DOI: https://doi.org/10.3986/ac.v55i1.14814

CAVE DEVELOPMENT IN THE QATAR PENINSULA: INSIGHTS ON THEIR ORIGIN AND ASSOCIATED GEOHAZARDS

RAZVOJ JAM NA KATARSKEM POLOTOKU: VPOGLED V NJIHOV NASTANEK IN POVEZANE GEOLOŠKE NEVARNOSTI

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Abstract

J. Perrin, G. Noury, S. Yart, C. Allanic, A. Ortiz, R. Couëffé, F. Masson, M. Métais Bossard, B. Lemaire, O. Higgins, B. Matti, C. Lerevenu, R. Pillai, E. Vartanian, S.A. Al-Yafei, E.A. Ahmed, U.S. Samad & S.J. Bukhari: Cave development in the Qatar peninsula: insights on their origin and associated geohazards

The geology of the State of Qatar comprises large spans of carbonate rocks at the surface and evaporitic rocks at shallow depth, and a number karst features (depressions, caves) spread across the country that may cause challenges during land development or infrastructure construction. The government of Qatar has identified that existing geodatabases and geological and hydrogeological maps require improvement to mitigate this risk. In this framework, a thorough assessment of the karst geohazard has been performed including a karst features survey, geologic study of karstification, and an assessment of associated ground subsidence related to karst. The main findings indicate the existence of two types of caves: one corresponding to shallow subsurface dissolution caves developed under phreatic conditions in the past and truncated by erosion at a later stage, the other corresponding to large roof collapse caves originating at depth (intrastratal karst). These latter caves are systematically located on the edge of large depressions. In agreement with the existing literature, it is proposed that the depressions and collapse caves are part of a same collapse/sagging process caused by loss of material at depth (e.g., dissolution of evaporites, compaction of weathered dolostone, or incremental collapse of coalesced

Izvleček

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Geologija države Katar je zaznamovana z obsežnimi območji karbonatnih kamnin na površini in evaporitnih kamnin v plitvi globini ter številnimi kraškimi pojavi (globeli, jame), razpršenimi po vsej državi, ki lahko ustvarjajo izzive pri urejanju zemljišč ali gradnji infrastrukture. Katarska vlada je ugotovila, da je treba za zmanjšanje tega tveganja izboljšati zdajšnje geografske podatkovne zbirke ter geološke in hidrogeološke karte. V tem okviru je bila izvedena temeljita ocena kraških geoloških nevarnosti, vključno z raziskavo kraških značilnosti, geološko študijo zakrasevanja in oceno s krasom povezanega pogrezanja tal. Iz glavnih ugotovitev sta razvidni dve vrsti jam: ene ustrezajo plitvim podzemnim jamam, ki so nastale z raztapljanjem in so se v preteklosti razvile v freatičnih razmerah, pozneje pa so bile okrnjene zaradi erozije, druge pa ustrezajo velikim jamam, katerih strop se je udrl in ki izvirajo iz globine (intrastratalni kras). Drugonavedene jame so sistematično na robu velikih globeli. V skladu z ugotovitvami proučene strokovne literature se predlaga, da so globeli in jame, nastale zaradi udrtja, del istega procesa udrtja/ugrezanja, ki ga povzroča izguba materiala v globini (npr. raztapljanje evaporitnih kamnin, zbitost razpadlega dolomita zaradi vremenskih vplivov ali postopno sesedanje združenih reliktnih jam). Da bi

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Received/Prejeto: 1. 10. 2025

relict caves). To extract the karst collapse depressions among the large number of depressions mapped using a recent (2017) LiDAR DTM dataset, it is hypothesized that the karst depressions shall have the same geometrical characteristics (width, length, area, depth) than the few ones containing a roof collapse cave. This results in the identification and mapping of 3537 karst depressions spread across the entire Qatar peninsula. Presently, these karst features seem mostly inactive and thus inherited from a geoclimatic context, which was more favorable to karstification. Under the present geoclimatic conditions, the karst subsidence geohazard appears to be generally low, as caves are inherited, and ongoing karstification processes are limited. However, this geohazard is present across large spans of the territory and any future land development shall include plans and strategies to consider the presence of karstified rocks in the subsurface and ensure that karst is not reactivated by human activity.
Keywords: karstification, arid karst, depression, collapse, caves, geohazard, Qatar.

med velikim številom globeli, kartiranih z uporabo najnovejšega (2017) podatkovnega niza LiDAR DTM, izločili kraške globeli, nastale zaradi udrtja, se postavlja hipoteza, da imajo te kraške globeli enake geometrijske značilnosti (širino, dolžino, površino, globino) kot tiste redke, v katerih je jama, katere strop se je udrl. Na podlagi tega je bilo opredeljenih in kartiranih 3.537 kraških globeli, razpršenih po celotnem Katarskem polotoku. Trenutno se zdi, da so ti kraški pojavi večinoma neaktivni in so torej posledica geoklimatskih razmer, ki so bile ugodnejše za zakrasevanje. V zdajšnjih geoklimatskih razmerah se zdi, da je geološka nevarnost zaradi kraškega pogrezanja na splošno majhna, saj so jame posledica preteklega dogajanja, potekajoči procesi zakrasevanja pa so majhni. Vendar je ta geološka nevarnost na prostranem ozemlju, zato morajo vsi prihodnji projekti prostorskega razvoja vključevati načrte in strategije, ki upoštevajo zakrasele kamnine v podzemlju in zagotavljajo, da se kraški pojavi ne bodo zaradi človeških aktivnosti znova aktivirali.
Ključne besede: zakrasevanje, suhi kras, globel, udrtje, jame, geološka nevarnost, Katar.

1. INTRODUCTION

The State of Qatar, one of the countries of the Gulf Cooperation Council (GCC), is situated on a peninsula surrounded on three sides by the Arabo-Persian Gulf. Its surface area is largely covered by dolostone and limestone rocks of Tertiary age. Karstic features such as depressions and caves have been described by a few authors (Embabi & Ali, 1990; Sadiq & Nasir, 2002; Duggan, 2014), however these descriptions remain fragmentary: caves were only partly visited, and no proper map and geological/karstological descriptions were provided, whereas some caves remained unexplored. Thus, the karst of Qatar remained poorly documented so far.

A project initiated by the Ministry of Municipality (MM) with a focus on karst geohazards made possible to carry out a complete survey of the caves of Qatar, which represents a unique opportunity to document the caves of an entire country within a single project.

This paper summarizes the main findings on the surficial karst features and caves of Qatar encompassing their morphology, a description of their main endokarstic features, and proposing a cave typology related to hypotheses on their origin. The results of cave sediments dating using OSL method are also presented. Outcomes of this work are important for the assessment of potential associated karst geohazards.

This work is a contribution to the karst and endokarstic features in a hot and arid desertic climatic context, following the pioneering work of Jennings (1983). Karst in such geoclimatic context remains still poorly documented as stated by Ford & Williams (2007). In the low-deformation platform part of the Arabic Peninsula, karst features were mostly described in the eastern region of the Kingdom of Saudi Arabia (KSA): Edgell (1993) observed surficial karst morphologies that he attributed to Pleistocene pluvial periods. A presentation of the twelve limestone caves (located in the Umm er Radhuma or Aruma formations) surveyed in this area is provided in a report by the Saudi Geological Survey (SGS) cave unit (2007). Accounts of karstification of evaporites in central KSA (south of Riyadh) are provided by Kempe et al. (2009) with occurrence of sinkholes in the upper Jurassic Hith evaporitic formation.

In Qatar, Embabi & Ali (1990) and Sadiq & Nasir (2002) have also proposed that karstification developed during humid periods of the Pleistocene. They propose an explanation of the depressions/sinkholes development, which, however, remains highly hypothetical: in northern Qatar, depressions would be the result of the coalescence of vertical pits enlarged by drainage focused dissolution; in central Qatar, sinkholes would have been formed due to subsurface dissolution of gypsum.

In the literature, authors (e.g., Sadiq & Nasir, 2002; Duggan, 2014) have generally used the word “sinkhole” to describe caves in Qatar. In this study, we chose not to use this wording as it can be misleading in terms of underlying process. It has therefore been systematically replaced by “cave”, corresponding to the Arabic word “Dahl”, which is the commonly used word by Qataris.

2. OVERVIEW OF THE STUDY AREA

The State of Qatar is located on the eastern part of the Arabic Peninsula and is represented by a north-south elongated peninsula surrounded by the Arabo-Persian Gulf with a total land surface of 11,521 km². The maximum length of the country's territory is 180 km and a maximum width is 85 km (Baalousha, 2024) (Figure 1).

It experienced a fast-growing economy over the recent years and its total population increased dramatically from less than 100,000 inhabitants in the 1950s to almost 3 million currently (Baalousha, 2024). As such, the country underwent large land cover transformation, with nearly half of the land surface being anthropized

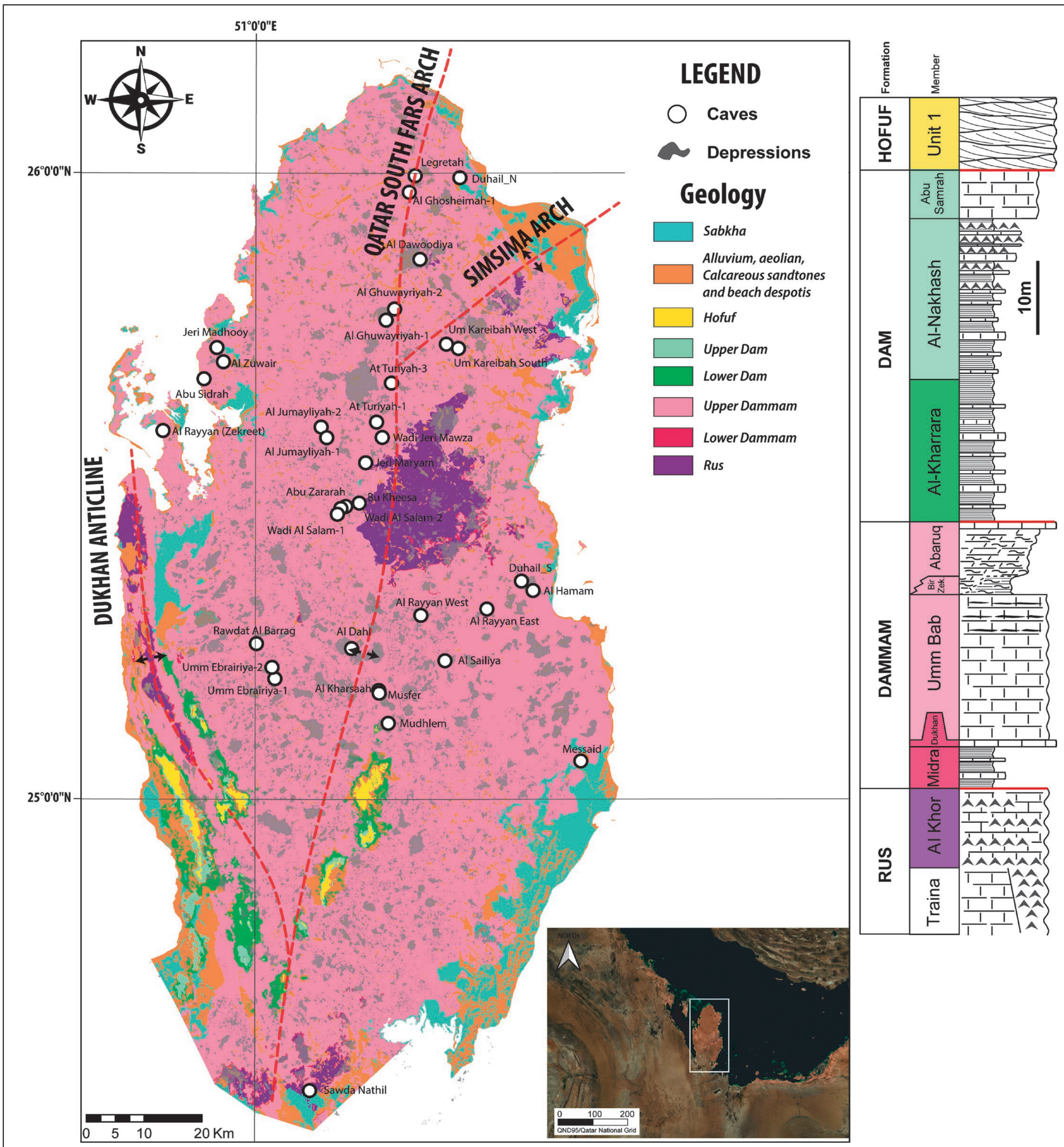


Figure 1: Map of the Qatar peninsula with surface geology, natural depressions and cave locations (left); stratigraphic column of the shallow subsurface (right).

Figure 2: Picture of the land surface showing the entrances (two small black spots, the left one just to the right of a bush) of Al Jumayliyah-1 cave surrounded by a fence opening within a flat topography (left) and the entrance of a small cave (Wadi Al Salam-1) in the middle of a flat rocky desertic area (right).

(urbanization, roads, quarries, etc.). Qatar is characterized by a hot and arid climate (i.e., desertic): the average maximum temperature is 41.9°C in July, and the average minimum is 13.5°C in January (Baalousha, 2024). Rainfall occurs in winter and is erratic, as it may vary between 10 mm to 200 mm in any given year. Rainfall long-term average varies between 55 mm in the south and 109 mm in the north, with a country average of around 80 mm per year (Alsharhan et al., 2001).

The low relief of the Qatar peninsula (Figure 2) is coincident with a broad, north-trending fold called the Qatar- South Fars arch, its axis being nearly equidistant from eastern and western coastlines. The surface and near subsurface stratigraphy include Tertiary carbonate and evaporite rocks with some interbedded clastic units (Figure 1): the dominant formation at outcrop is the Dammam carbonate, and more specifically the Umm Bab member, which is silicified in places, and weathered at the surface with a brecciated aspect. It is separated from the underlying Rus formation by the Midra shale that is not present everywhere. The underlying Eocene Rus formation also demonstrates lithologic changes between the northern and southern parts of the country. Thick sequences of gypsum in the lower part of the Rus formation (Traina member) are present in the south, but not in the north where both depositional conditions and secondary dissolution may explain its absence (Eccleston et al., 1981). The underlying Paleocene and lower Eocene Umm er Radhuma formation is a dolomitic limestone in its upper part and harder vesicular dolomite in the lower part, with minor gypsum and anhydrite (Rivers et al., 2019). Both the Rus Traina member and Umm er Radhuma are present only in the subsurface at depth ranging from about 10 to 70 m below ground surface for the former, and 50 to >100 m for the latter.

The peninsula of Qatar is characterized by low relief, muted topographic features and bedrock at the surface, with predominance of the Umm Bab member of the Dammam formation, which constitutes over 70 % of the land surface. Neither drainages nor drainage divides have much topographic expression (Duggan, 2014). The Qatar arch forms the backbone of the mainland with higher elevation in the south-central area and lower elevations northwards and southwards. The highest reliefs are located in the southwestern part of the peninsula. They are constituted by the Dukhan anticline, which is an elongated south-north topographic ridge, culminating 90m above sea level and klippes of Miocene rocks, one of them forming the highest point of Qatar (Qurain Abu al-Bawl, 90 m). Some sabkhas (salt flats), like Dukhan Sabkha just to the north of the anticline, are up to 6 m below sea level (Al Yousef, 2003).

Hydrogeological conditions in Qatar are dominated by fracture flow and permeability enhancement by dissolution of carbonate host rock. In the context of present-day groundwater resources, only two geological units can be designated as aquifers throughout most of the peninsula, and even these have very variable characteristics: the upper part of the Umm er Radhuma Formation and the Rus Formation (Lloyd et al., 1987).

3. METHODOLOGY

The first step of the caves investigation consisted in the compilation of existing information from two different sources: (i) existing publications (Embabi & Ali, 1990; Sadiq & Nasir, 2002; Duggan, 2014; Ellis, 2018; Abdulrahman et al., 2021), and (ii) a "sinkholes" database by MM with related field reports. On the basis of this preliminary caves database, the project local team carried out a caves census via field investigations to verify the accuracy of the cave entrances coordinates, their accessibility, and whether they were not backfilled.

The caves surveying was performed during two field campaigns in November 2024 and March 2025. It included the use of a DistoX mapping digital device, which was used to measure the length, orientation, dimension and geometry of cave passages (e.g., Trimmis, 2018) and had to be properly calibrated before the survey. In addition to these measurements, the cave passages were drawn onsite, and geologic observations and rock sampling were also carried out. Photographs and short movies were also shot for complete documentation. In March 2025, surveying (mapping using a MNEMO© and filming with a waterproof camera) of water-filled cave passages was carried out by an experienced cave diver. The MNEMO (Ariane's Line 2025) is digital device that is used by the diver to record the water-filled cave passage lengths, azimuth and depths along the safety line (i.e., the line is setup along the gallery by the diver before MNEMO measurements are taken). During the same mission, three caves were mapped in 3D using a GeoSLAM ZEB-REVO mobile laser scanner (Faro 2025). The head of the device consists of a 2D "time of flight" Lidar sensor coupled to a three-axis accelerometer. The assembly is rotated by a motor to ensure scanning of all directions of space by the laser beams emitted by the Lidar. Maximum reachable distance of the scanner is 30 m and the typical accuracy of measurement is 1-3 cm. The acquisition is carried out as the operator moves along, holding the scanner head in his hand and describing a path in the form of loops (the acquisition must start and end at the same point) for a duration of approximately 15 to 30 minutes. After acquisition, the data is processed by a SLAM (Simultaneous Localization And Mapping) algorithm, which reconstructs the environment in the form of 3D point clouds based on (i) the recognition of singular objects scanned from different viewpoints and (ii) the data recorded by the accelerometer. At the end of this post-processing, a 3D point cloud is generated.

The depression mapping was performed from a High-resolution LiDAR DTM dataset (0.5 m spatial resolution, centimetric elevation accuracy) acquired in 2017 by MM following several steps in a GIS environment (QGIS): 1) application of the fill sink tool (Wang & Liu, 2006) followed by subtraction between the filled DTM and the DTM to extract the depressions, 2) execution of a Python code developed by the project team to obtain the geometrical characteristics (length, width, area, perimeter, circularity index, elongation, depth, volume) of each depression, 3) removal of depressions that are considered of human origin. For this operation, the geometrical characteristics of the depressions located in anthropized areas were compared with the ones located in natural areas. This highlighted significant differences in their elongation, surface area, and depth. These three criteria were then used to automatically filter the natural depressions (elongation <3, surface area >2000 m^2, depth >0.3 m) from other depressions.

In addition, two samples of sand were collected into one cave for dating using the optically stimulated luminescence (OSL) method. Before analysis, the sediments were sieved to select a grain size between 100 and 150 µm. The powders obtained for each sample were then chemically treated: 8 % HCl to remove carbonates, 30 % H_2O_2 to remove organic material, and then 40 % HF to remove feldspars and thus allow the exclusive selection of quartz. In parallel, radioactivity measurements were performed on the raw, dried sediments (105 °C for 24 hours), which were then placed in airtight plastic containers to allow for low-background gamma spectrometry measurements after a one-month waiting period to ensure radon equilibrium.

Luminescence signals were then measured using the SAR protocol on multi-grain aliquots (Murray & Wintle, 2000; Banerjee et al. 2001; Wintle & Murray, 2006; Wang & Wintle, 2012) with a Risø TL/OSL DA-15 reader with blue optical stimulation (470 +/- 40 nm), and infrared lighting (870 +/- 40 nm) performed to test the effect of potential remaining feldspars. These measures under IR stimulation confirmed the absence of feldspar contamination. The aliquots were exposed to a sequence of regenerative doses interspersed with test doses, systematically applied to normalize the signal. Eighteen discs were analyzed, and the natural-to-test dose luminescence ratio (Ln/Tn) was interpolated from growth curves obtained by controlled irradiation. The Ln/Tn values were subsequently incorporated into the age calculation using the central age model (CAM). It should be noted that in the case of fluvial or fluvioglacial sediments, the risk of insufficient exposure to sunlight, leading to an overestimation of ages, cannot be ruled out (Rhodes & Pownall, 1994; Singarayer et al., 2005). For both samples, the recycling rate was found to be well below 10%, and the recovery (signal obtained without additional irradiation, relative to the natural background dose) was also less than 10 %. The dose-recovery ratio (dose estimated from a new dose-response curve at a given known dose, approximately 15 Gy) is also less than 10 %. All these values guarantee the reliability of the equivalent doses measured for both samples.

4. GEOMORPHOLOGICAL FEATURES AND CLOSED DEPRESSIONS

Along the Qatar arch, the Dammam carbonate outcropping bedrock is marked by irregular drainages that originate along the crest and drain east and westward towards the coast. Superimposed on the fluvial drainage pattern are closed basins (i.e., depressions), some of them having radial internal drainage patterns. As a result, only some surface catchments have an outlet connected to the sea, the others are internal drainage basins (i.e., endorheic basins) (Baalousha, 2024).

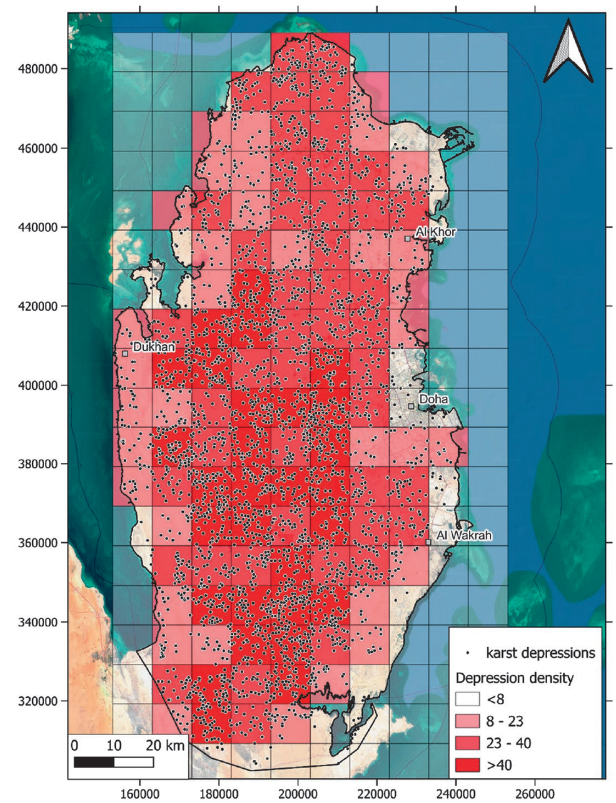
These surface depressions are characteristics of Qatar's topography, and they are locally known as Rowda (or Rodha). During heavy rainfall events, rainwater would runoff and accumulate in these land depressions, bringing soil in, and making the depression suitable for agriculture (Baalousha et al., 2023). At least part of these depressions is of karstic origin (Eccleston et al., 1981; Embabi & Ali, 1990; Duggan, 2014) and constitutes the main karstic surficial features across the peninsula. Sadiq & Nasir (2002) indicate the presence of more than 9,700 large and small depressions. Duggan (2014) carried out an inventory of these depressions using a DEM dataset (10m cell size) and mapped about 10,616 karst depressions across Qatar territory: the northern depressions tend to be hierarchically integrated low-lying depressions with gentle slopes, while depressions in the south are larger, more isolated, with well-defined ridges and terraces.

In the present study, the processing of the LiDAR DTM data acquired in 2017 made possible to map a total of 23,218 depressions spread across the entire peninsula (Figure 1). The larger number of mapped depressions as compared to estimates in the literature (Sadiq & Nasir, 2002; Duggan, 2014) illustrates the capacity of the LiDAR high spatial resolution dataset processing in detecting additional depressions, mostly of smaller areal extent (refer to histogram, Figure 2). Only some of these depressions are of karstic origin. In his review paper, Jennings (1983) emphasized the difficulty to distinguish between karst and desert factors in making arid landscapes. For instance, Brundsen (1979) discussed all the depressions observed in Bahrain as being caused by deflation (i.e., an aeolian erosion process). To sort the depressions that are most likely of karstic origin, the geometric characteristics of depressions containing a cave surveyed in the present study via field investigations (refer to the "cave distribution and characteristics" section) were used as a filter based on the assumption that other karstic depressions (without caves) shall have similar characteristics. In the end, 3,537 depressions are considered of karstic origin and correspond the ones having the largest areas (>35,000m^2) and being deeper than 0.45 m. This sorting approach shall identify depressions that are potentially linked to (paleo)collapse, which is significant regarding the geohazard assessment. It is possible that some of the smaller depressions may have also a karstic origin via surficial dissolution, however they do not represent a significant hazard, considering the low dissolution rates. For instance, Goodie (2010) describes solutional depressions called "dayas" in a range of arid to semi-arid regions including southern Qatar hypothesizing a formation mechanism by surficial dissolution of carbonate rock.

The karstic depressions distribution map shows their presence across the entire territory (Figure 3), with a density ranging from less than 8 to 70 depressions per 100 km^2. The lowest depression density along the eastern coast is likely partly due to the high urbanization of this area that conceals at least the smaller depressions. In addition, the south-eastern part of the country is an area of sand dunes, which also strongly contribute to covering and hiding any existing landform on the rocky ground below. The western part of the country also exhibits a lower density and this may be explained by the presence of younger rock formations (Dam and Hofuf, Figure 1) that are not karstified (even if they can be affected by collapse from deeper origin), and a different geomorphological context along the Dukhan anticline with more pronounced reliefs made of elongated ridges.

A number of these depressions constitute internal drainage basins. However, they do not seem to act as naturally active infiltration points (like dissolution dolines do) as they accumulate water after heavy rainfall and their bottom part may be flooded. To overcome this flooding hazard, and as these depressions are often used for agriculture because of the presence of soils, recharge wells were dug since historical times. These wells are also beneficial for the groundwater balance as they contribute to augment the recharge. According to Al-Muraikhi & Shamrukh (2016) there are 166 recharge wells existing in depressions across Qatar.

Unconsolidated sediments fillings within depressions were also studied by several authors (Vita-Finzi, 1978; Smith, 1978; Babikir, 1986; Engel et al., 2020). Unconsolidated material (sand, silt and clay, gravel locally) accumulates in the depressions after being transported by wind and local runoff. These deposits can reach up to several meters thickness (Smith, 1978); according to Babikir (1986), northern and central depressions contain a higher percentage of clay compared to the ones in the south. Such accumulation of surface transported deposits inside depressions makes their bottoms have a low permeability resulting in the ponding of runoff water after rare storm events (Eccleston et al., 1981). This tends to corroborate the absence of recent karstic activity with-



	Length (m)	Width (m)	Area (m^2)	Elongation	Depth (m)
Min	53	18	2001	1.00	0.31
First quartile	105	65	3422	1.27	0.33
Median	151	94	6913	1.58	0.47
Third quartile	256	160	19638	1.97	0.76
Max	8955	7183	31678790	16.7	16.4
Abu Sidrah	383	192	37286	1.99	0.50

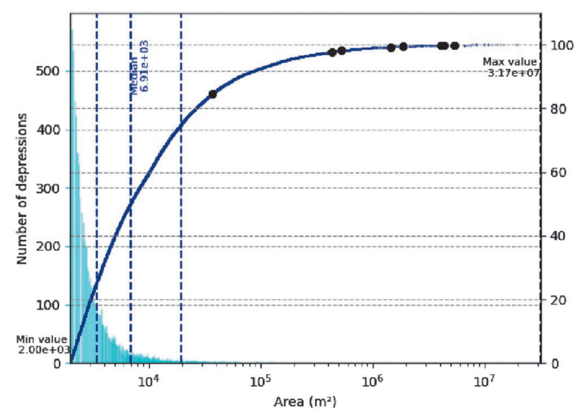


Figure 3: *Map of the karst depression locations and their density (calculated for 10 x 10 km cells) (left); statistics on the 23,218 depressions with their geometrical characteristics compared to the smallest depression containing a collapse cave (Abu Sidrah) – elongation is the ratio between the longest and the shortest axis (top right); histogram of depression surface areas with black dots indicating the depressions containing a collapse cave (bottom right). The histogram represents the number of depressions per class intervals (computed on 1000 m^2 interval size).*

in the depressions (i.e., absence of significant dissolution, absence of open conduits favoring infiltration).

In summary, these depressions constitute the only evidence of karst morphology at the surface, even if large spans of the land surface are constituted by the Umm Bab dolostone (over 70 % of the land surface) with no or very thin soil cover. It means that no small-scale dissolution features such as karren or epikarstic forms could be observed (Figure 2).

However, these karstic depressions presently do not play any hydrogeological role as it is known from classical karst settings where dolines favor infiltration. On the contrary, depressions constitute passive internal drainage basins, where surficial flow accumulates, and as such seem to correspond to features inherited from paleoclimatic settings (relict karst). Also, in none of these karstic depressions, a collapse cave is present at the lowest point; only in a few of them collapse caves exist but they are systematically located on the edge or slope of the depression. Their origin is likely related to paleocollapse (described as collapse structures by Cavelier et al., 1970) and/or paleo-sagging.

5. CAVES DISTRIBUTION AND CHARACTERISTICS

The field surveys led to the documentation of 23 caves with total lengths ranging from 3m to 134 m (and total depths ranging from 1 m to 36 m). This represents in total 654 m of surveyed cave passages (Table 1). In addition, 8 caves were backfilled between the time of their inventory by MM and the field reconnaissance visit, and 5 caves were not found, possibly because of inaccurate coordinates in the preexisting database. In addition, five small subcircular collapse structures (max. 1-2 m deep) were observed in a Sabkha environment in the south of Qatar (Sawda Nathil) and are not presented here.

All the surveyed caves (23) develop in the Umm Bab member of the Dammam formation. The only exception is the bottom part of the deepest encountered caves (Misfir and Al Hamam), which penetrate through the upper member of the Rus formation (Khor carbonate) and Sawda Nathil collapses. The caves are mostly located in central and northern Qatar, and on the central and eastern sides of the peninsula (Figure 1).

Two distinct cave typologies were encountered (Figure 4, Figure 5):

Type-1 caves with a significant vertical dimension (up to 36 m deep for Misfir cave) characterized by a floor made of fallen rocks from the ceiling and rather large dimensions entrances, plurimetric and up to 14 m x 8 m for Al Hamam cave entrance size (8 caves classified as a type-1); they are usually located on the edge of large depressions. These caves also have generally larger entrance diameter as compared to the other cave type.

Type-2 caves dominated by sub-horizontal passages accessible via narrow and vertical (2-4 m high) entrances (12 caves classified as a type-2). Another characteristic of the type-2 caves is the presence of two or more entrances next to each other (7 caves); their entrances are not linked to any surficial feature: they are just narrow open holes in flat or gently sloping desertic environment. Most of the explored caves develop along subhorizontal bedding planes, corresponding to the inception horizon; one exception is the cave Um Kareibah West, which exhibits a development along a subvertical fracture (Figure 6).

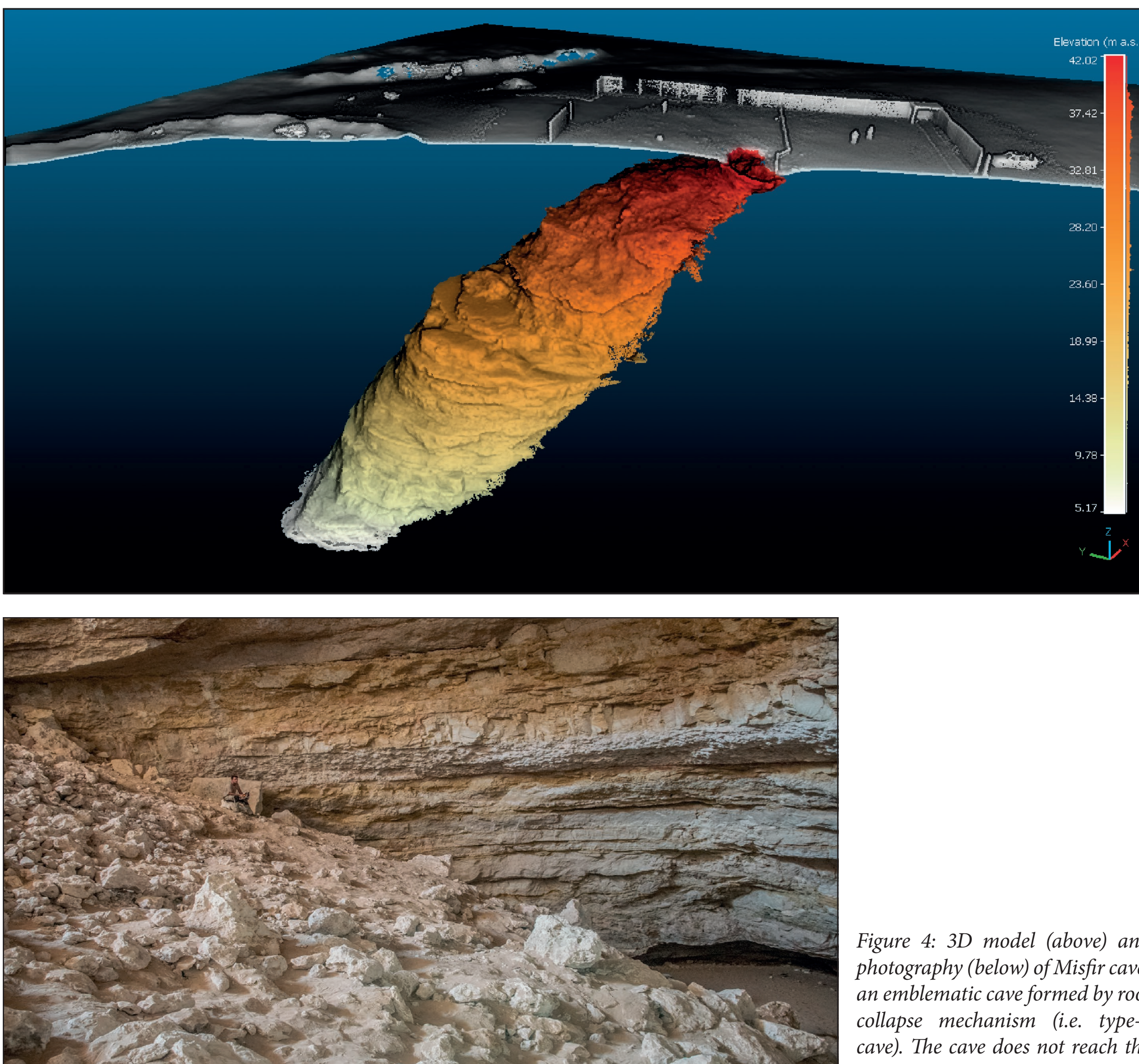


Figure 4: 3D model (above) and photography (below) of Misfir cave, an emblematic cave formed by roof collapse mechanism (i.e. type-1 cave). The cave does not reach the groundwater table.

The cave patterns are very different with type-1 caves presenting large volumes corresponding to inclined rooms and type-2 caves having much smaller volumes but with significant horizontal extensions close to the topographic surface (Figure 6).

Among the 23 visited caves, three were not classified as type-1 or type-2. Two of them (Messaid and Sawda Nathil) correspond to large depressions occupied by the groundwater table and are described by Jameson (oral com.) as flow-through ponds as they contain groundwater that seems less saline than in the shallow aquifer surrounding the depressions. These depressions with their evaporitic deposits and shallow groundwater may have similar hydrogeological characteristics to the Sabkha Matti, at the UAE-Saudi border, which was recently studied in detail, indicating it corresponds to a main discharge flow area of the underlying aquifer system (Saeed et al. 2020, 2021). The last cave cannot be classified due to its very short length (4 m long).

Four of studied caves reach the groundwater table: Messaid, Sawda Nathil, Al Hamam, Al Dawoodiya. However, in most caves, there is evidence of flow that shall occur during rare heavy rainfall events. The inflowing water draining the ground surface in the vicinity of the cave entrances may pond temporarily inside the caves before infiltrating completely. This remains hypothetical as no direct observation or measurements could be carried out. In any case, the catchment areas of water drained by

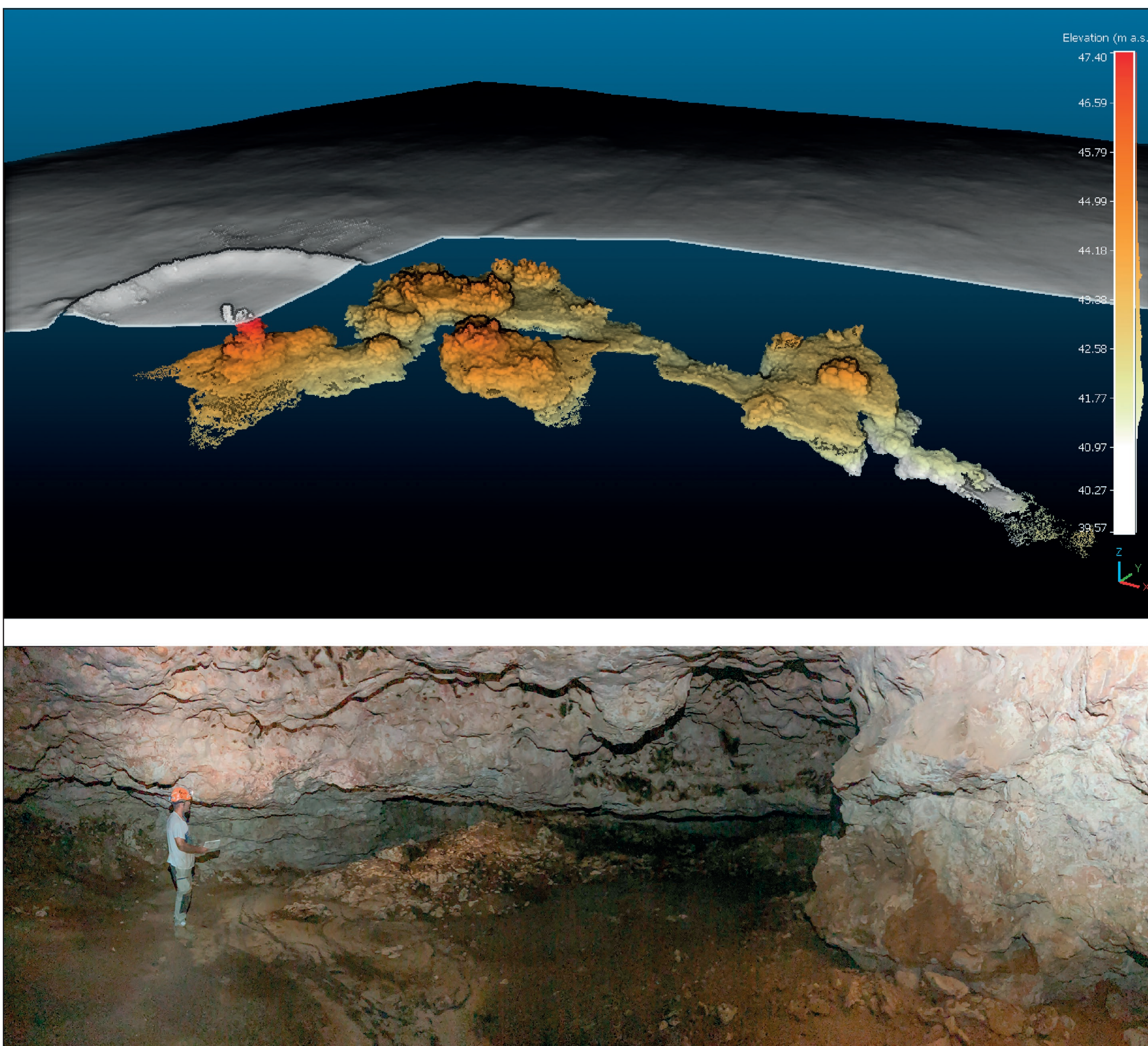


Figure 5: 3D model (above) and photography (below) of Al Jumayliyah-2 cave, an emblematic cave formed by dissolution mechanism (i.e. type-2 cave). The two samples of sand for OSL dating were collected at the location indicated by the white star on the 3D map.

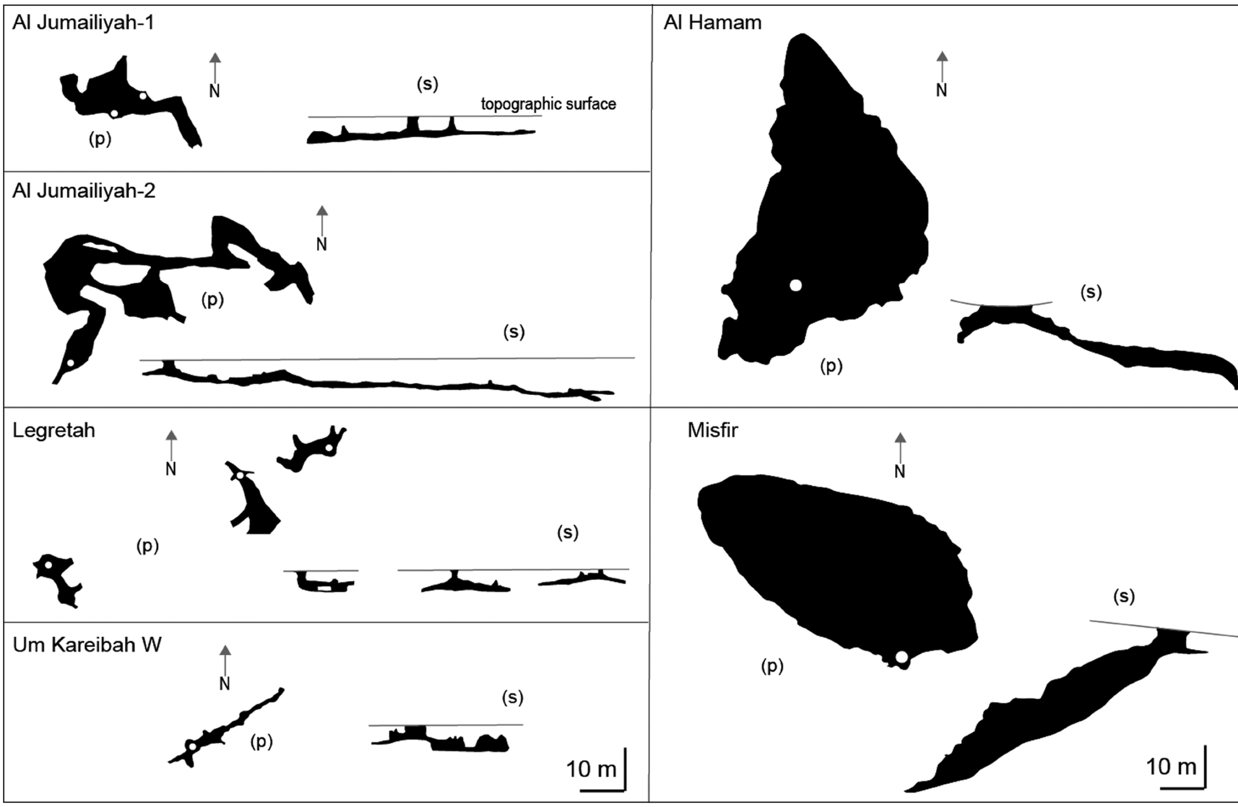


Figure 6: Comparison of the cave patterns (plan and cross-sectional views) with the most extensive type-2 (dissolution) caves on the left and the two main type-1 (roof collapse) caves on the right. All caves are drawn at the same horizontal and vertical scales and with the same orientation: (p) corresponds to plan views with small white circles indicating the cave entrances, (s) to section views.

the caves are limited because none of the cave entrances are located at the bottom of the internal drainage basins (i.e., depressions) described above.

Of note, the caves temperatures may reach up to 29 °C, similar to the groundwater temperature, when reaching passages away from the entrances. The entrance areas were cooler at the time of the surveys (November and March), on the order of 25 °C.

6. ENDOKARSTIC FEATURES

The surveyed caves have a limited lateral extent; this constrains the possibilities of endokarstic observations. However, specific endokarstic features were observed in both type-1 and type-2 caves. Table 1 summarizes the caves main features, in particular the speleometry, the cave entrance size, the number of entrances, the inception horizon if observed, the main endokarstic features, and the cave deposits.

Type-1 caves are characterized by a bell-shaped roof, along which the bedding planes are clearly visible, some of them being enlarged by decompression of the rock massif due to the underlying void (Figure 4). Cave walls do not show significant dissolution features and mostly correspond to fracturing plane surfaces. The cave sediments are mostly constituted by collapsed blocks of varying sizes, so me of them may have fallen from the ceiling recently (fresh broken surfaces).

Type-2 caves exhibit dissolution features on their walls (Figure 7a) including numerous ceiling cupolas. These features are clearly indicative of a development under phreatic conditions with slow groundwater movement. Cave entrances are usually narrow vertical pits. Seven of these caves (out of a total of 12) are accessible through more than one entrance and these entrances have no morphological links with surface topography. Therefore, it strongly suggests that these entrances correspond to the truncation of ceiling cupolas by surficial erosion (Figure 7c). The longest caves are a

Table 1: Cave inventory with main characteristics (dimensions, morphology, deposits). The entrance size corresponds to the largest entrance in the cases where a cave has more than one entrance. The total gallery length of Legretah corresponds to the total of the 5 caves located next to each other but not physically connected (no human-size passages between the caves). Inception horizons do not apply to collapse caves (intrastratal karst), therefore not applicable (N/A) is indicated

Cave Name	Typology	Entrance size (m)	Length (m)	Depth (m)	Number of entrances	Inception horizon	Endokarstic features	Deposits
Abu Sidrah	Type-1	2.6x1.5	5	1	1	N/A	none	sand, stones
Al Jumayliyah-1	Type-2	1.5x1.4	61	5	3	subhorizontal bedding plane	ceiling cupolas, fossil flowstone	sand, stones, guano
Al Jumayliyah-2	Type-2	1.4x1.3	134	9	1	subhorizontal bedding plane	ceiling cupolas, fossil flowstone	sand, stones, guano
At Turiyah-1	Type-2	0.6x0.6	9	4	2	undetermined	ceiling cupolas, fossil flowstone	sand, stones
Al Hamam	Type-1	14.5x8.2	91	19	1	N/A	none	collapsed rocks, stones, water
Duhail_S	Type-1	22.5x4.5	10	5	1	N/A	none	collapsed rocks, sand
Al Sailiya	Type-1	5.3x4.3	28	8	1	N/A	none	sand, stones, collapsed rocks
Misfir	Type-1	13.3x6.2	78	36	1	N/A	none	collapsed rocks, sand, mud
Mudhlem	Type-1	9.4x4.4	19	7	1	N/A	none	collapsed rocks, stones
Al Ghuwayriyah-2	Type-2	0.9x0.9	10	3	2	subvertical fractures	ceiling cupolas	mud, stones
Messaid	Collapse/ pond	50x49	11	11	1	N/A	none	evaporitic cristallisation, water
Wadi Jeri Mawza	undetermined	3.2x1.0	4	2	1	undetermined	none	stones
Wadi Al Salam-1	Type-2	0.5x0.5	6	4	2	subvertical fractures	none	sand, stones
Al Kharsaah	Type-1	16x1.5	2	2	1	N/A	none	garbage, rocks
Jeri Madhooy	Type-1	4.1x2.4	12	3	1	N/A	none	collapsed rocks, stones
Al Dawoodiya	Type-2	4.3x3.4	27	9	1	subvertical fractures & bedding plane	ceiling cupolas, fossil flowstone	sand, stones, guano, mud, water
Al Dahl	Type-2	1.0x0.8	3	2	1	undetermined	none	sand
Duhail_N	Type-2	3.3x2.3	6	3	1	subhorizontal bedding plane	none	sand, stones
Legretah	Type-2	1.4x1.3	75	6	5	subhorizontal bedding plane	ceiling cupolas	sand, stones
Um Kareibah West	Type-2	2.3x1.5	34	6	2	subvertical fracture	ceiling cupolas, fossil flowstone	sand, stones, guano
Um Kareibah South	Type-2	1.5x1.0	16	3	1	subhorizontal bedding plane	ceiling cupolas	sand, stones, guano
Al Rayyan (Zekreet)	Type-2	2.0x1.5	5	3	5	undetermined	none	sand, stones
Sawda Nathil	Collapse/ pond	28x20	8	8	3	N/A	none	evaporitic cristallisation, water

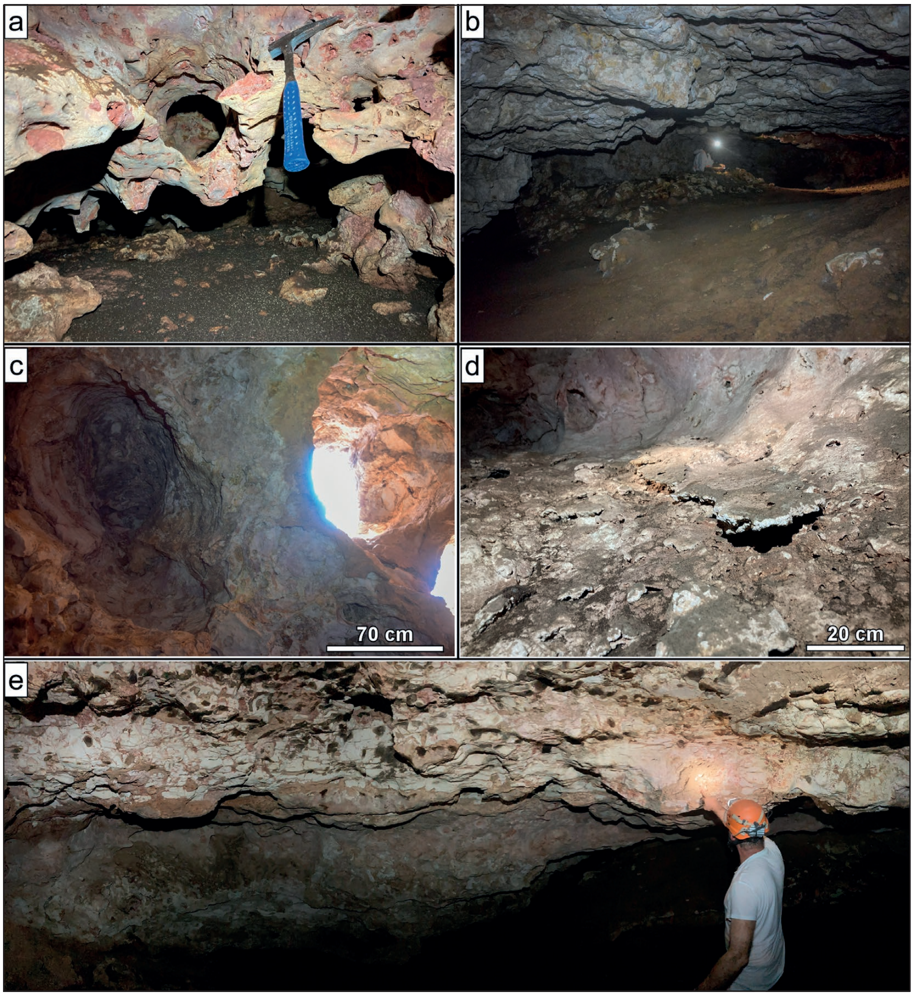


Figure 7: Endokarstic features and deposits encountered in type-2 (dissolution) caves: (a) Dissolution features along a subhorizontal bedding plane (inception) and floor covered by guano; (b) Low ceiling room with floor covered by some fallen blocks and significant amount of sand (samples for OSL collected just to the right of the picture); (c) Double entrance and ceiling cupola on the left that has not yet been truncated by erosion; (d) Remnant of a corroded flowstone on the floor at the edge of the room wall; (e) Low ceiling room developed along subhorizontal bedding (inception) with preserved sand infilling on part of the roof (brownish deposits) and traces of bats presence (black spots).

succession of chambers and narrow passages finishing on "dead ends" (i.e., blind passage with vertical walls and absence of large openings, even backfilled). The chambers exhibit circular sections in plan view (Figure 6). On a few locations (e.g., Legretah cave), rock bridges could be documented (i.e., superimposed passages leading to the same chamber). Deposits within type-2 caves encompass fossil inactive speleothems (flowstone, short stalactites), some of them being strongly corroded (Figure 7d). Cave floors are mostly covered by sand and limited amount of rock debris fallen from the ceiling (Figure 7b). Sand deposits may have reached up to the ceiling of some caves (Figure 7e) before being washed away to reach the present status of cave filling. Rock walls and ceilings are marked by the presence of bats (Figure 7e). Most caves present traces of present water circulation that shall occur during rare episodes of heavy rainfall with infiltration of runoff collected in the immediate surrounding of the cave entrances. Such events could not be observed directly, but presence of litter away from the entrances and traces of water flow on the floors (grooves in the sand, mud cracks) are clues of such water circulation.

It shall also be noted the lack of features attributed to recent water circulation (speleothems, flow deposits) issued from diffuse infiltration through the ceiling overlying rock.

Two samples of sand deposits in Al Jumayliyah-2 cave were collected at one location (see 3D model, Figure 5) for OSL dating. The following ages were obtained: 149.10 ± 10.57 ka for sample OSL1 and 141.97 ± 11.42 ka for OSL2 (sampled 20 cm below OSL1). These results are subject to some limitations: (i) the absence of in situ radioactivity measurements prevented accounting for local radioactivity heterogeneities, which makes the determination of the annual irradiation dose imprecise, (ii) the cosmic component determination, which is significant for calculating the annual irradiation dose, was approximated, (iii) the natural irradiation doses values are imprecise due to the measurements dispersion, possibly linked to an incomplete resetting of the signals, as observed for fluvial sediments (Rhodes & Pownall 1994, Singarayer et al. 2005). Considering the associated uncertainties, both OSL dating results are contemporaneous with each other, indicating that the sand deposited in less than 10-15 ka in this part of the cave. The ages place the deposition of the sand during the transition between MIS (marine isotope stage) 6 and MIS 5 (e.g., de Gelder et al. 2025).

7. INTERPRETATION

7.1. CAVES FORMATION PROCESSES

Dissolution caves (type-2 caves) present endokarstic features indicating a formation under phreatic conditions with slow groundwater movement. They got connected to the surface much later by truncation of ceiling cupolas caused by karst denudation. As such, they shall be considered as relict caves (or fossil caves) with present groundwater table located significantly below the caves (Figure 8). This explains why caves entrances have no connection to specific topographical or geological features. It is also possible that only the shallowest caves are accessible, i.e., the ones who could be truncated, and that (many) other caves exist deeper within the Umm Bab member.

The dissolution agent at the origin of these caves may originate from the surface, e.g., dissolution in the mixing zone between phreatic water and diffuse infiltration from the surface, close to the paleo-groundwater table (epigenic caves). Another hypothesis could be that hypogenic fluids (H_2S, CO_2) were the main source of acid for the formation of hypogenic caves. Existing caves are too short and do not present diagnostic features privileging one or the other hypothesis. Moreover, significant recent modifications (i.e., after caves were opened to the surface by erosion) of the endokarstic features were caused by biocorrosion (presence of bats), dissolution by condensation, and also sediment transport by infiltrating water. The most obvious changes are the smoothing out of some cave walls, the enlargement of preexisting cupolas and notches, the former ones being often polished and covered by dark spots related to bats presence, the corrosion of preexisting flowstones, and significant thickness of sand deposits at places (more than 2 m locally). The actual amount of recent dissolution via biocorrosion on the walls is however difficult to evaluate.

Some of the surveyed cave passages may be indicative of hypogenic karstification (Osborne, 2004; Klimchouk, 2009): there we can find alternating series of high and low ceilings, galleries ending into dead ends, irregular chambers, cave walls with circular sections in plan view, numerous ceiling cupolas, presence of rock bridges and wall notches. However, no diagnostic features such as rising feeder pipes could be observed, therefore the hypogenic origin of these caves remain hypothetical at this stage and their short lengths offer limited scope for further observations.

These caves experienced successive phases of development and sedimentation: 1) development in phreatic conditions, 2) drying up and abandonment due to drop in the groundwater table (or topographic rise caused by geologic processes) with some speleothems development under a more humid climate than present, 3) truncation by erosion resulting in their connection with the surface, which leads to the subsequent additional events: 3b) sediment filling up to the ceiling at least in some places (sediment transported by water and wind for sand deposited near the entrances), 3c) sediment removal by hydraulic transport during recharge events, 3d) modifications of the cave walls by biocorrosion (e.g., impact of bats) and effects of dissolution by condensation, 3e) disappearing of the cave with continuous karst denudation.

OSL dating of trapped sand within Al Jumayliyah-2 cave indicates that phase 3b occurred between MIS6 and MIS5, which corresponds to a rapid sea-level rise episode (de Gelder et al., 2025). Such an episode would have created favorable conditions for the sedimentation of fluvial sand within the caves as particle transport energy at the surface decreased. These OSL ages confirm the relict nature of the dissolution caves.

Collapse caves (type-1 caves) are systematically associated with a karstic depression and located on the edge of the depressions. It is proposed that they are part of a much larger paleo-subsidence process caused by a loss of material at depth. This loss may be due to dissolution of evaporites (i.e., intrastratal karst defined by Klimchouk, 2007) as proposed by most authors (Eccleston et al., 1981; Al-Hajari, 1987, Sadiq & Nasir, 2002), by compaction of weathered dolostone (“dologrus”) according to a hypothesis formulated by Rivers & Kaczmarek (2020), or by incremental collapse of coalesced paleocaves as documented in a carbonate sedimentary basin in the USA (McDonnell et al., 2007). As such, the collapse caves could correspond to the expression of tensile cracks within the extensional zone of the sag corresponding to the shoulder of the depression (McDonnell et al., 2007).

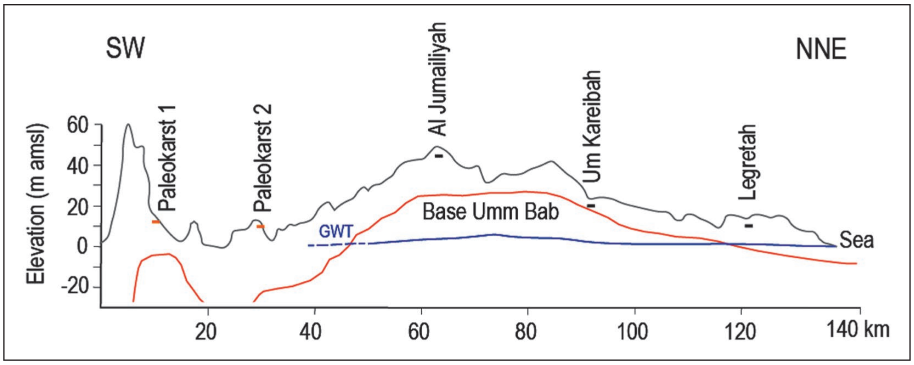


Figure 8: Cross-section from Dukhan anticline in the SW to the northern tip of Qatar showing the position of the main dissolution caves (type-2) and two paleokarst sites described in Ortiz et al. (in prep) with respect to present topography, groundwater table (GWT) of the Rus aquifer, and base of the Umm Bab member (Dammam formation). Note the 350x exaggeration on the vertical scale.

These collapse caves may correspond to the caprock collapse sinkhole model of Waltham et al. (2005), whereby the collapse form in least soluble rocks (Umm Bab member in the Qatar context) overlying a deeper karstified unit (Rus evaporites in the Qatar context).

In addition to these open caves (type-1 and type-2), paleokarsts were observed in quarries and outrcops in the western part of Qatar (Figure 8). The analysis of the karst infillings indicates an ancient phase of karstification, highlighting the existence of different phases of karstification in the peninsula (Ortiz et al., 2026).

7.2. CAVE SPATIAL DISTRIBUTION

Spatial distribution of the caves (Figure 9) shows that the roof-collapse caves (type-1) are located in the central and eastern Qatar whereas two exceptions are situated on the northwestern tip (Jeri Madhooy, Abu Sidrah), close to the coast. Dissolution caves (type-2) are located in the northern part of the peninsula close to the Qatar arch (i.e., in the central part of the peninsula), either on the eastern or western side.

We note the absence of caves in the southern part, except for the collapses in Sawda Nathil area, which may be linked to the presence of a large Sabkha area. Also, no cave is reported along the Dukhan anticline in the western part of the country. This may be partly due to limited outcrops of Umm Bab carbonates and the absence of evaporites at depth.

We believe that the cave inventory, if not thorough, is at least representative of the whole territory. It seems that the caves distribution may be controlled by some underlying factors. However, these could not be determined.

A pronounced change of topographic slope was mapped by Eccleston et al. (1981) and interpreted as the surface expression of lithological change in the Traina member from carbonate facies in the south to sulfate facies in the north and it is referred to as a topographic escarpment (Figure 9). According to these authors, the general removal of Rus anhydrite resulted in the deflation of the landscape and they proposed that the topographic escarpment (a.k.a. solution scarp) migrated southwards to be almost coincident with the northerly limit of the Midra shales, implying that the shales had a great influence on the dissolution process. This escarpment is named “V-shaped surface escarpment” by Rivers et al. (2019) who inferred it to be reflecting the presence of high-angle normal faults, active in the Eocene, and that created a high topographic separating the southern and northern sedimentary basins. The position of the topographic escarpment shows that the dissolution caves are located north of the escarpment (lower elevation), whereas roof collapse caves are located south of it (Figure 9). It is difficult to find a causal relationship, and it may be coincidental. For instance, roof collapse caves are associated with depressions (paleo sags/collapses) but these depressions are spread across the whole territory (Figure 3) and not limited to the area south of the escarpment.

7.3. KARST GEOHAZARDS

In a karstic environment, several types of geohazards may occur such as ground subsidence, landslides, floods involving highly transmissive aquifers, and groundwater contamination (Gutierrez et al., 2014; Parise, 2015). In carbonate karst settings, subsidence likelihood becomes especially significant when limestone is covered by unconsolidated deposits (mantled or buried karst) (e.g., Waltham et al., 2005).

In Qatar, only the karst ground subsidence geohazard is relevant: the dominance of relict caves and inactive paleo-collapse/sagging depressions in a barren carbonate environment are indicative of a generally low karst geohazard across the Qatar territory. The dissolution caves (type-2) setting corresponds to the lowest hazard level because these caves present small volumes and karstification activity (i.e., enlargement by dissolution) is no longer active. Therefore, a sudden ground collapse under these conditions has a low probability to occur. Because of their presence in shallow subsurface, geophysical methods are appropriate for detection of a possible presence. In contrast, roof collapse caves (type-1) settings together with the associated depression edges

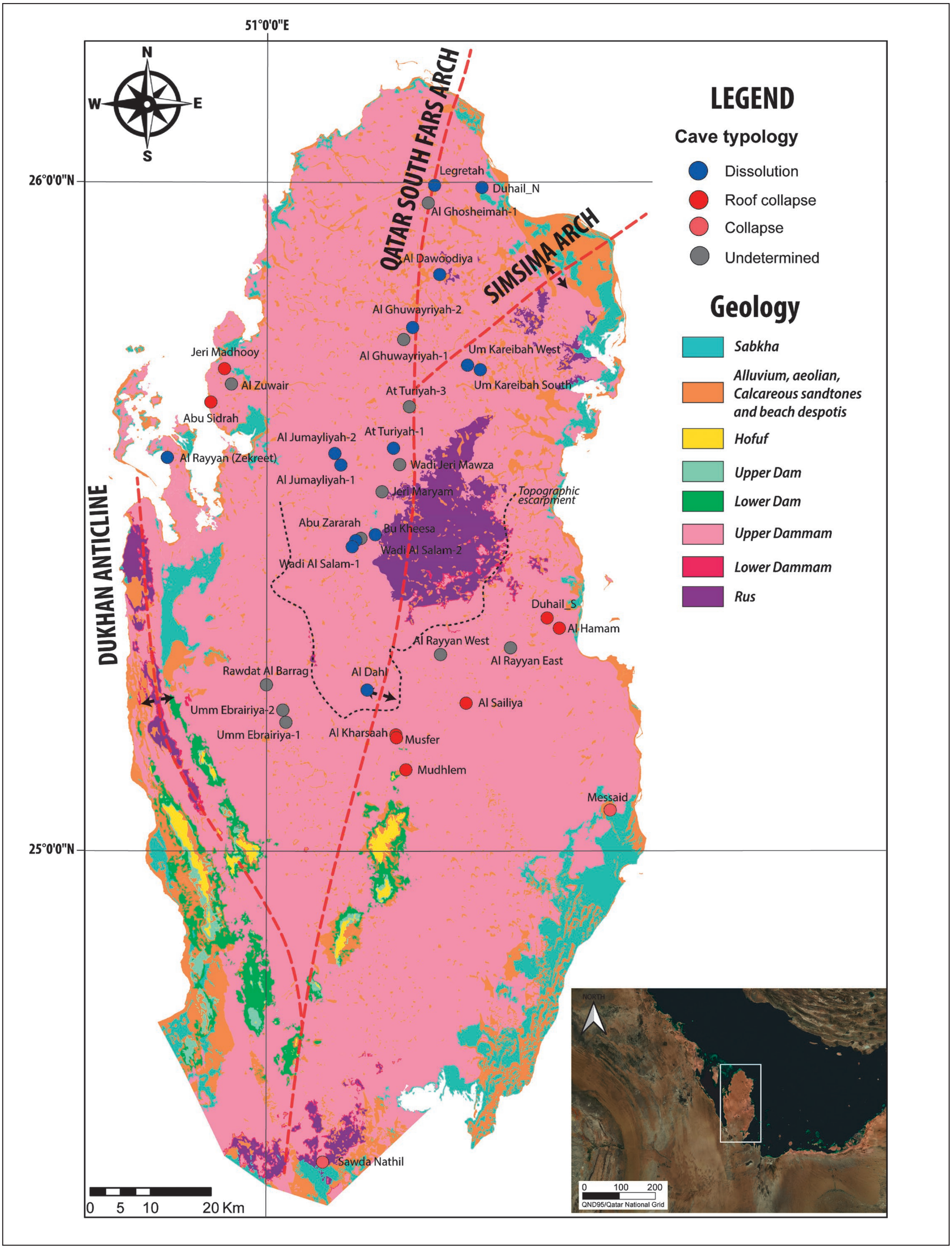


Figure 9: Spatial distribution of the surveyed caves with main structural features and the topographic escarpment derived from Eccleston et al. (1981) (a.k.a. solution scarp) represented by the dashed black line. The lower elevation is located to the north of the escarpment.

may reflect a higher level of hazard: these caves present larger dimensions that may result in the presence of large cavity roof spans close to the ground surface (e.g., Misfir cave roof span can reach 30 m with a roof thickness being less than 10 m). In addition, the processes leading to their development occur at depth and are not fully understood, which implies remaining uncertainties on the mechanisms leading to potential ground movement. Although, observed roof collapse caves and the associated depressions are no longer active, we may not rule out the possibility that cavities may continue to develop under specific circumstances (e.g., human-induced modification of prevailing groundwater flow) and trigger subsidence or collapse at the surface. The probability remains low as no recent events have been documented.

The most active area in terms of ground subsidence is in the far south of the country around a Sabkha in the Sawda Nathil area. Some observed collapse structures occur directly in Sabkha material and others are located on the edge of the Sabkha (Quaternary marine sands, carbonate of the Al Khor member at the surface). The biggest event being documented is Sawda Nathil collapse (28 x 20 m diameter, 8 m deep, Table 1) and occurred more than 20 years ago (documented in a picture by Al Saad, 2003). These ground movements may well be caused by the presence of the Sabkha and salt dissolution process at shallow depth and should likely be a localized phenomenon.

Even if the likelihood of ground subsidence appears to be low, the presence of subsurface karst cavities is ubiquitous across the Qatar peninsula, and this shall be taken into account in development projects.

8. SUMMARY AND CONCLUSION

A thorough documentation of the caves and depressions across the Qatar peninsula confirmed the development of karstic features in a large span of the country with a ubiquitous presence of collapse/sagging depressions and the existence of two main types of caves with different characteristics: one corresponding to large collapse cavities originating at depth, the other to shallow subsurface dissolution caves. These karst features seem presently mostly inactive and thus inherited from a paleoclimatic context, which was more favorable to karstification These ancient karstification processes would need to be studied in more detail to better constrain their origin and age.

The dominance of collapse depressions and the absence of other surficial karst features such as karrenfields or dissolution dolines as well as the prevalence of presently inactive karst processes seem to be the usual setting of karst in arid environments as presented in two review papers: Ford & Williams (2007) indicate the fluvial character of arid karst with a dominance of collapse dolines and presence of relict caves; Jennings (1983) also emphasizes on the prevalence of inherited karst features and very limited or non-existent current karstification.

To our knowledge, the closest other significant caves in the region are located in the Al Sulb plateau (KSA), about 350 km west of Qatar northern tip. These caves develop in the Umm Er Radhuma carbonate and some of them are several hundred meters long (Forti et al., 2003; SGS Cave Unit, 2007). In some aspects, they present similarities with the Qatar dissolution caves with a dominant subhorizontal development and succession of larger rooms and smaller interconnecting passages. A main difference is the relative abundance of speleothems in these KSA caves, some of them having been contemplated as possible candidates for show caves. Another difference is the hydrological functioning of this karstic plateau with the presence of active swallow holes recharging the aquifer (Schulz et al., 2016). Other significant caves have developed in the inner Umm Er Radhuma carbonate outcrops of the Oman platform (Al Kindi et al., 2022).

It is proposed that collapse/sagging depressions and collapse caves originated from dissolution (intrastratal karst) and compaction processes at depth (e.g., within the Rus formation that is partly constituted of evaporitic rocks). In contrast, the shallow dissolution caves have likely developed via the enlargement of rock discontinuities in the Umm Bab member (bedding planes and fractures) by groundwater. The origin of groundwater flow and dissolution agent is not elucidated, but it is possible that caves may have first developed in hypogenic conditions.

Due to the large outcropping areas of the Umm Bab member, the shallow subsurface dissolution karst cavities seem to be extensive as it is also observed in quarries cuts and in boreholes logs; the collapse/sagging depressions are also widespread across the Qatar territory, however, the associated roof collapse caves appear to be limited to the central and eastern part of the peninsula and in the vicinity of Doha.

Under the present geoclimatic conditions, the karst subsidence geohazard appears to be low, as caves are inherited, and ongoing karstification processes are limited. However, recent and upcoming land development shall include plans and strategies to consider the presence of karstified rocks in the subsurface and ensure that karst-related ground subsidence is not activated by human activity (e.g., water injection to the subsurface, damming of subsurface karst conduits, inadequate backfilling). The ongoing project will deliver operational recommendations and a monitoring plan for sensitive/exposed areas.

In addition, several research questions remain open, in particular the mechanisms involved in the occurrence of karst collapse depressions and caves. Further investigations on the shallow subsurface structural geology would be of interest to enhance the understanding of deep-seated groundwater circulations and their potential role in the karstification (i.e., hypogenic). This could be combined with a study of fluid paleo-circulations in the Rus and Dammam formations. The outcome of such additional investigations would certainly be beneficial for a better understanding of the underlying processes and help in refining geohazard management strategies.

ACKNOWLEDGMENTS

The authors would like to thank the State of Qatar Ministry of Municipality for their support and data contributions to this project. A preliminary review by Dr Jeremy Jameson was also much appreciated. The insightful comments of Prof. Philippe Audra and an anonymous reviewer greatly improved the manuscript.

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