MIDDLE PLEISTOCENE KARST EVOLUTION IN THE STATE OF QATAR, ARABIAN GULF

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Karst is widespread on the peninsula of Qatar in the Arabian Gulf, including depressions, sinkholes, caves, and solution hollows. More than 9700 large and small depressions, and several exposed sinkholes and caves are known. Field and air-photo studies indicate that the depressions, sinkholes, and caves of Qatar are genetically related, sinkholes representing an early phase in the development of depressions. Karst is concentrated mainly within the limestone, dolomite, gypsum, and anhydrite horizons of the Eocene Rus and Dammam Formations. Most karst features in Qatar show NE-SW and NW-SE orientations, similar to the joint and fracture systems. This observation indicates that rock type and the presence of joints and fractures played a major role in the development of karst in Qatar. Cylindrical, bottle-shaped, compound, and bowl-shaped morphotype karst pits were identified. These forms represent a genetic sequence in which the bowl-shaped pits evolved through a series of cylindrical and bottle-shaped compound intermediate stages. Most karst of central Qatar was formed due to extensive subsurface dissolution of carbonate and sulfate deposits under Middle Pleistocene wet climatic conditions and consequent subsidence. Joint-flow drainage may account for differential dissolution resulting in the formation of a pitted karst terrain in the northern part of Qatar.

Karst is a distinctive environment characterized by landforms that are the product of dissolution of surface and subsurface rock by natural water to a greater extent than in other landscapes. It occurs both as surface and underground features (White 1988; Ford & Williams 1989). The highly varied interactions among chemical, physical, and biological processes have a broad range of geologic effects, including dissolution, precipitation, sedimentation, and ground subsidence (White 1984; Trudgill 1985; Ford & Williams 1989; Smart & Whitaker 1991). Diagnostic features such as sinkholes (dolines), sinking streams, caves, and large springs are the result of the dissolving action of circulating groundwater (Ford & Williams 1989; Smart & Whitaker 1991).

Karst includes features such as large caves, called as *duhul* in Arabic. It is an important feature of Eocene exposure surfaces in Qatar as well as some large parts of the Arabian Peninsula (Abul-Haggag 1965; Edgell 1990; Mukhopadhyay *et al.* 1996). Several substantial caves are known in Qatar, but many have probably been filled with blown sand, or have collapsed to produce some of the thousands of depressions or dolines. The most pronounced topographic features of Qatar are created by the large number (9736) of shallow depressions (Embabi & Ali 1990). Many of these depressions are the surface expression of subsurface collapse structures. Most of them are circular with diameters ranging from a few hundred meters up to ~3 km. Some reach depths of 25 m while others are only a few centimeters deep. Embabi and Ali (1990) related most sinkholes to these depressions. Analysis of the morphometric and spatial distribution parameters of karst depressions reveals that the Qatari karst is represented by broad, shallow depressions with an average density of 1 depression per km² (Embabi & Ali 1990).

The purpose of this paper is to report the geologic evolution of exposed sinkholes in Qatar through an air photo study, field investigations, and petrology.

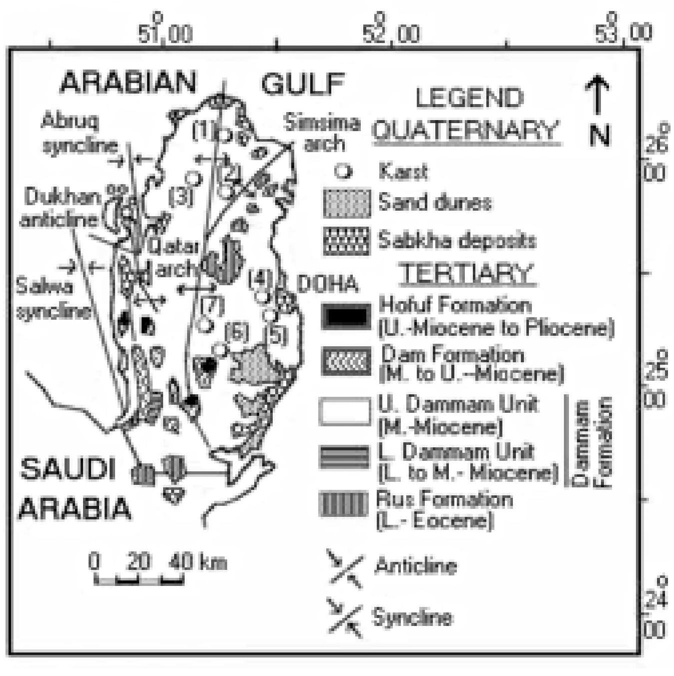


Figure 1. Geologic map of Qatar (modified after Cavelier 1970) showing location of investigated sinkholes; (1): Alghosheimah, (2): Umkareibah, (3): Alsuberiat, (4): Hamam, (5): Duhail, (6) Mudhlem, (7): Musfer.

Geologic setting

Qatar forms an exposed part of the Arabian shelf between the Arabian Shield and the mobile belt of Iran. It is centered at about 25°N., 51°E. Topographically, Qatar has a low-relief landscape with a maximum elevation of ~110 m msl. Structurally, Qatar is an elliptical anticlinal arch with a N-S main axis (Fig. 1). The exposed geologic succession is made up of Tertiary limestone and dolomite with interbedded clay, shale, gypsum, and marl, covered in places by Quaternary deposits (Cavelier 1970). Major faulting is not observed. Tertiary sedimentation started in Qatar with a marine transgression in the Paleocene. Shallow-marine to sabkha conditions prevailed until the end of the Eocene; a carbonate-evaporite sequence (Rus and Dammam Formations) was deposited during this time. The sea regressed at the end of the Eocene, marked by a widespread unconformity, causing the absence of Oligocene deposits over most of the area. Depressions and sinkholes are mainly distributed south of latitude 25° 20’, which coincides with the northerly limit of the deep gypsum and anhydrite horizons of Eocene age. Although a dry arid climate characterizes Qatar at present, moist and dry climatic conditions alternated during the Miocene and Pleistocene (Butzer 1961; Al-Saad *et al*. 2002). Karstification of the Upper Dammam Unit limestone, providing easier pathways for groundwater, took place during this period. Today, Tertiary sedimentary rocks constitute the main aquifers containing usable groundwater in Qatar, originating from recharge by occasional rainstorms on outcrops of the same rocks in Saudi Arabia. The water flows north and east in the direction of the regional dip and discharges along the present-day coast of the Gulf. The aquifers are presently being exploited at a comparatively high rate.

STRATIGRAPHY

The exposed rocks in Qatar consist of the following formations (Fig. 2):

LOWER EOCENE RUS FORMATION

The Rus Formation is composed of soft limestone, dolomitic limestone, chalky limestone, gypsum, anhydrite, and shale. The thickness ranges between 42-112 m. Most depressions are related to dissolution of the gypsum and anhydrite within this formation, resulting in the development of numerous surface-collapse depressions (Embabi & Ali 1990).

LOWER-MIDDLE EOCENE DAMMAM FORMATION

The Dammam Formation conformably overlies the Rus Formation and covers most of Qatar (Cavelier 1970). It ranges in thickness between 30-50 m, and is divided into the Lower Dammam Unit and Upper Dammam Unit. The former consists of the Fhiheil limestone member, the Midra shale member, and the Dukhan limestone member. The Upper Dammam consists of the Simsima limestone and dolomite member and the Abarug dolomite and marl member. All sinkholes of Qatar occur within the Upper Dammam Unit.

LOWER-MIDDLE MIOCENE DAM FORMATION

The Miocene was characterized by regression of the sea and continental erosion. The Dam Formation consists of shallow marine and lacustrine deposits, and reaches a thickness of 80 m.

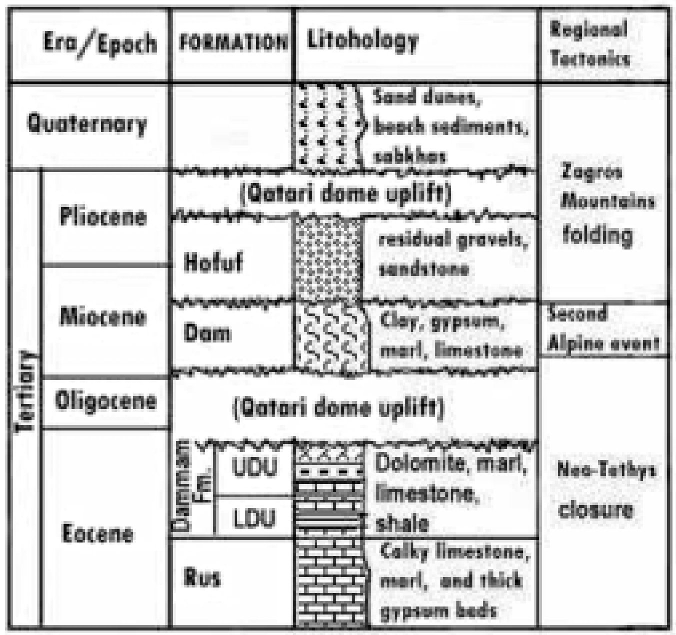


Figure 2. Simplified lithostratigraphy of surface rocks in Qatar in relation to regional tectonics. UDU: Upper Dammam Unit; LDU: Lower Dammam Unit. (Modified after Cavelier 1970).

UPPER MIOCENE TO PLIOCENE HOFUF FORMATION.

The Hofuf Formation consists of fluvial sediments and is ~18 m thick. The deposits consist of coarse sand and sandstone with pebbles of various rocks, mostly derived from the Arabian shield and the Arabian shelf, and transported by large river systems (Al-Saad *et al.* 2002).

QUATERNARY

Quaternary shallow-marine and continental sediments consists of sabkha deposits, sand dunes, and calcareous sand.

SINKHOLES IN QATAR

Air photos show that karst in Qatar occurs as three types: sinkholes, simple depressions, and compound depressions. Simple depressions are those with a single center. Compound depressions have more than one center, and are large and rectangular or irregular in shape. These depressions seem to have formed through the amalgamation of several simple depressions. Field investigations indicate that the areas between the depressions are extensively stylolitized and likely were originally characterized by small-scale, fretted and sculpted karren forms typical of subaerial karstification. Sinkholes are concentrated in the central and northern parts of Qatar (Fig. 1). Analysis of sinkholes and the major axis orientations of depressions shows a structural control on the karst develop-

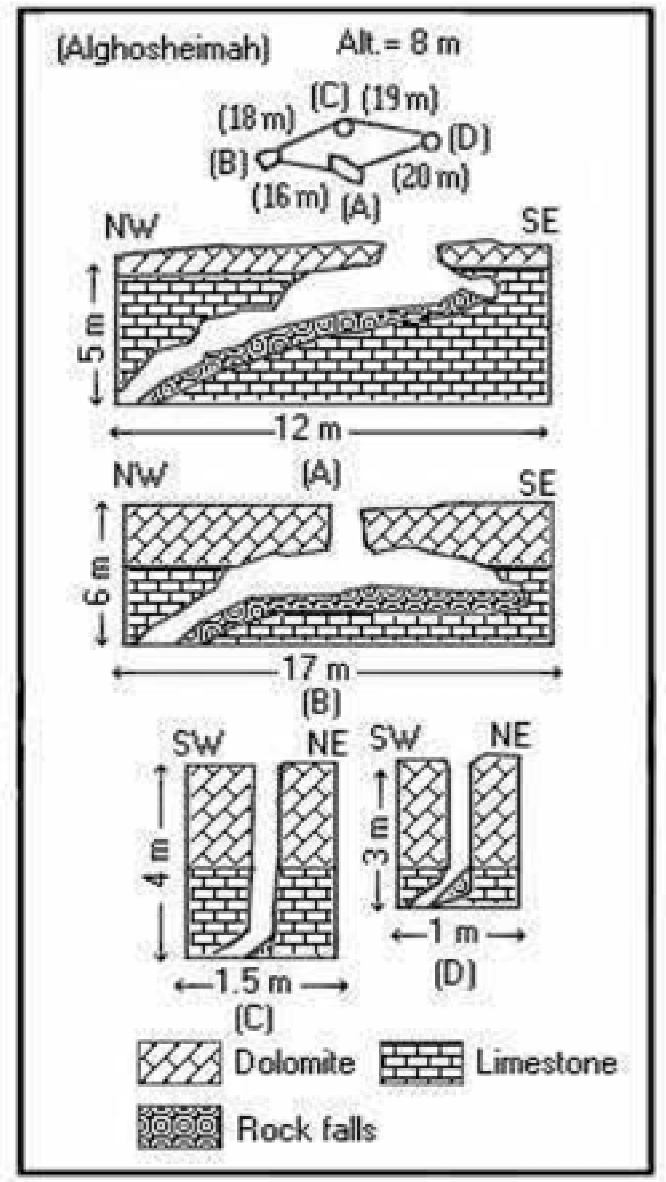


Figure 3. Idealized lithologic profiles of the Algosheimah sinkholes. Alt.; Absolute altitude above sea level.

ment. The long-axis orientations of sinkholes have pronounced NW-SE and NE-SW orientations, which correspond with the joint and fracture orientations in the study area. A 0.1-1 m thick calcrete surface is characteristic of karst areas in central Qatar. The wall rocks of sinkholes are highly jointed and fractured, with many stylolites, voids, and selective dissolution cavities. Thin-section studies of wall rocks from different sinkholes in northern Qatar show that the upper 1-2 m of the walls are dolomitic in composition, whereas the lower portion of the walls is biomicritic to biosparitic limestone with a significant proportion of dissolutional pores that are mostly filled with gypsum. The rocks belong to the Upper Dammam Unit. In central Qatar, marl underlies the upper calcrete whereas thick gypsum beds underlie the limestone. The rocks composing the

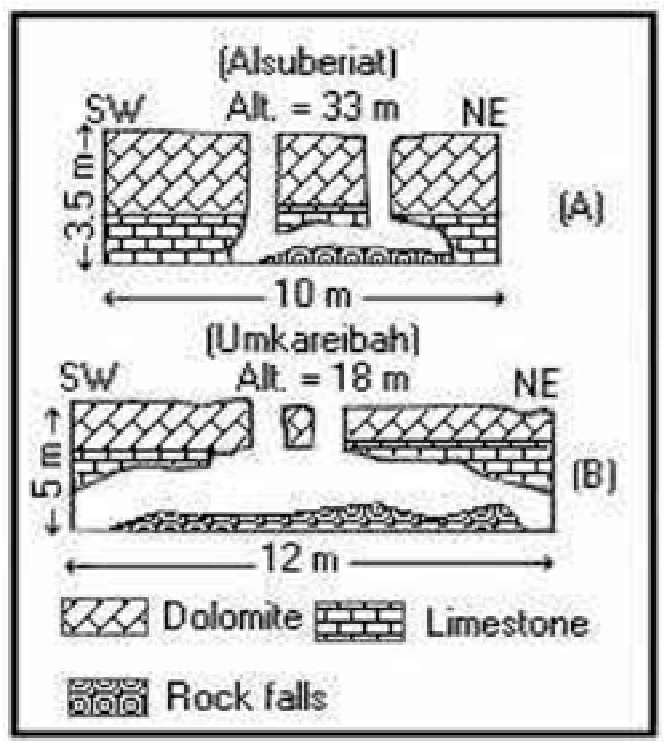


Figure 4. Idealized lithologic profiles through the Alsuberiat (A) and Umkareibah sinkholes (B). Alt.; Absolute altitude above sea level.

sinkholes of central Qatar belong to the Upper and Lower Dammam units. Speleothems, such as stalactites, stalagmites, columns, flowstone, and rimstone pools were not observed in any sinkholes or caves in the investigated areas. The lower part of most caves is either very dark or very steep and were not explored.

SINKHOLES IN NORTHERN QATAR

Most sinkhole entrances in northern Qatar are vertical (Figs. 3, 4) and formed by dissolution along planes of structural weakness that extend to the surface. Sinkholes are found in the following areas:

ALGHOSHEIMAH SINKHOLES (Fig. 3)

These are four vertical sinkholes formed in the Upper Dammam Unit. The holes are 15-20 m apart, occurring as an ellipse with a long axis of 40 m. Hole A is the largest (2 x 1 m); it is 1 m vertical then increases in size to 11 m in diameter with depth. Hole B has a smaller entrance (1.5 m in diameter), but is wider inside (12.5 m) than Hole A. Hole C has a small opening of 0.5 m and reaches a depth of 3.5 m. Hole D has an even smaller opening (0.4 m) and a depth of 2.5 m. Calcrete deposits (10 cm thick) cover the surface of all these holes. Holes C and D dip towards holes A and B. All holes may be interconnected.

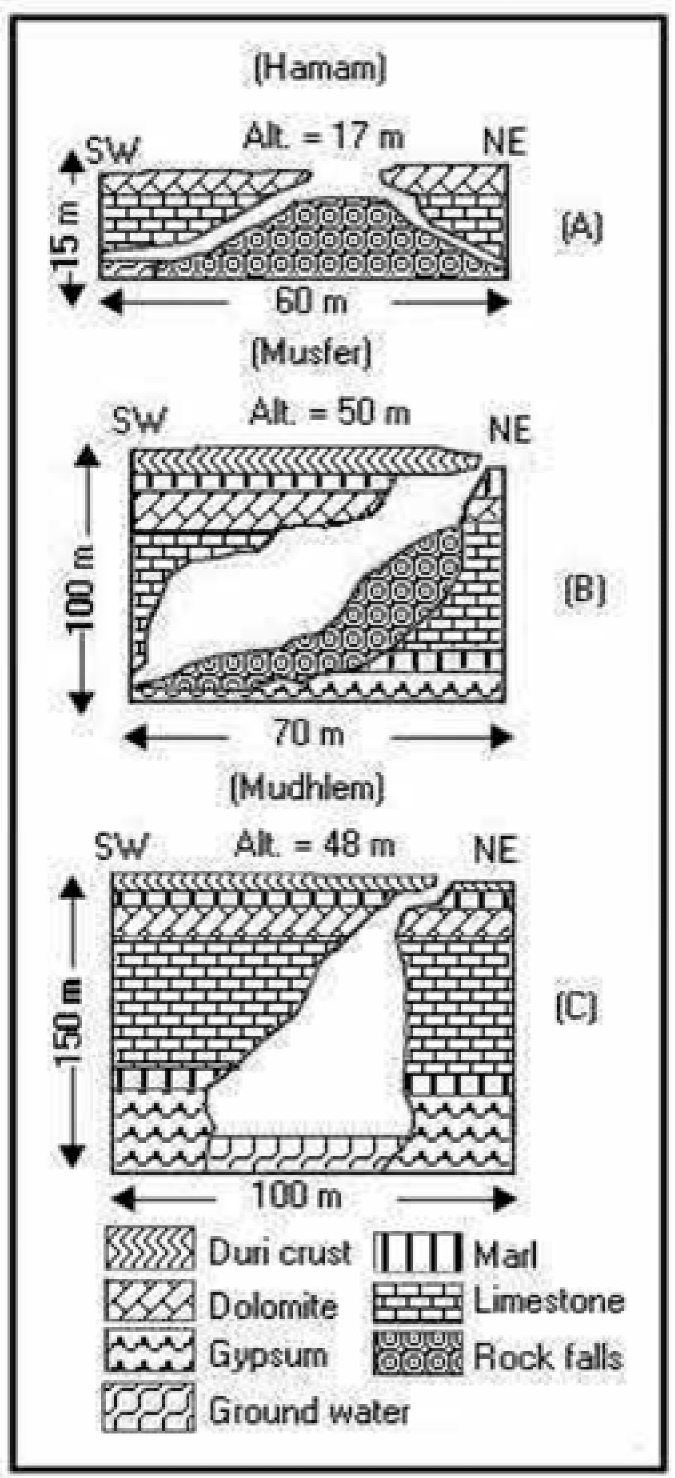


Figure 5. Idealized lithologic profiles through the Hamam (A); Musfer (B) and Mudhlem (C) sinkholes. Alt.; Absolute altitude above sea level.

ALSUBERIAT SINKHOLES (Fig. 4A)

The Alsuberiat area shows two separated sinkholes. Each has its own opening (0.8 m diameter), but they are connected at ~2-3 m depth. Both sinkholes are vertical and reach a depth of 3.1-3.3 m.

UMKAREIBAH SINKHOLES (Fig. 4B)

The Umkareibah sinkholes are similar to those of the Alsuberiat area and consist of two holes. The first has two openings, each 1.65 m in diameter and separated by ~1 m of dolomitic rock. The first sinkhole reaches a depth of 3 m and a size of 1.5-2 m in diameter. The second sinkhole (not shown) is of the vertical type, has an opening of 2 m in diameter, and reaches a depth of 2.3 m and a size of 13 m in diameter. All sinkholes dip in a NW-SE direction to unknown depth.

SINKHOLES IN CENTRAL QATAR

Sinkholes in central Qatar are generally larger in size and depth than those of northern Qatar. They occur as vertical shafts connected to steeply inclined passages (Fig. 5). Most sinkholes reach the gypsum layers of the Lower Dammam Unit and the Rus Formation. The investigated sinkholes include the following:

HAMAM SINKHOLE (Fig. 5A)

This sinkhole has an oval opening (14.1 x 9.1 m), oriented in a NE-SW direction. It is the only sinkhole containing saline water at a depth of 15 m. The hole is connected to the Arabian Gulf, which is 4 km east of the sinkhole. Several types of small fish live in the water, and the tidal fluctuation of the water table is ~30 cm.

MUSFER SINKHOLE (Fig. 5B)

Musfer sinkhole has an opening of 12 x 4.5 m and is at least 100 m deep, though filled with sloping loose sand at the bottom. Gypsum layers of the Lower Dammam Unit and the Rus Formation occur at the bottom of this sinkhole. We suspect that this sinkhole is part of a much larger cave system.

MUDHLEM SINKHOLE (Figs. 5C, 6)

This particular sinkhole, whose Arabic name means “the Dark Cave” is ~150 m deep, filled with sloping loose sand and brackish water at the bottom. The hole has an opening of 15 m in diameter. Gypsum of the Rus Formation is in the lower parts of the sinkhole.

DUHAIL SINKHOLE (Fig. 7)

Duhail sinkhole has a circular opening 40 m in diameter and a depth of 5 m. This hole is transitional to becoming a depression, as indicated by the presence of a collapsed roof in its center. The Municipality of Doha City uses this sinkhole as a dumping area.

MORPHOLOGY OF THE KARST PITS

Several types of karst-pit morphology/ies exist. Such variations in karst pit shape are illustrated by reference to distinct morphotypes, and shown on Figure 8:

Cylindrical karst pits have a narrow tubular form with verti-

Figure 6. The main passage of Musfer sinkhole (Photo was taken in 2002).

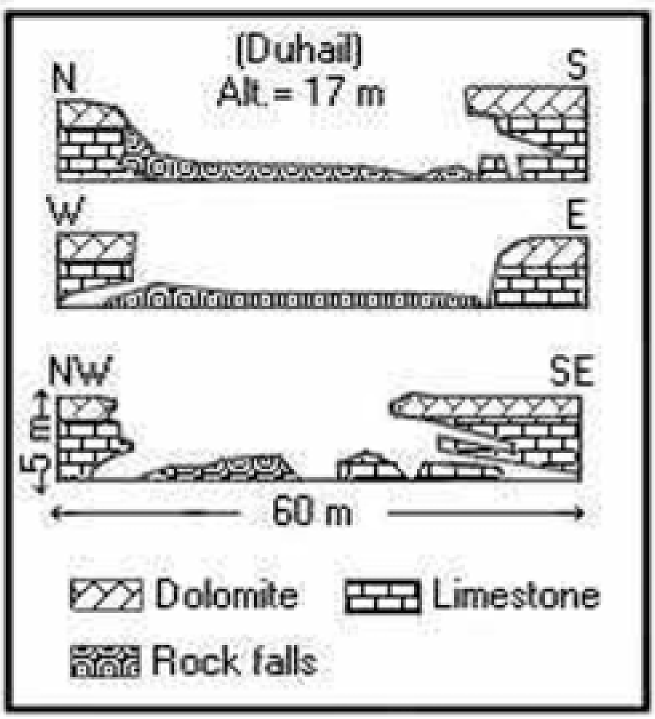
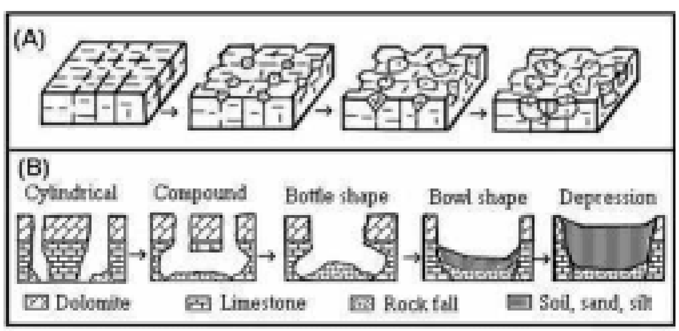


Figure 7. Idealized lithologic profiles through the Duhail sinkhole. Alt.; Absolute altitude above sea level.



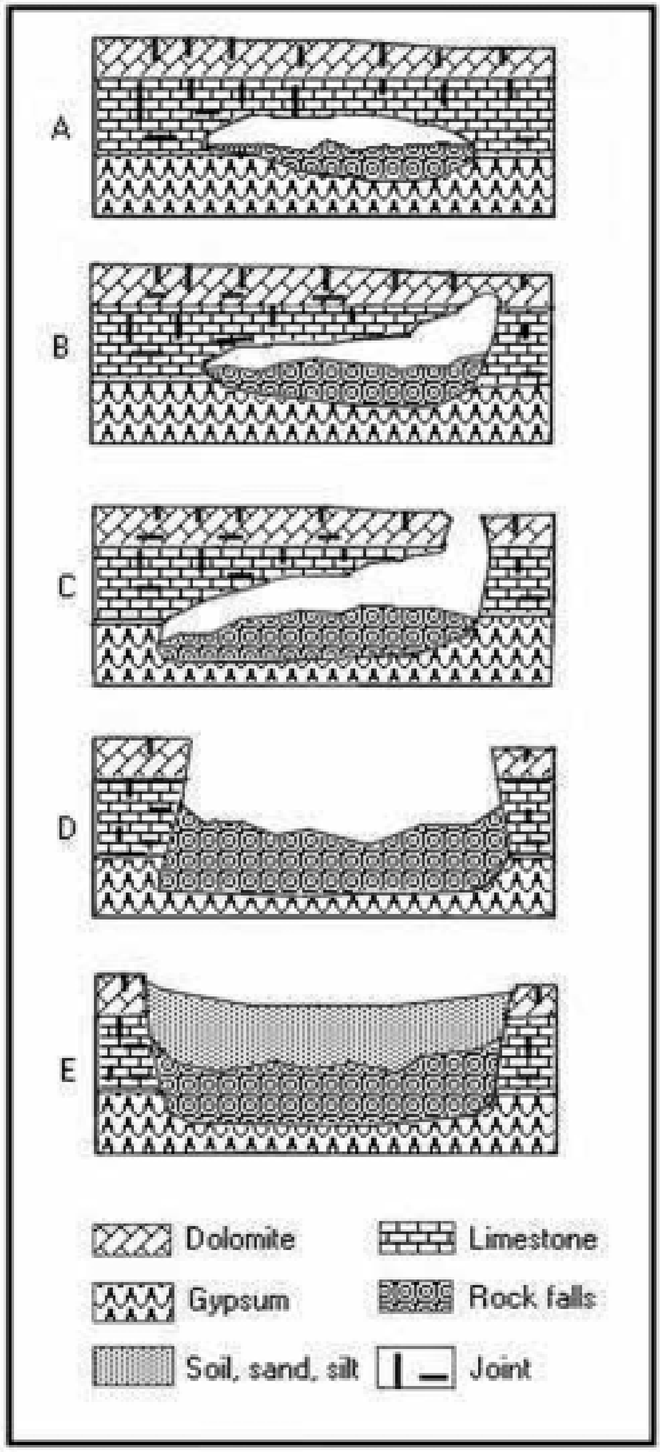


Figure 8 (left). Model for the origin of sinkholes in northern Qatar.
Figure 9 (above). Model for the origin of sinkholes in central Qatar.

Table 1. A provisional chronology of Quaternary climate and lithostratigraphy in the southwestern part of the Rub' al Khali and Qatar. (Modified after Edgell 1990).

Epoch	Date in years	Climate	Lithology and topography
Holocene	0-700	Hyperarid	Dunes, eolian sand
	700-5,500	Slightly moist	Hofuf river, dunes, lakes
	5,500-6,000	Hyperarid	Dunes, eolian sand
	6,000-10,000	Wet (pluvial)	Lakes, lacustrine sediments
Late Pleistocene	10,000-17,000	Hyperarid	Dune, eolian sand
	17,000-36,000	Wet (pluvial)	Lakes, lacustrine sediments
	36,000-70,000	Arid	Dunes, eolian sand
	70,000-270,000	Moist	Glacial and interglacial
	270,000-325,000	Arid	Plateau caves, dunes
Middle Pleistocene	325,000-560,000	Wet	**Active karstification and cave formation**
	560,000-700,000	Arid	Dunes, eolian sand
Early Pleistocene	700,000-2,500,000	Wet humid (pluvial)	Large alluvial fans, early drainage systems

cal or steeply inward inclined pit walls.

Bottle-shaped karst pits comprise cylindrical pits in which the lower portion of the pit wall has been removed to produce a beveled wall that slopes outwards.

Compound karst pits comprise two or more adjacent cylindrical or bottle pits with a common interpit area.

Bowl-shaped karst pits have steep sides with a gently concave, irregular, or flat base.

Depressions can be former sinkholes that are partly or completely filled with autochthonous material.

DISCUSSION

Karstification in Qatar, as well as in other parts of the Arabian Gulf area (Abul-Haggag 1965; Al-Sayaro & Zötl 1978; Jado & Zötl 1984; Mukhopadhyay *et al.* 1996), is associated with the calcareous, dolomitic, and gypsiferous Dammam Formation of Eocene age. Local stratigraphy and petrography suggest that the primary karst-forming process affecting the Dammam Formation is a selective dissolution of rock driven by rainwater as well as groundwater. Such karstification takes place along the subsurface contact between the upper dolomite layers and the lower gypsum-bearing limestone of the Dammam Formation. This indicates that most sinkholes were formed because of preferential dissolution associated with the difference in composition between dolomitic, calcitic, and gypsum rocks. Karstification in the Arabian Gulf area mainly formed in the Middle Pleistocene, between 325,000 BP and 560,000 BP (Rauert *et al.* 1988; Edgell 1990). During this time, a wet climate predominated in the Arabian Gulf region (Edgell 1990: Table 1). In addition, the large volumes of Neogene sediment deposited indicate a pluvial and humid climate during the Miocene and Pliocene (Whybrow & McClure 1981). Similar indications are also apparent from the large alluvial fans of Early Quaternary age (Al-Saad *et al*. 2002).

The rate at which limestone and gypsum dissolution proceeds within the surficial meteoric environment is dependent upon several factors, including rainfall regime, temperature, distribution of soil-cover and biological activity, and structural weakness and lithology of the carbonate substrate (Trudgill 1985; White 1984; Ford & Williams 1989; Smart & Whitaker 1991; Reeder *et al.* 1996; Hose 1996; Miller 1996; Frank *et al.* 1998; Hill 2000). Of these, dissolution is directly impacted by the amount of rainfall (White 1984); an increase in precipitation always results in an increase in the rate of limestone dissolution. Temperature primarily influences limestone dissolution through its effect on the level of biological activity. Lithology of the carbonate substrate also has a profound effect on karstification, calcite dissolving more readily than dolomite due to its higher solubility (Martinez & White 1999). Karstification can take place where dolomite and gypsum are in contact with the same aquifer (Bischoff *et al.* 1994). Gypsum dissolution drives the precipitation of calcite, thus consuming carbonate ions released by dolomite. Gypsum-driven dedolomitization may be responsible for the karstic system (Bischoff *et al.* 1994), but dedolomitization was not observed in thin sections.

Karst pits making up the sinkholes and depressions in Qatar are structurally controlled and seem to be initiated through fractures and joint-flow drainage (Fig. 8A). The profiles of all types of sinkholes in northern Qatar indicate strong vertical control, which is attributed to the numerous fractures and joints in the bedrock. Based upon sinkhole long-axis data, it appears that such lines of structural weakness in the bedrock influence sinkhole orientation. Sinkholes commonly form along high-permeability pathways through the vadose zone, which are sites of fracture concentrations and intersections (White 1988).

Sinkholes may also become elongated along lines of major weakness by a combination of dissolution and collapse (Reeder *et al.* 1996). Collapse can originate at some depth in the bedrock if it is assisted by fracture zones (Fig. 9). Rainwater, intercepted by joints and fractures, concentrates at specific sites on the emergent surface and causes dissolution along joint intersections, which produces cylindrical pits that propagate vertically downward with time (Fig. 8A). Gravity-driven drainage further explains the initial perpendicular attitude of the pits. In addition, joint-flow drainage accounts for the comparable width of shallow and deep cylindrical pits. Variations in depth may reflect differences in the length of time that drainage was focused at a particular site. Downward propagation of some pits was limited to the uppermost 1-2 m and enlargement primarily occurred through lateral amalgamation of adjacent pits. Once initiated, the continued development of the sinkholes would have been self-perpetuating. The smooth, rounded appearance of the investigated karst pits is comparable to that of modern karst terrains (Sweeting 1973; James & Choquette 1984).

A complete spectrum of karst-pit forms exists in Qatar. Cylindrical pits evolve into bowl-shaped ones and depressions through several bottle- and compound intermediates (Fig. 8B). This indicates that these forms represent a genetic sequence and that each started around a cylindrical pit. Figure 8B shows how sinkholes may represent the early phase in depression development. Dissolution and collapse caused the preferential removal of limestone and gypsum from the lower portion of the pit wall. Enlargement of the upper portion of the pit to form a bowl-shaped depression likely resulted from collapse (Fig. 7). The pathway along which further pit enlargement occurred was dependent upon the initial density of the cylindrical pits. Where pits were more densely packed, adjacent pits amalgamated through a gradual reduction in height of the interpit area, to form bowl-shaped pits (Fig. 8B). Once complete denudation of the interpit area had occurred, further dissolution at this site appears to have been minimal, pit enlargement occurring primarily through lateral dissolution and amalgamation.

As speculated by Walkden (1974), several features of the karst are consistent with the presence of a shallow water table during development. In particular, enlargement of the karst pits by lateral amalgamation rather than vertical deepening (Fig. 8B) and the occurrence of flat-based pits suggest that a water-saturated or carbonate-cemented zone existed a few meters beneath the sediment surface. Figures 8 and 9 synthesize the progressive formation of sinkholes in northern and central Qatar, respectively, as discussed above. The investigated sinkholes/depressions appear to have developed exclusively from collapse. However, other explanations are possible.

CONCLUSIONS

Analysis of lithologic and geomorphic features within northern and central Qatar revealed that the karst landscape is generally influenced by the lithology and structure of the bedrock. The upper 1-2 m of the rock consists of dolomite and dolomitic limestone underlain by gypsum and gypsum-bearing biomicritic to biosparitic limestone. Joints and fractures, formed during periods of uplift in Qatar, govern the orientation of karst landforms, including the long axes of depressions and sinkhole passages. Uplift and fracturing increased the secondary permeability of the rocks, and rainwater during Pleistocene humid periods began to dissolve the carbonate and gypsum along these planes of structural weakness. In northern Qatar, each depression started around a cluster of vertical cylindrical solution pits, with each pit interpreted to have formed through joint-flow drainage. Fracture and joint-flow drainage focused dissolution at particular sites in the carbonate substrate, with the locus of dissolution extending vertically downward through time. In many cases, growth of the cylindrical pits was limited to the uppermost 1-2 m of the carbonate top, with subsequent development occurring through the lateral amalgamation of adjacent pits.

In central Qatar, most sinkholes formed due to subsurface dissolution of gypsum and subsequent collapse of the overlying beds making up the roofs.

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