HYPOGENE POINT KARSTIFICATION ALONG WADI SIRHAN GRABEN (JORDAN): A SIGN OF OILFIELD DEGASSING?

ZAKRASEVANJE OB VADIJU SIRHAN GRABEN (JORDANIJA): POSLEDICA RAZPLINJANJA NAFTNIH POLJ?

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Abstract

Ahmad Al-Malabeh & Stephan Kempe: Hypogene Point Karstification along Wadi Sirhan Graben (Jordan): A Sign of Oilfield Degassing?

Jordan is a country with a large area of limestone. Nevertheless, only a few limestone caves are known. Here we report about two caves along Wadi Sirhan Graben of Jordan that appear to have formed by stoping upward of collapsed deep-seated hypogene cavities along breccia pipes. The first one, Uwaiyed Cave, is a small breakdown-dominated chamber in basalt of the Naslet Al-Dhirwa volcano; the second, Beer Al-Malabeh, is a large, bell-shaped sinkhole that has geologically recently opened up to the surface. We discuss the possible processes that led to their formation. The review of the existing stratigraphy as obtained by oil well drilling suggests that no salt layers occur below the caves. Gypsum layers seem to be limited to 4 m in thickness, probably not enough to form the observed features. The remaining process is dissolution caused by ascending gas (H2S or CH4) -rich waters from the underlying oil and oil-shale fields. When such solutions reach the water table, bacteri- rial oxidation may create enough dissolutional power to form localized and large cavities. Their collapse could lead to the observed collapse structures and would explain the paucity of other cave structures throughout southeastern Jordan.

Keywords: Jordan, hypogene caves, sinkholes, oil fields, methane.

Izvleček

Ahmad Al-Malabeh & Stephan Kempe: Zakrasevanje ob vadiju Sirhan Graben (Jordanija): Posledica razplinjanja naftnih polj?


Ključne besede: Jordanija, hipogene jam, udornice, naftna polja, metan.

INTRODUCTION

In Jordan features caused by karstic processes are particularly observed in the north where terra rossa occurs (e.g., Al-Malabeh 2000). These features include several limestone caves and shallow and deeper bowl-shaped depressions particularly in Al-Bwaidha Town south of Irbid. Dissolution holes of 1 m in diameter on average
and depths of 0.2–3 m and subsurface collapse structures occur adjacent to the Yarmouk river canyon. Others are circular to subcircular depressions with diameters ranging from tens of meters up to several kilometres. Some reach depths of 20 m while others are only a few meters deep. The most distinctive karst areas occur near the villages of Samar, Hartha, Hubras, Aqraba and Al-Rafeed in the northern high lands of Jordan. Several large caves are also recorded in Kufranja and Rasoun-Ajloun Districts (Al-Malabeh et al. 2007). The only larger limestone cave yet discovered in Jordan is Al-Daher Cave at Bergish (Kempe et al. 2006a). But even in the limestone deserts of Jordan many depressions are known. The recent decline of the Dead Sea (e.g., Abu-Ghazleh et al. 2009) is diverting fresh groundwater into salt layers that were previously protected from dissolution by salt-saturated groundwater. These salt layers are now dissolving creating a substantial sinkhole hazard along both sides of the Dead Sea (Closson 2005; Arkin & Gilat 2000).

Here we report about two caves, Uwaiyed Cave and Al-Malabeh Sinkhole (Kempe et al. 2009b), the first caves from the Harrat Al-Shaam and Wadi Sirhan Graben (Al-Malabeh 2007) which appear to have been created by hypogene processes and discuss the options for their genesis (see Fig. 1 for locations).

**CAVE DEVELOPMENT**

Karst has recently become a term difficult to define (e.g., Kempe 2008). Classically, “karst” is understood as a landscape type that is drained preferentially underground through secondarily developed caves. In this context we speak of a karstic aquifer that allows short-term passage of large volumes of water. These systems are mostly developed in limestone, dolomite or gypsum, rarely also in salt. The caves thus created are karstic caves *sensu stricto*.

However, not all caves are created by this sort of water passage. First of all the primary caves, like lava-tunnels (e.g., overview see Kempe 2002; in Jordan: Al-Malabeh et al. 2006; Kempe et al. 2006b), do not fit this picture. But even a large number of caves in limestone or gypsum have not been created by the horizontal passage of water from the surface via subterraneous cavities to distant springs (a type of caves called *epigene* Klimchouk 2007, epigene caves) but by waters rising vertically from underlying aquifers either into more soluble rocks (limestone, gypsum, salt) (see for example some of the large anhydrite/gypsum caves discovered by mining in the South Harz/Germany, Kempe 1996a), or by acquiring additional solution power in higher levels (a deep phreatic type of caves called *sensu* Klimchouk 2007, hypogene caves) (see for example development of the famous caves in the Guadalupe Mountains New Mexico, e.g. Palmer 2008, or of Al-Daher Cave in Jordan, Kempe et al. 2006a). Thus hypogene karstic features can sporadically appear outside the area of widespread underground drainage systems. Often the only expression of such cavities are large sinkholes at the surface (such as for example in Saudi Arabia above the Upper Jurassic Heeth Formation, see Kempe & Dirks 2008).

Understanding the hydrological pathways of cave formation is one aspect but the nature of the local undersaturation is another. In case of gypsum, water rising from a limestone aquifer can dissolve additionally gypsum/anhydrite, thus “eating” it away from underneath. In case of limestone (CaCO$_3$) dissolution we need however to understand how locally enough “dissolution capacity” (DC) arises, to create large caves. To estimate this, we need to know (i) local undersaturation ($C_{\text{saturation}}$-$C_{\text{actual}}$) measured in mol CaCO$_3$ kg$^{-1}$) and (ii) the flux (F) of the protons ([H$^+$]) (measured in mol kg$^{-1}$ s$^{-1}$) that produce and keep the local undersaturation of the percolating water:

\[
\text{DC} = F[H^+] \times (C_{\text{saturation}}-C_{\text{actual}})
\]

In nature, many processes can lead to local undersaturation and many different chemical pathways can be followed, generating protons to fuel carbonate dissolution. In most karst areas with longitudinally developed vadose or phreatic karst systems, CO$_2$ (i.e. its pressure) plays the major role in generating dissolution capacity (for extensive reviews on karst genesis see Klimchouk et al. 2000):

\[
\begin{align*}
\text{CO}_2 + \text{H}_2\text{O} \rightarrow & \text{H}^+ + \text{HCO}_3^- \\
\text{H}^+ + \text{HCO}_3^- + \text{CaCO}_3 & \rightarrow \text{Ca}^{2+} + 2\text{HCO}_3^-
\end{align*}
\]

Undersaturation is either primary, i.e. the sinking creek or percolating seepage water is undersaturated with respect to limestone or it is secondary, i.e. it is acquired within the karstifiable rock (Kempe 1996b). Primary undersaturation is probably among the major factors, since the dissolution velocity in natural rocks changes at about 70% of saturation to higher order kinetics, i.e. dissolution rate becomes slower and slower as the thermodynamic saturation is approached. Thus, dissolution capacity can be carried far (i.e. many kilometers) into the rock strata (e.g., Dreybrodt 2008). For a long time it was thought that mixing corrosion was the
major source of dissolution capacity (Bögli 1964). This term refers to the fact that the mixing of two waters in equilibrium with CaCO$_3$ and the PCO$_2$ (partial pressure of CO$_2$) (i.e. at a 100% saturation) generates additional free CO$_2$ that renders the mixture undersaturated again. This is possible because of the non-linearity of the H$_2$O–CO$_2$–CaCO$_3$ system (e.g., Wigley 1973; Wigley & Plummer 1976). Mixing corrosion theoretically occurs in those cases where seepage waters flowing along different tectonic planes (joints, bedding planes, faults) mix at intersections. Possibly both effects play a certain role in karst genesis (Dreybrodt 2008).

However, this is only part of the story. In many areas we find huge cavities that do not connect to lateral karst systems. These caves seem to obtain their dissolution capacity from in situ processes. Several processes have been identified that could do that:

1) cooling of thermal waters (e.g., Dublyanski 2000);
2) rising of gaseous volcanic CO$_2$ (e.g., Gary & Sharp 2006);
3) in situ respiration of organic matter (decaying wood for example) following:
   \[ C_6H_{12}O_6 + 6O_2 + 6H_2O \rightarrow 6CO_2 + 6H_2O; \]
4) oxidation of siderite by oxygen bearing ground-water to goethite following:
   \[ 4FeCO_3 + H_2O + O_2 \rightarrow 4CO_2 + 2Fe_2O_3 \cdot nH_2O; \]
5) oxidation of methane (CH$_4$) by oxygen-bearing groundwater following:
   \[ CH_4 + O_2 \rightarrow 4H^+ + CO_2; \]
6) oxidation of hydrogensulphide (H$_2$S) by oxygen-bearing groundwater following:
   \[ H_2S + 2O_2 \rightarrow 2H^+ + SO_4^{2-} \rightarrow H^+ + HSO_4^{-}; \]

TECTONIC AND STRATIGRAPHIC SETTING

TECTONIC SETTING

The tectonic setting of Jordan is closely related to the regional geology and tectonics of the Eastern Mediterranean area. Several intra-plate deformation phases affected the northern Arabian Plate between the Late Paleozoic and the Cenozoic (McKenzie et al. 1970; Gregory et al. 1982). Major rifting episodes occurred in the Late Carboniferous to Permian, Middle to Late Triassic, and at the end of the Early Cretaceous. Besides the major Dead Sea Transform Fault, the Wadi Sirhan Graben (WSG) is the second main regional structure in Jordan (Fig. 1). This graben belongs to the Erythrean Fault System: A structure that consists of NW–SE and E–W oriented normal and strike-slip faults from the Late Miocene to Early Pliocene (e.g., Barazangi 1983; Kazmin 2002). The WSG consists of fault systems more than 325 km long and extends from northwestern Saudi Arabia through Jordan up to the Antilebanon.

The Azraq Basin, located in the Jordan Plateau, is a tectonic depression associated with the WSG. The basin covers an area of about 12,220 km$^2$ and is underlain by layers of limestone interbedded with marl, sand, chalk, chert, and sandstone that overlie granitic basement rocks. North of Azraq, the graben is covered by the basaltic plateau of Harrat Al-Shaam (e.g., Al-Malabeh 1994).

Bender (1974) concluded that the depression is the result of epigenic subsidence without large scale faulting during the Cenozoic. Seismic investigations and deep drilling, especially those for oil exploration, indicated that the depression is a narrow asymmetric basin located between two fault zones, the WSG to the west and the Al-Fuluq Fault zone to the east. Three major tectonic periods affected the Azraq basin: the initial phase occurred in the Paleozoic, the next followed in the late Cretaceous and the final one in the Eocene. The Late Cretaceous phase occurred between Cenomanian and Early Maastrichtian time and led to the construction of the Hamzeh structure.

Groundwater is recharged by precipitation at an average volume of 24 * 10$^8$ m$^3$/a, and flows generally toward the center of the WSG. Groundwater is the principal source of freshwater in the basin and is supplied to wells and springs by three principal aquifer systems. The upper aquifer consists of basalt and Umm Riham Chert Limestone. The middle aquifer consists of the Amman Upper Kurnub Sandstones. The lower aquifer consists of Lower Cretaceous Kurnub Sandstones. The Basalt–Umm Riham system is the main aquifer of the Azraq Basin (Al-Kharabsheh & Al-Malabeh 2002).

STRATIGRAPHIC SETTING

Field investigations, deep drilling, seismic survey and Google Earth images show that almost a complete stratigraphic column exists in the Wadi Sirhan area from the Precambrian basement up to the Holocene.
The stratigraphy and lithology exposed in the Sirhan area is described following the nomenclature of the Natural Resources Authority (NRA) 1: 50,000 Geological Mapping Project (El-Hiyari 1985; Powell 1989a, b). The formations forming the largest aerial outcrops are from the Tertiary and Quaternary (Tab. 1), namely: The Muwagar Chalk Marl (MCM), Umm Rijam Chert Limestone (URC) and the wadi Shallah Chalk Formation (wSC). The MCM consists of pale yellow and grey chalky marl, marl and marly limestone, about 160 m thick (Powell 1989b). The URC overlaying the MCM consists of the intercalation of thick beds of limestone, chalk and varicolored chert (Powell 1989b). Finally, the WSC is dominated by thick beds of chalk intercalated with bands of chert. In this formation the Al-Malabeh Sinkhole occurs (Fig. 1). Many parts of the Sirhan and Azraq area are covered by Pleistocene or younger superficial deposits. Gypsum layers and lenses are recorded in the sediments by drilling and occur mainly in the Upper Cretaceous.

Gypsum occurs in thinner or thicker beds from the Triassic up to the Quaternary. These beds are mainly concentrated in central and southern Jordan (El-Hiyari & Abed 1985). There are five main localities of gypsum deposits in Jordan (NRA 2012) (Tab. 2). Except for the locally up to 60 m thick deposits in the Zarqa River Basin, gypsum thickness never exceeds 4 m in the other localities. Most of the beds belong to the Cenomanian–Turonian Fuhays, Hummar, Shu‘ayb, and wadi As-Sir Formations. The over 100 m thick Upper Jurassic Heeth Anhydrite Formation (e.g., Kempe et al. 2009a) outcropping in central Saudi Arabia does not reach Jordanian territory.

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Oil and gas fields discovered in Jordan and their productivity and known reserves are hardly worth mentioning at current consumption rates (Abu Jaber et al. 1989; Beydoun et al. 1994; Shinaq 1996). For the pur-
The authors visited this well in March, 2008. Oil currently flows out of the dam-aged well head and is used unprocessed as light oil (Diesel) by the local Bedus.

At present Jordan’s gas reserves are 230 billion cu-bic feet. In NE Jordan, the Risha gas field was discovered in Ordovician clastics close to the Iraq border. It yields 130 million cubic feet gas per day which is supplied to a nearby power station, furnishing merely about 10% of the total power used by Jordan (Al-Saideen 2001).

The 1980 discovery of from 10 billion to 40 billion tons of shale oil deposits in the wadi as Sultani area raised Jordanian hopes of greater self-sufficiency, but there were doubts that large-scale exploitation of the deposits would be commercially viable in the near future.

Since 1985 Jordan has attempted to interest western oil companies in exploring for oil. Amoco, Hunt Petroleum, Petro-Canada, Petrofina of Belgium, and the Japanese National Oil Company were conducting survey work in Jordan in the late 1980s (NRA 2012).

In the Dead Sea asphalt occurs. It floats up from sublacustrine Upper Cretaceous oil seeps and used to be collected and exported since antique times (e.g., Nissenbaum & Goldberg 1980).
UWAIYED CAVE
The first cave discussed here, Uwaiyed, (Fig. 2), is very small. It is a single, almost circular, chamber 11 x 9 m wide and less than 4 m high at its apex (Fig. 3). The entrance is through an artificially enlarged square pit to the NW. The cave has a slightly sloping floor, covered with breakdown blocks and stalagmites from pigeon guano. The roof of the cave is lava that is highly weathered and shows veins of hydrothermally (?) deposited chalcedony. The cave occurs half way up a small, highly eroded lava hill that appears to be a remnant of a former strato-volcano dominated by thick lava strata intercalated by scoria. It is locally known as Naslet Al-Dhirwa (Al-Malabeh 2007; Kempe et al. 2009b). Due to the breakdown character of the cave and its circular shape the only explanation for its existence is, that it formed by upward stoping above a much deeper collapsed cave. This cave would have formed in the underlying limestones and the fact that the cave is now a lava cave is purely due to incident.

THE BEER AL-MALABEH SINKHOLE
The second cave is much larger. It was discovered by the first author in 1999 during his eco- and geo-tourism field trips in the Jordanian Badia (Al-Malabeh 2000, 2006) and explored and surveyed by the second author and Dr. Horst-Volker Henschel on May 11th 2006 (Fig. 4). The area of the sinkhole is only sparsely inhabited seasonally by Bedus. For them the area of the sinkhole is the site of a meteorite impact. Smaller sinkholes are observed throughout the area from Al-Thlaythowat Mountains in the northern parts of the Sirhan area to Beer Al-Malabeh in the south. These holes vary in dimension from one meter up to several meters in diameter. But none opens up into an underlying cavity.

The Al-Malabeh sinkhole (Fig. 5) is entered through a window of about 9 x 5 m in size that leads into a bell-shaped large chamber occupied by a large pile of breakdown at its centre. The main axis of the bell is directed NW–SE and measures 38 m, while the minor axis measures 26 m. The apex of the central pile is at 11.5 m below the entrance and the deepest point reached is the NW corner at 22.4 m below the entrance. Access is by rope or cable ladder by a 16 m long drop (Fig. 6).

The walls of the cavity are composed of thinly bedded Eocene limestone, interbedded with marls. Pigeons use the cave as roosts and have left large deposits of guano. Bedus have discarded over 30 oil barrels in the cave and a broken ladder constructed of water...
pipes and a blue tarp are witnesses to earlier descent attempts.

The cave is clearly a natural collapse feature slowly stoping upward. It is just in the stadium of having opened up to the surface recently. The explanation that this cavity is a Nabtaean cistern (Nabataea.net 2003) is entirely unfounded because (i) there is no waste pile of the rocks removed (amounting to c. 8000 m$^3$ of solid and >10,000 m$^3$ of loose rock), (ii) there is no channel or water course approaching the inward sloping cave entrance, (iii) the opening is not in the deepest part of a valley but rather near to the water divide in between two wadis, (iv) the thinly bedded rock would not hold any water for any time and no artificial lining (such as plaster) is present in the cave and (v) there are no other above ground archaeological remains that should be associated with such an exceptionally large cistern (protective walls, foundations of houses, pens for sheep or camels; remains of stone tools, bones and pottery).
The occurrence of a collapse structure in a limestone area otherwise devoid of known caves suggests the existence of cavities with a very large volume at or below the water table. Such collapses occur for example in Germany over dissolving salt deposits. The “Wolkenbrüche” near Tren-delburg, Hessen, are such structures. Two sinkholes, one 150 m wide and 47 m deep, formed when at a depth of 1,300 m salt caves in Upper Permian deposits collapsed, creating a breccia pipe through the overlying Lower Triassic sandstone (Buntsandstein) and corresponding sinkholes at the surface. Such breccia pipes are sometimes more resistant to erosion than the surrounding rocks. In the Delaware Basin, western Texas/southeastern New Mexico, several such pipes composed of limestone have formed in anhydrite (e.g., Anderson & Kirkland 1980). The anhydrite is more easily removed than the limestone composing the pipes leaving them as hills.

A lava cave similar to Uwaiyed Cave, albeit much larger, was discovered in 1990 by basalt quarrying in Germany: the 52 m long Basalthöhle Ortenberg (Rühl et al. 1991). It consisted of a single large breakdown-shaped hall within the columnar basalt that must have formed but upward stoping of a collapsed cave in the underlying Zechstein evaporites.

Both of the caves discussed here have – geologically speaking – opened up to the surface relatively recently. They will eventually be transformed into vertically walled sinkholes and then into crater-like depressions thus forming “Erdfälle” or “breakdown dolines” (for terms see Kempe & Rosendahl 2000).

Thus, these sinkholes are only the weak surface traces of a cavity-forming process at great depth. Several options exist to explain these apparently existing hypogene cavities. In comparison with the referenced German examples one could first think about salt dissolution. However, the oil wells did not meet any salt deposits. The second possibility is forming a cave due to gypsum dissolution. Examples would be the Saudi Arabian Layla Lakes sinkholes and the Ain Heeth Cave (Kempe & Dirks 2008; Kempe et al. 2009a). Tab. 2, however, shows that only marginally thick gypsum layers occur within the stratigraphic column underlying the two cave sites. With layers at most 4 m thick is does not seem likely that a cavity large enough to progress upward to the surface

CONCLUSIONS

The occurrence of a collapse structure in a limestone area otherwise devoid of known caves suggests the existence of cavities with a very large volume at or below the water table. Such collapses occur for example in Germany over dissolving salt deposits. The “Wolkenbrüche” near Tren-delburg, Hessen, are such structures. Two sinkholes, one 150 m wide and 47 m deep, formed when at a depth of 1,300 m salt caves in Upper Permian deposits collapsed, creating a breccia pipe through the overlying Lower Triassic sandstone (Buntsandstein) and corresponding sinkholes at the surface. Such breccia pipes are sometimes more resistant to erosion than the surrounding rocks. In the Delaware Basin, western Texas/southeastern New Mexico, several such pipes composed of limestone have formed in anhydrite (e.g., Anderson & Kirkland 1980). The anhydrite is more easily removed than the limestone composing the pipes leaving them as hills.

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could be formed. Nevertheless, this possibility cannot be excluded entirely. Thus, we must look at processes that allow limestone dissolution away from general epigenetic karst aquifers. Plumes of rising gases could play such a role. Two possibilities exist: The cavity formed either by CO\(_2\) rising from below the limestone formations, or it formed by the oxidation of rising CH\(_4\) or H\(_2\)S. In the first case, a cavity would form at the base of the limestone stratigraphic column, possibly at the top of the Lower Cretaceous Sandstone. The source of such CO\(_2\) could be volcanic. However, in the area of the Al-Malabeh Sinkhole, no volcanic activity ever existed. Thus, rising CH\(_4\) and H\(_2\)S seem to be the most promising gases to cause speleogenesis in this case. There are plenty of candidate strata to generate these gases: the site is underlain by several oilshale formations and possibly small oil fields in the Ordovician (Hamza Field). CH\(_4\) or H\(_2\)S generated there could have risen along faults, such as the small fault running across the Al-Malabeh Sinkhole. Once the gases arrive at the local water table, which is within the limestone strata in that area at about a depth of 70 m, they can be oxidized bacterially by oxygen carried down by percolating water. The oxidation process (see Equations 5 and 6) produces the acids that allow a localized cavity to form. Thus the sinkholes and their hypogene cavities could be taken as possible signs of oil field degassing.

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