 2008; Tanner and Khalifa, 2010; Salama et al., 2012, 2013 & 2014; Afify et al., 2015a &b.

1.5. Methods

Fieldwork included measuring rock altitudes and coordinates using a differential global positioning system (GPS). We conducted a field geomorphic survey of the study area using a total station, a handheld GPS, a compass, and a clinometer. We used published topographical maps with scales of 1:50,000 and 1:100,000 to compare the existing geomorphology of Quaternary sediments with the points that were important to this study. Then, we analyzed the sections that went with the maps. We also compared the longest networks of surface drainage basins, image processing results, and reflection. We conducted a geomechanical analysis of the study area using satellite images and DEM.

2. RESULTS

2.1. Geologic setting

The Bahariya and Farafra depressions are located in the heart of the Egyptian Western Desert. The morphological shape of the Bahariya depression is oval, with its major axis running northeast, showing the greatest length, from northeast to southwest, of about 94 km, while the greatest width, measured at right angles compared with its length, is about 42 km, covering an area of about 1800 km2. On the other hand, the Farafra depression is smaller than the Bahariya depression, covering no more than 980 km2, and its location is roughly midway between the Dakhla and Bahariya depressions. In the current research, the study area is located on a plateau separating both depressions.

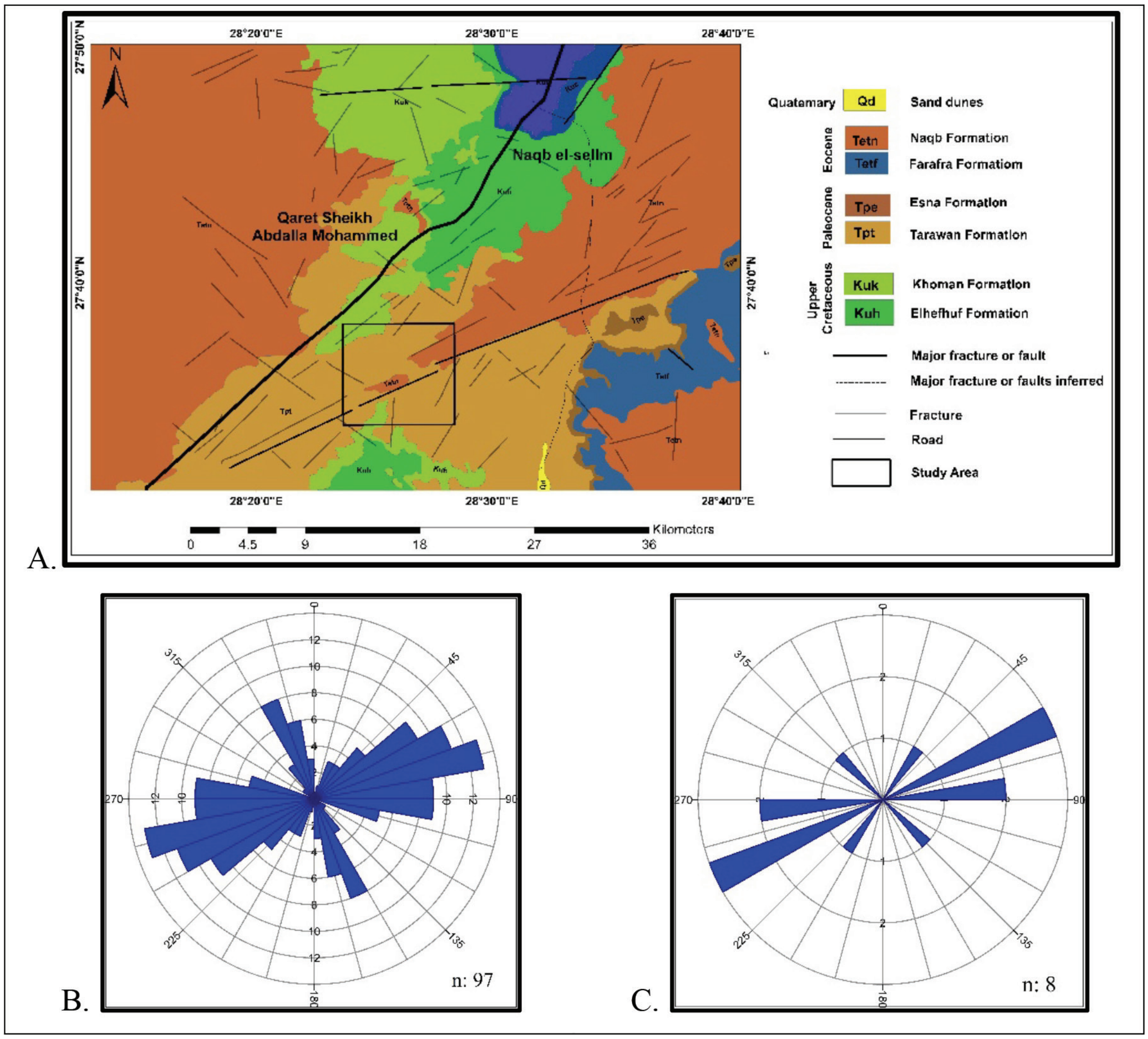

Fig.2: A. Geological map of the study area and its surrounded (EGPC, 1987),
B. Orientation rose diagram of 97 fractures &
C. Orientation rose diagram of 8 major fractures and faults.

2.1.1. The major geological rock units in the studied area are the following (Fig.2 & Tab.1)

The El-Hefhuf Formation, the oldest exposed rocks in the study area, is absent, and the Lower Eocene limestones uncomfortably overlie the Bahariya and/or Heiz formations in the Bahariya scarps. Besides, the formation covers separate hills in the northeastern part of the Bahariya depression and its northern scarp (El-Akkad & Issawi, 1963). The thickness of Hefhuf formation ranges between 11 and 34 m in some parts, and it may reach 120 m in other portions. The formation also has marl, sandy limestones, chalcedony nodules, and arenaceous beds, with thin bands of phosphatic grit in between. The formation suggests a shallow sea environment, whereas the conglomerates and sandstones suggest a land mass near the ancient sea.

The Khoman Formation, the primary carbonate unit in the study area, consists of snow-white chalk and chalky limestones, interspersed with patches of highly siliceous limestone. The upper part of the Khoman Chalk is a hard-dolomitic limestone bed formed in a deep marine environment (early Maastrichtian-Upper Cretaceous) (El Akkad & Issawi, 1963). The chalk beds of the formation cover the southern parts of the Bahariya and the floor of the Farafra Oasis. Notably, the thickness of such a formation increases from north to south, ranging from 25 m at the Bahariya to 50 m in Farafra.

The Tarawan Formation is made up of white chalk and chalky limestone, as well as marl beds. It covered a vast area of the Farafra Oasis and the western part of Abu Minqar, forming many karst hills, mounds, and domes. The Lower Eocene Esna Formation unconformably succeeds it (Hewaidy et al., 2006).

The Esna Formation is an early Eocene greenish-grey marine shale, characterized by calcareous interactions, shallow facies, and limestone facies towards the top. It is widely exposed along the scarp facies of the Farafra Oasis and north of Ain Dalla.

White hard lagoonal limestone, with an individual bed that varies in thickness between 20 and 80 cm, forms the Farafra Formation, which dates back to the Early Eocene. It covers the upper scarp facies and plateau surfaces of the Farafra Oasis. Said (1960) studied and described the alveolinid limestone in El Quss Abu Said, marking the end of the Cretaceous-Eocene succession (Hewaidy et al., 2006).

The Naqb Formation consists of a fossiliferous platform with minor shale intercalations in the upper part and selected non-fossiliferous dolomite in the lower part. The 68-meter-thick formation, consisting of pinky limestone, extends across the southeastern region of Bahariya's chalky recrystallized limestone. Locally, it replaces the lower part of the Minia formation, southwest of the Bahariya limestone facies, with some marl and clay interbeds. The middle Eocene deposited such a formation (Said and Issawi, 1964).

Tab.1. Characteristics of most rock units and their depositional environments of the study area (modified after Hewaidy et al., 2006).

Rock Units	Lithology	Sedimentary Structures	Depositional Environments
El-Hefhuf Fm. (11-34 up to 120m thick)	Shale, mudstone, sandstone and dolostone	Fissile shale, cross-bedded and massive sandstone	Upper intertidal, upper deep subtidal
Khoman Fm. (5-55m thick)	Chalk, partly dolostone and mudstone	Massive to stratified	Shallow inner to deep middle-outer shelf
Tarawan Fm. (1-23m thick)	Chalky limestone	Thick-bedded and massive	Shallow inner to outer shelf
Esna Fm. (20-100m thick)	Shale with argillaceous limestone	Fissile and massive	Shallow inner to middle- outer shelf and rarely supratidal
Farafra Fm. (13-50 m thick)	Limestone, chalk and dolostone	Thick bedded and massive and partly nodular	Lower intertidal to deep inner shelf

2.1.2. Geological structure

The Bahariya anticline extends on the major axis of the Bahariya depression from Gebel Ghorabi in the north, passing through the floor of the depression to the southern part of the depression. It continues southward, towards the Farafra Depression and the plateau separating the two depressions (Moustafa et al., 2003).

However, in addition to tectonic folding, Farafra's depression forms in a dome structure with an axis that extends in the NE/SW direction (Said, 1962). The sea covered the western and southern parts of the Bahariya depression, as well as the northern part of Farafra Oasis in the Maastrichtian (El-Emam et al., 1990). The Paleocene saw the uplift of the Bahariya Anticline, resulting in its appearance as an island. Moreover, the area of the present-day Farafra Oasis has deposits of Tarawan chalky limestones and overlying Esna shale (Issawi et al., 2009).

2.2. Geomorphology

The main geomorphic features in the study area include major and minor depressions, depression scarps, semi-arid wadies, drainage networks, residual hills of various shapes, rocky plateaus, mountains, ridges, sand sheets, dunes, sand seas, and micro-karstic features.

The major geomorphological landforms represented on the plateau surface separating the Bahariya depression and the Farafra depression are as follows:

The plateau of limestone and chalk often displays residual, isolated hills or inselbergs, varying in height from meters to several tens of meters from the surrounding plains. They appear in different shapes, such as pillars, domes, cones, and wavy shapes, as residual geomorphic features remain for karst dissolution activity.

Depressions are natural excavations in the desert. According to most recent scholars, these depressions owe their origin to tectonic factors at the first stage of their development (Knetsch & Yallouze, 1955; Said, 1960; Hermina, 1990). Weathering and erosion action subsequently supplemented these tectonic factors along the lines of weakness.

Hamada is an Arabic word for "dead, lifeless" plateaus. It is a type of desert landscape that consists largely of barren, hard, rocky plateaus with very little loose material. Hamadas are tabular, rocky trays restricted by cliffs, and they are of sedimentary origin, frequently calcareous.

Sand sheets are areas covered in sand, characterized by a featureless, low-relief surface that lacks superimposed individual dunes or high-order bedforms. These are smooth, mostly horizontal layers of fine-grained wind-blown particles with low thermal inertia (Grotzinger et al. 2005). While the surface of these sheets may appear smooth and nearly featureless, they frequently exhibit tabular-planar depositional characteristics and a variety of ripple-like bedforms (Breed et al. 1987). The earth extends sand sheets between 100 m2 and 100,000 m2, with thickness ranging from several centimeters to 10 m (Pye and Tsoar, 1990). Sand sheets are flat, gently undulating plots of sand surfaced by grains that may be too large for saltation. Such sheets make up nearly 40% of Aeolian depositional surfaces, and they exist once grain size is too large or wind velocities too low for dunes to form.

The limestone and chalky surfaces, or white deserts, owe their name to the presence of limestone and chalk that reflect white color where they are exposed. The Eastern Desert of Egypt and the Reg plain of Farafra Oasis stretch east of the Nile valley, displaying examples of such features (Said, 1990).

The northern part of the white desert is home to Hills of Calcite Crystals (Crystal Mountain), formed by sparkle ridges resembling crystals and subvolcanic vaults that likely emerged during the Oligocene Era. The visible layers are limestones from the Khoman Fm. (Late Cretaceous age), which include a coal seam and reddish to brownish ferruginous layers. The strata, either broken or brecciated, undergo intense folding with each other, indicating intense heat. Anthracite transformed the coal seam, and crystals grew out of climbed hydrovolcanic solutions. High concentrations of $BaSO_4$ and/or $CaCO_3$, dissolved from the sediments, permeated all cavities in the hot solutions. After cooling the solutions, the crystals could grow, forming columns or round domes with crystals (Hewaidy et al., 2006).

2.3. Cave morphology

The unroofed cave area reflects the remains of a much larger, water-filled cave that reached the surface some hundred thousand years ago. The remaining underground feature consists of collapsed passages and cave rooms. The floors of the smaller rooms have a very smooth surface. A small catchment houses the portal to the cave system in the northwest corner of the larger room. The unroofed cave area stretches approximately 8,100 m2 horizontally. The unroofed cave area is a layered sequence of Miocene and Pliocene sediments. The bedrock floor of the cave consists of dense limestone sediments directly overlying soft Cretaceous shales, showing a stratigraphy analogous to the surface present in the main cave. Two main collapsed passages dominate the unroofed area, and a smaller passage occurs in the middle of the unroofed area associated with a smaller room. The smaller, erratic hilltop closes the southeastern part of the unroofed cave area. A deep trunk channel, located in the west, could allow local run-off water collected within the catchment to exit the cave system. The catchment, which rises about 1 meter from the portal to this section, still connects to the highest point of the unroofed cave floor. Behind this micro-catchment, there are two raised rooms, with the most northern region being the highest. If the northernmost raised room floods to the floor, water can spill into the smaller room to the southwest. Heavy tropical downpours could emerge from the treed tunnel portal and continue to the northern entrance in the extreme northwest. In their current state, the cave and the unroofed portion remain disconnected. The forest has deposited materials within the catchment, along with blocks of debris, which may have restricted or prevented surface water from entering the cave.

2.4. Detailed surveying of unroofed cave remains

We use a total station to survey the remains of the two parts of the studied unroofed cave and create a detailed contour map of its sections [1] .

The contour maps (Fig. 3) show that the remnants of the studied cave appear on levels ranging from 226 to 228 meters in the northern part of the study area and on levels ranging from 230 to 232 meters in the southern section of the studied cave. Levels ranging from 228 to 242 meters in the northern section and about 229 to 236 meters in the southern part of the cave scatter them between a group of scarps and isolated hills.

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(1) We used the SDR basic total station (CX-62 YMO331) to survey 609 elevation points, starting from a fixed level point.

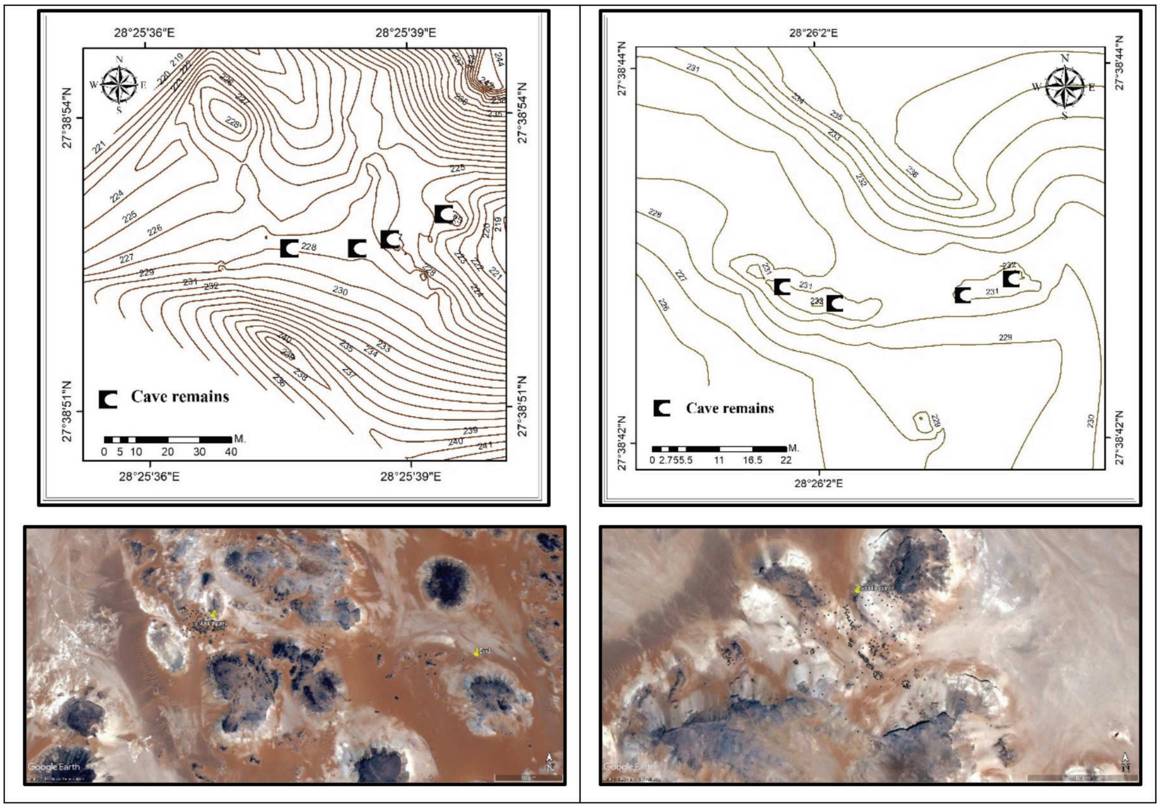

Fig.3: Detailed contour maps of the remains of the western (upper left) and eastern (upper right) parts of the unroofed cave (by using total station). Surveying points for the western (down left) and eastern (down right) parts

2.5. Characteristics of the cave's remains

In the study area, there are some pieces of paleokarst deposits made of Khoman chalk from the Maastrichtian period. The calcite crystal layers primarily adhere to the collapsed paleocave deposits in the study area. We discovered numerous collapsed breccias and paleocaves scattered throughout the study area, containing columnar-shaped stalagmites. The stalagmites range in length from a few centimeters to over two meters, forming chalky domes and several blocks of concentric calcite crystal layers.

2.6. Geographical distribution

The total extent of the eroded cave is about 1.7 km, but the lengths of the remaining parts of the cave are not more than 280 meters. They are spread in two basic parts: one in the west extends along an escarpment, and the second is a confined range of isolated chalky hills to the east, in addition to some scattered collapsed stalactite mounds.

The cave remains begin to appear from the piedmont slope of an elongated hilly ridge and extend along it for a distance of 180 meters. Then, they deviate to the southeast and appear in the form of hills or hills of limited height, extending from the northwest to the southeast. They then head for a distance of 545 meters in the semi-dry valley. Afterwards, they reappear in the form of blocks of Maastrichtian Khoman chalk combined with calcite crystal layers for a distance of 70 meters. Later, the fluvial degradation of a tributary of the dry valley's mainstream causes them to disappear once more. Finally, some chalky-calcite crystalline mounds scattered over a distance of approximately 250 meters appear at the cave's end (Fig. 4).

Fig.4: Some geomorphological evidence of the eastern part of the unroofed cave; A: Curved calcite crystal layers with recent loam fills, B: Remains of stalactites, C: Multi- cavern deposits: stalactites, calcite crystal layers and karstic window, D: Eroded curved calcite crystal layers, E: Multi-stages of stalactites and cavern column, F: Two stages of curved calcite crystal layers, G: General view of the northern part of the unroofed cave with photo sites.

Fig.5: Some geomorphological evidence of the western part of the unroofed cave: A) Karstic arch, B & C: Remains of stalactites, D & E: Curved calcite crystal layers, F: Remains of granular stalactites.

2.7. Orientation

The orientation rose diagram of the estimated cave parts[1] (Fig.6) shows that the main direction of the suggested cave passage is NW/SE, between 290°-340° and 110°-160°. The Pearson correlation coefficient calculation between the orientation of the cave passages (Fig. 6) and the orientation rose diagrams for fractures and faults (Fig. 2 B& C) results in a very weak positive relationship (0.0327). This means that the geological structure of faults and fractures plays a secondary role in the cave direction.

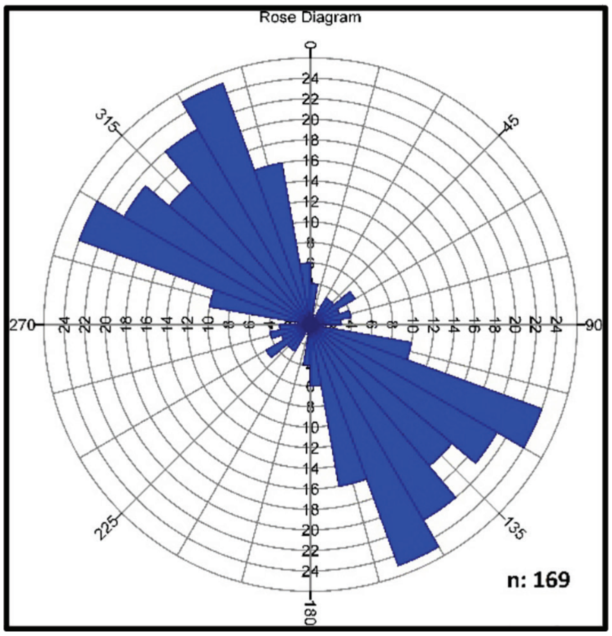

Fig.6. A rose diagram for orientation of the suggested cave passage

2.8. Topographic longitudinal profile of the ancient cave

We construct a topographic longitudinal profile of the cave remains' elevations from a Google Earth (2020) image using 1-meter vertical intervals (Fig. 7). The profile shows that the elevation of the suggested cave passage ranges between 231 m and 204 m, and the eastern portion of the cave is higher than the western portion. Although rougher, the middle part is steep due to recent fluvial erosion of the semi-arid valley.

2.9. Effect of erosion factors on the cave

Two areas, separated by a semi-dry valley stream that descends from the eastern scarp toward the lowlands in the west, contain the recognized remains of the karstic cave system. The valley stream is about 350 meters wide. It is responsible for the destruction and removal of cave remains between the two discovered parts (Figs. 6, 7, and 8).

Recent weathering processes, fluvial denudation during torrential storms, and wind degradation due to climate change-induced drought appear to have affected all of the cave remains. Additionally, winds deposit sandy accumulations on the outer edges of the cave remains.

Fluvial erosion from a semi-arid valley and its tributaries has completely erased most of the cave's central areas. The fluvial erosion of this valley has removed more than 800 meters of the cave's total length in the middle section, along with some scattered spots. Moreover, the gullies of the escarpment in the western part of the cave, along with the gullies of the slopes of the isolated hills in the eastern section, have erased portions of the ancient cave (Fig. 8).

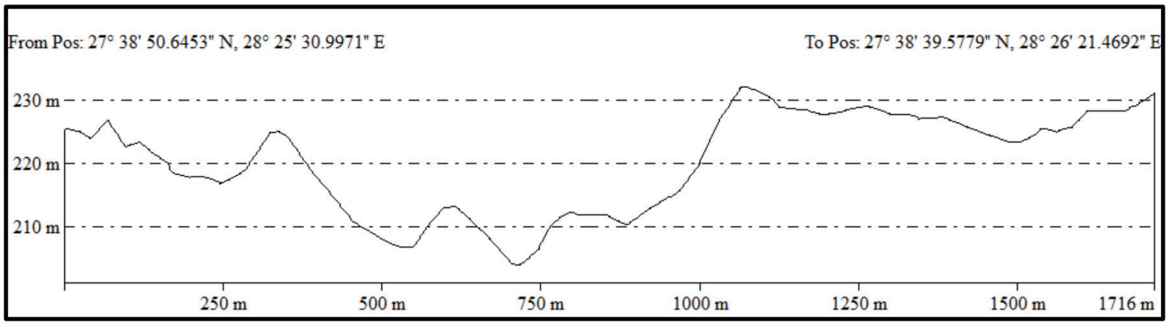

Fig.7: Topographic longitudinal profile of the ancient cave

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(1) We divide the proposed cave passage into 169 parts, each measuring 10 meters in length, and measure their directions to create an orientation rose diagram.

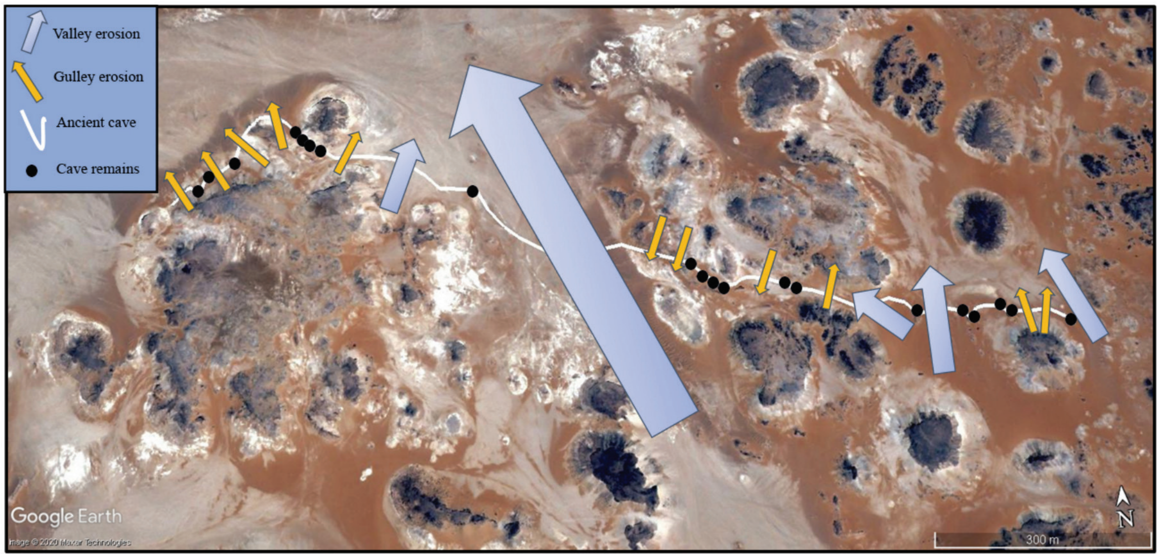

Fig.8: Effect of fluvial erosion on the ancient cave

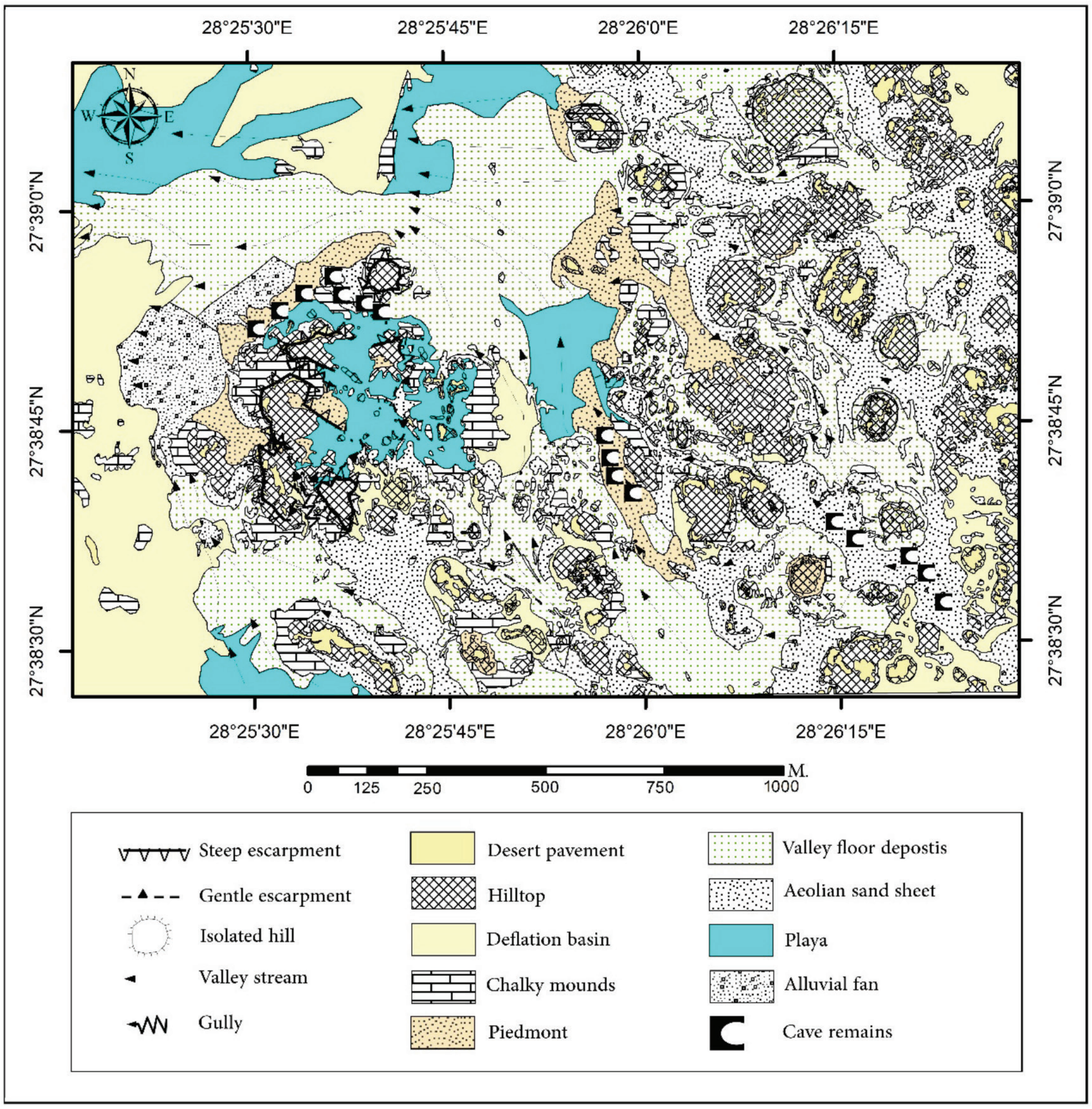

Fig.9: A Geomorphological map of the study area

2.10. Micro geomorphological karst features

The study area recognizes the following types of geomorphological micropaleo-karstic features (Fig. 10):

Granular stalactites are a geomorphological micropaleo-karstic feature filled with a variety of materials both during development and after their formation. This type of stalactites, however, is formed by chemical deposits from poorly soluble rock or granular materials (Gunn, 2004). The Paleo cave column is a type of speleothem that extends from the floor to the ceiling, formed either by the growth and joining of a stalactite and a stalagmite or by the growth of either material to meet bedrock. Stalactites and stalagmites connect inside caves or reach the cave floor to form cave columns (Gillieson, 1996). These columns vary in length from a few centimeters to approximately two meters, with some succumbing to weathering or collapse on the ground. Paleo cave curtains are a type of speleothem in the form of a wavy or folded sheet, often translucent and resonant, hanging from a cave's roof or wall (Gillieson, 1996). The karstic deposits may form a thin corrugated sheet composed of travertine or calcite crystals called "curtains" when they descend from the cave ceiling. A vertical tubular stalactite is a cylindrical or conical-shaped speleothem hanging downward from a roof or wall, usually with a central hollow tube (Gillieson, 1996). It appears as the remains of an open tube vertically deposited and interiorly descending from the ceiling of the ancient cave. The term "eroded horizontal tube" refers to a speleothem horizontal open tube that has been eroded from the cave walls and deposited underground. Composite stalactites encompass a variety of shapes, including granular, tubes, and needles. as granular, tubes, and needles. Thin films or trickles of water, usually calcite, form a deposit known as flowstone. This sheet-like deposit resides on cave floors and walls.

During the field survey in the studied area, we identified certain micro-geomorphic features that resulted from weathering processes on cave paleo-karst rocks, as illustrated in the following examples (Fig. 11): Multi-stages of onion wreathing consist of successive layers of rocks affected by thermal contrast, and they fall in several stages. Mechanical weathering processes exposed the crystalline rocks' remaining dome to the surface, shedding the sheets that had been covering them. The impact of weathering processes on vertical joints is significant, as the thermal contrast contributes to the expansion of these joints, resulting from the activity of mechanical weathering processes. Thermal contrast facilitates mechanical weathering activity, causing onion weathering;[1] to manifest as small domes that separate from rock sheets.

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(1) Onion weathering; same as onion-skin weathering Onion skin weathering is one of the insolation weathering processes that occurs as a result of thermal expansion and contraction caused by the breakdown of rock when the heat frequency changes (Dixon, 2004). Onion-skin weathering is also known as exfoliation, thermal expansion, and insolation weathering; this process often happens in deserts.

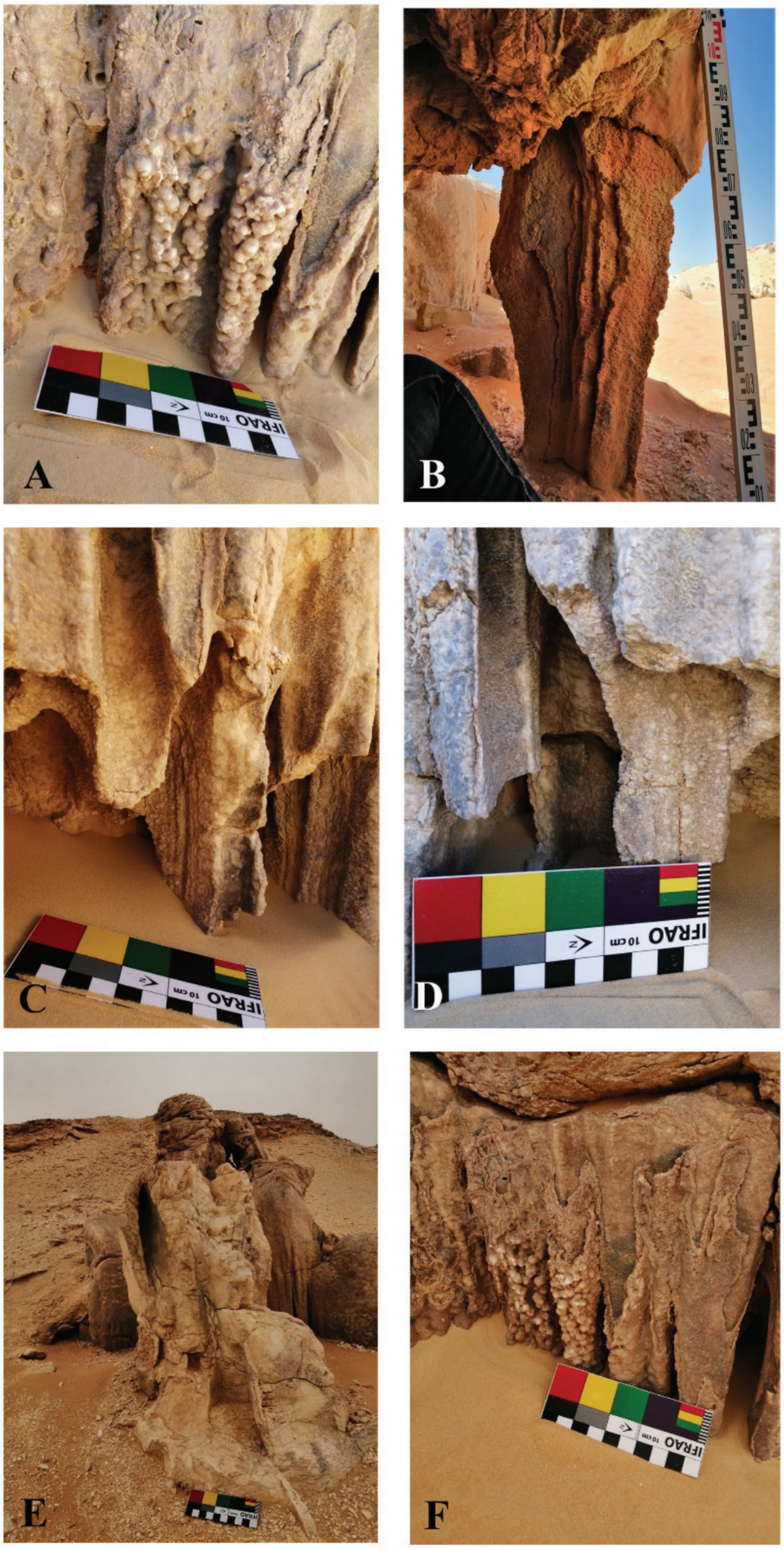

Fig.10: Types of paleokarst landforms: A) Granular stalactites B) Paleo cave column C) Paleo cave curtains D) Vertical tubular stalactite E) Eroded horizontal tube, F: Composite stalactites.

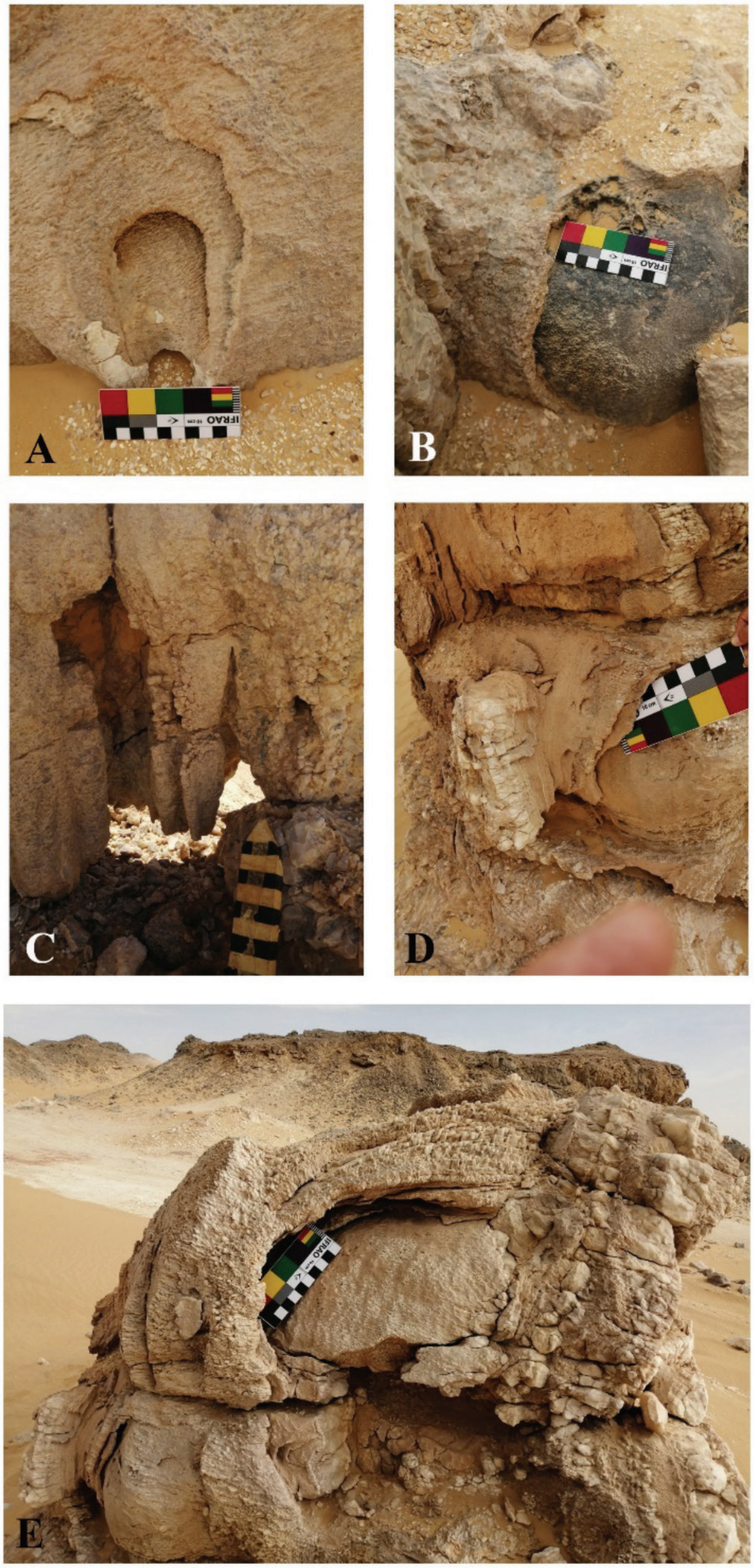

Fig.11: Some examples of the effect of weathering processes on cave paleokarst rocks: A) Multi-stages of onion wreathing B) A remaining dome of the weathering processes of the crystalline rocks C) Effect of weathering processes on vertical joint D) Onion weathering E) Eroded crystalline layers.

2.11. The cave dating

Wanas et al. (2009) determined the absolute age dating of the karst system at the Sheikh Abdallah area (about 4 km NW of the study area) during the Late Miocene, based on the dating of the clay content of the Sheikh Abdallah cave breccias. Wanas et al. used the diagenetic characteristics of the authigenic quartz inside cavities in fossil bones. The karistirization activities between 11 and 10 Ma indicate a relatively humid tropical environment in the area. This suggests that the region experienced a humid, rainy climate and dense vegetation cover during that time period.

2.12. Geomorphological evolution of the cave system

Discussion of the geological setup of the investigated cave has revealed that different generations of the vadose and phreatic passages have occurred. Level passages and horizontal wells represent the phreatic origin, which undergoes a re-geomorphosis under subsequent vadose conditions. A subsequent subsidence pit formed below the Phreatic Dome, allowing water to flow inside the cave. Therefore, we identified six geomorphological situations, each indicating a distinct phase in the development of the cave passages. The caves are characterized by three phases: inception, development, and degradation, which extended up to the present time. The first is associated with fluvial processes and subsidence. Occasionally, distinct cycles ranging from inception to degradation recur. The detailed reexcavation and reengineering of old cracks and collapses caused by subsidence show new events in the form of re-geomorphic agents. The caves represent a specific feature of the surface lithological, structural, and climatic conditions of various vadose and phreatic geomorphologies. The recorded material contains a high sediment load. The "rubble cave" areas feature unique "buffered" floors, supporting a network of debris-filled conduits and rifts filled with Amelik "Kreizt" type lava stalactites and stalagmites, primarily composed of less weathered rock and gravel. Geomorphic Evolution: By looking at the direction of the cross-cutting and the texture of the sediments that line the sides of the underground sandstone passages, one can tell the difference between different channels of falling, rising, boiling rate, and implosion flows. Over time, as the cave began to evolve, the water table dropped significantly due to the raising of the Farafra Depression.

The suggested geomorphological evolution of the cave system comes in the following stages:

First stage: The aridity that occurs in the warm phases of the Quaternary due to climate change causes some parts of the cave roof to collapse, especially on the vertical fractures, and weathering helps widen them.

In the second stage, the impact of the semi-arid valley's fluvial load destroys the cave's middle parts.

In the third stage, more parts of the cave in the western portion collapse due to fluvial erosion of the gullies and mass movements of the steep escarpments of adjacent hills.

Fourth stage: weathering processes, wind degradation, and recent human activities remove most parts of the cave remains.

3. DISCUSSION

The detailed geomorphological study of Crystal Mountain's cave entrances reveals that tectonic control cannot explain the cave's development in this region. On the contrary, the documented alignment of the karstification features showed an almost equal along- and across-strike development. This led us to conclude that these caves are dependent on the geomorphological conditions of the area during a wet period, which is in conformity with variations in similar karst systems around the world. We assumed that this area experienced varying water table levels and flow depths during the wet stages, based on the distribution of karstification features and trends. Therefore, we can correlate paleo-sequences with the unroofing rate of the caves from the inside out curves. For example, recording lateral phreatic tubes at different levels shows not only how the tubes' connections change during different times but also how the flow depths of different lateral phreatic veins vary at the level of a single phreatic tube.

In general, the geomorphological features of the Unroofed Cave in the Crystal Mountain cave area are not entirely distinctive and unique compared to other cave systems worldwide. However, the detailed geomorphological characteristics of this area can provide many opportunities for geomorphological studies, especially unraveling the complex processes of unroofing development. The different criteria used in this study give us (1) a better idea of how ancient semi-draining phreatic systems worked in terms of paleoclimate, (2) a better idea of how karst processes changed in different paleoclimatic conditions, and (3) a better idea of how karst changed in places where the plate tectonics aren't active.

In Egypt's Western Desert, we conducted a cave survey and topographic mapping of the main unroofed cave in the study area's Bahariya-Farafra depression. We analyzed the cave using Geographic Information System (GIS) technology, assuming that it occupies an area. This 2D analytical method, along with the furrow shape of the cave interior, suggests an expected 'top' elevation. We carried out similar topographic mapping for the largest cave, which recently emerged from a lithoclast block fall along the northeastern escarpment of the same area. With the help of the distorted void morphology and the interpretation of cave dimensions and landform profiles, it is possible to build a more complete picture of how Crystal Mountain's shape changed over time. The accompanied furrow floor-ribbed ceiling morphology of the El-Farafra unroofed cave suggests its formation from a lithoclast block fall.

In the Crystal Mountain area, the remnants of the cavernous system stretch for approximately 1.7 km. However, they manifest as limited-height and intermittent mounds due to their susceptibility to erosion processes, the effects of both mechanical and chemical weathering processes, the force of gravity on the cliffs, torrential floods, and the movement of material on slopes due to gravity.

The ancient karstic cave appears in a quirky, snaky shape through scattered parts of its remains, composed of Maastrichtian Khoman chalk and calcite crystal layers.

It was humid in the Late Miocene, which helped the chalky carbonate formations become karistirized. Faults and fractures had weak effects on the cave's passages and ancient chambers, but they did help with some of them.

In addition, the study area recognizes several remains of paleo-karst deposits, including stalactites, vertical and horizontal tubular stalactites, curtains, and flowstone. However, paleo-cave deposits, mainly composed of calcite crystal layers, collapse due to active weathering and carving by wind. Therefore, active water stripping, either during the humid Quaternary periods or during the current torrential floods, removed large portions of the cave. Additionally, researchers have identified and depicted the cave's remains on a geomorphological map of the surrounding area of the eroded paleo cave.

4. CONCLUSION

The main findings from this research highlight the importance of topography in controlling the evolution of unroofed caves in the Bahariya Mountain Pliocene Belt. The current study must address the real and urgent issue at hand. The current evolution of the unroofed cave can serve as a guide for predicting the future arrival point and location of additional unroofed caves in the region. To further identify the unroofed caves, the geomorphologists should assess the ground truth conditions in the field.

The present study underlines the geomorphological map and geomorphic characteristics of the ancient cave studied. Furthermore, we study the causes of the cave's collapse by examining the connections between the geographical deprivation of the cave remains and other geomorphological features, particularly escarpments, gullies, and semi-arid valleys. We investigate how these geomorphic agents contribute to the cave's collapse and the removal of remains.

The present study and previous works indicate ancient karstic activity during the humid climatic conditions identified as Late Miocene. Additionally, we study the stages of its geomorphological evolution, as well as its influence on weathering processes and contemporary erosion factors.

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