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Geology and hydrocarbon habitat in the Arabian Basin: the Mesozoic of the State of Qatar

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Abstract

The State of Qatar is situated in the southwestern Arabian Gulf and covers an area of about 12 000 sq km. The land portion is formed by a large, broad arch, which is part of the regional, NE-SW trending Qatar-South Fars Arch, separating two Infracambrian salt basins. The Dukhan Field on the west coast of the Qatar Peninsula, with its reservoirs in Upper Jurassic limestones, was the first oil field discovered. Since this discovery in 1940, a series of other discoveries have been made, and Qatar became a member of the Organization of Petroleum Exporting Countries (OPEC) in 1973.

Hydrocarbon accumulations are widely dispersed throughout the stratigraphic column with production from Middle Jurassic to Middle Cretaceous strata. The most prolific reservoirs are in shelf carbonate sequences and minor accumulations occur in Albian clastic sediments.

Seals, mainly anhydrite and shale, occur as formations of regional extent as well as intraformationally with smaller areal distributions. There are several stratigraphic intervals which contain source rocks or potential source rocks. Upper Oxfordian-middle Kimmeridgian source rocks were formed in an extensive, starved basin during a period of sea-level rise. They contain organic matter of sapropelic, liptodetrinitic and algal origin and have a total organic carbon content of 1 to 6%.

Both depositional environment and tectonic evolution through geologic time have influenced sedimentary facies and stratigraphic features, which controlled reservoir, source and seal characteristics and subsequent hydrocarbon generation, migration and entrapment.

Introduction

The State of Qatar, lying between the northern latitudes 24°30′ and 26°10′, has an area of some 12 000 sq km and projects about 170 km northwards into the Arabian Gulf in the Arabian Basin (Figs 1, 2). It is bordered by Saudi Arabia and the United Arab Emirates to the south and southeast. To the north, east and west it is surrounded by shallow waters of the Arabian Gulf. Its land surface is formed by a large, broad arch that has a Tertiary limestone carapace, which rises to a maximum elevation of 60 m in the interior of the peninsula (Fig. 3).

Geologically, Qatar is part of the Arabian Interior Platform (Fig. 1), in which, a thick sequence of sediments has accumulated since the Paleozoic. The thickness of this sequence is estimated by geophysicists to exceed ten kilometres. The surface is

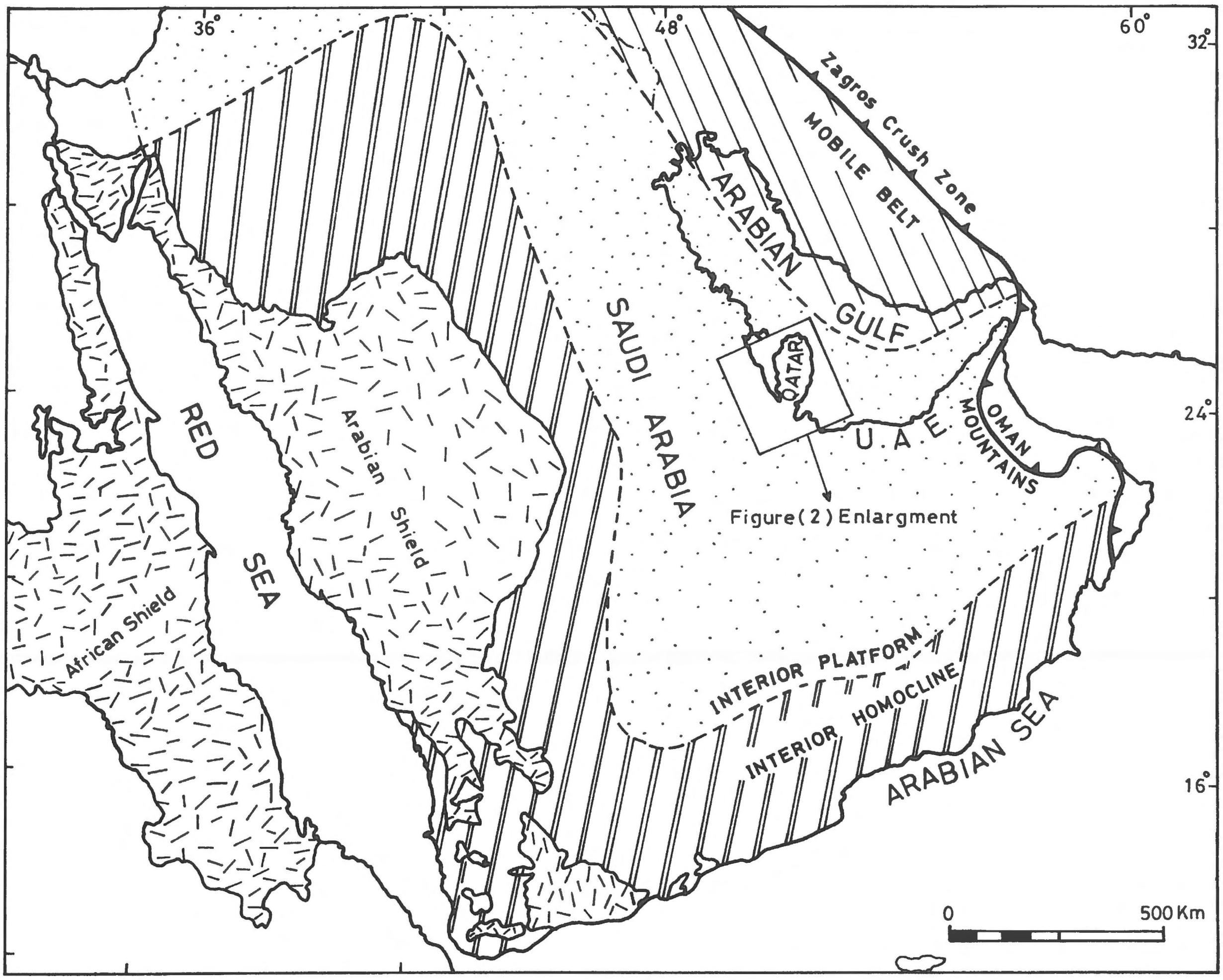

Fig. 1. Structural elements of the Arabian Basin showing the location of the State of Qatar.

mostly desert with Eocene carbonates exposed in the central area of the arch northwest of Doha, in the core of the Dukhan anticline in the western part of the country, and near the southern border of the state (Fig. 3). Miocene sediments form a number of low mesas and are overlain by continental sands and gravels which form a smooth and gently undulating topography. Consolidated Quaternary beach rocks occur in the coastal areas and extensive areas of sabkha deposits exist around the coasts, east of the Dukhan anticline, and in the southernmost part of the state. Recent sand-dunes occur only in scattered localities, increasing in frequency towards the south.

Little is known of the Pre-Ordovician in this area. However, as is the case in parts of Oman and the United Arab Emirates, the Huqf Group (Late Precambrian-Early Cambrian) may be present across the arch as non-evaporitic carbonates, explaining the lack of halokinetic phenomena. The salt in the domes of eastern offshore Qatar is known from both outcrops and drilled sections to be of Pre-Ordovician age. The deepest, penetrated subsurface rocks are Ordovician to Early Permian; these are almost exclusively composed of continental to shallow-marine siliciclastics. The Late Permian to Late Tertiary sequence is dominated by marine carbonates, with terrigenous clastics or evaporites during cyclic periods of regression.

The objective of this paper is to provide the depositional, stratigraphic and structural framework and evolution which controlled reservoirs, source rocks,

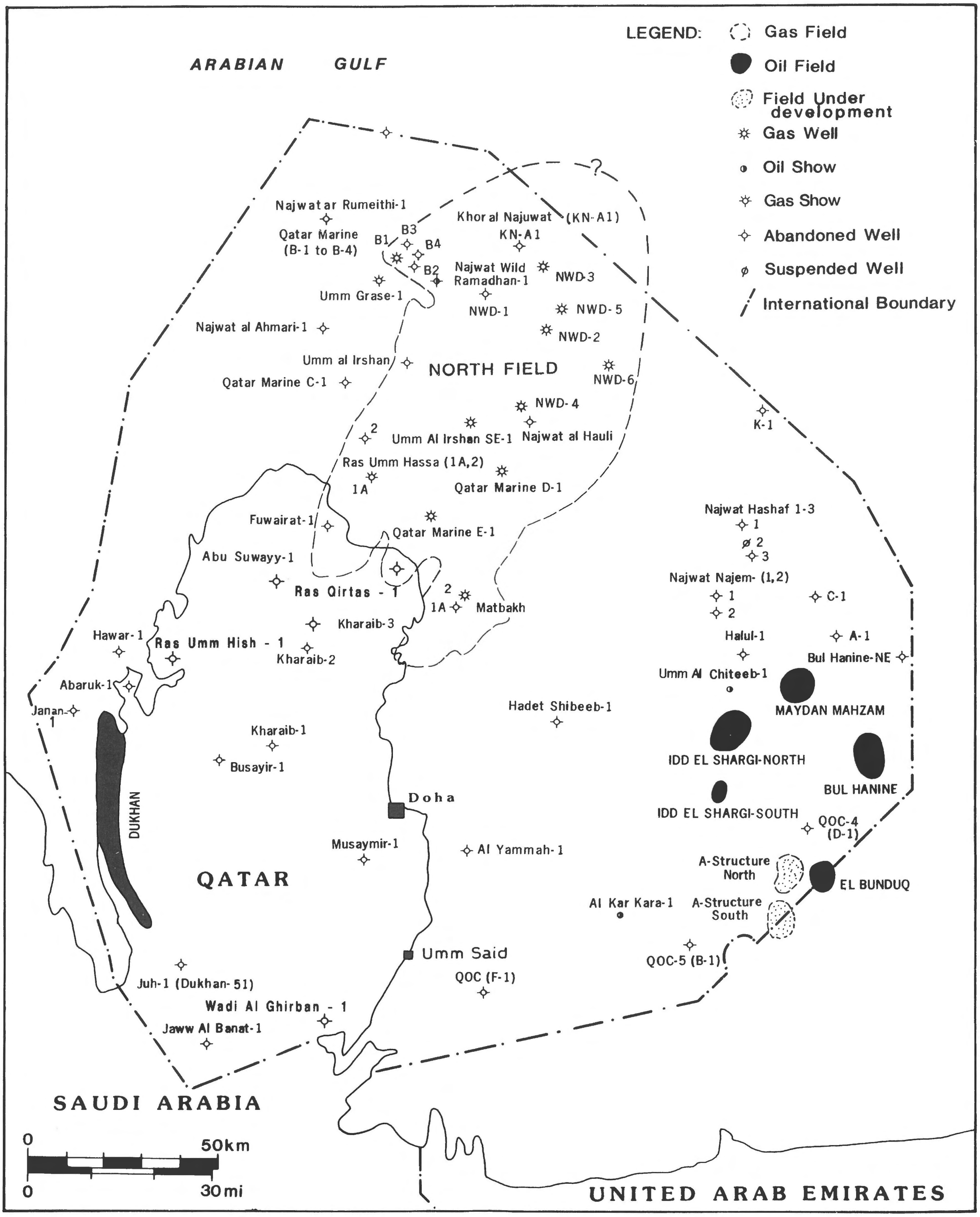

Fig. 2. Location map of the State of Qatar showing major oil and gas fields and exploration wells. Note that in the North Field, wells ND W-2 and 5 and KNA-1 were dry in the Permian, but contain oil in the Cretaceous as shown in Fig. 17.

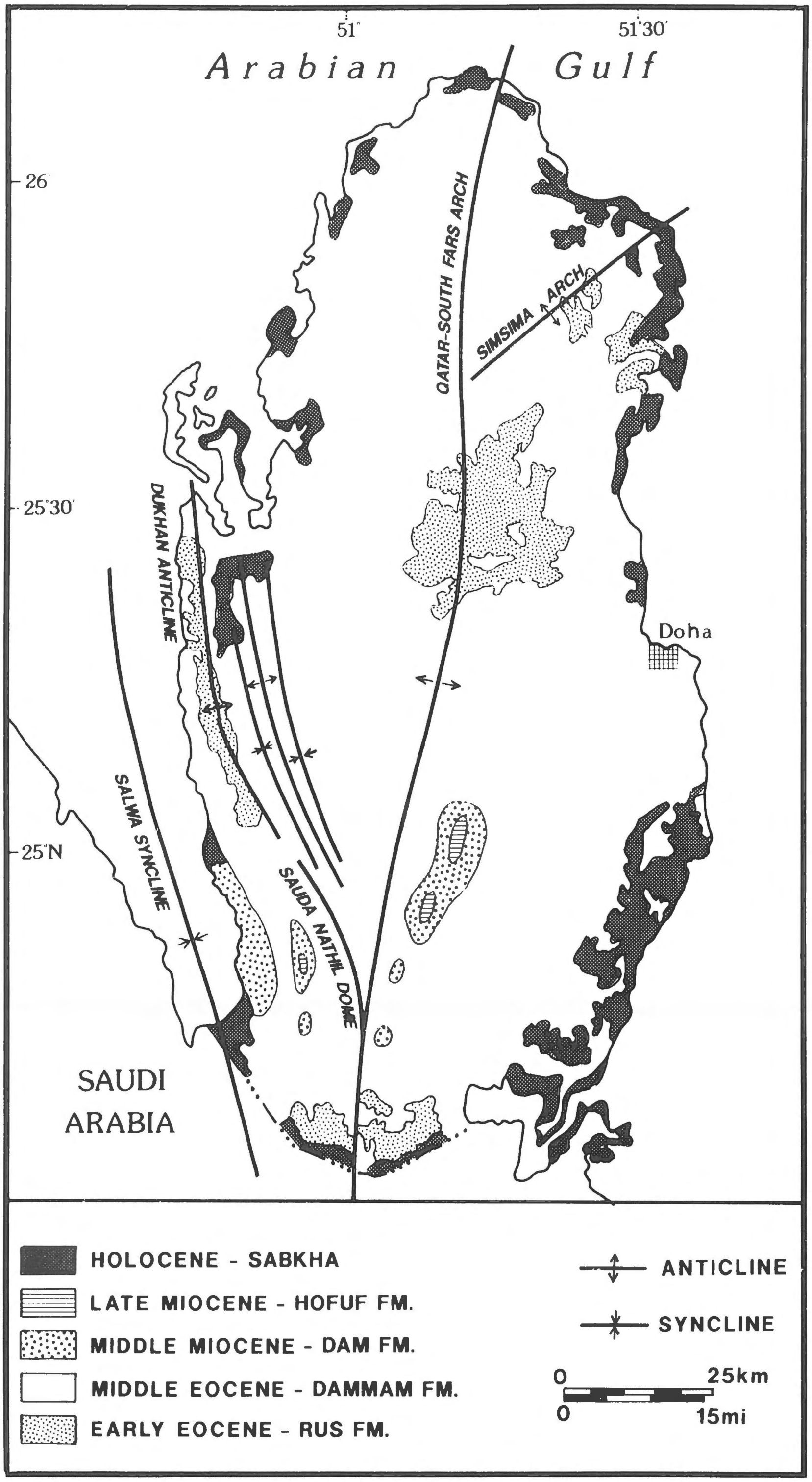

Fig. 3. Simplified geological map showing the main structural elements of Qatar. Sources: Cavelier (1970), QGPC Staff (1981) and Frei (1984).

maturation, migration and accumulation of hydrocarbons in the State of Qatar, and which are essential to the prospect evaluation. This study intends to present the first comprehensive, detailed interpretation of the geology and hydrocarbon habitat of the Mesozoic sequence of Qatar.

History of exploration and production

Brief accounts of the history of hydrocarbon exploration and production of Qatar, covering both onshore and offshore concessions, were given by Qatar Petroleum Co. (1956, 1960), Dominguez (1965), Sugden & Standring (1975), Owen (1975), Ministry of Finance and Petroleum (1977) and Beydoun (1988). They are summarized below.

The first geological investigation of Qatar was undertaken in 1933 by British geologists. They recognized that Qatar forms a large, broad arch that caused middle Eocene limestones to crop out over much of the country.

In May 1935, the Anglo-Iranian Oil Company obtained concessionary rights from the Ruler of Qatar. The company then transferred the concession contract to an Iraq Petroleum Company (IPC) affiliate and the operating company Petroleum Development (Qatar) Ltd. The company began exploration in 1937 and delineated a long, narrow anticline on the west coast, which forms Jebel Dukhan, to be the best prospective oil structure. In October 1938, Dukhan No. 1 was spudded. It became the discovery well after reaching 1 777 m in January 1940. Oil was found in the Upper Jurassic Number 3 Limestone Member of the Qatar Formation (equivalent to the Arab Formation in Saudi Arabia). In 1949, oil was discovered in the Number 4 Limestone Member, and later in 1954 a minor oil accumulation was also found in the Middle Jurassic Uwainat Member of the Araej Formation. The Dukhan Field was linked by a pipeline to the terminal at Umm Said on the east coast, and the first oil was exported from Qatar in 1949.

In November 1952, an offshore grant was awarded by the Ruler to Shell Overseas Exploration Company, which became the Shell Company of Qatar in August 1954. A gravity survey began in June 1953, followed by seismic reflection surveys six months later.

The structural interpretation of the seismic record showed that the eastern area is dominated by salt tectonics, whereas the northern area is very flat and featureless. In January 1956, the first offshore well was drilled on the crestal part of the elongated 'hourglass'-shaped Idd El Shargi structure (Fig. 2). It reached a depth of 3714 m but was dry. In December 1959, the second well (Idd El Shargi-2) was drilled on the northern dome of the structure to a depth of 2600 m, proving oil in the Middle Jurassic Araej Formation and the Upper Jurassic Arab III and Arab IV reservoirs of the Qatar Formation. In March 1961, well No. 4 on the southern dome proved oil in the Lower Cretaceous Shuaiba Formation. On 9 January 1964, the company started production from its Idd El Shargi Field. In the same year, the second and more prolific offshore discovery, Maydan Mahzam, some 30 km northeast of Idd El Shargi, was developed. Its discovery well, drilled in July 1963 to a total depth of 2811 m, had encountered oil in the Upper Jurassic Qatar (Arab) Formation. The El Bunduq Field, straddling the Qatar-United Arab Emirates boundary, was discovered in the following year by Abu Dhabi Marine Areas Company (ADMA). In July 1970, the El Bunduq Company was formed after a border adjustment agreement between Qatar and the United Arab Emirates; all ADMA rights in the field were assigned to the new company with a 50–50 production-sharing agreement between the two states. In March 1969, the Bul Hanine Field was discovered, the latest and most prolific of all the offshore oil fields in Qatar. It is producing from the Middle Jurassic Araej and the Upper Jurassic Qatar (Arab) formations. The large North Field, discovered in 1971 with well NWD-1, contains gas in the carbonate series of the Permo-Triassic Khuff Formation. In this field, the Khuff gas and condensate production is currently in the early development stage, whilst development of the oil discovered in the thin, Albian Nahr Umr clastic reservoirs is still in the planning stage.

Most of the oil in Qatar is produced from Jurassic carbonate reservoirs (Araej and Qatar/Arab formations) at depths of 1565 to 2500 m. Oil and gas

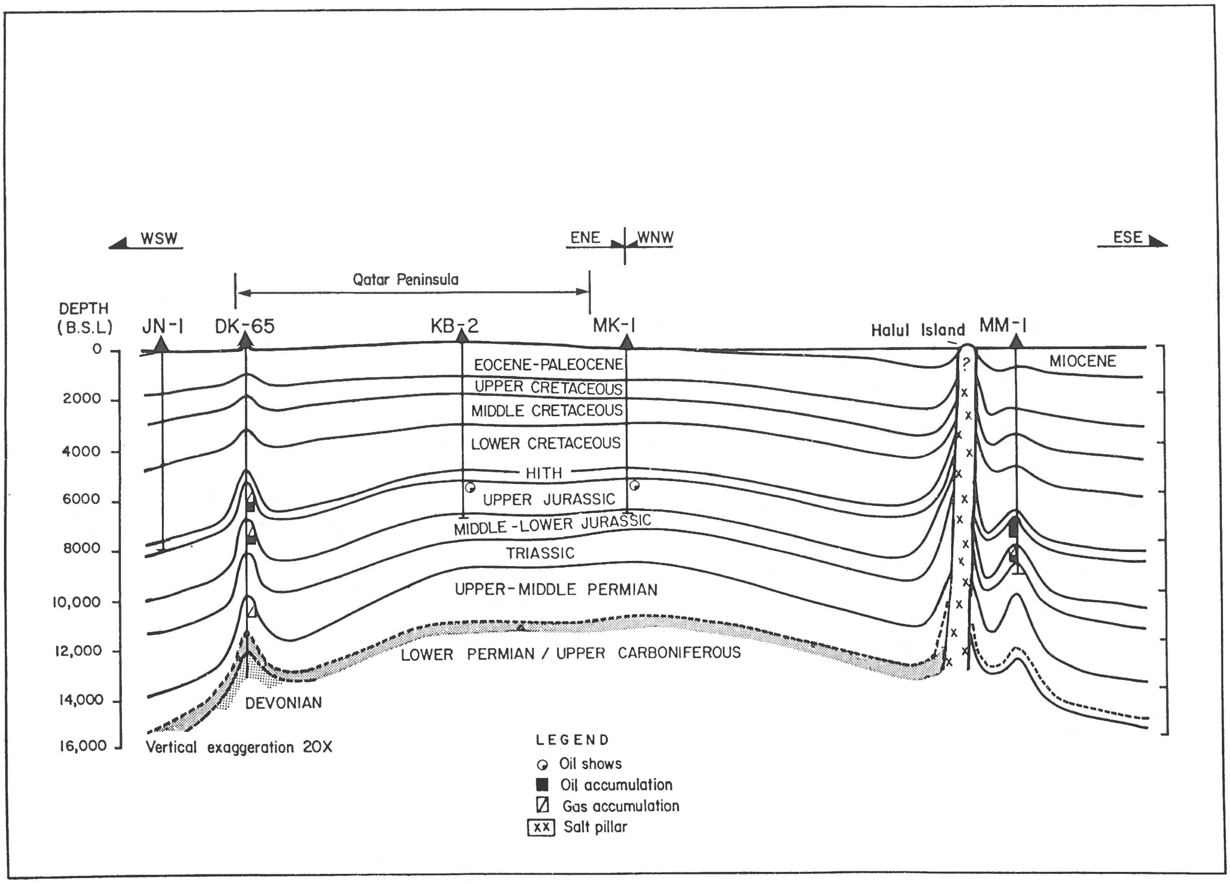

Fig. 4. Structural cross-section of the Qatar Arch (modified from QGPC Staff 1981). For location see Fig. 2. JN-1 = Janan-1, DK = Dukhan, KB-2 = Kharaib-2, MK-1 = Matbakh-1, MM-1 = Maydan Mahzam-1, Depth scale in feet.

accumulations are also found in the Cretaceous reservoirs: Shuaiba and Kharaib carbonates, lower Nahr Umr sandstones, and Khatiyah/Mishrif carbonates, at depths ranging from 940 to 1875 m. Crude oil production at the end of 1991 was 391 500 barrels per day (62 250 m^3/d) and the reserves were about 3.6 billion barrels (570 million m^3) of crude oil and condensate, and about 162 trillion cubic feet (4.6×10^{12} m^3) of gas (World Oil 1992).

Structural and tectonic development

The State of Qatar is situated on the southwestern side of the Arabian Gulf, which was a relatively stable platform for most of its geologic history, at least since the Early Paleozoic. It has a nearly complete geologic record for most of that period, except for the Pre-Permian. Variations in facies distribution and the presence of unconformities or erosional surfaces are due to regional epeirogenic movements concentrated along the axis of the Qatar Arch (Fig. 3), as well as to relative sea-level fluctuations throughout the Phanerozoic. The sedimentary succession of Qatar is only slightly complicated by a number of deep-seated north-south structural features, probably related to the movement of basement blocks, as well as by Infracambrian salt diapirism on the flanks of the Qatar Arch (Fig. 4).

Geophysical surveys and drilling have shown that Qatar occupies the southwestern half of the Qatar-South Fars Arch, a persistent regional high that has existed on the northeastern fringe of the Arabian Platform since the Early Paleozoic (Murris 1981). The arch trends NE-SW across the Arabian Gulf and separates two basins, the northern and the southern Arabian Gulf salt basins, both of Infracambrian age. The peninsula that forms the State of Qatar expresses the present surface culmination of the arch, whilst the subsurface culmination is further north in the offshore area (QGPC staff 1981). At the end of the Triassic the axial culmination of the Qatar Arch was at least 30–50 km east from its present position.

The Paleozoic tectonic evolution of Qatar is characterized by regional basement-rooted fault movements and localized halokinesis on the fringe of the northern and southern Arabian Gulf salt basins. Each of these basins has its own style of salt tectonics, suggesting differences in original salt thickness and overburden lithologies (Murris 1981).

The Dukhan structure in the northern salt basin is probably the combined result of halokinesis (an elongated salt pillow underlies the field) and deep, basement fault block tectonics. The flanks of the narrow Dukhan anticline dip 10° on average. Crestal collapse occurred in Dukhan at the end of the Triassic and resulted in the formation of an axial graben, about 125 m deep and 1.5 to 2 km wide, in the central part of the structure (QGPC staff 1981).

In the southern salt basin, pillows of various shapes but of limited areal extent are believed to underlie the Bul Hanine, Idd El Shargi, Maydan Mahzam and El Bunduq fields. In the Idd Shargi domes, salt movements have been responsible for crestal intraformational thinning and faulting.

During the Early and Middle Cretaceous, salt tectonics remained active. The Qatar Arch subsided slightly in the south-southwest as indicated by the progressive thickening in that direction of the Berriasian to Aptian sediments. During the Middle Cretaceous this southward tilt of the arch increased, resulting in its emergence in the north during Cenomanian-Turonian times (QGPC staff 1981). During the Late Cretaceous, regional structural changes occurred in Qatar and adjacent areas. Salt movements were reactivated and the Dukhan structure was uplifted with a concomitant thinning of the Upper Cretaceous sediments in western Qatar. Crestal collapse and radial faulting occurred at and around the present offshore oil fields such as Idd El Shargi (Frei 1984).

During the Tertiary, minor uplifting took place during the Early-Middle Eocene, and again at the end of the Middle Eocene. During the Late Eocene to Oligocene the Qatar Arch became clearly defined: concurrently a major unconformity developed (Cavelier 1970). Uplift began again during the Early Miocene and increased in intensity during the Late Miocene-Pliocene, a time during which the Jebel Dukhan anticline became increasingly pronounced.

Mesozoic stratigraphic and paleogeographic framework

Triassic

During the Early Triassic, following the Late Permian deposition of shallow marine carbonates, Qatar experienced a renewed influx of clastics from the Arabian Shield Area. Intercalation of these fine sandstones and siltstones with dolomite (Suwei/Sudair Formation; Fig. 5) suggests that Qatar was near the limit of clastic deposition during this period. During the Middle-Late Triassic, evaporitic conditions prevailed, so that the Ladinian-Carnian is characterized by the deposition of a carbonate-anhydrite series with intermittent influxes of clastics. As a result a mixed sequence of anhydrite, dolomite, limestone, siltstone and varicoloured shales accumulated. This series of anhydritic carbonates and clastics belongs to the Gulailah/Jilh Formation and was laid down on a shallow restricted shelf. The uppermost Triassic is characterized by the continental sandstones of the Minjur Formation (Fig. 5).

The Triassic is not everywhere complete in Qatar, because at the end of the Triassic and the beginning of the Jurassic, sedimentary hiatuses developed across the Qatar Arch, leading to the absence of the Minjur Formation in a large part of Qatar. The Minjur sandstones extend from the west in central Arabia, and are present onshore in the United Arab Emirates where they grade eastwards into shales and carbonates. There are two demonstrable disconformities: one at the base of the Jurassic Marrat Formation and one at the base of the Izhara Formation (Fig. 5). A general description of the Triassic formations in Qatar is given below, based on Sug-

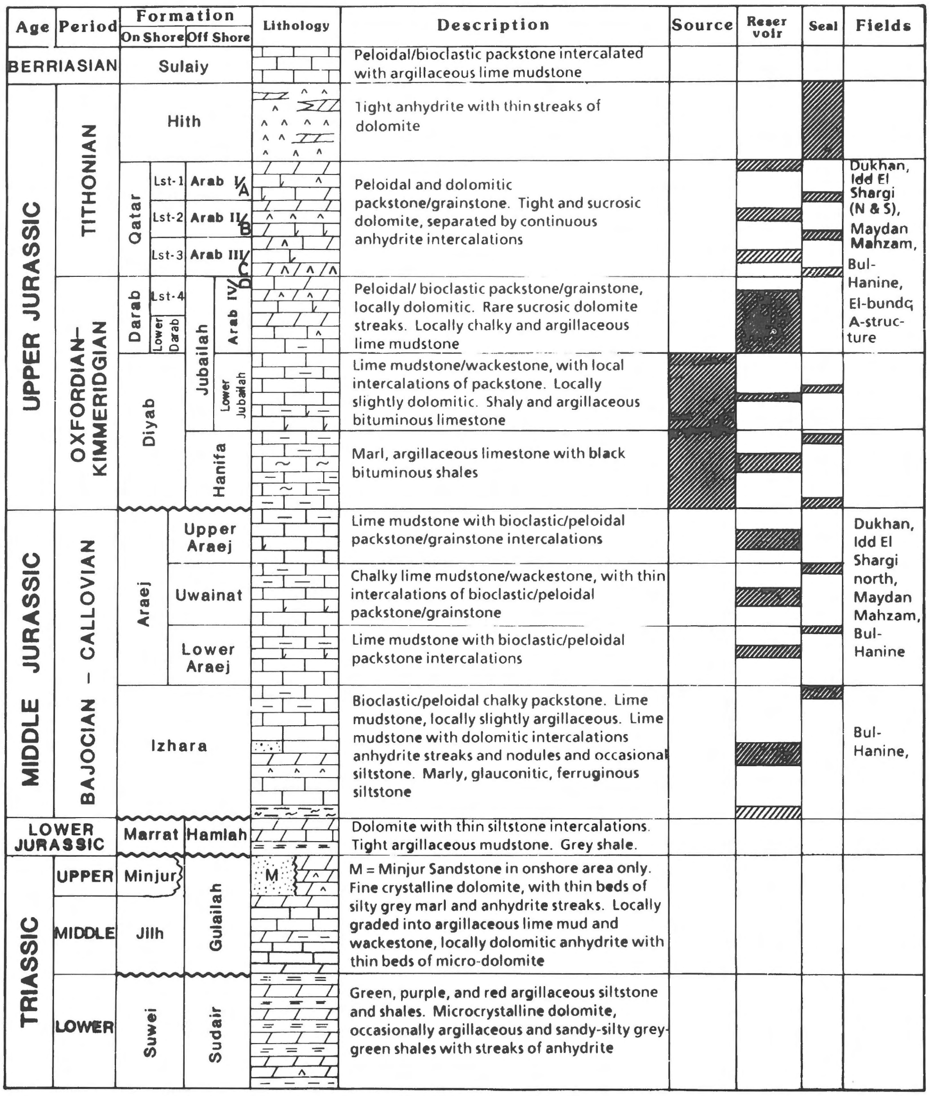

Fig. 5. Triassic-Jurassic stratigraphy, source-reservoir-seal distribution and producing fields of Qatar. Sources: Sugden & Standring (1975), QGPC Staff (1981), Murris (1981), Hamam (1985), Alsharhan & Kendall (1986) and OAPEC (1989).

den & Standring (1975), Qatar General Petroleum Co. (QGPC) staff (1981), Murris (1981) and Alsharhan & Kendall (1986).

The Early Triassic Suwei (Sudair) Formation (199 m) consists of micaceous shales with thin beds of dolomites at the base grading upwards into a sequence of dolomites with streaks of anhydrites, followed by alternating marl and dolomite, micaceous siltstones with interbedded glauconitic sandstones, and finally by shales with thin beds of dolomites and marls. Deposition was in a lagoonal-subtidal setting with an upwards increasing influx of fine-grained argillaceous clastics.

The Middle Triassic Gulailah (Jilh) Formation (160 m) is composed of limestones with calcareous dolomites at the base, grading upward into peloidal-dolomitic limestones and anhydritic dolomites in which authigenic quartz is common. The formation shows a cyclic pattern of sedimentation of dolomites interbedded with subordinate anhydrite and argillaceous and shaley limestones.

The Late Triassic Minjur Formation (30 m) marks a change in climatic conditions. The climate

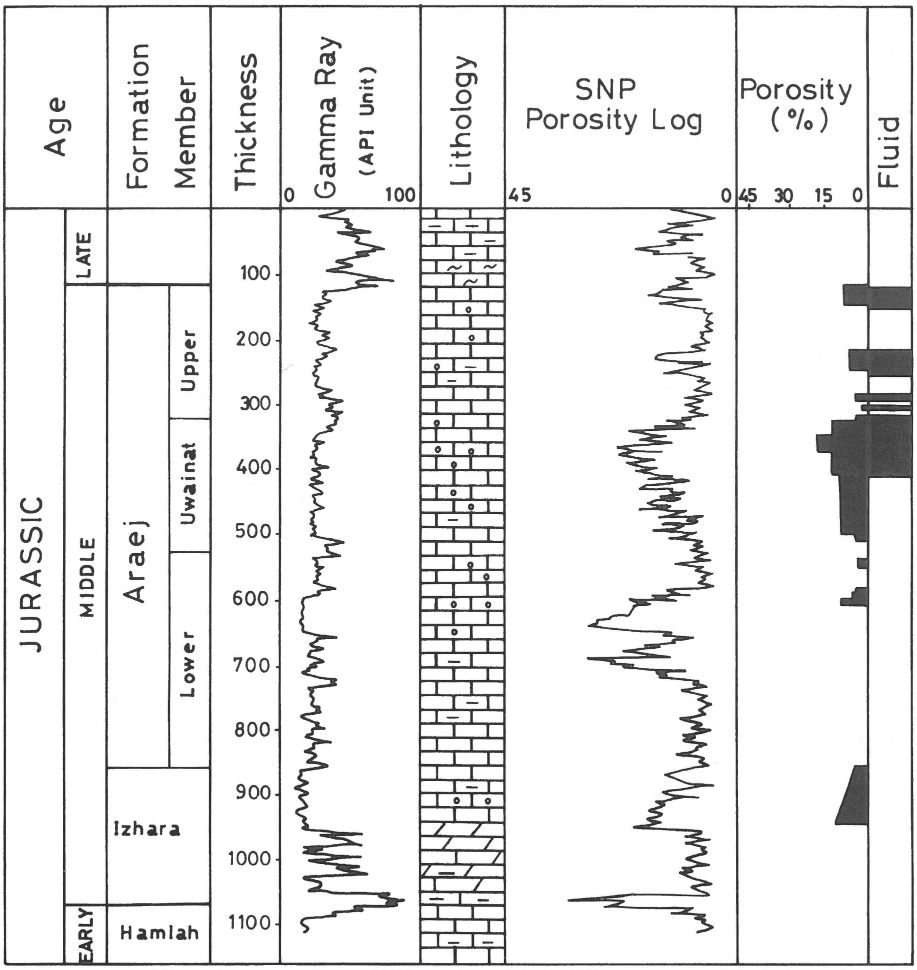

Fig. 6. General lithology and log characteristics, porosity and fluid distribution in the Izhara and Araej formations of Qatar (modified from Ministry of Finance and Petroleum, Qatar 1977). Black in 'Fluid' column indicates oil.

was less arid, and a relative fall in sea-level occurred whilst paleohighs such as the Qatar Arch were actively uplifted, leading to non-deposition and erosion. The fine to medium-grained sandstones and siltstones with shales of the Minjur Formation are of continental origin and restricted in distribution to westernmost onshore Qatar. R.J. Murris (pers. comm. 1991) believes that, because the sequence of Rhaetic sandstones, shales and siltstones, reappears on the other side of the Qatar-South Fars Arch in the Zagros, post-Triassic erosion rather than non-deposition is likely the cause of its absence across the arch.

Jurassic

Towards the end of the Triassic, emergence of the Qatar Arch and updoming of the flanking Infracambrian salt pillows resulted in erosion which cut deeply down into the Triassic succession. These areas remained emergent until the end of the Early Jurassic, for at these locations sediments of that age do not exist. The general Jurassic stratigraphy of Qatar (Fig. 5) has been discussed by Daniel (1954), Qatar Petroleum Co. (1956, 1960), Dunnington (1967a, b) Sugden & Standring (1975), Ministry of Finance and Petroleum (1977), Murris (1981), QGPC staff (1981), Frei (1984), Hamam (1985) and Alsharhan & Kendall (1986). It can be summarized as follows:

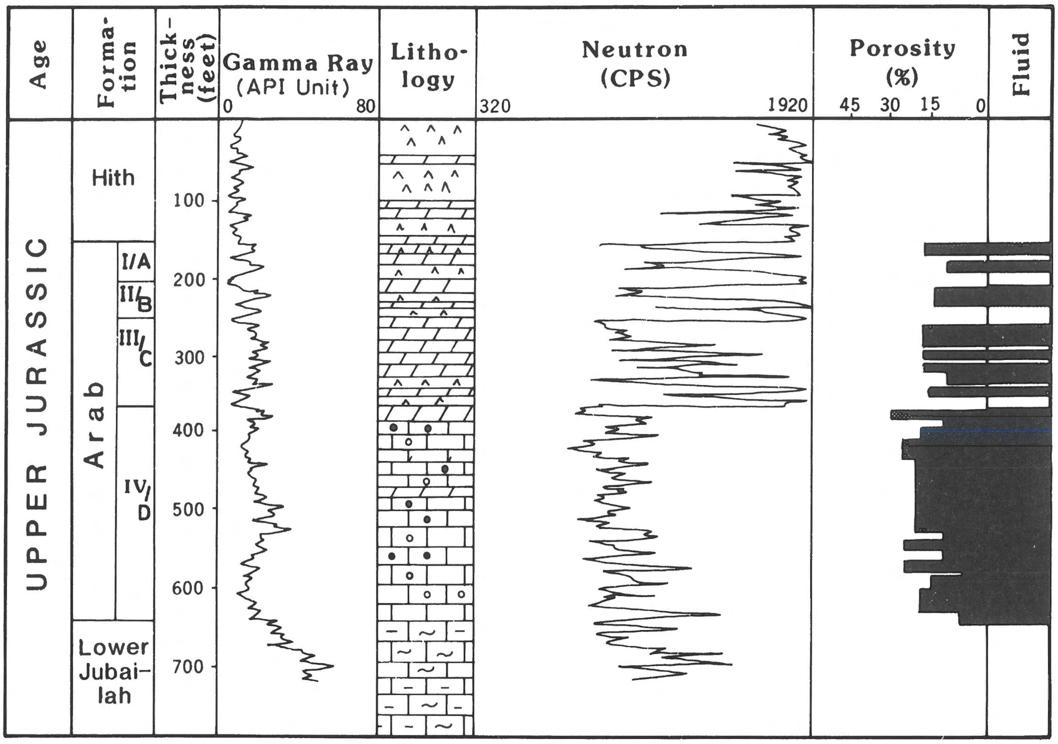

Fig. 7. General lithology, log characteristics, porosity and fluid distribution in the Upper Jurassic lower Jubailah, Arab and Hith formations in Qatar (modified from Ministry of Finance and Petroleum, Qatar 1977). Black in 'Fluid' column indicates oil.

The Early Jurassic Hamlah Formation (70 m), only developed in western onshore Qatar, consists of basal sandy marl and shale overlain by calcareous dolomites with streaks of anhydrite interbedded with shales. This sequence grades upward into shales with subordinate marl and some glauconitic sandstones and is ended by saccharoidal dolomites with stringers of nodular anhydrite.

At the beginning of the Middle Jurassic, the climate became more humid with a gradual rise in sea-level. Carbonate deposition kept pace with sea-level rise. The Izhara Formation (137 m; Figs 5, 6), deposited during Bajocian-Bathonian times, is characterized by a basal shale followed by interbedded marls, argillaceous limestones and dolomites which are overlain by a massive unit of partly dolomitized argillaceous limestone.

The Bathonian-Callovian Araej Formation (Figs 5, 6; 180 m) consists of three members. The Lower Araej Member is composed of argillaceous lime mudstones and wackestones with some interbedded marls and peloidal packstones, deposited in low to moderate energy conditions of shallow marine to lagoonal settings. The Uwainat Member, which forms the most important reservoir of the Araej, consists of relatively clean and porous lime mudstones and wackestones, with moldic and solution channel porosity, interbedded with oolitic and peloidal packstone and grainstone. The Uwainat Member was deposited under moderately high-energy conditions with occasional returns to low-energy marine-lagoonal conditions. The Upper Araej Member is dominated by tight lime mudstones and by peloidal wackestones and packstones, deposited in a low to moderate energy, shallow open marine environment.

The Late Jurassic depositional phase started with a relatively rapid eustatic sea-level rise resulting in a major flooding of the eastern Arabian Platform. An intrashelf basin formed in both eastern Arabia and the southwestern Arabian Gulf, and resulted in euxinic conditions. Black organic-rich argillaceous and laminated lime mudstones and wackestones with remains of foraminifera, sponge spicules and

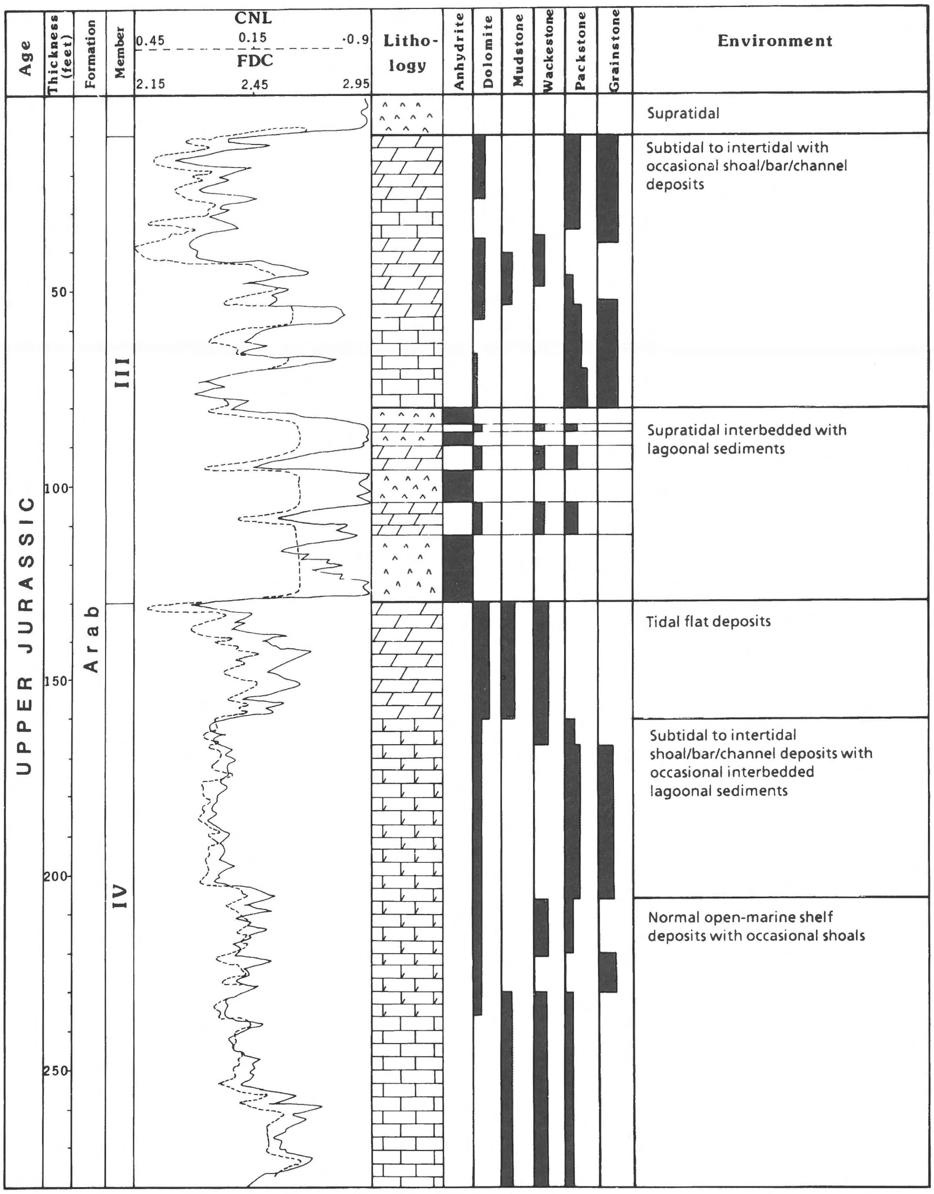

Fig. 8. General lithology, environmental interpretation and FDC/CNL log characteristics of the Arab IV/D and III/C reservoirs in the Qatar oilfields.

algae, were deposited, forming the Hanifa Formation (Murris 1981, Alsharhan & Kendall 1986). The basinal facies of this rock-unit is a prolific source for most of the oil in the Upper Jurassic and Lower Cretaceous reservoirs of Qatar, the United Arab Emirates, Saudi Arabia and Bahrain.

Following the Late Jurassic transgression, regression set in during the Kimmeridgian when the Jubailah Formation (100 m) was laid down: argillaceous lime mudstones and wackestones which grade upward into higher energy, grain-supported carbonates deposited on a very shallow shelf bordered by sheltered lagoons and broad tidal flats. Where the coastal (barrier beach) facies is developed, it constitutes the well-known Arab IV/D reservoir, which contains the major part of the giant oil reserves of Qatar, Saudi Arabia and western Abu Dhabi.

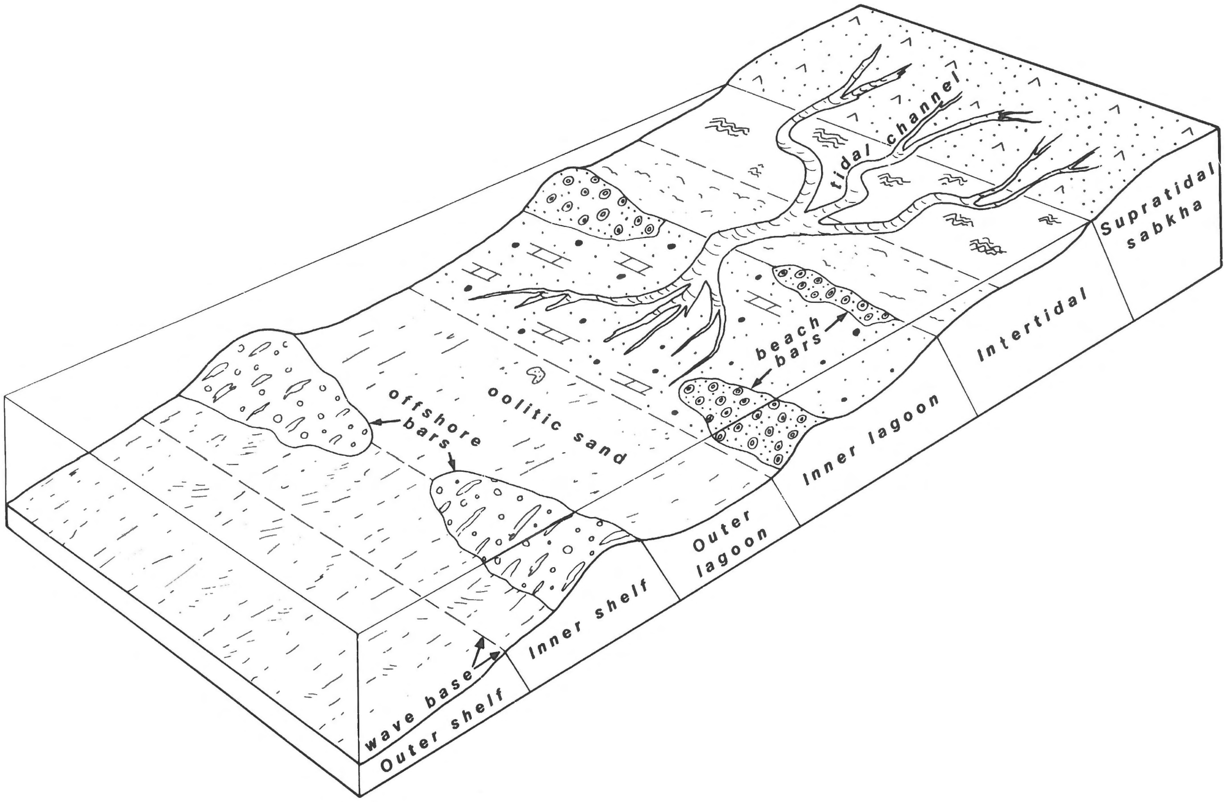

Fig. 9. Proposed depositional model of the Upper Jurassic Arab Formation in Qatar.

The shallow marine to coastal and sabkha deposits that form the Arab reservoirs and the interbedded seals of the upper Jubailah and Qatar formations, are well developed throughout the Qatar area and suggest the presence of a very widespread shallow platform subjected to numerous transgressive-regressive cycles. The upper Jubailah sequence, corresponding to the Arab IV/D or Fahahil Member, consists of bioclastic, oolitic and peloidal packstones and grainstones with intercalations of lime mudstones and sucrosic dolomites (Figs. 5, 7, 8). A sea-level drop and increased restriction of water circulation resulted in the development of extensive evaporitic lagoons and sabkhas (Fig. 9) leading to the deposition of an extensive anhydrite horizon on top of the Arab IV/D reservoir. In fact, this base Arab III/C evaporite is to be regarded as the terminal member of the Jubailah cycle.

The uppermost Jurassic regressive sequence continues with the Qatar Formation (Kimmeridgian; 90 m) which contains three relatively thin reservoirs of regional extent (Arab III/C, II/B, I/A; Figs 8, 10) and culminates with the deposition of the Hith Formation (a thick anhydrite with local minor dolomite intercalations) forming the regional seal to the Arab reservoirs. The Hith Anhydrite (140 m), which thickens towards the southwest of the country with the inclusion of halite, is interpreted by Murris (1981) as a sabkha deposit but has also been explained by deposition in a shallow basinal environment under extreme arid conditions, implying that a significant transgression occurred at that time. We consider that an extensive evaporitic lagoon could have covered almost the entire platform, but a true basin is not easy to envisage.

The Arab III/C is the thickest member of the Qatar (Arab I–III) Formation; the basal anhydrite with dolomite intercalations is the natural termination of the Jubailah cycle, while the upper part is mainly dolomitic limestone and limestone (Fig. 8). The laminated algal wackestones, packstones, algal boundstones and dolomitized oolitic grainstones of

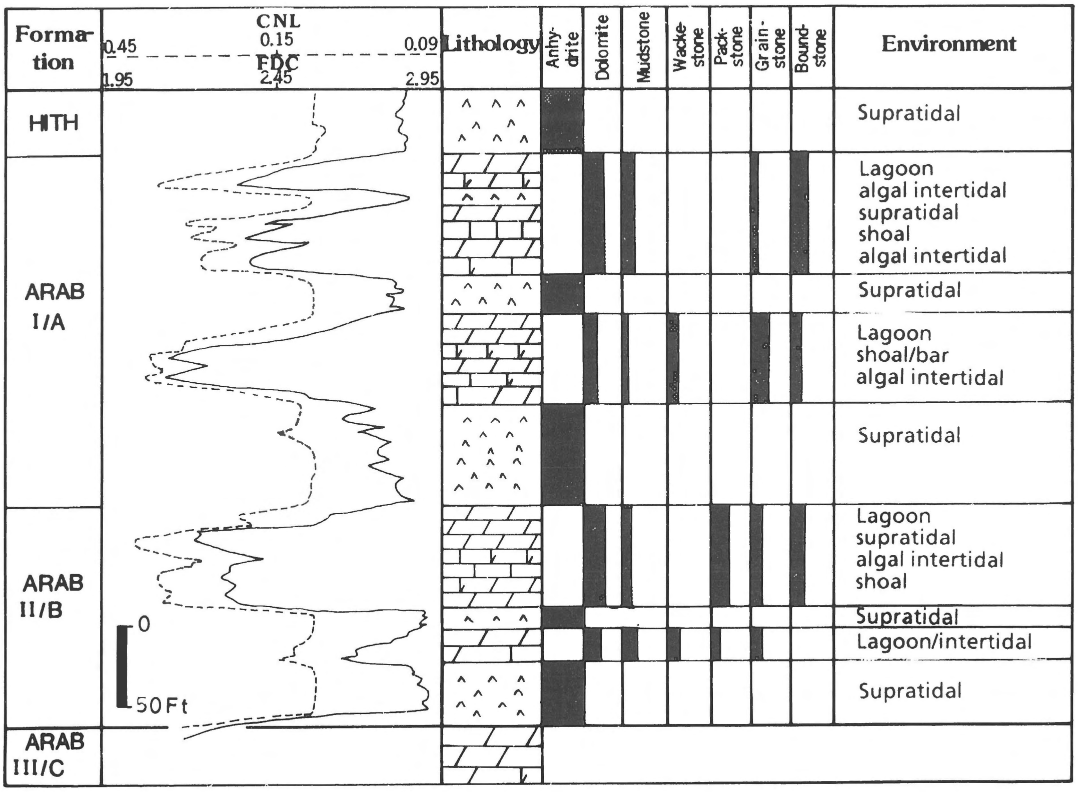

Fig. 10. General lithology, environmental interpretation and FDC/CNL log characteristics of the Arab II/B and I/A reservoirs and Hith Formation (seal) in the Qatar oilfields.

the Arab III/C reservoir represent a transgressive interval between the sabkha environments of the basal Arab III/C and Arab II/B anhydrites. The grainstones are subaerially leached and have well-developed moldic porosity.

A typical Arab II and I (B and A) depositional cycle begins with a transgression across the widespread sabkha terminating the underlying cycle (Figs 10, 11). Algal boundstone deposited in a shallow subtidal to intertidal environment is followed by oolitic grainstones that often show evidence of small-scale channelling. These shoal grainstones are commonly heavily dolomitized and often have a well-developed isopachous rim-cement, which probably represents stabilization of these sands during the later stages of the initial transgression. Algal boundstones and peloidal wackestones and grainstones follow upwards, marking the beginning of the regressive phase. The final stage of the regression is the widespread formation of nodular, chicken-wire and bedded anhydrite. The Arab II/B and I/A reservoirs have been extensively dolomitized. The Maydan Mahzam Field contains the most important accumulations of these reservoirs (R.J. Murris, pers. comm. 1991).

Cretaceous

A few important events such as the regional tilt and subsidence of the Qatar Arch towards the south-southwest, a change to a more humid climate and greater halokinetic activity marked the end of the Jurassic and the beginning of the Cretaceous. The Lower Cretaceous sediments are dominated by limestones with an influx of clastics from western Arabia. At the onset of the Middle Cretaceous (in the Middle East conventionally taken at the beginning of the Albian), shales with minor sands cover the Qatar area, resting disconformably on top of Aptian limestones. Tilting of the Qatar Arch increased during the Cenomanian-Turonian, result-

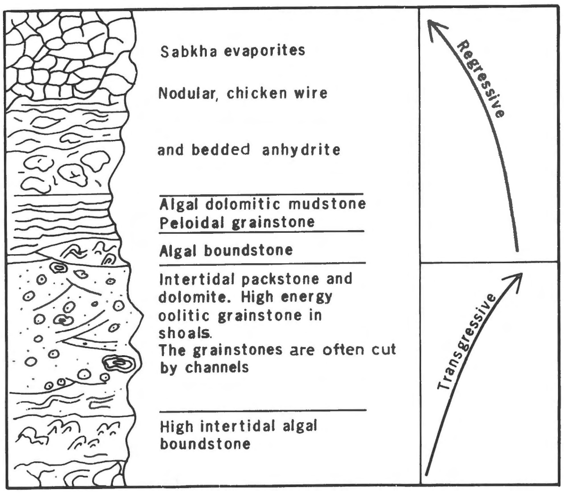

Fig. 11. Idealized depositional cycles of the Arab I/A and II/B reservoirs in the Qatar oilfields.

ing in the emergence of northern Qatar. Also during this period, intermittent halokinesis resulted in minor crestal faulting in the western onshore area (e.g. Dukhan Field) and moderate uplift with crestal thinning and faulting in the eastern offshore structures. The Arabian margin of the Tethys (including Qatar) up to Turonian time was a passive margin with no evidence of orogenic events. Emergence of the central part of the arch with thinning and/or erosion of Middle Cretaceous sediments, is due to local tectonic activity. By the Late Cretaceous, Qatar was covered by shallow water carbonates mixed with clastics while deep, open marine conditions prevailed in the north. The regional stratigraphic column of the Cretaceous sequence and its hydrocarbon occurrences are shown in Fig. 12, while a summary of the Cretaceous sediments in Qatar, based on Dominguez (1965), Dunnington (1967 a, b), Sugden & Standring (1975), Ministry of Finance and Petroleum (1977), Murris (1981), QGPC staff (1981), Wells (1985), OAPEC (1989), Alsharhan & Nairn (1986, 1988, 1990) and Beydoun (1988), is shown below.

In Qatar the Thamama Group is conventionally assigned to the Early Cretaceous (Berriasian to Aptian). It consists of six formations which are in ascending order: Sulaiy (lower Habshan of Abu Dhabi), Yamama (upper Habshan-lower Lekhwair of Abu Dhabi), Ratawi (upper Lekhwair of Abu Dhabi), Kharaib, Hawar and Shuaiba (Fig. 12). The Sulaiy Formation (Berriasian; 140 m) consists of argillaceous lime mudstones with thin beds of peloidal and oolitic limestones near the base and fine-grained dolomitic wackestones, with rare grainstones, in the upper part.

The Yamama Formation (120 m) consists of microporous partly argillaceous limestones with fine-grained peloidal and occasionally oolitic-intraclastic limestones. These pass upward into fine-grained peloidal wackestones and lime mudstones. The age is considered to be essentially Valanginian.

The Hauterivian-Barremian Ratawi Formation (145 m) consists of fine-grained, dense, argillaceous limestones with intraclasts and pellets, interbedded with marls. The formation is overlain by the Kharaib Formation. Regional evidence suggests marked thinning, perhaps accompanied by the presence of a sedimentary break at the base of the Kharaib across the Qatar Arch. The contact between the Kharaib and the underlying formation can be a disconformity marked by a lithified and bored surface.

The Barremian Kharaib Formation (Figs 12, 13; 85 m), starts with thick, transgressive, microporous limestone grading upward into a sequence of alternating marls and argillaceous limestones which can act as local seals. This sequence grades upwards into peloidal *Orbitolina* wackestones and algal grainstones and packstones. The unit is overlain by the Hawar marls and shales. Deposition was on a moderate energy, shallow open shelf influenced by currents.

The Hawar Formation (Figs 12, 13; 16 m) consists of marls and shales rich in *Chofatella decipiens*. The formation occurs throughout onshore Qatar but toward the offshore area it shows a progressive lithological change, passing into bioclastic, peloidal packstones and wackestones and dense, argillaceous, glauconitic lime mudstones. The fauna of the Hawar is non-diagnostic: an early Aptian age is assigned on stratigraphic position.

The Shuaiba Formation (Aptian; 130 m) in offshore Qatar can be divided into four units, each constituting a separate depositional cycle (Figs 13, 14). The lowest unit starts with *Bacinella* algal boundstones deposited in shallow water, grading

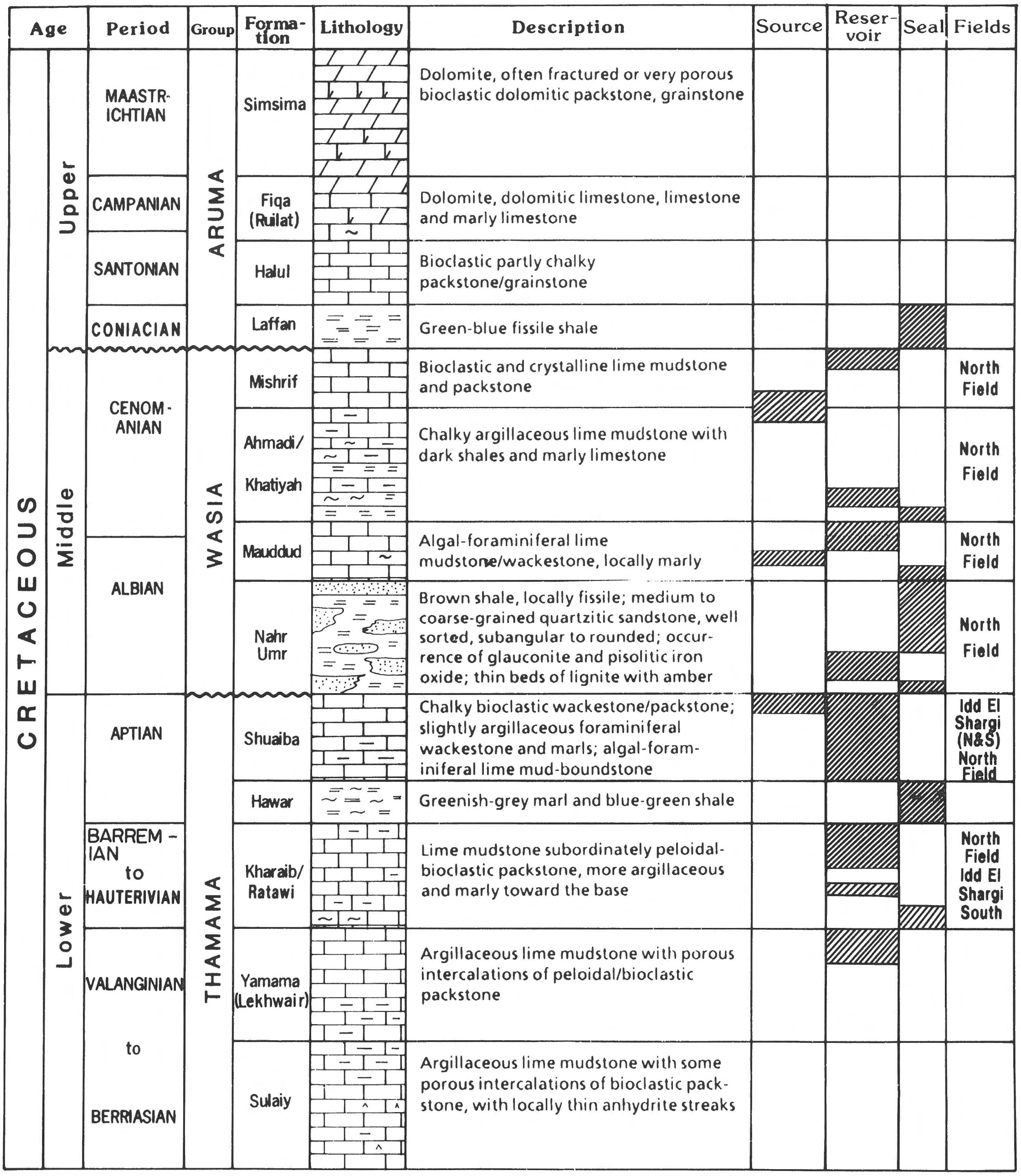

Fig. 12. Cretaceous stratigraphy and source-reservoir-seal distribution and producing fields of Qatar. Sources: Sugden & Standring (1975), QGPC Staff (1981), Alsharhan & Nairn (1986, 1988, 1990) and Dominguez (1965).

upward into bioturbated and burrowed lime mudstones characteristic of an open marine shelf. These beds are followed by a second unit of argillaceous, stylolitic lime mudstones and wackestones with a mixed benthonic-pelagic fauna indicating a fairly deep shelf environment. The third unit consists mainly of bioturbated lime mudstones and wackestones with calcareous foraminifera and echinoid fragments representing a quiet, open marine environment. The fourth unit was deposited in a relatively high-energy, shallow water environment and consists of boundstones with corals, rudists and gas-

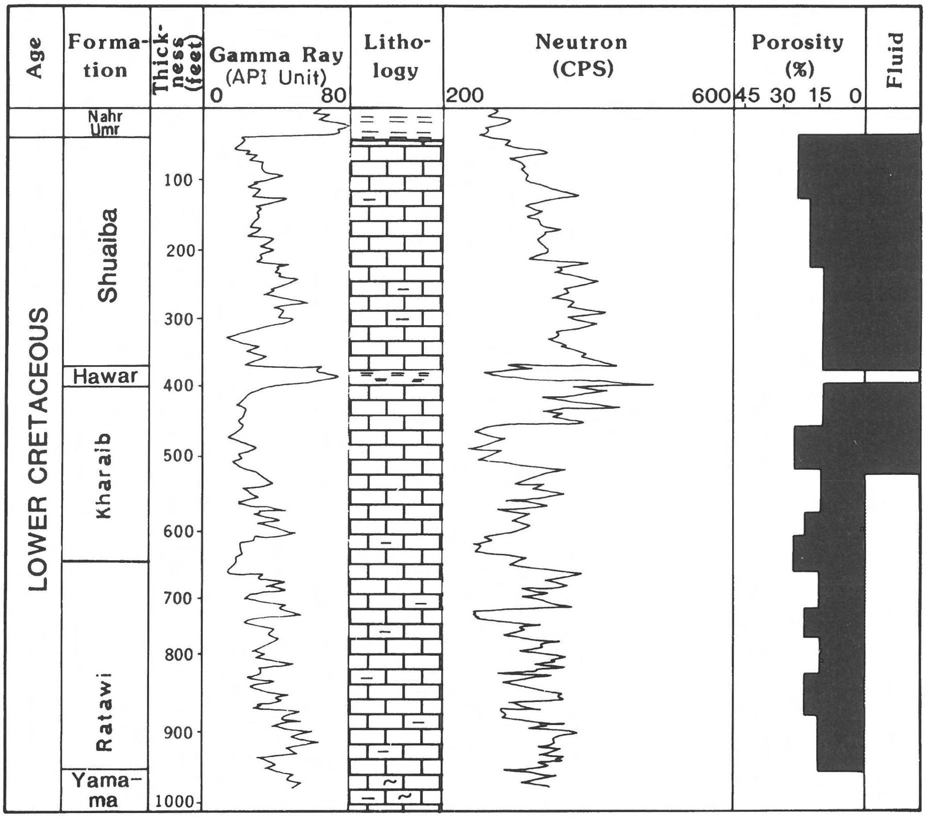

Fig. 13. General lithology, log characteristics, porosity and fluid distribution of the Lower Cretaceous Ratawi, Kharaib, Hawar and Shuaiba formations in Qatar (modified from Ministry of Finance and Petroleum, Qatar 1977). Black in 'Fluid' column indicates oil.

tropods, often encrusted with algae. In onshore Qatar, the Shuaiba Formation consists of chalky limestones with occasional dolomitic and argillaceous intercalations.

The Middle Cretaceous Wasia Group in Qatar comprises four formations in ascending order. These are: the Nahr Umr, Mauddud, Ahmadi/Khatiyah and Mishrif, which range in age from Albian to late Cenomanian (Fig. 12). It should be made clear that the Ahmadi, Khatiyah and Mishrif of the offshore area are the lateral equivalents of the Ahmadi as defined in the onshore area. The Ahmadi represents the most landward, clastic-rich facies, the Khatiyah the open marine, low-energy shelf facies and the Mishrif the higher-energy reefoidal (rudistid) facies.

The Nahr Umr Formation (Albian; 170 m) starts with a lower unit, best developed in the northern offshore, composed of argillaceous sandstones with thin beds of marls and shales, lignite, phosphatic concretions and ferruginous ooliths. The middle unit consists of shales with beds of marly glauconitic sandstones at the top. The upper unit is composed of glauconitic marly sandstones, shales and marls with a few thin beds of limestone. During this time, Qatar lay in the transition zone between a lower coastal plain in the west and a clastic to mixed shallow-marine shelf in the east.

The Mauddud Formation (late Albian-early Cenomanian; 55 m) represents a quiet phase of widespread carbonate sedimentation over much of the Arabian Gulf during a major regional transgression, locally accompanied by the deposition of organic-rich beds in intrashelf depressions. The Mauddud Formation in onshore Qatar consists of dense foraminiferal lime mudstones which grade upward into peloidal bioclastic wackestones and packstones. In the offshore area it consists of dense to microporous lime mudstone, wackestone, pack-

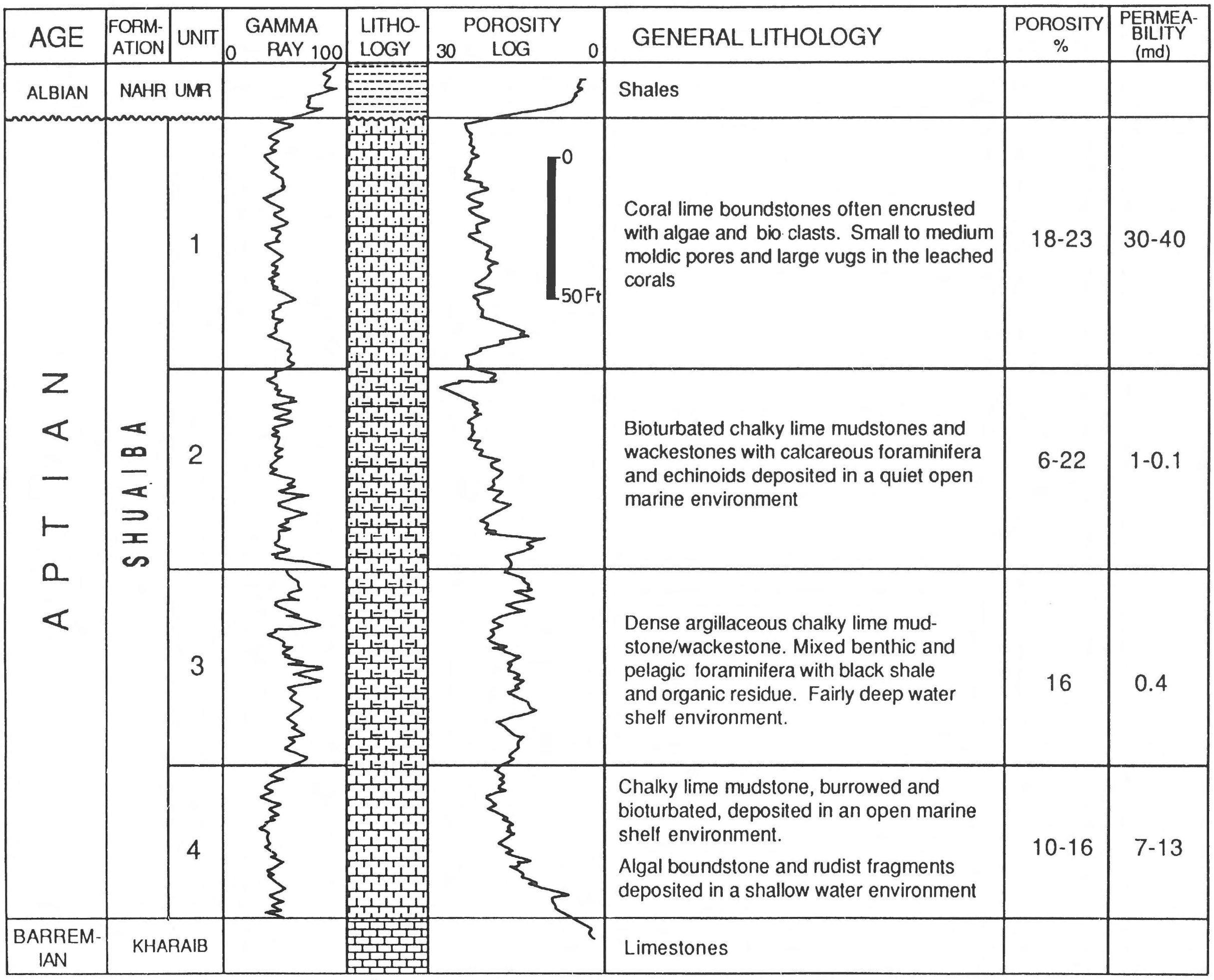

Fig. 14. General lithology, logs and petrophysical characteristics of the Aptian Shuaiba Formation in Qatar (based on data from Ministry of Finance and Petroleum, Qatar 1977, QGPC Staff 1981 and Jubralla & Hamam 1991).

stone and grainstone, with local rudist-skeletal concentrations in the upper part.

The Ahmadi Formation (early-mid Cenomanian; 200 m) is composed of shales with thin beds of argillaceous sandstone, passing upwards into argillaceous limestone with numerous thin intercalations of marls and shales.

The Khatiyah Formation, age-equivalent to the Ahmadi in offshore Qatar, is composed of dense to microporous lime mudstone, wackestone and packstone with foraminifera and algae. The formation is characterized by a predominance of *Praealveolina* and codiacian algae in a generally muddy matrix. Lithified and bored surfaces represent marine hard-grounds. The sequence is extensively bioturbated.

The Mishrif Formation (middle to late Cenomanian; 80 m) is defined as a reefoidal facies and is composed of shallow water, bioclastic wackestones and packstones, with rudist debris.

The Wasia Group is overlain by a clear regional unconformity on which the Coniacian to early Santonian Laffan Formation was deposited.

The Upper Cretaceous Aruma Group consists of four formations, in ascending order: Laffan, Halul, Ruilat/Fiqa and Simsima (Fig. 12). The group is separated from the overlying and underlying formations by regional unconformities.

The Laffan Formation (Coniacian-early Santo-

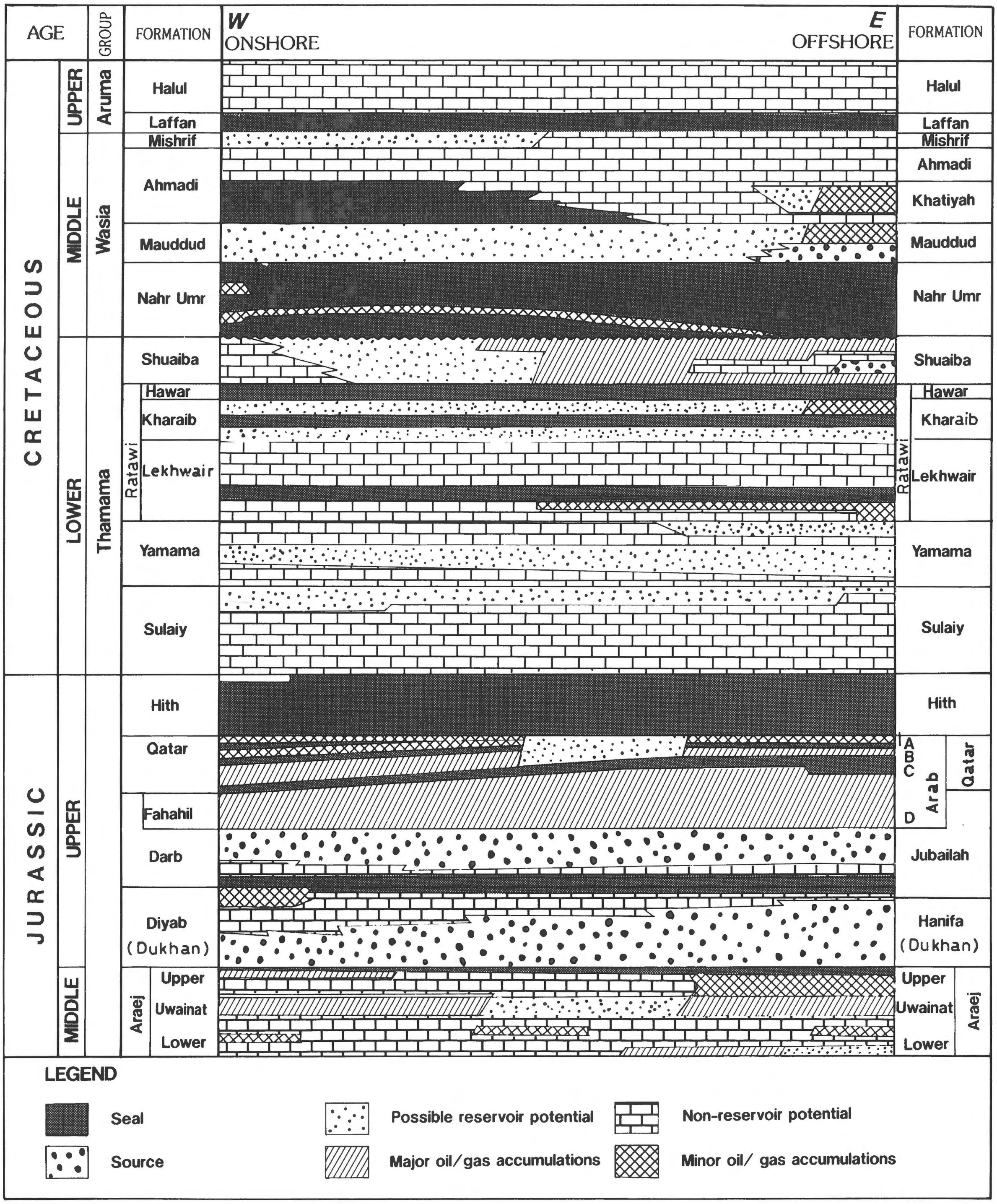

Fig. 15. Stratigraphic distribution of major oil and gas accumulations, source rocks and regional seals in the Jurassic and Cretaceous of Qatar (based on data from QGPC Staff 1981, Alsharhan & Kendall 1986, Murris 1981 and Frei 1984).

Table 1. Reservoir characteristics of the Dukhan oil field (modified from Al Kawari 1983). Limestones no. 3 and 4 belong to the Qatar (Arab) Formation

	No. 3 LIMESTONE	No. 4 LIMESTONE	UWAINAT
FLUID PROPERTIES			
– Oil gravity (° API)	37	42	43
– Oil viscosity (cP)	0.5	0.4	0.3
– Formation water salinity (ppm)	220000	220000	240000
ROCK PROPERTIES			
– Permeability (md)	30	70	15
– Porosity (average) (%)	15–20	19	19
– Lithology	Carbonate	Carbonate	Carbonate
RESERVOIR CONDITIONS			
– Initial reservoir pressure (psi)	2925	3216	3520
– Present reservoir pressure (average) (psi)	2450	2668	3360
– Reservoir temperature (° F)	195	202	225
– Depth (ft)	5600	6250	7050
– Dip (degree)	3–8	3–8	3–8
– Gross reservoir rock thickness (ft)	85	190	180

nian) forms the highest regional seal in Qatar. It consists of 30 m of olive-green to brown shales rich in marine ostracods. The overlying Halul Formation (Santonian-Campanian; 70 m) in offshore Qatar is composed of microporous, slightly marly limestone with some marl and shale interbeds. The Ruilat/Fiqa Formation (Campanian; 70 m) is composed mainly of bioclastic limestones, argillaceous and dolomitic limestones and some interbedded shales or marls. The Maastrichtian Simsima Formation (150 m) consists of microporous limestones and dolomitized bioclastic packstones and wackestones with intercalated foraminiferal calcareous shales and argillaceous limestones in the upper part.

Hydrocarbon habitat

Seven commercially significant hydrocarbon-bearing structures have been discovered in Qatar since 1940 (Fig. 2). One of them, the North Field, represents one of the world's largest known gas fields.

Table 2. Reservoir characteristics of the Maydan Mahzam oil field (modified from Al Kawari 1983). N.A.: no data available

	ARAB III/C	ARAB IV/D	UWAINAT
FLUID PROPERTIES			
– Oil gravity (° API)	36	38	37
– Oil viscosity (cP)	0.4	0.4	0.4
– Formation water (ppm) salinity	245000	255000	270000
– Formation water hardness (Ca^{++} + Mg^{++}) (ppm)	22000	23000	N.A
ROCK PROPERTIES			
– Permeability (md)	30–600	5–1000	2–300
– Porosity (average) (%)	19	9–22	17
– Lithology	Carbonate	Carbonate	Carbonate
RESERVOIR CONDITIONS			
– Initial reservoir pressure (psi)	3630	3625	4328
– Present reservoir pressure (average) (psi)	2800	2800	N.A.
– Reservoir temperature (° F)	206	206	229
– Depth (datum) (ft)	7200	7200	8800
– Dip (degree)	3–8	3–8	3–8
– Gross reservoir rock thickness (ft)	85	157–166	182

Table 3. Reservoir characteristics of the Bul Hanine oil field (modified from Al Kawari 1983)

	ARAB IV/D	UWAINAT
FLUID PROPERTIES		
– Oil gravity (° API)	35	37
– Oil viscosity (cP)	0.5	0.4
– Formation water salinity (ppm)	230000	260000
– Formation water hardness (Ca^{++} + Mg^{++}) (ppm)	21000	30000
ROCK PROPERTIES		
– Permeability (md)	2–1000	50–500
– Porosity (average) (%)	13–23	14
– Lithology	Carbonate	Carbonate
RESERVOIR CONDITIONS		
– Initial reservoir pressure (psi)	3825	4375
– Present reservoir pressure (average) (psi)	2300	N.A/
– Reservoir temperature (° F)	212	227
– Depth (datum) (ft)	7700	8850
– Dip (degree)	1–3	1–3
– Gross reservoir rock thickness (ft)	175–280	175

The hydrocarbons in Qatar are widely distributed in the stratigraphic column, occurring from Ordovician clastics to Cenomanian carbonates, and all the fields have more than one pay zone. Prolific reservoirs and source rocks and regional seals occur in the Middle and Upper Jurassic and fair to good reservoirs, source rocks and seals are found in the Lower to basal Upper Cretaceous (Fig. 15). The general aspects of the hydrocarbon habitat of Qatar are given by Wilson (1975), Ministry of Finance and Petroleum (1977), Murris (1981), QGPC staff (1981), Department of Petroleum Affairs, Qatar (1982), Al Kawari (1983), Rubbens *et al.* (1983), Frei (1984), Lehner (1984), Hamam (1985), Wells (1985), Alsharhan & Kendall (1986), OAPEC (1989), Droste (1990), Wilson (1991), and Jubralla & Hamam (1991). The following summary is based on data from these publications.

Table 4. Reservoir characteristics of the Idd El Shargi (North Dome) oil field (modified from Al Kawari 1983)

	SHUAIBA	ARAB III/C	ARAB IV/D	U. ARAEJ	UWAINAT
FLUID PROPERTIES					
– Oil gravity (° API)	26	28	32	36	36
– Oil viscosity (cP)	2.5	1.0	0.5	0.2	0.2
– Formation water salinity (ppm)	220000	220000	220000	240000	240000
– Formation water hardness (Ca^{++} + Mg^{++}) (ppm)	16000	N.A.	N.A.	N.A.	27000
ROCK PROPERTIES					
– Permeability (md)	1–1000	50–500	1–500	1–20	50–500
– Porosity (average) (%)	23–30	20	13–243	11	18
– Lithology	Carbonate	Carbonate	Carbonate	Carbonate	
RESERVOIR CONDITIONS					
– Initial reservoir pressure (psi)	2380	3580	3650	4010	4010
– Present reservoir pressure (average) (psi)	2000	3200	2900	3500	3500
– Reservoir temperature (° F)	158	205	212	230	230
– Depth (datum) (ft)	4650	7350	7300	8100	8100
– Dip (degree)	0.5–5	1.5–6	1–6	N.A.	3–6
– Gross reservoir rock thickness (ft)	60–180	85	110–225	155	185

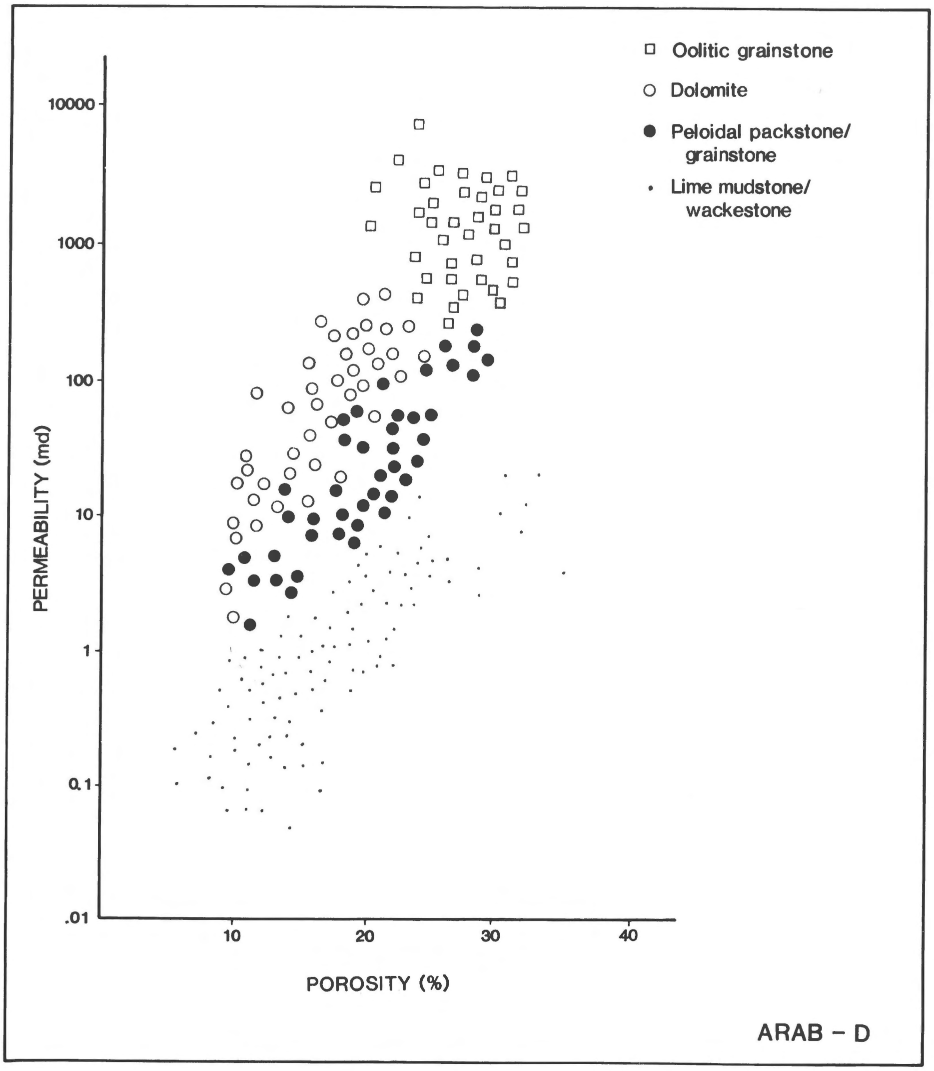

Fig. 16. Compiled porosity and permeability values of different rock types in the Arab IV/D reservoir of the Qatar oilfields (source: Ministry of Finance and Petroleum, Qatar 1977; Al Kawari 1983; Wilson 1991).

Reservoirs

Tables 1–4 summarize the reservoir characteristics in the Dukhan, Maydan Mahzam, Bul Hanine and Idd El Shargi (North Dome) oil fields respectively. The Middle Jurassic Izhara and Araej formations in Qatar contain only thin reservoir zones with exception of the Uwainat Member which contains significant reserves in the four fields just mentioned. The Uwainat limestone reservoir has generally good moldic, vuggy and solution channel porosity with related permeability enhancement, but overall permeability is rather poor. With increasing depth of burial the thin reservoir zones suffered from compaction and pressure solution. A tar mat is present within the present oil zone in Idd El Shargi and also in the gas cap of Bul Hanine. This interpreted as the result of settling of tar during an early stage of oil migration close to the initial free-water level. Subsequent stages of hydrocarbon migration may have extended the oil column in Idd El Shargi, or added a gas cap to Bul Hanine.

In Dukhan, the Uwainat reservoir is about 56 m thick and lies at a depth of around 2188 m. The up-

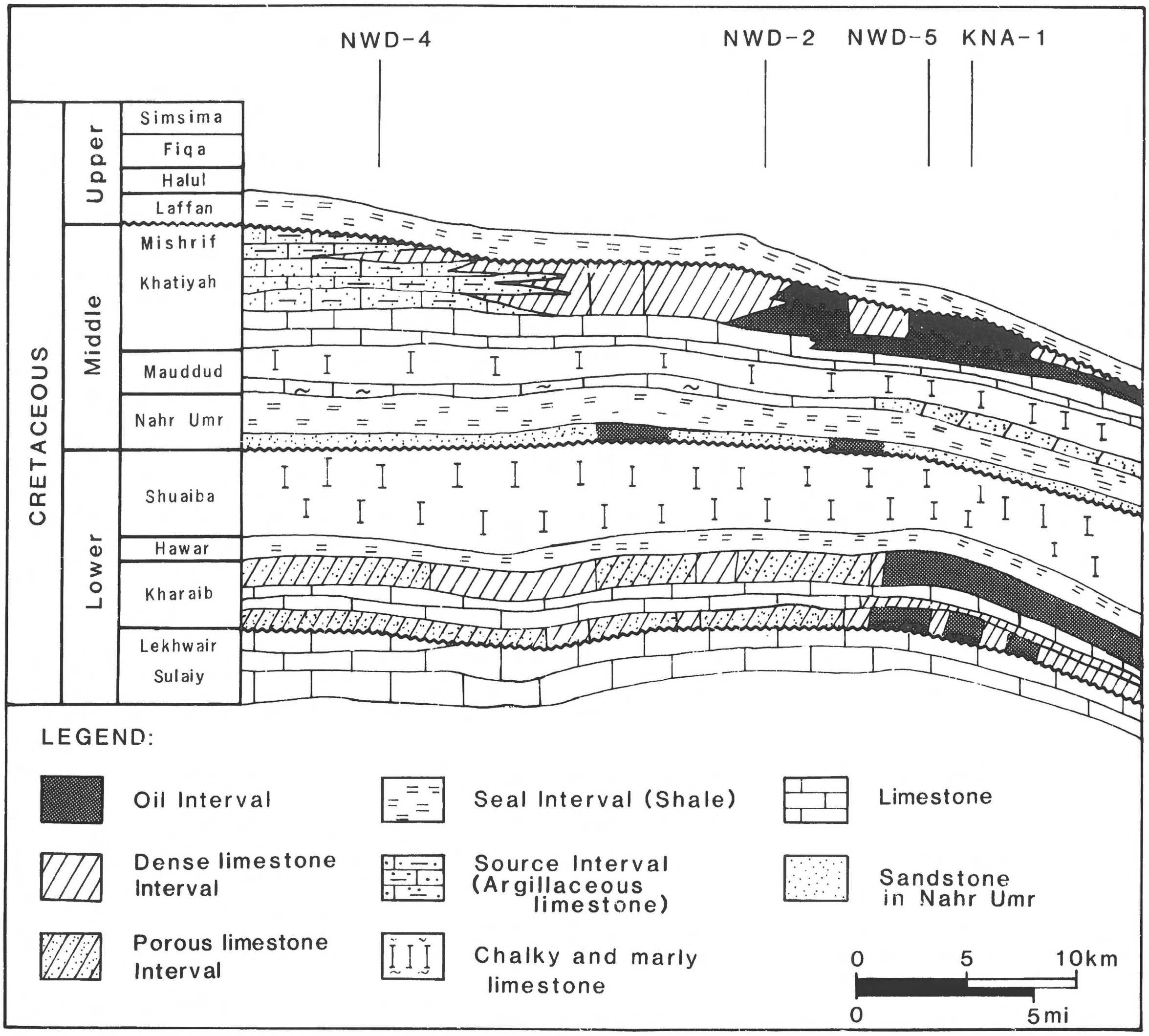

Fig. 17. Lithology and hydrocarbon distribution in the Cretaceous of the North Field, Qatar (modified from Frei 1984). See Fig. 2 for location of wells.

per 44 m of the reservoir has an average porosity and permeability of 18% and 15 millidarcies (md) respectively (Table 1). The reservoir contains a relatively thin oil rim with an overlying gas cap. Poor well productivity led to a closing down of early production in 1975; production was restarted in 1983 after water injection facilities were installed. The 55 m of Uwainat in Maydan Mahzam, at some 2735 m depth, has a porosity of 10–23% with permeabilities between 2–300 md (Table 2). The average net offtake per well from the thin oil rim was 785 barrels per day (b/d) of 38° API oil. The Uwainat in the Bul Hanine Field, at an average depth of 2774 m, is about 55 m thick, with porosity and permeability varying between 5 and 21% and 50 and 500 md respectively (Table 3). The average oil column is 31 m, and average net offtake was 190 b/d per well of 37° API oil. In the Idd El Shargi North Dome the Uwainat lies at an average depth of 2485 m. The reservoir is about 55 m thick with porosity varying between 5 and 20% and permeability between 1–1600 md (Table 4).

The Upper Araej reservoir has a low to moderate porosity and low to very low permeability. In the

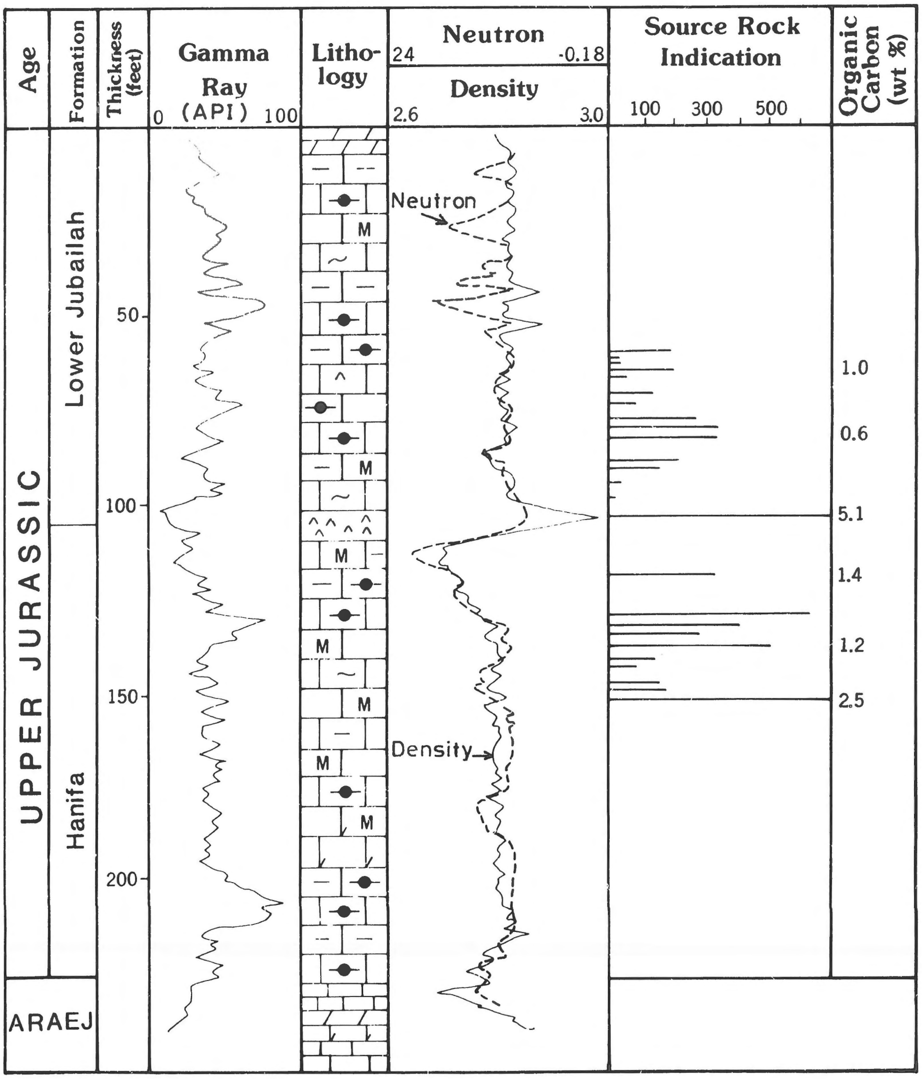

Fig. 18. Lithology, log characteristics and source rock analysis of Upper Jurassic Hanifa-Lower Jubailah formations of Qatar (modified from Frei 1984). Legend in Fig. 20.

better packstone and grainstone reservoir zones, the porosity ranges from 8 to 14% while permeability reaches up to some tens of millidarcy (Table 4). It is gas-bearing in the Maydan Mahzam and Bul Hanine fields. The presence of producible oil was only established recently in Maydan Mahzam.

The Upper Jurassic Arab Formation contains the most prolific reservoirs of Qatar in all the fields mentioned above. In the Ghawar Field of Saudi Arabia these reservoirs contain the largest oil accumulations of the world.

The Arab IV/D comprises four main reservoir types, whose porosity and permeability are shown in Fig. 16. Sucrosic dolomites in the eastern offshore fields form very good reservoir units; the high permeability of these rocks is due to the idiotopic and sucrosic texture and also to the development of a good intercrystalline porosity and permeability. The dolomitized lime mudstones and wackestones, which are often argillaceous and bioturbated, generally have a moderate to good porosity (10 up to 30%) and a permeability of generally less than 10 md. Good porosity may be found in peloidal packstone and grainstone due to the occasional occurrence of interparticle, vuggy and moldic pores (porosity ranges from 10 to 30% and permeability from less than 10 to more than 100 md). The oolitic grainstone shows that the porosity and permeability increases with increasing grain size, as a result of the well-rounded and well-sorted nature of these sediments. The porosity ranges from 15 up to 30% and permeability from 100 to over 5000 md.

The lower part of the Arab III/C reservoir consists of dolomitic grainstones and represents a major reservoir unit in some of the offshore fields such as Idd El Shargi and North Field. The grainstones are commonly leached and have moldic porosity. The upper part of the Arab III/C is the most variable interval and consists of a complex of dolomitized algal boundstones, mudstones/wackestones and peloidal packstones with occasional grainstones. The pore types are mainly moldic and interparticle and these sometimes have been totally leached and cemented by calcite cement. The porosity in the Arab III/C reservoir ranges from 1 up to 30% and permeability from less than 1 up to 1000 md.

The Arab I/A and II/B reservoirs consist of algal boundstones and oolitic grainstones. Often these grainstones have been leached and a common oomoldic porosity is developed. Porosity ranges from 7–30% with permeability ranging from less than 1 up to 800 md.

The Lower Cretaceous Kharaib Formation is oil-bearing in the North Field (Fig. 17) but generally shows poor reservoir quality. The microporous, peloidal packstones and grainstones have matrix porosity, and minor moldic porosity resulted from leaching of algal fragments. The porosity ranges from 15 to 30% but permeability is low (up to 12 md). The microporous, bioturbated wackestones show well-developed moldic and matrix porosity with total porosity in the range of 16–28%, but permeability is very low (up to 12 md).

The oil-bearing Shuaiba in the Idd El Shargi North Dome consists predominantly of microporous lime mudstones. The *Bacinella* algal boundstones and rudist fragments of the basal part of the Shuaiba Formation possess moldic porosity in the leached algae, with fair permeability up to 15 md and an average porosity of about 10%. Microporous

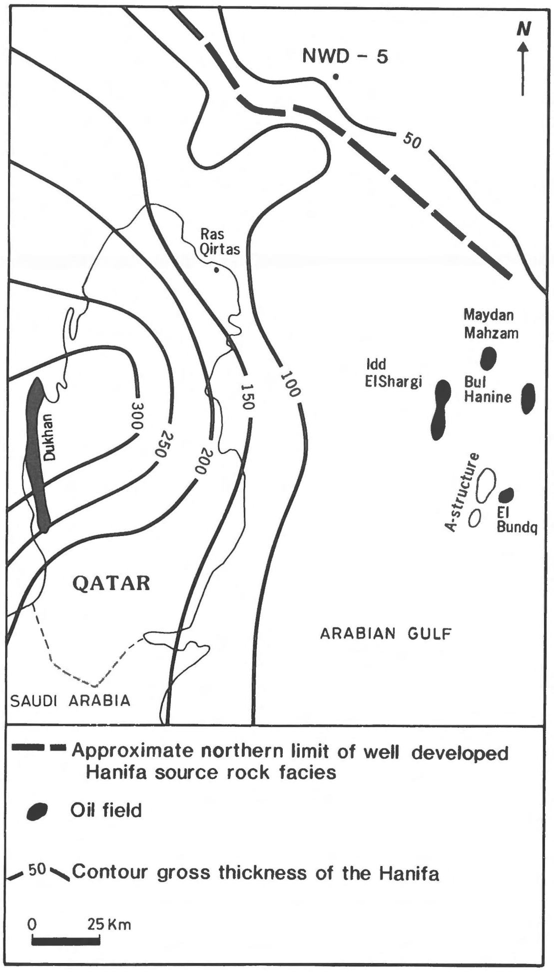

Fig. 19. Isopach map of the Hanifa source rock in Qatar (modified from Frei 1984). Contoured gross thickness is measured in feet (1 foot = 0.305 m).

lime mudstones, the dominant rock type, are bioturbated, compacted and stylolitic; their permeability is very low (up to 3 md), while the porosity ranges from 6 to 25%. The top of the Shuaiba reservoir with characteristic coral boundstones has a moldic-vuggy porosity in the range of 16 up to 30%, with permeability from 25 to 50 md, sometimes reaching up to 1000 md.

The Nahr Umr Formation encloses a good but relatively thin (3–5 m) sandstone reservoir in the North Field area, where it is oil and gas-bearing (Figs 15, 17). This reservoir of clean, well-sorted sands is unconsolidated to slightly cemented, and interbedded with well-cemented quartzitic sand-

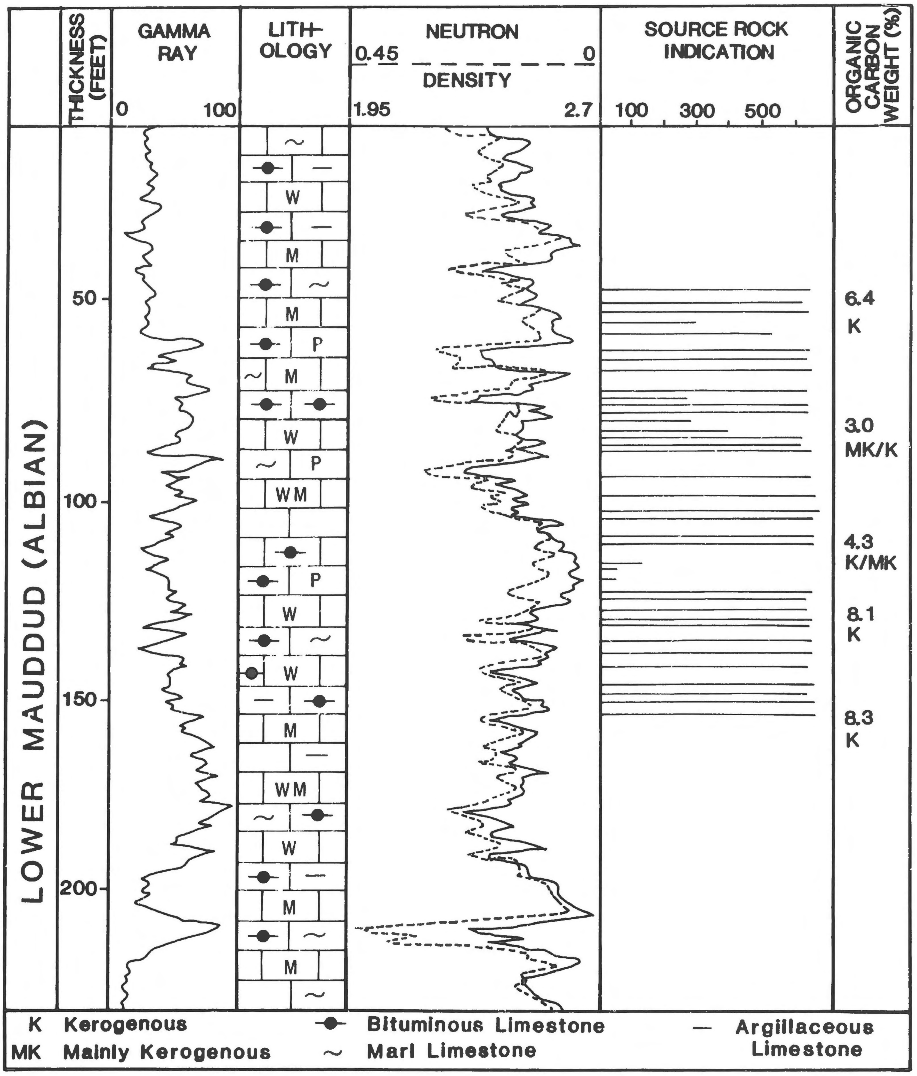

Fig. 20. Lithology, log characteristics and source rock analysis of the lower part of the Albian Mauddud Formation in Qatar (modified from Frei 1984). M: mudstone, W: wackestone, P: packstone.

stones. The cement consists of calcite and siderite, quartz overgrowths and clay minerals. Porosity is around 21% with permeabilities from 3 to more than 1000 md.

The carbonates of the Mauddud Formation constitute moderate to poor reservoirs in the North Field. The microporous peloidal wackestones to grainstones, foraminiferal peloidal packstones and local rudist-skeletal packstones and grainstones have interparticle porosity and some leached, vuggy porosity, ranging from 12 to 24%, with permeability from 0.1 to 70 md.

The carbonates of the Mishrif and Khatiyah in the North Field generally are poor reservoirs (Fig. 17), due to lithification and extensive bioturbation. Moldic porosity resulting from leaching ranges from 8 to as high as 28%. Permeability is very low, 0.1 to 5 md.

Seals

In the Jurassic Izhara and Araej formations, the seals are formed by dense lime mudstones and marls. The dense argillaceous limestones in the Hanifa and lower Jubailah formations seal minor oil accumulations in Bul Hanine and Idd El Shargi North Dome. Anhydrite layers between the Arab I/A to IV/D zones also act as intraformational seals, whereas the Hith anhydrite has proved to be the regional seal for the large oil and gas accumulations found in the Arab reservoirs in the Qatar area and elsewhere in the Middle East (Fig. 15).

The marl and shale of the Cretaceous Hawar Formation seal an oil column in the Kharaib reservoirs of the North Field and Idd El Shargi South Dome. In Idd El Shargi (North and South Domes), the seal for the Shuaiba reservoir is provided by the regional shales of the Nahr Umr Formation, which also cap the oil in the sandstone reservoir of the basal Nahr Umr in the North Field. The shale and argillaceous limestones in the lower part of the Khatiyah Formation act as a seal for the Mauddud reservoir in the North Field, and the Laffan shale seals the Mishrif reservoir in the same field.

Source rocks

The major inundation of the Arabian platform at the end of the Middle Jurassic resulted in the development of an intrashelf basin across Qatar. In this basin the laminated, bituminous lime mudstones and marls (Fig. 18) of the Hanifa Formation were deposited, which form the prolific source rocks for the oil in most of the Jurassic and Cretaceous reservoirs of Qatar. Figure 19 shows the regional isopach map of the Hanifa Formation and also indicates the approximate northeastern limits of its well-developed source facies. Organic matter varies from 1 to 6 wt% total organic carbon (TOC) and consists predominantly of sapropel which is partly bacterially degraded. Geochemical correlation between the oils trapped in the various reservoirs and the Upper Jurassic source rock is excellent, and it is therefore believed that virtually all the oil which accumulated in the Qatar fields originated from the Hanifa and the immediately overlying Jubailah source rocks (Fig. 18).

This lowermost part of the Jubailah Formation contains organic-rich, dark-grey, laminated, silty

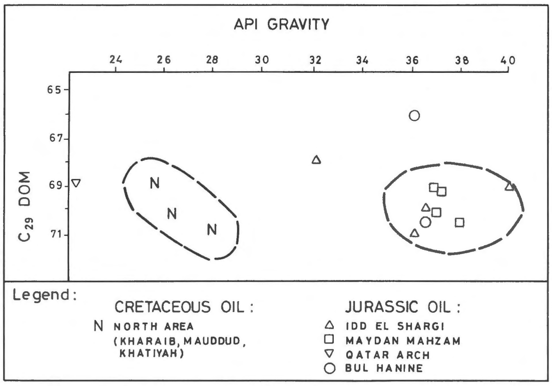

Fig. 21. Plot of API gravity versus C_{29} degree of organic metamorphism (DOM) for Qatar crude oils (modified from Frei 1984).

lime mudstones with a TOC content of 0.5–3.5 wt%. The laminated sapropelic matter is classified as mixed to kerogenous, indicating a source for both oil and gas.

The Cretaceous Shuaiba Formation in southeastern offshore Qatar (A-Structure, Fig. 2), has organic-rich intercalations that may have a TOC content up to 12.6 wt%. The amount of pyrolysible organic matter varies from insignificant to excellent. The organic matter contains a high proportion of partly micritized matter with some liptodetrinites and algae, which make the Shuaiba strongly oil-prone. This source rock horizon, as well as all younger ones, is not mature over the Qatar Arch due to shallow burial. It may, however, be sufficiently mature in the surrounding areas of deeper burial.

The limestones of the Mauddud Formation in eastern and southeastern Qatar are interbedded with globigerinal marls and calcareous shales with laminated organic-rich intercalations (Fig. 20). The TOC content ranges from 3 to 8.3 wt% and is mainly sapropelic with associated minor amounts of liptodetrinites and algae. It is classified as kerogenous to mainly kerogenous and constitutes an excellent potential source rock for oil (Frei, 1984). Argillaceous limestones of the Mishrif/Khatiyah in offshore areas have organic matter and represent minor source rock potential.

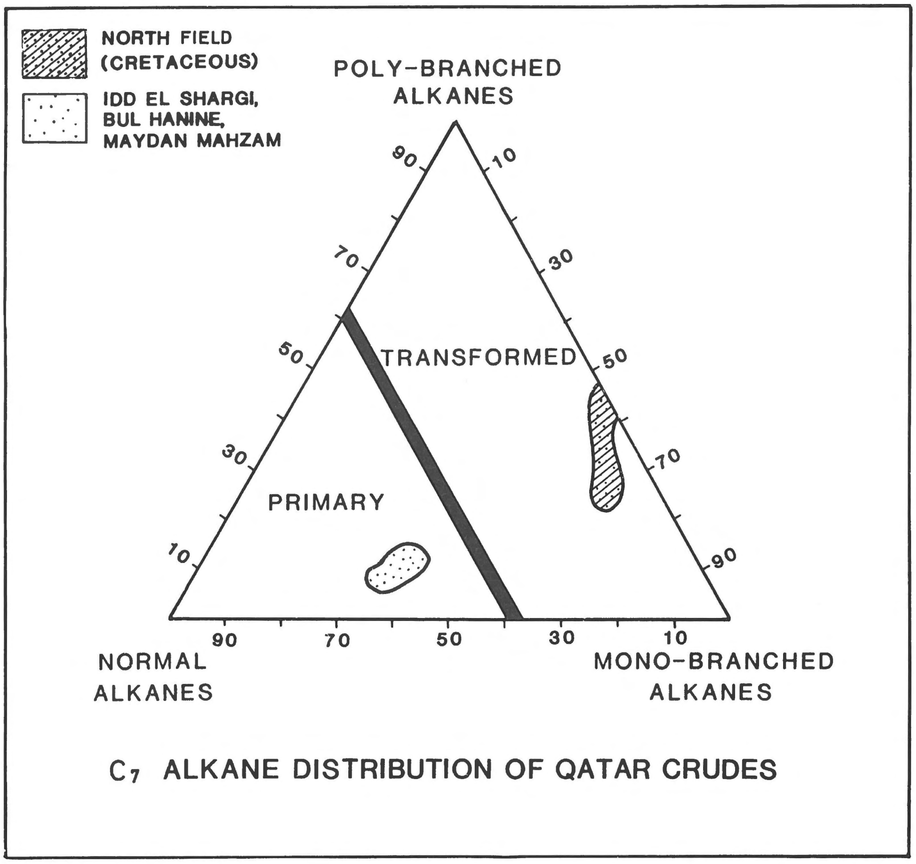

Fig. 22. Plot of C_7 alkane distribution of Qatar crude oils (after Frei 1984).

Oil characteristics

Analysis of the crude oils accumulated in the various Mesozoic reservoirs shows that the sulfur content ranges from 1 to 3 wt% and the API gravity mostly from 26 to 43°. A plot of API gravity versus C_{29} degree of organic metamorphism (DOM) made by Frei (1984) is shown in Fig. 21 and indicates a rather narrow range of DOM for such a wide range of API gravity. In other words, these oils are considered to have had a similar thermal history, and their wide variation of API gravity is probably due to biodegradation, water washing or evaporation of lighter fractions.

Primary light Jurassic crudes with gravities around and above 36° API occur onshore in the Dukhan Field (Table 1) and offshore in the Maydan Mahzam, Bul Hanine and Idd El Shargi fields (Tables 2–4) and the A-Structure (Fig. 2 for location). They contain higher percentages of normal alkanes (saturated hydrocarbons) as shown in the triangle plot of C_7 alkanes ('Primary' in Fig. 22). Crude oils with API gravity less than 30°, encountered in the Cretaceous reservoirs of the North Field, on the contrary, are plotted in another region of the plot ('Transformed'),probably due to bacterial degradation of similar primary light crudes. Some crude oils from the Jurassic reservoirs near the Qatar Arch are heavier than those of the Cretaceous, possibly due to evaporation of lighter fractions.

Figure 23 shows the C_{15}/C_{30} ring distribution of Qatar crudes and source rocks. The data of the Idd El Shargi, Bul Hanine, Maydan Mahzam and North Qatar Arch crudes are plotted in small areas of the triangle graph, suggesting a common source. They are most likely derived from structureless organic matter (SOM) and/or algal matter, with some mixing of other types. In addition, the plot shows that

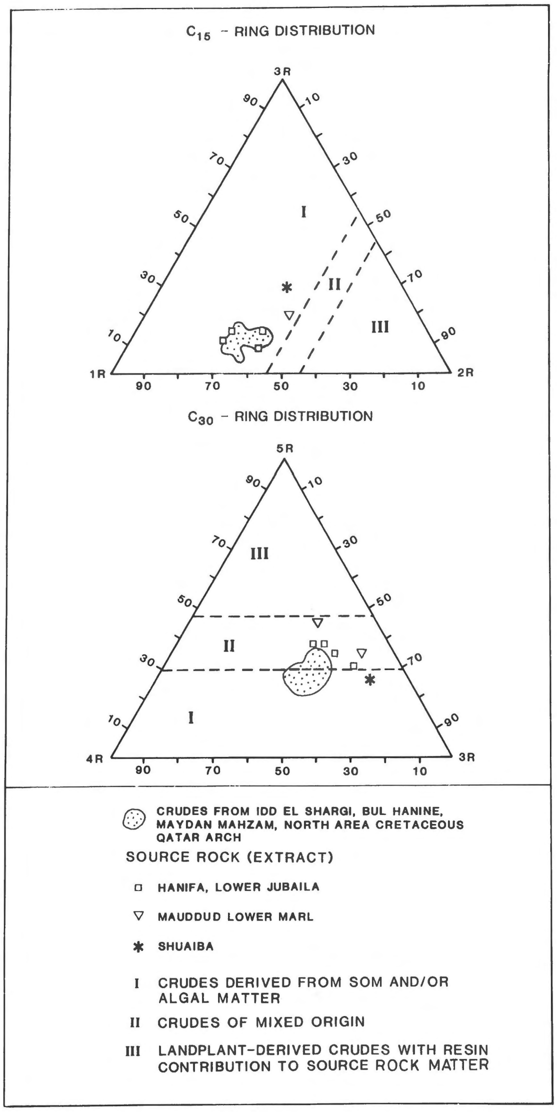

Fig. 23. Plot of C_{15}/C_{30} ring distribution of source rock extracts and crude oils from Qatar (after Frei 1984). SOM: structureless organic matter.

the Hanifa and lower Jubailah are the most likely source rocks, because of their closeness to the crude oil populations (Fig. 23). The stable carbon isotope ratio varies only by less than 1‰ around – 26.5‰, further suggesting a common source for these crude oils (Frei 1984). The comparison between gas chromatograms of the saturated hydrocarbons of a typical Arab IV/D reservoir oil and of extracts from the Hanifa and lower Jubailah source rocks (Fig. 24) also demonstrates a close relationship.

According to Frei (1984), the shape of the gas chromatograms and the sterane-triterpane distributions corroborate an origin from bacterially reworked phytoplankton. The low pristane/C_{17} and phytane/C_{18} ratios (0.2 to 0.4) of all crudes indicate that the oils were expelled from mature source rocks deposited in a reducing environment (Frei 1984).

Maturity and hydrocarbon distribution

The Upper Jurassic source rocks which are considered to be of the early expelling type probably began yielding oil beneath an overburden of about 1750 m equivalent to a vitrinite reflectance of 0.62 R_o. The distribution of the Jurassic accumulations is controlled by the distribution of the mature Hanifa-lower Jubailah source rocks and the regionally sealing Hith anhydrite. Most of Qatar lies geographically within the oil generation zone, whereas the southeastern offshore area lies in the gas generation zone (Fig. 25). Over most of the axis of the Qatar Arch, maturity of the Upper Jurassic source rocks was barely reached, whilst the structurally highest northeastern part remained immature. It is ironical that the thickest Hanifa source rocks are developed

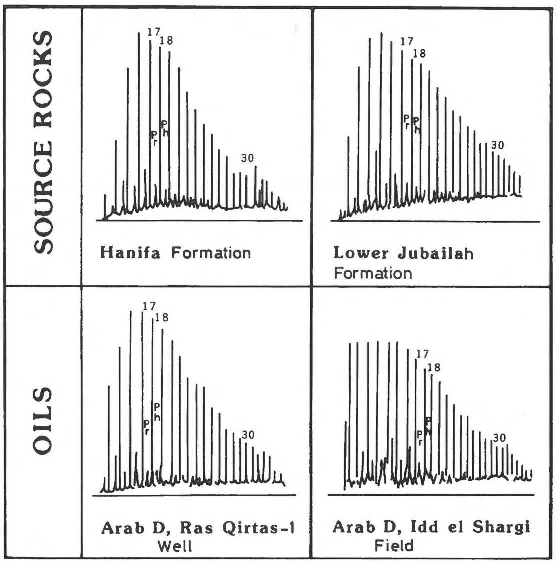

Fig. 24. Gas chromatograms of saturated hydrocarbons from Upper Jurassic (Hanifa and lower Jubailah) source rocks and Arab-D oils of Qatar (after Frei 1984).

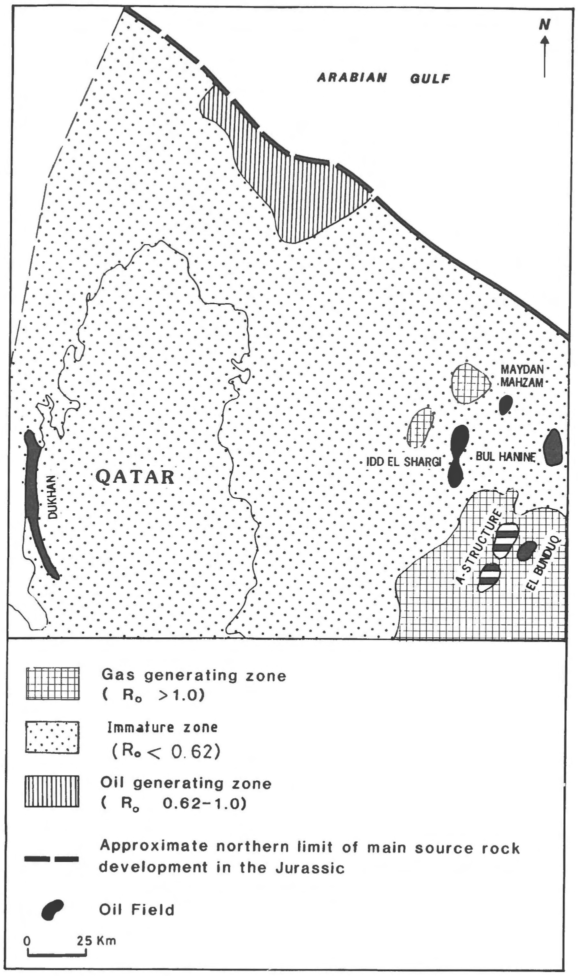

Fig. 25. Estimated maturity zones of Hanifa source rocks in onshore and offshore Qatar (modified from Frei 1984). NB: Symbols for 'oil generating' (= stippled) and 'immature' (= hatched vertically) were interchanged in the legend.

over the Qatar Arch (Fig. 19). The low number of Jurassic and Cretaceous oil discoveries over the arch is at least partly due to the scarcity of mature sections within the drainage areas and also to the lack of structural closures. Oil maturation in south-eastern offshore Qatar was first reached during Late Cretaceous times. Regarding the Cretaceous source rocks, they are still immature everywhere in Qatar.

Conclusions

Hydrocarbon occurrences are widely dispersed in the stratigraphic column in Qatar. The distribution of the Jurassic and Cretaceous hydrocarbon accumulations is controlled by mature source rocks, seals and availability of traps.

The Upper Jurassic Arab carbonate reservoirs are the most prolific. Together with the Upper Jurassic Hanifa-Jubailah and Hith formations, they form a source rock-reservoir-seal triplet. In the Middle East, this triplet constitutes the world's richest single hydrocarbon habitat. The Upper Jurassic formations represent a change from the basinal conditions of the Hanifa and lower Jubailah, to the shallow-water and sabkha environments of the Arab/Qatar Formation and the sabkha conditions of the Hith Formation. Several small transgressive cycles in the Arab/Qatar Formation gave rise to the development of the various Arab carbonate reservoirs.

Although there are some Cretaceous clastic reservoirs, the principal Cretaceous hydrocarbon reserves of Qatar are contained within the carbonates. The potential source formations that have been identified in the Cretaceous sequence are the Aptian Shuaiba and the late Albian-early Cenomanian lower Mauddud marl. The Albian Nahr Umr shale forms a good seal for the reservoirs of the underlying formations. The Coniacian Laffan shale caps the stratigraphically trapped oil in the Mishrif/Khatiyah Formation.

Inter- and intra-particle porosities in the Jurassic and Cretaceous carbonate reservoirs are generally enhanced by moldic and vuggy porosities resulting from the leaching of fragmented fossil material. Porosity is sometimes reduced by isopachous calcite cement or by occlusion of anhydrite.

Salt pillows of various shapes gave rise to the elliptical dome structures which contain major oil and gas accumulations in Qatar.

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