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The sedimentology of the Lower Eocene Rus Formation of Qatar and neighboring regions

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ABSTRACT

The Lower Eocene Rus Formation generally overlies the Paleocene Umm er Radhuma Formation, and underlies the Middle Eocene Dammam Formation. It is present in the shallow subsurface throughout Qatar. Only the upper part is exposed at the surface and it is a major element of Qatar's fresh-water aquifer.

The lithofacies and thickness of the Rus Formation are quite variable. More open marine facies are concentrated to the north while evaporite facies increase to the south and to the western, northern and eastern parts of Qatar offshore. A detailed study of the surface-subsurface lithostratigraphy of the Rus has permitted its subdivision into three units: a dolomitic unit, an evaporite unit and a chalky limestone unit. Cores from well QDH25 show the general character of the Rus sequence. This indicates that it consists of sedimentary cycles that shallow upward, culminating in a typical sabkha-lagoon complex.

The original facies distribution and thickness of the units was influenced by structural movements persistent from the beginning of the Tertiary, and eustatic sea-level changes. Carbonate facies were deposited over structurally high areas while the evaporite facies were deposited in the structural lows.

The solution and removal of evaporites, at depth in the Rus Formation, subsequently produced numerous depressions which have changed landforms and created caverns, cavities, sinkholes and V-shaped structures. It has also caused the development of secondary porosity and permeability.

INTRODUCTION

The State of Qatar (Fig. 1) is situated midway along the western coast of the Arabian Gulf and projects in a northerly direction to Latitude 25°00′ N and Longitude 51°10′ E. Qatar covers some 11,437 km^2. Its N–S axis is about 180 km long and its broadest E–W width is about 85 km. Qatar's border with Saudi Arabia generally follows low-lying areas of sabkha and sand dunes to the west and south. There is a maritime border with the State of Bahrain to the northwest and Iran to the northeast.

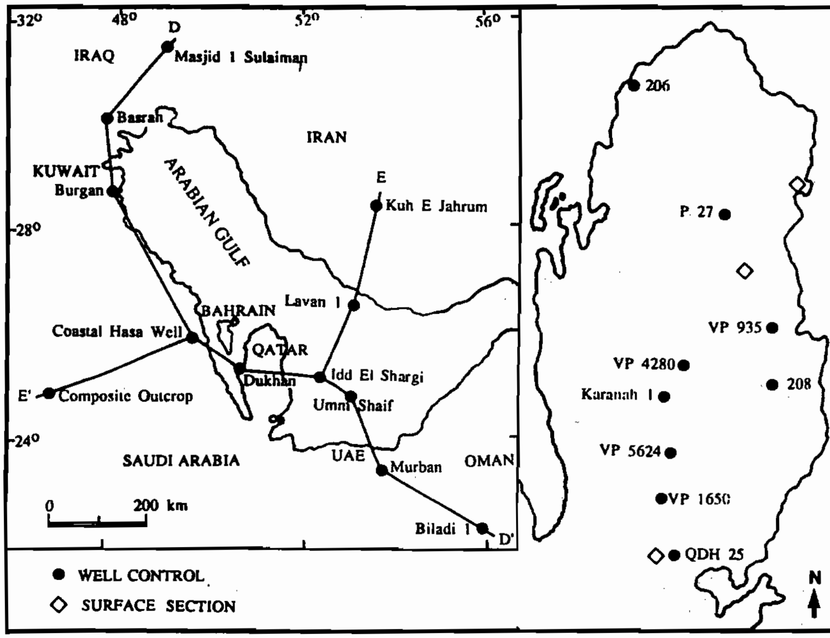

Fig. 1. Index map showing locations of wells and surface sections.

Qatar lies within a torrid sub-region of the northern Arabian desert belt and its average rainfall varies between 10 and 200 mm in any year (Eccleston *et al.* 1981).

On an otherwise flat landscape the most significant topographical features of Qatar are created by a large number of shallow depressions which are surface expressions of subsurface collapse structures. The stony desert surface sediment is composed mainly of depression colluvium, calcareous sands, continental gravels, silts, muds, aeolian sands and sabkha. The Rus Formation constitutes part of the rock outcropping on the surface of Qatar. It extends into the subsurface along the eastern portion of the Arabian Peninsula. It stretches from Iraq in the north to Oman in the south (Fig. 2). In Qatar it is composed of dolomitic limestone, evaporites and chalky limestone, interbedded with thin layers of marls and calcareous claystone.

The regional study described in this paper is based on data from 38 wells and a number of measured sections (Fig. 1). These data include cores and cutting descriptions, along with electrical, gamma ray, neutron and lithologic logs. Petrographic analyses were made of seventy-four thin sections of rock samples collected from different wells and measured sections.

Geological mapping of Qatar began in the early 1930's with the onset of oil exploration. Lamare (1936), Henson (1948 & 1951), Smout (1954), Powers (1968), Stoklin (1968), Blondeau & Cavelier (1972), and Abu-Zeid & Boukhary (1984) provided a synopsis of this initial work.

The first major and comprehensive geological survey to detail the whole of Qatar was carried out for the Department of Petroleum Affairs by Cavelier *et al.* (1970) from the Bureau de Recherches Géologiques et Minières (BRGM). This

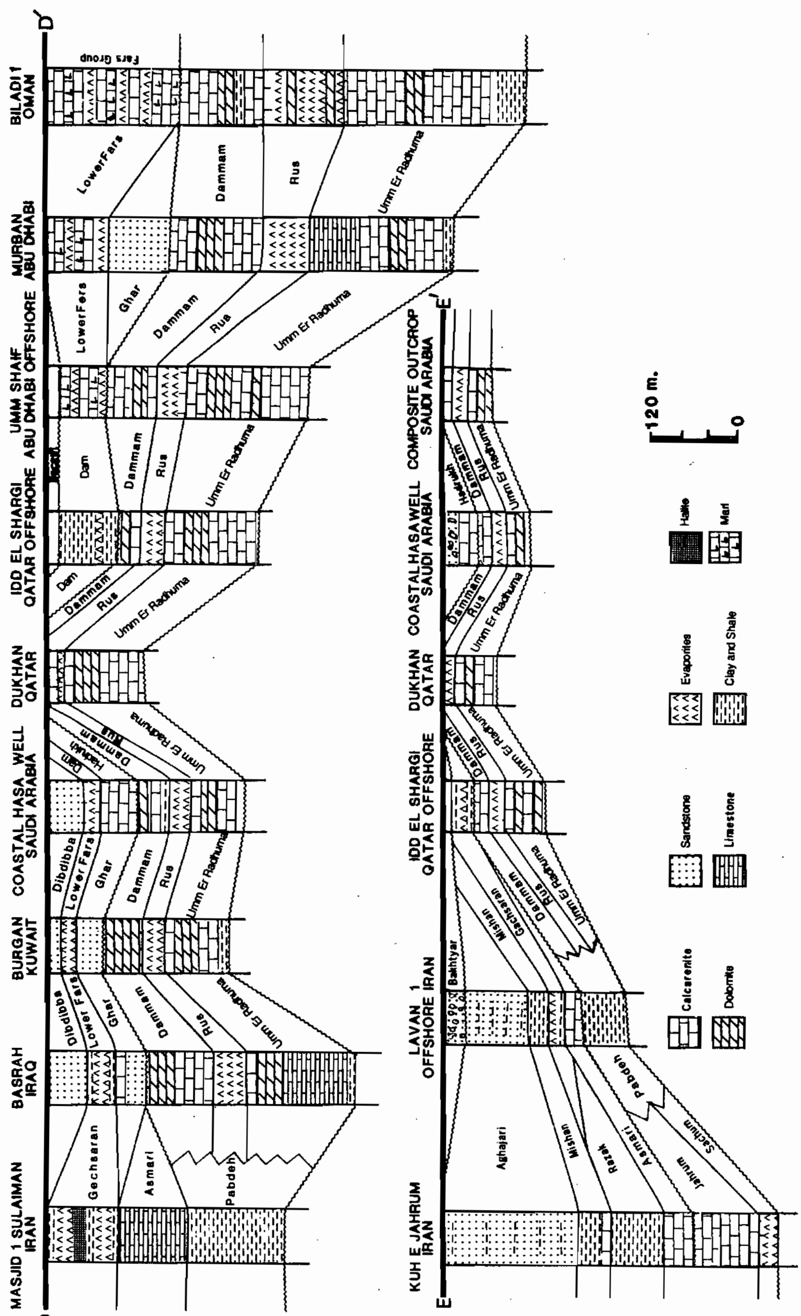

Fig. 2. Schematic cross sections through the Arabian Peninsula showing Tertiary formations. Complied and modified from James & Wynd (1965), Schlumberger (1975, 1981), and Hughes (1988).

survey revised and established the stratigraphy of Tertiary and Quaternary deposits and resulted in geological maps at scales of 1:100,000, and 1:200,000.

A major contribution of this paper is the study of the lithofacies distribution, thickness variation, post-depositional dissolution and the effect of structural framework on sedimentation of the Rus Formation.

GEOLOGICAL SETTING

The Arabian Peninsula, the southern projection of Asia Minor, is separated from Africa by the Red Sea, from Iran by the Arabian Gulf and the Gulf of Oman. It is bounded on the south by the Arabian Sea and the Gulf of Aden (Fig. 3). The Qatar peninsula is an integral part of the Arabian Peninsula lying between the exposed part of the stable Arabian shield of western Saudi Arabia and the mobile shelf of southwest Iran (Powers *et al.* 1966). Since the Paleozoic, the tectonic evolution of the Qatar area has been centered over an anticlinal dome, that has been gently warped and slightly folded (Cavelier *et al.* 1970). The present peninsula is dominated by this wide, gentle anticlinal arch with its north–south main axis oriented down the center of the peninsula (Fig. 4). This arch is complicated by the presence of several smaller pronounced structures, including the Dukhan anticline (the main oil-bearing

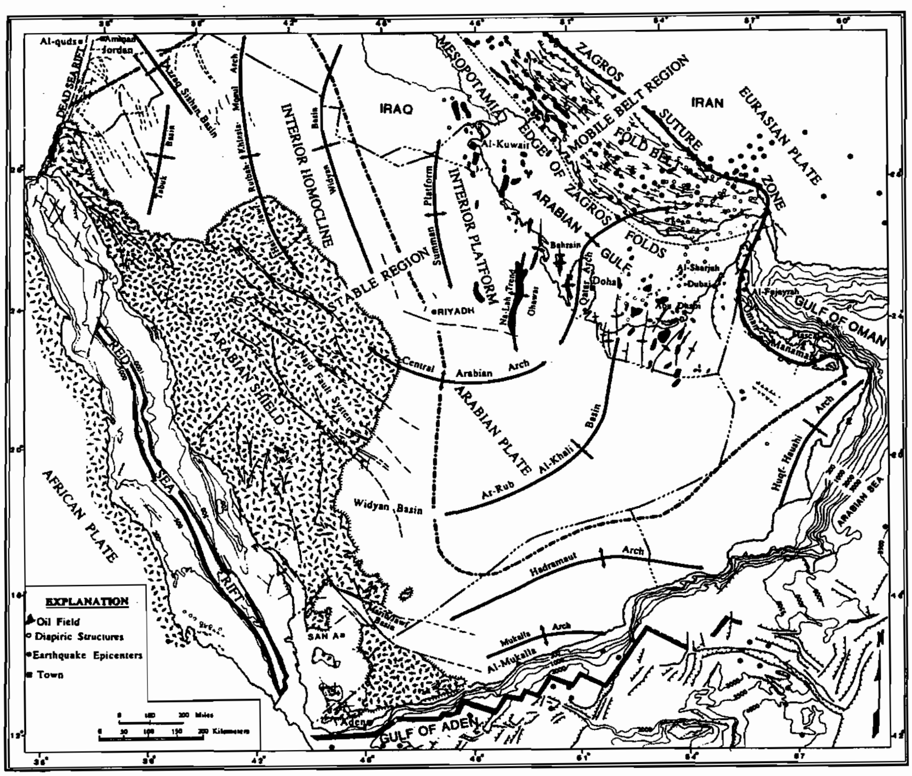

Fig. 3. Geological boundaries and main structural provinces of the Arabian Peninsula. Compiled from Brown (1972), Al-Laboun (1988) and Al-Sharhan (1989).

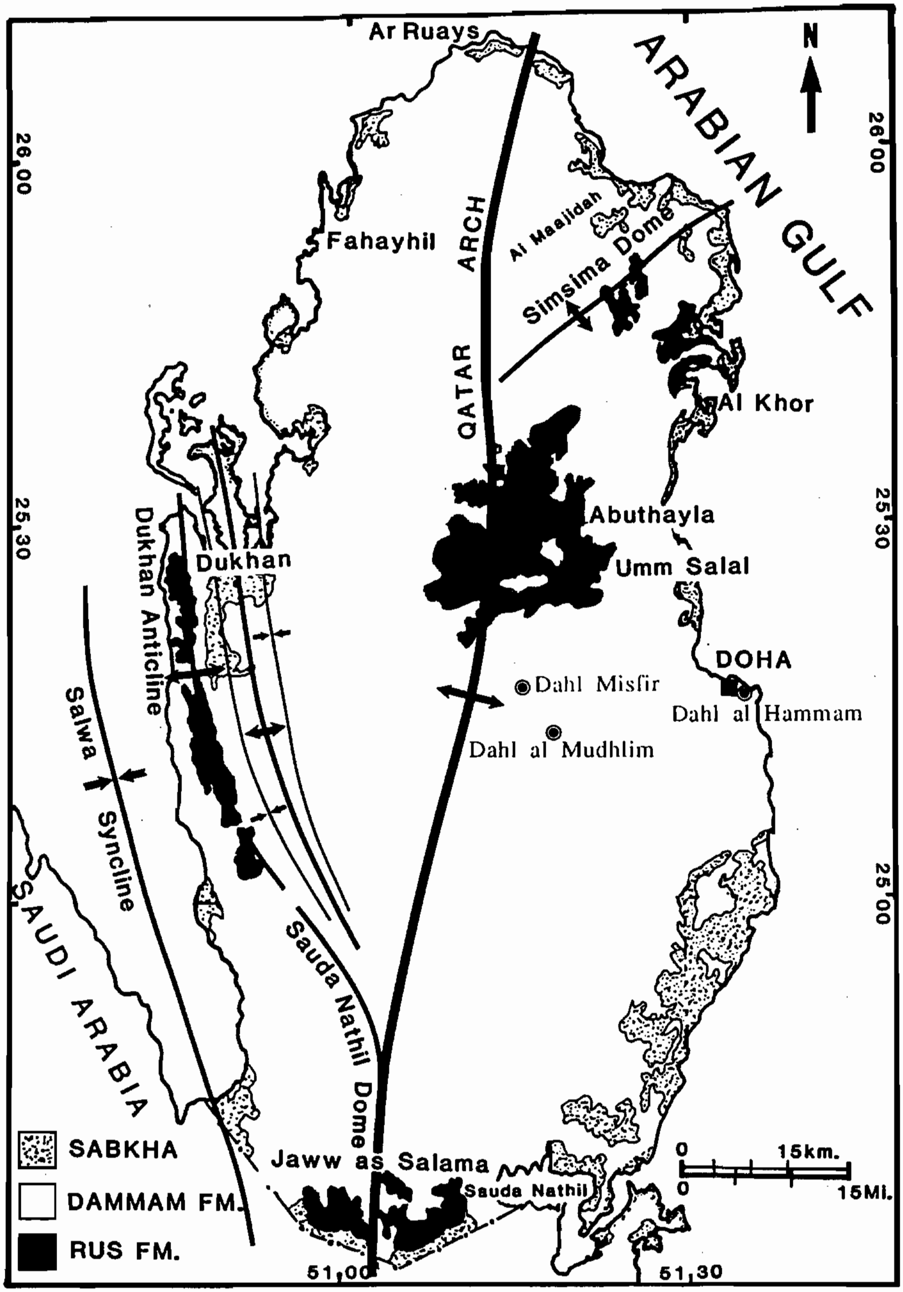

Fig. 4. Major structural features of Qatar.

structure of the region which lies along the western side of Qatar). The steepest limbs are associated with areas of epeirogenic folding, the Sauda Nathil dome and the Simsima dome (Cavelier *et al.* 1970). Other structural features of the area include unconformities, minor faults, joints and collapse structures.

TERTIARY STRATIGRAPHY

The Qatar Peninsula, with its position adjacent to the Tethys geosyncline, was subjected to periods of minor folding which had a significant influence upon the local sedimentation. The exposed succession in Qatar is composed of Tertiary limestones and dolomites with interbedded clays, shales and marls that extend out under the shallow waters of the central Arabian Gulf. Deposits of Pliocene, Miocene and Eocene ages crop out over the peninsula and are overlain locally by superficial Quaternary and Recent deposits (Fig. 5). The oldest strata exposed are the limestones of the Rus Formation, which is of early Eocene age. The most widespread outcrops are the dolomites and crystalline chalky limestone from the upper part of the overlying middle Eocene Dammam Formation (Cavelier *et al.* 1970). The Umm er Radhuma Formation, of Paleocene age, directly underlies the Rus Formation throughout Qatar, but is not exposed at the surface.

Several cross sections along and across Qatar reveal vertical and lateral lithofacies variations. The evaporite beds tend to thin toward structural highs and thicken away from the Dukhan anticline and Qatar central arch (Figs 4, 6 and 7).

The structural framework affected both the lithofacies distribution and thickness of the Rus Formation, and also had a significant influence on the overall hydro-

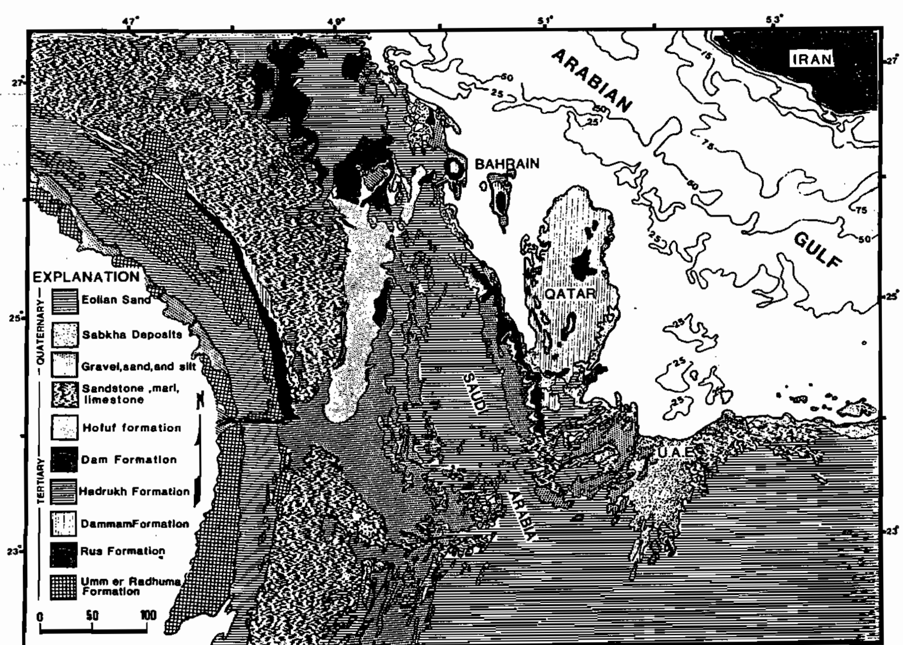

Fig. 5. Geological map. Adapted from geological maps of the Arabian Peninsula, 1963, and Qatar, 1980.

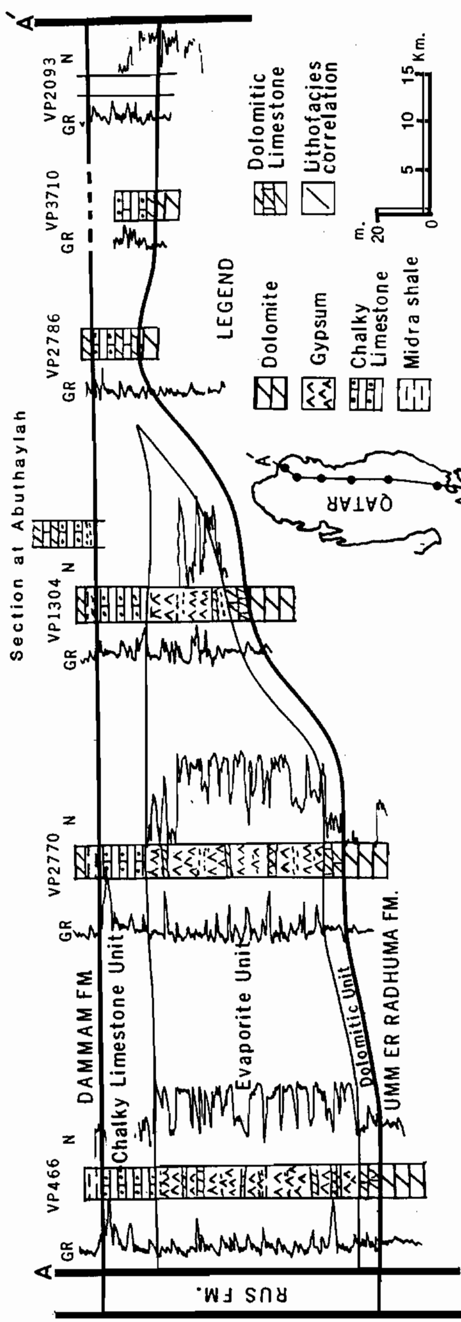

Fig. 6. North–south section along Qatar based on correlation of wells, with gamma ray and neutron logs shown.

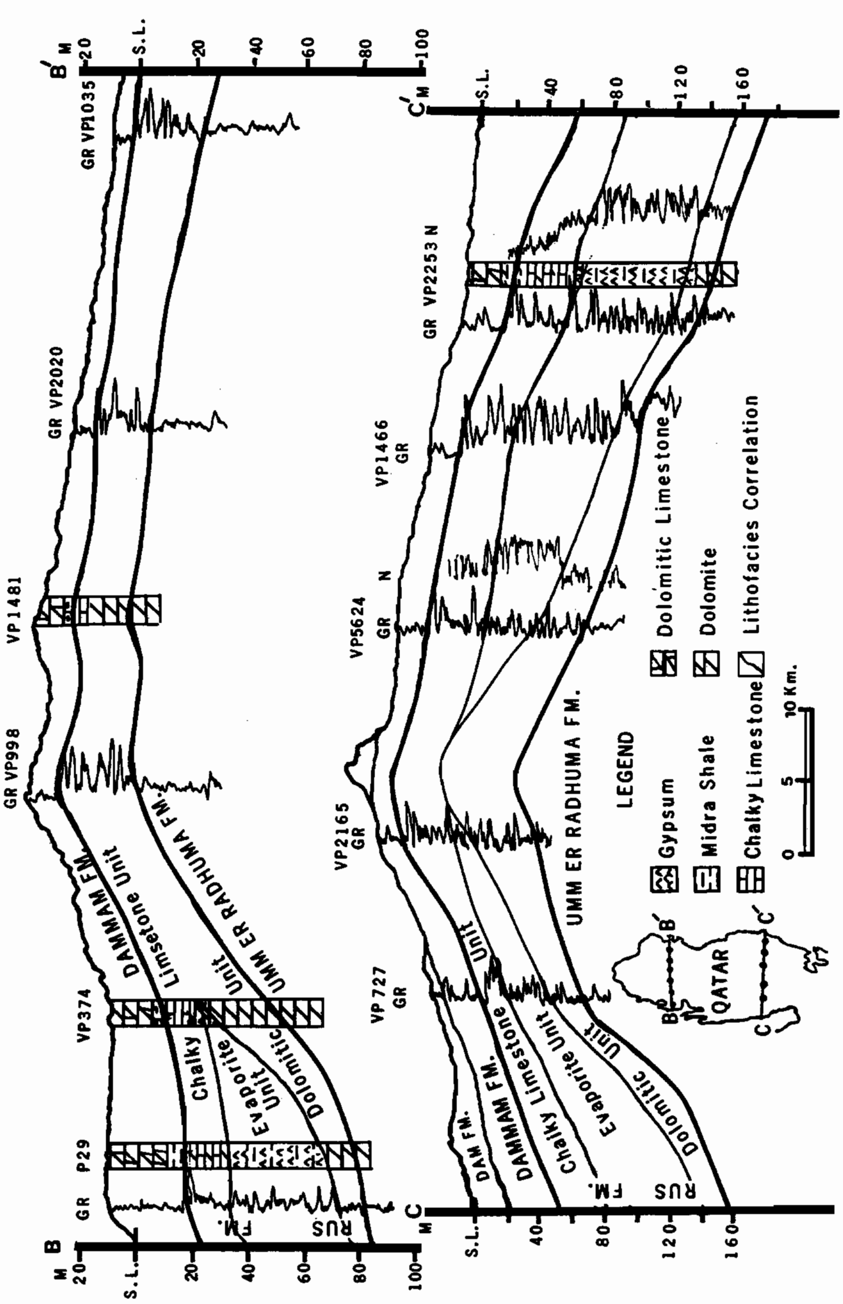

Fig. 7. East–west sections across Qatar showing evaporite units thinning toward structural highs.

geological system of Qatar. Two major groundwater provinces are recognised, a northern one which is characterized by carbonate facies and low salinities varying from 400–2,000 ppm, and a southern one which is characterized by thick evaporite beds, with salinities varying from 3,000–6,000 ppm (Al-Hajari 1987).

TYPE LOCALITY OF THE RUS FORMATION

The Rus Formation was first named from the rocks of the Umm er Ru'us (Lat. 26°19′04″ N, Long. 50°07′51″ E.), which outcrop in a small hill in Saudi Arabia (the Dammam Dome). 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 and below the Dammam Formation. Thralls & Hasson (1956) wrote the first formal publication which used the term Rus Formation. Steineke *et al.* (1958) gave detailed information on the type sequence and Sander (1962) published more details on the stratigraphic and paleontologic data.

REFERENCE SECTION

Cavelier *et al.* (1970) measured and established a reference section for the Rus Formation in the cliffs of Jabal Dukhan (Lat. 25°26′ N, Long. 50°47′ E) and west of that point on the coast. Unfortunately, the base of the formation is not exposed at the type locality, but a section 36 m thick can be seen. The formation conformably overlies the Upper Umm er Radhuma and is a wholly carbonate sequence. It is composed of dolomitic chalk with occasional harder, better-cemented limestone beds which sometimes contain pellety or oolitic debris. Chert nodules or small aggregates of quartz or chalcedony are common. In contrast, most subsurface sections in Qatar include some bedded or massive evaporitic facies. Upwards the Rus Formation is conformable with the Dammam Formation. The contact of the Dammam and Rus is almost one of shale or argillaceous limestone above, and chalky limestone below.

OCCURRENCE AND THICKNESS

The description that follows represents the results of extensive field work and subsurface studies. The Rus Formation is present in the shallow subsurface throughout Qatar but only its upper portions are exposed. It can be seen to the north of Doha (Umm Salal, Abuthaylah, Al-Khor and Al-Maajidah), to the west in the Dukhan anticline (Fahayhil and Dukhan domes), and to the southwest near Sauda Nathil (Jaww as Salama, Hazm Sauda Nathil and Uqlat al Manasir) (Fig. 4). Boreholes in Qatar reveal that the thickness of the Rus ranges from less than 30 m to more than 110 m.

Deep wells have penetrated the Rus Formation in the subsurface of large areas of the Arabian Peninsula, including South Yemen and Oman to the south and Kuwait and south Iraq to the north. The Rus Formation also crops out in Saudi Arabia, Bahrain, Oman and South Yemen (Powers *et al.* 1966; Cavelier 1975).

In Saudi Arabia the Rus Formation crops out in two small areas—a narrow band along the Wadi as Sahba extending 180 km north and at the Dammam Dome. Here the Rus has an average thickness of 25–30 m. Patches of Rus can also be observed in the southeastern Rub al Khali (Powers *et al.* 1966).

The Rus Formation is the oldest rock outcropping in Bahrain, and occurs in the central part of the island, and reaches a thickness of 67·7 m (Powers *et al.* 1966).

In Oman the Rus Formation occurs throughout the country except to the southeast where it has been eroded away (Hughes 1988). It crops out in Jabal Qara and the foothills between Thumrait and Salalah. The average subsurface thickness of the Rus ranges between 100 and 150 m, with a maximum thickness of 237 m observed in Butabul area. Generally, the formation thins eastwards and wedges out by truncation along a N–S trend line (Parker 1985).

CONTACTS

Basal contact: the basal part of the dolomitic unit (Lower Rus Formation) conformably overlies the Umm er Radhuma Formation. This contact is generally not obvious because the lithologies on either side are so similar. A common indication of this contact is evident from lost circulation in boreholes of the study area. In some areas the boundary coincides with evidence of dissolution and dolomitization.

Eccleston & Harhash (1982) indicated that the contact between the Umm er Radhuma and Rus Formations is characterized by a general facies change and the disappearance of marine fauna.

In Saudi Arabia the dolomite and dolomitic limestone of the Umm er Radhuma are conformably overlain by the typically soft, chalky limestone of the Rus Formation (Tleel 1973). A similar situation has been observed in Kuwait and Bahrain.

Upper contact: the top of the chalky limestone unit of the Rus Formation conformably underlies the Dammam Formation throughout Qatar. The contact is easily defined where the lower Dammam Formation "Midra Shales Member" is present. Elsewhere, where the Midra Shales are absent, the "*Alveolina* Limestone Member," or Khor limestone (Cavelier *et al.* 1970), occurs and is identified by an abundant *Alveolina elliptica* fauna.

In Saudi Arabia the chalky Rus Formation is conformably overlain by the tan, calcareous, and gypsiferous shale and interbedded marl of the basal Dammam (Powers *et al.* 1966).

Fossils and geologic age

Diagnostic fossils in the Rus Formation are rare, so age determinations are usually based on field relationships between older and younger beds. From its stratigraphic position the Rus Formation can be considered to represent the terminal, shallow phase of the Lower Eocene sedimentary cycle (Cavelier 1975).

The fossils that occur in the Rus are mainly found within the thin chalky limestone and dolomitic unit. The diagnostic fossils identified in the study area are the pelecypods (*Cardium* and *Corbula*), gastropods (*Hydrobia* and *Cerithida*), *Nummulites*, and some echinoid fragments. Powers *et al.* (1966) reported that diagnostic fossils are absent in the Rus Formation even though it is underlain and overlain by rocks of proven early Eocene age. It is thought that the Rus Formation falls entirely within the Ypresian.

STRATIGRAPHY OF THE RUS FORMATION IN QATAR

Field observations of Rus outcrops focus on three measured sections. Subsurface data in this paper are principally based on four cored drill holes, though lithology and well-log interpretations have been gathered throughout the study area. Le Grand Adsco (1959) drilled six out of eight holes in the northern part of Qatar and gave a lithologic description which can be applied to the overall character of the Rus Formation in Qatar. Two of these drill holes (ADSCO 206 located between Zubarah and Fahayhil, and ADSCO 208 located in the SW of Doha) contain thick gypsum layers.

In the present study three distinctive units have been recognized in the Rus Formation (Fig. 8). These units are based on the correlations of the lithology and sedimentary structure observed in the cores and in outcrop. Identification of units was also characterized by well log signatures. These units have been named to match their dominant lithology, which are in vertical sequence from older to younger, as follows:

1. DOLOMITIC UNIT

The general lithology of the dolomitic unit is composed of grey to buff, compact, crystalline dolomitic limestone, and white, chalky, porous limestone in the lower part.

At the onset of the deposition of this unit, sediment accumulated in a shallow sea in which there is evidence of a transition zone between an open marine and protected setting where interbedded evaporites accumulated.

Sander (1962) published a report on Saudi Arabia in which he concluded that the fossils observed at the base of the Rus Formation beds indicate a shallow marine depositional setting; and the abrupt facies change from the Umm er Radhuma Formation to the overlying Rus Formation suggests a possible hiatus in sedimentation following the deposition of the Umm er Radhuma. BRGM (1977) reported evidence in Saudi Arabia which indicates that the hiatus was associated with uplift and land emergence over structural highs.

2. EVAPORITE UNIT

The evaporite unit is highly variable in both lithology and thickness. This unit consists of abundant evaporites (largely gypsum), and grey marl interbedded with limestone and greenish clay. Some geodal quartz nodules are present at several levels. Local evaporite dissolution has taken place in this unit, causing the overlying blocks to slump. This intermediate thick evaporite unit and the disappearance of fauna indicate that maximum isolation of the basin was achieved. Evidence from sea level charts (Haq *et al.* 1987) also indicates a global sea level fall during the lower Eocene.

Comparisons of the core from QDH25 (Fig. 1) at the studied section with sediments from present day sabkha complexes suggest that the sequence of greenish clay, limestone and evaporites were deposited in a typical sabkha to lagoon transition.

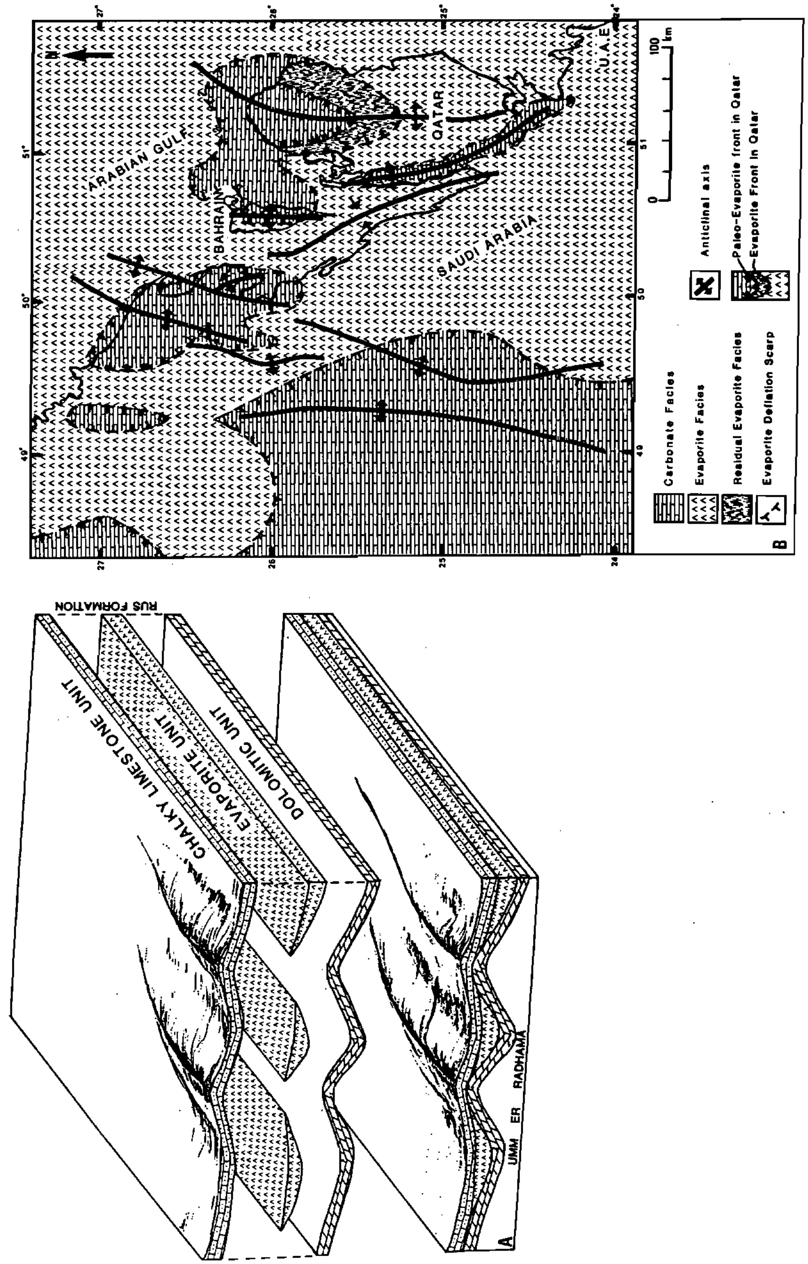

Fig. 8. (A) Schematic diagram showing relationship of the lithofacies units to structure, and (B) facies distribution of the Rus Formation. Modified from GDC (1980).

Near the bottom of the section in the south, at the Jaww as Salama section, there is a saccharoidal limestone, a gypsiferous bed, gypsum pockets and banded layers of carbonate. Recent gypsum crystals are common in the fractures and joints. The authors believe that this lower section represents a low-stand evaporite unit capping a shoaling cycle. These Rus Formation gypsum strata are not present in the northern areas either because the arch was uplifted penecontemporaneously with deposition, or because sea level was beneath its crest.

Sediments from coastal evaporite settings are well documented by modern examples (see Murray 1964; Illing *et al.* 1965; Holliday 1968; Wood & Wolfe 1969; Kinsman 1969; Kendall & Skipwith 1969; Butler 1969; Shinn 1973; Butler *et al.* 1982). A typical sabkha-lagoon transition can be summarized to contain sediments from three depositional settings which are laterally related. Many of these can be recognized in the Rus Formation (Figs 9 and 10):

A. Supratidal: characterized by storm sediments washed above the high water mark onto a salt-encrusted coastal plain and associated with the early diagenetic growth of nodular anhydrite.

B. Intertidal: characterized by generally broad intertidal flats with both carbonate muds and sand bodies which are frequently incised by channels.

C. Shallow subtidal: characterized by muddy pelletal and skeletal sediments which are deposited in quiet, saline lagoons with variable current activity.

The above sediments which are from laterally related peritidal settings, are expressed as vertical sequences in sabkhas in response to the diachronous progradation of supratidal flats across lagoonal settings, producing the cyclic character of these sediments. Such cycles, if completely developed, are characterized by five vertical sedimentary facies:

A. Supratidal
  1. Storm sediments including pelletal packstones and grainstones washed onto the sabkha surface.
  2. Diagenetic nodular anhydrite formed in the sabkha capillary zone.

B. Intertidal
  1. Broad intertidal zone characterized by pelletal sediments, usually cut by small tidal channels. Laminations, algal mats and desiccation features are common.
  2. Beach deposits characterized by current-embedded pelletal or skeletal grainstones and packstones. Chevron cross-bedding is usually well developed, and in high-energy settings textural inversion may occur, resulting in poorly sorted grainstones. One of the best known examples of both intertidal and supratidal environments has been observed in Recent coastal plain sabkhas of Abu Dhabi of the UAE (Kendall & Skipwith 1968).

C. Lagoonal
  1. Laminated pelletal wackestone and mudstones, with frequent evidence of compaction.
  2. Bioturbated or burrowed pelletal sediments with a mottled texture and absence of primary bedding.
  3. Brecciated sediments resulting from fragmentation of a syn-sedimentary marine cemented lithified carbonate crust.

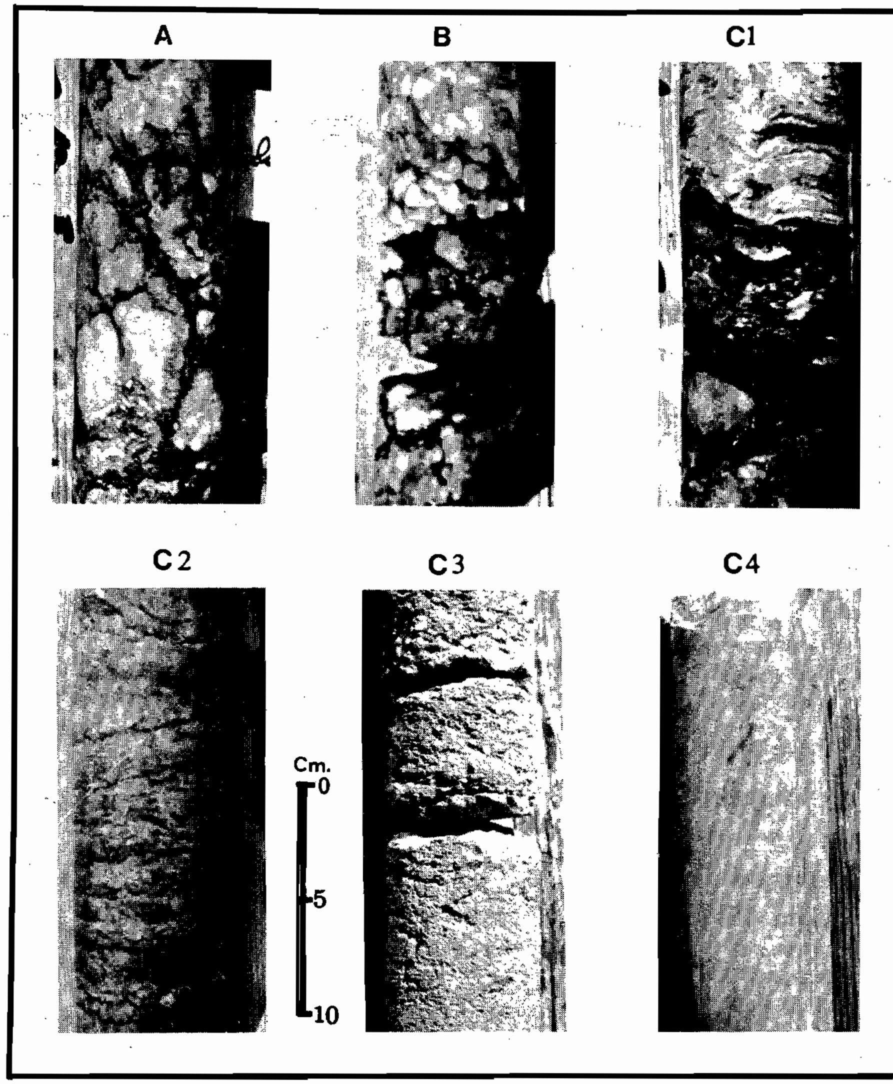

Fig. 9. Representative facies encountered in the Rus Formation sedimentary cycle: (A) Very fine greenish clayey sediments probably deposited in quiet lagoons (B) Marly limestone, directly overlies the greenish clay interval. Laminations are well preserved and grains coarsen upwards (C1) Bedded massive evaporite composed of layers of massive gypsum, characterized by horizontal dark bands of impurities (C2) The thin, wavy and domed laminations represent a relict, stromatolitic, algal mat, probably developed on the upper intertidal flats (C3) Crudely bedded mosaic anhydrite (C4) Nodular mosaic anhydrite interlayered with algal mat, indicative of sabkha capillary zone.

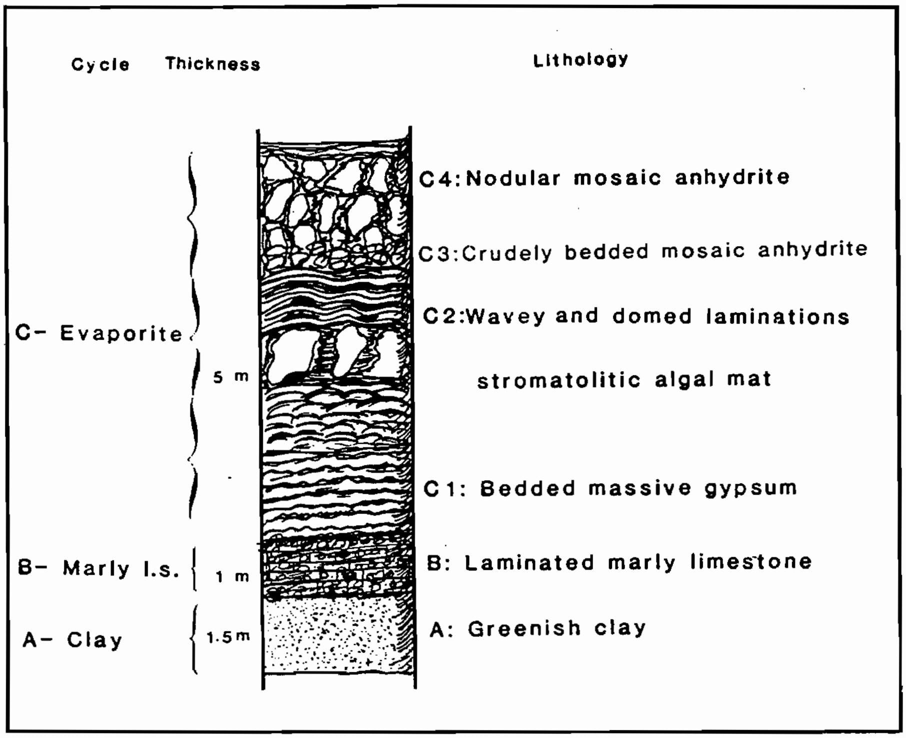

Fig. 10. Diagram showing typical sedimentary cycle seen in cores from the QDH25 well in the Rus Formation.

4. Pelletal/skeletal packstones, locally grainstones, winnowed by subtidal currents.

D. Channels and bars
1. Intertidal or subtidal channels characterized by an erosive base and a fining-upward sequence of current-bedded grainstones and packstones that pass into wackestones and mudstones.
2. Offshore bars and shoals developed within the lagoons that contain a coarsening-upward succession of grainstones.

E. Open marine
Away from the influence of the lagoon and tidal currents open marine deposits consist of typical shelf chalky limestones or clastic muddy sands and muds.

Comparison between the Rus cycles in cores suggests that these interacting settings formed eight cycles (Figs 9 and 10). These were recognized in the evaporite unit of the study area where a 110 m cored hole (QDH25) has been interpreted to penetrate a sabkha-lagoonal complex. Each cycle starts with a deposit of very fine greenish clay interpreted to have been transported by inland runoff to a quiescent semi-restricted lagoon setting. This fine clay is thought to have been deposited in response to climatic changes in the area and can possibly be related to regional and global climatic changes that caused gradual decline in temperature.

3. CHALKY LIMESTONE UNIT

The general lithology of the chalky limestone unit is a light-colored, soft, porous chalky limestone which is predominantly white, and intercalated with thin layers of marls and calcareous claystone. The uppermost part of this unit is characterized by grey, granular, vuggy, and fossiliferous laminated limestone beds of bioclastic grainstone and packstone.

Comparison of measured sections from outcrops in the northern part (Al-Khor and Abuthaylah) and in the southern part of Qatar indicate that the southern part appears to be relatively thick, averaging 36 m. The Midra Shale thickness is about 6 m, representing the lower portion of the Lower Dammam Formation where it overlies the Rus Formation in the southern part at the Sauda Nathil section, whereas in northern Qatar at Al-Khor the Midra Shale is absent. Cavelier *et al.* (1970) reported that "The Lower Dammam Formation shows considerable variation in thickness in Qatar; it is especially reduced or absent in the NE of Qatar over the anticline suggesting this area was emerging or formed shallows at this time." "The Khor Limestone bed" is well developed in northern Qatar while in the south it has been partly dolomitized and is not so well developed. This soft white chalky limestone of the south is interbedded with thin greenish and brownish clay.

The overall lithofacies of this unit suggest a gradual change from a more restricted and isolated environment to one with an open marine influence. Powers *et al.* (1966) and Cavelier *et al.* (1970) reported that the thick clayey limestone deposits of the overlying Lower Dammam Formation probably marked the subsequent inundation of the area with less restricted seas.

The gradual change in lithofacies from evaporites to chalky limestone and the return of the marine fauna (pelecypods, gastropods, and foraminifera) reflect the resurgence of the marine influence. Chert nodules near the top of the chalky limestone unit were observed in the measured sections of the Sauda Nathil, Abuthaylah and as scattered remnants on top of the mesa hills of the Umm Bab area. These probably indicate a marine incursion with the silica supplied by siliciclastics near a shoreline and/or sponges in the partially restricted environment. The topmost part of the chalky limestone unit, which is characterized by fossiliferous laminated limestone beds of bioclastic grainstone and packstone, marks the more advanced stages in the development of an open marine setting. Cavelier *et al.* (1970) reported that the quite variable fauna of the Lower Dammam Formation which overlies the Rus Formation is evidence for a complete return to normal marine conditions.

POST-DEPOSITIONAL DISSOLUTION

The Rus Formation has been extensively influenced by post-depositional dissolution which has changed landforms and created caverns, cavities, sinkholes and the development of secondary porosity and permeability. It had a profound significance to groundwater character of the aquifer system of the Qatar Peninsula.

Extensive dissolution which took place in the Rus Formation in the study area is shown by (1) surface evidence of a large V-shaped structure over the central part of Qatar (Fig. 8B); (2) the measured section at Jaww as Salama (Fig. 4); (3) the creation of several open caverns [Dahl Misfr, Dahl al Mudhlim, and Dahl al Hammam (Fig. 4)] and (4) numerous collapse depressions. In addition to information from surface and subsurface cores, four hand-dug holes in the As Sahlah area provide further data. Three of these hand-dug holes were placed in a depression in which gypsum strata apparently were dissolved. However, one hole dug uphill at the margin of a depression contains 6 m of gypsum. Moreover, lost circulation in the Rus Formation in boreholes VP 4280, VP 1466, VP 935, VP 5624 and VP 1055 is related to cavernous structures probably formed by gypsum dissolution.

COLLAPSE DEPRESSIONS

The widespread occurrence of depressions throughout Qatar is here divided into three types based on their origin: 1. Tectonic depressions; 2. Erosional depressions; and 3. Collapse depressions.

This study focuses on the collapse depressions because of their significant role as shallow internal catchments into which runoff accumulates and indirect recharge occurs (Fig. 11).

A major proportion of the land surface of Qatar is made up of some 850 contiguous depressions (Le Grand Adsco 1959; Cavelier *et al.* 1970). The depressions range in size from a diameter of 100 m up to several kilometers and their depth ranges from a few meters up to 20 m below the surrounding land surface. Many of these depressions are approximately circular in outline. They contain colluvial calcareous and sandy soils deposited during storm runoff and wind erosion. Cavelier *et al.* (1970) suggested that the collapse structures are post-Miocene. They note that there are no examples of the older Eocene land surface displaying depressions infilled by younger Miocene sediments. They therefore concluded that they are of Plio-Quaternary age.

An attempt has been made in this study to interpret the widespread occurrence of collapse dissolution in central and northern Qatar as the result of dissolution of the Rus Formation evaporite unit. Several factors have been considered and are outlined below:

1. The rainfall of northern Qatar is higher than that of the southern part. Cavelier *et al.* (1970) thought there was a period of high rainfall in the past which affected the Eocene surficial deposits.
2. Fractures and joints resulting from the growth of the Qatar arch allowed runoff to penetrate the formation and cause dissolution. This phenomenon has been clearly observed in a hand-dug well in Dahl Misfr.
3. The absence of the Lower Dammam impermeable "Midra Shale Member" in the center of Qatar where the northern and southern groundwater flow coincide has increased the infiltration and circulation of groundwater, and subsequently has led to the removal of the evaporite unit.

The dissolution process has not gone to completion in the southern part of Qatar because the relatively impermeable 6 m of "Midra Shale Member" in the south prevents the vertical and lateral infiltration of water through the thick evaporite beds. However, there are a few depressions along the main anticlinal axis in the southern part of Qatar which formed in response to fractures which break the surface layers and permit infiltration, and enhancement of water circulation. These

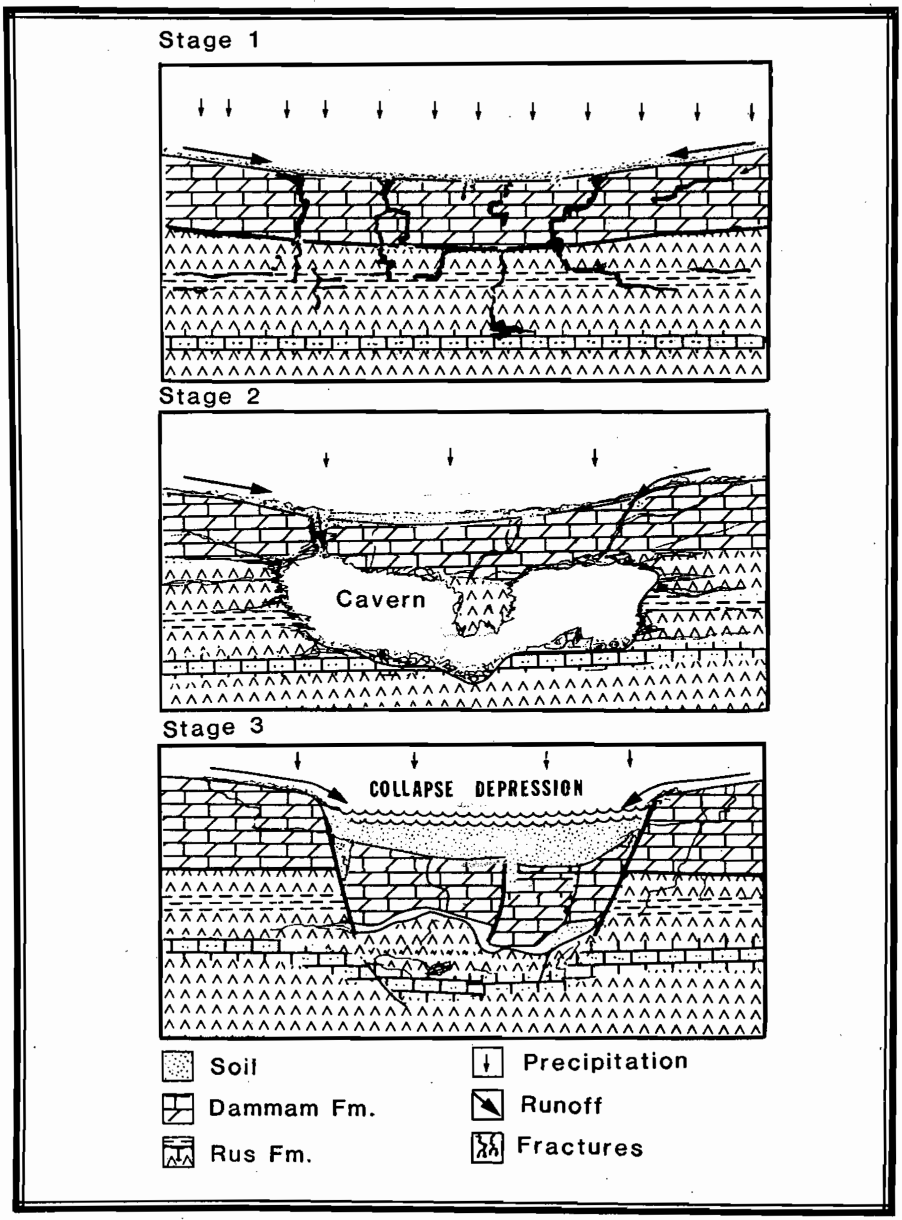

Fig. 11. Postulated mechanism of dissolution and formation of collapse depression. Stage 1: Fractures and joints allowed enhanced runoff to penetrate the formation and cause dissolution; Stage 2: Evaporite unit is partly dissolved and the rock is more fractured owing to collapse; Stage 3: Dissolution causes cavern development, followed by collapse and subsidence of overlying rock.

depressions in the south are often more crater-like in appearance, with their floors sometimes as much as 20 m below the adjacent ground level.

V-SHAPED STRUCTURE

Surface geophysical surveys of Qatar that were conducted as part of the first and second phases of FAO projects respectively, revealed that a V-shaped boundary exists between the more permeable northern province and the less permeable southern province (Fig. 8). The boundary was found to coincide with the central part of a major facies division in the Rus Formation which divides the country into two separate groundwater provinces.

The present study has attempted to reinterpret the V-shaped feature as a significant hydrogeological product. Data obtained from field observations, interpretation of wirelog data and lithological descriptions indicate the presence of a deflation scarp on the surface of central Qatar which correlates with the termination of the evaporite margin. Landscape deflation which coincides with the evaporite termination zone can be seen from the "LANDSAT" imagery, air photographs and contour maps. The general lithology observed in the northern part of the V-shaped feature consists mainly of dolomitic limestone interbedded with shales and clays. South of the V-shaped feature are the evaporite facies. In this study the V-shaped boundaries match the present evaporite front to the south and the paleo-evaporite front to the north (Fig. 8B). The zone between the present evaporite front and the paleo-evaporite front has been named the "Residual sulphate facies" by Eccleston & Harhash (1982).

In this study the appearance of the V-shaped feature is interpreted to coincide with vertical dissolution, particularly in the evaporite unit of the Rus Formation. The evaporite forms a half-ring shape that surrounds the high relief area which coincides with carbonate facies to the north. These evaporites have gradually retreated southward due to an extensive dissolution influence, which has been a continuous process since the emergence of the Rus Formation.

CONCLUSIONS

1. The Rus Formation was deposited in a sabkha-lagoonal setting to the south and west of Qatar, while a shallow open marine setting existed over the northern Qatar Peninsula.
2. The facies and thickness variations of the Rus Formation are quite variable in Qatar. The formation thickens away from structural highs (Qatar arch, and Dukhan anticline) as a result of an increase in evaporites.
3. The carbonate facies are concentrated to the north and over Dukhan anticline to the west, while the evaporite facies increases towards the south of Qatar and in the Gulf to the north of Qatar.
4. The structural framework and sea-level changes have had a significant impact on the sedimentation of the Rus Formation.
5. The thickness variations were mainly controlled by non-deposition of evaporite over structural highs and post-depositional dissolution.
6. The dissolution and removal of evaporites at depths in the Rus Formation subsequently resulted in the development of secondary porosity, permeability and

numerous collapse depressions which form shallow internal catchments into which runoff accumulates and some indirect recharge occurs.

7. The appearance of the V-shaped features at the ground surface is consistent with vertical dissolution, particularly the evaporitic unit of the Rus Formation.

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