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AL-DAHER CAVE (BERGISH), JORDAN, THE FIRST EXTENSIVE JORDANIAN LIMESTONE CAVE: A CONVECTIVE CARLSBAD-TYPE CAVE?

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In spite of the vast limestone area present in Jordan, no karstic caves to speak of were known there until 1995 when Al-Daher Cave was discovered. The cave is situated east of Bergish Reserve for Ecotourism in the mountains of Bergish at about 830 m above sea level. The cave formed in the Wadi As Sir Limestone Formation of Upper Cretaceous age. It is a maze developed along NW-SE and NE-SW striking joints which owe their existence to the Dead Sea Transform Fault situated a few kilometers to the west of the cave. Rooms, with a total area of 1750 m^2, were formed within a square of 70 × 70 m. The cave is constrained to certain limestone strata, laminated and non-laminated, divided by four chert layers that form distinctive markers throughout the cave. Chert nodules occur also within the limestone layers. The cave formed phreatically exclusively by dissolution within a small body of rising and convecting water. It is suggested that the very localized solution capacity derived from the oxidation of either H_2S, or possibly even CH_4, by oxygen present near the former water table. Thus, Al-Daher Cave may have formed by a process similar to that which formed the Guadalupe Mountain caves, New Mexico, among them Carlsbad Cavern. The altitude of the cave suggests that it may be as old as upper Miocene. The cave contains several relict generations of speleothems but also active forms. The local government is hoping to develop the cave into a show cave; it would be the first in Jordan.

Location and Topography

Al-Daher Cave is the first natural limestone cave in Jordan of any appreciable extent. It was discovered by Ahmad Al-Shreideh in 1995 and is currently being developed by the Ministry of Tourism (Kempe *et al.*, 2004). Other caves in Jordan include lava tunnels (Al-Malabeh *et al.*, 2004; Kempe and Al-Malabeh, 2005; Al-Malabeh *et al.*, 2005), a cave in the Lisan Marls (Rosendahl *et al.*, 1999) and numerous, mostly artificial shelter caves along the deeply incised wadis of the country (*e.g.*, Calandri, 1987; Hofmann and Hofmann, 1993).

Al-Daher Cave is located east of the Bergish Reserve for Ecotourism on Bergish Mountain at about 830 m above sea level (Figs. 1 and 2). The entrance was originally a vertical fissure, opening to the east near the top of the mountain that contains the cave. This flank was artificially terraced in ancient times for agricultural purposes, and a wine press has been carved out of the rock nearby. The terraces are now partly overgrown by oak forest and only locally used to grow olive trees and grapes. During the winter of 2003–2004 the entrance was widened with funding from the Ministry of Planning and a terrace was cleared in front of the cave. These excavations did not yield any archaeological findings, suggesting that the cave had not been known or used in antiquity.

On September 20, 2003, we made a reconnaissance trip through the cave and started to survey it on September 26 and 27, 2003. We returned to the cave in the spring of 2004 and completed the work on March 29 and 30. A total of 76 (2003) and 40 (2004) stations were surveyed. Currently only one tight lead and some upward shafts remain unexplored. Due to the maze character of the cave, a total length is somewhat irrelevant, but the total added survey lines sums up to 280 m and the area covered amounts to 1,750 m^2. The entire cave fits into a square measuring 70 × 70 meters (Fig. 3).

Tectonic Setting

Many prominent structural features are present in Jordan. However, the geology and tectonics of Jordan are closely related to the regional geology and tectonics of the Mediterranean area. This region is subdivided into three major plates: the African (Nubian), Arabian, and Eurasian Plates. Jordan lies on the northwestern side of the Nubian-Arabian shield. Tectonism was contemporaneous with the opening of the Red Sea (Africa Red Sea rift system), the collision of the Arabian and Eurasian plates, and the uplift of the Afro-Arabian dome (Barberi *et al.*, 1970; Gregory *et al.*, 1982; Schilling *et al.*, 1992).

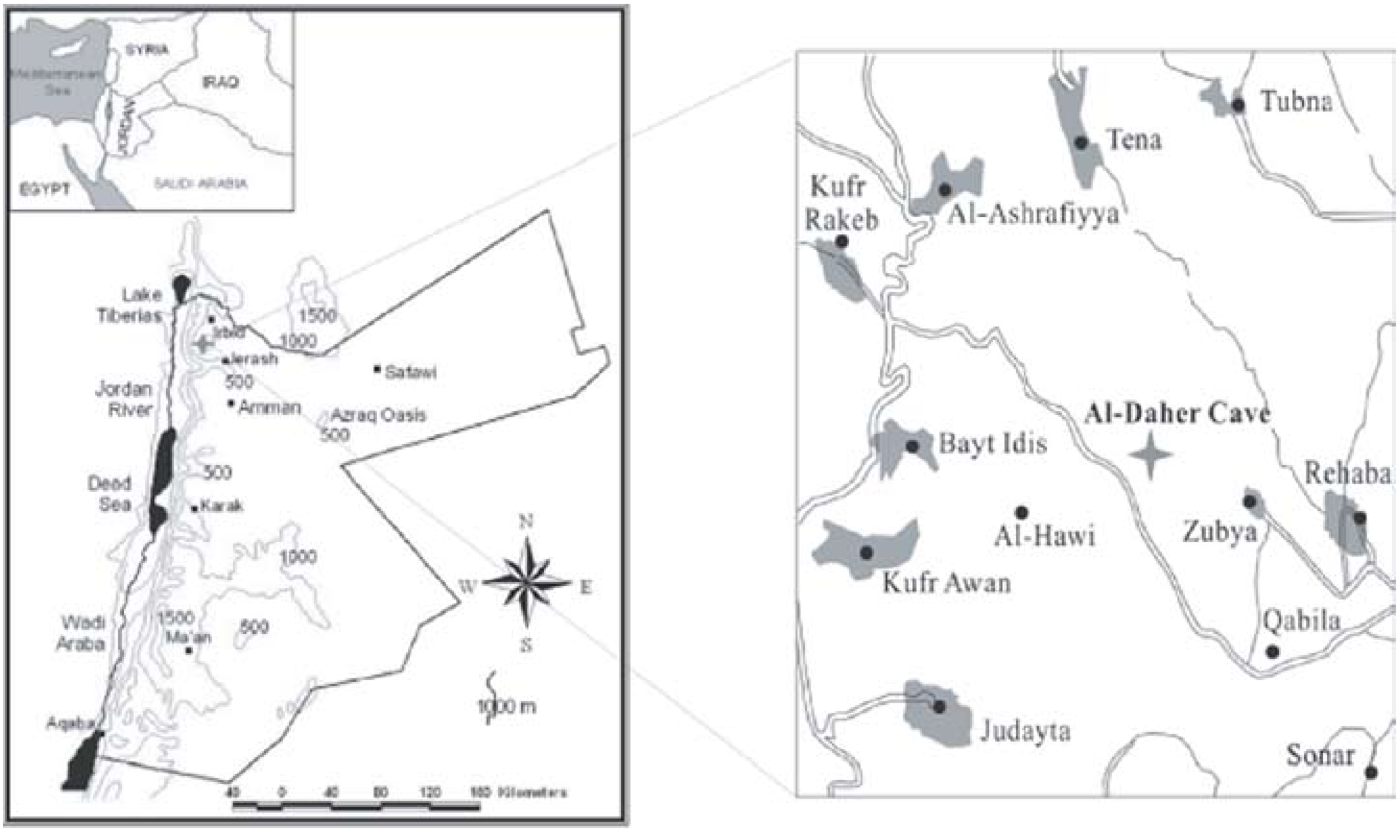

Figure 1. Location of Al-Daher Cave and its geologic setting along the eastern margin of the Jordan Graben.

The Dead Sea Transform Fault system (hereafter, DSFT) is considered the foremost structure of the region (Quennell, 1958; Ginzburg *et al.*, 1979; Mart, 1982). It is a major sinistral strike-slip fault zone, which is ca. 1000 km long, and strikes NNE-SSW from the Gulf of Aqaba to Lake Tiberias and to southern Turkey. It is connected with the Red Sea along the Aqaba Gulf transition zone. The tectonic association between the DSFT and the Red Sea was recognized about 85 years ago, and both are parts of the rifting system (the East African-Red Sea-Jordan Rift) that extends from southern Anatolia in Turkey to East Africa.

The present tectonic picture of the DSFT has been shaped mainly during the upper Tertiary and Quaternary periods (Picard, 1970). Estimates of the amount of horizontal displacement along the Jordan valley have been made previously: Dubertret (1929) suggested that a displacement of 100 km occurred in 36 million years; Quennell (1958) suggested that a 67 km displacement occurred during the Early Miocene, and an additional 40 km during the Late Pleistocene.

Field investigations, aerial photographs and satellite images indicate that four principal fault systems exist in the investigated area. The major trend is in the N-S direction and may be related to the main rift structure since they have a parallel to sub-parallel trend. The NW-SE-trending fault system has the same direction as the fault systems of the Red Sea, Wadi Al-Sirhan fault, and Wadi Abed fault zone (NE-Jordan). The E-W fault system in the study area is consistent with the trend of many E-W fault systems in Jordan (*e.g.*, Zarka Ma'in fault and Sawaqa fault, central Jordan). NE-SW is the least abundant trend, and the major-

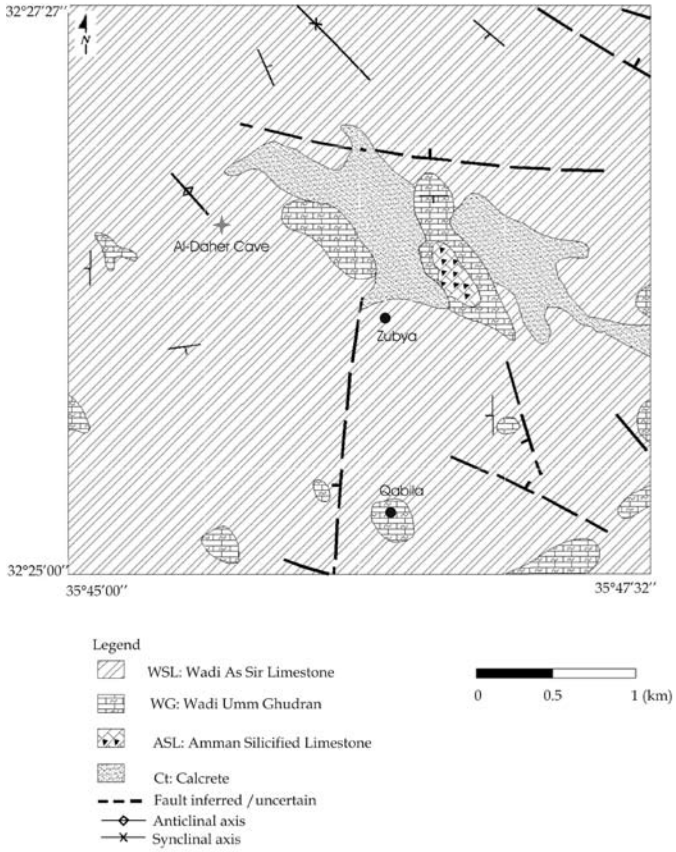

Figure 2. Geologic map of Al-Daher Cave area (modified by A. Al-Malabeh after Abdelhamid, 1995).

ity of these faults are local and of normal displacement type.

Al-Daher Cave is situated about 30 km to the east of the DSTF. The rocks have been jointed and fractured substantially, and the cave is formed mostly along NW-SE and NE-SW-striking joints (compare Fig. 3); directions that are also dominant regionally. Normal to the strike of the DSTF, structures developed that later have been transformed by erosion into deeply incised river courses.

Lithostratigraphic Succession

The rocks exposed in the cave area are of Upper Cretaceous age (Fig. 2). The beds belong to the extensive limestone platform developed on the African and Arabian Plates (*e.g.*, Bauer *et al.*, 2003; Lüning *et al.*, 2004). The Upper Cretaceous in Jordan is subdivided into two Groups: Ajlun (Albian-Turonian) and Belqa (Coniacian-Mastrichtian). The lithostratigraphic nomenclature of the Upper Cretaceous in Jordan used in this study is that adopted by the Natural Resources Authority (NRA) 1:50,000 Geological Mapping (El-Hiyari, 1985; Powell, 1989; Abdelhamid, 1995). The cave formed in the Wadi As Sir Limestone Formation. This formation represents the upper parts of the Ajlun Group. In general, this formation consists of dolomitic limestone (Powell, 1989). The uppermost massive beds contain chert nodules and calcite geodes. The fossil assemblage was that of a fully marine carbonate platform (Powell, 1989). The massive bedded Wadi As Limestone Formation forms a distinctive belt of cliff features. The formation ranges in thickness from 50 to 65 m in the study area.

The other two formations that are exposed in the study area (Wadi Umm Ghudran Formation and Amman Silicified Limestone Formation) belong to the Balqa group (Fig. 2). The Wadi Umm Ghudran Formation (Senonian) is characterized by a soft-weathered, white, massive chalk sequence (Powell, 1988). The Amman Silicified Limestone Formation (Campanian) consists of massive, hard, dark gray, autobrecciated chert interbedded with dolomitic limestone, chert, chalk, phosphatic chert and phosphatic marly limestone (Powell, 1989).

The cave is situated in the upper Wadi As Sir formation. Here, the cherts occur in several morphotypes: (i) as thick horizontal beds, (ii) as vertical sheets, (iii) as round, conical loafs, (iv) in the form of grape-like, small and bundled spheres, (v) or in massive, cone-like vertical bodies. Fossils of silicified rudists (a pachydont bivalve) are commonly found in the weathered layers outside of the cave. None have been noticed inside the cave. The soil above the limestone is terra rossa, mixed with masses of limestone and chert blocks.

The survey of the cave revealed that it is developed along a limited set of limestone beds which are divided by four distinct silicified layers, labled Cherts A to D, each between 0.2 and 0.5 m thick. The section can best be studied in the Geo-Pit, a cylindrical room that transects vertically through the 10 m of the stratigraphic column (Fig. 4). The four chert layers separate five limestone beds, each of which have characteristic properties and vary in the amount of contained chert. The layers between Cherts B–C, and C–D, contain most of the cavity and are the ones most susceptible to dissolution. Above and below Cherts B and D the amount of chert in the limestone increases; these layers are less susceptible to cave formation. The limestone above Chert A is rarely seen and heavily silicified. The chalk bed between Cherts A and B is characterized by chert boxwork formed by vertical sheets (Fig. 5). The next limestone layer is characterized by small chert nodules which form grape-like aggregates (Fig. 6). The limestone is micritic and non-laminated. This is in contrast to the next bed that is finely laminated and where the chert nodules are large, conical-downward and loaf-like (Fig. 7). The next limestone bed is also laminated but contains, at least in the Geopit, large, vertical and cylindrical chert nodules (Fig. 8). This layer is rarely seen in the cave because in the larger halls, the floor is covered with breakdown composed of the chert layers and nodules liberated from the dissolved limestone beds.

With this standard stratigraphy in mind, one can follow the layers throughout the cave. In Figure 9, a panorama view of Stalagmite Hall is given. The chert layers B and C can be followed along the ceiling and walls. The thickness of the layers varies somewhat throughout the cave, and in Fig. 10 a reduction of the non-laminated limestone to the back (*i.e.*, to the SW) is seen. The layers dip slightly towards the S; the lowest part of the cave is therefore SW of the entrance.

Description of Al-Daher Cave

Al-Daher Cave is a maze, dominated by two directions: NE-SW and NW-SE (Fig. 3). It consists of a series of interconnected halls, some of them more than 20 m long and up to 10 m high. These large halls are connected by relatively small passages. Apart from the entrance section (up to the Tea Passage) and the Stalagmite Passage at the southern part of the cave, travel through the cave involves climbing down into these halls and out of them at their far end. Large breakdown blocks, some of them over 10 m long, also characterize these halls. Most important is the observation that the halls have pits at their bottom. These are filled with loose silica nodules and boxwork, collected here as an insoluble residue of the cave-forming process. In spite of these ups and downs, the cave is restricted to one level, determined by two of the least silicified limestone beds (between Cherts B and D). Chert layers form much of the ceiling of the cave. Layer B, for example, defines the roof of the entrance passage (around Station 10) and dips about 5° SSW (ca. 200° N). Similar ceiling sections are seen throughout the cave, for example in the Stalagmite Passage.

Further features of note in the cave are small faults. At station 10-11 (the dead-end small passage parallel to the entrance passage; see Fig. 3) a fault running NE-SW occurs, down-faulting the northern block by ca. 10 cm. All-in-all, faults cannot amount to large displacements since the cave stays at the same stratigraphic level.

Perhaps the most striking character of the cave is the walls. They contain extensive silicified boxwork and protruding chert nodules, which have been left in situ during the limestone dissolution process. In addition, the limestone has been altered to

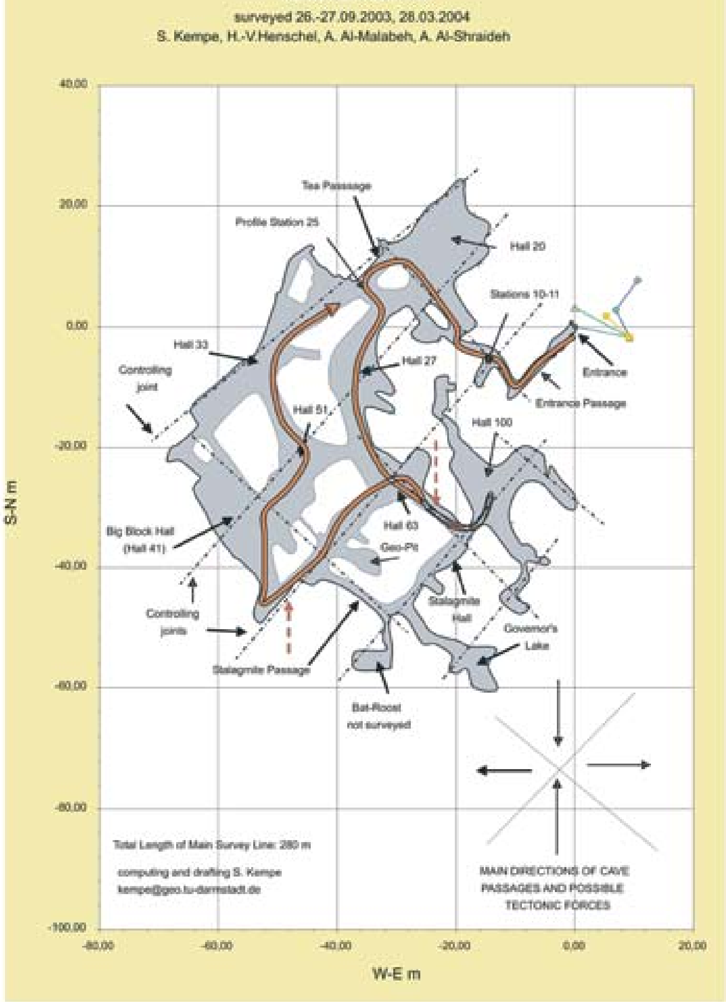

Figure 3. Map of Al-Daher Cave with passages shaded and highlighted directions of passages identical to the jointing of the rock in response to the pressure of the Dead Sea Transform Fault (map by authors, 2003 and 2004). Thick line suggests show cave trail with a minimum of impact to the cave. Dashed arrows indicate passages that must be widened if the cave should be commercialized. Lines mark 10 m squares, north is to the top.

Figure 5. Chert boxwork above Chert B.

Figure 6. Non-laminated limestone between Chert B and C with grape-like small chert nodules.

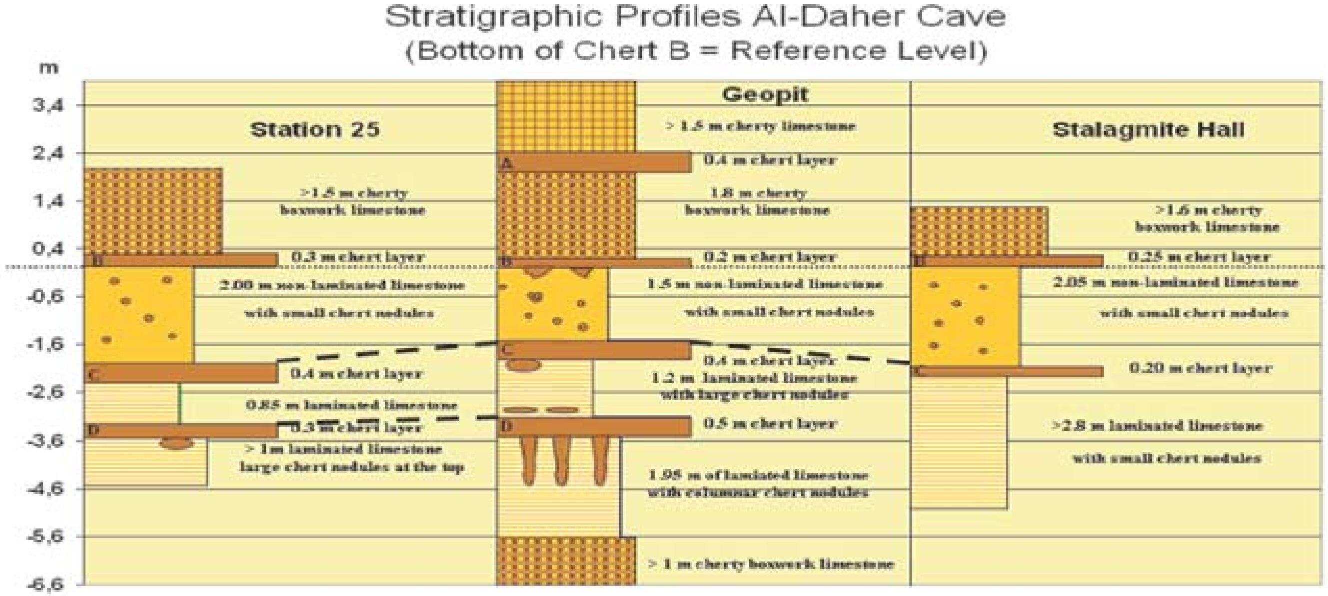

Figure 4. Stratigraphy of the cave (scale in meters) at three different sections. The Cenomanian limestone forms distinct layers with different textures and silica nodules interrupted by chert layers (A to D).

Figure 7. Laminated limestone between Chert C and D with loaf-like large nodules.

Figure 8. Vertical, large nodules from the laminated limestone layer below Chert D in the Geopit.

a soft and powdery white consistency, which can be dug up by hand (entfestigter limestone).

After descending the entrance corridor of the cave, one follows a widened joint-determined passage down to a sharp right turn. After a few meters a stalagmite fill has been removed to ease access to the main part of the cave. The following room leads to Hall 20, which is characterized by many large stalagmites, some of them grown on breakdown blocks. Hall 20 is the only one with an even floor. Three openings lead to the interior of the cave. The furthest connects into the Tea Passage and is still quite level. Further progress involves climbing down either into Hall 27 to the left or into Hall 33 straight on. To the right a narrow lead doubles back into Hall 33. Loose siliceous nodules occur everywhere on the floor. From Hall 33 one can climb down to the left into Hall 51 or ascend to the back of Hall 33 in order to gain access to the Big Block Hall. Big Block Hall has a monumental breakdown block at its center, propped up on other blocks. Hall 51 connects back to Hall 27 and Hall 63 (Fig. 10). It runs NE-SW and is quite high. At the far end, there is an ascent which leads into a passage connecting back into Big Block Hall. Left, the narrow Stalagmite Passage is accessed, blocked by speleothems at its end. We could not enter the small room (Bat-Roost) beyond, the only passage which was not completely explored. A few meters before this choke the low passage turns left (NE) leading towards Stalagmite Hall. Before reaching it, a

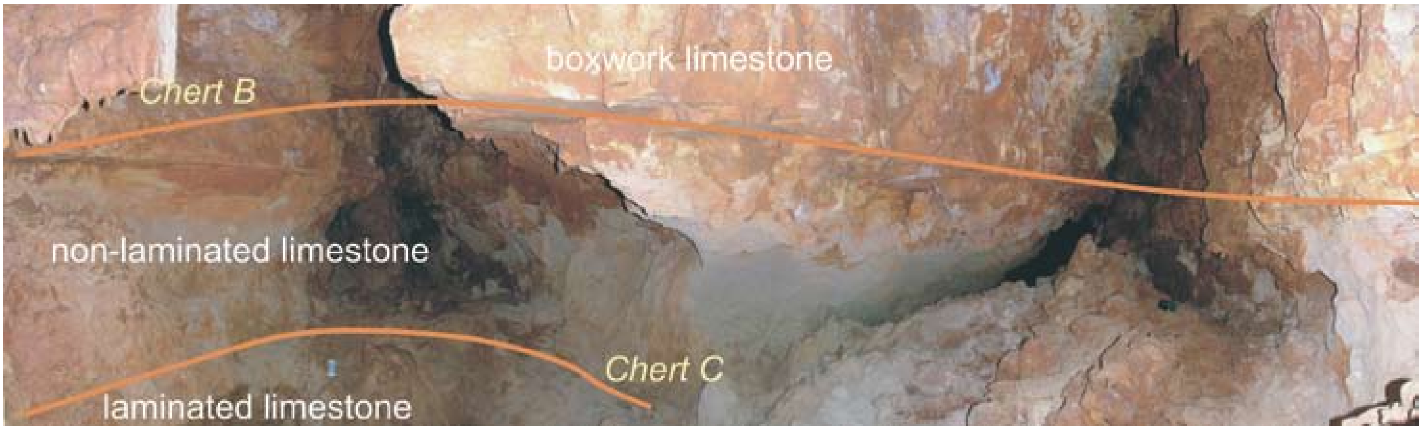

Figure 9. This panorama view (ca. 120°) of Stalagmite Hall (left) and the passage to Hall 63 (right) shows the stratigraphic setting of this part of the cave. Passages in the boxwork limestone are narrow, while in the non-laminated limestone and in the upper laminated limestone wide halls have been leached out. Note 10 cm scale above "s" of "laminated limestone".

Figure 10. View to the west into Hall 63 (>90° panoramic view). Note the band of Chert B in the upper third of the picture.

Figure 11. Panoramic eastward view into Hall 100 towards station 108 and 109. Note three layers (B, C, and D) of chert on far wall, with layer D forming a flowstone-covered ledge.

crawl turns right, which opens up into a series of small rooms, one with a small pool at its floor (Governor's Lake). In Stalagmite Hall the cave opens up again; in its SW part it even has two levels, the lower one leached out from underneath Chert C (background of Fig. 9). Climbing up again one can pass through a small opening into Hall 100 (Fig. 11). It is quite large with three passages leading off. Stalagmite Hall connects back into Hall 63 which has a high chimney near its NE end.

Speleogenesis

Today Al-Daher Cave is in a fossil state, no longer forming actively. In order to understand its speleogenesis we therefore rely solely on interpreting its morphology. The following observations serve as clues:

- Al-Daher is a maze cave following the local jointing.
- All of its passages fall within a square of ca. 70 × 70 m. No continuation seems to exist, and no further caves are known in the area.
- It consists of large halls, interconnected incidentally by small passages.
- The halls have pits at their floors, largely filled with insoluble silica rubble.
- The cave follows in essence one stratigraphic level, consisting of two limestone units with the least silica content.
- The limestone surface is very soft and silica nodules protrude from the walls.
- Allochthonous sediments are absent; no significant authochtonous sediment layers were encountered (apart from the residual chert and silt).

These observations suggest that the cave has been formed phreatically, (*i.e.*, at or below the water table) by a slow corrosion process, bound to a certain level. The water apparently came from below, rising through the pits in the halls and, after having been saturated with limestone, disappearing again through these holes into the deeper ground water. No lateral outflow channel existed. Examples for such systems caused by water rising from a deeper aquifer and disappearing back into it and are known, for example, from the South Harz Mountains, Germany (*e.g.*, Kempe, 1997a). There, carbonate-saturated phreatic water rises into the overlying gypsum and anhydrite where it dissolves large domes of a principally similar morphology as Al-Daher Cave. The gypsum-saturated water is denser and sinks back into the carbonate aquifer into the deeper ground-water body. Such phreatic slow convective systems have been shown to be responsible specifically for the formation of caves with large halls that are not connected by stream channels, as discussed below.

Well-known examples for this type of cave development are the caves in the Capitan Reef limestone of the Guadalupe Mountains, foremost Carlsbad and Lechuguilla Caverns (New Mexico, U.S.A) (*e.g.*, Hill, 1987; 2000). In fact, Al-Daher Cave can be directly compared to Endless Cavern in the Guadalupe Mountains (*e.g.*, Palmer and Palmer, 2000; map in McClurg, 1986, p. 14–15). Both are developed laterally along stratigraphic units and both are well developed maze caves lacking all morphological and sedimentological indications of turbulently flowing water. Other examples of caves formed by convecting water are reported from Frankonia and the Harz Mountains, Germany, (*e.g.*, Kempe, 1996; 1997a; 1997b; 2005) and from Italy (Galdenzi and Maruoka, 2004).

In the case of the Guadalupe caves it is now clear that rising warm and H_2S-rich formation waters were the cause of their genesis (*e.g.*, Hill, 1987; 2000; Palmer and Palmer, 2000; Palmer and Hill, 2005). The H_2S was oxidized in the shallow groundwater zone, a process which leads to the formation of sulphurous and sulphuric acid according to:

$$H_2S + 2O_2 \rightarrow 2H^+ + SO_2^{2-} \leftrightarrow H^+ + HSO_4^{2-} \quad (1)$$

It in turn attacks the limestone and dissolves it. Due to the high sulfate concentration in the waters, gypsum solubility can sometimes be surpassed, resulting in the precipitation of this mineral. In Carlsbad Cavern, Endless Cavern, and others, some of this gypsum still remains as a testament to this process. In Al-Daher Cave no gypsum was observed, but this does not exclude the possibility of a sulfuric acid genesis. First of all, the precipitation of gypsum does not necessarily occur if the water is circulated down fast enough. Secondarily, the cave receives enough drip water that the gypsum could have been removed long ago.

Nevertheless, geochemically a second oxidation mechanism; for example, that of methane (bacterially mediated) (*e.g.,* Valentine, 2002) could theoretically also lead to the in situ formation of protons plus free CO_2, according to:

$$CH_4 + O_2 \rightarrow 4H^+ + CO_2 \quad (2)$$

both of which could be used in attacking the limestone. This reaction could also create a cave with the observed morphological pattern. It would be very difficult to verify either of the reactions in a fossil cave (specifically in the absence of characteristic deposits such as gypsum and/or endellite, a clay mineral forming under very acid conditions). Nevertheless, both processes could be fueled by locally rising anaerobic water plumes (one for each of the large halls) which mix with oxygenated surface waters seeping in along the fractured chert beds.

This interpretation is in accordance with the observation that there is no sign of any turbulent flow during the cave-forming process (*e.g.*, no stream channels, no stream pots, no scallops, and no water-worn pebbles anywhere in the cave). The cave therefore could not have been formed by the sinking of a stream, nor by an underground vadose river, or phreatically by ground water flowing along a marked pressure gradient. It is remarkable that so far no cave with such characteristics is known from Jordan, in spite of its large limestone area and deeply incised river valleys.

Figure 12 shows the Geopit water-filled with presumed inputs of water and chemicals that could have driven the cave formation. Arrows indicate the kind of slow convective turnover driven by dissolution and in accordance with the morphology of the walls of the cave.

Since the cave is situated near the top of a mountain today, it must predate much of the tectonic uplifting and faulting in the area and must also predate the down-cutting of the adjacent valleys. According to Wakshal (2005) the oldest generation of karst in neighboring Israel dates into the Late Miocene. Its paleo-water-level is now at >500 m a.s.l. (*i.e.*, in accordance to the high elevation of Al-Daher Cave).

Speleothems

This speleogenic interpretation (*i.e.,* the relatively old age of the cave) is supported by the state of the speleothems occurring in the cave. The cave has many up to 2 m high stalagmites and some remarkable ceiling flowstone. First inspection shows that they represent many generations; older specimens with a dull and partly corroded surface stand next to still growing ones. Moreover, much of the flowstone is naturally damaged, a sign of age of these formations. The damage (Figs. 13, 14) could be either caused by earthquakes (*e.g.*, Kagan *et al.*, 2005) or by cave ice that might have formed even in Jordan during cold continental glacial climates (for a discussion of natural speleothem breakage including cave ice see Kempe, 2004). The existence of several speleothem generations suggests that the cave is not of recent age, but could have formed several hundred thousand, if not even millions of years before present.

Anthropogenic Impact/Utilization

This outline shows the scientific potential of this geological feature which is unique within Jordan. The stalagmites offer the possibility to study paleoclimatic changes over a long and possibly continuous time span, and the cave structure offers the possibility to study this relatively rare type of convective phreatic cave. The cave also holds biospeleological potential. It is used by bats which have left copious piles of guano, possibly forming the food base for other cave life.

The potential for tourism in this cave is interesting. It could well become the first show cave in Jordan. The halls and some of the passages are large enough to allow a limited number of visitors to the cave. In Figure 3 we suggest a path through the cave which causes the least impact to the cave and features most of the sights and educational highlights of the cave. However, the local government must act quickly because the cave has been heavily vandalized since its discovery and is being deprived of much of its original stalactite splendor. The opening of the entrance will encourage this activity if the cave is not gated immediately. Before proceeding with any plans to open the cave to the public, a thorough survey must be conducted determining the best possible guide path through the cave, causing the least damage as well as offering the best views and the largest educational impact. The cave is, however, not large and spectacular enough (in international comparison) to expect a sizeable income from it for the community.

Acknowledgements

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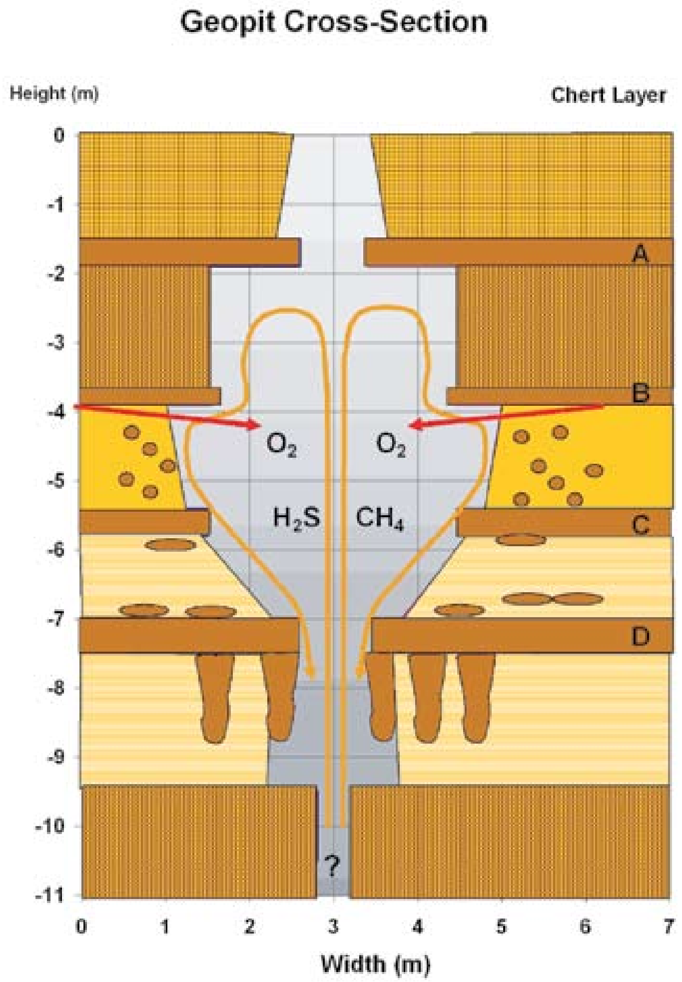

Figure 12. Model of dissolution-driven convection in a stratigraphic cross section of the "Geopit" in the southern part of the cave.

Figure 13. Naturally damaged stalagmite (note new growth across breakage surfaces). This sort of damage could be caused by compression of stalagmitic column between ceiling and floor during an earthquake.

Figure 14. Naturally broken stalagmite, sheared off its base. The nature of such damage is unclear. Earthquakes are suggested as one possible cause, as well as cave ice that could have formed during continental cold climate during glacial maxima.

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