Surface Geology, Lithostratigraphy and Tertiary Growth of the Dammam Dome, Saudi Arabia: A New Field Guide

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ABSTRACT

The surface geology of the Dammam Dome, Saudi Arabia, is documented in the geographic context of the modern and extensive urban and industrial developments in this area. A new geologic road map shows where key Tertiary outcrops occur relative to major roads, and columnar sections and field photographs illustrate the stratigraphic relationships and support the discussion on depositional environments. Surface geology is also used to infer growth rates for the Dammam field. These rates are generally consistent with those determined from subsurface data in the Awali field. The Dammam Dome is here estimated to have risen at time-averaged rates of 7.5 meters per million years for the Neogene and 7 meters per million years for the Oligocene. The nearby Awali Dome below Bahrain Island, likewise cored by Hormuz Salt, grew at 2.5 meters per million years during the Early Cretaceous, accelerated to 9 meters per million years during the Late Cretaceous, and uplift continued at 5.6 meters per million years during the Tertiary and Quaternary. This paper may also serve as a practical field guide for geologists visiting the Eastern Province, whether industry professionals, students or faculty.

INTRODUCTION

The Dammam Dome represents a classical hydrocarbon structural trap and yielded the first producing oil well in the Kingdom of Saudi Arabia. Oil was first discovered in Dammam-7 on March 3, 1938, fifteen months after the onset of drilling. Dammam-7 was not removed from service until 1982, but the underlying Arab reservoir continues to supply oil at present.

Until 1938, the Dammam Peninsula was a barren desert landscape, which hosted only two small coastal settlements at Dammam and Al-Khobar. Subsequent to the oil discovery, the Dammam Peninsula has developed into a major economic center. Much of the surface area of the peninsula is now covered by an extensive network of major highways, urban centers, factories, a large airport and extensive harbour facilities (Figures 1 and 2).

The Eastern Province, in which the Dammam Dome is located, was previously covered by a low-resolution, 1:500,000 scale regional geologic map (GM-208A), accompanied by map notes (Steineke et al., 1958) and the corresponding type sections have been included in Powers et al. (1966). A detailed surface map of the core region of the dome has been published, drawing on proprietary Saudi Aramco data, aerial photographs, and field observations (Tleel, 1973). Apart from this detailed coverage of the central part of the dome, no published geological map is available other than the 1:100,000 scale industrial minerals map by Roger (1985).

In the present study, a new geological compilation of the Dammam Peninsula has been superimposed on a modern road map in order to facilitate academic and professional field studies, as well as engineering operations (Figure 1). The basic outline of the Dammam Formation is after Steineke et al. (1958), but the external and internal boundaries of the Rus Formation were mapped from high altitude aerial photographs by Tleel (1973). The outline of the Hadrukh Formation follows Roger (1985). The rock units traditionally are marked by one upper-case letter indicating the stratigraphic age, and by one or two lower-case letters indicating the assigned formation for that unit, after Steineke et al. (1958). All units in the Dammam Peninsula are of Tertiary (T) and Quaternary (Q) age and include the Rus...
Figure 1: Geological road map of the Dammam Peninsula. Geology was partly mapped by the author and generalized from existing sources (Steineke et al., 1958; Tleel, 1973; Roger, 1985). Indicated geological boundaries are between the Lower and Upper units of the Rus Formation, between Rus and Dammam Formations, and Quaternary and sabkha outlines.
Quaternary deposits are assigned two lower-case letters expressing the predominant lithology or facies: sabkha (Qsb), coastal deposits (Qcd), and eolian sand (Qes). Also outlined are areas of reclaimed land (Re), which are composed of a variety of landfill materials.

The structural domes of Dammam and Awali, the latter occupying the core of the nearby island of Bahrain located 50 kilometers to the southeast of Dammam, are commonly ascribed to halokinesis or salt diapirism in the subsurface (Edgell, 1991). A deep-seated salt intrusion below the Dammam Dome was first interpreted on the basis of a strong negative gravity anomaly coinciding with the outlines of the dome (Powers et al., 1966). In fact, much of the eastern part of the Phanerozoic sequence of the Arabian Platform is underlain by the InfraCambrian Hormuz Salt (Beydoun, 1991). This salt surfaces in salt stocks exposed in the Great Kavir Basin south of Teheran (Jackson et al., 1990), in salt glaciers emanating from the breached cores of anticlines in the Fars Platform south of the Zagros Main Fault.

Figure 2: False color, enhanced Landsat TM-image of the Dammam Peninsula. Image recorded May 28, 1990. Area of reclaimed land is still increasing by ongoing coastal construction projects.
Weijermars (Koyi, 1988) and in salt-dome islands off the United Arab Emirates coast, such as Yaz Island (Kassler, 1973). Hormuz Salt beneath the Fars Platform seems to have been initially overlain by competent and stable overburden rocks, and salt movement did not commence there until the Jurassic, with Infra-cambrian salt first surfacing in the Cretaceous (Kent, 1979). The tilting of Miocene and Pliocene rocks as well as uplift of Pleistocene and Holocene beach deposits at Yaz Island (Kassler, 1973), indicate that structural salt growth continues at present.

Although the interior of the Arabian Platform is locally subject to regional strike-slip deformation due to the impingement of the Fars Platform (Weijermars, 1998), the tectonic style of the Dammam and Bahrain areas is dominated by vertical rather than lateral displacement. The vertical growth, outlined here, is documented further on the basis of geomorphology, lithostratigraphy and geological structure of the Dammam Peninsula. Episodes of dome growth caused by buoyant subsurface salt can be reconstructed from the sedimentary record exposed at the Dammam Peninsula. The growth rates estimated for the Dammam Dome are compared with those inferred from subsurface data of the Awali Dome.

GEOMORPHOLOGY OF DAMMAM PENINSULA

A generalized topographic map of the Dammam Peninsula (Figure 3) reveals that it consists of an extremely gently sloping topographical dome on which at least three small hills stand out. These are Jebel Umm Er Rus (150 meters, m) at the very top of the dome, Jebel Midra Ash Shamali (125 m) along the north margin of the dome, and Jebel Midra Al-Janubi (92 m) due west of Jebel Umm Er Rus. Figures 4a to 4c are field photographs of Jebel Midra Al-Janubi, Jebel Umm Er Rus, and the promontory 1.5 kilometers (km) to the southeast of it, on top of which King Fahd University of Petroleum and Minerals (KFUPM) is built.

Although the topographical contours clearly reveal the dome-shaped surface-relief, the slopes of the surface dome are almost imperceptibly small. The average surface slope within a 2 km radius of the base of Jebel Umm Er Rus is only 1° 58' and decreases gradually further outward. The surface relief in the peak region of the Dammam Dome is more pronounced than suggested by the low resolution regional contour map of Figure 3. A high resolution elevation contour map of the area around Jebel Umm Er Rus is shown in Figure 5 (modified from Chapman, 1971). The surface of the Dammam Dome is now covered by the extensive premises of Saudi Aramco, KFUPM, and the Dhahran International Airport. The outlines of these premises are included in the maps of Figures 1 and 5 for convenient field orientation.

GEOLOGICAL STRUCTURE OF DAMMAM DOME

Comparison of the geological map of the Dammam Peninsula (Figure 1) and the topographic map (Figure 3) indicates that the surface dome coincides with a structural dome of rock strata gently uplifted in the subsurface. The core of the surface dome is occupied by the Rus Formation, in which a lower and upper unit can be distinguished. The structural dome is not perfectly circular in horizontal cross-section, but oval-shaped, as outlined by the boundaries of the upper part of the Rus Formation (Figure 6). The semi-axial lengths of the outer ellipse of Figure 6 are 5.5 km and 3.5 km, respectively. The structural center of the dome is situated 1 km south of Jebel Umm Er Rus. The first successful well Dammam-7 was located on the southwest flank of Jebel Umm Er Rus, close to the structural culmination of the subsurface dome. The long axis of the dome strikes N30°W to S30°E. If the ellipse pattern is assumed to be the result of deformation of an original unit circle, the normalized axes or stretches are 0.8 and 1.25, respectively. However, the dips of the flanks of the present dome are too shallow to justify an explanation of its oval shape by tectonic shortening.

About 70 square kilometers (sq km) of the core area of the Dammam Dome is occupied, nearly uninterrupted, by outcrops of the 56 m thick Rus Formation. This extensive surface exposure is due to the fact that Rus strata dip at almost exactly the same angle as the topographical slope, and the central Dammam Peninsula is largely a geological dip slope. The average slope of outward dip (θ) for the Rus strata, implied by the map outcrop width (W) and the true thickness (T), is only 1° 6' (from T=W sin θ).
The top of the Rus Formation disappears beneath the strata of the overlying Dammam Formation only when the topographical slope becomes less than 1° 6'. This shallowing of surface slope occurs approximately at, and below, the 25 m topographical contour of the Dammam Peninsula, outlined in Figure 3.

Figure 3: Generalized topographic map of the Dammam Peninsula. Contour interval is 5 m. Cluttering contours near Jebel Umm Er Rus, Midra Ash Shamali and Midra Al-Janubi have been omitted for clarity.
Figure 4: (a) The highest peak of the Dammam Peninsula, Jebel Umm Er Rus (150 m), photographed from King Fahd University of Petroleum and Minerals (KFUPM) premises looking north. Rocks of the Rus Formation are unconformably overlain by rocks of the Dam Formation. (b) Jebel Midra Al-Janubi (90 m high), comprises a 60 m section of the Dammam Formation, here lying unconformably on top of Midra Shales of the Dammam Formation. (c) View of the promontory 1.5 km south of Jebel Umm Er Rus on which the KFUPM is built. The academic building are anchored in dolomitic limestones and marls of the Rus Formation.
Figure 5: High resolution topographic map, 10 m contour interval, of the central area of the Dammam Peninsula (after Chapman, 1971). Modern road network is superimposed together with the fenced boundaries of the compounds of Saudi Aramco, KFUPM and the Dhahran International Airport. This is the principal basemap formally authorized by Saudi Aramco for geographical referencing of public field trips. Marked (crosses) are a known outcrop of Umm Er Radhuma rocks (Location 1) and a new locality at KFUPM identified here in the text (Location 2).

Because the structural dome outlined by the Rus Formation coincides very closely with the topographical dome, the pattern of elevation contours within a 3 km radius of the summit (Figure 3) can also be read as an approximate structure contour map for the top of the Rus Formation. The dome shape is barely visible in a cross-section due to the very small regional dip of the strata (Figure 7). Two cross-sections, with vertical scales exaggerated seven-fold, so as to visually enhance the dome shape, were published by Tleel (1973), but the distortions in such exaggerated sections are avoided here. Albeit very gentle, the dome shape of the Dammam region is important because it provides significant reservoir capacity for past and possibly sustained migration of hydrocarbons into this structural high. Reservoir rock of the Arab Formation occurs at 4,727 feet (ft) (1,441 m) below the surface in Dammam-7, and is capped by anhydrite of the Upper Jurassic Hith Formation. A minimum structural closure of 100 m was reported for the Rus Formation (Tleel, 1973). Although the section of Figure 7 is conjectural as proprietary subsurface data could not be consulted, the salt structure below the Dammam Dome shall be classified as a salt pillow rather than a structurally more mature salt stock (see Figure 20 for terms), for which no space is available using the stratigraphic constraints outlined here.
Table 1
Tectonostratigraphic Time-Table for Dammam Region.

| PERIOD   | EPOCH | AGE   | Ma   | DEPOSITION                  | Producing Reservoir | Uplift Rates Dam and Awali | TECTONICS                                      |
|----------|-------|-------|------|------------------------------|---------------------|---------------------------|------------------------------------------------|
| Quaternary |      |       |      |                              |                      |                           | Formation of Half Moon Bay                      |
| Neogene  | Oligocene | MIOCENE | 3.4  | Sabkha Eolian Sand           |                      |                           | Continued Zagros Collision                      |
|          |       |       |      |                              |                      |                           | Opening of Red Sea                             |
|          |       |       |      |                              |                      |                           | Formation of Mesopotamian Foredeep of Zagros Fold Belt |
|          |       |       |      |                              |                      | 7.5 m/Ma                   | Closure of Sanandaj-Sirjan Suture in Zagros Hinterland |
|          |       |       |      |                              |                      | 7 m/Ma                     | Slumping of lower Rus beds due to Dammam doming |
|          |       |       |      |                              |                      | 5.6 m/Ma                   | Meteoric Impact at Xugulub                       |
|          |       |       |      |                              |                      |                           | (Extinction of dinosaurs)                       |
|          |       |       |      |                              |                      |                           | Turonian Ophiolite emplacement in Oman           |
|          |       |       |      |                              |                      | 9 m/Ma                     | Surfacing of Hormuz Salt in the Zagros area      |
|          |       |       |      |                              |                      |                           | Tethys reaches maximum extent                    |
|          |       |       |      |                              |                      |                           | Onset of uplift of Dammam and Awali Domes        |
|          |       |       |      |                              |                      |                           | Opening of South Atlantic                        |
|          |       |       |      |                              |                      |                           | Onset of halokinesis of Hormuz Salt in the Zagros area |
|          |       |       |      |                              |                      |                           | Extensional growth faults in Tethys Margin - Oxfordian break-away of India from Africa |
|          |       |       |      |                              |                      |                           | Break-up of Pangea into Gondwanaland and Laurasia |

The continuous sequence of Mesozoic carbonates comprise Wasia Group (Mishrif, Rumaila, Ahmadi, Wara, Maudud and Nahr Umr formations), Thamama Group (Shu’aiba, Hawar, Kharai, Ratawi, Yamama, and Sulaiy formations), Riyadh Group (Hith and Arab formations), and the Tuwaiq Group (Jubaila, Hanifa, Tuwaiq Mountain, Dhruma and Marrat formations).
Figure 6: Outcrop pattern of the Upper Rus Formation (after Tleel, 1973), and superimposed ellipses with normalized semiaxes of 0.8 and 1.25. The outcrop pattern cannot be explained by regional shortening.

Figure 7: Isometric vertical section across the center of the Dammam Dome. Formation thicknesses are inferred from Powers et al. (1966). Depth of the Arab Reservoir of the Upper Jurassic in Well-7 is commonly publicized in Saudi Aramco reports to occur at 4,727 feet (1,441 m). The depth of the basement rocks is inferred from regional isopach maps for the entire Phanerozoic sequence (Beydoun, 1991). The shape of the Hormuz Salt pillow is highly conjectural, because seismic records could not be consulted. However, the Dammam Dome coincides with a subcircular anomaly of low gravity (Powers et al., 1966).
LITHOSTRATIGRAPHY OF DAMMAM PENINSULA

The lithostratigraphy of the Dammam Dome rocks is briefly outlined in this section. Table 1 is a tectono-stratigraphic chart, which emphasizes depositional hiatuses and coeval tectonic events.

Rus Formation

The base of the Rus Formation is exposed 500 m east of Jebel Umm Er Rus, where some 3 m of vuggy dolomite is exposed (in Location 1, marked on Figure 5), ascribed to the top of the Paleocene Umm Er Radhuma Formation (Tleel, 1973). The Rus Formation itself dates to Eocene (Ypresian, 57.8 to 52.0 Ma; Palmer, 1983). Although the Rus Formation occupies about 70 sq km of the core area of the Dammam Dome (Figure 1), only few good outcrops are available, because the slope of the terrain is generally gentle. The type section at Jebel Umm Er Rus was first measured by Bramkamp (unpublished Aramco report 1934). Powers et al. (1966) documented Saudi Aramco’s subdivision of the Rus Formation in three lithologic units (discussed below). The subdivision of the Rus Formation was somewhat confusingly redefined in the description by Tleel (1973) for mapping convenience. Table 2 summarizes the different subdivisions used for the Rus Formation by various geologists and includes a subdivision advocated here for field use at KFUPM. Figure 8 is a schematic stratigraphic column for the Rus Formation at the Dammam Peninsula.

The basal Rus Unit 1 of Powers et al. (1966) consists of 21 m thick, grey to buff, partly dolomitized limestone. Massive quartz geodes, up to football size, are typical for the upper part of this basal unit (Figure 9a). Chert nodules also occur, and minor amounts of soft limestone have become porous by dissolution of organic remains, the abundance of indeterminate molds and casts of leached small molluscs is a marked characteristic of the basal Rus Unit. The top of the underlying Umm Er Radhuma is brown dolomite, containing Lockhartia huntii.

The Middle Rus Unit 2 of Powers et al. (1966) consists of 31.8 m of alternating light-colored marl and limestone beds. The unit contains quartz geodes as well as masses of irregular gypsum crystals. The unit may also comprise fine crystalline anhydrite with interbedded green shale and minor amounts of dolomitic limestone, or grey marl with coarsely crystalline calcite and interbedded shale and limestone.

The Upper Rus Unit 3 of Powers et al. (1966) consists of 3.6 m thick, white, soft chalky, porous limestone. Calcarenite occurs at the top, which gives way to tan-colored gypsiferous and calcareous shale and interbedded marl found in the base of the Dammam Formation.

The map of Figure 1 differentiates the Rus in a lower and upper unit according to Tleel (1973). The lower unit comprises 21 m of Unit 1 (“zone of quartz geodes”), but also includes the lower 10 m of Unit 2 distinguished by Powers et al. (1966). The latter 10 m section (yellow-grey, microcrystalline, massive limestone) characteristically weathers into large blocks and contains “wafer-like” mud balls and calcite geodes (5-10 cm in diameter). It is referred to by Tleel (1973) as the “zone of calcite geodes”. Outcrops exhibit a cavernous vuggy weathering where calcite geodes have weathered out (Figure 9b). Thin section study reveals pellets and fragments of pelecypods, gastropods and miliolid foraminifera.

The upper unit of Tleel (1973), termed by him the “Chalky Zone”, comprises the remainder of the Rus section and therefore includes the upper 21.8 m of Unit 2 and the entire 3.6 m of Unit 3 of Powers et al. (1966). The composite thickness, suggested by Tleel (1973), is 25 m rather than 25.6 m. The “Chalky Zone” comprises yellow-grey, microcrystalline to cryptocrystalline, partly dolomitic, limestone and white chalky aphanitic limestone. Three thin bands of continental, yellow-orange, gypsiferous shale,
Table 2
Compilation of terms used by various workers to refer to the Rus Formation and its subdivisions.

| This Study | Tieel (1973) | Powers et al. (1966) | Bremkamp (1946) | Henry and Hoover (1934) |
|------------|--------------|---------------------|-----------------|-------------------------|
| Upper Rus Formation | Chalky Zone (25 m) | Chalky Zone (25 m) | Unit 3 Chalky Zone (3.6 m) | | |
| Middle Rus Formation | Jointed Limestone (10 m) | Zone of Calcite Geods (10 m) | Unit 2 (31.8 m) | | |
| Lower Rus Formation | Marls (21 m) | Zone of Quartz Geods (21 m) | Unit 1 (21 m) | | |

Figure 8: Schematic stratigraphic column for the Rus Formation of the Dammam Peninsula (based on composite sections by the author at KFUPM and Saudi Aramco premises).
Weijermars

Figure 9: (a) Geodes in the marly unit of the Lower Rus Formation. (b) Vuggy appearance of ancient weathering surface in massive limestone of the Middle Rus.

locally purple weathered, are valuable markers in the upper Rus section. They may be as much as 1 m thick in the central part of the dome and are composed of equal quantities of smectite and illite, associated with a small kaolinite fraction (Roger, 1985). Locally, some gypsum and dolomite enrichment may occur. Perhaps the most striking feature in the white “Chalky” limestone at the top of the Rus Formation is the dark-brown to black, commonly flat, chert pods or nodules of pebble to boulder size. Thin section study reveals indeterminate pelecypods, gastropod molds, miliolids, echinoid spines and poorly preserved *Nummulites* spp.
Figure 10: Geological map of Rus outcrops at KFUPM-campus. Distinguished are massive, jointed limestone (Middle Rus, see Table 1) and an underlying marly unit (Lower Rus, see Table 1). Bed dips do not exceed 8°, but gently fold around a WSW-NNE anticlinal axis superposed on the regional dome structure outlined in Figure 1. Location marked X between buildings 10 and 19 has a landmarked, geographical calibration point with ground coordinates as follows: 26°18’N, 50°08’E.
Figure 11: Basal, marly unit of Lower Rus Formation seen overlain by ledge forming, jointed, massive limestone of the Middle Rus (see Figure 8 and Table 2). Stratigraphic sections exposed are below (a) Building 21, (b) Building 14, (c) Building 7, and (d) south of the central mosque. See Figure 10 for locations.
Exceptionally good exposures of Rus rocks occur at the premises of KFUPM. These exposures, not mapped in any detail before, are outlined in Figure 10. The stratigraphy is described below and compared in Table 2 with the description of rocks of the Rus Formation by Powers et al. (1966) and Tleel (1973).

Careful study of the outcrops at the KFUPM campus suggests that Tleel’s (1973) massive limestone (zone of calcite geodes), of 10 m thickness, is indeed an easily recognizable rock unit in the field because it forms ledges (Figures 11a to d). The academic buildings are generally located on top of this massive,

Umm Er Radhuma and Rus Formations at
King Fahd University of Petroleum and Minerals Campus

Figure 12: Bedding of dolomitic limestone intercalations in the Lower Rus is better developed in the northern part of KFUPM campus (a) as compared to that in the central and southern campus area (b). Photos (a) and (b) are located below Buildings 5 and 10, respectively. See Figure 10 for locations.
vuggy limestone bed (Figure 11c). It contains chert nodules, quartz geodes and calcite geodes. The colour is grey to yellow and it is transected by joints which created vertical walls which facilitate further fragmentation into large weathering blocks. The maximum thickness observed for the massive limestone bed is 10 m. This rock hosts solution cavities of several meters length, two of which were discovered during construction work at KFUPM (Jado and Johnson, 1983).

The campus map (Figure 10) outlines the boundary between the Middle Rus unit of massive limestone ("weathering in large blocks"), and the underlying marly unit of the Lower Rus. The lower unit is usually poorly exposed, and can be best studied in exposures below Buildings 5 and 10 (Figures 12a and b). The nature of the Rus below the massive limestone unit is variable but characterized by the presence of numerous marl intercalations between thin to thick-bedded limestone layers. Jointing is irregular and rare in the lower unit due to the presence of the incompetent marls, whereas regularly spaced joints are characteristic for the middle unit of massive limestone. Below Building 7, vertical beds in the marly unit, due to slumping, are overlain by the massive limestone of the Middle Rus.

The promontory on which KFUPM is built includes elevation drops of up to 25 m. Consequently, green carbonaceous shales and purple calcilutite to arenite, exposed directly east of the faculty recreation center and at Rawdah courts, could possibly be part of the top of the Umm Er Radhuma Formation. This outcrop, located 500 m south of the area shown in the map of Figure 10 (marked as Location 2 in Figure 5), has not been reported in previous studies. This is significant because there is only one other Umm Er Radhuma outcrop reported before to occur within the Dammam Dome region, namely as several square meters in a small depression about 500 m east of Jebel Umm Er Rus (marked as Location 1, in Figure 5) according to Tleel (1973).

**Dammam Formation**

The Dammam Formation (Figures 1 and 13), named by Bramkamp (Saudi Aramco report of 1941; see Powers et al., 1966), rests conformably on top of the Rus Formation and is subdivided into five members. These are the Midra Shale (up to 3 m in outcrop, but as much as 8 m in subsurface), Saila Shale (up to...
The four lower members of the Dammam Formation are exposed in the core of the dome at a small ridge directly east of Saudi Aramco’s Hospital, where Dammam rocks occur down-faulted in a graben structure between east-west trending normal faults (Figure 14). The most extensive and accessible outcrops of this formation occur in the southwest rim of the Dammam Dome. Extensively quarried, the landscape is continually changing, but good exposures of the entire Dammam sequence are plentiful.

The two lower members are principally composed of shale, but are separated by 0.6 m of yellow-grey to off-white, fossiliferous calcarenitic limestone. The basal Midra Shale Member comprises “sharks tooth” shale, yellow-brown, fissile, thinly-laminated, and includes grey marl and soft limestone beds. Blackened shark teeth, up to 2 centimeters (cm) long, can be found in the shale. Washed samples reveal fish teeth, scales, and spines (Tleel, 1973). Also reported are gypsum crystals, ironstone nodules and well-preserved specimen of *Ostrea turkestanensis*. The Saila Shale Member comprises dark, brown-yellow, subfissile clay. Pale-orange beds occur at the top. The shale contains some shark teeth, gastropods, fish spines and indeterminate pelecypods. The clay fraction of both shale units is composed only of attapulgite (Roger, 1985). This clay could be suitable for production of drilling mud or as an industrial absorbent. Carbonate enrichment may not exceed 10% (Roger, 1985) and is a possibly unfavourable factor, but reserves are substantial. The 0.6 m of fossiliferous limestone in the base of the Saila, separating it from the Midra shale below, contains *Alveolina* spp. and *Nummulites globulus*, *Coskinolina ballasillei* and *Dictyoconoides* sp.

Figure 14: Jebel near Saudi Aramco’s Hospital, seen from KFUPM’s academic circle road. This hill exposes the four lower members (Midra Shale, Saila Shale, Alveolina and Khobar) of the Dammam Formation, and is faulted by east-west trending normal faults at either side.
The three upper members of the Dammam Formation are all in carbonate facies. The Alveolina Limestone Member is a pale-orange to yellow-grey, microcrystalline, recrystallized and partly dolomitized limestone. The Alveolina spp., on weathered surfaces, resemble rice grains. Also reported are Lucina pharaonis, Coskolina and Nummulites spp. (Tleel, 1973). The Khobar Member comprises a lower, 1.5 m thick marl unit, overlain by 4 m off-white non-porous nummulitic limestone, in turn overlain by 1 m yellow-brown limestone, topped by 3 m light-brown non-porous nummulitic limestone with Nummulites somaliensis (Powers et al., 1966). Limestone samples studied by Roger (1985) have low magnesia contents, with silica ranging between 1% and 13%. The point-load strength is between 4 and 6 Mega Pascals (MPa). Los Angeles abrasion loss is 28% to 31%, water absorption is less than 2% and the apparent gravity is between 2.57 and 2.89 gram/cm³. These rocks are extensively quarried as crushed aggregate (major quarry area is marked in Figure 2) for use in concrete and road works. Roger (1985) suggests the limestone of low magnesia content is suitable for use in manufacture of cement, or in metallurgic fluxstone where silica contents are less than 2%.

The Alat Member, exposed at Jebel Alat (Figure 3), comprises 6 m thick basal unit of dolomitic marl overlain by 9 m of dolomitic limestone, light-colored, porous and chalky. Both the Khobar and Alat are aquifers of regional importance. Dolomite samples described by Roger (1985) consist of 19% to 21% magnesium oxide (MgO), 30% to 33% calcium oxide (CaO) and 2% silicon dioxide (SiO₂) with less than 0.5% aluminium (Al) and iron (Fe). Apparent porosity is between 20% and 37%. The average point-load strength is between 1.4 and 2.5 MPa, and the Los Angeles abrasion loss is between 40% and 50%, making it less suitable for use as aggregate. Roger (1985) remarked that the low degree of fracturing might make this unit suitable for use as building stone. The towns of Ras Tanura and Qatif withdraw water from the Alat and Khobar aquifers (Powers et al., 1966).

Hadrukh Formation

The Hadrukh Formation was first named by Steineke and Koch after Jebel al Haydaruk (see Powers et al., 1966) (Figures 1 and 15). Hadrukh rocks fringe the outer rim of the Dammam Dome. The Hadrukh is considered of Lower Miocene age, Aquitanian to early Burdigalian (23.7 to ca. 20 million years (Ma), after Palmer, 1983), because of its stratigraphic position beneath the late Burdigalian Dam Formation. The basal bed of the Hadrukh is a few meters of cream colored, sandy limestone, which rests unconformably on the Dammam Formation. The formation is up to 120 m thick, the top of which is a calcareous sandstone, locally overlain by Echinocyamus-bearing limestone and marl of the Dam Formation. The formation comprises, green and grey-green, fine, calcareous sandstone, and shales, interbedded with minor amounts of marl and gypsum. Chert nodules and gravel lenses occur at several levels. The clayey shales in the Hadrukh, generally enriched in dolomite and detrital quartz, is composed predominantly of attapulgite with accessory smectite (Roger, 1985). Carbonate units in the Hadrukh are mainly dolomitic with up to 18% silica. The point-load strength is between 2.5 and 8.6 MPa, and Los Angeles abrasion loss is less than 27%. Hadrukh rocks could provide limited resource for aggregate, and use in road and construction foundations (Roger, 1985).

Dam Formation

The type locality of the lower part of the Dam Formation is at Jebel Al-Lidam, some 50 km west of Jebel Umm Er Rus, outside the map area. Dam rocks unconformably overlie either Rus or Dammam rocks, depending upon location. The Dam rocks probably range from Upper Burdigalian to Neogene (Kier, 1972). This means even where Dam rocks rest on Dammam rocks, deposits of post-Ypresian to Oligocene are missing. The hiatus corresponds to a time gap of some 22 Ma (Table 1), extending from the end of the Ypresian (43.8 Ma) until the onset of the Burdigalian (21.8 Ma). Outside the central Dammam Peninsula, the hiatus may represent a slightly shorter time gap because of the presence, below Dam rocks, of the Aquitanian Hadrukh Formation for which deposition started some 23.7 Ma.

At Jebel Midra Ash-Shamali (Figures 3 and 5), the basal Dam is exposed as a 0.5 to 1.5 m thick multi-colored conglomerate containing boulders of Khobar Limestone set in a sandy, argillaceous limestone matrix (Figure 16). The unit contains fragments of vertebrate bones and unangular teeth of Perissodactyl
or Artiodactyl (Tleel, 1973). At Jebel Midra Al-Janubi (Figure 4b), the basal unit consists of 1.8 m yellow-grey, microcrystalline sandy limestone resting unconformably on top of the Midra Shale. In both locations, stromatolitic limestone (1 m thick), pink to purple weathering, overlies the basal sandy beds. At Jebel Midra Al-Janubi, the stromatolitic beds are overlain by 31 m thick sequence of alternating calcarenites, clastic carbonates, and calcarenite with microcrystalline matrix. Included are algal limestone, with fecal pellets in microcrystalline matrix and argillaceous limestone. Cross-bedding is abundant in the clastic carbonates. The uppermost 15 m is a cliff-forming, massive limestone with 6 m of calcirudite at the base, containing pebbles and boulders of cryptocrystalline limestone and calcarenite. The minimum thickness of the Dam Formation at Jebel Midra Ash Shamali is 75 m. Up to 16 m of the Dam Formation unconformably overlies the Rus Formation at Jebel Umm Er Rus, where it represents

Figure 15: Schematic stratigraphic column for the Hadrukh Formation of the Dammam Peninsula (mainly after Powers et al., 1966).
Weijermars

Unconformity

up to 9 m massive reef facies limestone

6 m massive calcirudite honeycomb weathering brecciated, ancient subaerial collapsed dissolution caves

31 m rhythmic sequence of well-bedded, cross-stratified, blue clastic limestone, and intercalations of brown-yellow micro-crystalline limestone with calcite geodes

1 m stromatolite limestone

2 m sandy variegated purple conglomerate

Figure 16: Schematic stratigraphic column for the Dam Formation of the Dammam Peninsula (based on author’s sections at Jebel Midra Al-Janubi and Jebel Umm Er Rus).

a bioherm reef facies and contains in situ corals (Siperastrian type), blue-green algal growths and mollusks (pelecypods and gastropods, Powers et al., 1966). *Peneroplis farensis* has also been reported from the Dam at Jebel Umm Er Rus (Henson, 1950, p. 29), and is used as an index fossil for basal Fars rocks of the Miocene in Iraq. Echinoids and a range of Neogene foraminifera have also been reported from the Dam Formation (Tleel, 1973).

DEPOSITION ENVIRONMENT OF RUS, DAMMAM, HADRUKH AND DAM ROCKS

The basal Rus Formation has been suggested to represent a sabkha environment in which gypsiferous marl was deposited together with growing clusters of calcite and quartz crystals that formed geodes (Tleel, 1973). The beds are deformed by compaction around the geodes. The sabkha was episodically inundated by shallow-marine incursions depositing thin carbonate beds with *Nummulites*. The massive limestone of the calcite geode zone occasionally shows surface markings suggestive of cross-bedding (Figure 17) and was possibly formed by a shallow-marine transgression. The upper part of the Rus Formation indicates regressive features, including chert pods precipitated from silica gels in a restricted lagoon and the orange shale represents brief intervals of continental facies.

The Dammam Formation represents a transgressive sequence where the sabkha and subtidal to continental lagoon were progressively transformed into an open-marine environment. Shallow-marine facies is indicated by shark teeth, *Ostrea*, gastropods, and mud deposits that formed the Midra and Saila shales. The Alveolina Limestone indicates water depths of perhaps 14 m to 20 m according to Houbolt (1957; in Tleel, 1973).
During the Miocene and Pliocene epochs, drainage from the Arabian Shield uplifted by the Red Sea rifting, led to the deposition of vast amounts of sandy Neogene formations dominated by siliciclastic sediments of partly continental facies (Hadrukh and Hofuf formations). The Hadrukh Formation represents continental to shallow-marine facies (Powers et al., 1966). The Miocene and Pliocene climate of Saudi Arabia was dominantly pluvial, depositing a rather large volume of Hadrukh and Hofuf rocks (Whybrow and McClure, 1981). These formations in turn provided the source for part of the huge volumes of sand now stored in the sand seas of Ad-Dahna, Jafurah and Rub’ Al-Khali (McClure, 1978).

The Dam Formation is the result of a major Neogene transgression and is dominated by shallow-marine, warm-water fossils such as stromatolites and species of reef facies. Stromatolites of the Dam Formation at the type locality of the Al-Lidam escarpment indicate a shallow, subtidal to intertidal environment of deposition (Irtem, 1986). In the Dammam Peninsula, the mollusc, echinoid and foraminiferal limestone above the basal stromatolites indicate shallow-marine deposition with fluctuating sea-levels. The Umm Er Rus reef itself must have grown at very shallow depths (Tleel, 1973).

Rocks of the Hofuf Formation are not preserved in the area on which this study focuses, but these occupy the crestal zone of the Ghawar Anticline. The Hofuf Formation represents continental facies, but its age is poorly-constrained, estimated to be Miocene to Pliocene by Powers et al. (1966), but Middle to Late Miocene by Thomas et al. (1978). At the end of the Pliocene and in the Early Quaternary several very large alluvial fans, comprising conglomerate and sand, were deposited near the terminal plains of all major wadis covering the Arabian Platform, such as the gravel plains of Wadi As-Sahba and Dibdibba (Holm, 1960).

Figure 17: Suggested cross-bedding in Middle Rus unit as seen west of Building 14. For location see Figure 10.
STRUCTURAL GROWTH OF THE DAMMAM AND AWALI DOMES

Aspects of the timing and growth mechanism of salt domes in the Arabian Gulf region are outlined in this section. Table 1 gives a tectono-stratigraphic time-table for the area studied. The early growth of Hormuz Salt structures in the Jurassic and Cretaceous (Kent, 1979) may have taken place in a regime of shallow extensional tectonics driven by gravity sliding over the basal Hormuz Salt, accompanied by upward migration of salt along faults. The subsequent closure of the Tethys in the Miocene (Grabowski and Norton, 1995; Hooper et al., 1995) and resulting compression may have accelerated the upward motion of Hormuz Salt.

Episodes of dome growth caused by the buoyant Hormuz Salt can be reconstructed from the sedimentary record exposed at the Dammam Peninsula. Upper Burdigalian (ending at 16.6 Ma; Palmer, 1983) rocks of the Dam Formation are exposed at the summit of the 150 m high Jebel Umm Er Rus occupying the apex of the Dammam Dome. The Dam was deposited at sea-level and is elsewhere in the Eastern Province overlain by up to 100 m of Hofuf Formation. It seems unlikely that Hofuf rocks were ever deposited over the Dammam Dome locality and the 150 m elevation of the Dam rocks at Jebel Umm Er Rus may reflect continued growth of the dome since the Burdigalian. Some change in global sea-level may be superimposed on the tectonic uplift inferred here, but 150 m uplift over the past 20 Ma would correspond to a Dammam Dome uplift rate of 7.5 m/My for the Neogene. Some evidence of Quaternary growth is provided by raised beach terraces around the periphery of the Dammam Dome (Powers et al., 1966), although these coastal deposits may be due to the Flandrian transgression rather than tectonic uplift (Weijermars, 1999).

The unconformity between the Dam and Dammam formations represents a maximum time gap of some 22 million years (My) (Table 1) without preserved sediments in the central Dammam area. The lack of deposition during the Oligocene is widespread throughout the entire Arabian Platform and is generally referred to as the Pre-Neogene Unconformity (PNU) (Tleel, 1973). However, at the Dammam Peninsula, structural growth certainly has occurred during the Oligocene, because the Eocene Dammam rocks were entirely eroded away from the apex of the dome at Jebel Umm Er Rus during the Oligocene. This can be inferred because lower Miocene Dammam rocks are now resting, at Jebel Umm Er Rus, directly onto the Lower Eocene rocks of the Rus Formation, whereas the Dam has a maximum thickness of 32.5 m in the rim of the Dammam Dome. The Hadrukh Formation is also missing below the Dam Formation in the central area of the Dammam Dome, but elsewhere reaches a maximum thickness of 120 m. The maximum hiatus of 150 m in the stratigraphic section over a maximum time of 22 My corresponds to an approximate uplift rate of 7m/My for the Oligocene. The Dam Formation itself, exposed in the margins of the Dammam Peninsula, has been observed to reduce in thickness by 10 m from the periphery toward the interior of the dome. This observation can be further interpreted to reflect minor structural growth during the Middle Eocene.

The above reconstruction of relative tectonic uplift-rates for the Dammam Dome suggests its modern uplift occurs at rates of 5.6 to 7.5 m/My, corresponding to time-averaged rates of 0.56 to 0.75 mm per century. It is surprising that the topographic high of the Dammam Peninsula is maintained by a structural dome growing at such slow uplift-rates. The uplift is not entirely outpaced by the leveling power of erosion and weathering, possibly only because of the arid climate prevailing at present. The Dammam Dome was also protected from erosion for some time during the Dam transgression and the high sea-level of the Early Pleistocene (Weijermars, 1999).

Further inferences of salt uplift and dome growth can be made from the Awali Dome of Bahrain (Willis, 1967), which is a north-south trending, asymmetrical, doubly-plunging anticline (Figure 18). Awali’s structural growth is inferred to have initiated in the Permian and continues at present (Alsharhan and Kendall, 1986). The top of the Arab Formation in the Bahrain field occurs at approximately 4,300 ft depth (Figure 4, Mendeck and Al-Madani, 1995), as compared to its 4,727 ft depth below the Dammam Dome surface at Dammam-7. Paleostructural analysis of the Awali structure (Figure 19) used isopach maps for back-stripping the thickness of overlying formations to reconstruct the growth of the anticlinal dome (Chaube and Al-Samahiji, 1995). Using the Tithonian Hith surface as a measure of growth, a structural growth of 365 m (731-366) has occurred in the time span of 65 My since the end of the
Cretaceous. This corresponds to a time-averaged growth rate of 5.6 m/Ma. The preceding 25 My between the Cenomanian and Maastrichtian saw an Upper Cretaceous growth of 229 m at a rate of 9 m/My. The (137 m-76 m) 61 m growth in 23 My corresponds to very slow growth of 2.6 m/My between Aptian and Cenomanian. The 76 m doming of the Hith Formation during the 30 My between the Aptian and the Late Jurassic deposition corresponds to a slow uplift rate of 2.5 m/My. The rate of growth of the Awali closure was 2.5 m/My during the Early Cretaceous, sped up to 9 m/My during the Late Cretaceous, and continued at 5.6 m/My during the Tertiary and Quaternary.

Figure 18: Simplified geology and location map of the Dammam and Awali Domes. Inset: subsurface map of structure contours indicating spatial depth distribution of the top of the Lower Cretaceous Mauddud Formation of the Awali Dome, a very gentle, doubly plunging anticline, below the island of Bahrain. The dome is extended in N-S direction by WNW trending normal faults (after Chaube and Al-Samahiji, 1994).
DISCUSSION

Salt diapirism, initiated in the Arabian Gulf region at Jurassic-Cretaceous times, has been facilitated by progradational loading of overburden sediments onto a basal Hormuz Salt layer. This suggests that the early growth of salt structures occurred by mechanisms documented in detail for hydrocarbon-trap development in the Gulf of Mexico. The analogy between the Jurassic-Cretaceous passive continental margins of the Arabian Gulf and the Gulf of Mexico is important to understand Jurassic and Cretaceous salt tectonics. An early phase of sedimentation prograding seaward above a mobile basal salt layer resting on rigid basement is similar for the Cenozoic Gulf of Mexico and the Arabian Platform sequence during Jurassic-Cretaceous times. In the Gulf of Mexico, modern high-resolution seismic studies document increasingly complex salt structures in the subsurface. The Jurassic Louann Salt has migrated extensively to form an exotic variety of salt stocks, pillows, ridges, tongues and nappes (Figure 20). Halokinesis principally occurred by migration along extensional faults in the overburden due to gliding of overburden rafts over the lubricating salt layer itself after overburden became sufficiently thick (Worall and Snelson, 1989). A review of the rheological properties of salt and the strength of sedimentary overburden rocks has been discussed elsewhere (Weijermars et al., 1993).

Similar structures as portrayed in Figure 20 are likely to have existed in the distal part of the shelf deposits of the Arabian Platform before closure of Tethys initiated the modern shortening tectonics. In the Arabian Gulf region, however, the Jurassic-Cretaceous extension of overburden at the passive continental shelf has been overprinted by Miocene compression due to closure of Neo-Tethys Ocean. The closure of the Neo-Tethys in the Miocene (Grabowski and Norton, 1995; Hooper et al., 1995) and resulting compression may have accelerated the upward motion of Hormuz Salt. The exhaustion of the salt lubrication beneath the Fars Platform by upward migration and extrusion may locally have controlled the fold amplitude in the Asmari Limestone so that anticlinal ridges coincide with older salt plugs (Kent, 1958). Alternatively, the linear distribution of plugs in the Zagros Mountains may be related to early extensional growth faults rather than the basement faults suggested by Kent (1979).

The tectonic scenario developed here for the growth of the Dammam and Awali Domes may provide new insight in the relative timing of hydrocarbon maturation, migration and trap formation. Maturation and migration in Late Cretaceous and Tertiary carbonates occurred coeval with relatively rapid rise of...
the domes. The rise of the domes also led to decapitation of the Tertiary formations by erosion, faulted the Upper Cretaceous units, and is thus thought to have led to reservoir losses. Hydrocarbons, consequently dissipated out of the Tertiary beds surfacing in these domes. This could explain the relative absence of payzones in the Upper Cretaceous and Tertiary formations. In contrast, the rich hydrocarbon accumulations in the continuous Jurassic and Lower Cretaceous carbonate sequence (Wasia, Thamama, Riyadh, and Tuwaiq groups, Table 1) did not migrate prematurely, because most of the doming post-dates their maturation. These carbonates were structurally stable during deposition and remained so until the end of the Early Cretaceous. The sequence was blanketed by the younger formations during the rise of the dome and no reservoir losses have been incurred. Important seals such as the Late Jurassic Hith have remained intact.

CONCLUSIONS

The Dammam Peninsula has been progressively uplifted by a central structural dome similar to the slightly more elongated Awali Dome on the Island of Bahrain. Both structures are inferred to be underlain by Hormuz Salt of Infracambrian age. Detailed stratigraphic studies of the Fars Platform suggests that the Hormuz Salt started to migrate upward during the Late Jurassic and first surfaced in the Early Cretaceous (Kent, 1979). Paleostructure-contour maps of the Awali Dome of Chaube and Al- Samahiji (1995) have been used to infer Early Cretaceous growth-rates of 2.6 m/My, and Late Cretaceous rates of 9 m/My. The average Cenozoic growth-rate inferred for the Awali structure is 5.6 m/My. Stratigraphic relationships within the Dammam Dome suggest uplift rates of 7 to 7.5 m/My for most of the Cenozoic. Cretaceous growth rates for the Dammam Dome, believed to have started simultaneously with the Awali structure, are likely to be similar to those inferred for Awali.
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