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THE JABAL AL QARAH CAVES OF THE HOFUF AREA, NORTHEASTERN SAUDI ARABIA: A GEOLOGICAL INVESTIGATION

MAHBUB HUSSAIN[1], *mahbub@kfupm.edu.sa;* FADHEL AL-KHALIFAH[1]; NAZRUL ISLAM KHANDAKER[2], *ramanaz@aol.com*

[1]*Earth Sciences Department, King Fahd University of Petroleum & Minerals, Dhahran 31261, SAUDI ARABIA*

[2]*Department of Natural Sciences, York College of CUNY, 94-20 Guy R. Brewer Blvd., Jamaica, NY 11451, USA*

The Jabal Al Qarah Caves, located approximately 13 km east of Al Hofuf, Eastern Province of Saudi Arabia, are an intricate cave system developed in the calcareous sandstone, marl and clay of the Upper Miocene to Lower Pliocene Hofuf Formation. Physiographically, the hill of Jabal Al Qarah is an outlier mesa that is located at the eastern edge of the Shedgum Plateau, the southern extension of the As Summan Plateau, and the larger Syrian Plateau to the north. Based on cave morphology and interpreted evolutionary history, the Jabal Al Qarah caves appear to be significantly different from other limestone caves reported in the As Summan Plateau. Jabal Al Qarah is known for its tall, linear cave passages and narrow canyons. The boxwork of linear passages is better developed here than any other known cave locations in the Eastern Province. Field observations, including orientations of the escarpment face of the Shedgum Plateau, joints, and fractures, coupled with a review of the tectonic history of the region, suggest that these caves resulted from erosional enlargement of a series of very deep and narrow joint-controlled fissures in the Hofuf Formation. Petrographic data, especially an abundance of well-preserved palygorskite type clay minerals, suggests that the Hofuf Formation was deposited in a mudflat-dominated coastal plain environment.

INTRODUCTION

The Al Hofuf area of the Eastern Province of Saudi Arabia (Fig. 1) is a part of the Shedgum Plateau (Fig. 2), the eastern edge of the greater As Summan Plateau. The Shedgum Plateau is covered by a succession of Tertiary carbonates and evaporites of the Um er Radhuma, Rus, Dammam, Hadrukh, Dam and Hofuf formations (Fig. 3). The Shedgum Plateau, including the Hofuf area, is dotted with numerous karstic features including sinkholes, solution cavities and caves (Pint, 2000, 2003). Edgell (1990a, 1990b) reported over 58 caves in an area of 500 km^2 in the As Sulb area of the Summan Plateau.

Jabal Al Qarah, which hosts the Jabal Al Qarah Caves (N 25º 24.69'; E 49º 41.62' at the main cave entrance), is approximately 130 km southwest of Dammam, and 10 km northeast of Al-Hofuf, in the Eastern Province of Saudi Arabia (Fig. 1). The jabal, named after a large, well-known village in proximity of the mountain, is technically an outlier mesa located close to the eastern escarpment of the As Summan Plateau (Hotzl *et al*., 1978). Locally known as Ghar Al Nashab (t*he Cave of the Archer*) and also as Ash-Shab'an (*the Satiated*), the Jabal Qarah caves have developed in the Upper Miocene to Lower Pliocene Hofuf Formation (Fig. 3). The cave is an interesting and popular geologic and geomorphic feature. Its cool protected passages have been a gathering place for visitation and commerce for generations. Hotzl *et al*. (1978) provided a brief description of the geomorphology of the cave area, and a map of the cave was prepared by Hotzl and Maurin.

GEOMORPHOLOGY

The area immediately east of the Shedgum escarpment contains several isolated erosional remnants, as outliers, buttes and mesas, including Jabal Al Qarah, Barqa Ar Rukban, Jabal Burayqa and Jabal Sha'bah. The main entrance of the cave system is located at the eastern edge of Jabal Qarah overlooking the date plantations of the Al-Hasa Oasis. At the main cave (Ghar An Nashab I, Hotzl *et al*., 1978) entrance, the top of the hill is approximately 75 m above the local street level. Jabal Al Qarah is characterized by an alternation of small plateaus and near-vertical cliffs. Like most of the hills around the area, Jabal Al Qarah is a flat-topped hill with a maximum elevation of about 225 m above mean sea level (Fig. 2). The eastern edge of the Jabal, close to the cave entrance, is interpreted to be bounded by several north-south trending high-angle normal faults with throws of up to 10 m. The mushroom-like pillars of the Hofuf Formation observed close to the cave entrance appear to be on one of these down fault blocks. The cave system has approximately 28 linear passageways totaling about 1.5 km in length, in a rectangular area roughly 132 m x 216 m (Fig. 4).

A meter-thick limestone bed that caps the Hofuf Formation elsewhere in the region is not present at Jabal Al Qarah. This zone is characterized by a cap of caliche (Fig. 5a). When caliche covers the top of the isolated pillar-like erosional remnants of the Hofuf Formation, they have an appearance resembling giant mushrooms (Fig. 5b). Well-developed caliche caps commonly overlie the Hofuf and Dam formations elsewhere in the Shedgum Plateau, including the escarpment face to the east of the cement factory close to Al Ayun, north of Al Hofuf.

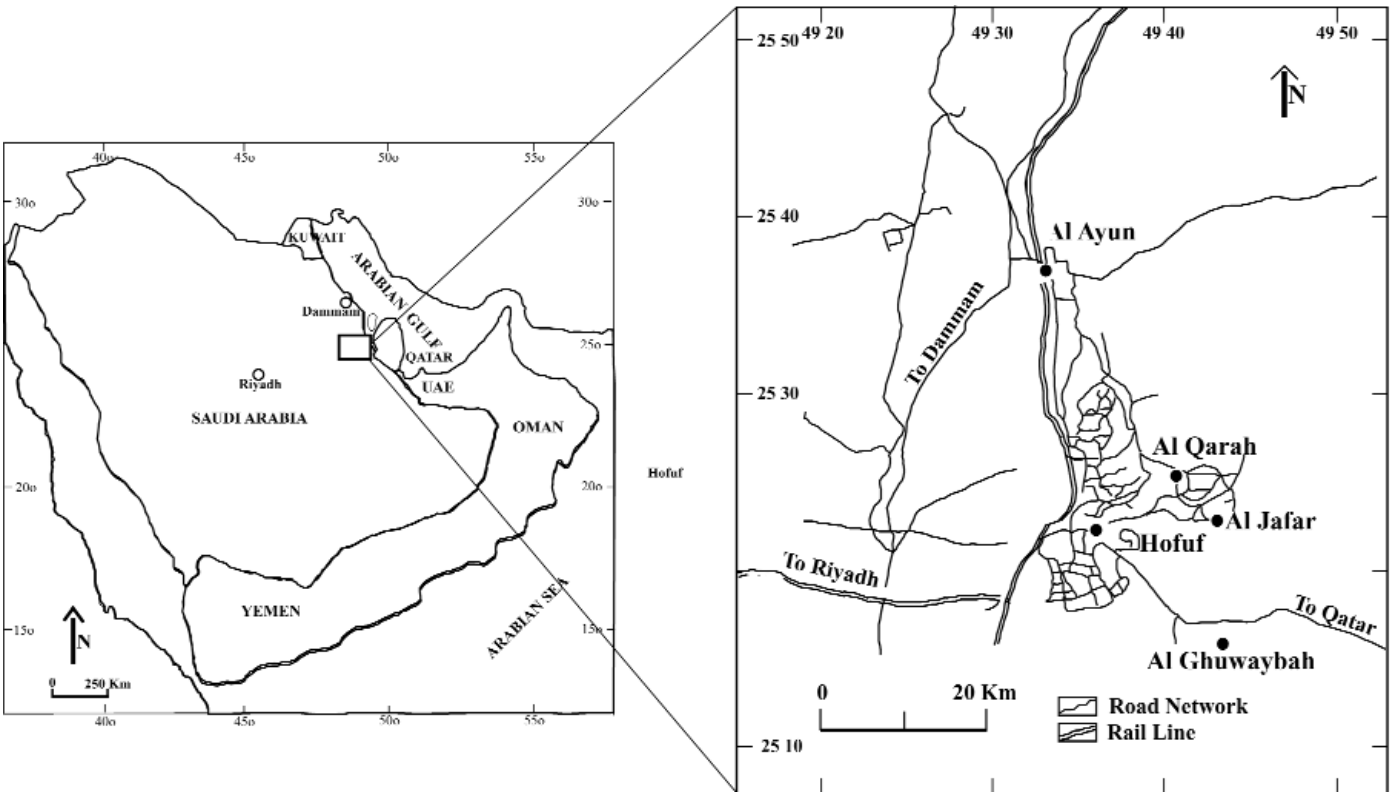


Figure 1. Location map. The Jabal Al Qarah caves are located approximately 10 km east of Hofuf, Eastern Province, Saudi Arabia.

STRATIGRAPHY AND SEDIMENTOLOGY OF THE HOST FORMATIONS

The rocks exposed at Jabal Al Qarah consist of limestone, marls and clays of the middle Miocene Dam and Hofuf formations (Fig. 6). The basal section of the Hofuf Formation at Jabal Al Qarah is a thin layer of marl overlain by a conglomerate bed, up to 17 m thick, followed by an 18 m thick sequence of lacustrine sandy limestone. At the cave section, however, the Dam and the basal part of the Hofuf Formation are not exposed. The sandy limestone is overlain by an approximately 75 m thick sequence of light grey calcareous sandstone with reddish marl/silty marl intervals (Fig. 7a,b). A thin limestone bed, up to 2 m thick, caps the sequence.

The Hofuf Formation, that hosts the main Jabal Al Qarah cave section, is a white to light grey, massive, calcareous sandstone inter-bedded with soft, reddish to yellowish brown marl and clay. The cave section (including the interior of the caves) of Jabal Al Qarah is characterized by two distinct reddish marl/silty clay intervals of which the thicker one, approximately 5 m thick, is at ground level close to the main entrance of the cave. The other reddish interval is thinner, up to 2 m thick, and is at the mid-level of the jabal. The reddish marl/clay intervals appear continuous to the west and north of the jabal. When freshly exposed, these horizons often show an intricate network described by Hotzl *et al*. (1978) as a *"network of cemented small pipes of roots"* (Fig. 8). Goldring (pers. comm., 2000) believes that these features are *rhizocretions* of possible mangrove plant origin. Concretionary bodies, of possible algal origin, range in diameter from 10 to 30 cm and are common in the grey horizons.

Unlike many of the limestone caves in the As Summan Plateau, where the cave floor, walls and ceiling are characterized by the presence of various features including stalactites, stalagmites, cave pearls, guano, different mineral deposits, and wind-blown fine dusts (Pint, 2000; Pint, 2003), the interior of the Jabal Al Qarah caves is either clean or covered only by a thin veneer of wind-blown dust and guano.

Thin-section petrography confirmed that the light grey unit is a calcareous sandstone comprising fine- to medium-grained quartz sand embedded in a calcareous or clay matrix or cement (Fig. 9). Sand and silt-sized calcite grains are also common in this horizon. The sand is poorly sorted and shows a bimodal grain-size distribution.

Clays recognized (x-ray diffraction and scanning electron microscopy) in the grey intervals of the Hofuf Formation often occur both as pore-filling and pore-lining cement. Palygorskite $(Mg,Al)_2Si_4O_{10}(OH)•4(H_2O)$ and smectite are the two dominant clay types recognized (Fig. 10a,b). SEM study shows bundles of fiber-like palygorskite radiating out from a smectite core (Fig. 10b). Palygorskite is a common mineral in the soils from the Arabian Peninsula (McKenzie *et al.,* 1984). Jenkins (1976) reported abundant palygorskite from the soils from the

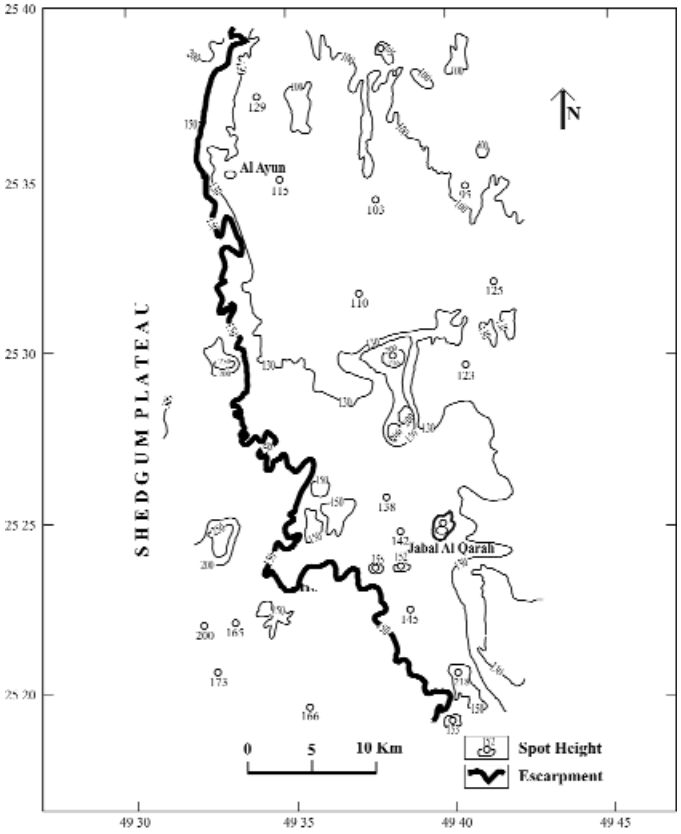


Figure 2. Topographic map of part of the Shedgum Plateau showing Jabal Al Qarah and the surroundings. (modified after Hotzl *et al*., 1978).

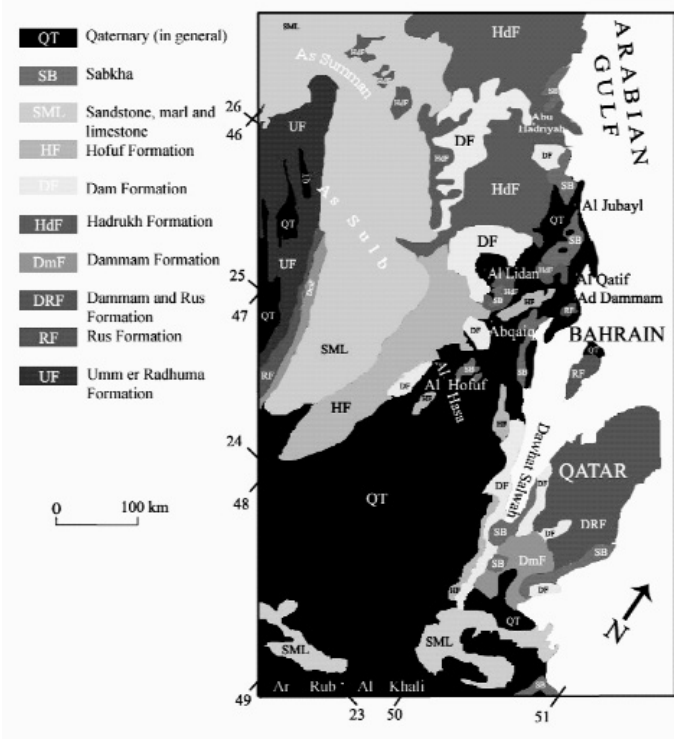


Figure 3. Geologic map of part of the Shedgum Plateau. Al Hofuf and adjoining areas including Jabal Al Qarah are covered by the Mio-Pliocene age Hofuf Formation. (modified after Hotzl *et al*., 1978).

Hofuf area. According to Ingles *et al*. (1998), Mg-rich smectite is common in modern and ancient saline lakes. Palygorskite, however, often forms in ephemeral saline lakes and saline flood plains either by the transformation of precursor clay minerals or by dissolution-precipitation mechanism (Velde, 1985; Jones and Galan, 1988). Ziegler (2001) discussed the tectonics, paleogeography and deposition of the post-Paleozoic sequences in the Arabian Peninsula, and noted that during the Miocene-Pliocene, a halo of mainly continental (Hadrukh Formation) to transitional-marine sediments (Dam Formation) were deposited around this region. The Hofuf Formation is the age-equivalent lacustrine sediments deposited in the interior of the Arabian Plate.

Compared to the grey horizons, the grain size of the reddish to yellowish brown horizons is fine and composed of both marl and clay (Fig. 11). SEM study shows that in addition to calcite and clay, both gypsum and halite are common in the reddish intervals (Fig. 12a,b). Owing to the loose and friable nature of the marl and clay, the reddish horizons appear to weather more readily than the grey calcareous sandstone horizons.

FORMATION OF THE JABAL AL QARAH CAVE

Limestone caves usually form by dissolution and erosional enlargements of the hosts along zones of relatively soluble rocks, or zones of textural and structural weakness. Such caves often consist of irregular underground chambers constituting a series of passages. The cave chambers and passages are often characterized by the presence of various dripstone features such as stalactites and stalagmites. Most of the limestone caves reported in Saudi Arabia are of this category (Pint, 2000; Forti *et al*., 2003; Pint, 2003). Caves of various shapes and sizes are common in the Shedgum Plateau and these isolated hills including Jabal Al Qarah. The dominant caves of Jabal Al Qarah are joint-controlled, steep-walled, and located above most of the nearby terrain (Fig. 13a,b). The caves are at varying stages of development with heights ranging from a few meters to tens of meters, and are up to 3 m wide. Devil's Thumb Cave (N 25º 52.62, E 48º 45.83) is another cave in the area that exhibits tall linear passages similar to Jabal Al Qarah. Other common cave types in the Hofuf area of the Shedgum Plateau include dissolution-controlled caves and caves formed by collapse of the overlying strata resulting from weathering, erosion, and removal of the underlying strata. One such cave (Fig. 13b) is located at the west side of the Jabal Al Qarah close to the base of the wireless (radio) station (N 25º 24.32, E 49º 40.89).

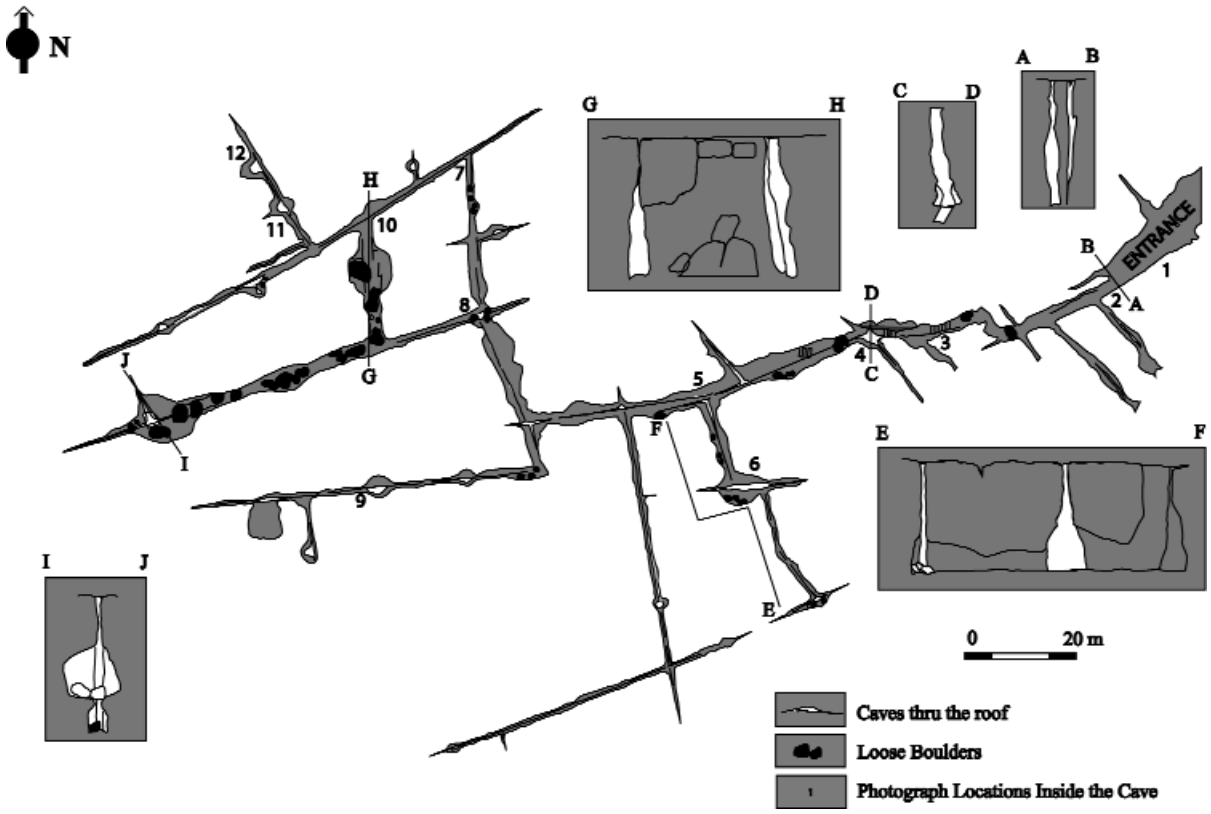


Figure 4. Distribution of major cave chambers in the Jabal Al Qarah caves. The dominant NNW and NE orientations of the caves coincide with the orientations of the regional joint/fracture systems (Figure 16). (modified after Hotzl *et al*., 1978).

Earlier workers investigating the Jabal Al Qarah caves including Hotzl *et al*. (1978) believe that marine erosion in a sea-cliff setting was responsible for the development of the caves in the Jabal. The model proposed by Hotzl *et al*. (1978) suggests that breakers and tides associated with a high sea level during the Quaternary, as well as infiltrating precipitation in the past, played a role in the development of the cave system in Jabal Al Qarah. In support of the role of marine erosion, they cited the presence of numerous wave-cut gorges along the joint openings, and several levels of wave-cut platforms (terrace). One such gorge is up to 10 m wide, reaching almost 300 m in extent into the Jabal. The elevation of cave-bearing sec-

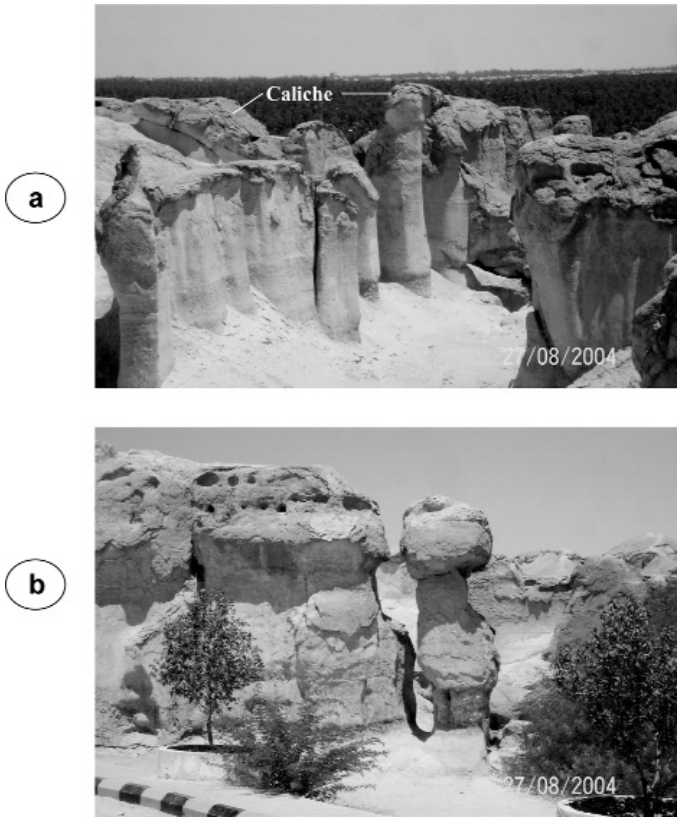
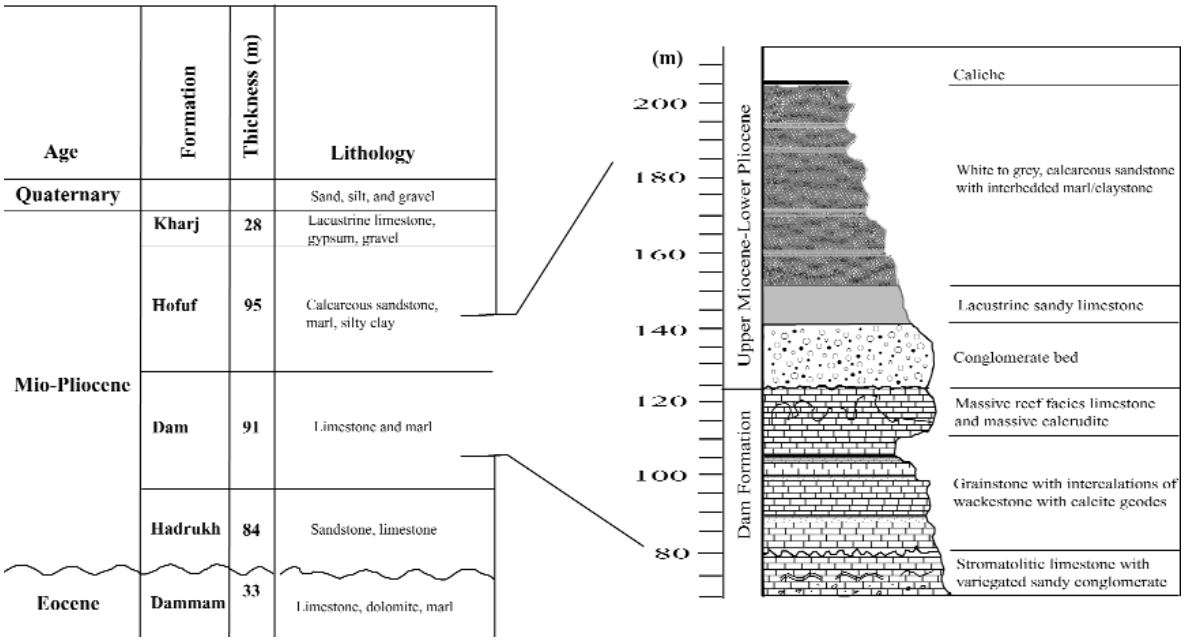


Figure 5. These photographs show the nature and extent of weathering in the Hofuf Formation (a & b). Mushroom-shaped pillars are weathered Hofuf Formation close to the main entrance of the caves. Note well-developed caliche horizons (dark) capping the pillars.

Figure 7. Lithology of the exposed Hofuf Formation at Jabal Al Qarah. As seen in these photographs (a & b), the Hofuf Formation at the jabal comprises an alternation of grey, massive calcareous sandstone and reddish brown marl/silty clay. These photographs were taken on the eastern edge of the jabal close to the main entrance.

Figure 6. Generalized stratigraphy of the Hofuf area. The Jabal Al Qarah caves are hosted in the Mio-Pliocene Hofuf Formation.



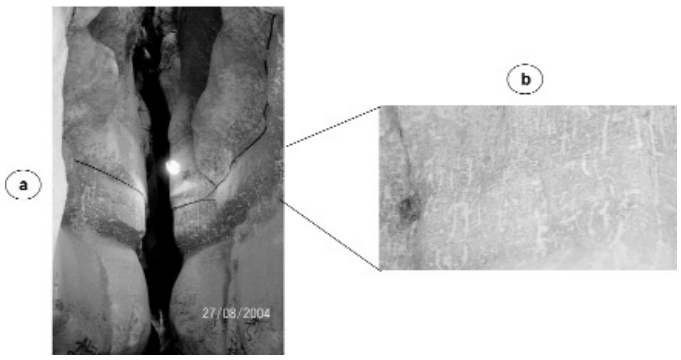


Figure 8. Closer views of the red interval of the Hofuf Formation at Jabal Al Qarah. (a) Outside wall of the main entrance. (b) Cave interior. Intricate textures observed in this interval are interpreted as *rhizocretions* of possible mangrove plant roots.

tions of the Jabal Qarah is over 205 m above present sea level, however, and as the highest Quaternary sea level in the area is less than 100 m (Fairbridge, 1961; Darwish and Conley, 1990; Evans and Carter, 2002; Fig. 14), the role of marine erosion in forming the caves is unlikely.

Jabal Al Qarah is marked by well-developed joint systems with dominant trends to the N 5–30º W and N 55–60º E (Fig. 4). Many of the major caves in the Shedgum Plateau, including those of the Jabal Al Qarah, are oriented along these two general directions (Saner *et al*., 2005, Fig. 15a–g). These joint-controlled caves have vertical or near-vertical walls that often extend from the floor all the way to the roof. When extended through to the roof, these joints often appear as straight-line openings along these general directions (Fig. 16a,b). As indicated by the fresh rock exposures along the cave walls, the

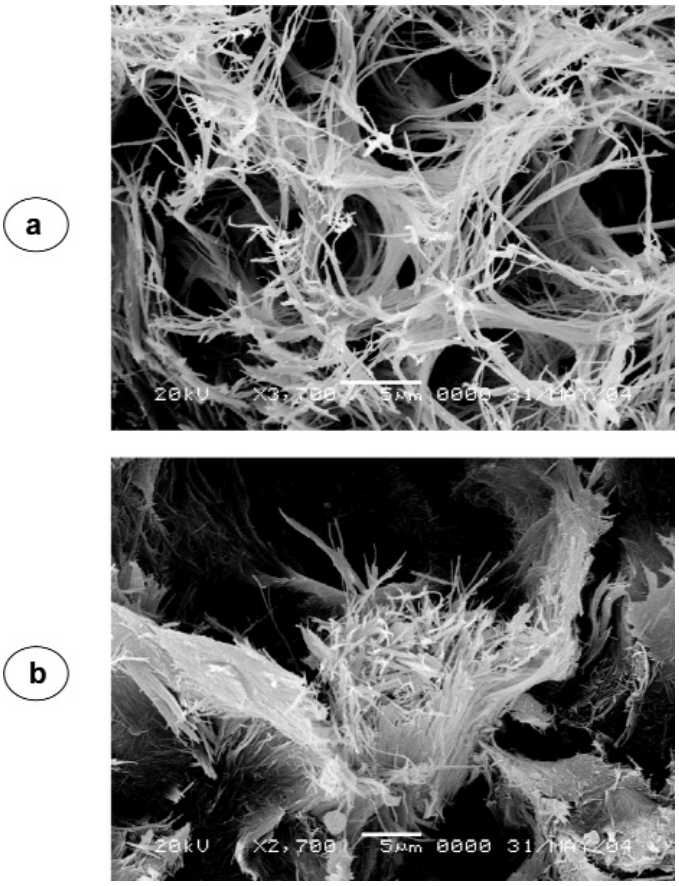


Figure 10. SEM images showing clay type in the grayish intervals. (a) Palygorskite showing typical bundle-shaped morphology, (b) Palygorskite radiating out from a smectite core. Palygorskite and Mg-smectite are common clay minerals in saline lake and coastal plain type depositional settings.

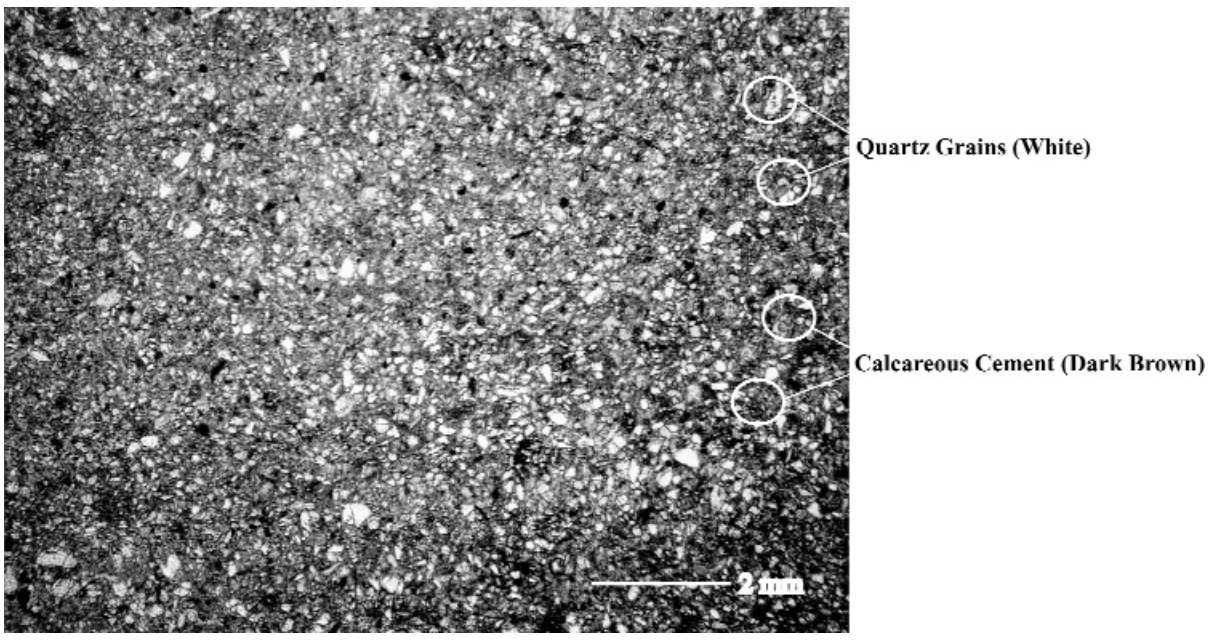


Figure 9. Photomicrograph of a representative sample from the grey horizon. The grey horizon comprises fine to medium-grained quartz embedded in a calcareous or clay matrix/cement.

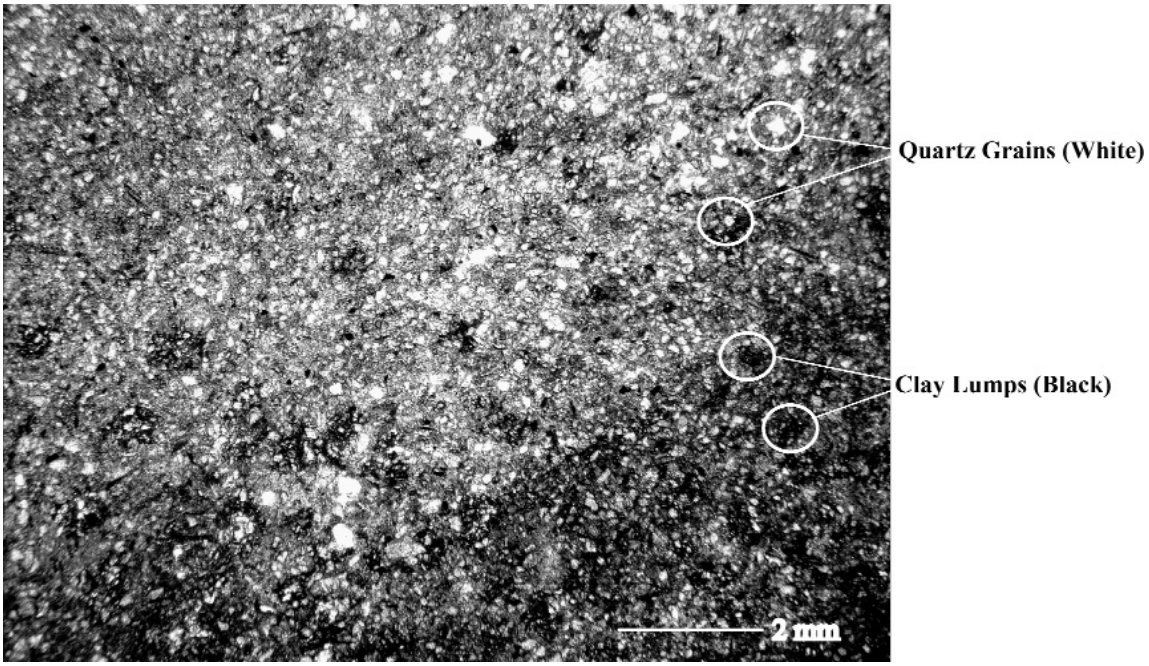


Figure 11. Photomicrograph of a representative sample from the reddish horizon. Compared to the composition of the grey horizons, the reddish horizons are made of finer grained sediments and consist dominantly of marl and clay.

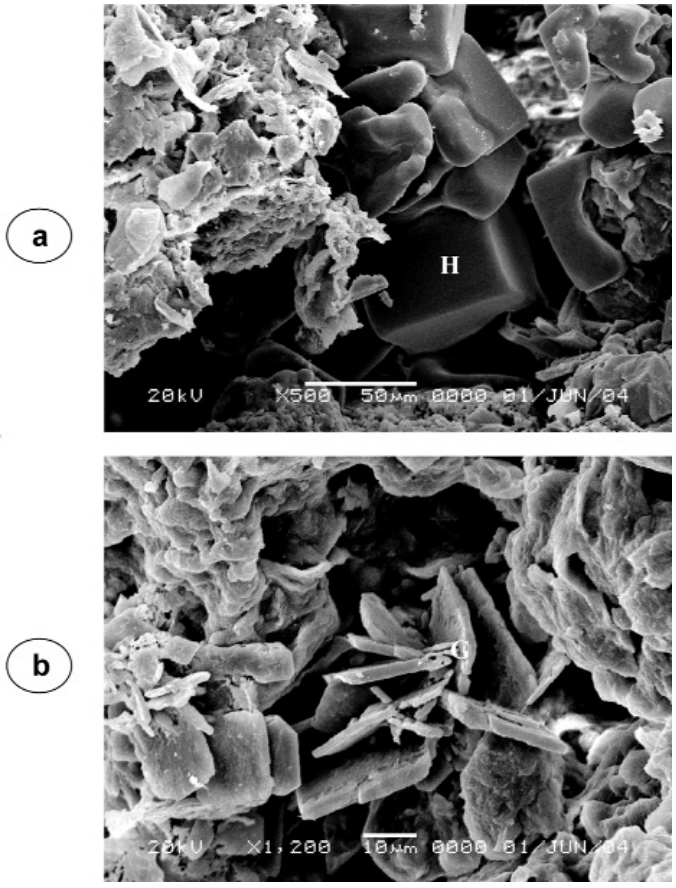


Figure 12. SEM images showing details of a sample from the reddish horizon (a & b). Note that in addition to calcite and clay, both halite (H) and gypsum (G) are also common in this horizon.

Figure 13. Different types of caves recognized in the Shedgum Plateau. (a) Joint-controlled, steep-walled caves at the escarpment face near to the cement factory north of Al Ayun (N 25° 41.62'; E 49° 29.05') approximately 10 km north of Al Hofuf. (b) A dissolution-dominated circular, flat-bottomed cave at the western face of the Jabal al Qarah, close to the wireless/microwave tower (N 25° 24.32'; E 49° 40.89').

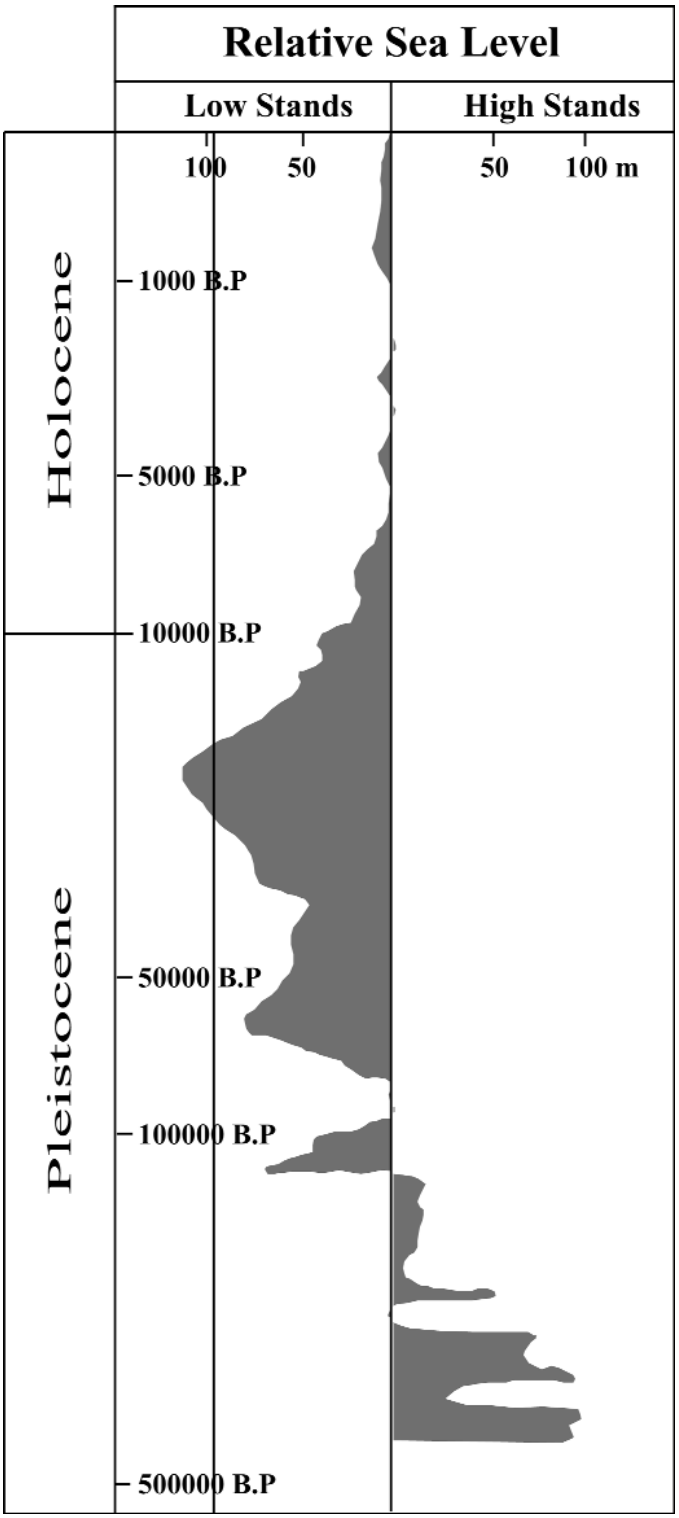


Figure 14. Quaternary sea level changes in the Arabian Gulf area. (Data source: Fairbridge, 1961; Darwish and Conley, 1990).

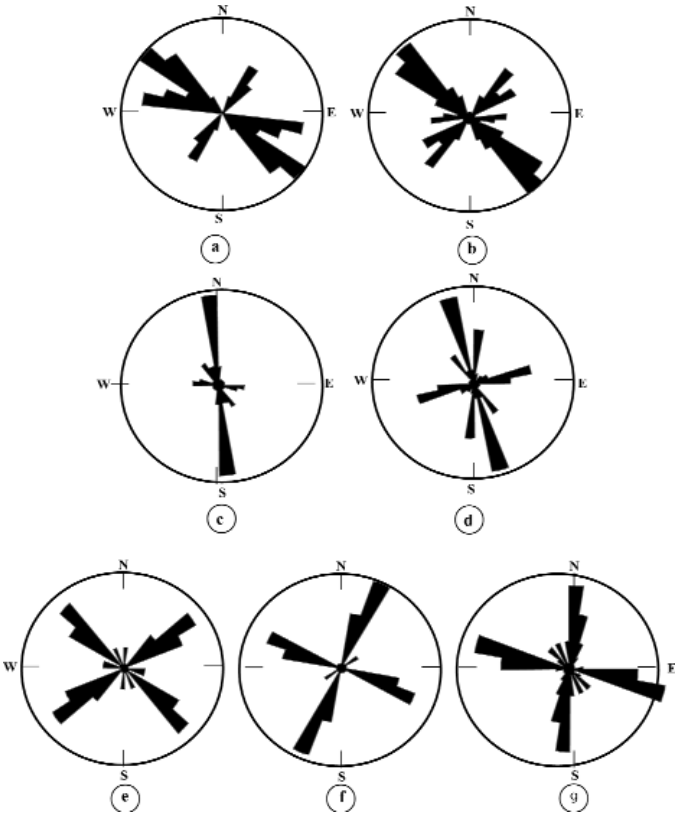


Figure 15. Orientations of the joint/fracture systems in the exposed upper Tertiary formations in the Shedgum Plateau. (a) Orientation of the major cave chambers and branches, Jabal Al Qarah, (b) Hofuf Formation, entrance of Jabal Al Qarah caves. (N 25º 24.690', E 49º 41.616'; n = 43), (c) Dam Formation. (N 25º 39.143', E 49º 29.356'; n = 39), (d) Dam Formation. (N 25º 32.871', E 49º 31.879'; n = 74), (e) Hofuf Formation. N 25º 42.621', E 49º 30.437'; n = 20), (f) Hofuf Formation. (~ 300 m east of e; n = 16), (g) Hofuf Formation. (N 25º 40.137', E 49º 28.828'). (Data source: Saner *et al*., 2005; present study).

cave-forming processes are still in progress, suggesting normal subaerial weathering and enlargement of the joints as a dominant cave-forming process.

A Distinct Type of Saudi Arabian Cave

Caves are common geomorphic features in any karstic terrane, and Saudi Arabia is not an exception. These caves form largely due to dissolution of limestone by slightly acidic ground water at the shallow subsurface. As noted earlier, such limestone dissolution caves are common features in limestone terranes of Saudi Arabia including the Shedgum Plateau. However, the Jabal Al Qarah caves lack many features that often characterize limestone-dissolution caves. For example, limestone-dissolution caves are often irregular in shape and contain many dripstone features like stalactites, stalagmites,

Figure 16. Surface openings in the Jabal Al Qarah cave chamber through the roof. (a) A N–S oriented straight-line opening. (b) An E–W oriented opening. Such openings usually form when erosional enlargement of the caves extends all the way to the top of the jabal.

etc. In contrast, the distribution of the majority of the Jabal Al Qarah caves is strongly controlled by the distribution of the joint/fracture systems of the host Hofuf Formation. Table 1 compares the the Jabal Al Qarah caves with other known caves in Saudi Arabia.

CONCLUSIONS

Jabal Al Qarah represents a mesa comprising the Upper Miocene to Lower Pliocene Hofuf Formation in front of the escarpment that marks the eastern edge of the As Summan or Shedgum Plateau.

The Hofuf Formation hosting the Jabal Al Qarah caves consists of an alternation of red and grey intervals of dominantly calcareous sandstone. Based on overall lithology (calcareous sandstone), and more specifically, the presence of palygorskite showing delicate morphological features, the sediments of the Hofuf Formation hosting the Jabal Al Qarah caves were deposited in a mud flat to lacustrine depositional setting.

Unlike most of the caves reported from the As Summan Plateau, formed by dissolution of limestone by ground water, the Jabal Al Qarah caves represent an above ground (street level) cave system that appears to have developed due to subaerial weathering and enlargement of the well-defined joint and fracture systems in the Hofuf Formation. Due to subaerial development, the caves in Jabal Al Qarah do not show many cave features typical of other caves in eastern Saudi Arabia.

Table 1. Comparison of the features of the Jabal Al Qarah caves with other limestone caves in northeastern Saudi Arabia.

Feature/Parameter	Jabal Al Qarah	Limestone Caves in Saudi Arabia (Benischke *et al*., 1997; Pint, 2000, 2003)
Ground position	Above the street level	Below the street level
Lithology	Calcareous sandstone and marl	Dominantly limestone and dolomite
Cave deposits	Mostly wind-blown dust and weathered debris from the cave walls	Stalactite, stalagmite, wind-blown dust and sand
Structural (joints, faults) controls	Prominent	Not commonly recognized
Role of ground water in cave development	Uncertain. Well above the regional ground water level	Dominant. Many caves still contain water
Distribution	Confined to the areas with jointed and fractured rocks	Anywhere in the karstic terrain with soluble rocks
Internal cave structure	Vertical or semi-vertical	Irregular
Surface opening	Straight continuous linear opening or isolated linear opening along a straight line	Usually circular; semi-circular and irregular

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