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ORIGINAL RESEARCH

Stratigraphic Lexicon: A revised guide to the Cenozoic Surface Formations of Qatar, Middle East (excluding the islands)

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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. Here, he reviews and updates the surface stratigraphic knowledge of Qatar since the last lexicon was published back in 1975. The geology and macro-paleontology of the Lower Eocene Rus, Middle Eocene Dammam, Lower Miocene Dam and Mio-Pliocene Hofuf formations are described in detail and well illustrated.

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1 Introduction

The history of stratigraphy in Qatar (both surface and sub-surface) was well documented in LeBlanc (2015b)'s publication. In the "Conclusions" of this document, the author highly recommended to update Sugden et al. (1975)'s Stratigraphic Lexicon of Qatar. Therefore, as an initial step in that direction, I now take upon myself to update the current knowledge of the four Cenozoic Surface Formations of the country (Fig. 1 & Fig. 2). Essentially, this work is an update to Cavelier (1975)'s "Tertiary in Outcrops" which is an integral part of Sugden et al. (1975)'s Lexicon. With regards to the islands of Qatar, the reader is directed to LeBlanc (2015b) in which are found a good summary of their geology and a reference list of the best publications describing them. Also, the present work does not discuss the Pleistocene and Holocene deposits sparsely found around Qatar since they are not Formations in the strict sense of the term.

Other than the expected detailed discussion on the stratigraphy of the four formations and their members, this highly illustrated revision introduces the following topics:

A) Rus Formation:
   a. Uses the stratigraphic nomenclature from Al-Saad (2003) instead of Cavelier (1975);
   b. Includes the silicified paleo-fluid escape structures described by LeBlanc (2017) ;
   c. Includes examples of faults, fractures and folds visible in the Rus and previously detailed in LeBlanc (2017);
   d. Includes the thickness details of the Rus Formation (and few Dammam members) in the "Dahl al Misfir" cave.

B) Dammam Formation
   a. Offers a Reference Section made up of a composite of 5 different localities.
   b. Includes a poster describing the Umm Bab dolomite and Limestone Member from the Naslat Umm Hadidah area.
   c. Includes a poster describing the lithology and fossils of the Formation.
   d. Illustrates the bio activities of the molluscs and echinoderms in the Umm Bab dolomite and Limestone Member.
   e. Stress the occurrence of nautiloids in its

Umm Bab dolomite and Limestone Member; LeBlanc (2019).

f. Discusses the paleo-fluid escape structures associated with the occurrence of silica in younger layers; LeBlanc (2017).
g. Includes the new Bir Zekreet Shale Member first described by Kok & LeBlanc (2012).
h. The "Rujm Aïd Velates limestone Member" of Cavelier (1975), also previously known as “Fhaihil Velates Limestone Member” of Cavelier, (1970a), formerly at the base of the Dammam Formation is now obsolete. This rock interval has now been incorporated in the Al-Khor Limestone bed of the Rus Formation; Al-Saad (2003).
i. Includes the thickness details of some Dammam members (and Rus Formation) in the “Dahl al Misfir” and Dahl al-Hammam caves.

C) Dam Formation

a. Officially incorporates the stratigraphic subdivisions (3 members) proposed by Dill et al. (2003) and cease to use the simpler terminology of Cavelier (1975); i.e: Lower/Upper Dam
b. Renames Dill et al. (2003)’s lower member of "Salwa" to "Al-Kharrara" as proposed by Al-Saad (2002a).
c. Uses Djebel Al-Nakhash as the Reference section locality
d. Offers an updated poster describing its lithology and fossil content; LeBlanc (2009).

D) Hofuf Formation

a. Officially incorporates the stratigraphic section of the formation from Al-Saad et al. (2002b).
b. Explains/Illustrates the formation's origin
c. Interprets a section within the QNCC sand quarry
d. Briefly discusses the contaminants afflicting the Hofuf

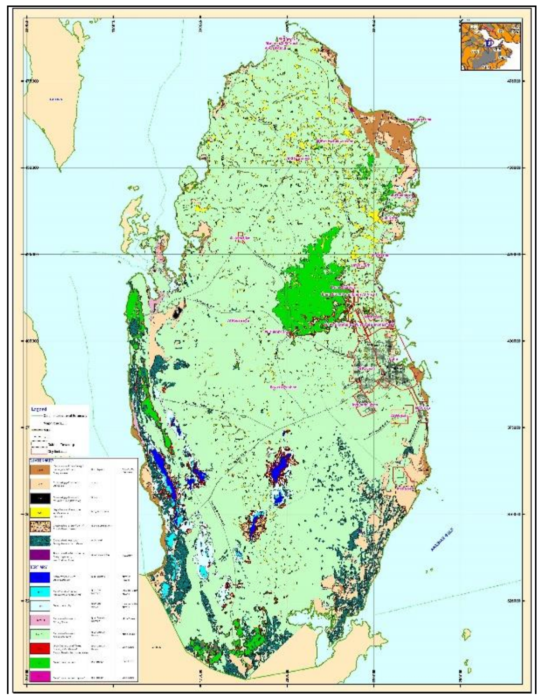
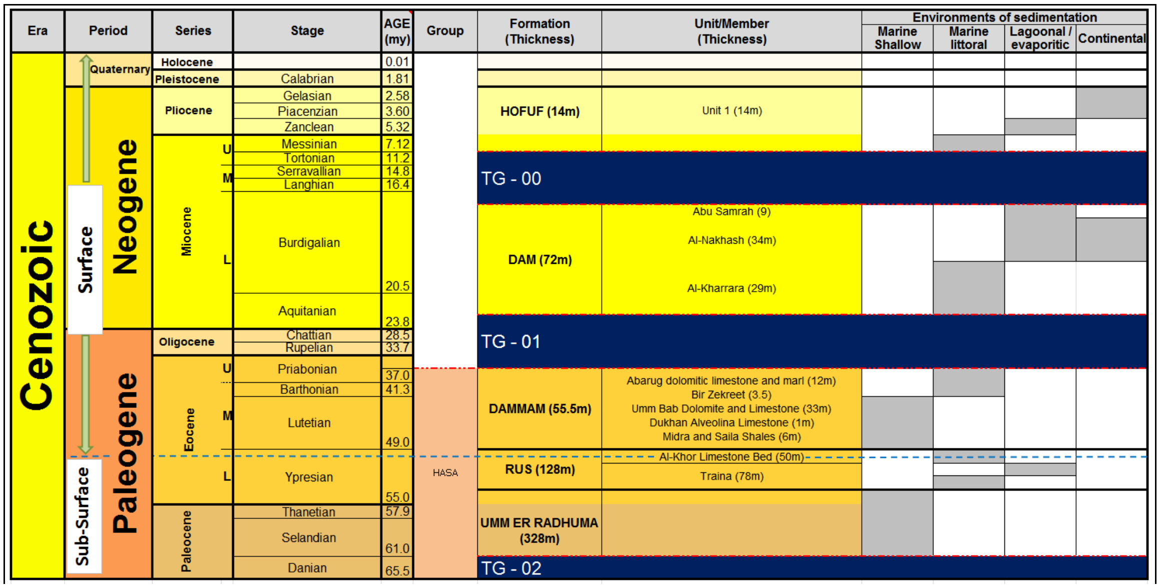


Figure 1. Geological Map of mainland Qatar. (not an authority on international boundaries)



Note 1: Color codes and Stage names are taken from the "Commission for the Geological Map of the World (CGMW)", Paris, France. **Note 2:** The "Rujm Aïd Velates limestone Member" of Cavelier (1975), also previously known as "Fhaihil Velates Limestone Member" of Cavelier, (1970a), formerly at the base of the Dammam Formation is now obsolete. This rock interval has now been incorporated in the Al-Khor Limestone bed of the Rus Formation; Al-Saad (2003). **Note 3:** TG = Time Gap

Fig. 2. Geological Section of the Cenozoic Formations of mainland Qatar (Surface & Sub-Surface)

2 Lower Eocene Rus Formation

A) Origin of the name and main authors: Bramkamp (1946, cited in *Powers et al*. 1966) first applied the name Rus Formation as a direct replacement for the term "Chalky Zone" which had been informally used for Lower Eocene beds above the Umm er Radhuma (UER) and below the Dammam Formation. Thralls & Hasson (1956) wrote the first formal publication which used the term Rus Formation. The same nomenclature was adopted for Qatar by Sugden (1956) and for Bahrain by Willis (1967). Steineke et al. (1958) gave detailed information on the type sequence and Sander (1962) published more details on the stratigraphic and paleontologic data. Detailed descriptions were also provided by Powers (1968) in Saudi Arabia) and Cavelier (1970a) in Qatar).

B) Type locality: The Rus Formation was first named from the rocks of the Umm er Ru'us (Lat. 26°19'30"N, Long. 50°10'00"E), which outcrops on the Dammam Dome in Saudi Arabia (Powers et al. (1966)). A description of the Rus at that location follows:

Description of the exposed Rus Formation at the Type Locality (Type Section) in Saudi Arabia:

Thickness: 183.72 ft (56 m)

Lithology: The lithology and thickness of the Rus Formation are variable, with most of the variation occurring in the middle unit of the three units described as follows (thicknesses are those of the type section).

1	Top: White, soft, chalky porous limestone, with one or more calcarenite beds at the top; 11.48 ft (3.5 m)
2	Light-colored marls with local irregular masses of crystalline gypsum and occasional thin harder limestone beds; geodal quartz at several levels. In other areas this unit is highly variable, including as common equivalents – (a) white, compact, finely crystallized anhydrite with interbedded green shales and minor amounts of dolomitic limestone, or (b) gray marls with coarsely crystalline calcite and interbedded shale and limestone; 103.67 ft (31.6 m)

3	Base: Gray to buff compact crystalline limestone commonly partly dolomitized, with minor amounts of soft limestone made porous by the leaching of small organic remains and occasionally with strata containing abundant molds and casts of small bivalves and gastropods. Quartz geodes occur rarely in the lower part, and are typical of the uppermost part; 68.57 ft (20.9 m)

Limits: The base is at the contact of dolomite containing *Lockhartia tipper* Davies of the upper Umm er Radhuma, with overlying light-colored dolomitic limestone commonly with leached indeterminate molds of small molluscs of the basal Rus. The top is at the contact of light-colored calcarenite layers of the upper Rus, with overlying thin-bedded impure limestone and shale of the basal Dammam formation.

C) Qatar Reference Section: Cavelier et al. (1970a & 1970b) measured and established a reference section for the exposed Rus Formation (about 26m thick) in the cliffs at Lat. 25°17’15.79”N, Long. 50°48’12.60”E. Sugden et al. (1975) also reconfirm it in the official stratigraphic lexicon of Qatar (Figs. 3 & 5).

Figure 3. Type section locality of the exposed Rus Fm suggested by Cavelier (Sugden et al.1975).

The Rus deposits, in the Qatar Reference section area, are variably dolomitized limestones, soft, generally whitish, with minute argillaceous intercalations and green to brown dolomitic marl. Some harder greyish limestone beds, generally dolomitic, intercalate and are the only fossiliferous beds in the section. Some siliceous occurrences (chert & quartz crystal geodes) can be observed towards the base of the section (Fig. 5) that evoke the existence of former levels of gypsum lenses and/or indicate mineralization through the presence of nearby faults.

In addition, from LeBlanc (2017)’s investigation, the silica present in an area NW of Dukhan town is related to the tectonic setting of the anticline of the Dukhan oil field and its origin is linked to the silicified remains of the main tubular conduits of paleo-freshwater springs charged with a high content of sulphide (and possibly oil) (Fig. 4). While these paleo-springs can be observed today in the Rus Formation, they were most likely active during the Miocene. The environment that existed at the time must have looked similar to the water-gas-oil seepage taking place today in Azerbaijan.

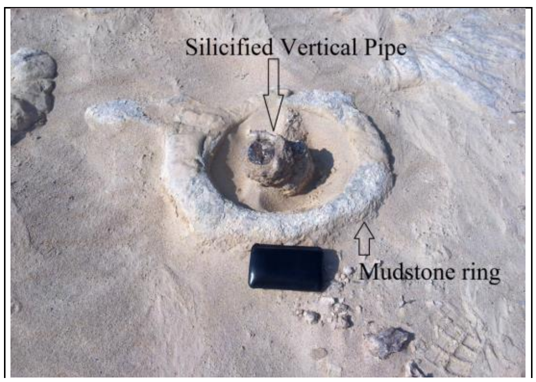


Figure 4. Silicified vertical pipe with circular mudstone features around it. The inner axial portion of the ring is bent upward around a near vertical core structure that is also silicified. These structures reach a maximum diameter of 45 cm. Their form and size are consistent with a fluid escape structure. They apparently formed by breaching the sediments of a shallow paleo-sea.

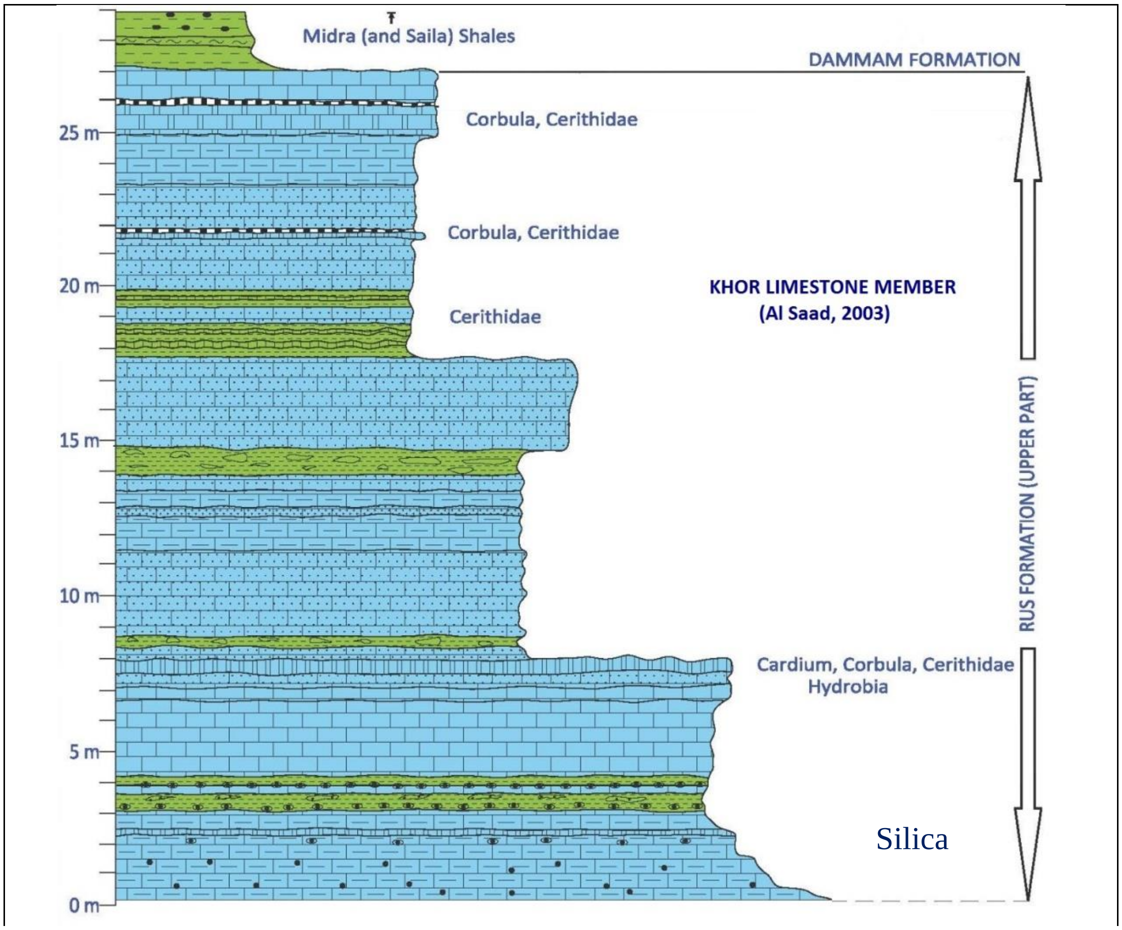


Figure 5. Qatar Reference Section: Cavelier (1970a & 1970b)'s section at Lat. 25°17'15.79"N, Long. 50°48'12.60"E which displays the exposed section of the Rus Formation. The Khor Limestone member's nomenclature is taken from Al Saad (2003) (see also Fig. 6).

D) Age: Lower Eocene; Cavelier (1975).

E) Top (MD): From 0 m in the south by Sawda Nathil and north of Dukhan town to about 25 m above sea level also north of Dukhan town.

F) Thickness: 85.30 ft (26 m) of limestone is exposed at the Qatar Reference section. The total thickness of the Rus (at surface and in the sub-surface) varies greatly within the country. The minimal known thickness is 91.9 ft (28 m) at Latariyah, NW of Doha, in anticlinal position. In the sector affected by the Simsima Dome (NE Qatar), it varies from 98.4 to 147.6 ft (30 to 45 m). In synclinal position, the Rus is thicker [275.6 ft (84 m) in Doha and reaches 419.9 ft (128 m) at Traina farm in southern Qatar]. In the offshore it displays a thickness of 367.5 ft (112 m) in Idd-el-Shargi; Cavelier (1975) and Al-Saad (2003).

G) Lithologic Description (Sudgen et al. (1975) In Qatar, the Rus outcrops over the Dukhan anticline, in north-central Qatar and in the South by the border with Saudi Arabia (Fig. 8). Boukhary, Al Sharhan (1998) divided the exposed Rus Formation in Qatar into 2 Members (Doha and Sulaimi) and named the unexposed portion of the Rus as "Abu Samra" based on observations from boreholes in northern Qatar. Al Saad (2003) renamed Boukhary, Al Sharhan (1998)'s subsurface "Abu Samra" Member as "Traina" Member from well DW4 near the village of Traina in Southern Qatar. He also renamed their Doha and Sulaimi members to only Al Khor (Fig. 6, Fig. 7).

1956 Thralls & Hasson	**1970** Cavelier (all surface of Qatar)	**1975** Cavelier (Lexicon) (all surface of Qatar)	**1984** Abu-Zeid & Boukhary (surface of Dukhan anticline)	**1991** Abu Zeid (Northern Qatar)	**1998** Boukhary & Al-Sharhan (Northern Qatar)	**2003** Al Saad**
Rus	**Fhaihil *Velates* Limestone Mbr*** (Dammam Fm)	**Rujm Aid Mbr*** (Dammam Fm)	**Member B**	**Member C**	**Doha**	**Al Khor** (50m)
	Khor Limestone Bed	**Khor Limestone Bed**		**Member B**	**Sulaimi**	
	(unnamed)	*(unnamed)*	**Member A**	**Member A**	**Abu Samra**	**Traina** (78m)

*=
1) Originally included at the base of the Middle Eocene Dammam Formation by Cavelier.
2) The name changed from 1970 to 1975 because the name of "Fhaihil Velates limestones member" was homonym of the Fahahil Formation, Upper Jurassic, defined by Sugden in 1959 (see LeBlanc (2015b).
3) There is enough evidence today to include it under the Rus Formation (as shown above from 1984 to 2003). This publication will therefore follow Al Saad (2003)'s members nomenclature for the Rus Formation
**= The surface sections are in the areas of the Dukhan Oil Field (western Qatar), Umm Sala Ali (central Qatar), Al-Khor and Al-Zakheira (north-east Qatar). The subsurface samples are obtained from Traina farm (southern Qatar) and Ras Laffan area (NE).
Fig. 6: Members of the Rus Formation over time.

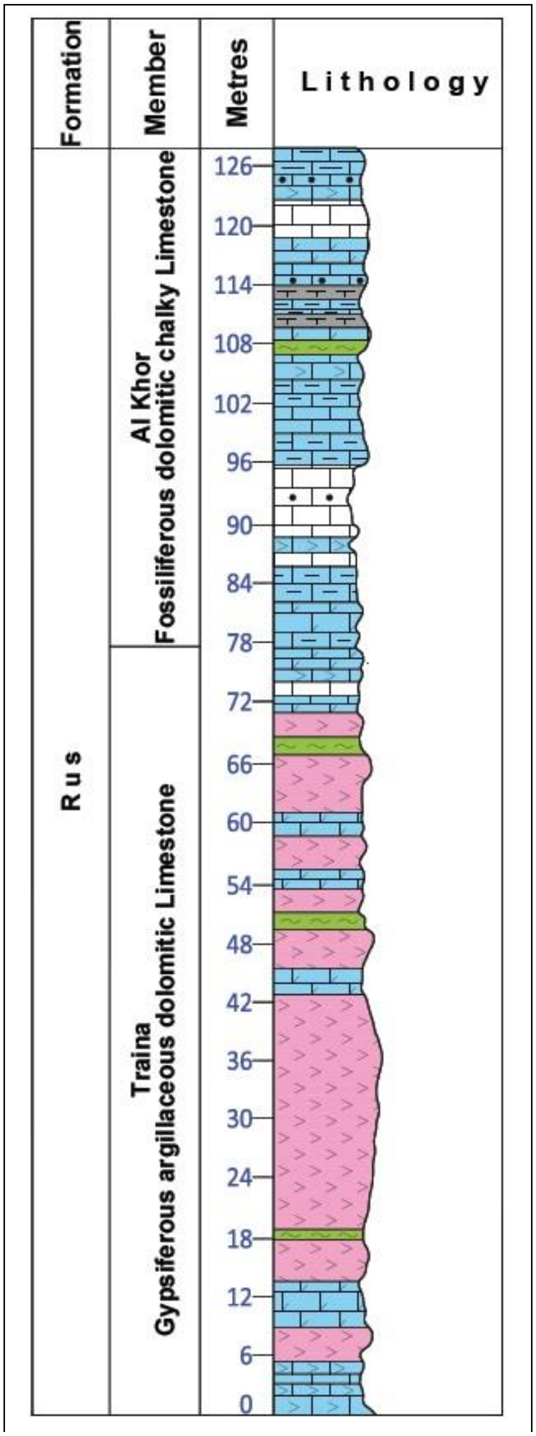


Figure 7. Generalized composite stratigraphic section of the complete Rus Formation in Qatar. Based on Al-Saad (2003).

The contact between the underlying Umm er Radhuma (UER) sequence and the Rus Formation in many areas is abrupt. In Qatar it is characterised by the disappearance of a marine fauna and generally by facies change. However, as described below, facies similarity and post-depositional dissolution processes pose certain difficulties in establishing the formational contact locally.

Sander (1962) reports Saudi Arabian fossil evidence from the basal Rus Formation beds which indicate a shallow marine depositional environment. Hewaidy et al. (1993) reports on foraminifera in the formation in Qatar. The abrupt facies change into the Rus Formation over much of the area suggests a possible sedimentary hiatus after the deposition of the Umm er Radhuma. Evidence from Saudi Arabia indicates that the hiatus was associated with uplift and land emergence in some positive structurally controlled areas.

With the continuation of sedimentation, the Rus Formation appears to have been deposited in a shallower sea than the Umm er Radhuma. The distribution of facies in the Rus Formation and the thickness variation of the unit, however, show that the depositional environment was variable over Qatar and it is believed that sedimentation was controlled by gentle structural movements. Eccleston (1981) states "*deposition took place in warm, shallow, sometimes turbid waters, which resulted in predominantly thinner purer chalk and limestone (with only subsidiary evaporites) in areas of positive structural influence, whilst relatively thicker, turbid and evaporitic sedimentation occurred in the structurally negative areas*". However, some doubts persist with regards to this statement. Restriction and high rates are usually associated with shallow, barred lagoons. Areas lacking evaporites are more likely to have been more open and deeper. May be the lack of evaporites along the crest is diagenetic (Jameson, 2017).

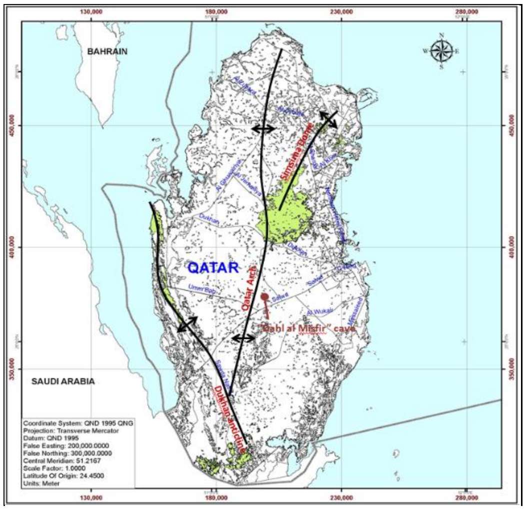


Figure 8. Occurrences of the Rus Formation at the surface of Qatar in relation to the main structural features of the country (Qatar Arch, Simsima Dome and Dukhan Anticline). It also shows the location of the "Dahl al Misfir" cave in relation to the crest of the Qatar Arch.

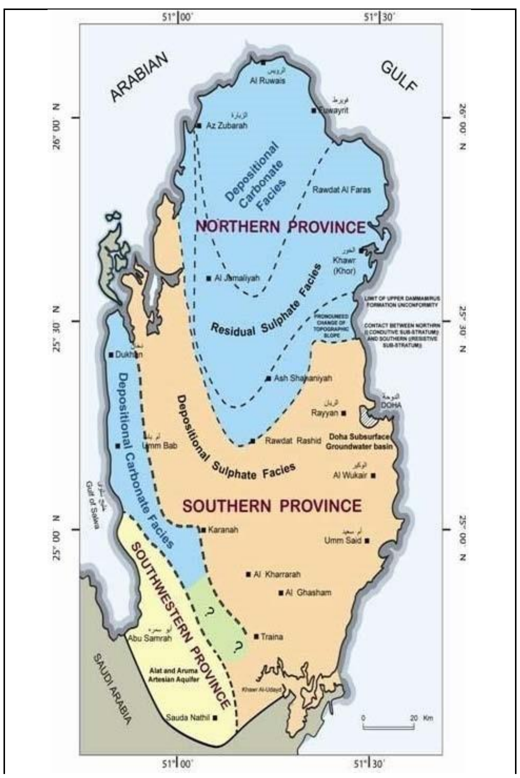


Figure 9. Surface & Sub-surface depositional facies of the Rus Formation in Qatar (Eccleston, et al., (1981) modified by Elobaid: In Tollenaere (2015).

The marked increase in the thickness of the Rus Formation deposits from the structurally high to the structurally low areas suggests that compensatory epirogenetic subsidence was occurring at the time of deposition. The regional distribution of the different depositional environments is shown in Fig. 9. The structural influences are believed to have persisted from the beginning of the Cenozoic and possibly earlier (Eccleston, 1981).

The variable mode of deposition of the Rus Formation has led to two major facies being present in Qatar; these are a gypsiferous, argillaceous, facies termed the Sulphate Facies and a calcareous facies or Carbonate Facies. The evaporitic areas are restricted from marine circulation, thus the reason they have sulphates. They are more likely shallow. The carbonates are open marine, possibly shoals, beaches. 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. Fig. 9, Fig. 10, Fig. 11 illustrate the distribution of the two facies and indicate the southward shift to the present-day contact between the predominantly carbonate Rus of the north and the sulphate Rus of the remainder of Qatar due to dissolution of the anhydrite within the formation.

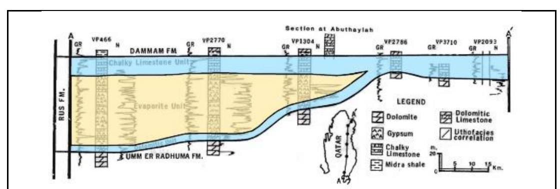


Figure 10. North-South cross-section of Qatar showing the various lithologies and thicknesses of the Rus Formation (Al-Hajari et al, 1992).

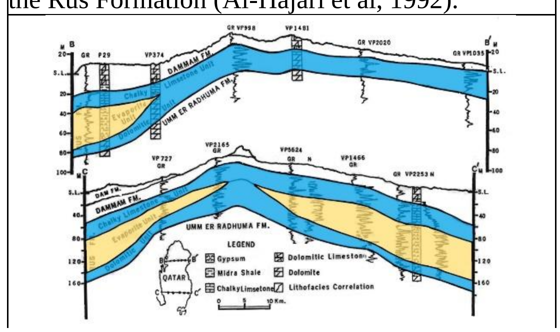


Figure 11. Two East-West cross-sections in the North & South of Qatar showing the structure, lithologies and thicknesses of the Cenozoic formations, including the Rus; Al-Hajari et al. (1992).

H) Fossil Content: Rare bivalve & gastropod impressions and molds, little diversified, were recognized: *Cardium sp*., cf. *Cuneocorbula*, small *Veneridae*? and especially *Cerethidae*, such as *Trypanaxis cf. daviesi* Cox; Cavelier (1975).

I) Faults, Fractures, Folds and Caves: Faults are very much present everywhere in the Formation whether at the surface or in the subsurface but more specifically over the Qatar arch (Fig. 12a, Fig. 12b) and Dukhan anticline (Fig. 13, Fig. 14). Abu-Zeid (1991) studied several wells in northern Qatar which penetrated the Rus Formation in the subsurface and observed two normal longitudinal and transverse faults, the transverse fault having a northward down-throw of about 25 to 30 ft (7 to 9 m). The two faults were also cutting through the younger Umm Bab Member of the Dammam Formation (Fig. 12a, Fig. 12b). LeBlanc (2017) illustrates and interprets a Normal fault at the surface over the Dukhan oil field (Fig. 13, Fig. 14).

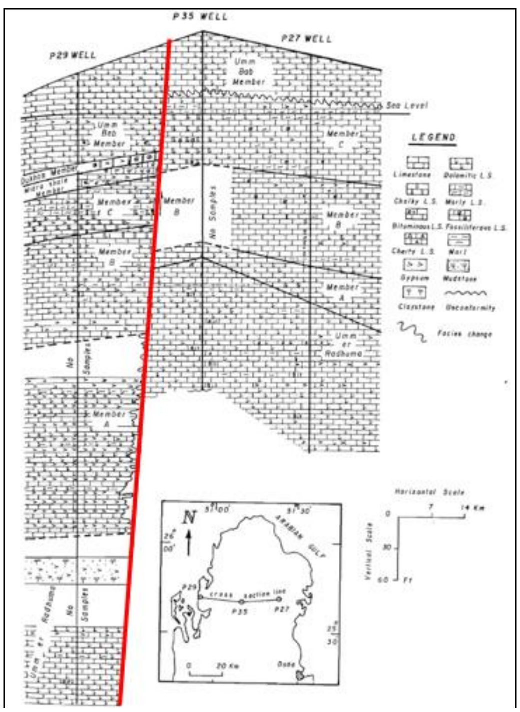


Figure 12a. East-West lithostratigraphic correlation of the Paleogene rock units in the northern region of Qatar showing occurrences of faults cutting through the Rus Fm. (Abu-Zeid (1991)).

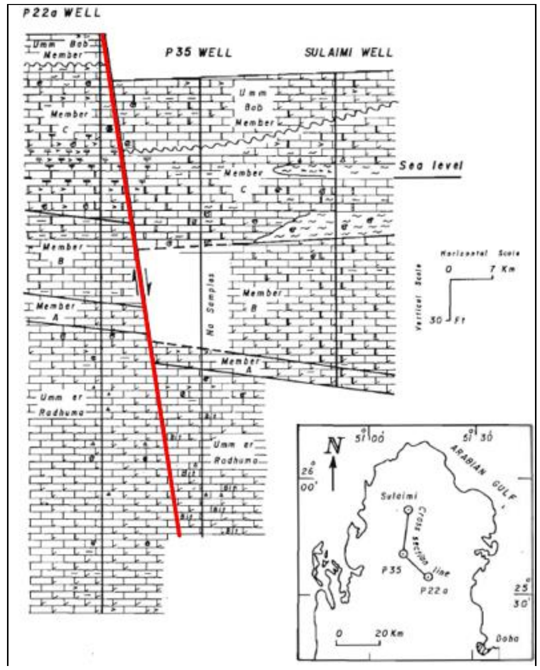


Figure 12b. North-South lithostratigraphic correlation of the Paleogene rock units in the northern region of Qatar showing occurrences of faults cutting through the Rus Fm. (Abu-Zeid (1991)).

Figure 13. Normal fault seen in the Rus Formation at locality Lat. 25°26’18.95”N, Long. 50°47’3.05”E (LeBlanc, 2017).

Figure 14. Interpretation of the Normal fault seen in Fig. 13.

Minor folds, or compressional deformations, are also visible and frequent in manmade pits cutting through the Rus in the Shahaniya area, located over the Qatar Arch (Fig. 15).

Figure 15. Small folds within the Rus Formation in Shahaniya at 25°21'58.04"N, 51°14'27.60"E.

Fractures are also very common and remain the best indicator of the stress experienced by the rocks that make up Qatar today whether over an anticline (Fig. 16) or Arch (Fig. 17, Fig. 18) position.

Figure 16. Fracture in the Rus Formation located over the Dukhan anticline and filled in with quartz (Lat. 25°29’37.94”N, Long. 50°46’14.99”E) (picture by Kok, Pers. Com.)

Figure 17. Few of the many fractures (shown with arrows) and small folds observed in the Rus Formation at the bottom of the “Dahl al Misfir” Cave (Fig. 8), at Lat. 25°10’30.56”N, Long. 51°12’42.23”E (LeBlanc, 2017). See Fig. 18 below for a more general view. People on the picture are: Christian Strohmenger (left) and John M. Rivers (right), both geologists from ExxonMobil-Qatar.

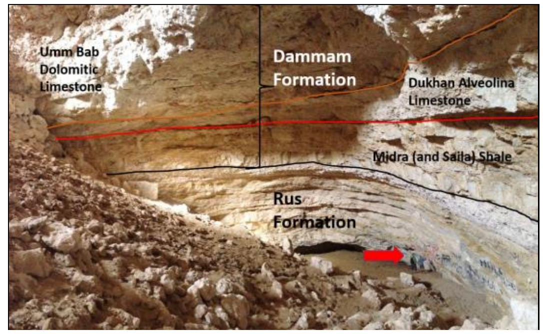


Figure 18. Rus (and Dammam) Formation in the “Dahl Al Misfir” cave (Fig. 8). Red arrow in the Rus points to the wall of the Rus Formation seen in Fig. 17. The Dammam Formation displays its main members (Midra (and Saila) Shale, Dukhan Alveolina Limestone and Umm Bab Dolomitic Limestone); only the Bir Zekreet Shale and the Abarug dolomitic Limestone and Marl Members of the Dammam Formation are absent at this locality

Our[1] stratigraphic measurements in the Dahl Al Misfir cave (from the entrance of the cave to the bottom) using a "Jacob Staff" and a laser pointer are:

Top

- 18.75m (61.52ft) - Umm Bab Dolomite and Limestone Member of the Dammam Formation
- 01.75m (05.74ft) - Dukhan Alveolina Limestone Member of the Dammam Formation
- 02.00m (06.56ft) - Midra (and Saila) Shales Member of the Dammam Formation
- 15.25m (50ft) - Rus Formation (top portion of the Al-Khor Member)

Base

Total Depth: 37.75m (123.85ft)

In comparison, the measurements taken by Shaw & Cox in 1933 showed a depth of 45.42m (149ft) (LeBlanc, 2015b). The difference could be due to:

A) The cave filled up with sediments/debris since 1933.
B) Shaw & Cox could have measured to the surface above the roof top of the cave (slightly higher than the entrance of the cave).
C) Shaw & Cox could have made some errors in their measurements, or
D) A combination of all the above.

[1] A team effort composed of the author and Mr. Pim Kaskes, Mr. Dylan Bastiaans, Dr. Kaveh Samimi (all from “Naturalis” in Netherland, under contract with the National Museum of Qatar)

3 Middle Eocene Dammam Formation

A) Origin of the name and main authors: First used by Bramkamp R.A. in an unpublished 1941 report, Saudi Arabia, and formerly described by Powers et al. (1966), Saudi Arabia. Other authors also studied the formation in Bahrain and Qatar, such as Willis (1967) and Cavelier (1970a) respectively.

B) Type locality: Along Dhahran-Al'Alah road in Saudi Arabia from where this road intersects the rimrock (lat. 26°19'16"N, long. 50°04'50"E) northwest to the Eocene-Miocene contact; Powers (1968).

Type Section:

Thickness: 106.6 ft. (32.5 m).

Lithology: Limestone, tan to light brown with interbeds of marl in upper part and shale in the lower part.

Fossils: *Alveolina* cf. A. *decipiens* SCHWAGER, *A. eliptica* (SOWERBY) var. *flosculina* SILVESTRI, and Nummulites spp.

Age: Lower and Middle Eocene (Ypresian-Lutetian). After Powers (1968); however, see comments for Qatar under "Age" below.

Underlying Formation: Rus Formation; contact conformable, taken at sharp change from brown shale above to chalky calcarenite below.

Overlying Formation: Hadrukh Formation; contact unconformable, marked by clean limestone below and sandy limestone above.

C) Qatar Reference Section[2]: A composite section, made up from 5 different Qatar localities is presented for the first time in Fig. 19.

- **A)** Abarug dolomitic Marl and Limestone Member – Natural exposure at Lat. 25°26'31.56"N, Long. 50°50'57.56"E; Leblanc (2015a). (Fig. 64)
- **B)** Bir Zekreet Member – Natural exposure at Lat. 25°26'32.20"N, Long. 50°51'52.70"E; (Kok, LeBlanc (2012) (Fig. 62, Fig. 63).
- **C)** Top portion of the Umm Bab Dolomite and Limestone Member[3] – Natural exposure at Naslat Umm Hadidah at Lat. 25°24'5.52"N, Long. 50°53'7.59"E (Fig. 42 & Appendix C)
- **D)** Thick portion of the Umm Bab Dolomite and Limestone Member from its base at the QNCC quarry pit – Lat. 25°11'47.87"N, Long. 50°50'15.28"E; LeBlanc (2015a). (Fig. 44, Fig. 45)
- **E)** Natural exposure of the bottom portion of the Umm Bab Dolomite and Limestone Member and full section of the Dukhan Alveolina Limestone, and Midra (and Saila) Shales - Lat. 25°17'15.79"N, Long. 50°48'12.60"E [1Km east of QP's Fahahil plant; Cavelier (1970a). (Fig. 21, Fig. 22)

D) Age: Middle Eocene (in Qatar). During his 1969-70 survey of Qatar, Cavelier collected several specimens of micro & macro fossils. Foraminifera, very easily collected from all surface formations and very useful in dating a rock unit, comprised a large part of his collection. Together with Dr. Alphonse Blondeau, a palaeontologist at the "Centre National de la Recherche Scientifique" in France, he published an article on the Foraminifera collected during his survey (Blondeau, Cavelier (1972)). Previous authors (Henson (1948); Sander (1962); Smout (1954)) had attributed the Lower part of the Dammam Formation as Lower Eocene and its Upper part to the Middle Eocene. These older studies however were based essentially on samples originating from drill cuttings; this could have led to some errors with regards to the exact rock unit they came from. Blondeau, Cavelier (1972)'s investigation resulted in defining more accurately that the whole of the Dammam formation is of Middle Eocene age. Casier (1971) also came to the same conclusions

[2] In Sugden et al. (1975) Standring suggests to use the "complete" section of the Dammam Formation between Dukhan town (lat. 25°26' N, long. 50°47' E) and the head of Zekreet bay (lat. 25°28' N, long. 50°49' E), however, the Umm Bab Dolomite and Limestone Member between these two points is not well exposed, being mostly covered with sand and loose detritus/rubble resulting from weathering. Cavelier (1970a), on the other hand, recognized that no well-exposed and complete section of the Dammam Formation exists in the country.

[3] A secondary option, but not as thick as the one selected, is seen in Fig. 43; LeBlanc (2015a).

while studying the ichthyological fauna (shark & ray teeth, etc..) samples also brought back by Cavelier; while Cavelier's study on fossil Mollusca from Qatar also resulted in the same findings.

Therefore, based on the "Grand Foraminifera" alone, the authors were able to link the Dammam Formation to the Lutetian of Western Europe; the lower Dammam being from the Lower Lutetian while the upper Dammam is of Upper Lutetian age.

E) Top (MD): From 0 metre along the coast of Qatar to 74 metres at Jebel Dukhan

F) Thickness[4]: As per our current knowledge, the maximum thickness of the Dammam Formation in Qatar is 173.9ft (53 metres) (Fig. 19).

G) Lithologic and fossil Descriptions: The deposits composing the Dammam Formation cover about 80% of the surface of the Qatar Territory (Fig. 20). The subdivisions of the Dammam Formation were regrouped into two sets in Qatar by Cavelier (1970a): the Lower Dammam Subformation[5] which includes the two lower members (Midra (and Saila) Shales and the Dukhan Alveolina Limestone), and the Upper Dammam SubFormation composed of the Umm Bab Dolomite and Limestone[6], Bir Zekreet[7] and Abarug Dolomitic Limestone and Marl[8] members Fig. 19.

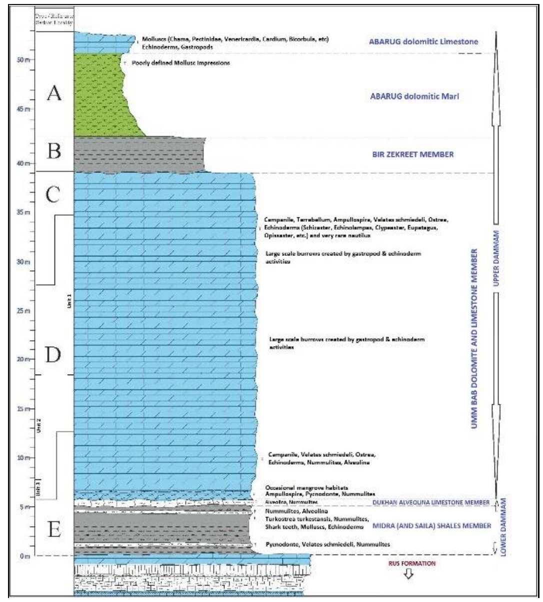


Figure 19. Composite section of the Dammam Formation in Qatar from 5 different localities. See under "Qatar Reference Section" above for the locality coordinates of "A" to "E". Units 1, 2 and 3 within locality "D" refer to the QNCC quarry section in Fig. 44.

[4] See below some comments about the thickness of the Umm Bab Dolomite and Limestone Member

[5] Today, it excludes the Rujm Aïd member of Cavelier. This name is obsolete. The rock unit is now part of the Rus Fm.

[6] This member is wrongly called "Simsima" by the GeoTechnical companies working in Qatar. This is a misleading practice since the name "Simsima" has been used for many years by the oil industry to refer to a sub-surface Cretaceous formation; Dunnington (1959, p. 239) and in J. Inst. Petr., 1967, 53 (520), pl. I, as well as by Dominguez (1965).

[7] New member described by Kok, LeBlanc (2012).

[8] The spelling of this member is with "g" and not "k" [Abarug]; Cavelier (1970a); Sugden et al. (1975).

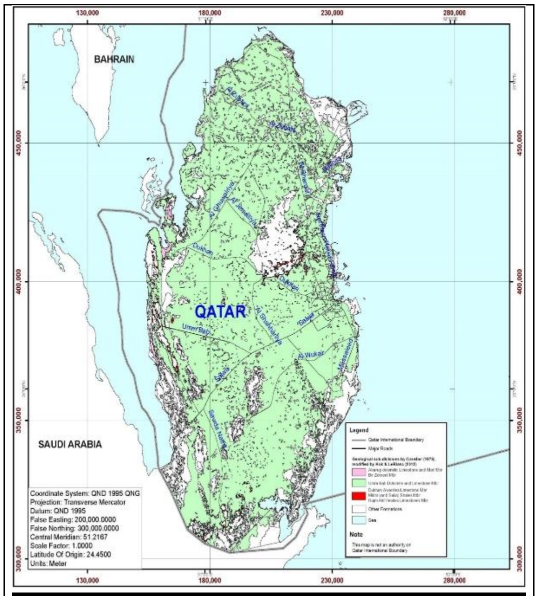


Figure 20. Distribution of the Middle Eocene Dammam Formation over Qatar. The red, purple and green colored areas are all part of the Dammam Formation.

Midra (and Saila) Shales Member[9]

Made up of attapulgitic[10] shales, generally brown to green (Fig. 22), containing pseudomorphs of pyrite and hematite (Fig. 33), with intercalations of phosphatic discontinuous limestones. The member is irregularly fossiliferous and is 16.4 ft. (5m) thick at the reference section (Figs. 21 & 22). It can reach 26.2 ft. (8 metres) on outcrops in the extreme south and disappear in the Northeast. In boreholes, the Midra (and Saila) Shales also exhibits variable thicknesses over the area between Doha and Messaid; some time absent and some other time to around 10m (Appendices A & B).

The fauna is variable and include rare branched Bryozoa, indeterminable (Membraniporide?), some Echinoderms (Fig. 27) and Molluscs. Gastropods (Fig. 25) are very few. The ichthyofauna (Figs. 23, 24, 28, 30, 31, 32 and Table 1) is very abundant and was described in detail by Casier (1971) - and discussed by LeBlanc (2008) - who recognized 28 types. The Elasmobranchs are most prevalent with the Lamniformes and Carcharhinides orders. The large Foraminifera (Fig. 26) are sometimes common in the shales (especially *Dictyoconoides kohaticus* (Davies)) and are usually more abundant in the calcaro-phosphatic intercalations.

The author (LeBlanc, 2008) also found the first ever sirenian Middle Eocene bones from the Arabian Peninsula (Fig. 29). Before this discovery, the closest known localities of sirenians from this time period were in Egypt and India.

Figure 21. Natural exposure at the Reference section locality of the Dammam Formation (Lat. 25°17'3.18"N, Long. 50°48'20.07"E) suggested by Cavelier, Sugden et al. (1975). The Midra (and Saila) Shales, the Dukhan Alveolina Limestone and the bottom portion of the Umm Bab Dolomite and Limestone Members are the only ones that can be observed – Equivalent to letter "E" in the section shown in Fig. 19.

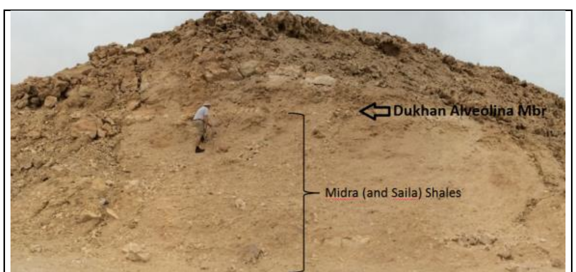


Figure 22. Exposure of the Midra (and Saila) Shales at the Reference Locality (Fig. 21). The author is seen measuring the section.

[9] In Saudi Arabia the Midra Shales (s.l.) were subdivided late in time in two members: Midra Shales (s.s.) at the base, Saila Shales at the top. This distinction, based mainly on the color of the shales, was not retained in Qatar, where Cavelier (1970a) introduced a composite term to remember the similarity with Saudi Arabia.

[10] Palygorskite or attapulgite is a magnesium aluminium phyllosilicate.

Figure 23. Odontaspis (shark) tooth in its natural position (left) and professionally photographed (right) by the University of Qatar, Environmental Studies Center

Figure 24. Various shark teeth from the Midra shale professionally photographed by the University of Qatar, Environmental Studies Center

Figure 25. Ferricrete and oxydized gastropods.

Figure 26. Nummulites.

Figure 27. Echinoderm (sea-urchin) spines

Figure 28. Rostral teeth of Pristis fish (or sawfish).

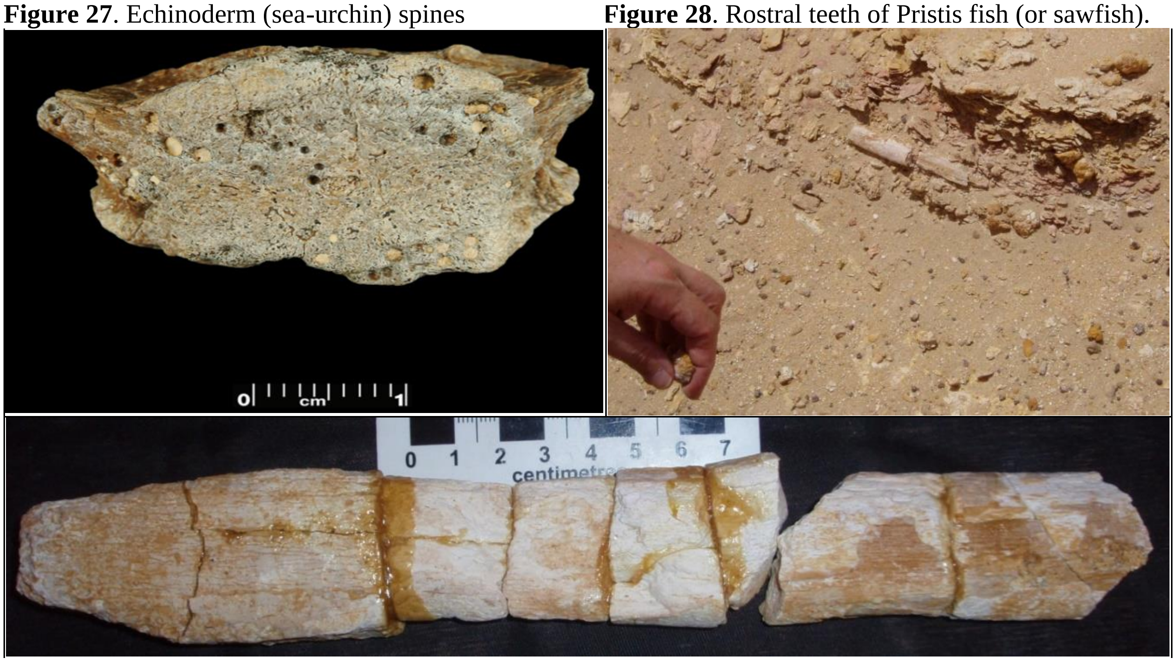


Figure 29. Sirenian/Dugong bones: Top left - the Centrum of a cervical vertebra. Top right - First ever sirenian Middle Eocene bone discovered on the Arabian Peninsula (July 6th 2007 in Qatar). This is a shaft of the 11th, 12th or 13th rib. Bottom: Large rib. All found by the author and interpreted by Dr. Iyad Zalmout.

Figure 30. Left - Teeth from Pycnodont fish. They lived from the Middle Cretaceous to the Middle Eocene in calm reef waters and ate hard-shelled molluscs, corals and sea urchins. Fig. 31: Right – Stingray tooth plate

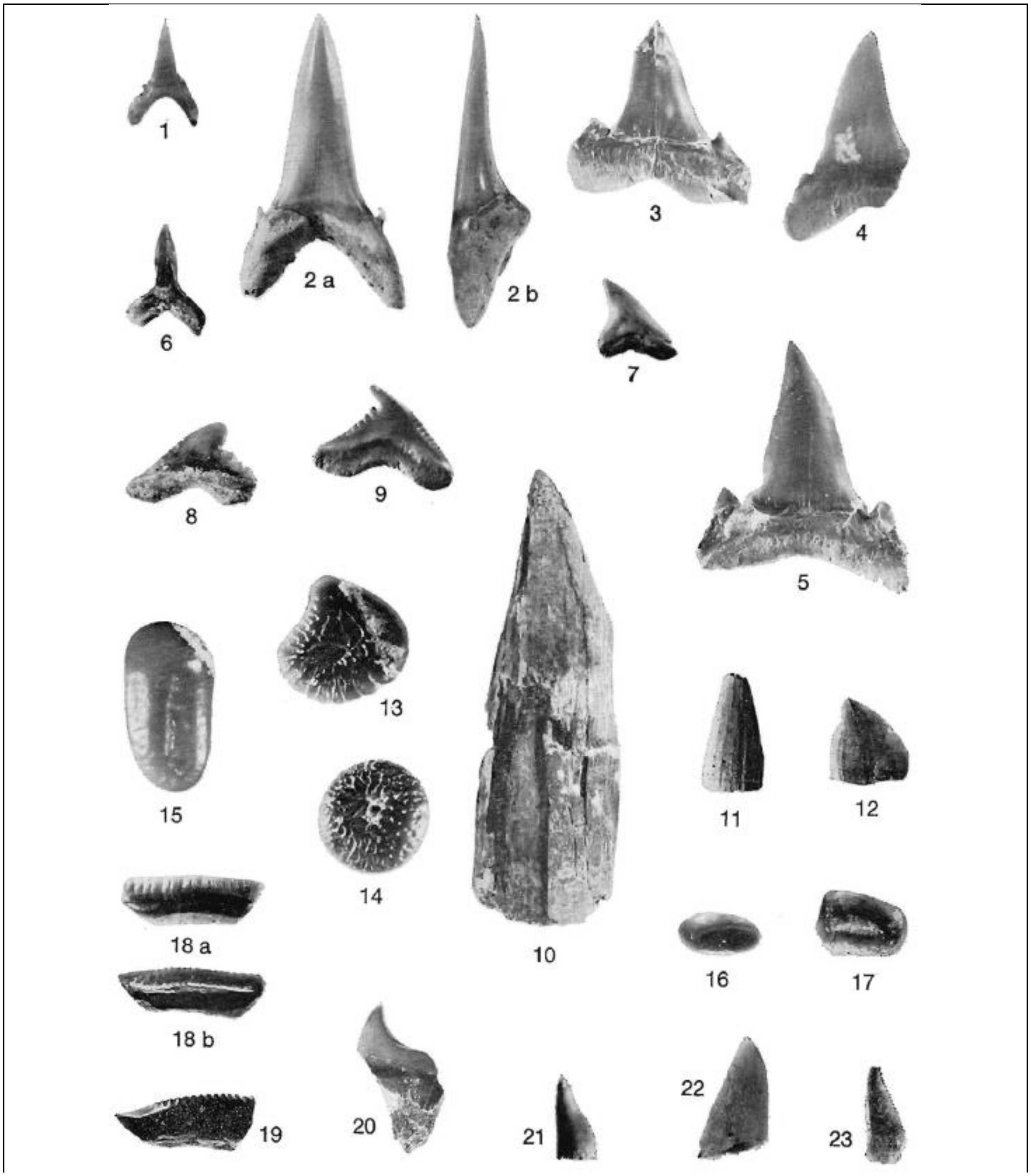


Figure 32. Shark teeth (and other marine vertebrates) described in detail by Casier (1971). See Table 1.

Table 1: Detail of the shark teeth (and other marine vertebrates) seen in Fig. 32
Unless otherwise mentioned, the above samples were photographed in their natural size
_1) *Odontospis aff.* Winkleri LERICHE. 1905. External face of a anterior tooth
_2a & b) *Odontospis aff. hopei* (Agassiz L. 1844) Lower frontal tooth. **a** = external face, **b** = Profil
_3) *Lamna gafsana* White E.I. 1926. Lateral tooth, external face
_4) *Lamna gafsana* White E.I. 1926. Lateral tooth, external face
_5) *Lamna gafsana* White E.I. 1926. Lateral tooth, external face
_6) *Aprionodon frequens* (Dames W. 1883) Side-frontal tooth. External face. Zoom X 2
_7) *Galeocerdo* (?) sp. Side-frontal tooth. External face.
_8) *Galeorhinus minor* (Agassiz L. 1835) Side tooth. External face. Zoom X 2
_9) *Galeocerdo latidens* Agassiz L. 1843. Side tooth. External face.
10) *Pristis lathami* GALEOTTI H. 1837(sawfish). Rostral tooth. Superior face
11) *Pristis imhoffi* LERICHE M. 1933. Rostral tooth
12) *Propristis schweinfurthi* DAMES W. 1883. Rostral tooth
13) *Pycnodus mokattamensis* PRIEM F. 1897. Vomerine tooth. External face. Zoom X 2
14) *Pycnodus mokattamensis* PRIEM F. 1897. Vomerine tooth. External face. Zoom X 2
15) *Pycnodus sp.* Splenial tooth. Oral face. Zooom X 2
16) *Pycnodus cf. P. toliapicus* Agassiz L. 1839. Splenial tooth. Oral face
17) *Pycnodus sp. Cf. mokattamensis*. PRIEM F. 1897. Oral tooth, interior face
18a & b) *Eotrigonodon serratus* (GERVAIS P. 1852) aegyptiaca type (PRIEM F. 1908) Oral tooth, a = external face, b = internal face
19) *Eotrigonodon serratus* (GERVAIS P. 1852) aegyptiaca type (PRIEM F. 1908) Oral tooth (incisive) external face
20) *Eotrigonodon sp.* (GERVAIS P. 1852) pharyngal tooth seen from the side
21) *Sphyraena fajumensis* (DAMES W. 1883) anterior tooth
22) *Sphyraena fajumensis* (DAMES W. 1883) anterior tooth
23) *Sphyraena fajumensis* (DAMES W. 1883) anterior tooth seen from the side

Figure 33. Amalgamation of cubic crystals of an iron-rich mineral, probably with a high percentage of pyrite and hematite.

Dukhan Alveolina Limestone Member

Composed of a bed of white to yellowish, more or less argillaceous, limestone which sometimes bifurcates. It is intimately linked to the Midra (and Saila) shales, at the base, and progressively merges with the marls at the base of the Umm Bab limestone, at the top. Its thickness rarely reaches one metre but it is an excellent marker because of the extreme abundance of Alveolina (Fig. 38). It can be observed throughout most of Qatar; the exception being the NE regions (Fig. 34).

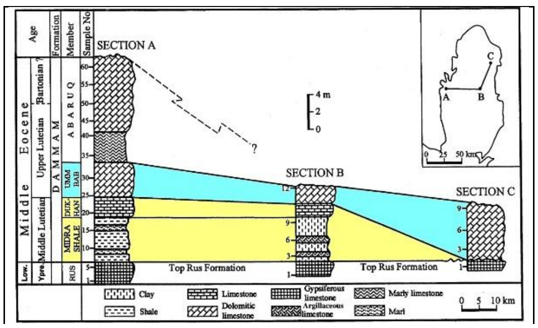


Figure 34. Correlation between the surface sections. A= Reference Section; B= Umm Slal Ali; C= Al Khor. Al-Saad (2005).

The Reference section is located as per Fig. 21, however the Dukhan Alveolina Limestone outcrops at several localities over the Dukhan anticline and in Southern Qatar. Good examples are seen in Figs. 35, 36 & 37.

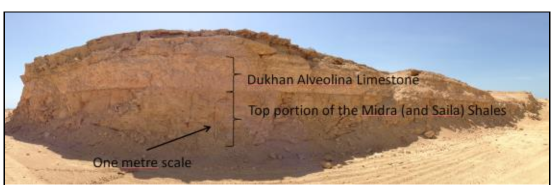


Figure 35. The Dukhan Alveolina limestone at locality Lat. 25°30'22.74"N, Long. 50°45'55.30"E

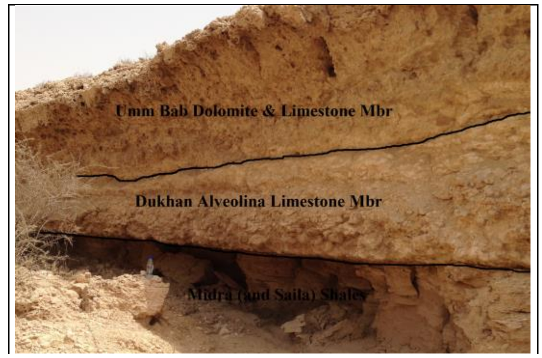


Figure 36. The Dukhan Alveolina Limestone Mbr at locality 25°29'51.82"N and 50°46'34.14"E. Use the water bottle as scale.

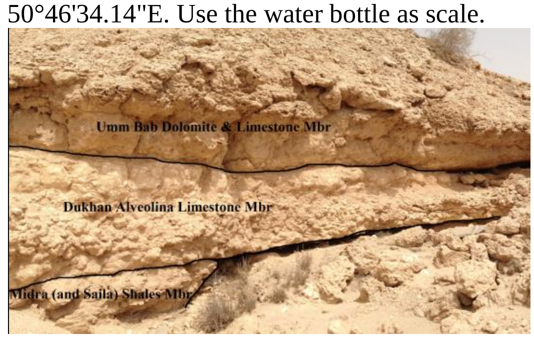


Figure 37. The Dukhan Alveolina Limestone Mbr at locality 25°29'51.23"N and 50°46'33.27"E.

The fauna includes rare Bryozoa, small Echinoderms, Molluscs (including Nautiloids) (Fig. 40), Gastropods (molds) (Fig. 41), rare fish remains and abundant large Foraminifera (Fig. 38). The present author also found in April 2015 a bone of a toothed-whale (Fig. 39).

Figure 38. Abundance of *Alveolina* (Foraminifera) in the Dukhan Alveolina Limestone.

Figure 39. Bone from a Toothed-Whale. Note also the presence of Alveolina. (Identified by Dr. Iyad Zalmout)

Figure 40. Nautiloid (left & right) of the *Deltoidonautilus* species. LeBlanc (2019).

Figure 41. Gastropods. Left = *Conus*; Right = *Campanile* sp.

Umm Bab Dolomite and Limestone Member

The base is commonly marly (attapulgite) and very fossiliferous from 0 to 6.6 ft. (2m) or 9.8 ft. (3 m). Its overall composition is a compact crystalline white limestone, with local layers of chert and red attapulgite; with some hard brownish dolomites irregularly developed in the upper half in the absence of a more recent cover. The total thickness is variable. The Umm Bab Dolomite and Limestone Member is not fully exposed in Qatar. Chatton (1948) evaluated the thickness of the Umm Bab Limestone Member to be 93.2 ft. (28.4m) on the northern part of the Dukhan anticline. Cavelier (1970a) concludes, with no explanation provided, that the Umm Bab

Member could vary from a thin 98.4 ft. (30 m[11]) to a thick of 164.0 ft. (50 m) throughout the whole of Qatar. In addition to the above, a communication with Gulf Laboratories[12] dated March 31st 2015, states that the thickest sequences so far discovered in boreholes are along the east coast of Qatar between Doha and Messaid. A sequence up to around 29 metres thick in southern Doha near the coast and 33.9 metres (the thickest in Qatar) north of Messaid at coordinates 25º01'58.49" and 51º36'30.93" were penetrated in 2009. Unfortunately, no log suites were run in this latter well. Pictures of the core were taken (Appendix A) and its detailed description made (Appendix B) before the core itself was destroyed. Lastly, the boreholes that completely penetrated the Umm Bab Member at the locality of two important projects in Doha encountered only thicknesses of 42.9 ft and 65.6 ft. (13 m and 20 m).

Generally, the Umm Bab Dolomite and Limestone Member is extremely variable lithologically (both laterally and vertically) as it has undergone various degrees of alteration and weathering. The unit can vary from a moderately strong crystalline dolomitic limestone to a very weak calcareous siltstone over very short distances and can contain various proportions of the weaker material as vugs and pockets. In and around Doha, particularly towards the coast, the upper layers are generally highly weathered and frequently very difficult to core.

At the bottom (over a 5m maximum thickness), the Umm Bab limestone locally includes marls and even thin stringers of attapulgite shales quite rich in fossils (*Pycnodonte* sp., *Ampullospira* sp., *Gisortia* sp., *Alveolina* and especially *Nummulites*) overlain by an often-reddish granular limestone (Fig. 42). The overlying fairly calcareous layers carry less *Nummulites*; on the contrary, Echinoderms (Figs. 46, 47, 48, 49, 50) are abundant (*Scutellina*, *Echinolampas*, ...) as well as some large Molluscs/gastropods (*Campanile* sp.. *Velates cf. schmiedeli*) (Fig. 51) - with their respective trace fossils / burrows (Fig. 53) - bivalves, large Foraminifera, rare nautiloids (Fig. 52), fossil mangrove root system (Fig. 54) and corals (Fig. 55). The Echinoderms are common in the upper half: *Echynocyamus polymorpha* (Duncan et Sladen), *Porocidaris aff. Schmiedeli* (Munster), and especially at the top, where they make up large deposits on the western coast of Ras Abarug (Fig. 43), with: *Porosoma aff. Lamberti Checchia-Rispoli*, *Echinocyamus polymo*rpha (Duncan et Sladen), *Echinolampas perrieri de Loriol*, *Oppisaster derasmoi Checchia-Rispoli*, *Schizaster beloutchistanensis* (d'Archiac), *Eupatagus formosus de Loriol*. Cavelier, 1975; Gelin (2020).

Figure 42. Reddish granular limestone near the top of the Umm Bab Dolomite and Limestone Member in a sector of Naslat Umm Hadidah area at Lat. 25°23'53.08"N, Long. 50°52'59.78"E

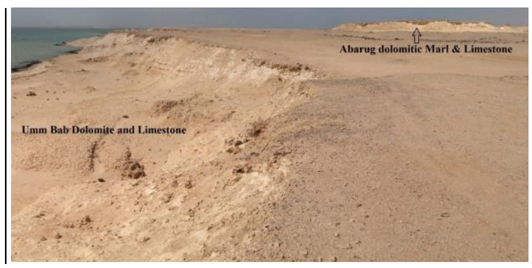
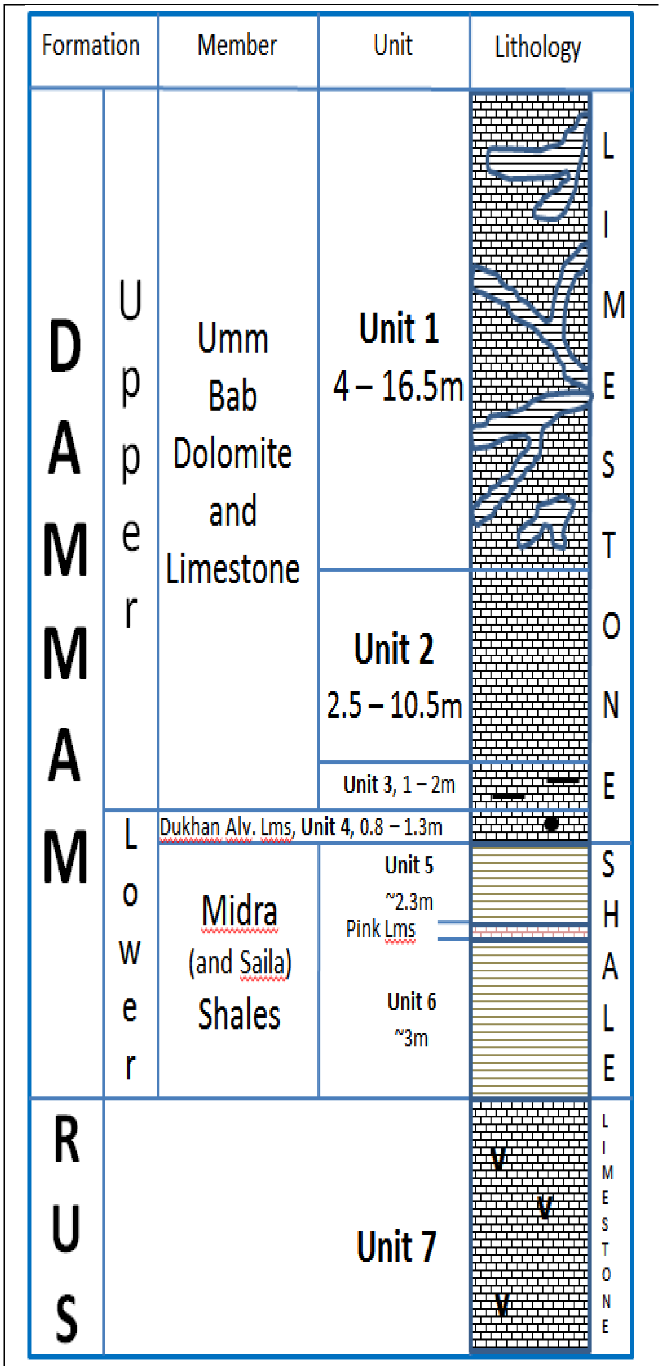


Figure 43. Area on Ras Abarug Peninsula (Lat. 25°34'52.99"N, Long. 50°49'56.70"E) displaying few metres of the top portion of the Umm Bab Dolomite and Limestone Member. Echinoderms are frequent. Immediately above it, and in the background, is the Abarug Member (the Bir Zekreet Shale member is not present/visible at that particular locality).

One naturally occurring partial, but thick (~11m), exposure of this member (upper portion) was measured in Naslat Umm Hadidah area (western Qatar) and is shown in Appendix C. In addition, a measured section at the QNCC limestone quarry[13] east of Umm Bab town (Figs. 44 & 45) shows a continuous portion of the Umm Bab dolomite and limestone member at the level and below the Naslat Umm Hadidah section, down to the Rus Formation.

[11] Cavelier did not have access to Chatton's report
[12] http://www.gulflaboratories.com

[13] Courtesy of Mr. Ahmed Fouad, Head of Quarries Section at Qatar National Cement Company (QNCC)



Unit 1: Large boulders of very hard buff compact recrystallized limestone where more clayey softer material occurs in veins around the boulders, white, pale green or brown in color, often show silky bright and nodular texture. Some gypsum is distributed in the matrix. Echinoderms, bivalves, large gastropods, ostracods, corals and large burrows. Some silicification occurs in the unit.

Unit 2: Massive, porous, medium hard to soft, chalky, granular, dolomitic limestone or dolomite, fossiliferous.

Unit 3: Pale brown, slightly argillaceous limestone, iron oxide of brown color stains along thin veins. It is limited upwards by the porous dolomitic limestone of Unit 2.

Unit 4: White fossiliferous chalky Limestone, large Alveolina foraminifera. Shale pebbles occur at the base as irregular contact infers an erosion level with the Midra.

Unit 5: Non-fossiliferous brown shale. Some gypsum veins are recorded.

Unit 6: Fossiliferous shale, containing some levels of hard calcareous rocks, characterized by a greenish color and the presence of glittering pyrite cubes.

Unit 7: One metre of white, crystalline, compact, fossiliferous limestone followed by dolomitic limestone.

Figure 44. Lithological section at the QNCC Limestone quarry east of Umm Bab town. See Fig. 45 and Fig. 19.

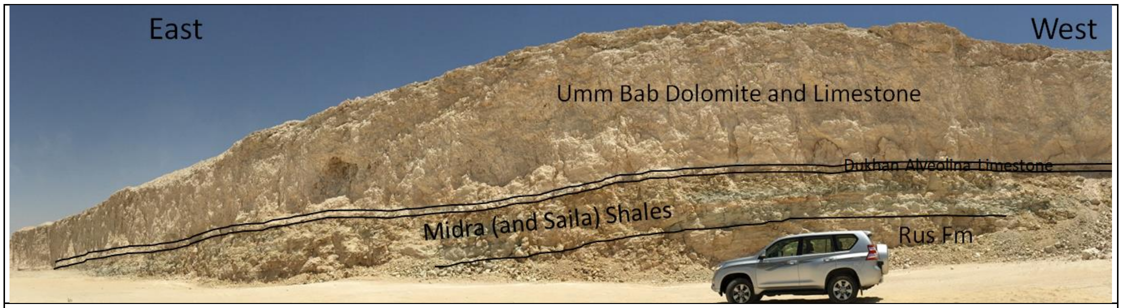


Figure 45. Umm Bab Dolomite and Limestone Member seen from its base at the Umm Bab QNCC limestone quarry (25°11'18.49"N, 50°50'9.83"E). Picture also shows a 3 to 4° dip in the Dammam & Rus Formations in this area resulting from the uplift of the nearby Dukhan anticline [The Dukhan Alveolina Limestone and the Midra (and Saila) Shales outcrop less than a kilometre to the west].

Figure 46. *Echinolampas*. Front, Back & Side views (left, centre & right).



Figure 47. *Opissaster*. **Figure 48**. *Clypeaster*. **Figure 49**. *Eupatagus*.

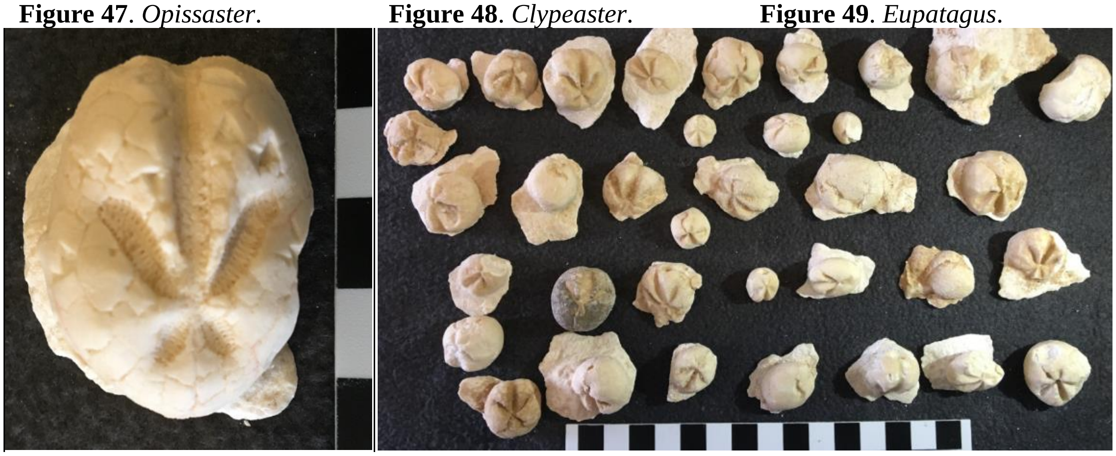


Figure 50. *Schizaster*. Single specimen (left); various specimens (right).

Figure 51. Various specimens of gastropods.

Figure 52. A rare Nautiloid (species unknown) from the Umm Bab Dolomite and Limestone Member. Left = Natural position; right = partially extracted.

Figure 53. Large gastropod/echinoderm burrows/trace fossils. Profile view (top; see watch as scale) at Lat. 25°16'20.04"N, Long. 50°51'50.34"E, and aerial view (bottom) at Lat. 25°22'56.94"N, Long. 50°52'43.72"E. Refer as well to Appendices C & D.

Figure 54. Left = Fossil mangrove root system at Lat. 25°41'33.41"N, Long. 51°32'58.67"E; Sadooni, Al-Saad (2012). Right = Present-day mangrove habitat

Burrowing by gastropods (Fig. 53) is essentially a continuation of surface locomotion obliquely into soft substrata. Burrows are nearly as large as the borers (Fig. 56). An important difference between bivalves and gastropods in respect to their burrowing habits is that bivalves commonly burrow vertically into the substratum, whereas gastropods generally enter the sand or mud at an oblique angle and only burrow to a limited depth so as to maintain access to the water above the surface of the substratum by means of the siphon (Fig. 57). Deeper burrowing may, however, occur under certain circumstances, as when females are carrying eggs or in response to rough seas. (Trueman et al., 1992)

Figure 55. Fossil coral specimens.

Figure 56. A fossil gastropod still inside its lithified burrow.

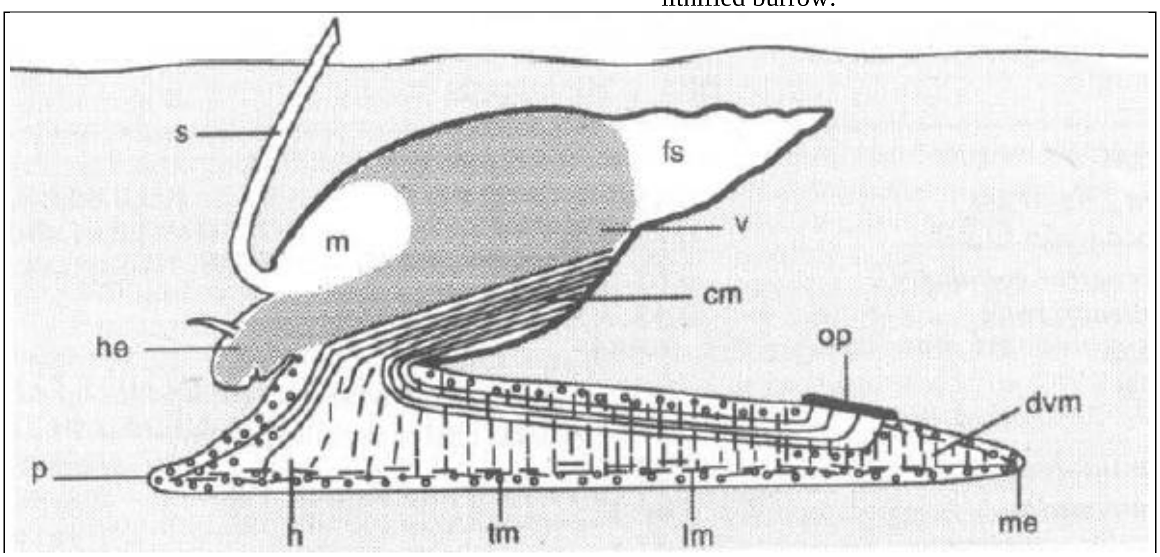


Figure 57. Burrowing activities of a gastropod. The siphon is kept at the surface of the substrata. (Trueman et al., 1992).

Paleo-fluid escape structures

Paleo-fluid escape structures, such as those described in the Rus Formation, are also common in the Umm Bab Dolomite and Limestone Member (Figs. 58 & 60). When overlaid by a younger limestone, the latter is normally highly silicified (Figs. 58 & 59).

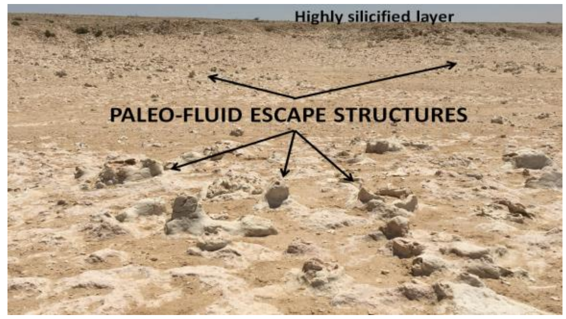



Figure 58. Paleo-fluid escape structures (gryphons) at locality 25°29'30.68"N and 50°54'50.62"E, just southeast of the Ras Abarug Peninsula. While these structures are not silicified, compared to those found in the Rus Formation over the Dukhan area (Fig. 4), the layer just overlaying them demonstrates a high degree of silicification.

Figure 59. The silicification of the younger limestone affected by the paleo-fluid structures is better appreciated on a road cut. At this Naslat Umm Hadidah locality 25°22'11.85"N and 50°52'46.2"E, multiple horizontal layers of silica are observed.


Figure 60. Paleo-fluid structures (gryphons) found in a locality of the Inland sea in SE Qatar (24º 43' 40.92"N and 51º 24' 10.31"E) at the level of a sabkha. This is the stratigraphically highest level of the Dammam Formation in this area; thus, no younger silicified horizon is present. Left - Large gryphons protruding from the ground. Right - Some gryphons with their tubular core infilled with recent sediments.

Caves

The three bottom members of the Dammam Formation (Midra, Dukhan & Umm Bab) are often observed in the caves/sinkholes of Qatar. Other than at Dahl Al-Misfir (Fig. 18), stratigraphic measurements were also taken in Dahl Al-Hammam near Landmark Mall in Doha (Fig. 61).

Figure 61. Dahl Al-Hammam near Landmark Mall (25°20'4.19"N, 51°28'49.30"E). Only Umm Bab Mbr is visible. Bottom of the cave was too dark to photograph the stratigraphy.

The thicknesses measured in the Dahl Al-Hammam were:

Top
- 10m (32.81ft) - Umm Bab Dolomite & Limestone Mbr of the Dammam Formation
- 01m (03.28ft) - Dukhan Alveolina Limestone Mbr of the Dammam Formation
- 04m (13.12ft) - Midra (and Saila) Shales Mbr of the Dammam Formation (including the submerged portion)

Base
Total depth[14]: 15m (49.21ft) from the top metallic stair

Bir Zekreet Shale Member

Due to its very localized occurrence, this member[15], described by Kok & LeBlanc (2012), has its own type locality at Lat. N 25°26’32.2”, Long. E 50°51’52.7”. The outcrop is at the bottom of the second Mesa directly behind the Islamic school of Zekreet (Fig. 62). The Member can also be found at the bottom of the many mesas on the Ras Abarug Peninsula. It is also well represented south of the Doha-Dukhan highway, slightly further south of the Naslat Umm Hadidah area at Lat. N 25°22'55.00", Long. E 50°52'47.98"E.

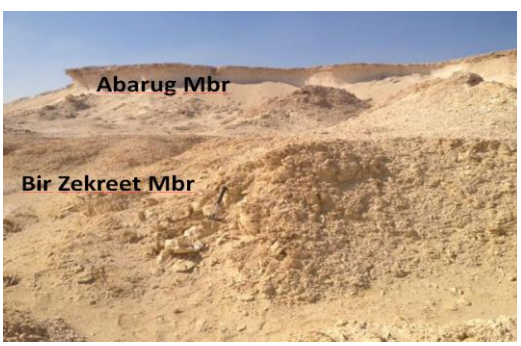


Figure 62. General view of the Bir Zekreet Member type locality (Letter “B” in the section shown in Fig. 19). The Abarug Dolomitic Limestone and Marl Member is seen in the background.

The Bir Zekreet Member (Fig. 63) consists of 6.6 to 16.4 ft. (2 to 5 meters) of thinly laminated, very fissile, ferruginous shales. The shales are yellowish-brown-gray to beige, in places reddish or with a greenish hue. They are very soft and friable and in some areas show a typical “paper shale” weathering. They are non-calcareous in all locations, in places slightly gypsiferous, sometimes silty. They have a very low density and have a “light” feel. They resemble the Midra (and Saila) Shales very much but at the type locality do not contain any fossils, nor pseudomorphs of pyrite (they were observed at other localities), nor thin limestone layers.

The Bir Zekreet Member is underlain by the Umm Bab Member and overlain by the Abarug Marl Member. When the latter has been eroded, the Member is often overlain by thinly parallel laminated and cross-bedded, fine-grained sandstones representing Pleistocene dune deposits.

The Bir Zekreet Member is interpreted as a low-stand supra-tidal, low energy deposit with minor supply (wind blown?) of terrigenous clay material from a temporarily emergent hinterland.

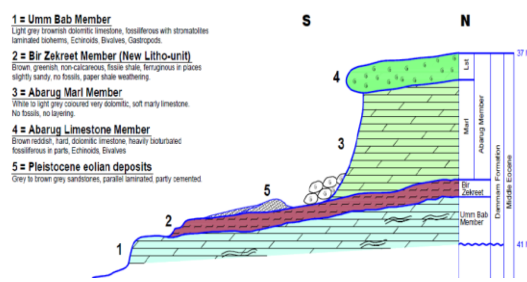


Figure 63. Stratigraphic position of the Bir Zekreet Member. Kok & LeBlanc (2012).

[14] A team effort composed of the author and Mr. Pim Kaskes, Mr. Dylan Bastiaans, Dr. Kaveh Samimi (all from “Naturalis” in Netherland, under contract with the National Museum of Qatar) and Mr Fareed Krupp, Qatar Museums. The Rus Formation is not observed in this cave. The measurements were taken on April 29th 2017 and performed with a "Jacob Staff". The water depth at the bottom of the cave was estimated at about 1m. The author has been told that this water depth can increase up to 4 or 5 metres during the wet season.

[15] Chatton (1948) mentions very briefly “The ordinary base of the cliff of Abaruk bed is marked by a 1.50m bed of fine flakey chalky marl” and places the marl within the Abarug member. Sugden & Standring (1975) also includes it in the Abarug member and states “In sections other than the reference section, the basal part of the Abaruk Beds is a thin (1.5 m) marl”. Cavelier (1975) does not make any mention of the marl; he stresses only the names and the nature of the Abarug dolomitic limestone and the Abarug dolomitic marl.

Abarug Dolomitic Limestone and Marl Member

The reference section (Fig. 64) of this member was surveyed South of Zekreet[16], in the Ras Abarug Peninsula, just behind the Cuban Hospital. In this locality, two units crop out that are found everywhere in Ras Abarug. A basal unit, resting on the crystalline limestones of the Umm Bab Member (or the Bir Zekreet Member when present), is comprised of dolomitic marls and soft, but compact, argillaceous dolomite, yellow-orange to green, nodular at the top, of a fairly constant thickness (27.9 ft (8.5 m)), called Abarug dolomitic Marl; an upper unit comprised of an irregularly dolomitized limestone that frequently changes to a calcareous dolomite (or not), grayish yellow to brown, hard, cavernous due to the dissolution of abundant Mollusc impressions and molds, generally not too thick (about 6.6 ft.(2 metres)) called Abarug dolomitic Limestone.

While the deposits of the Abarug Member are best known for their occurrence on the Ras Abarug Peninsula, they also occur close to the western coast, west-southwest of the town of Umm Bab. In this locality the Member is reduced in thickness with a very much reduced fossil content to not fossiliferous at all. Some isolated djebels composed of the Abarug Member south of the Doha-Dukhan highway are also not drawn on the geological map (Fig. 1); the latter would require to be updated.

The fauna of the Abarug dolomitic Marl is restricted to poorly defined Mollusc impressions observed in the nodular level at the top. The Abarug dolomitic Limestone is rather rich in Molluscs (Gastropods, bivalves) (Fig. 65) impressions and molds that are more or less determinable, Echinoderms (Figs. 66 & 67), Trace fossils (Figs. 67 & 68) and Large Foraminifera.

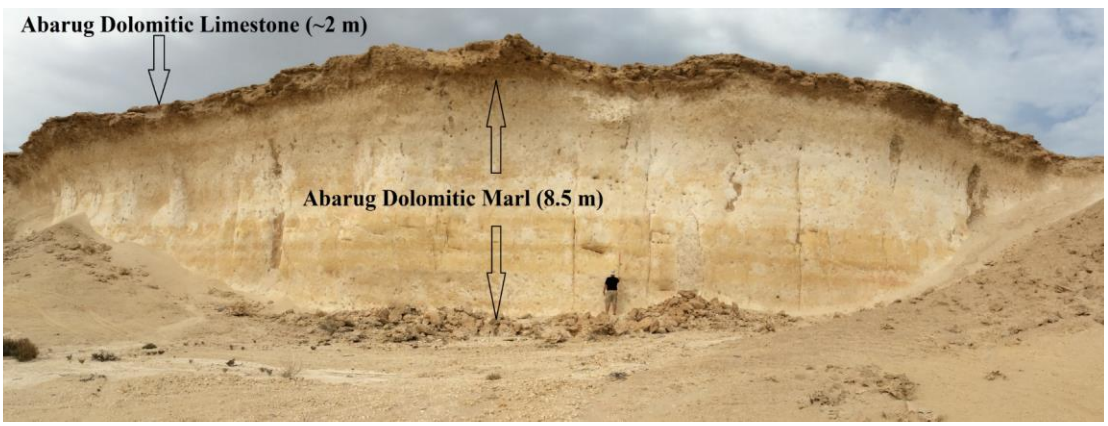


Figure 64. Abarug Dolomitic Marl (8.5 m) and Dolomitic Limestone (~2 m). See "A" in section shown in Fig. 19.

[16] Cavelier (1970a) selected a reference section "3kms south of Zekreet town" but did not mention the exact coordinates. Therefore, it could not be accurately located. It was judged preferable to select a more appropriate one.

Figure 65. Gastropod.

Figure 66. Echinoderms.

Figure 67. Echinoderm with a trace fossil (burrow).

Figure 68. Trace fossil.

4 Lower Miocene Dam Formation

A) Origin of the name and main authors: Used for the first time by Steineke M. and Kock T.W., in an unpublished 1935 report, Saudi Arabia and formally described later by Powers (1968) in Saudi Arabia and Cavelier (1970a) in Qatar.

B) Type locality: The Dam Formation is named for Jabal al Lidam (Fig. 69), Saudi Arabia (lat. 26°21'42"N, long. 49°27'42"E) where the lower part of the type unit crops out. Lower beds of the formation were measured in the east face of Jabal al Lidam and the upper part of the 294.6 ft. (89.8 m) interval at Al Umayghir (lat. 26°17'15"N, long. 49°30'24"E) (Powers et al. (1966), (Table 2). The Dam Formation of Qatar can be correlated with the Asmari Formation (Lower Fars) of Iran and the Dam Formation of Saudi Arabia and UAE (Fig. 70). The formation in Saudi Arabia and UAE was deposited in continental environments, whereas the depositional environments in Qatar are clearly of marine origin.

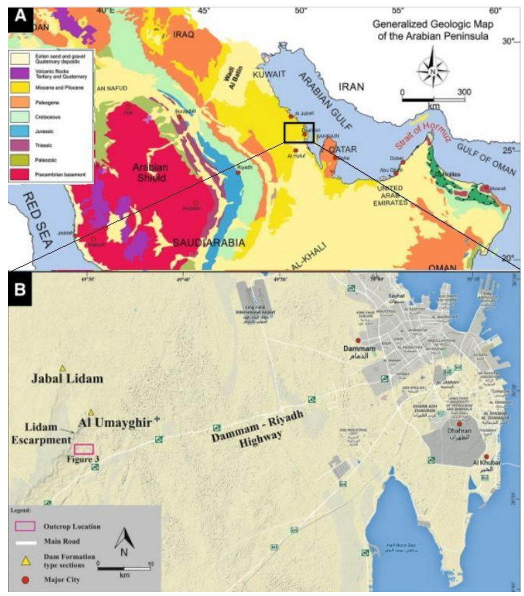


Figure 69. Location of the Type Section of the Dam Formation at Jabal al Lidam; modified from Chan et. al. (2017).

DAM FORMATION SECTION	
Section 57: Jabal al Lidãm, Saudi Arabia	
Clay of the Hofuf Formation (Miocene or Pliocene)	
Dam Formation:	**Thick (m)**
Marl, gray, fragmental, fossiliferous	1.0
Marl, pink, strongly argillaceous	1.0
Marl, white, tough	1.0
Clay and sandstone; red and green sandy and silty clay and red sandstone	8.0
Marl, buff to white, pebbly; abundant red marl fragments. Thin bed of conglomerate at top	1.7
Marl, white, chalky	1.6
Chalk and sandstone; white chalk and gray cross-bedded sandstone; fossils at base	1.0
Marl, gray and buff, thin-bedded, fossiliferous	1.0
Marl and clay; white marl and green clay	1.8
Marl and clay; yellow fossiliferous marl and green clay	1.0
Sandstone and marl; gray-green sandstone and buff conglomeratic fossiliferous marl	1.0
Clay, green	7.5
Covered	0.5
Limestone and marl; tan tight sandy limestone and buff fossiliferous marl	1.4
Marl, limestone and sandstone; buff and white marl, yellow fossiliferous limestone and sandstone	12.6
Covered	0.5
Limestone, tan, sandy	0.5
Marl, greenish-tan,fossiliferous, sandy	2.6
Sandstone, greenish-yellow	1.0
Marl, white, chalky	0.2
Marl and sandstone; white tough foraminiferal marl and gray oolitic sandstone	2.0
Marl, white, fossiliferous	8.8
Marl, off-white to yellow, chalky, sandy, fossiliferous; Foraminifera common	4.8
Limestone, tan, marly, fossiliferous; abundant Foraminifera	3.6
Marl, buff and white, tough	1.0
Clay, green	1.8
Limestone, greenish-tan, fossiliferous, sandy	1.8
Marl, greenish-gray, fossiliferous, chalky	7.3
Marl, abundant echinoids from “Button bed” essentially an echinoid coquina	1.0
Marl, white, chalky, foraminiferal	3.5
Sandstone, marly	2.0
Marl, buff, fossiliferous	1.5
Sandstone, hard, oolitic; few fossils	1.0
Sandstone, white, very fossiliferous, marly; few echinoids	2.8
Clay, green	0.5
Marl and sandstone; white sandy marl and marly sandstone	0.5
Total thickness of Dam Formation	**90.8**
Hadrukh Formation	

Table 2. Dam Formation type section measured and described by Max Steineke and T.W. Koch at Jabal al Lidãm Saudi Arabia in an unpublished 1935 report, and formally described by Powers et al. (1966) and Powers (1968).

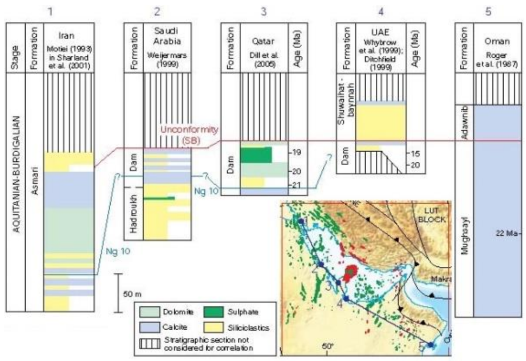


Figure 70. Correlation of the Lower Miocene sedimentary sequences along the northeast boundary of the Arabian Platform; Dill et al. (2007).

C) Qatar Reference Section: Surface location at Jebel Al-Nakhash (lat. 24°52’25.07 N, long. 50°54’12.81 E) (Figs. 71 & 72, Table 3).

Figure 71. The Dam Formation exposed on the east side of “Jebel Al-Nakhash” along Salwa Road in SW Qatar (lat. 24°52’25.07 N, long. 50°54’12.81 E); LeBlanc (2015a). At that location, the Abu Samrah Member is also capped by about 3.3 ft. (1 m) of gravel from the Mio-Pliocene Hofuf formation.

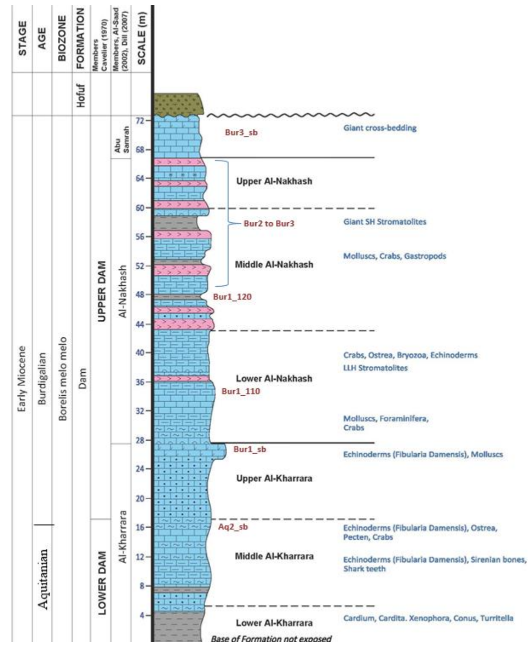


Figure 72. Stratigraphic column at Jebel Al-Nakhash (Lat. 24°52’25.07 N, Long. 50°54’12.81 E) showing the Lower & Upper Dam Formation of Cavelier (1970a) and the more specific subdivisions established by Dill et al. (2007) & Al-Saad et al (2002a); modified by LeBlanc (2015a). Grey = shale, Blue = limestone, Pink = gypsum, Sb = Sequence boundary, Bur = Burdigalian, Aq = Aquitanian, Bur3 = 18.7Ma, Bur1 = 20.5Ma, Aq2 = 22.2Ma

In Qatar, the Dam Formation is present in two discontinuous belts in the southwestern part of the peninsula and forms some of the highest ground (Figs. 73 & 74). The more western belt extends southwards, on both sides of the Dukhan anticline, from the vicinity of Umm Bab to the border beyond Abu Samrah. The second group of outcrops extend from north of Sawdaa Natheel northeastwards to beyond Al Kharrarah and nearly to the main Doha-Abu Samrah road. Dam Formation rocks are also preserved in post-Miocene collapse structures such as at Karanah, Al Markhiyah and Mukaynis (Seltrust, 1980). The Dam formation unconformably overlies the Middle Eocene limestone of the Dammam Formation and is overlain by the Late Miocene to Early Pliocene conglomerate and sandstone of the Hofuf Formation (LeBlanc, 2008). The present-day occurrences of the Dam Formation are directly related to the uplift of the Qatar Arch (a broad, gentle anticline draping a major block uplift which caused Qatar to emerge from the Gulf). New observations by Rivers & Larson

(2018) and Rivers, Skeat et al. (2019) favor a fault-controlled model for the Dukhan structure in the western part of the peninsula over an earlier fold-related and regional erosion model by Seltrust Engineering (1980) (Fig. 73). The effect of gypsum dissolution in the underlying Rus Formation was also a factor.

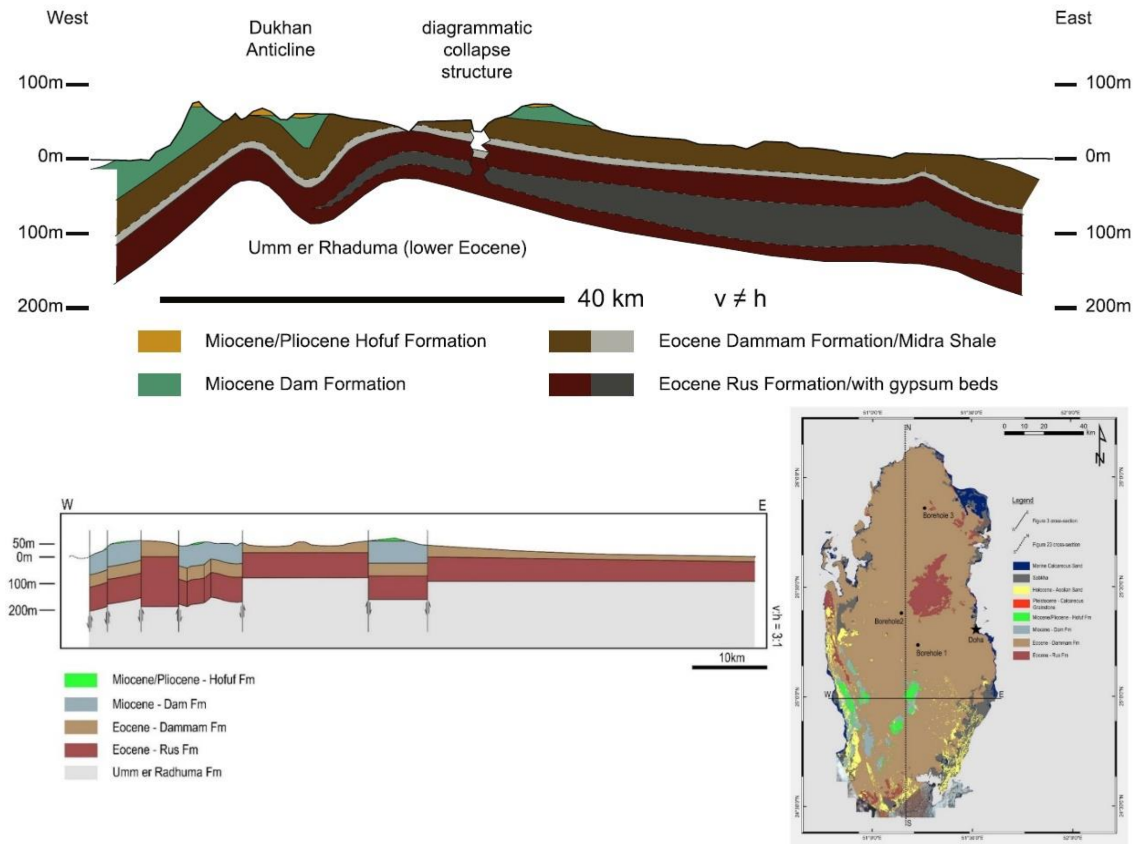


Figure 73. Comparison of vertical geological sections across Qatar (East-West, as seen while driving on Salwa Road) from work by Seltrust Engineering (1980) (Top) and Rivers & Larson (2018) and Rivers, Skeat et al. (2019) (Bottom). Sections are vertically exaggerated as indicated.

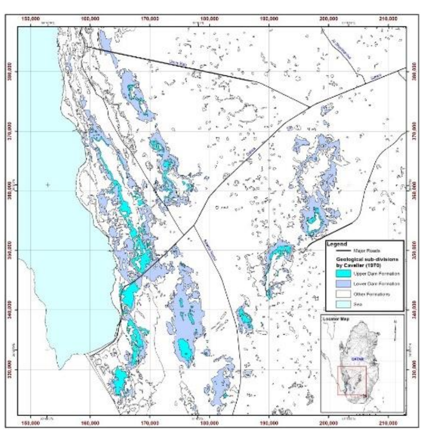


Figure 74. Map of the Miocene rocks of Qatar. The Dukhan Anticline extends in NNW–SSE direction along the western coast of Qatar.

D) Age: Dill et al. (2007) analyzed several samples from the Al-Nakhash Reference Sections with respect to their $^{87}Sr/^{86}Sr$ isotope ratio. Most samples analyzed fit the marine Sr isotopes of the Miocene time interval and thus suggest a late Aquitanian to early Burdigalian stratigraphic age for the section (between 22 to 18 Million years) (Fig. 72).

E) Top (MD): From 0 metre by the shore in SW Qatar to 84.6m above sea level on top of Al-Nakhash

F) Thickness: 72 m (236 ft) over Jebel Al-Nakhash of easily identifiable sections. Cavelier (1970a) also reported a thickness of about 78m (256ft) over the massif 1.5 km

NNE of the Qarn Abu Wail[17], however because this location is too close to the Qatar/Saudi Arabia border it is not selected as the reference type.

G) Lithologic Description; Cavelier (1970a) and Cavelier 1975 describe the lithology of the Dam Formation outcropping in Qatar over the Hazm Mishabiyah area (Lat. 24°44'16.13"N and Long. 50°53'43.14"E) (Fig. 75) and split this rock unit into Lower and Upper. Al-Saad et al (2002a) constructed a Geological Section of the Jebel Al-Nakhash, which contains the most representative column of the Dam Formation in Qatar (Fig. 72). Dill et al. (2005) and Dill et al. (2007) subdivided the succession of sedimentary rocks belonging to the Dam Formation over the Jebel Al-Nakhash area into seven lithofacies associations (Fig. 72). These lithofacies associations were stratigraphically grouped by Dill et al. (2005) from top to bottom into three members called Abu Samrah, Al Nakhash, and Salwa Members (*Dill's Salwa Member was renamed as "Al-Kharrara" in the present document, as per Al-Saad et al. (2002a), due to conflicting nomenclature since the name "Salwa" was already used as a member of the Cretaceous Simsima Formation*). Al Nakhash and Al-Kharrara Members both allowed for a refinement of the stratigraphy as each is comprised of an upper, middle, and lower unit. It is this tripartite sub-division that is being used in the present publication (Fig. 72, Table 3, Appendix E).

The Dam Formation in Qatar represents, from bottom to top, a succession of offshore marine sediments to continental sabkha deposits; Dill et al. (2005). Calcareous and evaporitic sediments (gypsum, celestite) of the Dam Formation in Qatar reflect deposition under subtidal through supratidal conditions, which towards the base and the top of the series grade into a modern beach deposit. All carbonate and siliciclastic sediments younger than the Middle Al-Kharrara were subjected to strong dolomitization, excluding the uppermost part of the Abu Samrah Member; Dill et al. (2007).

Figure 75. A representative section cutting through the Upper Al-Kharrara and Lower Al Nakhash Members of the Dam Formation over the Hazm Mishabiyah.

Cavelier (1970a)	Al Saad (2002) Dill (2005/07)	Lithological Description & Environment of Deposition
Upper Dam	**Abu Samrah**	These thick marine calcareous sediments were deposited in a microtidal wave-dominated environment. Dissolution of Eocene evaporites at depth governed the lithofacies differentiation in the Miocene Dam Formation. Irregular burrows occur and a shell bed marks the boundary between the Abu Samrah and Al-Nakhash Members. This fossiliferous layer is contained in a thinly bedded sequence of calcareous and siliciclastic rocks. In the Abu Samrah Member the marine setting has almost completely turned from a tide-dominated into wave-dominated beach environment. *Hydrobia* (a gastropod) appear in great numbers. The calcareous beds immediately beneath the Dam/Hofuf unconformity are beach rocks. Thin ripple marked sandstones have been observed near the top in the An Nafkhah - Qarn Abu Wail area indicating a coastal depositional environment.

[17] Qarn Abu Wail is located at Lat. 24°40'23.62"N and Long. 50°51'33.99"E. It is one of the points used to delimitate the southern border of Qatar with Saudi Arabia.

	Al-Nakhash	Upper	Brown and red in color with thick gypsum seam. Celestite and Bassanite are also present. It is the most landward member (inland sabkha) of the Dam Formation. Mega cross-bedding in the Upper Al-Nakhash, with foresets dipping at an angle of 27º, suggests that these clastic sediments are of aeolian origin. The red bed facies with gypsum-bearing coarsening-upward cycle represents the maximum regression following the supratidal regime of the Middle A1-Nakhash. The beds of massive gypsum are only locally present as one moves northwards along the scarp of Jebel Al-Nakhash.
		Middle	The clay and siltstones are rich in gypsum nodules and crystals as long as 1 metre. The climax of stromatolites growth is reached in the Middle Al Nakhash with as much as 2 m in diameter and 0.5 m in height
		Lower	At 48 m LLH stromatolites appear in the Lower Al Nakhash with tepee structures and centimeter-thick laminae. At 50 m, patches of columnar microbial structures (SH), covering several hundreds of square meters developed on top of LLH stromatolites. The individual columns form a sort of a stromatolite pavement. Tidal channels are indicated in the sedimentary record by the bioclastic pure limestones in the lower section of each cycles (subtidal)
	Al-Kharrara	Upper	Horizontal stratification with even bedding planes and bedsets measuring up to 1 m is widespread particularly in the siltstones and fine grained sandstones. Some fine-grained siliciclastics of the Al-Kharrara lithofacies associations developed planar cross stratification. Red [shale] beds are particularly widespread in the Upper Al-Kharrara, locally alternating with dark gray and green [shale] beds. They are by far the most reliable marker which occurs at the top of the marly sequence. *Ostrea*, known to be widespread in estuaries and tidal flats, paves the way from the subtidal environment of the Al-Kharrara Members into the inter- to supratidal subenvironments of the Al Nakhash Members. The fauna that created the ichnofossils had their habitat in the subtidal to lower intertidal or shoreface environments.
Lower Dam	Al-Kharrara	Middle	The environment was the distal part of a tidal delta complex while a lagoonal environment prevailed lower in the sequence. The water depth reached a maximum of 20 m. Part of the Middle Al-Kharrara has also been interpreted as a restricted platform sedimentary unit. The top strata, however, are interpreted as a beachrock (intertidal environment) very much like the lithologies in the Lower Al-Kharrara. Red and green rock colors observed in this sub-member indicate varying oxidising and reducing conditions. From the sequence stratigraphic point of view, the maximum flooding surface is likely to lie within the Middle Al-Kharrara Member. Impressive quantities of the echinoderm *Fibularia damensis* are found in white (chalk) limestone beds called "button-bed".
		Lower	Silicate-dolomite-calcite sequence. The base is a deeper marine environment (Fine-grained siliciclastics) while the top stratum (Calcitic clay-rich marlstone) is an inter-tidal to beach environment. Water depths between 5 and 25 m. Horizontal stratification with even bedding planes and bedsets measuring up to 1 m is widespread particularly in the siltstones and fine grained sandstones. Contains mammal [dugong] bones & associated shark teeth.

Table 3: Lithological description of all members of the Dam Formation. Dill (2005 & 2007), LeBlanc (2009).

H) Fossil content: (Refer in most part to Appendix E)

In the Lower and Middle Al-Kharrara Members

The molluscs are very abundant, with *Ostrea latimarginata* Vredenburg, sometimes common, are also found *Pectinidae*, *Anomia*, *Spondylus*, *Lima*, *Avicula*… and impressions and molds of *Clementia papyracea* (Gray), *Diplodonta*, *Chama gryphoides* Linne, *Venericardia*, *Trachycardium*, *Veneridae*…. and very locally some *Cyrenidae*.

The Gastropods, generally found as impressions, include *Fissurella*, *Natica*, *Xenophora*, *Turritella*, *Cerithidae*, *Cypraea*, *Conus*, *Bulla*… and very locally some *Hydrobia*, *Potamides*, and other brackish water genus.

The Echinoderms are very common but relate primarily to the small species *Fibularia* *damensis*, especially characteristic of the top of the Middle Al-Kharrara.

The Bryozoa corresponds to species not yet described: *Steginoporella(?) sp*., *Thalamoporella n.sp*. 1 et n.sp. 2.

Sirenian/dugong bones (*mainly vertebrae and ribs, however a Palatal view of right posterior corner of a skull, exactly at the squamosal, part of the pterygoid and part of the palatine was discovered in 2009 and a possible skull roof in 2017*) are common in the Lower and Middle Al-Kharrara Members and less so in the Upper Al-Kharrara. A "graveyard" exists on the eastern side of Hazm Mishabiyah in the Lower Al-Kharrara (LeBlanc, 2009).

Marine mammals, other than sirenians, were also present during the Lower Miocene, as they are today, attested by the author's discovery of a tooth from a toothed whale (dolphins/tortoises) in the Middle Al-Kharrara.

The fishes are not common: *Aetobatus arcuatus* Ag. (genus of eagle rays) and *Diodon sp*. Indet. (Porcupine fish), and rare shark teeth normally associated with the remains of sirenians, as well as some remains of Reptiles(?) according to Cavelier (1970a, 1970b).

The algae are locally abundant: *Halimeda eocenica* Morellet.

Let's note finally the frequence of Crustacean remains and the abundance of Large Foraminifera of the genus *Archaias*. The corals occur very locally at the extreme base.

From the Upper Al-Kharrara to the Abu Samrah Members

In the synclinal area of the town of Abu Samra, the deposits display essentially marine features, with intercalations in the upper half, of organogenic limestones, with loads of *Clausinella ersica* Cox (a bivalve) and locally some Hydrobiidae (fresh & brackish mud snail – gastropod), indicating an environment abnormal in salinity. Towards the North and Northeast, these levels with *Clausinella persica* make up the major part of the subformation, here much thinner.

The Molluscs from the marine layers, where the bivalves (clams) predominate, include *Chlamys senatoria* (Gmelin), *Anomia sp*., *Ostrea latimarginata* Vredenburg and impressions and molds of *Clementia papyracea* (Gray). *Capsa lacunosa* (Chemn), cf. *Capsa fragilis* (Linne), *Tellina* (peronidia) *bipartita* basterot, *Diplodonta cf. rotundata* (Montagu), *Barbatia barbata* (Linne), *Anadara cf. turonica* (Dujardin), *Cardiocardita cf. monolifera* (Dujardin), *Cardiocardita aff. Turonica* (ivolas et Peyrot), *Solenocurtus basteroti* (Desmoulins), *Timoclea* (Venus) *subspadicea* (Cossm), *Modiola* (*Amygdalum*) sp., some *Cardium*, *Lucina*, *Mactra*, *Tapes*, *Eastonia*, *Panopea*… The Gastropods, represented by internal molds, belong to the genus *Xenophora*, *Ampullina*, *Turritella*, *Cerithium*, *Cypraea*, *Cassis*, *Fasciolaria*, *Voluta*, *Conus*, *?Olivella*, *Bulla*…

The Echinoderms are abundant at certain levels: in the Upper Al-Kharrara *Schizaster sp*., *Agassizia aff. Persica* Olegg and locally in the Middle and Upper Al-Nakhash are abundant spines of *Cidaris sp*. 1 de Noetling 1901.

The Bryozoa are not very common, among them *?Cupuladria gr. haidingeri*, as well as remains of fishes: *Scoliodon (or Physodon) sp.* (shark)

The remains of Crustaceans are abundant in the carbonate rocks.

5 Mio-Pliocene Hofuf Formation

A) Origin of the name and main authors: It was first named by Steinecke M. and Koch T.W. in an unpublished 1935 report, Saudi Arabia) and used formally for the first time by Thralls and Hassan (1956). More detailed descriptions were made by Powers (1968) in Saudi Arabia; and Cavelier (1970a) in Qatar. It is equivalent to the Dibdibba Formation of Kuwait; Al-Sulaimi (1994); Al-Sulaimi and Mukhopadhyay (2000).

B) Type locality: The Hofuf Formation is named after its type locality, some 17 km NNE of

Al-Hofuf town in the Eastern Province of Saudi Arabia, at 25°31'30.0''N, 49°31'00''E (Fig. 76).

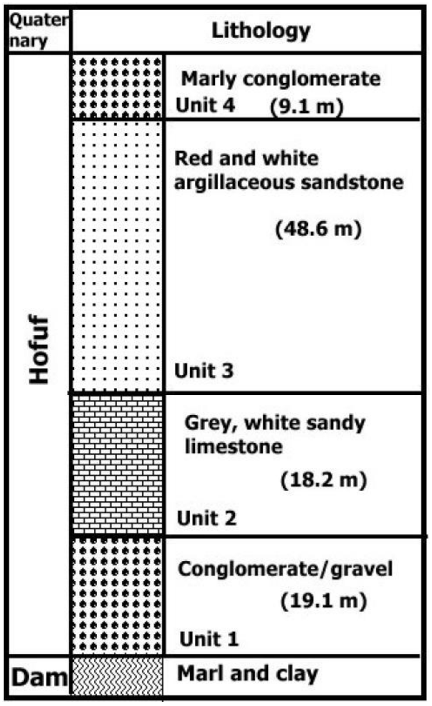


Figure 76. Hofuf formation at the type section locality in Saudi Arabia. Al-Safarjalani (2004). Unit 1 is the only portion of the Hofuf present in Qatar.

C) Qatar Reference Section: In the Qatar National Cement Company (QNCC) quarry in Al-Subaiha/Wadi Al-Huweila area south of Umm Bab (Figs. 77, 78, 79, 80).

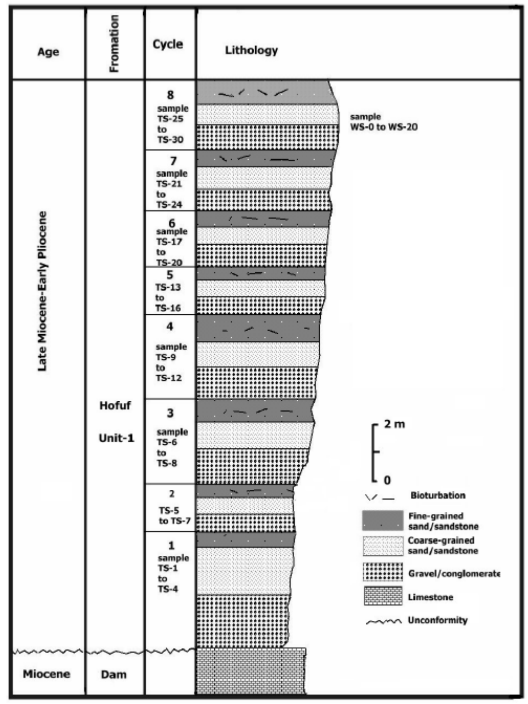


Figure 77. Composite section of Unit 1 of the Hofuf formation in the Al-Subaiha/Wadi Al-Huweila area. After Al-Saad et al. (2002b).

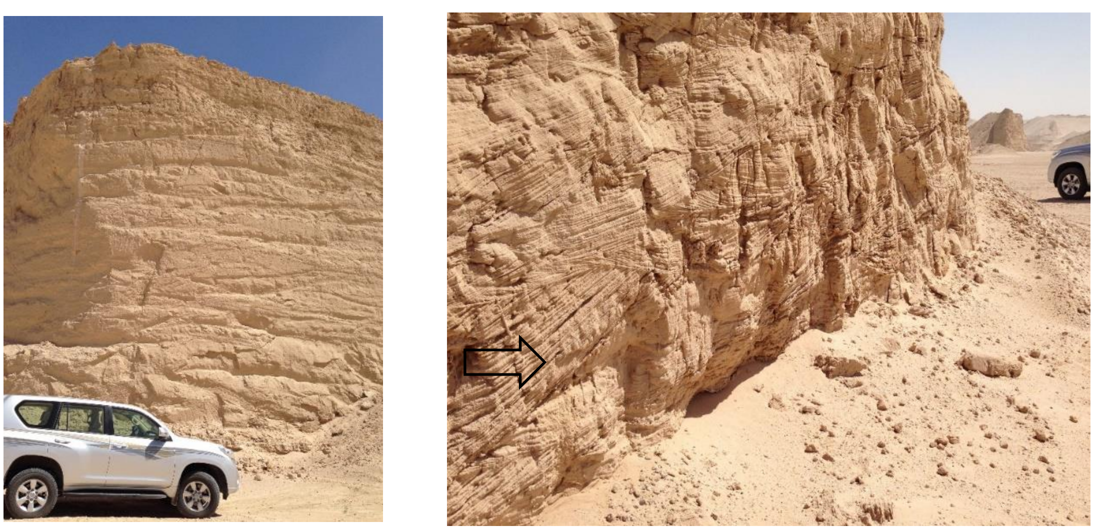


Figure 78. Thickness of the sand & gravel Hofuf Formation in the QNCC's quarry (left) and some cross-bedding of fluvial origin (right) (25°03' 06"N, 50° 51' 8.5"E); LeBlanc (2015a)

Figure 79. A 12m thick section of the Hofuf Formation in the QNCC quarry at locality 25°03'45.75"N and 50°49'53.33"E (see interpretation in Fig. 80).

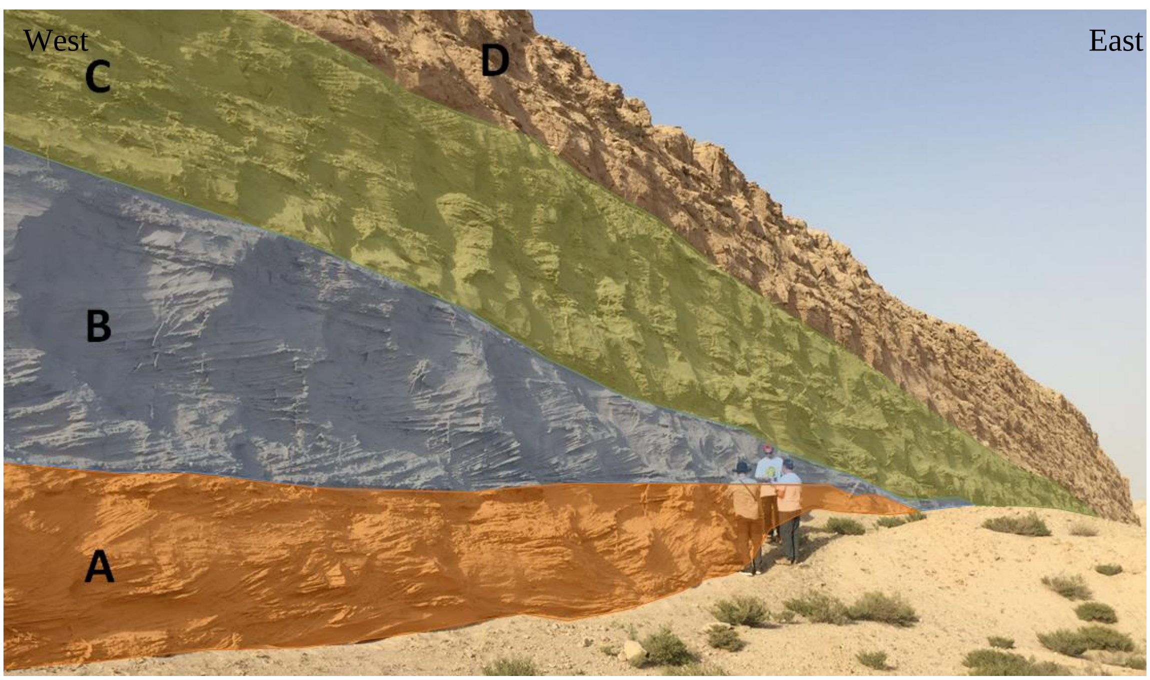


Figure 80. Interpretation of features seen in Fig. 79

- **D** Not interpreted
- **C** Channel abandonment formation (displaying soil/root remains) cross-cutting "B" (and "A" in the sub-surface). Compared to "B", it displays less internal cross-beddings.
- **B** Channel abandonment formation (displaying soil/root remains) cross-cutting "A" and displaying internal cross-beddings
- **A** Channel and sand bar formation with internal cross-beddings. (Its accurate thickness is unknown due to it being embedded under surface layer)

Note: All the above concur with Al-Ansary et al (2012)'s interpretation of the Hofuf environment

D) Age: It is generally considered to be from Late Miocene to Pliocene (7,120,000 to 1,810,000 years old), even though Al-Saad (2002b) includes it within the Late Miocene to Pleistocene (7,120,000 to 120,000 years old) in Qatar. The accurate age will be known only when well defined fossils are found (see section "H" below).

E) Top (MD): ~ +70m (surface location at Subaiha/Wadi Al-Huweila, 25°03' 06"N, 50° 51' 8.5"E)

F) Thickness: ~14 m (~ 46 ft). The thickest sequence of Hofuf sediments present in Qatar is 14 metres of Unit 1 from the Al-Subaiha/Wadi Al-Huweila area[18]; however, if a composite of few sections within this area is stacked together, the whole 18 metres of Unit 1 can be observed (Fig. 77):

G) Lithologic Description - Sudgen et al. (1975) and Al-Safarjalani (2004):
The main body is composed of sand, gravels and pebbles (quartz, jasper, crystalline rocks, limestone, etc.). The base usually consists of sandy red and green clay, and sometimes at the base of bulky sands and sandstones.

Well-exposed, fine-grained to pebbly coarse-grained fluvial sandstone of Late Miocene to Pliocene age crops out in Southern Qatar (Fig. 81). These sandstones belong to the lower unit of the Hofuf Formation as exposed in Saudi Arabia and were deposited largely in paleostream channels along Wadi As-Sahba (Fig. 82) that extended into eastern Saudi Arabia and Qatar, a distance of over 450 kms. The upstream sediments were deposited in a deltaic environment. Wadi As-Sahba's alluvial fan, which extends southeastward, represents the largest of several other nonactive fans in central and south Arabia. It is the existence of this huge former drainage system, which is seen as the fundamental explanation for the occurrence of the Hofuf Formation in Saudi Arabia and comparable gravels elsewhere on the eastern flank of the Arabian Peninsula (e.g., Kuwait and Qatar). The sandstones are derived from the Precambrian basement and Phanerozoic rocks, and are mostly granitic rocks in addition to lesser amounts of volcanics, metamorphic and sedimentary rocks (granite, basalts, gneiss, schist, quartzite and amphibolites).

In the Al Subaiha/Wadi Al-Huweila area, the composite section has a thickness of 59.0 ft. (18 m) (Fig. 77) At least 8 sedimentary cycles are present. Each cycle is composed mainly of sandy conglomerate followed by coarse-grained sandstone and capped with bioturbated fine-grained sandstone. The thickness of these cycles ranges between 3.9 and 10.8 ft. (1.2 and 3.3 m). The main sedimentary structures observed in the different lithofacies are cross-beddings (Fig. 78). Biogenic features include bioturbation and soil/root remains. Three sedimentary facies can be recognized within the formation: clast-supported sandy conglomerate, coarse-grained sandstones, and fine-grained sandstones.

H) Fossil content: Very rare fragmented unidentified bivalve shells were observed (LeBlanc, unpublished, 2017). Other than those, it is safe to say that the Hofuf formation in Qatar lacks in any diagnostic fossil remains that would help in pinpointing the exact age of the deposits. In Saudi Arabia, only trace fossils of plant origin were ascertained in a reddish and yellowish brown horizon; Al-Safarjalani (2004).

I) Remark on the exploitation of the Hofuf sand: As explained by LeBlanc (2009), in certain areas the sand of the Hofuf Formation is contaminated by the presence of calcium carbonate (calcium, aragonite, etc), calcium sulphate (gypsum) and magnesium sulphates which negatively affect the quality of concrete and mortars that use this sand. This author demonstrated that mining the sand deposits of the Hofuf which directly overlay the Middle & Upper Al-Nakhash Members of the Miocene Dam Formation (from which most of these contaminants originate) will result in less economical exploitation. Al-Ansary et al. (2012) went one step further by stating that for the fluvial sand of the Hofuf it is recommended to mine from channel and sand bar layers and to avoid abandonment paleosol layers.

[18] Pers. Comm. Qatar National Cement Company (QNCC)

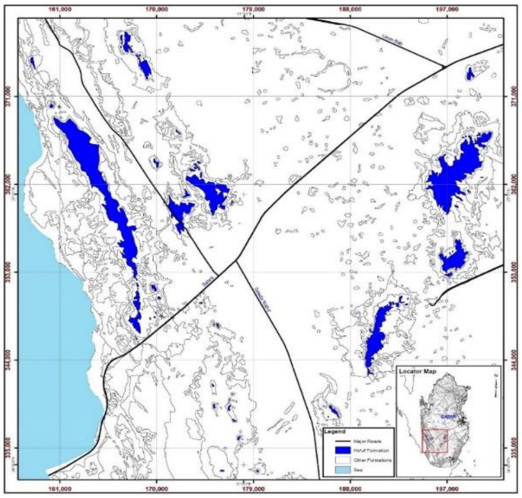


Figure 81. Occurrence of the Hofuf Formation in Qatar.

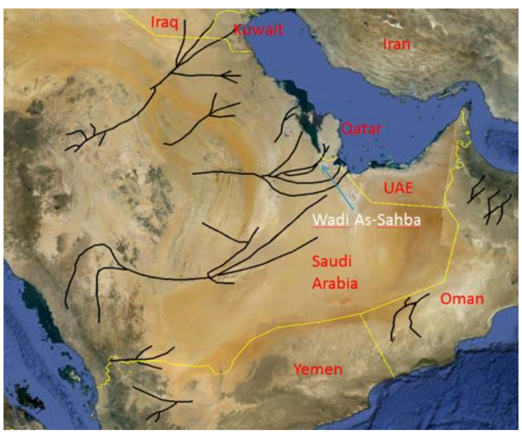


Figure 82. The Hofuf Formation was deposited largely in paleostream channels along Wadi As-Sahba that extended into eastern Saudi Arabia and Qatar. Other such paleostreams also exist but do not reach into Qatar; instead, they divert into UAE, Kuwait or Iraq.

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References

Abu-Zeid Mohamed M. (1991). Lithostratigraphy and framework of sedimentation of the subsurface Paleogene succession in northern Qatar, Arabian Gulf. N. Jb. Geol. Palaont. Mh. Pages 191-204. https://doi.org/10.1127/njgpm/1991/1991/191

Al-Ansary Marwa, Poppelreiter Michael C., Al-Jabry Asia, Iyengar Srinath R. (2012). Geological and physiochemical characterisation of construction sands in Qatar. International Journal of Sustainable Built Environment, 64-84. https://doi.org/10.1016/j.ijsbe.2012.07.001

Al-Hajari Saif Ali, Kendall C.G.St.C. (1992). The sedimentology of the Lower Eocene Rus Formation of Qatar and neighboring regions. J. Univ. Kuwait (Sci) Vol. 19. 153-172. Retrieved from http://pubcouncil.kuniv.edu.kw/kjs/home.aspx?id=8&Root=yes&authid=1262

Al-Saad, H., & Ibrahim, M. I. (2002a). Stratigraphy, micropaleontology, and paleoecology of the Miocene Dam Formation, Qatar. *GeoArabia*, *7*(1), 9-28. https://www.gulfpetrolink.com/ and https://pubs.geoscienceworld.org/gpl

Al-Saad, H., Nasir, S., Sadooni, F., & Alsharhan, A. S. (2002b). Stratigraphy and sedimentology of the Hofuf Formation in the State of Qatar in relation to the tectonic evolution of the East Arabian Block. *Neues Jahrbuch fur Geologie und Palaontologie-Monatshefte*, (7), 426-448. https://squ.pure.elsevier.com/en/publications/stratigraphy-and-sedimentology-of-the-hofuf-formation-in-the-stat

Al-Saad, H. (2003). Facies analysis, cyclic sedimentation and paleoenvironment of the Middle Eocene Rus Formation in Qatar and adjoining areas. *Carbonates and Evaporites*, *18*(1), 41-50. https://doi.org/10.1007/BF03178386

Al-Saad, H (2005). Lithostratigraphy of the Middle Eocene Dammam Formation in Qatar, Arabian Gulf: effects of sea-level fluctuations along a tidal environment. Journal of Asian Earth Sciences, 25, Pages:

0781-0789. https://doi.org/10.1016/j.jseaes.2004.07.009 and https://www.sciencedirect.com/science/article/abs/pii/S136791200400166X

Al-Safarjalani, Dr. Abdulrahman Mohieddin (2004). Placer gold deposits in the Hofuf Formation The Eastern Province of Saudi Arabia. King Faisal University, Faculty of Agriculture, Department of Soil and Water. Al-Hofuf 2004, Research Project Nr.4022. www.kfu.edu.sa/main/res/4022.pdf

Al-Sulaimi, J. S. (1994). Petrological characteristics of clasts in the Dibdibah gravel of Kuwait and their relevance to provenance. *Journal-University of Kuwait Science*, *21*, 117-117. http://pubcouncil.kuniv.edu.kw

Al-Sulaimi, J., & Mukhopadhyay, A. (2000). An overview of the surface and near-surface geology, geomorphology and natural resources of Kuwait. *Earth-Science Reviews*, *50*(3-4), 227-267. https://doi.org/10.1016/S0012-8252(00)00005-2

Blondeau Alphonse, C. C., (1972). Le Tertiaire de la presqu'ile du Qatar (Golfe arabique). Donnees nouvelles fournies par les grands Foraminiferes de l'Eocene moyen. Bulletin de la Societe Geologique de France, 7e Serie, Tome XIV. https://ur.booksc.eu/book/78704750/871d7f

Boukhary, M., & Alsharhan, A. S. (1998). A stratigraphic lacuna within the Eocene of Qatar: an example of the interior platform of the Arabian Peninsula. *Revue de paléobiologie*, *17*(1), 49-68. https://pascal-francis.inist.fr/vibad/index.php?action=getRecordDetail&idt=14724473

Casier, E. (1971). Sur un materiel ichthyologique des 'Midra (and Saila) shales' du Qatar (Golfe Persique). *Bulletin de l'Institut royal des Sciences naturelles de Belgique*, *47*(2), 1-9. https://core.ac.uk/download/pdf/80827573.pdf

Cavelier, C. (1970a). *Geologic description of the Qatar Peninsula (Arabian Gulf)*. Publ Government of Qatar, Dept of Petroleum Affairs [39 pp].

Cavelier, C. (1970b). *Geological Survey and mineral substances exploration in Qatar*. BRGM – Bureau de recherches geologiques et minieres, Government of Qatar, Department of Petroleum Affairs. 109 p.

Cavelier, C. (1975). Tertiary in outcrop. In: Sugden Walter; Standring A.J.; Cavelier C. (1975). *Stratigraphic lexicon: Qatar Peninsula*. ASIE, Volume III, Fascicule 10 b 3. Union Internationale des sciences geologiques.

Chan, S. A., Kaminski, M. A., Al-Ramadan, K., & Babalola, L. O. (2017). Foraminiferal biofacies and depositional environments of the Burdigalian mixed carbonate and siliciclastic Dam Formation, Al-Lidam area, Eastern Province of Saudi Arabia. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *469*, 122-137. http://doi.org/10.1016/j.palaeo.2016.12.041

Chatton, Max (1948). Geological Report on the Dukhan Anticline accompanying the 1:20,000 structural map of this area. Unpublished report. 12 p.

Dill, H. G., Nasir, S., & Al-Saad, H. (2003). Lithological and structural evolution of the northern sector of Dukhan anticline, Qatar, during the early Tertiary: With special reference to sequence stratigraphic bounding surfaces. *GeoArabia*, *8*(2), 201-226. https://www.gulfpetrolink.com/ and https://pubs.geoscienceworld.org/gpl

Dill, H. G., Botz, R., Berner, Z., Stüben, D., Nasir, S., & Al-Saad, H. (2005). Sedimentary facies, mineralogy, and geochemistry of the sulphate-bearing Miocene Dam Formation in Qatar. *Sedimentary Geology*, *174*(1-2), 63-96. https://doi.org/10.1016/j.sedgeo.2004.11.004

Dill, H. G., & Henjes-Kunst, F. (2007). Strontium (87Sr/86Sr) and calcium isotope ratios (44Ca/40Ca-44Ca/42Ca) of the Miocene Dam Formation in Qatar: tools for stratigraphic correlation and environment analysis. *GeoArabia*, *12*(3), 61-76. https://www.gulfpetrolink.com/ and https://pubs.geoscienceworld.org/gpl

Dominguez, J. R. (1965). Offshore fields of Qatar. *Institute of Petroleum Review*, *19*(222), 198-210.

Dunnington H.V.; Wetzel R.; Morton D.M.; Bellen R.C. van. (1959). The Stratigraphic Lexicon of Iraq. *Lexique stratigraphique International*. Retrieved from http://paleopolis.rediris.es/LEXICON/IRAQ/

Eccleston B.L., Pike J.G., Harhash I. (1981). The water resources of Qatar and their development (2 volumes). Food and Agricultural Organization (FAO) of the

United Nations, Doha: 1981. Technical report No. 5.

Gelin, G. R. J.-P. (2020). Middle Eocene echinoids from the Dammam formation of Qatar, Arabian Gulf. *Historical Biology*, *32*(9), 1277-1289. https://doi.org/10.1080/08912963.2019.1575376

Henson, F.R.S. (1948). Larger Imperforate Foraminifera of South-Western Asia; Families Lituolidae, Orbitolinidae and Meandropsinidae. British Museum Natutal History. https://www.science.org/doi/pdf/10.1126/science.109.2834.415.c

Hewaidy, A., & Al-Saad, H. (1993). Surface Eocene stratigraphy of Qatar Peninsula. *Al-Azhar Bulletin of Science*, *4*(1), 165-193.

Jameson, Jeremy (2017). Personal Communication

Kok Cornelius P. (Cees), LeBlanc Jacques (2012). The Bir Zekreet Member: A new lithostratigraphical unit of the Dammam Formation in Qatar. 11 pages. DOI: 10.13140/RG.2.1.1064.8161 http://leblanc.jacques.googlepages.com/fossilhome

LeBlanc, J. (2008). A fossil hunting guide to the Tertiary formations of Qatar, Middle East. 82 pages. DOI: 10.13140/RG.2.1.3850.0966. https://www.researchgate.net/publication/280042253_A_fossil_hunting_guide_to_the_Tertiary_formations_of_Qatar_2008 and http://leblanc.jacques.googlepages.com/fossilhome

LeBlanc, J. (2009). A Fossil Hunting Guide to the Miocene of Qatar, Middle East: A Geological & Macro-Paleontological Investigation of the Dam Formation. 192 pages. DOI: 10.13140/RG.2.1.1228.6567 . https://www.researchgate.net/publication/280042013_A_fossil_hunting_guide_to_the_Miocene_Dam_Formation_of_Qatar_2009 and http://leblanc.jacques.googlepages.com/fossilhome

LeBlanc, J. (2015a). *Unpublished personal notes and pictures*.

LeBlanc, J. (2015b). A historical account of the stratigraphy of Qatar (1816 to 2015). 1220 pages. DOI: 10.13140/RG.2.1.5165.6725 . https://www.researchgate.net/publication/285396912_A_Historical_Account_of_the_Stratigraphy_of_Qatar_Middle-East_1816_to_2015 and http://leblanc.jacques.googlepages.com/fossilhome

LeBlanc, J. (2017). Origin and types of silica in the Lower Eocene Carbonates of the Rus Formation, Qatar, Middle-East. https://www.researchgate.net/publication/313824172_Origin_and_types_of_silica_in_the_Lower_Eocene_Carbonates_of_the_Rus_Formation_Qatar_Middle-East and http://leblanc.jacques.googlepages.com/fossilhome

LeBlanc, J. (2019). Identification of the Middle Eocene Nautiloid Genera of Qatar, Middle East. DOI: 10.13140/RG.2.2.28135.09125 . https://www.researchgate.net/publication/330037167_Identification_of_the_Middle_Eocene_Nautiloid_Genera_of_Qatar_Middle_East and https://sites.google.com/site/leblancjacques/fossilhome

Powers R.W., L.F. Ramirez, C.D. Redmond, E.L. Eleberg, Jr. (1966). Geology of the Arabian Peninsula, Sedimentary Geology of Saudi Arabia. United States Geological Survey Professional Paper 560D. https://doi.org/10.3133/pp560D and https://pubs.er.usgs.gov/publication/pp560D

Powers R.W. (1968). [Lexicon of] Saudi Arabia (excluding Arabian Shield). Lexique stratigraphique international - ASIE. 3(10). Retrieved from http://paleopolis.rediris.es/LEXICON/KSA/droite.htm

Rivers, John M.; Larson, Kyle P. (2018). The Cenozoic kinematics of Qatar: Evidence for high-angle faulting along the Dukhan anticline. Marine and Petroleum Geology, 92, 9 Pages. https://doi.org/10.1016/j.marpetgeo.2018.03.034

Rivers, John M.; Skeat, Sabrina L.; Yousif, Ruqaiya; Liu, Chengjie; Stanmore, Elizabeth; Tai, Po; Al-Marri, Sharifa M. (2019). The depositional history of near-surface Qatar aquifer rocks and its impact on matrix flow and storage properties. Arabian Journal of Geosciences, 12, 380, 33 Pages. https://doi.org/10.1007/s12517-019-4498-6

Sadooni, F. N., & Al-Saad, H. (2012). Mangrove-bearing limestone from the Eocene Dammam Formation, Arabian Gulf: implications for the mangrove dispersal controversy. *Carbonates and evaporites*, *27*(3), 243-250. https://doi.org/10.1080/08912963.2019.1575376

Sander N.J. (1962). Paleontologic and stratigraphic overview of the Paleocene in Eastern Saudi Arabia. Reprinted in 2012 by "Notebooks on Geology" and available under http://paleopolis.rediris.es/cg/CG2012_A04/index.html

Seltrust Engineering Limited (1980). Qatar Geological Map: explanatory booklet

Smout, Alan Hilder (1954). Lower Tertiary foraminifera of the Qatar Peninsula: British Mus. Nat. Hist. Bull., London, Jarrold and Sons Ltd., 96 p. A copy is included in "LeBlanc, J. (2015b)"

Steineke Max, Bramkamp R.A., Sander N.J. (1958). *Stratigraphic relations of Arabian Jurassic oil*. In AAPG: Habitat of oil, pp. 1294-1329. https://archives.datapages.com/data/specpubs/basinar2/data/a125/a125/0001/1250/1294.htm

Sugden (1956). The first Dukhan Type Section. Illustrated in "A Historical Account of the Stratigraphy of Qatar, Middle-East (1816-2015)" by LeBlanc (2015b).

Sugden Walter; Standring A.J.; Cavelier C. (1975). Stratigraphic lexicon: Qatar Peninsula. In: ASIE, Volume III, Fascicule 10 b 3. Union Internationale des sciences geologiques. Centre National des Recherches Scientifique. 120 pages

Thralls, H.W., & Hassan, R.C. (1956). Geology and oil resources of eastern Saudi Arabia. Intern. Geol. Cong. 20th, Mexico. Symposium sobre Yacimentos de Petroleo y Gas. 2, 9-32 pp.

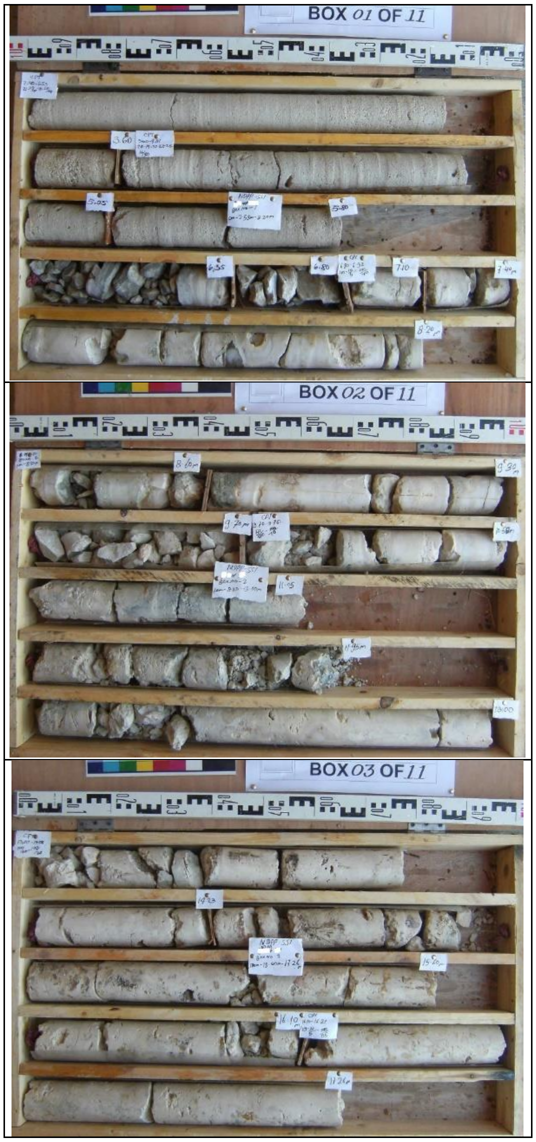
Tollenaere, Joren De (2015). Modelling the influence of the Abu Nakhla pond on the phreatic aquifer in Qatar: present and future scenarios. Retrieved from http://lib.ugent.be/fulltxt/RUG01/002/213/951/RUG01-002213951_2015_0001_AC.pdf

Trueman, E. R., & Brown, A. C. (1992). The burrowing habit of marine gastropods. *Advances in Marine Biology*, *28*, 389-431. https://doi.org/10.1016/S0065-2881(08)60041-3

Willis, R.P. (1967). Geology of the Arabian Peninsula: Bahrain. Geological Survey Professional Paper, Washington 560E, 1-4. https://doi.org/10.3133/pp560E or https://pubs.er.usgs.gov/publication/pp560E

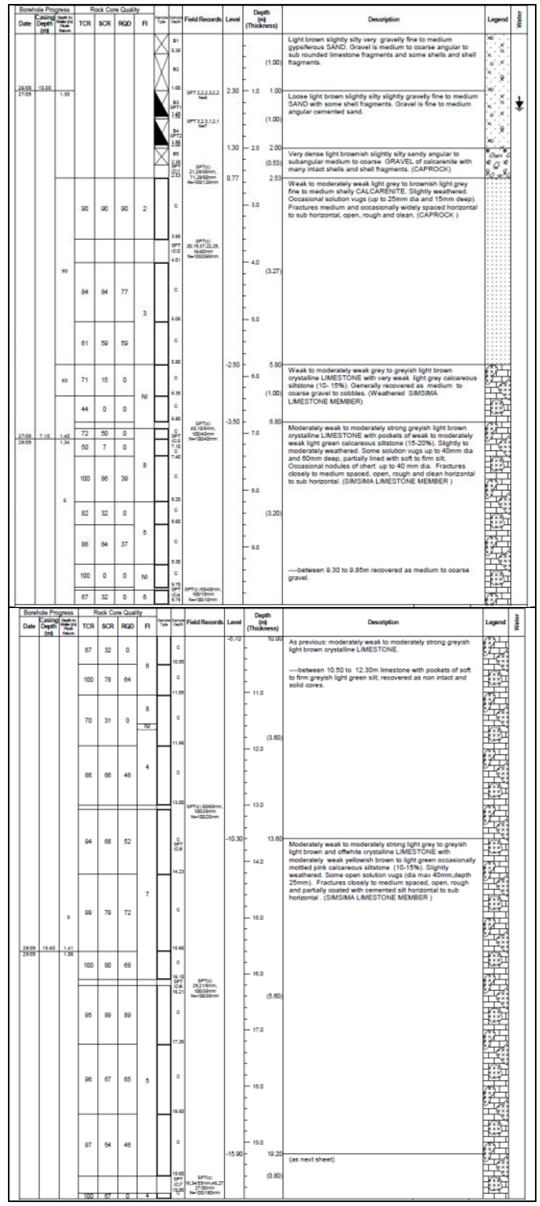
Appendices

Appendix A. Core photos of the Messaid well with the thickest Umm Bab Dolomite and Limestone Member penetrated so far in Qatar[19]

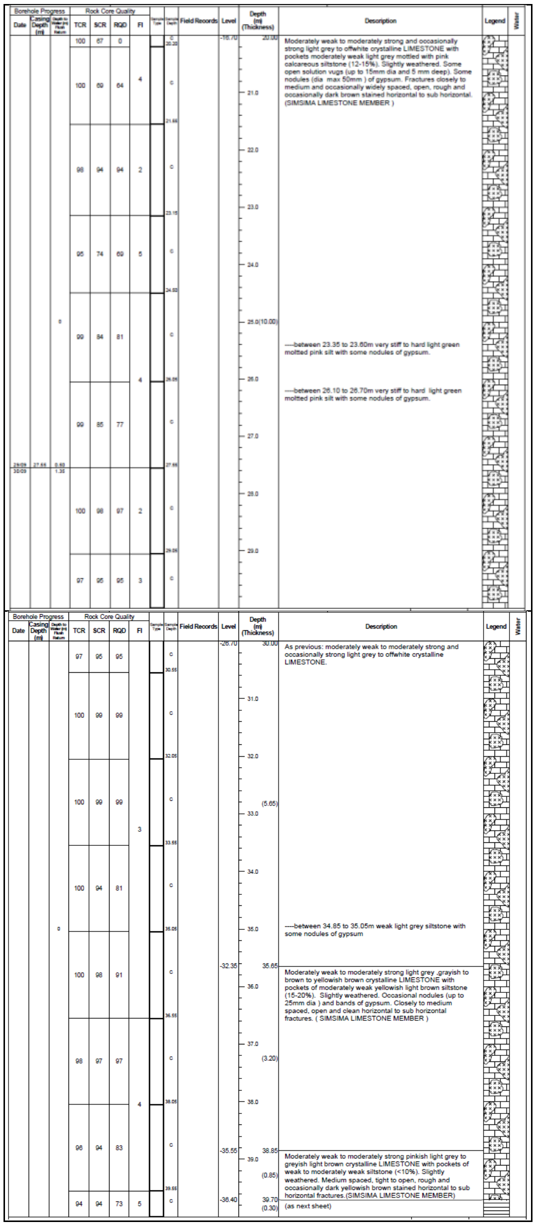


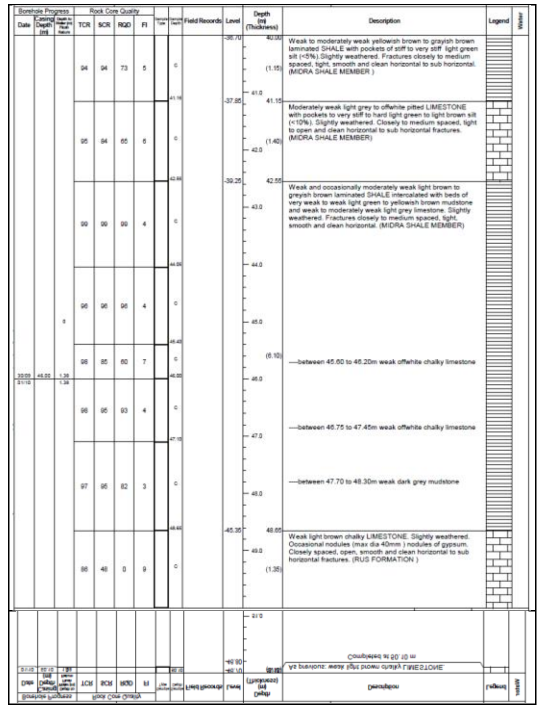
[19] Courtesy of Gulf Laboratories. http://www.gulflaboratories.com

Appendix B. Borehole description of the Messaid well with the thickest Umm Bab Dolomite and Limestone Member penetrated so far in Qatar[20]



[20] Courtesy of Gulf Laboratories. http://www.gulflaboratories.com


Borehole Progress
Rock Core Quality
Field Records
Level
Depth (m) (Thickness)
Description
Legend
Water
Moderately weak to moderately strong and occasionally strong light grey to offwhite crystalline LIMESTONE with pockets moderately weak light grey mottled with pink calcareous siltstone (12-15%). Slightly weathered. Some open solution vugs (up to 15mm dia and 5 mm deep). Some nodules (dia max 50mm) of gypsum. Fractures closely to medium and occasionally widely spaced, open, rough and occasionally dark brown stained horizontal to sub horizontal. (SIMSIMA LIMESTONE MEMBER)
----between 23.35 to 23.60m very stiff to hard light green mottled pink silt with some nodules of gypsum.
----between 26.10 to 26.70m very stiff to hard light green mottled pink silt with some nodules of gypsum.
As previous: moderately weak to moderately strong and occasionally strong light grey to offwhite crystalline LIMESTONE.
----between 34.85 to 35.05m weak light grey siltstone with some nodules of gypsum
Moderately weak to moderately strong light grey ,grayish to brown to yellowish brown crystalline LIMESTONE with pockets of moderately weak yellowish light brown siltstone (15-20%). Slightly weathered. Occasional nodules (up to 25mm dia) and bands of gypsum. Closely to medium spaced, open and clean horizontal to sub horizontal fractures. (SIMSIMA LIMESTONE MEMBER)
Moderately weak to moderately strong pinkish light grey to greyish light brown crystalline LIMESTONE with pockets of weak to moderately weak siltstone (<10%). Slightly weathered. Medium spaced, tight to open, rough and occasionally dark yellowish brown stained horizontal to sub horizontal fractures.(SIMSIMA LIMESTONE MEMBER)
(as next sheet)


Borehole Progress
Rock Core Quality
Field Records
Level
Depth (m) (Thickness)
Description
Legend
Water
Weak to moderately weak yellowish brown to grayish brown laminated SHALE with pockets of stiff to very stiff light green silt (<5%).Slightly weathered. Fractures closely to medium spaced, tight, smooth and clean horizontal to sub horizontal. (MIDRA SHALE MEMBER)
Moderately weak light grey to offwhite pitted LIMESTONE with pockets to very stiff to hard light green to light brown silt (<10%). Slightly weathered. Closely to medium spaced, tight to open and clean horizontal to sub horizontal fractures. (MIDRA SHALE MEMBER)
Weak and occasionally moderately weak light brown to greyish brown laminated SHALE intercalated with beds of very weak to weak light green to yellowish brown mudstone and weak to moderately weak light grey limestone. Slightly weathered. Fractures closely to medium spaced, tight, smooth and clean horizontal. (MIDRA SHALE MEMBER)
----between 45.60 to 46.20m weak offwhite chalky limestone
----between 46.75 to 47.45m weak offwhite chalky limestone
----between 47.70 to 48.30m weak dark grey mudstone
Weak light brown chalky LIMESTONE. Slightly weathered. Occasional nodules (max dia 40mm) nodules of gypsum. Closely spaced, open, smooth and clean horizontal to sub horizontal fractures. (RUS FORMATION)