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A NEW DEPOSITIONAL MODEL AND SEQUENCE STRATIGRAPHIC INTERPRETATION FOR THE UPPER JURASSIC ARAB "D" RESERVOIR IN QATAR

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Deposition of the Arab Formation on the Arabian Plate followed a eustatic sea-level high during the Oxfordian that deposited the open-marine shelfal carbonates of the Hanifa and Jubaila Formations. Oolite/peloidal shoals and local coral-algal stromatoporoid banks were subsequently deposited on the platform margin. These acted as barriers and led to the differentiation of intrashelf basins from open-marine (Tethyan) waters to the east. During the subsequent Kimmeridgian lowstand, gypsum wedges were laid down in the intrashelf basins. Slight changes in water depth, which exposed or flooded these barriers, are believed to be responsible for the cyclic nature of the Arab Formation sediments. Arab Formation cycles show a 4th order frequency but have thicknesses more typical of 3rd order Vail-type sequences. This is probably explained by the 4th order flooding events merely topping-up pre-existing accommodation space of tens of metres water depth in the intrashelf basin. Diagenesis associated with movement of hypersaline brines may have been responsible for the development of widespread dissolution porosity and dolomitization. The laminated, organic-rich, bituminous lime mudstones of the Hanifa/Jubaila Formations are the probable source of oil in the Arab Formation in Qatar. The main reservoir types are oolitic-peloidal grainstones and dolomitized limestones.

INTRODUCTION

The Jurassic section in Arabia is one of the World's most important hydrocarbon systems (e.g. Beydoun, 1988). Upper Jurassic source rocks have probably generated one quarter of the World's discovered oil and gas (Klemme, 1993; 1994). In Qatar, Upper Jurassic reservoir rocks are important in several oilfields. Their distribution is controlled mainly by the NNE-SSW trending Qatar-Fars Arch (Fig. 1). This structure was positive during most of the Palaeozoic and started to subside gradually during the Jurassic, thus controlling the depositional regime during that period (Sugden and Standring, 1975; Saint-Marc, 1987).

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Jurassic carbonates in Arabia had been investigated in the subsurface by many researchers. Steineke *et al.* (1958) were the first to propose a stratigraphic framework for the Jurassic sediments of the Arabian Peninsula. Powers (1962, 1968) formulated our basic understanding of Upper Jurassic sediments in Arabia. Sugden and Standring (1975) described the general characteristics of Jurassic rocks in Qatar. Beydoun (1988) reviewed the regional geology of these sediments and their oil potential. Other recent studies include Alsharhan and Kendall (1986), Wilson (1991) and Alsharhan and Nairn (1994, 1997). More recently, Al-Siddiqi and Dawe (1999) reviewed the oil- and gasfields of Qatar.

The present work is based on 57 core and cuttings samples collected from three wells in Qatar: one from the onshore *Dukhan* field, and one each from the offshore *Idd El Shargi* and *Bul Hanine* fields (Fig. 1). Data includes thin sections and well logs. Poroperm and geochemical data were either obtained from a publication of the Qatari General Petroleum Corporation (QGPC) (Focke *et al.*, 1986) or from the archives of the QGPC. Our intention is to clarify the stratigraphic relationship between the Upper Jurassic sedimentary units in Qatar and the equivalent units in the type locality in Saudi Arabia and in other neighbouring countries, and to delineate the units' depositional and diagenetic history within the context of their petroleum potential.

LITHOSTRATIGRAPHY OF THE ARAB "D" MEMBER IN THE ARABIAN GULF BASIN

Lithostratigraphic overview

The type locality of the Arab Formation is located in central Saudi Arabia (Powers *et al.*, 1966). In both Qatar and throughout the Arabian Gulf, the formation consists of four members — in ascending order the Arab D, C, B and A (Fig. 2) – which are composed mainly of shallow-water carbonates capped by anhydrites. Most of these units are oil reservoirs in different parts of Arabia (Alsharhan and Nairn, 1997).

The Arab "D" is the most prolific reservoir unit throughout the eastern part of the Arabian Peninsula. It consists mainly of dolomitic limestones in the lower part, limestones in the middle, and alternations of limestones with thick layers of anhydrite above.

The Arab "D" Member was described for the first time by an anonymous author in 1939, and was redefined by Powers *et al.* (1966) from well *Dammam-7* in eastern Saudi Arabia due to the extensive dissolution of anhydrite beds at the outcrop type-section. At its type locality, the Member is 58.5m thick. The lower 46m is made up of partially-dolomitized aphanitic limestones interbedded with porous calcarenites and calcarenitic limestones; the upper 12.5m consists of massive anhydrites interbedded with dolomites and dolomitic limestones. Macrofauna include *Clypeina jurassica*, *C. cf. hanabatensis*, *Cylindroporella arabica*, *Kurnubia* spp. and *Nautiloculina* spp. Based on these fossils, the member is assigned an Early Kimmeridgian age (Powers, 1962).

Upper Jurassic sediments across Arabia and the Gulf region had been given different names in spite of their similar lithologies and stratigraphic status. The Arab "D" of Qatar may be equivalent to the lower part of "unit 3" of the Musandam Group in the northern parts of the UAE (Alsharhan and Kendall, 1986); in the central UAE, the Arab "D" may be equivalent to the Kimmeridgian Fateh Formation. Further west (offshore Abu Dhabi), the stratigraphic nomenclature used there is similar to that of the type-section in central Saudi Arabia and Qatar (Alsharhan, 1989). In Oman, the Arab "D" may be correlated with the upper part of Member F of the Musandam Group. The Arab "D" of Qatar may be equivalent to the lower part of the Gotnia Formation in Kuwait and southern Iraq, which is composed of anhydrite and halite (Sadooni, 1997).

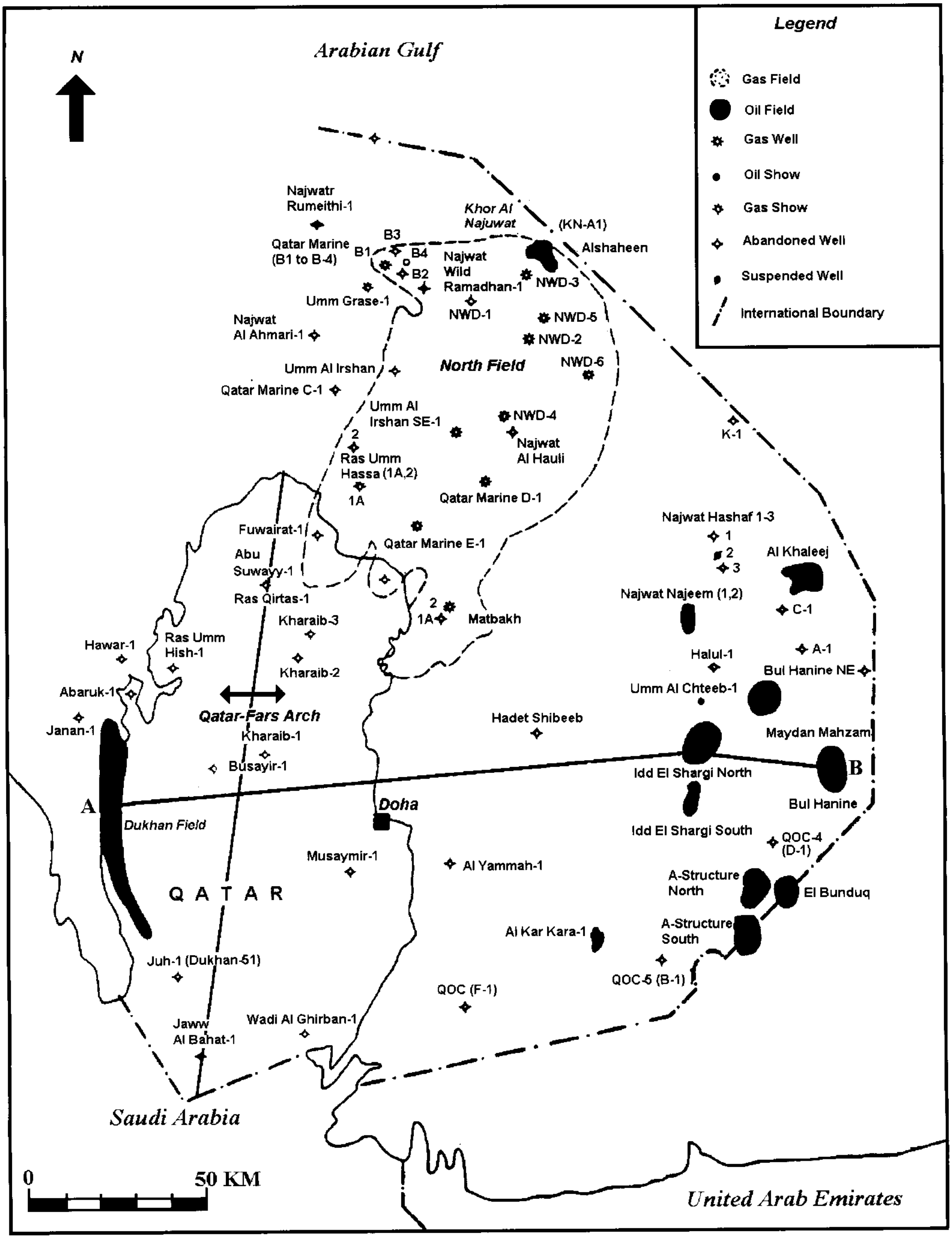


Fig. 1. Location of major oil- and gasfields in Qatar. Line AB indicates the cross-section shown in Fig. 6. (Modified after Alsharhan and Nairn, 1997).

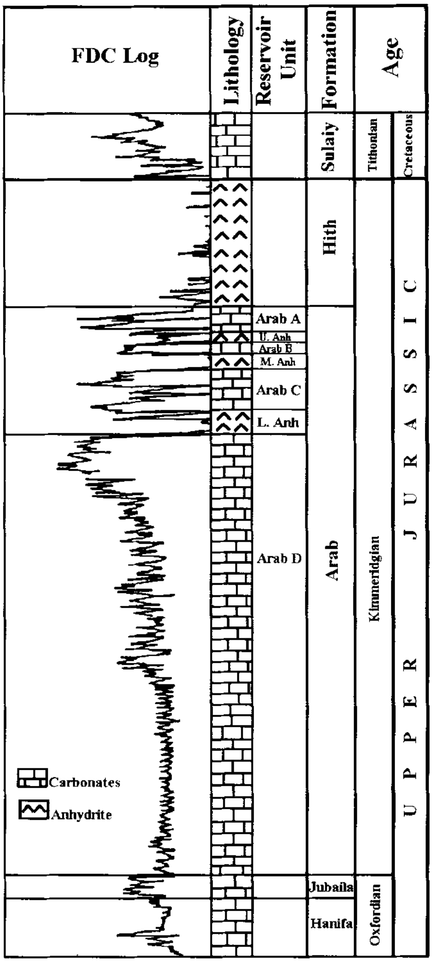
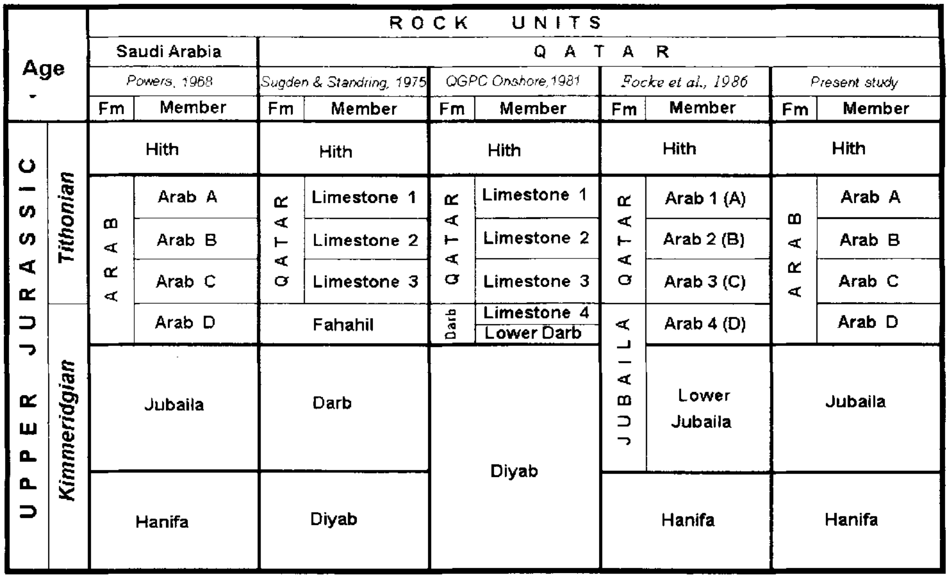


Fig. 2. Stratigraphy of the Upper Jurassic subsurface sediments from a typical well in Qatar (modified after Focke *et al.* 1986).

Lithostratigraphic revision

Although the Saudi stratigraphic nomenclature for the Jurassic (Powers *et al.*, 1966) has been adopted in Qatar, several authors have attempted to replace it with local names. In an unpublished report (cited by Sugden and Standring, 1975), Sugden proposed the name Fahahil Formation to encompass Arab "D" sediments in Qatar. In the proposed type locality at well *Dukhan-66*, the Fahahil Formation (57 m) consists of dolomitic limestones in the lower part, clean limestones in the middle, and dolomitic limestones interbedded with thin horizons of anhydrite above. Qatar General Petroleum Corporation (1981) considered the Fahahil Formation to be a synonym for the Darb Formation, which at its type locality (well *Dukhan 51*) consists of 211 m of argillaceous dolomitic limestones. They subdivided the Darb Formation into two members — the lower Darb below and the Fourth Limestone Member above. Later, Focke *et al.* (1986) introduced the term "Arab 4 unit" to the stratigraphy of the offshore area as equivalent to the Fahahil Formation.



Age		ROCK UNITS									
		Saudi Arabia		QATAR							
		Powers, 1968		*Sugden & Standring, 1975*		*QGPC Onshore,1981*		*Focke et al., 1986*		*Present study*	
		Fm	Member	Fm	Member	Fm	Member	Fm	Member	Fm	Member
UPPER JURASSIC	*Tithonian*	Hith		Hith		Hith		Hith		Hith	
		ARAB	Arab A	QATAR	Limestone 1	QATAR	Limestone 1	QATAR	Arab 1 (A)	ARAB	Arab A
			Arab B		Limestone 2		Limestone 2		Arab 2 (B)		Arab B
			Arab C		Limestone 3		Limestone 3		Arab 3 (C)		Arab C
	Kimmeridgian		Arab D	Fahahil		Darb	Limestone 4 Lower Darb	JUBAILA	Arab 4 (D)		Arab D
		Jubaila		Darb		Diyab			Lower Jubaila	Jubaila	
		Hanifa		Diyab				Hanifa		Hanifa	

Fig. 3. The different stratigraphic nomenclatures which have been used for the Upper Jurassic sediments in Qatar.

The Arab "D" in Qatar has similar lithologic characteristics throughout the country, and to that of the type locality in Saudi Arabia. There are no major lithologic or age differences that justify the introduction of a new terminology. Therefore, we believe that the above-mentioned local names complicate a regional understanding of Upper Jurassic sediments in Arabia. We propose that they should be dropped in favour of the original stratigraphic nomenclature derived from the type-section in Saudi Arabia. This practice will be followed below (Fig. 3).

The transition from limestones interbedded with thin streaks of anhydrite (Jubaila Formation) to the overlying dolomitic limestones of the Arab "D" unit seems to be gradual. The Arab "D" is separated from the overlying dolomitic limestones of the Arab "C" reservoir by an anhydrite horizon. In Qatar, the Arab "D" ranges in thickness from 60 to 100 m.

SEQUENCE STRATIGRAPHY OF THE ARAB "D"

Based on a literature review of boundary beds in seven regions from five continents, Norris and Hallam (1995) reported the occurrence of a global high sea-level phase during the late Callovian — early Oxfordian. This phase appears to have followed Toarcian rifting, and led to the deposition of the Hanifa and Jubaila Formations in Qatar, formatons which are correlated with the Najmah Formation of Kuwait and Iraq (Sadooni, 1997).

Upper Jurassic sediments in Qatar can be divided into three major sequences (Fig. 4) based on large scale flooding events:

i. An Oxfordian – early Kimmeridgian sequence that encompasses sediments belonging to the Hanifa and Jubaila Formations. These units consist of laminated, organic-rich, bituminous lime mudstones with some nodular and mosaic anhydrites, and were probably deposited in highstand, stratified, anoxic marine conditions (Sharland *et al.*, 2001).

ii. A Kimmeridgian-Tithonian sequence, which mainly comprises the Arab Formation (D, C, B and A units). This consists of shelfal carbonates alternating with lowstand wedges

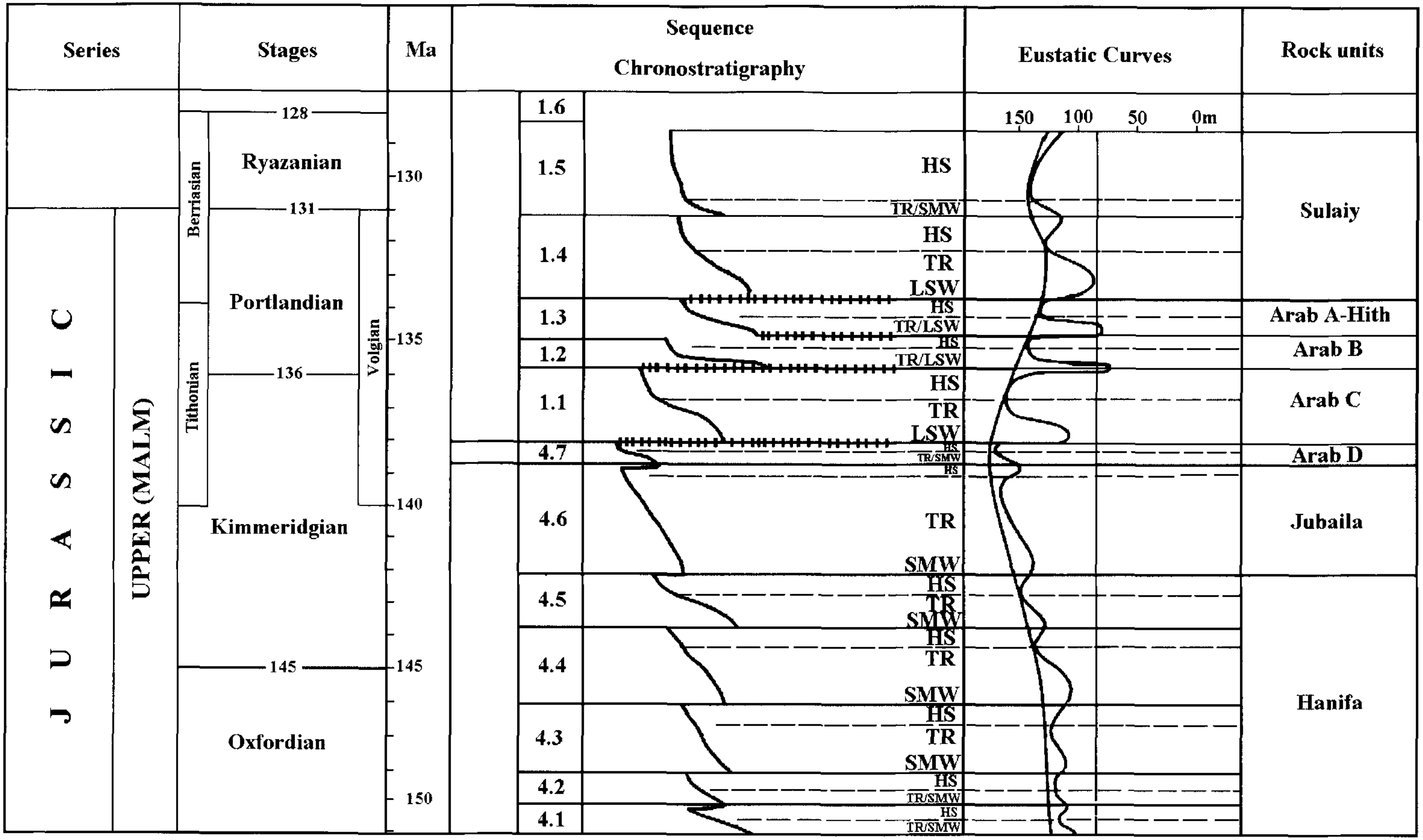


Fig. 4. Chronostratigraphy of Upper Jurassic subsurface sediments of Qatar compared to the global eustatic curves of Haq *et al.* (*1987*) (compiled from Focke *et al.* 1986 and Al-Husseini, 1997).

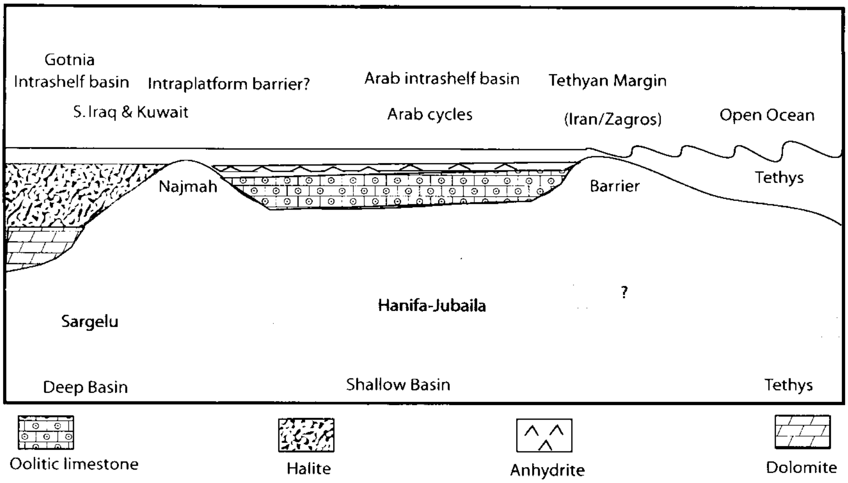


Fig. 5. Configuration of the intrashelf Arab Basin compared to other nearby Tethyan basins during the Late Jurassic.

of gypsum (LSW-G) and laminated basin-centre evaporites (probably equivalent to the lower part of the Gotnia Formation in Kuwait and southern Iraq) (Fig.5).

iii. A Tithonian sequence which is made up of the Hith Formation in Qatar, equivalent to the upper part of the Gotnia Formation in neighbouring countries. The Hith Formation consists of basin-fill halite (BFH) and lowstand wedge gypsum (LSW-G).

Al-Husseini (1997) proposed a sequence stratigraphic framework for the Jurassic sediments of the Arabian Gulf. He suggested that Arab "D" deposition started with a highstand systems tract followed by a transgressive/shelf margin wedge, and ended with a second highstand phase. These can be correlated with short-term oscillations in the eustatic curve of Haq *et al.* (1987) (Fig. 4).

Bouroullec and Meyer (1994) reported that the Arab "D" in Qatar consists of three shallowing-up cycles: prograding shoreline deposits passing up into a layer of algal laminites; beach rock passing up into a burrowed and bioturbated layer; and supratidal backshore deposits passing to upper-shore deposits. These cycles may be recognizable in *Dukhan,* but there are significant changes in thickness and lithological characteristics in the fields we studied, as shown in Fig. 6. The succession at *Dukhan* has many horizons of algal lamination which may be used to divide the section into cycles; but at *Bul Hanine,* the section probably represents a single shallowing-up cycle which starts with outer-shelf deposits, passes up into inner-shelf, shoals and build-ups, and ends with a sabkha.

FACIES DESCRIPTION

Microfacies

Petrographic analysis of thin sections prepared from the Arab "D" unit suggest that its microfacies is similar to that of Upper Jurassic sediments in other parts of Arabia. The unit consists mainly of mudstones with some dolomites at the base, which gradually pass upwards to packstone-grainstones with local coral-algal-stromatoporoid boundstones capped by anhydritic dolomites and anhydrites. The principal microfacies are described in the following section:

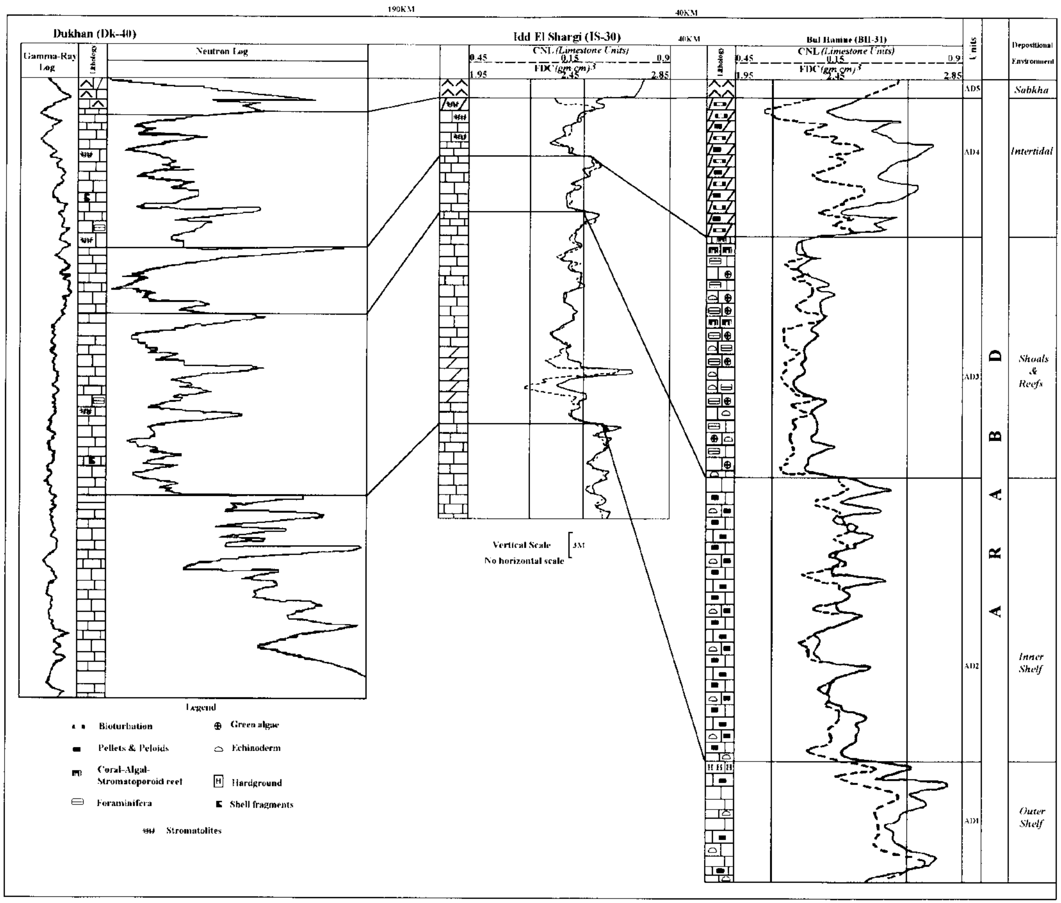


Fig. 6. A tentative vertical subdivision of the Arab D member in three wells from the on- and offshore of Qatar (compiled and modified from Focke *et al.*, 1986).

Deepwater limestones

Mudstones represent a major component of the Upper Jurassic sediments throughout Arabia, and comprise micritic limestones with rare calcispheres, small benthic foraminifera and shell fragments (Fig. 7). This facies is interpreted to have been deposited under deepwater conditions (Flügel, 1982; Adams *et al*., 1984). In the lower part of the Arab "D" unit, the mudstone facies is interbedded with thin horizons of grainstones and dolomites.

Some of these limestones are characterized by the presence of thin-shelled pelagic bivalves forming what is known as a "feathery texture" (Fig. 8). This facies is characteristic of pelagic and hemipelagic carbonates in Tethyan Jurassic sediments. Late Jurassic calcareous dinocysts have been used successfully to date deepwater sediments in Yemen (Toland *et al*., 1995).

Peloidal grainstones

This facies includes peloids and micritised grains of different sizes and shapes, some of which are derived from benthonic foraminifera and ooliths (Fig. 9). It also contains some unmicritized shell fragments. The groundmass is replaced by granular calcite cement. Most of the peloids are covered with acicular rim cement. Some of the peloids are of faecal origin; others are the crustacean coprolites *Favreina* and the gastropod coprolites *Prethocoprolithus* (Peebles, 1997; Sadooni, 1997).

The different shapes and sizes of the peloids and the extensive micritization indicate that these components were micritised *in situ* or shortly after deposition.

Crustacean coprolites such as *Favreina* are found mainly as transgressive lag deposits or hardgrounds, closely related to condensed sections or maximum flooding surfaces. *Prethocoprolites* are deposited during the flooding of intertidal areas, and are found mainly in pelletal packstones or grainstones in upward shoaling sequences (Peebles, 1997).

Foraminiferal packstones-grainstones

This facies includes benthonic foraminifera with dascycladacean algae, rare peloids, echinoderm debris, solitary corals and bivalve fragments. Foraminifera can be extensively micritised and therefore difficult to identify (Fig. 10). The facies is best developed in the upper part of the Arab D reservoir. Very fine rhombic dolomite and some argillaceous component were occasionally recognized within this microfacies.

Large benthonic foraminifera can be found in a wide range of environmental settings. Their association with dascycladacean algae and solitary corals, and the extensive micritisation of their tests suggests a low-energy depositional environment, for example a restricted platform or lagoon.

Algal packstones and grainstones

This facies is quite common in the Jurassic sediments of Arabia (Elliot, 1968). The main algae recorded are *Clypina* sp. and *Likanella* sp. (Fig. 11), which are present in great abundance. Their exceptional preservation indicates very quiet depositional environments such as lagoons.

Oolitic grainstones

Oolitic grainstones are important in the Upper Jurassic throughout Arabia. The facies is variable but where best developed it consists entirely of well-sorted sand-grade ooliths. This facies is characterized by relatively large intergranular pores enlarged by later leaching or filled by granular cement. Elsewhere, the sorting deteriorates and the ooliths become smaller and mixed with foraminifera, coated grains and lithoclasts (Fig. 12). The widespread distribution of ooliths in the Jurassic Arabian Basin is associated with the development of shallow, intra-shelf basins. It is believed that the ooliths probably formed as highstand basin-wedge shoals in an evaporitic setting.

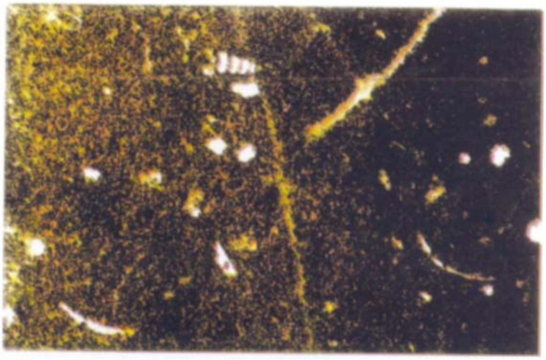


Fig. 7. Lime mudstone facies with rare foraminifera and thin shell fragments. This facies comprises the lower part of the Arab "D", unit AD1 (x25, crossed nicols).

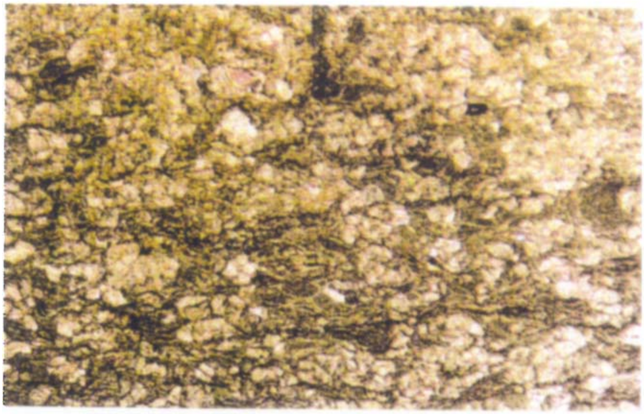


Fig. 8. Thin-shelled pelagic bivalves forming a "feathery" structure. Unit AD4 (x25, crossed nicols).

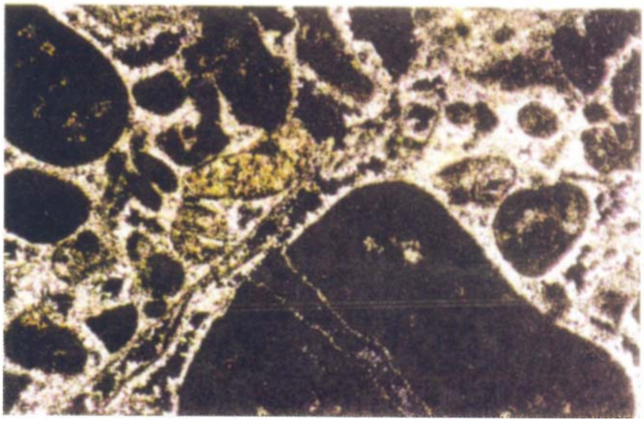


Fig. 9. Peloidal grainstone facies. The peloids are probably micritised skeletal grains with some fecal pellets. Grains are surrounded by a thin isopachous cement crust. Upper part of the Arab "D", unit AD4 (x25, crossed nicols).

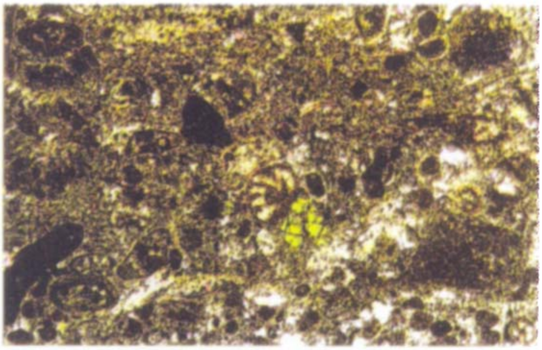


Fig. 10. Packstone of extensively micritised benthonic foraminifera with some peloids. Middle part of the Arab "D", unit AD3 (x25, crossed nichols).

Fig. 11. Algal packstone composed mainly of large algae with some foraminifera and peloids. Middle part of the Arab "D", unit AD3 (x25, crossed nicols).

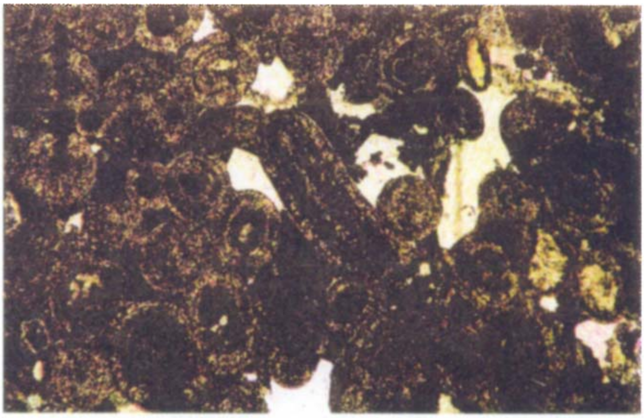


Fig. 12. Oolitic grainstone. This is the main reservoir unit of the Arab D. It consists of well-developed, normal ooliths. Some are slightly elongated with granular calcite cement partially filling the intergranular pores. Middle part of the Arab "D", unit AD3 (x25, crossed nichols).

Stromatolitic dolomites

These dolomites represent the final part of the deposition cycle and occur in the uppermost 5 m of the Arab "D". They have an aphanitic to xenotopic texture. The facies is heavily bioturbated with traces of algal laminations in the form of darker filaments; it is also characterized by the presence of poikilotopic anhydrite and laths of nodular anhydrite. The facies represents intertidal to sabkha conditions.

Facies succession

According to the available petrophysical and petrographic data, the Arab "D" reservoir unit in Qatar can be divided into five units designated AD1 (at the base) to AD5. These units can be identified at and correlated between the three wells studied — *Dukhan 40* (*Dk-40*), and offshore wells *Idd El Shargi 30* (*IS-30*) and *Bul Hanine 31* (*BH-31*) (Fig. 6). The five units are described briefly in the following paragraphs:

AD1: This unit consists of bioclastic wackestones and mudstones with occasional grainstones, and is capped by a hardground in the *Bul Hanine* field. Its average thickness is around 10m at *Bul Hanine* and *Idd El Shargi*, increasing to around 20m at *Dukhan*.

AD2: This unit consists mainly of wackestones containing peloids, echinoderms, foraminifera and shell fragments with some stromatolites at *Dukhan*, and may indicate a shallowing-up trend in this part of the basin. The unit is also dolomitized at *Idd El Shargi*. It reaches a maximum thickness of around 33m at *Bul Hanine*, thinning to around 24m and 21m at *Idd El Shargi* and *Dukhan*, respectively.

AD3: This unit is best developed at *Bul Hanine* where it consists of packstones/ grainstones with foraminifera, green algae and echinoderms with coral-algal-stromatoporoid boundstones. The unit is around 28m thick at *Bul Hanine* but thins considerably to only 6m at both *Idd El Shargi* and *Dukhan*.

AD4: This unit typically consists of intensely bioturbated, stromatolitic and dolomitic limestones. The unit is around 8m thick at both *Bul Hanine* and *Dukhan*, but thins to around 3m at *Idd El Shargi*.

AD5: The unit is an evaporitic cap rock that marks the end of Arab "D" deposition or the beginning of Arab "C" deposition. It consists of around 3m of anhydrite and anhydritic limestones.

DEPOSITIONAL MODEL

Previous models

To explain the carbonate-evaporite cycles of the Arab Formation, Wood and Wolfe (1969) were the first to propose a sabkha model for the depositional setting of the Arab/ Darb Formation of the Trucial Coast (UAE). They compared the lithologic succession in the formation with the sabkha sediments of the present-day Arabian Gulf. Leeder and Zeidan (1977) also studied what they called the giant Late Jurassic sabkhas of the Arabian Tethys. Lapointe (1991) investigated the sabkha versus salt basin (salina) model as a possible mechanism for the deposition of the Arab Formation in the *Umm Shaif* field, UAE. Many other attempts have been made to reconstruct the depositional regime of the Arab Formation in different parts of Arabia – e.g. Wilson (1985) from the *Qatif* field, Saudi Arabia; Suzuki and Ohsawa (1987) from Offshore Abu Dhabi; Mitchell *et al.* (1988) from *Ghawar* field, Saudi Arabia; Bouroullec and Meyer (1994) from Qatar; Alsharhan and Whittle (1995) from southern and SW parts of the Arabian Gulf; and Al-Silwadi *et al.* (1996) from offshore Abu Dhabi.

Most of these authors suggested that arid climatic conditions were prevalent during the deposition of the Arab Formation, and that the depositional regime was characterized by a cyclic pattern of evaporite and carbonate deposition which dominated much of the eastern part of the Arabian region (e.g. Murris, 1980; Alsharhan and Kendall, 1986). Mitchell *et al.* (1988) noted that the Arab "D" member at *Ghawar* consists of two shoaling-upward cycles that were deposited in a highstand setting. No explanation was given for the causes of these repetitive cycles. The proposed causes — epeirogenic subsidence, eustatic changes or variation in carbonate productivity — cannot explain such frequent lithological changes.

According to Wilson (1985) and Alsharhan and Nairn (1997), the Arab "D" Member in Saudi Arabia represents final, upward-shoaling, basin-fill deposition. The Member's sedimentary architecture was controlled by epeirogenic subsidence and eustatic sea-level changes. A similar conclusion was reached by Hughes (1996) who attributed lithologic variations to either a reduction in subsidence rate, a fall in sea-level or increased carbonate productivity, or to a combination of these factors.

Problems associated with the depositional model of the Arab Formation

In our view, any model of the depositional history of the Arab Formation should address the following problems:

1. The Arab Formation consists of a repetition of cycles which have a frequency of 250 ka. These represent the lowest "order" Milankovitch cycle related to eccentricity of the Earth's orbit (Fischer, 1982; Goldhammer *et al.*, 1990). The Jurassic was, however, a "greenhouse" period when there was no significant sea-level change, and typical cycles are 2-5m thick (Read and Horbury, 1993). However the Arab Formation cycles are tens of meters thick and in that sense they are similar to Vail-type 3rd order cycles which are deposited over a time interval of 1-10Ma. But the whole of the Arab Formation was probably deposited in a considerably shorter time than this (Sharland *et al.*, 2001).
2. The mechanism required to create the accommodation space which fits such abnormal thicknesses should also be considered.
3. The lateral progradation of the Arab system (both highstand carbonates and gypsum wedges) in from the basin margins must be addressed. This kind of progradation cannot be accomplished on a perfectly flat-topped platform.

The proposed depositional model

The Arab Formation was deposited in a series of intrashelf basins (or deeper lagoons) that were separated by reefal barriers both from each other and also from the open Tethys in the Zagros area to the east. These barriers were most probably build-ups of sponges, stromatoporoids and algae. Bouroullec and Meyer (1994) reported the presence of local buildups of stromatoporoids and calcitic spongiomorphs from the Arab "D" of Qatar. Sadooni (1997) described sponge build-ups from the Upper Jurassic sediments of northern Iraq. From another part of the Tethys, Schorr and Koch (1985), Wirsing and Koch (1986) and Schweizer (1987) described algal-sponge bioherms from the Swabian Alps in Germany. Schorr and Koch *(ibid.)* reported that the bioherms consist of a combination of algae, sponges, ooid-bearing grainstones, and algal stromatolites.

These intrashelf basins were flooded during 4th order or 3rd/4th order flooding events which generally result in 2-5m thick cycles (Read and Horbury, 1993), but as noted above, the Arab Formation cycles are much thicker (tens of meters). This difference in thickness could be explained by the possibility that the 4th order cyclicity "topped-up" the intrashelf basin which was sediment starved, and allowed the cycles to "stretch" in a way that normal 4th order platform-top cycles (starting with zero accommodation space prior to transgression) cannot. In fact, the Arab Formation cycles essentially "plugged" pre-existing accommodation space, and plugged it rapidly.

In such a setting, the Arab "D" Member was probably deposited when the basin was fully connected to the Tethys Ocean and the sea level was well above the barrier height. Therefore, the oolitic and bioclastic limestone units of the Arab "D" represent the transgressive and highstand systems tracts that were forming on the intrashelf basin margin. The calcisphere-bearing mudstone facies is interpreted as a condensed section deposited in the intrashelf basin centre (Noel *et al.*, 1991; Bucur, 1992).

When the sea-level fell below the barrier level, the shelf margin would have been exposed and became subjected to dolomitization and dissolution. Evaporites were precipitated around the intrashelf basin margins forming marginal evaporite wedges. In the intrashelf basin centre, carbonates continued to form during the early stages of shallowing, but gradually became interlaminated with evaporites forming "bull's-eye" deposits. Therefore, evaporites were either deposited in sabkhas or in the hypersaline lagoons behind the carbonate shoals, or in the basin centre. Flooding of the intrashelf basin would have created a new transgressive systems tract, leading to the re-establishment of renewed shelf-margin carbonates. Such a mechanism will cater for the lateral progradation of the Arab Formation sediments. It will also explain the greater thickness of the formation in Qatar (especially in the offshore area to the east) compared to Saudi Arabia. This may suggest that this area was much closer to the area where the main barrier was developed, since the initial progradation of shelfal sediments away from the barrier will create an isopach thick into pre-existing accommodation space. This is analogous to the Najmah Formation, which is thick because it prograded into the pre-existing accommodation space in the Sargelu Basin in northern Iraq (Sadooni, 1997). Subsequent Arab Formation cycles are much thinner, but are still thicker than the 2-5m cycles expected in a "greenhouse" period. The model assumes that there was remnant accommodation space (with some subsidence) following Arab "D" deposition. This can only be achieved if the Arab D and subsequent Arab cycles show an offlapping geometry into the basin which would make them late highstand to onset of lowstand (i.e. prograding, but with sea-level dropping slightly at every prograde) (Fig. 13).

The Arab cycle oolites in Saudi Arabia are more probably related to intrabasinal highs but would have developed by essentially the same mechanism.

This depositional model attempts to explain the repetitive nature of carbonate-evaporite beds in the Arab Formation in a more reasonable way than the standard "cycle" theory. The cycle theory assumes that the whole depositional system underwent shallowing up so that evaporites could be deposited, and it requires another marine flooding for carbonates to be deposited. In an area of relatively stable tectonism with no extreme climatic changes, it is difficult to explain the causes of such repetition. By contrast, our proposed model requires only a slight change in the water level to cover or expose the barrier.

Further work

The limited materials we had available prevented us from gathering further evidence in support of the proposed model. There is a need to search for possible build-up materials in the offshore fields of Qatar or Iran which would indicate the presence of some of the barriers. Further work should indicate where shallow-water gypsum wedges with sabkha-like fabrics were developed, where deeper subaqueous anhydrites with laminated fabrics were developed, and where the carbonates are dominantly deeper-water and where they are dominantly shallow. We can speculate that subaqueous evaporites are interbedded with deep-water carbonates in the Qatari offshore fields, whereas sabkha evaporites and shoal carbonates may occur in the areas further to the west.

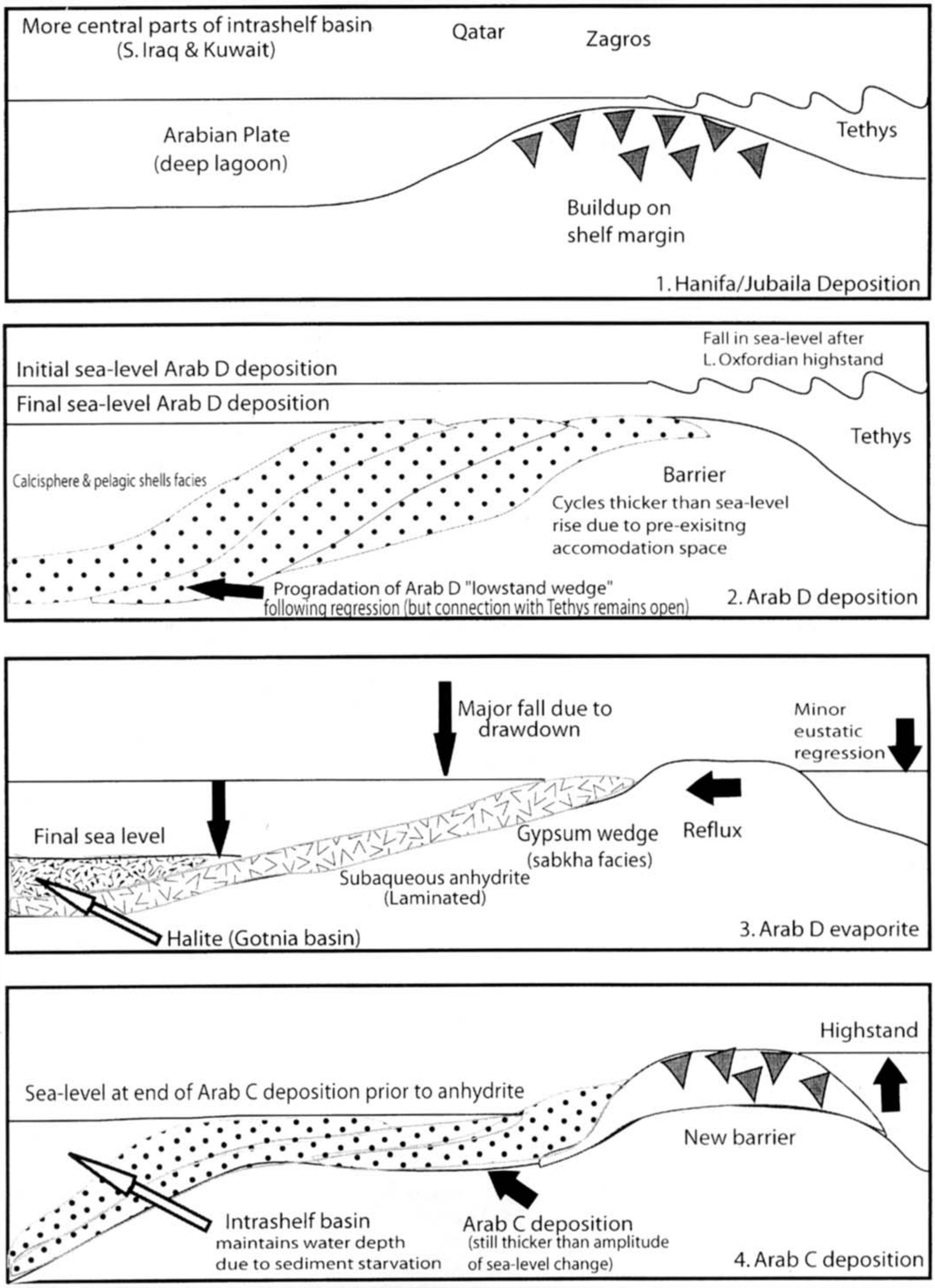


Fig. 13. A proposed depositional model for the Arab Formation in Qatar and neighbouring areas.

Similar cases

Several cases have been reported of carbonate-evaporite cycles in which thick evaporites were developed in essentially plate-centre settings. These are not thin sabkha cycles, but occur where a barrier of some sort developed and was flooded (even slightly) by high-frequency transgressions. Among these are:

- the Gotnia-Najmah succession of southern Iraq and Kuwait (Sadooni, 1997);
- the Jawan Formation (Albian) of north Iraq, which also consists of thick anhydrite deposited behind a platform-margin barrier (in this case, a combination of foraminifera shoals and rudist banks); this barrier allowed top-up to occur, and resulted in internal cyclicity in the Jawan (Sadooni, 1978, Al Shdidi *et al.*, 1995);
- and the Neogene Zagros foreland, where the Basal Anhydrite-Serikagni, Euphrates/ Dhiban Anhydrite, Jeribe/Lower Fars, and Mubaddad Limestone/ Mishan alternation exhibits a comparable cyclicity (although probably of lower frequency), with shelfal carbonates prograding into the basin from the basin margin (Sahib and Lateef, 1976; Ibrahim, 1978; Shawkat and Tucker, 1978; Goff *et al.*, 1995).

Outside Arabia, the Zechstein evaporite-carbonate cycles of the North Sea may represent a similar case. There, deep-basinal evaporites and "platform top" evaporites occur behind a high-energy margin, the latter cropping out in northern England (Tucker, 1991; Horbury, *pers. commun.*). A more direct analogue is the Late Jurassic (Kimmeridgian) Olvido Formation of NE Mexico. This formation consists of thick anhydrites developed behind a major platform margin barrier (San Andres Formation), though tongues of oolites are interbedded with the Olvido Formation in a back-barrier setting and provide the reservoirs in the *Lerma* gasfield (Wilson, 1990; Salvador, 1987; and Horbury, *pers. commun.*).

RESERVOIR CHARACTERIZATION

Source rocks

Little data has been published on the source rocks which have charged the Jurassic reservoirs in Qatar. The Upper Jurassic Hanifa Formation, which consists of laminated, bituminous mudstones and marls, is probably a major source. According to Alsharhan and Nairn (1997), the total organic matter in this formation ranges between 1-6 wt% and is composed of partially degraded sapropelic material. Frei (1984) attempted a geochemical correlation between the oils found in the Upper Jurassic reservoirs and the organic matter in the Hanifa Formation, and concluded that most of the oils are probably derived from these source rocks.

Another probable source rock is the Jubaila Formation (also Upper Jurassic). The lower part of this formation consists of organic-rich, laminated, silty mudstones with relatively high TOC values that range between 0.5-3.5-wt% (Alsharhan and Nairn, 1997) (Fig. 14).

Ibe (1985) proposed that ancient ooliths may be "syngenetically oil-bearing". Although ooliths may contain a considerable amount of organic matter associated with cyano-bacteria which can encrust their cortical laminations, it is unlikely that they form a major source for such large volumes of oil. Furthermore, oolites are normally deposited in high-energy oxidizing environments and so the organic material in them has little chance of being preserved unless the ooids are redeposited in deeper, anoxic waters, which is difficult to visualize in the depositional system of the Arab Formation. Wilson (1987) discarded Ibe's

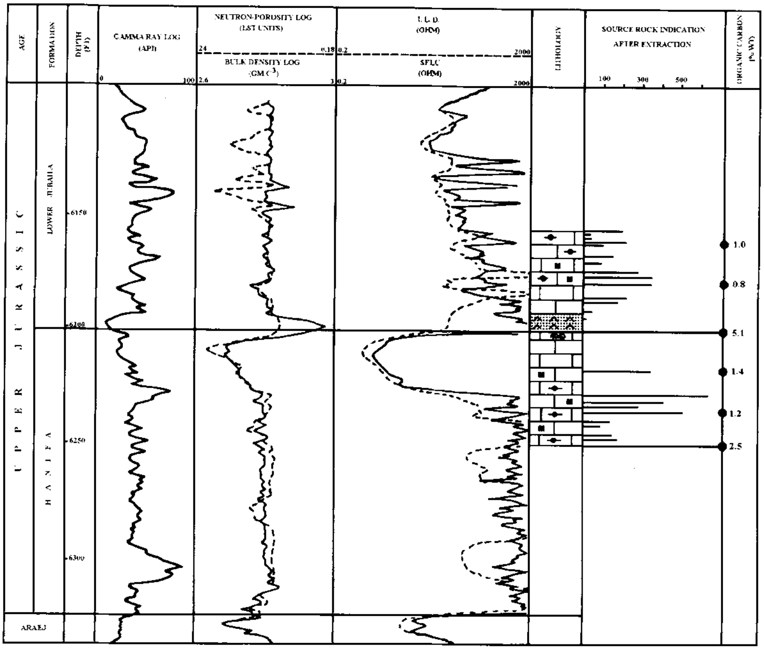


Fig. 14. Lithologic section and source rock indication of the Hanifa Formation in the *Ras Qirtas* field, Qatar (for location see Fig. 1) (after Frei, 1984).

proposal, and noted that Callovian-Oxfordian source rocks are the main source for the Arabian Jurassic oil.

Reservoirs

The Arab "D" reservoir is capped by around 18m of anhydrite that separates it completely from the overlying "C2" reservoir. This unit occupies an area of 60 km by 6 km with an average thickness of 56m, thinning to around 53m in the south. There are three main reservoir units:

(i) The dolomites of the eastern offshore fields. Scattered partial dolomitization occurs mainly as thin beds of fine- to medium-grained, limpid rhombs floating in a lime mud/ wackestone matrix. Some of the original texture can be still recognized (Fig. 15). In the lower part of the reservoir, dolomitic horizons separate the different mudstone facies.

Extensive dolomitization affects a significant part of the Arab Formation's volume. The dolomite in the samples studied is generally associated with high dissolution porosity, indicating a high degree of solution cannibalization. Sun (1992) attributed the extensive dissolution of anhydrite-dolomite sediments in the Miocene Lower Fars Formation to hypersaline brines of the early stages of transgression within an arid evaporitic basin. Before the brines become too diluted, they flood over the shelf and cause dissolution of aragonite and initiate precipitation of dolomite. Magara *et al.* (1993) noted that porosity increases during early and intermediate stages of dolomitization, but tends to decline in the later or near-completion stages of dolomitization. Porosity and permeability values range between 10-30% and 1-800 mD, respectively.

(ii) Dolomitized lime mudstones resulting from the partial dolomitization of the mudstone facies. Dolomitization improves the texture of these rocks and the connectivity between their pores (Fig.16). Some of these mudstones are also bioturbated and some of

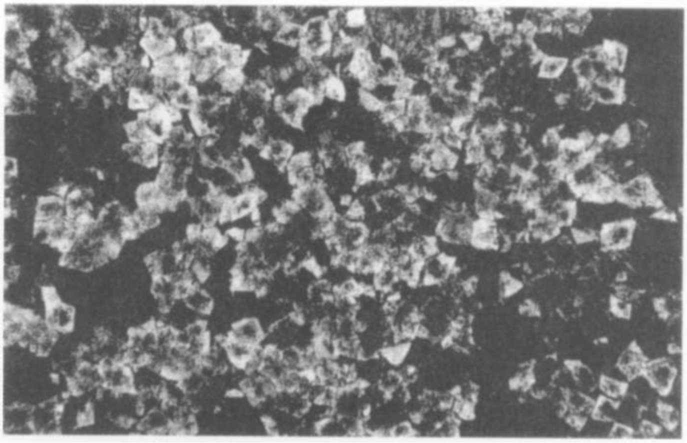


Fig. 15. Extensive dolomitization has totally replaced the original rock and is associated with the development of high intercrystalline and dissolution porosity. This is one of the major reservoir units of the Arab "D". Upper part of the Arab "D", unit AD4.

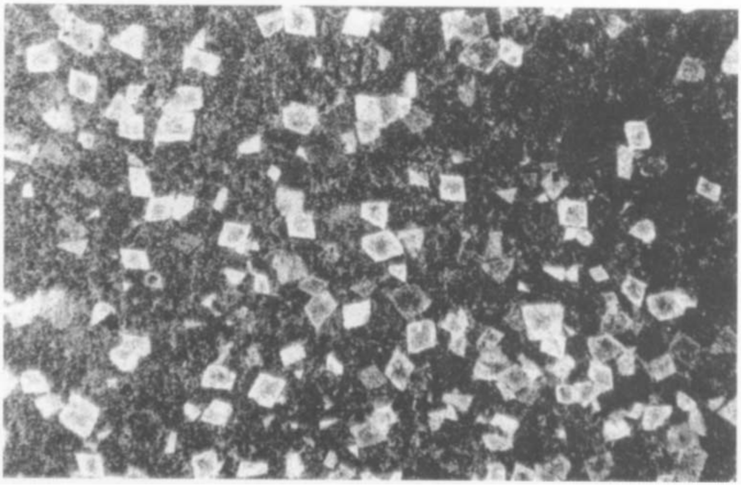


Fig. 16. Selective dolomitization of lime mudstone facies. The dolomite is made up of idiotopic rhombs but not much visible porosity enhancement can be seen. Upper part of Arab "D", unit AD4.

these zones have a relatively loose fabric, which may act as permeability channels. Porosity values in this unit range between 10 and 30% with a permeability of 1-60 mD.

(iii) Peloidal and oolitic packstone and grainstone units with intergranular, mouldic and vuggy porosity. This is the most important reservoir in the Arab "D" Member. This lithology has a relatively narrow range of porosity values (25-35%) but has a relatively wide range of permeability values (300-10,000mD). The porosity versus permeability plot for the three main reservoir types is shown in Fig. 17.

The porosity-permeability values of the above reservoir units indicate a direct relationship with each other, with the exception of the peloidal-oolitic grainstone. This may be attributed to differential dissolution of the grainstone facies.

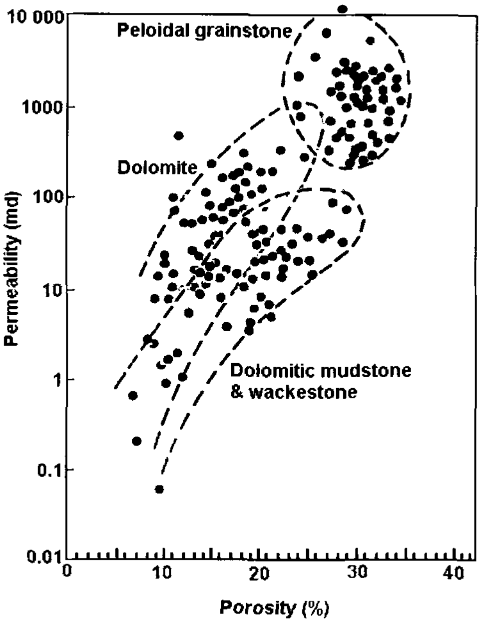


Fig. 17. Porosity versus permeability plot of the main reservoir units of the Arab "D" in *Bul Hanine* field, Qatar (compiled from Focke *et al.*, 1986).

CONCLUSIONS

(1) Deposition of the Arab Formation followed a global sea-level high during the Oxfordian. The formation is divided into four units – "A", "B", "C" and "D". The top three units are composed of alternations of carbonates and evaporites; the lowermost unit is composed only of carbonates and is capped by a thin layer of anhydrite.

(2) The Arab "D" is the major reservoir unit in Qatar. It consists of mudstones/wackestones passing upward to oolitic/peloidal grainstones and coral-algal-stromatoporoid reefal boundstones that are occasionally extensively dolomitized. These are capped by stromatolitic, bioturbated dolomite and anhydrite.

(3) The Arab Formation consists of a repetition of cycles of frequency 250ka, which represent the lowest "order" Milankovitch cycle. The Jurassic was a "greenhouse" period with no significant sea-level change, and typical cycles are 2-5m thick. But Arab Formation cycles are tens of meters thick, and are similar to Vail-type 3rd order cycles which were deposited over time intervals of 1-10Ma. This difference in thickness can be explained by the 4th order cyclicity "topping-up" the intrashelf basin, which was sediment starved.

(4) We propose the presence of a build-up barrier in the Zagros region during the Late Jurassic. The Arab "D" Member was deposited when the Arab Basin was fully connected to the Tethys. The oolitic and bioclastic limestones represent the transgressive and the highstand system tracts which formed on the intrashelf basin margin. The mudstone and the hemipelagic facies were deposited in the intrashelf basin centre. When the water level fell below the barrier level, evaporites were precipitated around the intrashelf basin margins, forming marginal evaporite wedges. In the intrashelf basin centre, carbonates continued to form during the early stages of shallowing, but gradually became interlaminated with evaporites. Therefore, evaporites were either deposited in sabkhas or in hypersaline lagoons behind the carbonate shoals.

(5) The proposed model explains the lateral progradation of Arab Formation sediments, and justifies the greater thickness of the formation in the offshore area of Qatar compared to Saudi Arabia.

(6) Further work is needed to search for build-ups in the offshore fields of Qatar or Iran, and to find where both shallow-water gypsum wedges with sabkha-like fabrics and deeper, subaqueous anhydrites with laminated fabrics were developed.

(7) The laminated, organic-rich bituminous lime mudstones of the Hanifa/Jubaila Formations are a possible source for the oil in the Arab Formation in Qatar.

(8) The main reservoir rocks of the unit are dolomites; dolomitized lime mudstones resulted from the partial dolomitization of the mudstone facies; and the peloidal and oolitic packstones and grainstones, which have intergranular, mouldic and vuggy porosity.

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