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ORIGINAL RESEARCH

A 3-Day Geological Field Trip in Qatar

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ABSTRACT

The author learned first-hand about the surface stratigraphy and geology of Qatar by dedicating most of his weekends at conducting field works and public guided field tours from 2007 to 2020 while employed by Qatar Petroleum (now QatarEnergy). Here, he summarizes his knowledge of the surface geology of Qatar in a 3-Day field trip designed to provide the participants a hands-on overview of the stratigraphy of the country. The field trip is based on his publication (LeBlanc, 2021) which is an integral part of this geological tour (the participants are referred to it on several occasions) and his other geological publications on Qatar referenced herein (LeBlanc, 2008, 2009, 2014, 2015, 2017, 2019). During this 3-day field trip, outcrops of the Lower Eocene Rus Formation, Middle Eocene Dammam Formation, Lower Miocene Dam Formation, Mio-Pliocene Hofuf Formation, as well as Pleistocene and Holocene deposits will be visited. The fieldtrip's aim is to help the participants at recognizing the various formations and their members, as well as the most obvious features (faults, folds, dissolution, mineralization, fossils, etc..) that characterize them.

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Introduction

This field trip uses the stratigraphic column seen in Fig. A. The text in the document is kept to a minimum since the author, if hired for the occasion, intends to explain in more details the features and characteristics of all stops visited.

Day 1 of this field trip will be the most important and most likely the most exhausting of the three days. In fact, this first day could be splitted in two to make it a 4-day field trip or simply to keep it as a 3-day field trip while removing the less important 3rd day described herein.

Should the field trip be formally conducted by the author, or someone else knowledgeable on the topic, the "**Pre-Activity Safety Assessment**" document (Appendix A), the "**Safety Acknowledgement**" and "**Medical Certification**" forms (Appendix B & Appendix C) should be carefully read, signed, and returned to the trip leader at least two days prior to the event.

Access permission of some sites (detailed herein) must first be secured prior to the event taking place.

Unless otherwise mentioned, all pictures are from the author.

Day 1 of 3 - A full day (8+ hours) in the field:

06:30AM (Please be on time) - Meet at Hyatt plaza (Day 1-Fig. 01). Your Guide will welcome everyone and introduce himself, provide a short safety briefing, and distribute some material.
06:45AM - Leave Hyatt Plaza.

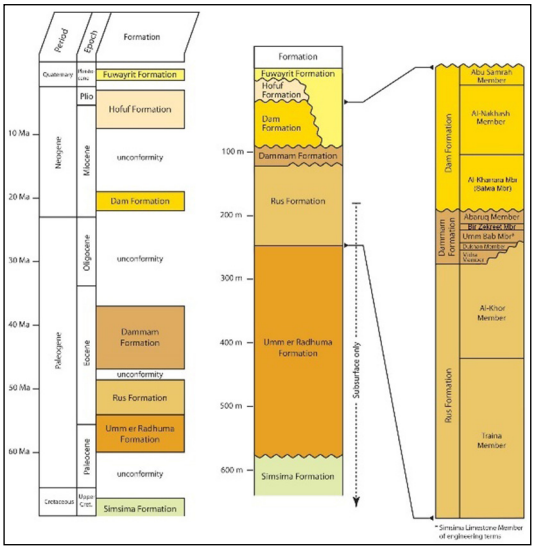
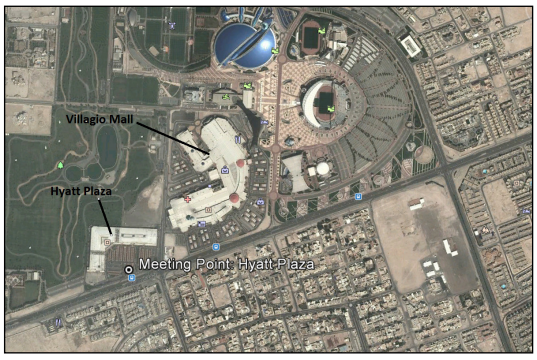


Figure A. Qatar Surface and near surface stratigraphy (modified from Orndorff *et al*., 2018).



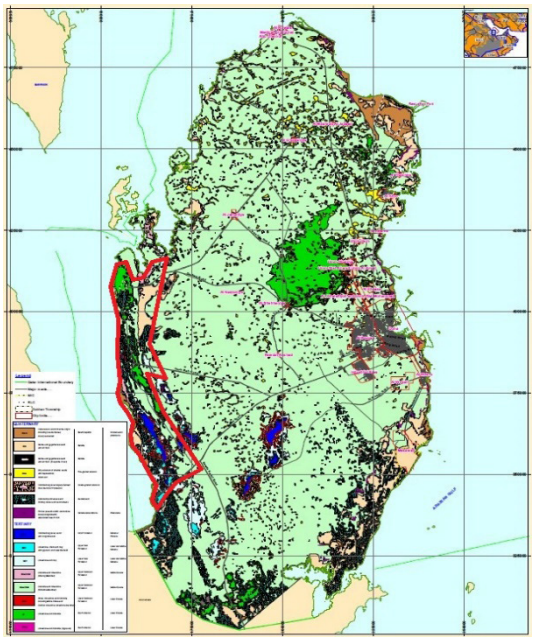
Day 1-Figure 01. The Hyatt Plaza meeting Point, in the parking lot (see Table 1 for the coordinates)

12:00PM - Since it is not clear where we will be around lunch time, we will break for **30 minutes** around 12PM at the most appropriate location.

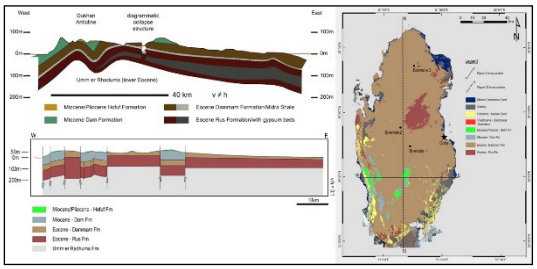
The general area we will be visiting today is outlined in red in Day 1-Fig. 02. If time is too tight, we will skip some stops, however, if we have the time to visit them on the third day, we will do so.

The access permissions that are required for this day are:

- The whole of the QatarEnergy's Dukhan field
- The QNCC Hofuf sand quarry south of Umm Bab
- The QNCC Limestone quarry east of Umm Bab



Day 1-Figure 02. General area (in red) to visit on Day-1



Day 1-Figure 03. Comparison of vertical geological sections across Qatar from work by Seltrust Engineering (1985) (Top) and Rivers & Larson (2018) and Rivers, Skeat *et al*. (2019) (Bottom). Sections are vertically exaggerated as indicated. Inferred faults are as marked in the vertical section from Rivers & Larson (2018)'s study.

Brief discussion at our meeting point: As we will go along the Salwa Highway in a southwesterly direction, we will drive over the Qatar Arch (a broad, gentle anticline draping a major block uplift which caused Qatar to emerge from the Gulf). While doing so, we can imagine the newer observations made by Rivers & Larson (2018) and Rivers, Skeat *et al*. (2019) regarding the structure of the Qatar Arch and the Dukhan anticline, compared with the older work of Seltrust Engineering (1985) These new observations favor a fault-controlled model for the Dukhan structure in the western part of the peninsula over previous fold-related and regional erosion models (Day 1-Fig. 03).

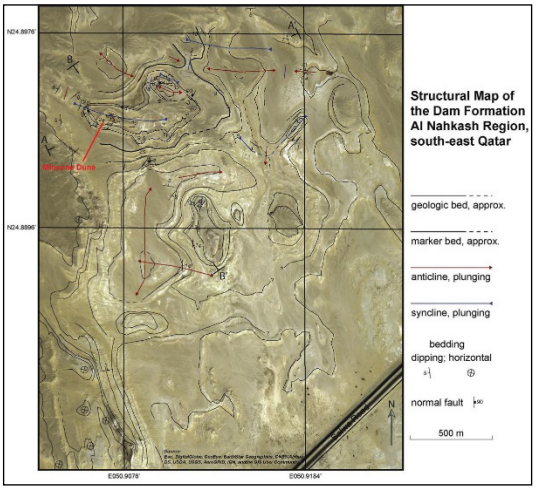
STOPS	LATITUDE	LONGITUDE	REMARKS
DAY 1			
--	25°15′20.08″N	51°26′17.04″E	Meeting Point (Hyatt Plaza); Day 1 & Day 2
1a	24°53′28.45″N	50°54′30.24″E	Start of walk - Miocene Stromatolite Mounds
1b	24°53′29.48″N	50°54′27.22″E	Miocene Gypsum deposit
1c	24°53′35.11″N	50°54′24.30″E	End of walk - Miocene Lithified Dune
2a	24°52′8.76″N	50°54′21.13″E	Start of climb – Miocene Upper Al-Nakhash Mbr
2b	24°52′24.05″N	50°54′13.12″E	End of Climb – Mio-Pliocene Hofuf
3	25° 3′28.34″N	50°53′12.43″E	Midra and Dukhan Members
4	25° 3′45.75″N 25° 2′51.21″N	50°49′53.33″E 50°51′23.03″E	- Hofuf sand quarry (general area) - Dam Formation: 10° dip in opposite direction to the western slope of the anticline
5	25° 3′52.35″N	50°49′26.80″E	Miocene channel cut
6	25° 2′35.70″N	50°49′8.32″E	Pleistocene aeolian deposit
7	25° 1′19.87″N	50°49′34.67″E	Holocene deposit
8	25°11′24.04″N	50°50′2.87″E	QNCC Limestone quarry
9	25°17′12.86″N	50°48′35.77″E	Overview of Cavelier (1970a, 1970b)'s Rus & Dammam Reference Section
10	25°17′8.95″N	50°47′27.54″E	Fault in the Dammam
11	25°26′45.10″N	50°45′42.24″E	Silicified pipes in the Rus Formation
12	25°26′19.14″N	50°47′3.27″E	Fault in the Rus Formation
13	25°26′43.43″N	50°51′41.68″E	Type section of the Bir Zekreet Member
14	25°26′31.56″N	50°50′57.56″E	Reference Section of the Abarug Member
15	25°23′52.13″N	50°53′2.60″E	Top part of the Umm Bab Member
16	25°22′11.85″N	50°52′46.20″E	Silica layers in the Umm Bab Member
17	25°22′10.96″N	50°54′34.90″E	Metre High Vents in the Dammam
DAY 2			
1	25° 8′52.92″N	51°13′2.42″E	Overlooking Umm Al Shabrum sinkhole
2	25°10′30.45″N	51°12′42.18″E	Misfir Cave
3a	24°49′57.78″N	51° 6′50.33″E	Gypsum nodules in Lower Al-Nakhash member
3b	24°49′52.22″N	51° 6′56.18″E	Coral reefs in Lower Al-Nakhash member
4	24°50′8.86″N	51°18′2.43″E	Naqa Felaiha sinkhole
5a	24°53′14.48″N	51°26′48.31″E	PLeistocene Beach
5b	24°53′54.29″N	51°28′4.84″E	Holocene Beach
5c	24°54′31.18″N	51°28′4.76″E	Pleistocene aeolian dune
DAY 3			
--	25°23′9.61″N	51°26′24.11″E	Meeting Point (IKEA)
1a	25°44′0.82″N	51°33′6.50″E	Thakira Rus Outcrop
1b	25°43′57.05″N	51°33′14.16″E	Thakira Rus Outcrop
2	25°47′43.47″N	51°33′11.61″E	Thakira Rus Outcrop
3	25°47′36.88″N	51°26′15.52″E	General area of the Simsima depression, Rus Fm.
4	26° 2′16.55″N	51° 7′30.78″E	Dump site of Al-Ruwais Port expansion
5	25°22′44.60″N	51°14′6.77″E	North of Shahaniyah – Dukhan Mbr Nautiloid
6	25°21′57.63″N	51°14′28.38″E	Shahaniyah pit

Table 1. Location of all stops.

Stop 1: We will enter the field in an area of Lower Miocene rocks; the Dam Formation. This formation occurs on the western and eastern flanks of the Dukhan anticline (which emerged also during the Miocene Period) and in south-central Qatar (Page 33 in LeBlanc, 2021). It has been greatly affected by faulting and in certain areas by dissolution of gypsum in the underlying Rus formation; as can be seen in Day 1-Fig. 04. At the stop, we will start our walk at the Middle Al-Nakhash member displaying large stromatolite mounds (Day 1-Fig. 05) and progressively walk our way up the stratigraphy, passing through large (up to 1 m) gypsum crystals (Day 1-Fig. 06), limestone (chalks and packstone) and complete our short walk at a Miocene dune (Day 1-Fig. 04 and Day 1-Fig. 07). (Pages 30-36 in LeBlanc, 2021).

Stop 2: We will continue with the vehicles near the base of Al-Nakhash Hill and start walking up its flank starting at the Upper Al-Kharrara member up to the top of the Dam Formation and then to the Mio-Pliocene Hofuf Formation which is found at about 90 metres of altitude. While the Hofuf here is not spectacular, the view on a clear day can be breathtaking. During our way up (and down), we will observe Oolitic limestones, Beachrocks, Algal/vertical stromatolites (Day 1-Fig. 08), and discontinuous gypsum beds increasing upward in the Al-Nakhash member, and cross-beddings in the Abu Samrah Member.

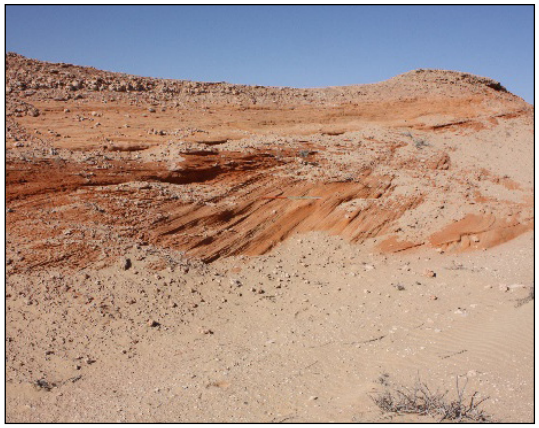
Stop 3: We then take to the road again heading East on Salwa Road and then North on the Dukhan Highway to a natural area of rock ridges displaying the Midra, Dukhan Alveolina and Umm Bab Members of the Middle Eocene Dammam Formation on the East side of the Highway (Day 1-Fig. 09). Here we will observe the Midra shale and its make up; this will be useful later



Day 1-Figure 04. Geological map for the Al Nakhash region of south-west Qatar. The Miocene dune is shown in red. Rivers & Larson, 2018.

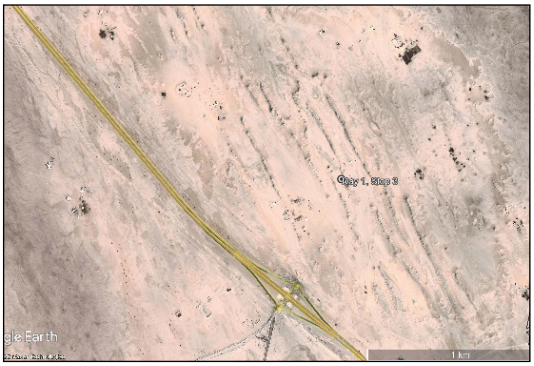
Day 1-Figure 05. Large stromatolite mounds. Miocene Dam Formation, Middle Al-Nakhash Member.

Day 1-Figure 06. Large gypsum crystals. Miocene Dam Formation, Middle Al-Nakhash Member.



Day 1-Figure 07. A lithified sand dune (bottom) and interdune (top). Lower Miocene Dam Formation, Upper Al-Nakhash Member.

Day 1-Figure 08. Oolitic limestones (top), Algal/vertical stromatolites (center), Beachrocks/ Hardground (bottom).

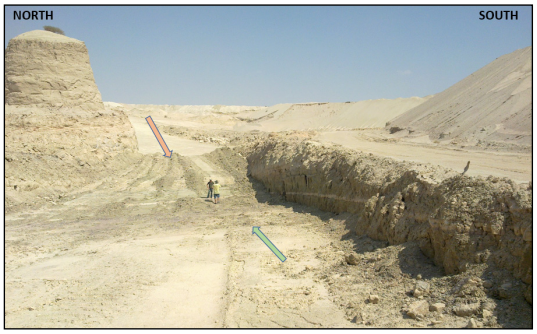


Day 1-Figure 09. Dammam formation ridges oriented North-South along the Dukhan highway over the Dukhan anticline.

during the day when a comparison will be made between the Midra Shale and the Bir-Zekreet Shale Members of the Dammam Formation. We will also observe the relation between the Midra shale and the overlying Dukhan Alveolina Member.

Stop 4 (few stops within this large quarry): We head west across the Dukhan Highway and to the QNCC Hofuf sand quarry where a thick section of the Mio-Pliocene formation can be observed. The section we will look at will depend on the recent activities at the quarry and the orientation with the sun (we want to see it in the sunlight) (Pages 36-40 in LeBlanc, 2021). At the bottom of the quarry is seen the several levels of the Lower Miocene Dam Formation. At one location, the green shale at the bottom of the Middle Al-Kharrara Member is seen dipping 10° in opposite direction to the western slope of the anticline (Day 1-Fig. 10).

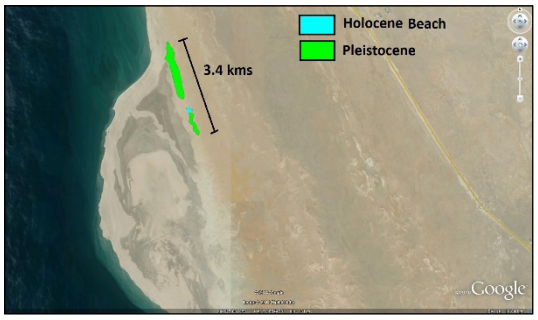
Stop 5: We then continue to an area of the quarry displaying a channel cut in the Lower Miocene Dam Formation (Upper Al-Kharrara Member). Day 1-Fig. 11.



Day 1-Figure 10. The dip of the Miocene Dam Formation is 10° East (green arrow), which goes in opposite direction to the western slope of the anticline (orange arrow).

Day 1-Figure 11. Channel cut in the Upper Al-Kharrara Member of the Dam Formation.

Stop 6: We then come out of the quarry on its western side and head towards the Gulf of Salwa. There, we will observe the northern tip of a Pleistocene aeolian deposit. At that location, the deposit occurs at 0.6 kms from the beach while the southern tip is found 3kms inland. It stretches 3.4 kms from north to south (Day 1-Fig. 12 & Day 1-Fig. 13). Most of the deposit is covered by sand but archeological remains, mostly red and blue pottery fragments (Day 1-Fig. 15), are frequent at various exposed locations. Flint material and possible fire pits (Day 1-Fig. 14 and Day 1-Fig. 15) are rare. To the author's knowledge, this Pleistocene aeolian deposit is not on any of Qatar's geological map; Cavelier (1970a) mapped it as Miocene, and subsequent authors never corrected the misinterpretation. The deposit was discovered and mapped by the author in 2010 and the respective authorities at QatarEnergy, Qatar Museum and Qatar Center for Coastal Research were informed.



Day 1-Figure 12. Location of Pleistocene and Holocene deposits on the western coast of Qatar.

Day 1-Figure 13. Pleistocene aeolian deposit in Western Qatar.

Stop 7: Before we leave this area, we will go to a Holocene deposit located towards the center of the Pleistocene aeolian deposit (in blue in Day 1-Fig. 12). This deposit is located 2.5 kms inland and displays well preserved bivalves (Day 1-Fig. 16).

Stop 8: This stop is at the QNCC Limestone quarry east of Umm Bab. Since we are now on the eastern flank of the Dukhan anticline, we will observe a 3° to 4° dip in the Dammam & Rus Formations resulting from the uplift of the nearby Dukhan anticline [*The Dukhan Alveolina Limestone and the Midra (and Saila) Shales outcrop less than a kilometre to the west*]. (Pages 21-22 in LeBlanc, 2021). Day 1-Fig. 17.

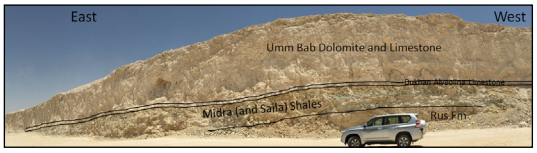
Stop 9: We will go to a lookout overlooking the location that Cavelier (1970a) selected for the natural Reference Section of the Lower Eocene Rus Formation and the Middle Eocene Dammam Formation. We will not go directly to the location of Cavelier's section. (Pages 13 & 21 in LeBlanc, 2021). At the lookout, a good section of the Midra can be observed.

Stop(?) 10: We will then head back to the main highway going north. At the level of the Fahahil

Day 1-Figure 14. Archeological remains?

Day 1-Figure 15. Red & green pottery fragments (top & center) together with a flint tool (bottom).

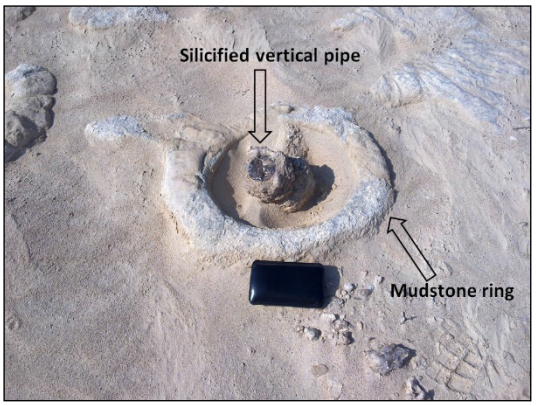
Day 1-Figure 16. Holocene deposit with loose shells, located at the center of a Pleistocene aeolian deposit in western Qatar.



Day 1-Figure 17. Umm Bab Dolomite and Limestone Member seen from its base at the Umm Bab QNCC limestone quarry (25°11′18.49″N, 50°50′9.83″E).

Main Plant, the Guide will point out where the road crosses a fault in the Dammam Formation (at the level of the road to the left will be seen the Midra Shale while on the right, the same shale will be much lower). We will stop if we can.

Stop 11: This stop is to observe some silicified vertical pipes occurring in the Rus formation over the Dukhan field. The reason for this occurrence will be explained. (LeBlanc, 2017). Day 1-Fig. 18.

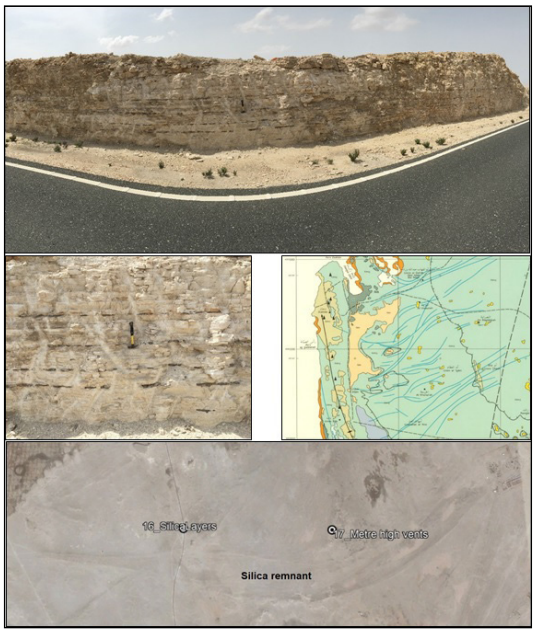


Day 1-Figure 18. Silicified vertical pipe with circular mudstone features around it in the Rus Formation. The inner axial portion of the ring is bent upward around a near vertical core structure that is also silicified. These structures reach a maximum diameter of 45 cm. Their form and size are consistent with a fluid escape structure. They apparently formed by breaching the sediments of a shallow paleo-sea. General area at 25°26′45.10″N and 50°45′42.24″E.

Stop 12: We will now head back just to the North of Dukhan town in an area near the golf club displaying an obvious fault in a cliff of the Lower Eocene Rus Formation. (Page 9 in LeBlanc, 2021).

Stop 13: We then head east on the Dukhan-Doha highway and turn north on the Zekreet road. In this area, our first stop will be the type section of the Bir-Zekreet Member of the Middle Eocene Dammam Formation at the base of a cliff composed of the Abarug Member (Kok & LeBlanc, 2012). Here we will take the time to compare this shale with the Midra shale observed earlier. Note: This member is most likely correlatable to the "Orange" Member of Bahrain. (Page 28 in LeBlanc, 2021). **Note**: A better section of the Bir-Zekreet member is encountered at another Mesa south of the Doha-Dukhan highway at 25°22′58.87″N and 50°52′49.46″E.

Stop 14: We then continue west for a short distance to the Reference Section of the Abarug Member which makes up a large Mesa behind the "Cuban" Hospital. (At this location, the Bir-Zekreet Member is not visible. It is visible only on the south side of the Mesa near the Dukhan highway). (Page 29 in LeBlanc, 2021).



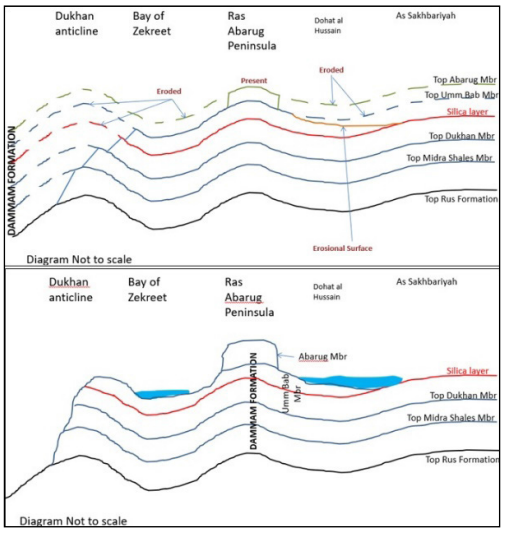
Day 1-Figure 19. Several layers of silica within the Umm Bab Member of the Dammam Formation (top & center left). This silica outcrops naturally at several locations (blue lines in the image to the center right) and are interpreted (I believe wrongly) by Hunting (1983) as paleo-river traces. We will drive on one of them between stops 16 and 17 (bottom image).

Stop 15: This stop will be south of the Dukhan road where a thick section of the top part of the Umm Bab Member of the Dammam Formation will be observed. In this limestone, large burrows/trace fossils make up the limestone (some say they are mangrove roots). Gastropods and echinoderms are the main fossils. (Page 24-25 in LeBlanc, 2021).

Stop 16: This stop, as well as everything that comes between stops 16 and 17, relate to mineralized water escaping from the sub-surface at one point in time. What we see in this small road-cut is part of the Umm Bab Member of the Middle Eocene Dammam Formation displaying several layers of silica. Between stops 16 and 17 we will drive on one of these extensive layers (Day 1-Fig. 19). Other similar areas exist in Qatar (Day 1-Fig. 20 & Day 1-Fig. 21). Stop 17 will provide a possible explanation for the occurrences of these silica layers.

Stop 17: Our last stop of the day will take us to a cluster of metre-high vents formation occurring within the Dammam Formation (Day 1-Fig. 22). These vents show the structural stress that the area was under at the time and were probably a

Day 1-Figure 20. Line of cross-section seen in Day 1-Figure 21 over satellite imagery (left) and geological map (bottom right). One silica layer can be seen on the satellite imagery (Google Earth). All others have been interpreted by Hunting (1983) (top right). As per Hunting (1983)'s interpretation, these lines occurred mostly on the western side of the Qatar Arch.



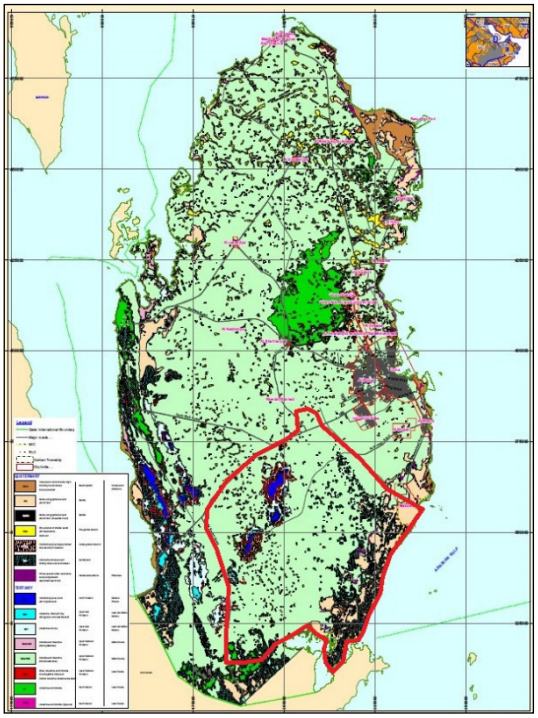
Day 1-Figure 21. Rough schematic (not to scale) of the stratigraphy and erosional surfaces interpreted in relation to the occurrence of one silica layer in the area of As Sakhbariyah in ENE Qatar.

precursor sign that would lead to the uplift of the nearby Dukhan anticline.

Day 2 of 3:

06:30AM (Please be on time) - Meet at Hyatt plaza (Day 1-Fig. 01).
06:45AM - Leave Hyatt Plaza.
12:00PM - Since it is not clear where we will be

Day 1-Figure 22. Non-Silicified vents (gryphons) as high as one meter.



Day 2-Figure 01. General area (in red) to visit on Day-2.

around lunch time, we will break for **30 minutes** around 12PM at the most appropriate location.

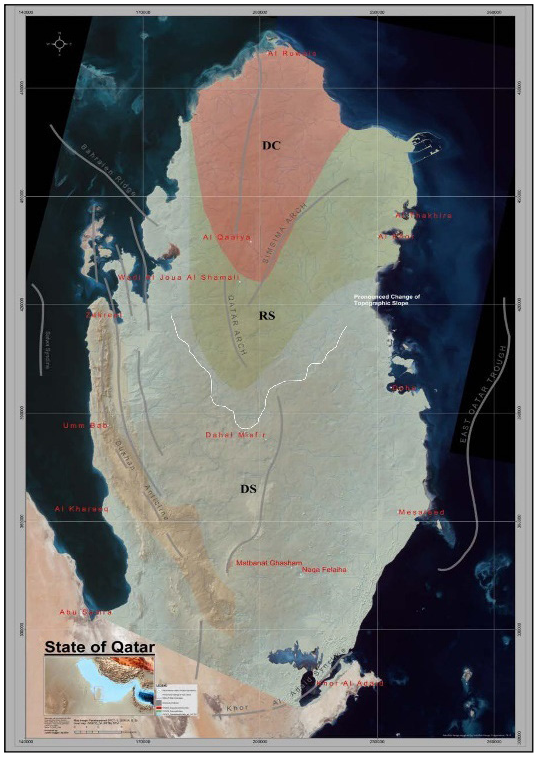
Mandatory equipment for the day: Hard hat/ Safety helmet to enter the Misfir cave.

The general area we will be visiting today is outlined in red in Day 2-Fig. 01

Access permissions required for this day: NONE

The variable mode of deposition of the Rus Formation in Qatar has led to the recognition of at least three major facies being present in the country (Day 2-Fig. 02); these are: a lower largely evaporitic gypsiferous, argillaceous facies, termed the "**Depositional Sulphate (DS)"** facies and upper calcareous facies, or "**Depositional Carbonate (DC)"** facies. Although the distinction clearly exists on a sedimentary basis, post-depositional gypsum dissolution has complicated the recognition and separation between the facies in boundary areas. The sulphate facies (DS) predominates in southern Qatar and on the east and west flanks of the main Qatar arch. The Umm Al Shabrum sinkhole (Day 2-Fig. 03 & Day 2-Fig. 04), the Misfir Cave (Day 2-Fig. 05 & Day 2-Fig. 06) and the Naqa Felaiha sinkhole (Day 2-Fig. 08 & Day 2-Fig. 09) all occur in or over this facies. The Rus Formation in the Dukhan anticline is developed in the Depositional Carbonate (DC) facies.

In the northern and eastern part of Qatar, away from the Dukhan anticline, a third facies has been described as the "**Residual Sulphate (RS)"** facies.

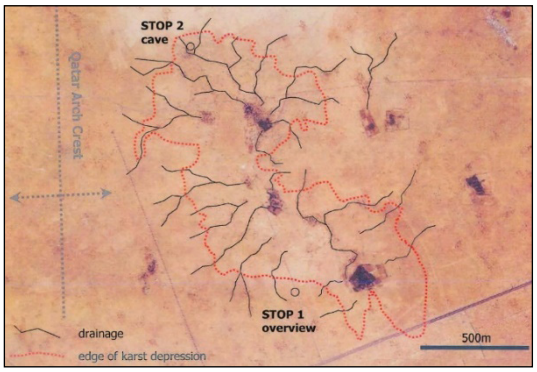


Day 2-Figure 02. Statewide facies types, drainages, and structures (DC=Depositional carbonate, RS=Residual sulphate, DS=Depositional sulphate). Duggan, 2014.

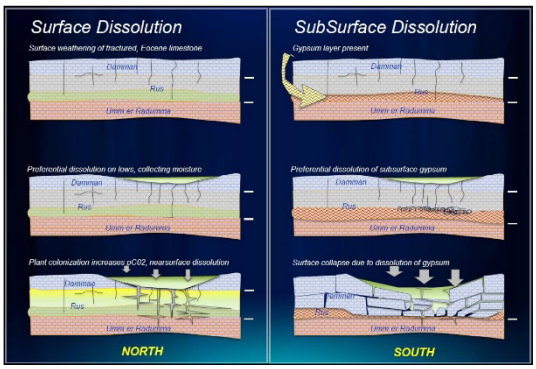
This is the facies that we will see in the three Thakira outcrops during Day 3; thus, the erosional remnant of the Lower Rus Sulphate Member.

Referring to yesterday's discussion (Day 1-Fig. 03), we will inspect some geological features associated with the arch crest, particularly the expression of karst which occurred through dissolution along crestal fracture systems (Day 2-Fig. 03). This will be especially emphasized once we enter the Misfir Cave which exposes the Lower Eocene Rus Formation and several members of the Middle Eocene Dammam Formation (Day 2-Fig. 06).

Stop 1: We will identify a large karst collapse feature which is expressed by a surface depression 1.5 by 0.5 km in extent. The surface is depressed up to 20m from the edges. Due to the related drainage, current day oases are often located in the karst depressions along the desert surface (Day 2-Fig. 03, Day 2-Fig. 04). The initial dissolution took place in Pliocene time and later collapsed to form this large depression. The karst features were caused by the dissolution of the



Day 2-Figure 03. The sinkhole of Umm Al Shabrum (Al-Kuwari & Puls, 2007).

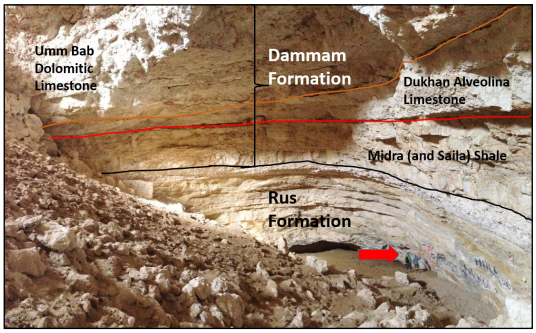


Day 2-Figure 04. Qatar Karst Models (Duggan, Jameson *et al*., 2014).

Rus Formation gypsum beds during humid and wet periods in the Pliocene and Pleistocene (Hofuf Formation deposited in Pliocene). Note the position of the Qatar Arch Crest in Day 2-Fig. 03.

Stop 2: (*Use of a safety helmet is mandatory. If you do not feel comfortable entering the cave, wait for us outside*). The Misfir cave is part of the large depression we saw at Stop #1. The cave extends downward for a total depth of 37.75m (123.85ft) from the entrance to the bottom (measured in early 2017 by the Guide and some colleagues). A large room has formed by the collapse of carbonate material. The cave walls are composed of the Lower Eocene Rus Formation (bottom) and, going upward, the Midra Shale, Dukhan Alveolina and the Umm Bab Limestone Members of the Middle Eocene Dammam Formation. (Pages 22-23 in LeBlanc, 2021). (Day 2-Fig. 05 & Day 2-Fig. 06)

Stop 3: We drive west on Salwa Highway, then 3.6 kms south on Sauda Nathil road and then east towards the hill in the background. At this stop we will see small erosional canyons with their limestone walls filled with gypsum nodules (Lower Al-Nakhash Member of the Lower Miocene Dam Formation). At a walking distance and slightly higher in the stratigraphy (Lower Al-Nakhash Member), a layer of fossilized coral reefs will be observed (Day 2-Fig. 07). While the general trend within the Dam Formation goes from a marine environment (at the base) to a terrestrial one (at the top), the occurrence of gypsum nodules and corals so close to each other in the stratigraphy demonstrates that within the Miocene fluctuations of the sea level occurred periodically; the gypsum nodules unit most likely representing an environment of sabkha (low sea level) and the corals layer representing an increase in sea level.



Day 2-Figure 06. Stratigraphy of the Misfir cave (LeBlanc, 2021).

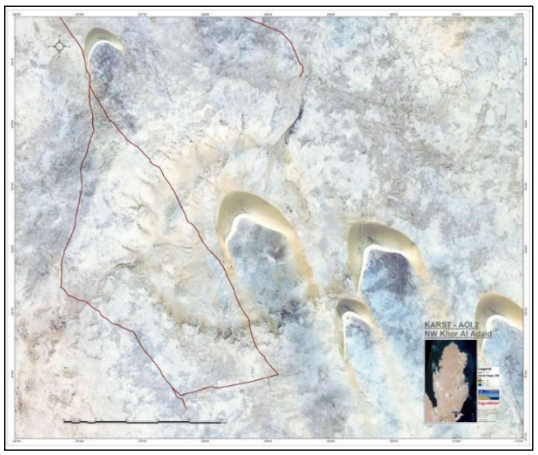
Day 2-Figure 05. Misfir cave entrance (top) (Orndorff *et al*., 2018) and inside (bottom).

Day 2-Figure 07. Gypsum nodules on the wall of small canyons (bottom) and a fossilized coral reef layer higher up in the stratigraphy (top).

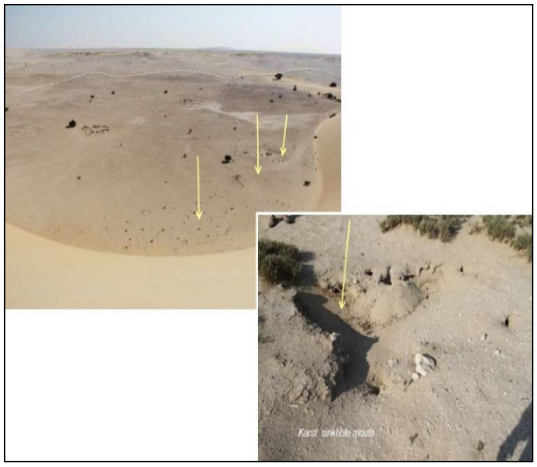
Stop 4: The Naqa Felaiha sinkhole is a super karst occurring within the Depositional Sulphate (DS) facies type (Day 2-Fig. 02). It forms a massive circular bowl or depression of 1.6 kms in diameter and with 20 meters in elevation between its center and the surface (Day 2-Fig. 08). The barchan dune at the center is barely visible on the drive in. There are three evident sinkhole openings between the two "horns" of the dune. (Day 2-Fig. 09).

Stop 5 (Last stop of day 2): This location (Day 2-Fig. 10) is 6 kms inland from the present-day eastern coast (Day 2-Fig. 11). We will visit a lithified Pleistocene dune, a Pleistocene beach, and a Holocene beach; the latter displaying well preserved loose seashells.

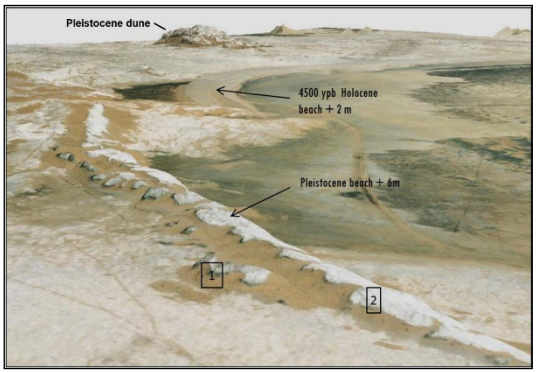
During the Last Glacial Maximum (LGM) 18,000 yr BP, sea level was 120m lower (Day 2-Fig. 11) and the Arabian Gulf was a fluvial valley with an axial river system (Day 2-Fig. 12A). Marine flooding of the Gulf began approximately 14,000 years ago, creating marshy plains in the valley floor (Day 2-Fig. 12B). Between 14,000 and 9,000 years ago sea-level rose extremely rapidly, at rates close to 2m per century (Day 2-Fig. 12C). The Holocene high stand took place about 6,000 years ago (Day 2-Fig. 12D). Sea-level dropped to present levels approximately 2,000 yr BP.



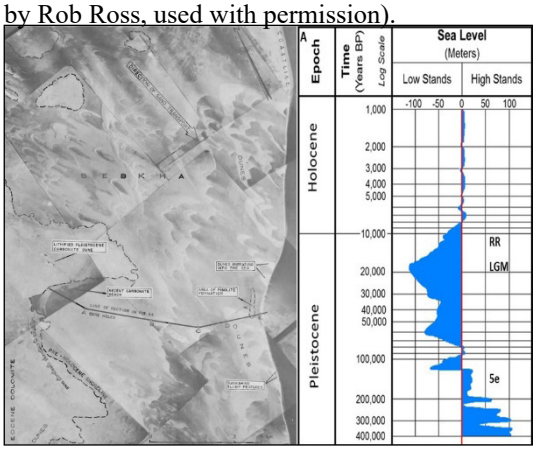
Day 2-Figure 08. The Naqa Felaiha sinkhole from a satellite image (Duggan, Jameson *et al*., 2014).



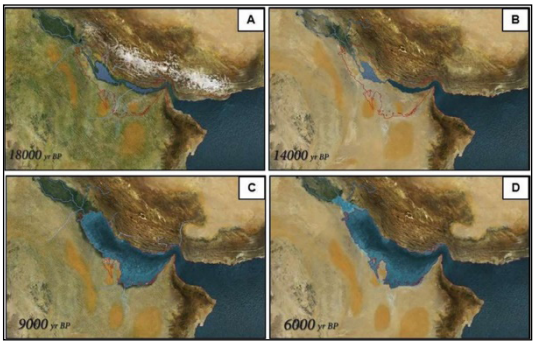
Day 2-Figure 09. Naqa Felaiha showing the sinkhole openings (yellow arrows) between the two "horns". (Duggan, Jameson *et al*., 2014).



Day 2-Figure 10. Showing a prominent complex of Pleistocene beach ridges, Pleistocene dune aeolian facies and, seaward of the Pleistocene outcrop belt, a low-relief Holocene beach. The aeolian facies overlies the beach facies. Aeolian facies are peloid grainstones with well-developed moldic porosity. (Original research image created by Rob Ross, used with permission).



Day 2-Figure 11. Paleoshoreline & Paleoenvironment in SE Qatar (left) (Purser *et al*., 1973). Qatar's sea-level curve (Jameson & Strohmenger, 2014).



Day 2-Figure 12. Paleoshoreline and paleoenvironment reconstructions of the Arabian Gulf from 18,000 to 6,000 years BP (Jameson & Strohmenger, 2014).

Day 3 of 3:

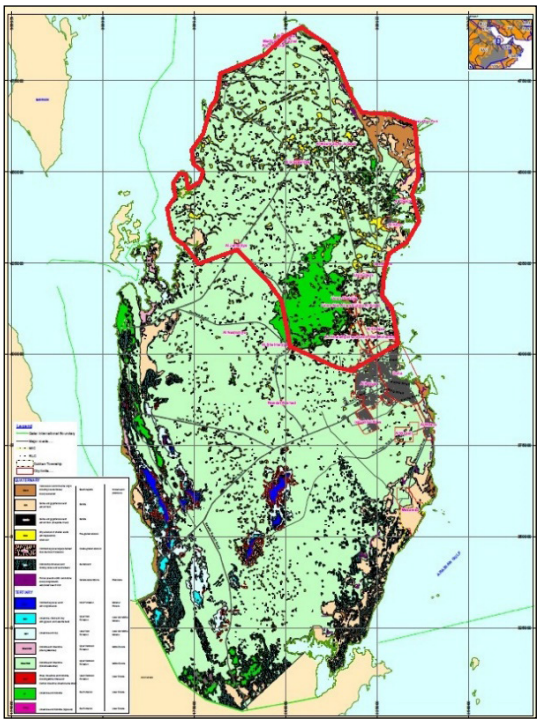
06:30AM (Please be on time) - Meet at IKEA parking lot (Day 3-Fig. 01).
06:45AM - Leave IKEA.
12:00PM - Since it is not clear where we will be around lunch time, we will break for **30 minutes** around 12PM at the most appropriate location.

The general area we will be visiting today is outlined in red in Day 3-Fig. 02, however, if we did miss some important stops in the northern portion of our itinerary on the first day, and time allows to visit them today, we will do so.

Access permissions required for this day: NONE

Stop 1 (a & b): Our first stop is a series of low, buff white-colored cliffs (about 5-6 meters high) topped by an overhang of brown to reddish colored more resistant rock (Day 3-Fig. 03 & Day 3-Fig. 04).

Day 3-Figure 01. Meeting point at IKEA parking lot.



Day 3-Figure 02. General area (in red) to visit on Day-3.

Day 3-Figure 03. Rus Formation at stop 1a (Kok, 2012).

Day 3-Figure 04. Rus Formation at stop 1b (Kok, 2012).

The main lithology at stops 1a and 1b (located at about 50m from each other's) is a white to very light grey colored gypsiferous, very dolomitic sometime chalky limestone, in places containing gypsum.

The white chalky rocks have a typical "flaky" weathering due to their very fine fabric (Day 3-Fig. 05). All over the outcrop can be observed large and small holes and cavities, sometimes aligned. In some of these cavities can be seen nicely shaped crystals of Quartz (SiO_2) mostly opaque milky white in color (Day 3-Fig. 06). Along the bottom of the cliff, irregularly shaped forms can be seen, slightly darker grey in color and much harder and denser than the white dolomitic rock. This is also the same quartz but now in a micro or crypto crystalline (you do not see the individual crystals) form, or Chert (Day 3-Fig. 07).

Walking a bit further along the outcrop, a series of oval shaped cavities are found (Day 3-Fig. 08). These cavities are caused by solution. The original rock was probably a soluble mineral such as Gypsum, Anhydrite, Salt or Dolomite. Over millions of years, but probably fairly recent in the Late Pliocene or even younger Pleistocene, when the climate became cooler and more rain, fresh water percolated deep into the surface and dissolved and washed away the original rocks. At a later stage mineral rich waters percolated through these cavities and minerals such as Quartz precipitated in them.

Day 3-Figure 05. "Flaky" weathering of the chalky limestone (Kok, 2012).

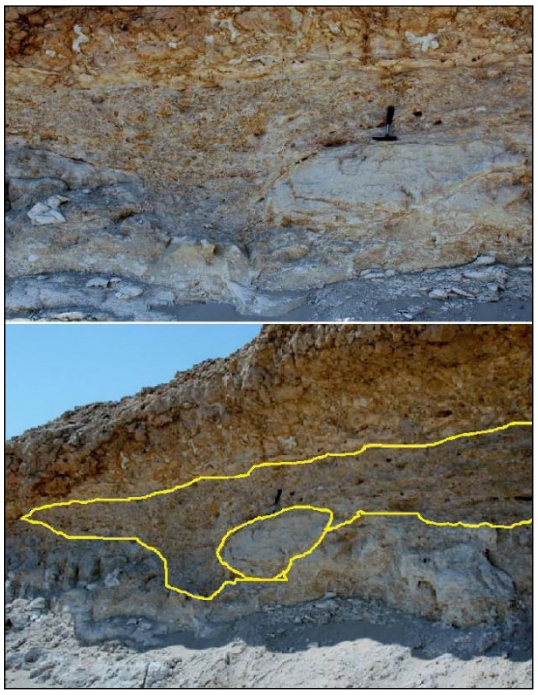
Day 3-Figure 06. Close-up of cavity filled with cm size Quartz crystals (Kok, 2012).

Day 3-Figure 07. Close Typical Chert nodule from the Rus Formation (Kok, 2012).

Day 3-Figure 08. Solution cavities along the bottom part of the section (Kok, 2012).

Day 3-Figure 09. The Rus Formation at Stop 2 (Kok, 2012).

Stop 2: In front of us (Day 3-Fig. 09) can be seen the same white to light grey Dolomite / Dolomitic limestone as at the previous stop. In it, however, is seen a filled in cave; a big lump of Dolomite (below the hammer) sits on the bottom, covered by brecciated (broken up) material. (Day 3-Fig. 10).



Day 3-Figure 10. Filled-in cave, with and without the outline (Kok, 2012), clearly showing that another brecciated layer goes across the collapsed cave. Thus, the layer is of a (much?) later date and was deposited after the cave had been formed through solution, and after it collapsed and was filled by brecciated (broken up) material.

Day 3-Figure 11. Filled in cave in the Dammam Formation as seen in a construction site in Doha (Duggan, 2014).

Such cave-fills occurs frequently in the Rus (Day 3-Fig. 10) and Dammam (Day 3-Fig. 11) formations and are considered a hazard in geotechnical works in Doha and other urban areas.

The top of the outcrop can be reached by walking around it and up from the back. Here can be observed the weathered, hard broken up and recrystallized cap rock, full of strangely shaped cavities, sometimes razor sharp and hard with lots of Quartz. In places the rock is dark red or purple colored caused by traces of iron in the rock. The purple colors (Day 3-Fig. 12) may indicate that this rock was once

Day 3-Figure 12. Purple rock sample. The colour most likely confirms that it was once covered by a soil (Kok, 2012).

covered by a soil rich in organic matters. This must have been in a considerably cooler climate than today, probably during Pleistocene (ice ages) times.

Stop 3: Watson *et al*. (1959) described occurrences of quartz and quartz nodules in boreholes which penetrated the Rus Formation. In his report, Cavelier (1970b) states "*Celestite nodules occur in the region of Khor (Umm Abdah) and likewise a crystalline quartz bed with bitumen in cavities in the upper part of the white limestones in Simsima*".

We will spend some time walking in the Simsima depression area to look at the Rus Formation, especially observing how the quartz and quartz nodules occur in it. Quartz (nodules, chert, etc..) occur at the contact with two limestone layers or in fractures (Day 3-Fig. 13), while others are associated with stromatolites (Day 3-Fig. 14 and Day 3-Fig. 15) or just spread out on hill tops or slopes (Day 3-Fig. 16 and Day 3-Fig. 17).

Stop 4: In 2010 and 2011, the Port of Al-Ruwais, at the northern tip of Qatar, was expanded and modernized. Dredging works took place for some distances offshore (Day 3-Fig. 19) and the material extracted was disposed onshore at the location of our stop. This is a good opportunity to investigate the type of corals currently thriving in the Gulf without getting our feet wet. Corals of all sorts can be found in this disposal site. Four examples are given in Day 3-Fig. 20, Day 3-Fig. 21, Day 3-Fig. 22, Day 3-Fig. 23 while Day 3-Fig. 24 shows examples of corals still in-situ at Umm Tays (we will not visit this location).

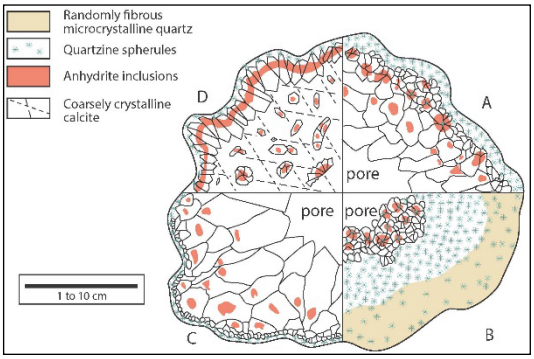
Day 3-Figure 13. Quartz nodules in limestone (top) and spherical amalgamation of quartz crystals (bottom) at the contact of two limestone layers and fractures (LeBlanc, 2017).

Day 3-Figure 14. Large concentric quartz nodules (or large stromatolites?) in limestone (LeBlanc, 2017).

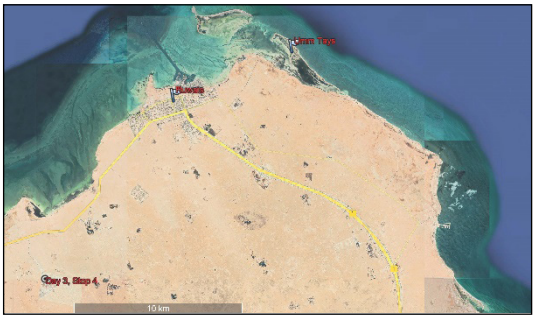
Day 3-Figure 15. Loose and in-situ Quartz field. The quartz occurs just below and at the same level of a stromatolite layer. Quartz nodules (some of cauliflower type - Day 3-Figure 18) also occur and when broken in two, they often display large crystals, often with spherical amalgamation of quartz (LeBlanc, 2017).

Day 3-Figure 16. Field of quartz cobbles & nodules on a limestone hill (LeBlanc, 2017).

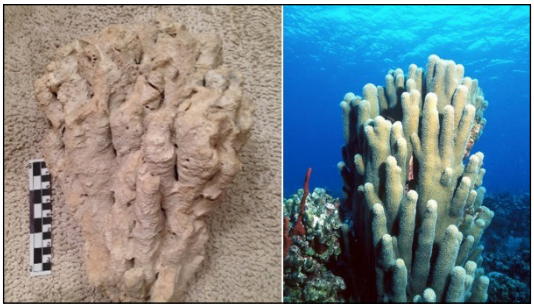
Day 3-Figure 17. Quartz field of cobbles and nodules (LeBlanc, 2017).



Day 3-Figure 18. Texture in silicified-calcitized gypsum nodules (cauliflower chert). **A)** Most common style of nodule with thin rim of spherulitic quartzine followed inward by megaquartz characterised by increasing crystal size and with frequent anhydrite inclusions. **B)** Nodule with a large proportion of fibrous quartz. Thick rim of spherulitic quartz passes inward to strongly undulose megaquartz. Some of the megaquartz has anhydritic nuclei. **C)** Nodule with a thin rim of spherulitic quartzine passing inward to a large proportion of megaquartz. **D)** Nodule with megaquartz rim and an interior filled with calcite. Calcite may have filled a cavity or replaced earlier silica. Late stage cavity-fill calcite is often defined by a thin rim of authigenic, vapor or sulphide, prior to precipitation (LeBlanc, 2017 & Warren, 2016).

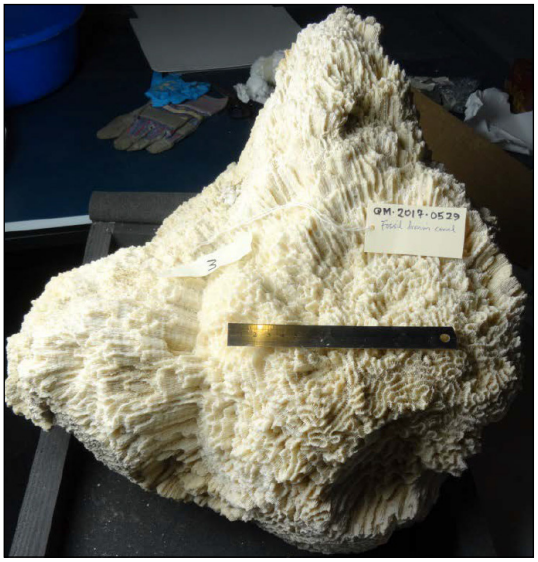


Day 3-Figure 19. Location of our stop in relation to the town of Al-Ruwais and Um Tays Island.



Day 3-Figure 20. Cyphastrea coral, a type of Pillar Coral.

Day 3-Figure 21. Large Dipsastraea Coral.



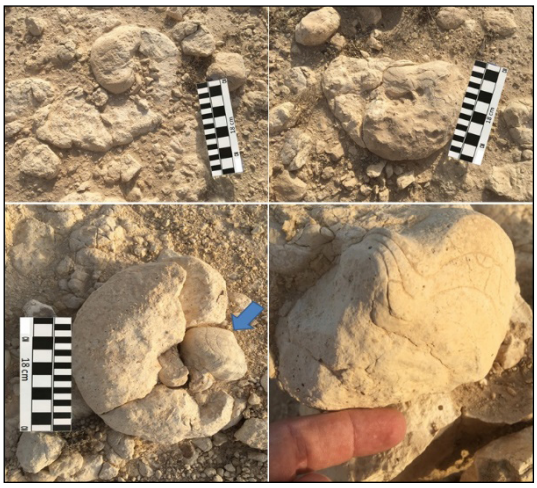
Day 3-Figure 22. Platygyra coral (50 x 45 x 25 cm).

Day 3-Figure 23. Acropora coral.

Day 3-Figure 24. In-situ Holocene corals at Um Tays Island (not visited).

Stop 5 (a, b): This stop in Shahaniya will help us recognizing the Dukhan Alveolina Member of the Dammam Formation on an undulating surface as opposed to a vertical section. We will look at its color, fabric, composition and fossil content (Day 3-Fig. 25) in order to differentiate it with the above/younger Umm Bab Member.

Stop 6 (Last stop): We will park our vehicles outside of a pit in Shahaniyah (located over the crest of the Qatar Arch) on the Dukhan Alveolina limestone and walk down the pit. There, we will observe a compressional deformation (minor fold) within the Rus Formation (Day 3-Fig. 26) as well as a vertical section from the Rus Formation, Midra shale, Umm Bab and Dukhan Alveolina Members. (Day 3-Fig. 27).



Day 3-Figure 25. Nautiloids of the the Dukhan Alveolina Member of the Dammam Formation at stop 5a (top) and 5b (bottom) (LeBlanc, 2019).

Day 3-Figure 26. Small folds within the Rus Formation in Shahaniya (LeBlanc, 2021).

Day 3-Figure 27. A vertical section from the Rus Formation (bottom), Midra shale, Umm Bab and Dukhan Alveolina Members on the wall of a pit in Shahaniyah.

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APPENDIX – A: Pre-Activity Safety Assessment

Activity Name:	Qatar Geology	**Type:**	3- Day Field trip	**Dates:**	

To: Activity Participants

Congratulations on your selection to participate in this Qatar field trip! Because all this activity will take place in field locations, this letter outlines the associated health and safety issues and serves to inform you of potential hazards that need to be considered for your participation. It is important for you to evaluate the stated risks with regard to your own personal health and safety, request reasonable modifications to course delivery, and modify your participation or attendance accordingly.

Sections and Attachments	The following sections and attachments outline the health and safety issues that need to be considered for your participation, as well as the measures in place to prevent and mitigate them: • Field Safety & Health Considerations* • Identification and Mitigation of Potential Safety Hazards* • Guidelines for Driving Company Vehicles (attachment) • Field Activity Safety Acknowledgment Form (attachment) • Emergency and Medical Information Form (attachment) * *Keep these information sheets for reference before and during the Activity*.
Required Actions	• Read all sections and attachments. • Complete and sign the **Field Activity Safety Acknowledgement and Medical Certification form** indicating that you have reviewed and understand the health and safety material provided. • If and only if you are **willing to drive** during the Activity, review and sign the **Guidelines for Driving Company Vehicles** in the attached **Driver Safety Briefing Sheet**. • Return all signed forms to the field trip guide
Deadline	**As Soon As Possible After Receipt.** The signed Safety Acknowledgment form enables your participation in this field trip. Your participation will not be confirmed until you have signed and returned all the forms.
Questions	Questions can be directed to the below email address:

	Name	**Telephone**	**Email**
Guide			

Field Safety & Health Considerations

Field Environmental Conditions	• Be prepared at the beginning of each day to spend 8 hours in the field. Bring a daypack with any medicines you might need, sunscreen, change of shorts, windbreaker and a hat, comfortable shoes (tennis shoes, hiking booths, etc..). A hat that provides sun protection and sunglasses are recommended. It can get dusty if the wind comes up, so those with contacts should bring glasses and be able to change if necessary. Also, lip balm with an SPF rating is useful. • Field trips should take place during the cooler October to April season. Expect the daily temperatures to vary from 20 to 35C. • Most locations are within about an hour from Doha, however, one day will involve a lot of driving to go from one stop to another. There are no bathroom facilities in the field; we will take advantage of vegetation and rocks for little privacy.

Identification of Potential Safety Hazards

Slips, Trips, and Falls	In the field, we will be hiking through flat area and walking up and down limestone cliffs/ slopes, terrasses and quarries; especially in the west and southwest of Qatar.
Personal health/ hazardous conditions	• Poor physical conditioning may lead to overexertion and severe fatigue, which can exacerbate pre-existing medical conditions and contribute to accidents. As detailed in the attached ***Medical Certification*** form, participants with certain serious medical conditions must check with their physician or health services department prior to attending this field work. • Use protective eyewear if hammering on the outcrop. • Beware of loose rocks and avoid drop offs. • Participants are expected to wear reflective and/or high visibility safety vests when situated along busy roads. • Allergic reactions to insect bite or plant puncture wound are unlikely, but possible. Individuals with a history of serious allergic reactions, especially to insect bites or stings should take precautions to avoid bites and stings and speak to their physician about obtaining auto-injectable epinephrine, such as an EpiPen®. • Heat-related illness/dehydration. • Sunburn; use high factor sun protection at all times. • Beware of local inhabitants and camels; also broken glass and sharp objects. • We will enter the Misfir cave. **Bring your own safety helmet** to prevent any hazards with falling rocks. Helmets are mandatory. If you do not feel comfortable with entering the cave, wait outside. • Closest Hospitals/Health Centres during the field trip: o Day 1: The Cuban Hospital east of Dukhan at 25°26′20.58″N and 50°51′34.96″E o Day 2: Messaid Hospital at 25° 0′45.09″N and 51°33′34.49″E o Days 2 & 3: Hamad Hospital (Doha) at 25°17′37.26″N and 51°30′17.89″E o Day 3: Hamad Medical Coprt (Al-Khor) at 25°42′57.20″N and 51°30′58.06″E o Day 3: Al Ruwais Health Centre at 26° 7′28.85″N and 51°12′27.39″E
Motor vehicle hazards	• Local driving habits differ from your country of origin. Take exceptional care when near vehicles, in parking lots, along roadways. • Flat tires are a common potential hazard. • Fatigue, distractions, and inattention during driving are potential hazards. • Fuel spills during fueling are a potential hazard.

Mitigation of Safety Hazards

Overview	• Each person is primarily responsible for his or her own safe conduct, as well as contributing to the welfare of the entire group. Every morning and at each Field Site, the Field Trip Guide will brief the participants on the expected and potential hazardous situations and conditions. • If you are not comfortable participating in any of the particular activities for any reason, you are encouraged to notify the Field Trip Guide. There are no negative implications for this decision.
Trip and fall hazards	• Extreme care and attentiveness while digging/hammering and when approaching the field vehicles and getting in and out of the field vehicles. • Reckless behavior in the field (running and jumping over gullies, etc.), crossing roads without group, or wandering away from the group is unacceptable. • Extreme care must be taken when entering caves

Behavior based risks	• All participants are required to follow the risk assessment and standard operating procedures identified in this pre-trip letter, any trip or site specific orientations, and\or any safety instructions given by the Field Trip Guide. • All participants are required to self-identify any discomfort or pain associated with all field activities. Do not continue to participate if you are experiencing pain or have exceeded your personal tolerance for fatigue/risk acceptance. Notify the Field Trip Guide, and arrangements will be made to modify the activity or provide an alternate level of participation. • Any deviation from these required behaviors are grounds for removal from the field activity and transportation back to your home office.
Personal health hazardous conditions	• Persons under medical care or taking daily medications are advised to consult with their physician or health services department prior to committing to participate in the school. It would also be helpful to alert the Field trip guide of any special medications you may be taking before any emergency situation arises. • Persons with known dangerous allergies to insect bites, foods, etc. should make such allergies known to the Field trip guide so that the appropriate care can be taken of you in the event of an emergency. • Sun block, insect repellant, and proper clothing are needed to reduce the chance of sunburn, insect bites, and overexposure.
Motor vehicle hazards	• Driving safety is the responsibility of all participants, whether driving or not. • Driving is always voluntary, and is reserved for pre-identified, qualified drivers. If you are asked to drive, and are unwilling to do so, inform the Field trip guide that you do not wish to be identified as a driver. • All participants who drive during this field activity must have prior experience operating a large Sport Utility Vehicle and understand the size, handling, and responsiveness of these types of vehicles. • All participants should take responsibility for driving safety. Inform the Field trip guide immediately if you are uncomfortable with any driving habits you observe. • All Participants should pay careful attention to periodic briefings by the Field trip guide on potentially hazardous conditions associated with roadways and the use of the vehicles. • Participants are expected to wear red safety vests when situated along busy roads. • Documented safety procedures on the changing of flat tires and fueling of vehicles must be followed. Participants will wear high-visibility safety vests when working along busy roads. • Take time to familiarize yourself with the vehicle and routes before setting out.

APPENDIX – B: Safety Acknowledgement

Activity Name:	Qatar Geology	Type:	3- Day Field trip	Dates:	

I certify that I have read and understand the content of the Safety Briefing Letter that describes the conditions and potential hazards that may be encountered during the Activity. I have completed and forwarded my **Emergency Contact** information and **Medical Certification** to the Field Activity Leader. I understand the safety precautions that I need to take to minimize the risk to myself and other participants in the Activity. I agree to follow the required safety guidelines and briefings and certify, to the best of my knowledge, that I am physically capable of participating in this Activity. *I consent to the release of the information herein to Activity Staff for the purpose of preparing for and conducting the Field trip and to the retention of this Acknowledgment by the Field Activity Leader so long as evidence of the consents and acknowledgments provided herein are required.*

	Name (Print)	Signature	Date (yyyy/mm/dd)
Your Details			

Background Information: Provide the following to assist the Activity Staff in preparing for the Field Work.

- Dietary Restrictions of Dangerous Allergies (including food allergies). Note: All participants are required to bring their own lunch to the field:

- Do you require any modifications to the Activity methods or activities to participate? (due to, for example, limited mobility/hearing/sight, fear of heights, plant or insect allergies, medical conditions (heart trouble, breathing problems, diabetes, etc.), pregnancy, etc.). Do you require any special emergency response preparations (e.g., medications requiring cold storage)?

☐ No ☐ Yes (specify below)

- What Safety, Health, and environmental training do you have?

Subject	Course Name	Date of Completion
First Aid		
CPR		
AED		
Defensive Driving		
Water Safety		
Small Craft Safety		
Other		

- **Briefly** describe your relevant experience in field activities:

Personal Information (please type or print legibly)[1]

Name (Print):		Date of Birth:	
Email:		Mobile Phone #:	

Personal Emergency Contact:

Contact Name	Relationship	Mobile #	Work #	Home #

[1] Personal information is treated as private and confidential

APPENDIX – C: Medical Certification

Personal Information:

Full Name (Print):		**Date of Birth:**	
Field Activity:	Qatar 3-Day Geological Field Trip	**Dates:**	

The following information may be critical to caring for you in case of an injury or sudden illness during the Activity. It will be used only in the event of an emergency, and only if you are unable to communicate this information to those treating you. This form will be destroyed at the conclusion of the Activity.

Personal Health/Accident Insurance:

Company:		**Policy/ID #:**	

Known Dangerous Allergies (please list): (e.g. medicine, food, plant, animal, insect toxin):

Miscellaneous: I normally wear/use: ☐ Contact Lenses ☐ Dentures ☐ Other (list):

I hereby authorize release of the information herein to medical personnel in case of emergency:

Signature:		**Date:**	
Name (Print):			

Stop here unless the Medical Conditions BELOW apply to you

Medical Certification:

Please provide any information you wish regarding medical condition currently requiring special care, medication, or diet that can adversely affect or limit personal health or safety in the activities described in the overview letter. These may include, but not be limited to: (limited mobility/hearing/sight, fear of heights, dangerous allergies, medical conditions other than those listed below, and pregnancy).[2]

The following conditions require a licensed physician or nurse practitioner to certify your fitness to participate in the Activity:

	Asthma		Convulsions/seizures		Fainting Spells		High blood pressure
	Bleeding disorders		Diabetes		Heart Trouble		

Health-care provider's statement: I have examined this patient and certify that the existence of the conditions checked above do not prohibit him/her from participating in the activities described in the Safety Briefing Letter.

Medical Signature:		**Date:**	
Name (Printed)			

[2] Personal information is treated as private and confidential