

The Petroleum Geology of The Cretaceous Formations in Abu Dhabi, United Arab Emirates

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Abstract: The Early Cretaceous/Thamama Group is a major oil-bearing carbonate sequence which represents the economically most important reservoir unit in the studied area. The structural pattern of this part of the Arabian Shield is relatively simple with prevailing gentle folding and warping, which formed and modeled the major reservoir – traps "aggregated reservoirs" in Abu Dhabi area. The distinctive structural style is together with the tripartite development of the source–reservoir–seal. Two petroleum systems are identified in the Cretaceous successions and two major source rocks have been predicted. The development of an exploration model for the studied lithostratigraphic section requires an understanding of the source and migration conduits in the two identified petroleum systems. Accordingly, this paper is an additive effort to clarify the petroleum geology of the United Arab Emirates area.

Keywords: Abu Dhabi, cretaceous formations, source – reservoir – seal, tectonic structural, petroleum geology

1 Introduction

The U.A.E. is situated in the south-eastern part of the Arabian basin between Lat. 22°40' and 26°00'; and long. 51°00' and 56°00'. Abu Dhabi, the study area is the largest Emirate within the U.A.E., and covers an area of 6,000 km².

The lithostratigraphic petroleum-bearing subcropping section in Abu Dhabi area ranges in age from the upper Paleozoic/Khuff Formation/Permian ascendingly till the Late Mesozoic/Simsima Formation/Maestrichtian and reached the Cenozoic/Oligocene rocks at the Qatar Arch tectonic province (Fig. 1).

The Mesozoic lithostratigraphic section in the study area as well as in the Middle East countries, especially the Early Cretaceous and the Jurassic sequences are the main prolific hydrocarbon-bearing rocks (source and reservoirs). The greatest oil accumulation occurs in the carbonate sequence of the Thamama Group in the U.A.E.

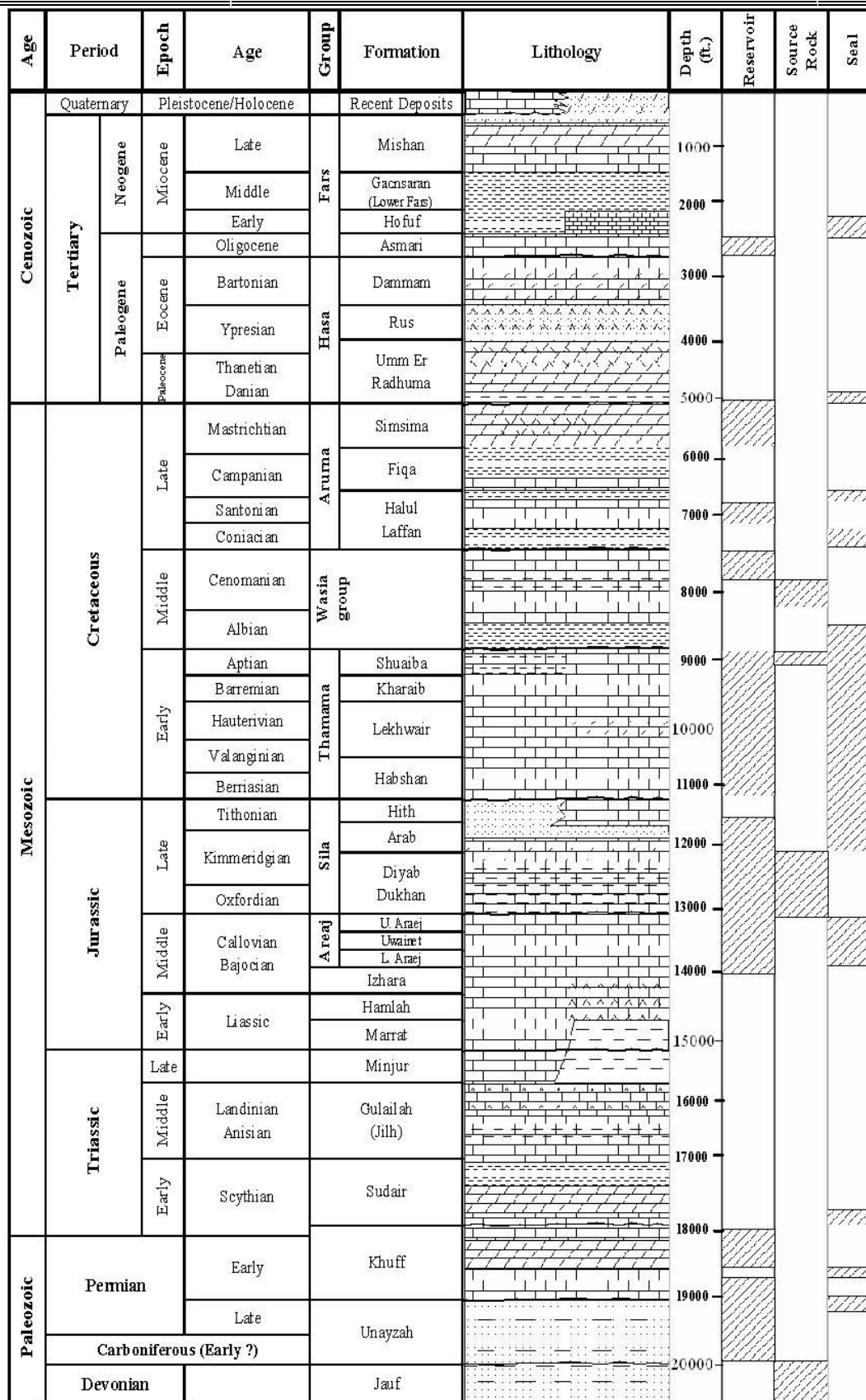


Fig. 1 The lithostratigraphic petroleum-bearing section in Abu Dhabi, U.A.E.

area, where the best reservoirs are formed in shelf carbonates. However, clastic reservoirs also occur but exhibit poor reservoir petrophysical characteristics (reservoir capacity in short) in comparison with the carbonates. The stratigraphic sequence in offshore Abu Dhabi area comprises a thick sedimentary succession (1800 ft) of Permian to Recent carbonates (limestones and dolomites), with minor anhydrite and shales deposited in shallow marine to supratidal environment along the eastern edge of the Arabian Platform corresponding to the southern passive margin of the Neotethys.

The tectonic history of the U.A.E. area in the Mesozoic-Cenozoic is connected with opening (Permian) and closure (upper Cretaceous-Paleocene) of the Neo-Tethys Ocean. The distinctive structural styles, together with the tripartite development of source-reservoir-seal, have produced in the U.A.E. one of the World's richest Jurassic-Cretaceous oil habitats. Significant oil discoveries have also been made in the Permian; middle and upper Jurassic; lower-middle Cretaceous and Oligocene-Miocene carbonates.

The petroleum geology of the Pre-Cretaceous in Abu Dhabi is a subject of another paper which will be published shortly.

The Early Cretaceous/Thamama Group is divided into three para-sequences: the lower Thamama/ Berriasian-Valanginian; the middle Thamama/ Valanginian-Huterivian; and the upper Thamama/Aptian-Barremian. These para-sequences form the Thamama formations carbonate sequence. Abu Dhabi area is a part of the eastern margin of the Arabian Shield, situated between two major structural highs: the Qatar Arch and the Oman Mountains. The structural pattern of this part of the Arabian Shield is relatively simple with prevailing gentle folding and warping which modeled the major reservoir-multiple traps which enclose many separate traps, holding many separate pools formed by one fold with different gas and/or oil water contacts level for each productive zone.

Most of the oil and/or gas fields in the study area are simple domal anticlinal growth structures, which consist of gently folded and faulted carbonate rocks.

Two major source rocks have been predicted, one of which is post or late mature, which is believed to generate large volumes of oil; and the other is of low maturity level and is capable of generating only limited amounts of oil. Most of the variations in the oils characteristics in the onshore fields in Abu Dhabi can be attributed to differing maturity levels and minor facies changes within their source rocks.

The development of an exploration model for the Thamama formations requires an understanding of the source and migration conduits of petroleum in the petroleum system of the Early Cretaceous which is controlled by several limits.

2 History of petroleum prospection and exploration in Abu Dhabi

The exploration activities for hydrocarbons in Abu Dhabi started in 1936 which included surface geology reconnaissance surveys. The geological exploration activity in the onshore concession of Abu Dhabi area started in 1947 to put an end to the former earlier informal reconnaissance of the first forty years of the 20th Century (1904 - 1937). The period of the years 1937 - 1939, pertained a former exploration activity in this region inspite of the lack of favourable surface structures and surface hydrocarbon showings.

The surface geology of the study area is formed regionally of eolian sand, sabkha deposits, lag and other gravels of local origin, unconsolidated surficial deposits of gravel and terrace, mud flat, and gypsum deposits of marine terrace deposits and raised beaches consisting of gravel, sand, oolitic and coquinooidal components of Quaternary age. These Quaternary deposits and its variability from eolian sand, sabkha deposits terrace mud flat, salt and gypsum prevented the seepage of hydrocarbons from the subcropping sections to the surface of the study area. Accordingly, the absence of surface occurrence of hydrocarbons was the obligatory cause of intensive geophysical and subsurface geological prospection for the subsurface occurrences of petroleum in the study area and other U.A.E. concessions.

At the end of the forties of the 20th Century (1947 - 1948), the onshore areas of Abu Dhabi Emirate were covered by gravity and magnetic surveys. But the seismic surveys started in 1949 - 1950. The close of the World War II, brought an immediate stimulus for the start of the geological exploration activity for petroleum in Abu Dhabi onshore area in 1949, together with gravity surveys in the period 1947 - 1948, but the seismic surveys began in 1949 onwards. In February 1950, the first onshore dry wildcat well Ras Sadr no.1 was drilled by the Petroleum Development in Trucial Coast Company (PDTC). It reached a total depth of 13,000 ft (3,963 m) within the Arab/Dukhan Formation/Late Jurassic. It was followed by three other onshore wells (PDTC). Bab/Murban well no.1 was the first onshore oil and gas discovery in the study area. It reached a total depth of 12,588 ft (3,837 m) within the Arab Formation/Fahahil member/Late Jurassic in 1954. This first oil and gas discovery was followed by two other dry onshore wells (PDTC). Gezira no.1 (1955), T.D. 12,500 ft (3,180 m) within the Uweinat Formation/middle Jurassic; and Shuweifat no.1 (1957), T.D. 12,360 ft (3,767 m) within the lower Araej Formation/middle Jurassic which tested oil and gas showings.

Accordingly, the history of petroleum producing fields in Abu Dhabi started by the discovery of the Bab/Murban onshore oil field. In 18th May 1954, Abu Dhabi (offshore) Marine Area Company (ADMA) was established. ADMA started its exploration activity by the drilling of the first offshore discovery well Um Shief no.1 (1958). It reached a total depth of 8,756 ft (2,669 m) within the Diyab Formation/Late

Jurassic. It was the first discovered offshore oil and gas field in Abu Dhabi Emirate.

The discovery of Bab/Murban onshore oil field (PDTC,1954), and Um Shief offshore oil field (ADMA, 1958) in Abu Dhabi concessions made a great pace as an optimistic stimulus which changed the former face of Oman Tropical Coast Emirates. It was a historic change in these remote desertic countries started from Abu Dhabi Emirate which comes from a long range of time units and successive lithostratigraphic sequences.

During the period 1955-1957, the evaluation of the drilling data raised from the onshore wells (PDTC): Bab/Murban no.1 and Shuweifat no.1 was not certain and without apparent success. But the improvement of the seismic data and the analysis of the of the proved seismic structure promoted the drilling of the second well Bab/Murban no.2(PDTC), on the crest of the Bab/Murban reservoir-traps in July 1959 confirmed the gas and gas condensate productivity from the discovered structure.

In 1962, PDTC continued its drilling activity activity in the onshore concessions in Abu Dhabi by the drilling of Bida Al-Qemran no.1. This well reached a total depth of 10,109 ft (3,082 m) within the Lekhwair Formation/Early Cretaceous and tested oil. Bu Hasa no.12 (PDTC, 1962) reached a total depth of 8,667 ft (2,642 m) within the Kharab Formation/Early Cretaceous and tested oil. This latter well was the first well in Bu Hasa onshore giant oil field.

During the period 1962-1963, Abu Dhabi Petroleum Company (ADPC) carried out the seismic refraction surveys and drilled the following three onshore wells: Rawais no.1, T.D. 9,272 ft (2,826 m) within the Lekhwair Formation/Early Cretaceous and was dry. Umm Al Ishtan no.1 (1962), reached T.D. 11,482 ft (3,502 m) within the Dukhan Formation/Late Jurassic and tested gas shows. Qamra no.1 (1963), at the South-East border of Abu Dhabi with Saudi Arabia, T.D. 13,940 ft (4,249m) within the Izhara Formation/Early Jurassic and was dry.

The first onshore and offshore petroleum discoveries in Abu Dhabi concessions were therefore a great boon to ADPC drilling program inspite of the observation that its first three wells were dry.

Accordingly, ADPC employed the seismic reflection surveys during the period 1964-1971, and continued its onshore drilling program and further seismic surveys were carried out during 1976-1971. These condensed onshore seismic surveys were going parallel with the offshore seismic surveys by ADMA, which resulted into numerous discoveries and petroleum fields. After the establishment of ADMA in 18th May, 1954, in the next year of the discovery of Murban /Bab onshore first exploratory and exploitation well no.1, ADMA started its offshore drilling activity by the drilling of the first offshore exploratory well in 1958. The onshore and offshore oil fields were based on structure drilling. The offshore exploratory drilling reached the Late Jurassic stratigraphic sequence which penetrated the Diyab Formation which underlies the Arab Formation and overlies unconformably the upper Araej Formation/middle

Jurassic. The penetrated limestone pay-zone produced crude oil (29° API).

ADMA started the combined bathymetric, geological and gravity surveys in the offshore areas during the early months of 1954. It continued its offshore reconnaissance "seismic surveys" during 1954-1955. These seismic surveys continued till 1968. Based on these surveys, ADMA drilled a group of offshore well-sites into the Arabian Gulf. Mandous well no.1 penetrated the Early Cretaceous succession within the Thamama Group. The reached bottom hole formation T.D. was 8,957 ft (2,739 m). The subcropping lithostratigraphic section in Mandous field area was hydrocarbon-bearing within different stratigraphic horizons. It is oil-bearing till the Oligocene. The Mandous well no.1, penetrated section was gas-bearing within the Late Cretaceous rock units and oil-bearing in the Early Cretaceous/Thamama Group.

In 1969, ADMA drilled three successful wells at the N-E direction from Abu Dhabi City which are : Umm Ad Dalkh no.1, Saath Al Rass Booth no.1, and Abu Al Bukhoosh no.1. ADCO drilled also two successful wells in 1969: Mubarraz nos.1 and 2. After the discovery of Umm Ad Dalk oil field within the Thamama Group carbonate sequence. ADMA increased the drilling depth to reach older stratigraphic horizons in the north-western offshore concessions in Abu Dhabi area and announced crude oil discoveries within the middle Jurassic carbonate sequence at Saath Al-Raaz Booth and Abu Al-Bukhoosh detected structural trends trapping crude oil.

ADMA/OPCO, 1979, drilled a deep test well: Umm-Sheif 88 DT, which reached the Late Paleozoic /upper Permian /Khuff Formation at T.D. 15,369 ft (4,684 m). This well reported gas and oil (45° API) in the Khuff lithostratigraphic unit and was located at 5 km to the N-E of Umm-Sheif well no.1 (Fig. 2), which produced also oil and gas from the Khuff Formation.

In 1981, ADMA/OPCO drilled Umm-Al-Lulu well no.1, T.D. 12,770 ft (3,892 m) within the Thamama Group and it was reported as an oil discovery. In the same year ADCO drilled west Mubarraz well no.1 (WMA-1) which reached T.D. 12,370 ft (3,770 m) within the Izhara Formation/middle Jurassic and was reported as an oil well. Other wells have been drilled by different companies and partners during 1982.

ADMA/OPCO, 1982, drilled Hail well no.1 (Ha-1) which reached the Diyab Formation/Late Jurassic. This well reported oil shows at T.D. 12,500 ft (3,810 m). In addition ADCO, 1982, drilled Al-Batteel no.1 which reached T.D. 12,200 ft (3,719 m) within the lower Araej Formation/middle Jurassic and reported 3000 BOPD. Umm-Al-Anbar no.1 (ADCO, 1982), T.D. 12 000 ft (3,658 m) within the Diyab Formation and reported 5000 BOPD. ADMA/OPCO, 1982, drilled Nasr well-7DT, which reached the Khuff Formation/Permian, at T.D. 17,425 ft (5,312 m) and was reported as a gas well. Several other wells have reached the Jurassic oil, gas and gas condensate horizons.

In 1986, ADMA/OPCO, drilled the Saath-Al-Raaz Boot well-8-DT, T.D. 16,561 ft (5,049 m) within the Pre-Khuff/Uneiza Formation/Late Paleozoic succession. This

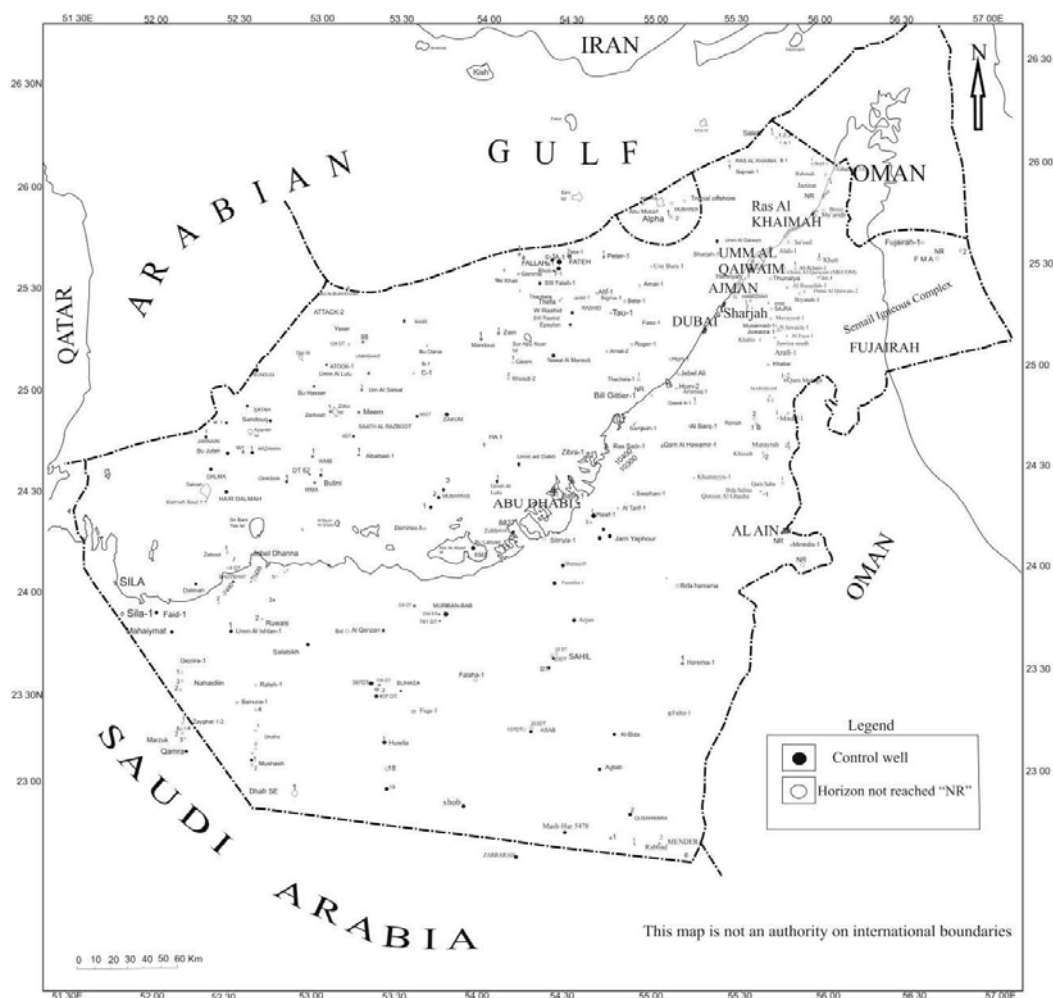


Fig. 2 a Location map of the drilled wells and the main oil fields in Abu Dhabi area, U.A.E.

well was reported as a potential Permian gas, gas-condensate test well.

Most of the exploratory drillings in Abu Dhabi area (onshore and offshore) led to the discovery and development of several petroleum fields till now; and several former concessions and fields have been owned by other owners, partners and companies (Fig.2).

3 The geology setting and occurrence of petroleum the studied area

The U.A.E. area is situated within the interior platform of the Arabian Shelf, bounded on the N-E by the Qatar–South Fars Arch, and on the East and N-E by the foreland basin, and adjacent forelands fold and thrust belt of Oman (Fig.3). Two passive plate margin basins were developed in the area: the Rub-al-Khali and Ras

al-Khaimah basins. However, Stampfli, 2000 and personal communication, proposed that, there is only one passive margin along the Arabian side of Gondwana and Abu Dhabi area is quite at the rear part of the margin, may be in a rim basin initiated during the Neotethys rifting. But, Stampfli's theory needs further improvement

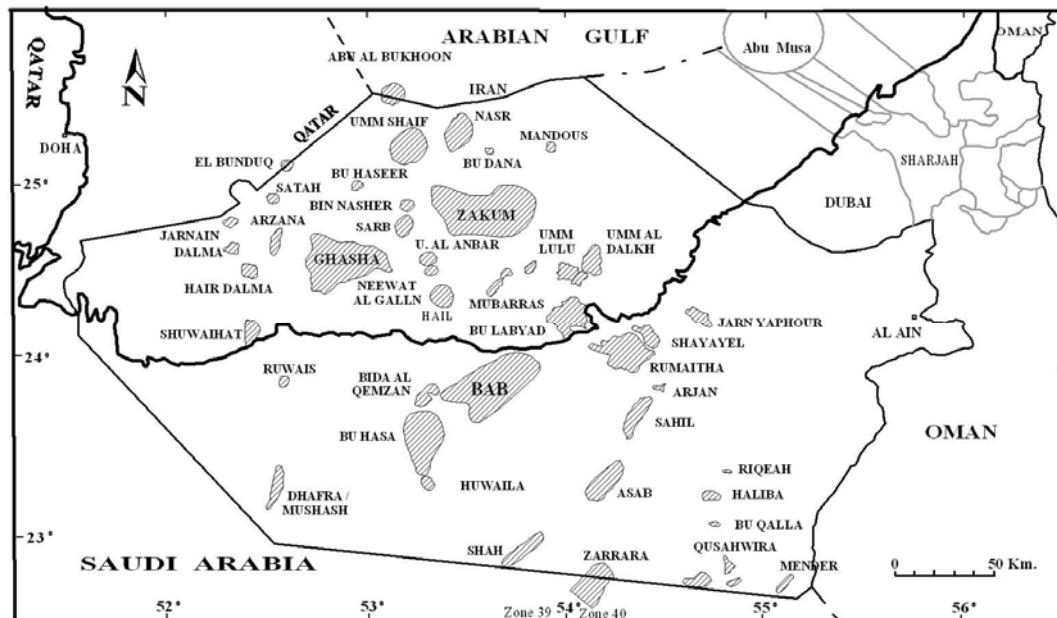


Fig. 2 b. Location map of the drilled wells and the main oil fields in Abu Dhabi area, U.A.E.

The Permian to Recent sequences in the U.A.E. area are dominated by marine carbonates with occurrences of terrigenous clastics and evaporates associated with cyclic periods of marine regression.

The sedimentary section in the area reaches a thickness of about 6,500 m (21,320 ft) at the south-western part and thickens toward the basin depocenter at the northern part.

The Thamama Group carbonates sequence of approximately Early Cretaceous (Hauterivian to Aptian) age is overlain by the blue, gray, green mainly non-calcareous shale of the Nahr Umr Formation/Wasia Group/middle Cretaceous; and is underlain by the Early Jurassic/Hith Formation, massive nodular and subordinate dolomite. The lithostratigraphic scheme of Hassan et al., 1975, has been widely adopted and has come to be accepted as the standard when describing the Thamama Group/Early Cretaceous in Abu Dhabi area.

The Thamama Group can be subdivided into lithostratigraphic succession of multiple traps- reservoir zones. Single traps are not common and the majority are multiple traps superimposed within an anticline in the informal lithostratigraphic units.

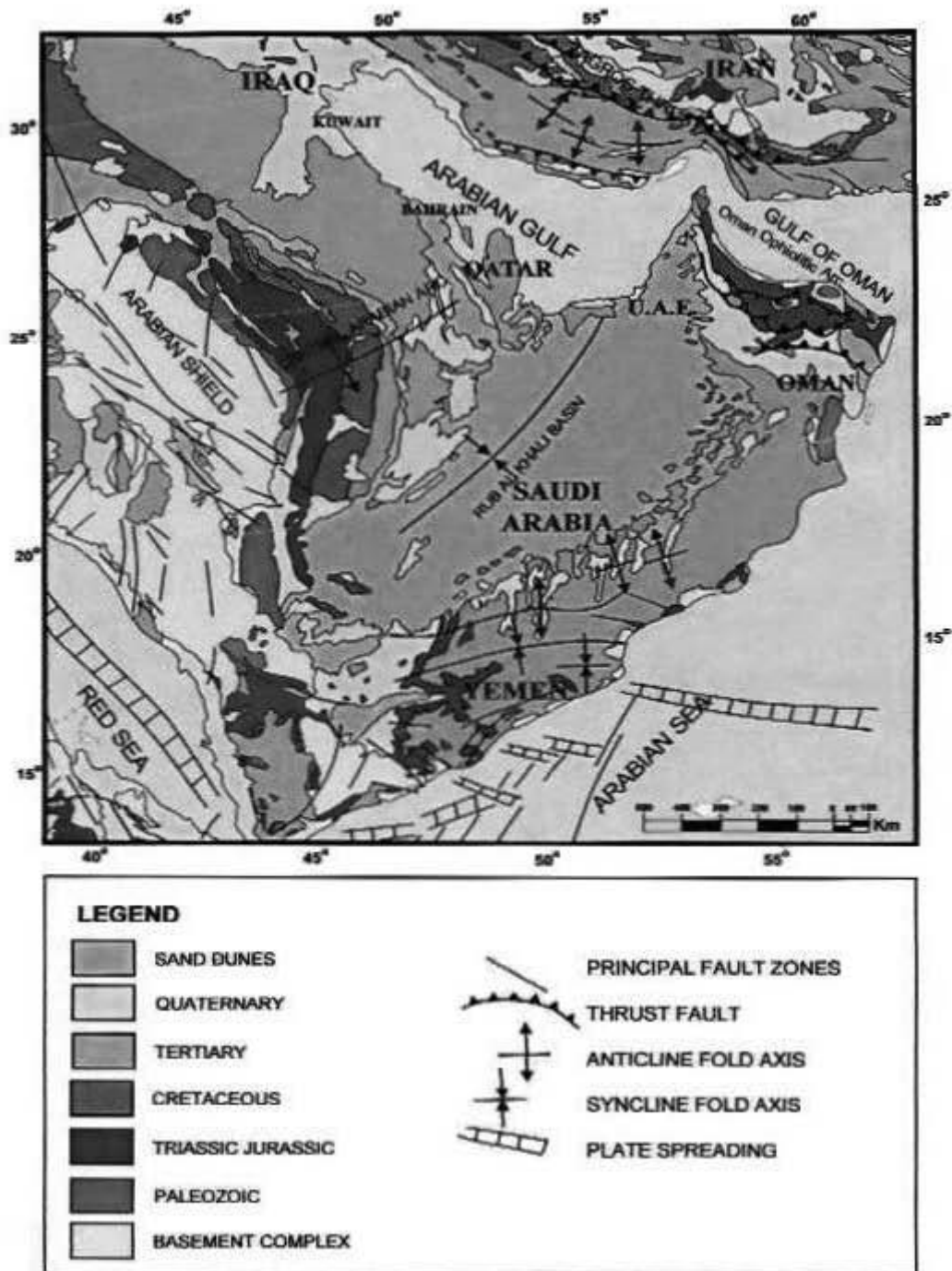


Fig. 3 The tectonic framework of the U.A.E. area, within the Arabian Peninsula constructed from data compiled from several sources.

Boichard et al., 1994, stated that the concepts of sequence stratigraphy have not been fully applied to analyse the lower Cretaceous of the Arabian Gulf. This fact is traced to two main factors. Firstly, the Cretaceous is predominantly a carbonate succession; and secondly, seismic profiles lack clear geometric features, with an exception in the Bu Hasa field area (Calavan et al., 1992). Both of these factors hinder the application of sequence stratigraphy as originally developed at a seismic scale and within siliciclastic deposits. Nevertheless, the works of Azer and Toland, 1993; and Calavan et al., (op.cit.), showed the possibilities of this approach in understanding the origin of porosity of the Thamama Group.

Murris, 1980, reported that, during the Early Cretaceous in the Middle East there was a gradual return to a more humid climate, and evaporates disappeared from the record. Relative sea level dropped and ramp-type carbonate deposition replaced the differentiated shelf. The Early-mid-Valanginian time showed a wide carbonate platform which existed at that time, building out into the Tethys Ocean in the East, where the prograding carbonate front is preceded by tintinnid-bearing slope and basinal marls. Through the Hauterivian and Barremian times the trend toward increased clastic influx continued. By mid-Late Barremian time the clastic regime occupied the western half of the basin pushing the carbonate realm, which has a model ramp-type development, in front of it toward the East. The Lurestan basin was much reduced through progradation of the shelf, whereas the margin of the open Tethys was again located beyond today's mountain front. The Gulf of Aden swell in the South was still in evidence, but had apparently been subsiding since the earlier Cretaceous, whereas the Qatar Arch was the locus of marked thinning, non-deposition and even pre-Aptian erosion. The extensive sheets of pelletoidal-bioclastic pack-grainstones which form the higher energy parts of the cycles of deposition contain oil and gas accumulations in the southern part of the gulf, where they are sealed by interbedded marls and argillaceous limestones. Further North, the coastal plain sandstones of the Zubair Formation/Barremian age, contain major oil reserves in several fields in South Iraq and Kuwait areas. Hydrocarbon charge has been provided by the euxinic Late Jurassic to Early Cretaceous deposits of the Lurestan basin, whereas interbedded coastal shales form the seals.

The Aptian was a period of renewed basinwide inundation, and by mid-Late Aptian a shallow carbonate shelf had spread westward over the previously deposited clastic rocks. The Lurestan basin expanded and a new sub-basin was formed in the Khuzestan area of Iran, providing the source for at least part of the oil in the giant Iranian oil fields. In the southern gulf another intrashelf basin is evident, occupying about the same location and area of the Late Oxfordian-Early Kimmeridgian basin. On the fringing shelf margins rudist pleycypods "reefs" grew where conditions were favourable, creating the prolific Shuaiba reservoirs.

The Aptian rise in sea level, though very marked in its effect on the paleogeography,

was of lesser magnitude and duration than the Late Jurassic sea-level rise, with no evidence of an encroaching continental margin. The climate was also more humid than the Late Jurassic, though evaporites were again deposited on the northern end of the platform. The temporary flooding during the Aptian was followed by the most pronounced regression since the Rhaetian time. By mid Albian time the clastic regime had spread across the whole platform except for a narrow belt in the northeast. The Lurestan basin was at its smallest, and separated by a shallow mixed-carbonate shelf from the Khuzestan sub-basin which was filled by shales deposited in front of the Burgan delta lobe (Q Kuwait). The Ga'ara – Mosul, Qatar, and Gulf of Aden highs were areas of little or no deposition. The coastal and alluvial sandstones of this interval (the Burgan Formation) are very rich reservoirs in the northern gulf area. They are sealed by interbedded shales, and have access to charge from the Early Cretaceous euxinic deposits of the Lurestan basin.

The Late Albian, Early and Late Cenomanian environments of deposition resulted into lithologic associations of shelf and intrashelf carbonates and evaporite platform which demonstrate how during the remainder of this megacycle which lasted until the Late Turonian, the carbonate and clastic realms waxed and waned. Post-Turonian erosion removed part of the section not only over regional paleohighs and the NNE-SSW – striking axes, but also along the Zagros crush zone, where slope erosion may have occurred along the continental margin fronting the encroaching ocean. The intrashelf basins are typically filled with oligosteginal (calcispheres) marls and radiolarian lime mudstones (in deeper parts), which are potential source rocks. On the shallow shelf, foraminiferal-algal wacke-packstones and rudist pack-grainstones were deposited and these now form the petroleum reservoirs.

Different reservoir terminology in the lithostratigraphic schemes of the Early Cretaceous/Thamama Group in the studied area has been adopted by the two main operating petroleum companies in Abu Dhabi (ADCO and ADMA) which lead to a profusion of lithostratigraphic terms (Fig.4). Accordingly, the Thamama Group in Abu Dhabi is formed informally of seven formations descendingly : Shuaiba, Khariab, Nasr, Zakum, Habshan, Salil and Rayda. When originally defining the Thamama Group formations in Abu Dhabi area, the stratigraphic position of its reservoir zones was taken into consideration and their boundaries are locally coincident with the formations stratigraphic boundaries. However, these zones have never been given any formal lithostratigraphic status; no type or reference sections have been published, and often no descriptions are available outside of oil companies reports.

The component stratigraphic units (subgroup) of the Thamama Group described in an ascending stratigraphic order as follows:

1) Lower Thamama subgroup:

Setting $c=c_T$, the resultant force E of standard soil pressure acting on the wall back of reinforced earth retaining wall under the condition of tensile failure can be obtained

by (3) and (6) as following:

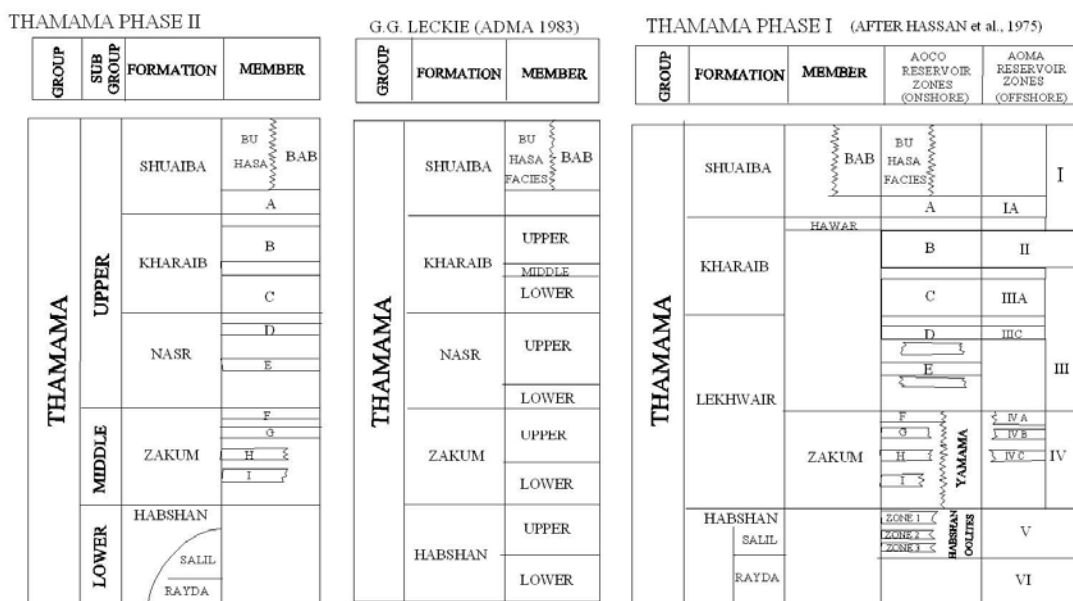


Fig. 4 Comparison of lithostratigraphic schemes for the Thamama Group in Abu Dhabi area.

This subgroup comprises the shelfal carbonates of the Habshan Formation and the Rayda and Salil formations (Fig.5), which are the deeper water equivalent units developed in the eastern part of the studied area. These three formations form a part of the same depositional sequence and represent a natural subdivision of the Thamama Group.

The lower Thamama subgroup is formed of the following formations ascendingly.

(a): Rayda Formation :

The type section of this formation lies S-E of Akhdar Mountain (57 41' 30" E and 23 02' 00" N), 2 km East of Mi'aidin valley. It attains a thickness of about 500 +or- 50 ft in its type section (Clarke, op.cit.). It comprises a sequence of thin-bedded lime mudstones and wackestones with fine argillaceous partings or levels of chert. There is a condensed horizon comprising a bed of corroded limestone pebbles, numerous vertebrate teeth and bones. This formation grades upward into lime mudstone rich in radiolaria and ammonite casts. It overlies unconformably the Jurassic carbonates and underlies alternating thin limestones and marls of the Salil Formation (Fig.5). Simmons and Hart (1987), related this formation to the middle Berriasian age based on the presence of a distinctive fauna of Calpionellids of the C. alpine zone.

Rayda Formation reported oil (34° API) in Belbazem field; oil (38.5° API) in Umm Al-Salsal field; and relatively light oil (44.5° API) in Zakum field inclusively with Salil Formation together with gas in Abu Dhabi area.

(b): Salil Formation :

GROUP	SUB-GROUP	FORMATION	MEMBER	AGE
WASIA		NAHR UMR		
THAMAMA	UPPER THAMAMA	SHUAIBA	BU HASA	APTIAN
			BAS	
		A	BARREMIAN	
		B		
		C		
		NASR	D	
	E			
	F			
	MIDDLE THAMAMA	ZAKUM	G	VALANGINIAN - HAUTERIVIAN
			H	
			I	
	LOWER THAMAMA	HABSHAN	SALIL	BERRIASIAN - VALANGINIAN
RAYDA				
SILA		HITH	ASAB	BERRIASIAN

Fig. 5 The lithostratigraphic scheme of the Thamama Group in Abu Dhabi area.

This formation was first reported by Scherer (1969, unpublished company report). Its name is derived from Salil valley near the Lekhwair field in Oman. Its type section

lies southeast of the Akhdar Mountain. It attains 6300+or - 65 ft thick in its type locality (Clarke, op.cit.), and comprises a monotonous sequence of black argillaceous lime mudstones and wackestones with thin limestone interbeds. Radiolaria is common in this formation, whereas ostracods and benthonic forams occur in small quantities. Mega fossils are less common than in Ryda Formation, and bioturbations are more intense.

The Salil Formation overlies conformably and transitionally the Rayda Formation, and underlies conformably clean carbonates of the Habshan Formation. Its lower part is questionably of Berriasian age, whereas the middle and upper parts are considered to be of Valanginian age.

(c) Habshan Formation:

The name Habshan is derived from the name of the Bab field central pumping station located 13 km to the southwest of the section in Bab well no.2 in the onshore concession in Abu Dhabi area. Its type section lies at the stratigraphic interval 9525-10555 ft in Bab well no.2 (Hassan et al., 1975) and attains a thickness of about 1030 ft. This formation has its thickest development in the central and southeastern parts of the onshore concessions in Abu Dhabi area, while it thins gradually northwards into the offshore concessions. It comprises a sequence of chalky lime mudstone and locally includes nodules of anhydrite and variable amounts of pelletal and skeletal material. In Umm Al-Lulu offshore field (West Abu Dhabi City) as an example, a massive oolitic limestone unit is developed at the base of the Habshan Formation in some wells. In the easternmost Abu Dhabi the Habshan basal oolite facies represents an important reservoir unit. The facies thickly developed in southeastern Abu Dhabi in wells Salil-23, Agrab and Qusahwira-2. However, a good reservoir quality appears to be restricted to the uppermost part of the unit, the lower part has suffered widespread dolomitization, which has both occluded porosity and obscured primary depositional fabrics.

In central and eastern Abu Dhabi area, the Habshan Formation succeeds the evaporite unit of the Hith Formation with an apparent conformity. Further more east and where the Hith Formation is absent; it overlies the carbonates of the Asab Formation/Sila Group/Late Jurassic. In the eastern-most Abu Dhabi and in northern Oman, the Habshan Formation conformably overlies the Salil Formation /Berriasian age. A Berriasian-Valanginian age is assigned to the Habshan Formation based on the occurrence of *Salpingoporella annulata* and *S. Pygmaea*, subzone of the *Pseudocyclamina lituus* zone by Hassan et.al., 1975.

2) Middle Thamama Subgroup:

This subgroup consists solely of the Zakum Formation/Valanginian-Hauterivian age. This formation was formerly nominated as the Zakum member of the Lekhwair Formation in Oman/upper Valanginian - lower Barremian (Hassan et al., op.cit.). It is overlain and underlain by a regional stratigraphic breaks and represents a single

depositional sequence. It is missing in the subcropping section at the East of the studied area, while the Thamama Group shows a remarkable thickening trend towards the South, southwest, and at the southeastern onshore area in Abu Dhabi (Fig.6). It is oil-bearing in the following offshore oil fields : Umm Adalak (37° API), Fallah (31° - 32° API), Rashid (39° API) and Mubarek (27.2° API).

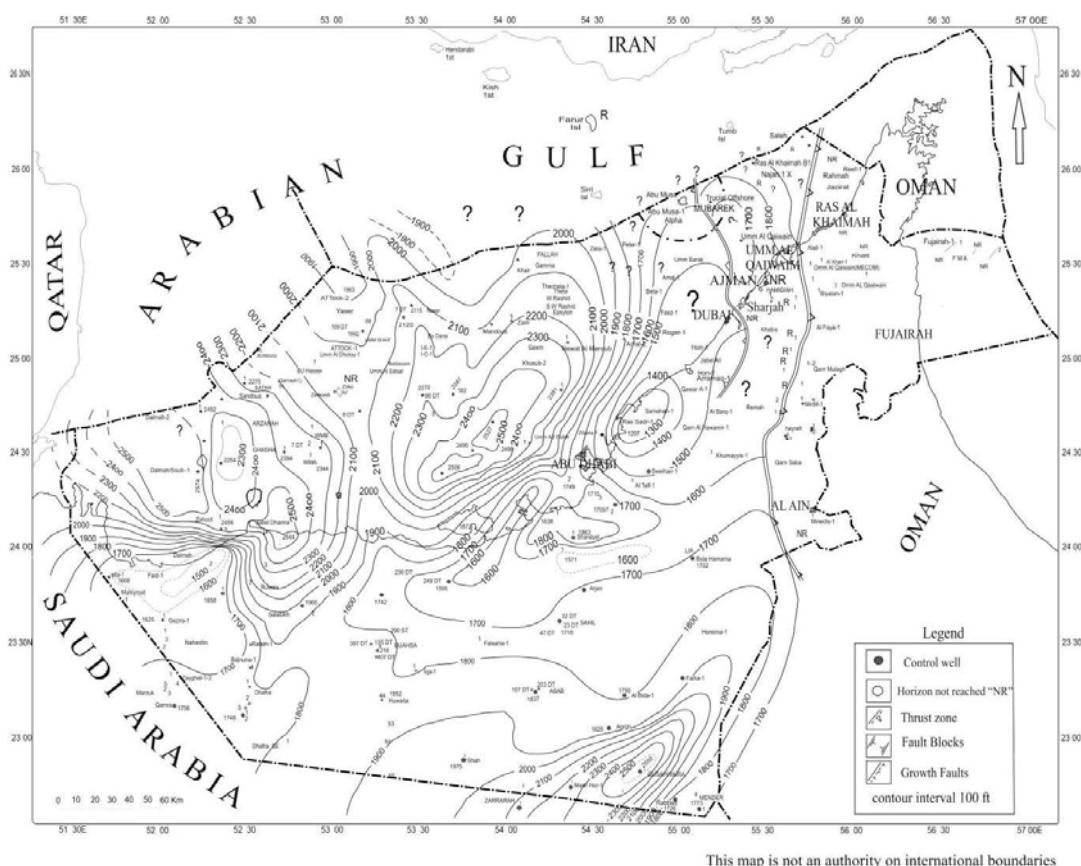


Fig. 6 Isopach map of the Thamama Group in U.A.E. region.

(d) Zakum Formation

This formation name is derived from the Zakum offshore field, Abu Dhabi. Its type section is in Zakum discovery well-1, at the interval 8,004-8,242 ft (Hassan et al., op.cit.; and Hassan and Wada, 1981).

The Zakum Formation is divided into four members : F, G, H and I. The three members F, G and H are synonymous with the reservoir zones F, G and H of ADCO and ADMA zones : IV A, IV B and IV C, while the member I is synonymous with ADCO reservoir zone "unit 22". No equivalent unit has been named in the ADMA - OPCO offshore area. This formation attains a thickness of about 238 ft in its type section and reaches a maximum thickness of about 390 ft in some wells. It is formed of wackstones to grainstone texture, commonly bounded by encrusting algae *Bacinella*, with intervening units of dense variably argillaceous lime mudstone. It is

oil-bearing in the following offshore oil fields: Um Shaif (36° API), Belbazem (39° API) and Zakum (39° API). The Zakum Formation overlies unconformably the Habshan Formation and underlies unconformably the Nasr Formation/Hautervian-Barremian. Its age is assigned on the microfaunal assemblage: *Dukhania arabica*, *Pseudocyclamina lituus* and *Salpingoporella pygmaea* (Maync, 1959; and Sigal, 1965).

3) Upper Thamama subgroup :

This subgroup comprises ascendingly, the Nasr, Kharaib and Shuaiba formations (Fig.4). The interval from the base of the Nasr Formation to the top of the lowermost member of the Shuaiba Formation (member A) represents one largely unbroken sequence of carbonate cycles, generally comprising regionally extensive units of tight lime mudstones grading upwards to porous lime packstones and grainstones. This sequence appears to represent very widespread and uniform depositional cycle, under conditions of fluctuating water depth, on an extensive carbonate platform with negligible bathymetric relief. The uppermost part of the upper Thamama (Bu Hasa and Bab members of the Shuaiba Formation) succeeds this sequence with apparent conformity and marks a change to a more differentiated depositional setting, with the development of shelf and basin facies.

The thickness of the upper Thamama subgroup shows a general thickening trend to the South and S-W over most of the central and western parts of Abu Dhabi area with a marked thickening trend to the East of the studied area (Fig.6).

This subgroup is formed of three formations in an ascending order :

(e): Nasr Formation:

Its name is derived from the Nasr offshore field. It is equivalent to that part of the Lekhwair Formation which lies above the previously called Zakum member (Hassan et al., op.cit.). The type section is the interval 7394-8004 ft in Zakum well-1. The Nasr Formation attains about 610 ft thick in its type section, and reaches about 1100 ft in some wells. Lithologically, it consists of a series of stacked carbonate cycles, grading from tight lime mudstone to porous chalky lime wackestone and grain-supported limestone. The porous beds are grainstones to packstones which contain pellets, algal, bivalve pelecypodes and gastropodes fragments.

The base of the formation is marked by an abrupt upward transition from clean algal-rich limestone of the Zakum Formation to argillaceous and pyritic lime mudstones. The top is considered at the base of the thick and regionally developed wackestone to grainstone textured reservoir unit developed in the lower part of the Kharaib Formation/Barremian. The Nasr Formation spans the *Dukhania* Arabian subzones and the *Salpingoporella muchlbergii* zone and is of Hauterivian-Barremian age. This is consistent with the conclusion of Clark (1975).

The crude oil gravity in the Nasr Formation ranges between 25° API in Zakum field to 37° API in Belbazem field and reaches 41° API in Fateh S.W. field.

(f): Kharaib Formation :

Its name was proposed by Sugden (1953). Its type section is in Kharaib well no.1 in northern onshore Qatar at the depth interval 3689-3962 ft (Sugden and Standring, 1975). Its reference section is Zakum well no.1, in ADMA-OPCO area offshore Abu Dhabi, while Alsharhan and Nairn (1986), considered its reference section in Shah well-1 at the depths of 6,202-6,555 ft (1,938-2,048 m) in the onshore Abu Dhabi area, where its thickness varies from 265-375 ft.

The Khariab Formation contains two major reservoir rock units, distinguished as members B/ lower Aptian-Barremian and C/ Barremian. Lithologically, this formation consists of two thick grain-supported reservoir units (B and C members), each is overlain by a relatively thinner lime mudstone unit which acts as sealing rock. The lower reservoir unit (member C), consists of brown, chalky, bioclastic, foraminiferal packstone to wackestone with algal and rudist debris and abundant Orbitolinids. The upper B member consists of brown, lime packstone and grainstone rich in pellets, forams, rudist, algae and echinoderm debris. The larger skeletal fragments are commonly associated with significant vuggy porosity.

The base of the Kharaib Formation is picked at the top of the Nasr Formation and its top is at the porous algal limestone of the succeeding Shuaiba Formation.

Boichard et al., (1994), concluded that, the study of the upper Thamama deposits in their field example (field A), showed that its good reservoir potential is controlled by four factors : (1) paleogeographic setting as a carbonate ramp; (2) highstands systems tract type; (3) subaerial (exposure) type sequence boundary; and (4) genetically related diagenesis, including autolithification. Within the sediments of the Kharaib Formation these factors and their associated processes were particularly efficient and helped create during early burial a reservoir layering system still recorded at the present day.

The petroleum reservoirs in this formation contain crude oils of variable gravities (34° API, in Umm-Al-Dholou; 38° API in Abu Al-Bokhoush; 44° API in Umm Al-Salsal offshore fields; 40° API in Sahil; and 52° API gas condensates in Bab (Murban) onshore fields). The variability of the crude oils gravities in the offshore and onshore oil fields in Abu Dhabi area and their significance will be discussed later on.

The age of the Kharaib Formation is Barremian - lower Aptian based on its microfaunal content. Sugden and Standring (1975); and Hassan et al., (1975), reported the presence of *Pseudochrysalidina* sp., *Lithocodium aggregatum* Elliot, and *Bacinella irregularis* Radoicic.

(g) Shuaiba Formation :

The Shuaiba Formation was named by Rabaint (1951), in Van Bellen et al., (1959), from a locality near the type section in southern Iraq. Its reference section in Abu Dhabi is the interval 6856-7091 ft in Zakum offshore well-1. This formation is

divided into three major lithostratigraphic subunits (Hassan et. al., op.cit.; Gouadain, 1981a and b. These subunits are member A at the base of formation, and two laterally equivalent subunits called Bab and Bu Hasa members at the top.

The Shuaiba Formation reaches 235 ft thick in Zakum well-1, in the central offshore area of Abu Dhabi and the thickness varies between 132-468 ft. Member A consists of algal (*Lithocodium*) boundstone at the base which grades upwards into porous, chalky lime mudstone containing abundant *Orbitolina lenticularis*, *Globogerina* spp., and molluscan debris. The Bu Hasa member consists of a thick rudistid build-up containing closely packed whole caprotinid and caprinid rudist shells and debris. It is also rich in *Orbitolina lenticularis* and other shallow water agglutinating forams. The laterally equivalent Bu Hasa member comprises highly argillaceous lime mudstones and wackstones with a sparse deep water fauna including globigerinids and ammonites. Thick bioherms with abundant rudists pelecypods, algae and orbitolinids as a possible "pinnacle reefs" occur locally within the Bab member in the vicinity of Mandos well-1 and Zerkouh well-1. Less well developed subunits in Zibarra-1 and Jarn Yaphour-7 wells have been interpreted as "patch reefs" (BP, 1986).

The Shuaiba Formation succeeds the tight limestone at the top of the Kharai Formation with apparent conformity. The upper boundary which is equivalent to the top of the Thamama Group is a regional conformity. In southern Abu Dhabi the upper boundary is a subareal unconformity (Mills et al., 1983) and is overlain by mudstones and argillaceous limestones of the Nahr Omar Shale/ Late Aptian to Albian/ base of Wasia Group which acts as a regional sealing rock for the Shuaiba crude oils and the underlying petroleum - bearing formations in the onshore and offshore oil fields in Abu Dhabi area.

The age of the Shuaiba Formation is dated as Early to Late Aptian based on the presence of: Codiocian green algae (*Lithocodium aggregatum* and *Bacinella irregularis*), *Saplingoporella dinarica* Radoicic (Barremian-Aptian; Elliot, 1968) and *Orbitolina lenticularis* Blumenbach, a typical Barremian - Aptian shallow water facies (Henson, 1948 and Schroeder, 1963).

The Shuaiba / Bab Formation is one of the most productive reservoirs in some giant oil fields in Abu Dhabi area, e.g. Murban-Bab (40.6° API), Bu Hasa (39.5° API), and Asab (40.7° API) onshore oil fields; and Umm Shaif (38° API) and Zakum (37° API) offshore oil fields.

Abou-Choucha and Ennad, 1990, stated that, there are mainly two stratigraphic play concepts related to the Shuaiba Formation. The primary is Shuaiba prograding highstand multiple reef trends with its shelf margin buildups. These trends have stratigraphic relief and contain porous, shoal-water carbonates. Adjacent carbonates, both shelfward and basinward, are less porous. In strike direction of the trend structural assist is required to provide a strike closure. The secondary play is associated with basinward and shelfward pinchout of porosity within the upper Bab

member, again structural is needed.

Fischer et al., 1994, reported that the shallow water carbonates of the Shuaiba Formation were deposited on a vast shelf covering the eastern Arabian Peninsula. The formation of intrashelf basins significantly influenced the facies distribution within the Shuaiba Formation by localizing the deposition of basinal and shallow shelf carbonates. A buildup prone belt interpreted to be present in this area consists of a band of scattered mounds with a wide range of sizes. It partially rims the intrashelf basin centered in Abu Dhabi.

Generally, the various lithostratigraphic subunits of the Thamama Group are related to each other in time and space along a transect trending from Mi'aidin valley in Akhdar Mountain in northern Oman, West-northwest to Zakum field area in offshore Abu Dhabi and then southwest to Qamra-1 well and Marzuk wells nos. 1,2,3,4 and 5 at the Saudi Arabian borders with U.A.E.. The thickness of the Thamama Group/ Early Cretaceous reaches 1756 ft in Qamra-1 well, and its top subcrops at -7703 ft depth.

The lithofacies transition showed the occurrence and significance of unconformities (Boichard et al., 1994). From regional stratigraphic evidence, and using of available seismic stratigraphic studies, the Thamama Group in Abu Dhabi and northern Oman is recognized as a single sequence. Three parasequences are recognized within the Thamama sequence. In considering the impact of sequence boundaries on the porosity evolution, Boichard et al., (op.cit.) have subdivided the upper Thamama boundaries into three groups. The first group consists of two sequence boundaries which have a strong impact on the early porosity evolution due to an intense genetically related diagenesis as evidenced by intensive secondary dissolution. These are subaerial sequence boundaries. The second group consists of two sequence boundaries which are not associated with intense early diagenesis and their impact on secondary porosity is very low. These boundaries are intrashelf basin sequence boundaries. The third boundary is linked to a high aggrading neomorphism and a coeval porosity reduction. It is a sequence boundary of unconformity type.

The first group type within the Kharaib Formation, separates Highstand from transgressive Systems Tracts deposited on a carbonate ramp. They are of small-type 1 nature due to the lack of evidence of fluvial incisions or karstic and paleosoil features. Nevertheless, the ramp exhumation accompanying the relative sea level fall was long enough to permit the establishment of a regional aquifer. This latter is responsible to an autolithification by coeval dissolution of aragonite and precipitation of calcite. Despite later cementation the effect of this early diagenesis is still evident on the porous Highstands since dissolution pores are more abundant than primary pores. The second type refers to two environments within the Shuaiba Formation, which were formed during the initiation and development of an intrashelf basin. They are not associated with an early change of the interstitial water and do not have a major impact on the porosity evolution. The main pores of the underlying Highstands are of

primary origin whereas dissolution pores are subordinate. The third type corresponds to the unconformity between the top of the Shuaiba Formation and the overlying seal/ Nahr Umr Formation/ lower middle Cretaceous. However, the Shuaiba Formation / Bab member produces oil in the following offshore fields (Umm Al-Salsal 44° API, Fallah 31° API, and Fateh S.W.38° API); and in the onshore fields (Buhassa 39.5° API and Qusahwaira 36.6° API) from sediments of lagoonal environment-rising of sea level shallow deposition condition.

The petroleum occurrences can be related to the reservoir porosity which is the result of the meteoric leaching of the sequence boundary beds during the highstand before being covered by transgressive deposits which was responsible for the high porosity and fair permeability (reservoir capacity in short), whereas the tops of sequences of the intrashelf basin were never exposed. It is more probable that the meteoric leaching occurred during the next fall in sea level instead, where exposure was more pronounced and thus perhaps the leaching was indeed during the Highstand. Anyway, this phenomenon is a matter of future investigation.

4 Structural modeling of the reservoir-traps

Abu Dhabi area is a part of the eastern margin of the Arabian Shield, situated between two major structural highs: the Qatar Arch and the Oman Mountains. The structural pattern of this part of the Arabian Shield is relatively simple with prevailing gentle folding and warping, which formed and modeled the major reservoir-traps in the studied area. Periodic epeirogenic movements of the basement blocks (basement tectonics) appear to have been the major tectonic factors controlled the structural development of the area. Salt tectonics is also important as most of the structural traps probably have their origin in deep-seated salt pillows and intrusions.

In the structural framework of Abu Dhabi offshore area, four broad structural elements are recognizable and like the Qatar and Oman highs, their main alignment is North-South. These structural features are: (1): The eastern flank of the Qatar Arch. (2): A western trough or syncline where piercement salt domes are common. (3) A broad central high with prominent anticlinal development. (4): The western flank and hing line of Ras Alkaimah basin.

The most important and dominant structural element for petroleum accumulation is the central high. This element has been a positive structural feature since the upper Jurassic times and controlled the lithofacies and source rocks distribution.

Most of the oil and gas fields in the U.A.E. area are simple domal anticlinal growth structures, which consist of gently carbonates (e.g. those in the Araej, Arab, Thamama Group and the Simsima formations) above the salt or the sealing rock that lies above the salt. In most cases a source rock is overlain by shale, and supplies the reservoir lithology, which is capped by an impermeable seal.

The structural and tectonic developments in the U.A.E. area are the result of two

main tectonic (intracratonic) regions, including Abu Dhabi offshore and part of onshore Dubai—Ras Alkhaimah area; and a foreland basin and adjacent foreland fold and thrust belt region in onshore northern U.A.E. area (Fig.3). These two tectonic provinces and their boundaries interaction led to the occurrence of broad structural and stratigraphic traps.

The passive plate-margin region is dominated by large gentle folds of various shapes and sizes related to differential regional subsidence or uplift along the deep seated basement fault-blocks.

The geologic and tectonic settings of the Arabian Gulf countries and the U.A.E. areas have been reported by several authors, among them were : Lees (1950 and 1953); Kent (1970); Glennie et al., (1974); Metwalli et al., (1974); Murriss (1980); Lippard et al., (1982); and Khouri (2001 and 2006).

The tectonic elements which modeled the structural configuration of the studied area had been governed by several interdependent factors which were in intervals of quiescence mostly during the Mesozoic intervals interchangeably highly active during the Late Cretaceous-Early Tertiary periods, i.e. the pre-Miocene vertical movements which affected and remodeled both the unfolded and folded zones of the Arabian platform.

The constructed regional structural contour map on the top of the Thamama Group (Fig.7) reflects domal and plunging anticlinal structures as concentric-structural models in the studied area are mostly periclinal and plunging in style, with flanks dips generally less than 5. The N-S folds dominated in the area e.g. Bu Hasa–Hail trend, and may represent an alignment of drap-folds over an east-dipping N-S listric normal faults in the basement, reactivated in reverse slip in response to the E-W Oman stresses. East of the Falaha syncline, the structural style is dominated by NE-SW trending fold-axis (the Shah, Asab and Salil trend), representing a series of drap folds over a reactivated basement right-slip fault. To the N-E, a NW-SE trending fold is dominated (the Jarn Yaphour trend), and a system of faults runs parallel to this trend. The NE-SW and NW-SE trends are similar to the trends that define the central Arabian Arch. In the central part of offshore Abu Dhabi, folds aligned E-W (the Zakum and Ghasha fields trend) related to Zagros folding system.

Diapiric structures of the large shallow dome type are common in the U.A.E. area. They were first explained by Elder and Grieves (1965), as being due to salt pillows subcropping at depths, e.g. at Zakum, Umm Sheif and Fateh fields areas. These fields were formed by the diapiric movement of the Hormuz salt which began early in the Cretaceous. Periodic mobilization of the salt had created unconformities across the top of some structures, e.g. Fateh offshore field.

The influence of salt is deep-seated, because no structural complexity or serious stratigraphic anomalies have been found. The characteristic circular and sub-circular domal geometry of the structures implies the presence of a localized epicenter of

upwarping. Accordingly, it is clear from Fig. 7 that the large scale structures of the studied area are controlled by two sets of structural elements.



Fig. 7 Structure contour map on the top of the Early Cretaceous / Thamama Group in U.A.E. region.

One is trending N-S, and the other NE-SW. The dominant N-S trending structures are the Ras Al-Khaima trough and the western syncline. The major NE-SW structural features are the Qatar-South Fars Arch, the Falaaha syncline-faulted area and adjacent Shah-Sahil trend of the structural highs; and the Mender-Lekhwar high in the onshore concessions of the studied area. The Ras Al-Khaimah trough represents a part of the foreland basin of the Oman Mountains thrust complex and dates from the Late Cretaceous times. The other structural elements appear to be controlled by movements on deep-seated basement faults, and may appear to have had a long history of structural reactivation. Accordingly, the basement tectonics played the significant role in the in the structure of the overlying sedimentary cover. It is apparent from the

structural contour map (Fig. 7), a series of smaller scale highs and lows offshore Abu Dhabi area. These can be related to local mobilization of the deeply buried infra-Cambrian Hormuz salt. The Late Cretaceous thrusting in the Oman Mountains and development of a foreland basin in eastern Abu Dhabi and Oman caused rapid burial of the earlier carbonate sequences and also led to reactivation and interference with the NE-SW trending Shah—Asab—Sahil structural trend and the Mender—Lekhwair high.

The regional isopach map of the Thamama Group (Fig. 6), illustrates the influence of the major structural lineaments exerted during sedimentation in the Early Cretaceous times.

The main Thamama Group depocenter trends approximately E-W through southern Abu Dhabi and into northern Oman. The thickest Thamama Group development is coincident with the Rayda basin, where a thick Rayda and Salil succession is present within the lower Thamama. The NE-SW trending Qatar—South Fars Arch, Mender—Lekhwair high and Huqf Arch are associated with marked thinning of the Thamama sequence and all appear to have been relatively positive features in the Early Cretaceous basin of deposition. The Huqf Arch is the most significant of these positive features. It formed the southeast margin of the lower/ middle Thamama basin of deposition, and after being onlapped by the upper Thamama was subsequently reactivated leading to erosion and complete removal of the Thamama succession.

5 The petroleum reservoir -traps models in Abu Dhabi fields areas

The Early Cretaceous/ Thamama Group is a major oil-bearing carbonate sequence which represents the economically most important reservoir lithostratigraphic unit in the studied area.

The distinctive structural style, together with the tripartite development of the source—reservoir—seal has produced in Abu Dhabi, U.A.E., one of the World's richest petroleum province, which comprises several super-giant Middle East oil fields, e.g. Bab, Bu Hasa and Asab onshore fields; and Zakum, Umm Shaif, Nasr, Ghasha and Mubarras offshore fields.

The oil fields structural models in Abu Dhabi area (onshore and offshore) demonstrate multilevels gas-oil and water-oil contacts which form multiple traps or more than one trap in a successive order overlying each other, i.e. the traps form aggregations within the same reservoir and each trap has its oil-water contact (hydrostatic or nearly hydrodynamic equilibrium) in the same anticlinal reservoir model (Figs. 8,9 and 10). Accordingly, the petroleum reservoirs in the studied area can be nominated aggregated reservoirs, i.e. formed of more than one or several traps in the same reservoir.

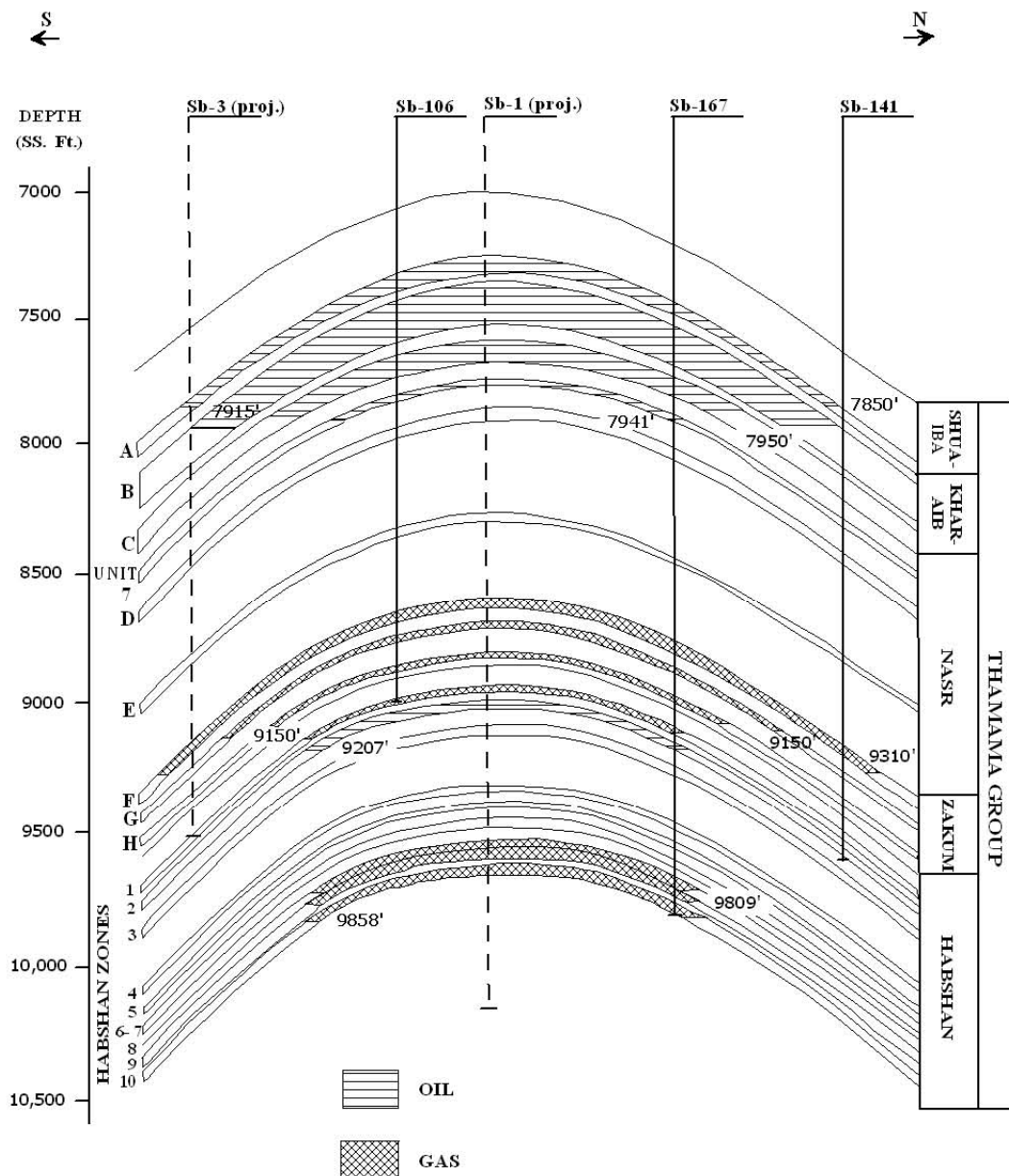


Fig. 8 Example : Asab onshore aggregated reservoir-traps modified after ADNOK, 1985.

6 The source, reservoir and seal relations

The interpretations of the source rocks potential of the various formations in the U.A.E. area have been reported by several authors, among them are Clark (1975), Schlumberger (1981), Murriss (1981), ADNOK (1984), El-Bishlawy (1986), Lutfi and Sattar (1987), and Mohamed and Ayoub (1994). The most pronounced major source rocks defined in the succession are the Diyab-Dukhan formations (Oxfordian-lower

Kimmeridgian), and the Shilaif-Khatiyah formations (Late Albian-Cenomanian). The main source rock stratigraphic levels in the U.A.E. area which have been identified by the formerly mentioned works were summarized by Lijmbach et al., (1992).

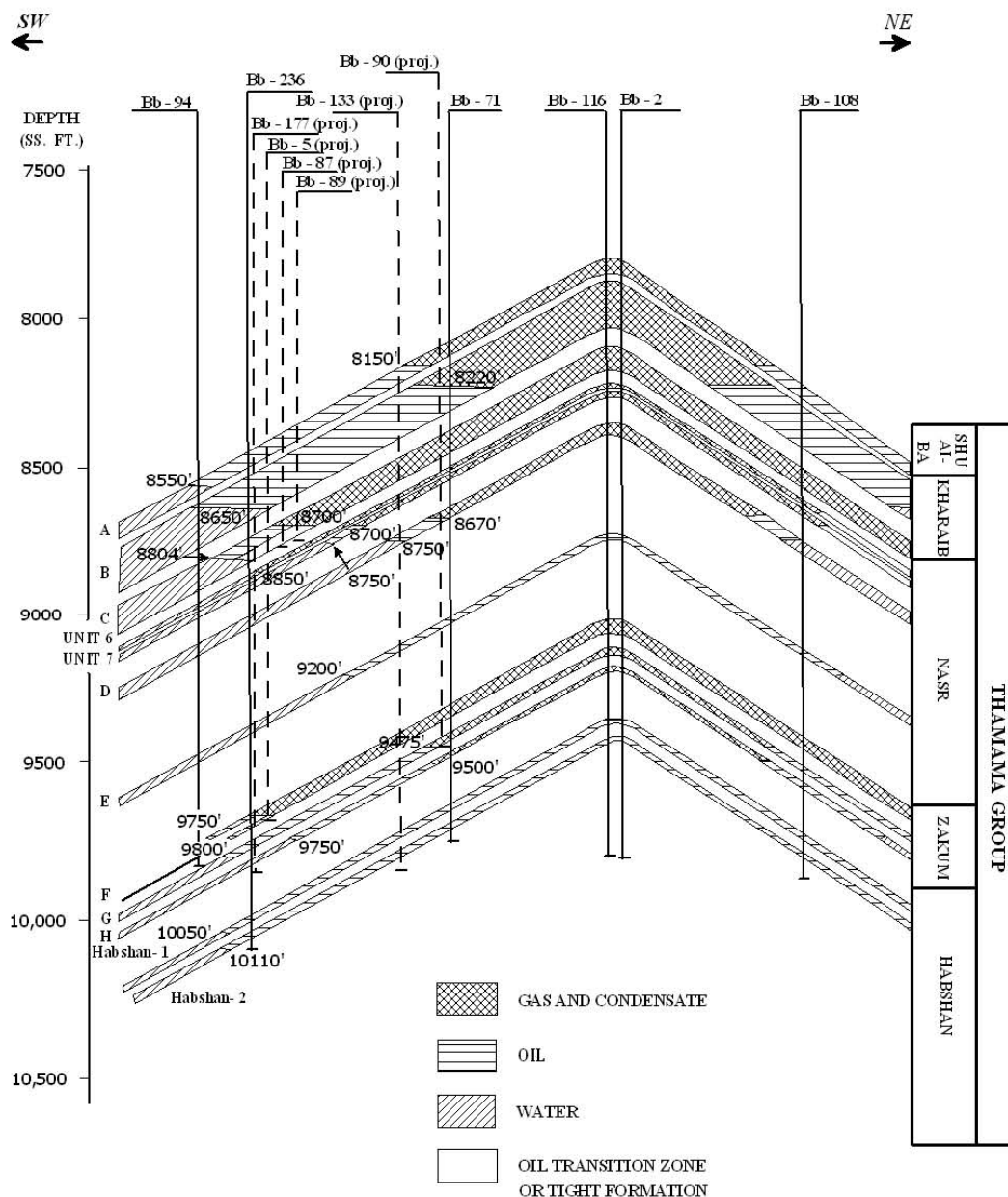


Fig. 9 Example : Bab onshore aggregated reservoir-traps modified after ADNOK, 1985.

The principal source rock in the Cretaceous succession in the studied area is the Shilaif Formation of middle Cretaceous age. This is immature over most of the area but reaches maturity locally where regional dip or salt tectonics have taken it deep

enough to become mature. Other potential source rocks have been identified which are of upper Cretaceous age (the Fiqa and Gurpi formations) in the eastern offshore Abu Dhabi area. There are also traces of oil in the Thamama Group in the western syncline which are probably sourced by a minor source rock within the Thamama Group/Early Cretaceous.

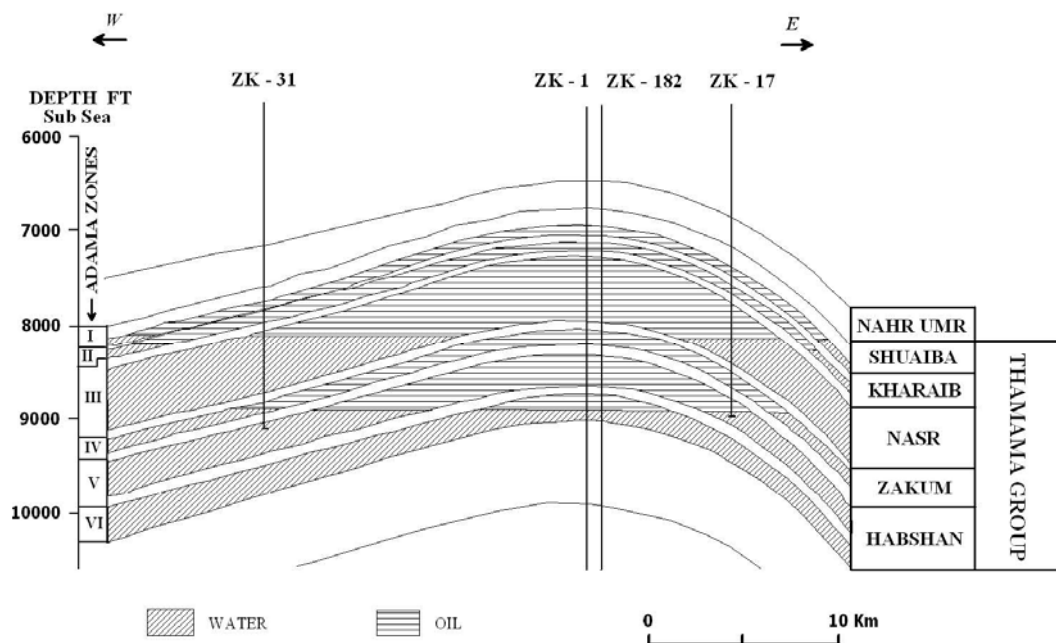


Fig. 10 Example Zakum offshore aggregated reservoir-traps modified after ADNOK, 1987.

Bitumens have been observed in the Thamama Group and older reservoir rocks in wells penetrated the western syncline and in the central high. These bitumens are believed to be produced by alteration of precipitated material from early maturity oils and can be considered as secondary products of oil generation and not primary organic matter capable of generating oil. The bitumens in the Thamama Group are of relatively low maturity compared with others reported from older formations, suggesting a lesser thermal exposure through time. The bitumens in the Arab Formation/ Sila Group/Jurassic and older formations are advanced in maturity. It is suggested that they were probably deposited with the first phase of oil generation in the Late Cretaceous times and might had high thermal exposure in the Late Tertiary times.

Most of the structural growth of the main oil fields in Abu Dhabi area took place during the Late Cretaceous providing timely traps for hydrocarbon accumulation. The distribution of the oils in the studied area was controlled by the distribution of the Hith anhydrite edge or where the Hith seal was not wholly anhydrite, where facies change or where the integrity of the seal was predominantly affected by compaction,

overpressures, microfractures and faulting permitting the vertical migration of the underlying crude oils in the Jurassic reservoirs to the overlying Thamama reservoirs to a certain extent. As there is a mature Diyab/ Late Jurassic source rock but no oil accumulation is reported in the overlying Arab/Dukhan Formation at Ruwais onshore field. It is probable that the Hith anhydrite seal at this location is locally ineffective, allowing migration of Diyab sourced oil up into the overlying Thamama formations.

The dense argillaceous units interbeds between the various Thamama Group reservoirs have been considered as a possible source for the Thamama oils, and in particular the Shuaiba basinal facies (Bab member) which is thought to be a good source rock by Lijmbach et al., (1992). These basinal facies consists of argillaceous lime mudstone and wackstones, dominated by pelagic and planktonic faunas, in which the TOC content ranges between 1-6 % and pyrolysis yields reach 16 kg/ ton. Volumetric calculations for the Shuaiba source rock by Azzam and Taher (1995) indicate that most of the upper Thamama oils have been generated and migrated from a mature Shuaiba source. The beginning of hydrocarbon generation from the Shuaiba source rock was as early as the Eocene time.

The Shuaiba Formation/Aptian age is sealed by Nahr Umr Shale/Albian age which consists of a sequence of sub-fissile gray shales which are predominantly non-calcareous, but becoming highly calcareous at the base. It is characterized by having generally no significant quantities of pyrolysable kerogen. Any kerogen present would appear to be inert based on the low hydrogen values.

No significant accumulations of free oil are present and wellsite gas chromatography indicates total gas values consisting of methane and ethane of 0.04 % in core samples raised from 8190–8250 ft depth in Umm Al-Lulu offshore well no.4 as an example. Accordingly, Nahr Umr Shale Formation has no potential as a hydrocarbon source rock but acts as an effective upper seal for the underlying Thamama Group oils. However, it is sometimes difficult to differentiate Nahr Umr gray shales from possible Thamama gray shales, inspite of the fact that the analysis has revealed that the Thamama limestones and their argillaceous equivalents are organically very clean and there is little or no evidence to suggest that there is any significant oil generating potential within the Thamama Group. It seems that there has been little organic preservation during the Early Cretaceous times and what preserved was of terrigenous origin.

The development of an exploration model for the Thamama reservoirs in Abu Dhabi area requires an understanding of the source, migration cycles, accumulation, and the nature and deposition of potential reservoir and seals units. These subjects are studied in detail and will be published shortly.

The zonation of the Thamama reservoir units ascendingly into Rayda, Salil, Habshan (lower Thamama), Zakum (middle Thamama), Nasr, Kharaiib, and Shuaiba formations (upper Thamama) by the various operating companies (Fig.5), imply that

intervening "dense zone" units are seals and that the individual reservoir units are truly stacked. However, analysis of reservoir pressure data and the vertical distribution of petroleum pay-zones suggests that the number of major seals within the Thamama formations, i.e. seals of sufficiently high capacity to impart controlling influence on the pattern of migration and entrapment of petroleum are relatively few. These seals have allowed petroleum fluids to segregate vertically, giving rise to apparently separate reservoir units with identical or closely similar pressure regimes and petroleum-water contacts, i.e. one petroleum pool. Further major seals might be detected locally within the Thamama Group through further consideration of remarkable variation in petroleum type and more required analysis of pressure data which are not available.

A regional exploration model of the Thamama Group indicates that at least two main reservoir complexes are present: (1) A lower reservoir complex corresponding to the Habshan and Zakum formations are capped by a major seal represented by the basal lime mudstones of the Nasr Formation/ Hauterivian-Barremian age; and An upper complex consisting of the Nasr, Kharaib and Shuaiba formations sealed of beneath Nahr Umr Shales/ Formation (Wasia Group/ middle Cretaceous). The Zakum offshore field is a typical example of this arrangement, with reservoir units in the upper and lower reservoir complexes having common or very similar oil-water contacts (Fig. 10).

Major seal units are locally developed within the two major reservoir complexes which appear to have locally modified the pattern of petroleum migration and accumulation. This led to rather more vertical aggregates of petroleum pay-zones as e.g. the case in the Bab-Murban onshore field area where there is a vertical succession of gas-oil pay-zones located from the top of the Habshan till the Shuaiba Formation (Fig.9). The locally developed major intra-Thamama seals may be the intra-Habshan Formation seal in the peritidal platform carbonates of the Asab onshore field area (Fig.8). The seal potential within the Habshan facies improves the chance that stratigraphic plays may be effective in the lower Habshan Formation at eastern Abu Dhabi area.

7 The petroleum systems in the cretaceous succession in Abu Dhabi area,U.A.E.

Exploration and development activity has increased significantly in the Cretaceous succession in Abu Dhabi Emirate since the discovery of the Bab/ Murban onshore field in 1954 and Um Shief offshore field in 1958.

The subcropping lithostratigraphic section in the Mandous field area was hydrocarbon-bearing within different stratigraphic horizons. The penetrated section was gas-bearing within the Late Cretaceous rock units and oil-bearing in the Early Cretaceous till the Oligocene / Asmari Formation.

Abu Dhabi area is an active major exploration province in the onshore and offshore

subprovinces. Consequently, variable companies of various sizes are involved with different areas. The petroleum industry in Abu Dhabi is pleasantly surprising by the extremely high sustainable rates of production from the Carbonate reservoirs of the Early Cretaceous as well as the Jurassic. These rates clearly have demonstrated that the carbonate reservoirs are the excellent reservoirs capable of sustainable production followed by the second order sandstone reservoirs in the pre-Cretaceous successions, till the Permo-Carboniferous continental deposits which are the subject of another work.

The petroleum deposits in the studied area are widely distributed in its stratigraphic section from the Permian / pre-Khuff clastics ascendingly till the Miocene—Pliocene (Gachsaran Formation) limestone.

The level of certainty for a petroleum system represents the degree to which the available geological and geochemical data support the hypothesis that petroleum within the reservoir rocks originated from the designated source rocks (Magoon and Dow, 1994). General agreement exists that the principal source of oil for the Cretaceous reservoirs in Abu Dhabi area is the Shilaif Formation of middle Cretaceous age. Other potential source rocks have been identified in the upper Cretaceous age, and minor source rock within the Thamama Group/ Early Cretaceous as mentioned before. Accordingly, two petroleum systems are proposed for the Cretaceous petroleum-bearing lithostratigraphic section which have fulfilled the four critical attributes for their essential requirements :

(1)The organic rich source beds within the sedimentary sequence; (2) The appropriate heat for thermal maturation of liquid hydrocarbons or thermal gas; (3) Permeable migration paths or conduit beds and sealing beds; and (4) The porous reservoir—traps confined by impermeable sealing beds. The lower petroleum system (I) is the lower Thamama Group which is underlain by the Hith anhydrite seal and overlain by Nahr Umr Shale seal. The upper petroleum system (II) overlies Nahr Umr (coastal shales) till the Simsima Formation / upper Cretaceous / Aruma Group. However, we believe and propose that there is a contribution of oil from the pre-Cretaceous source to the lower Thamama reservoirs from the underlying Jurassic source where the Hith seal was not wholly anhydrite and affected by compaction, overpressures, microfractures and faulting permitting the vertical migration of some of the underlying crude oil in the Jurassic reservoirs to a certain extent. The pre-Cretaceous petroleum systems are beyond the scope of this study and will be published shortly.

8 Conclusion

The writers believe that large amounts of petroleum can be found in carbonate rocks and second order clastics in Abu Dhabi area (U.A.E.). The majority of production can be obtained by structural exploration and drilling. Hence the study of

the source - reservoir - seal relations in Abu Dhabi onshore and offshore areas are of great value in understanding the reservoir modeling. This study will facilitate further exploration and prospecting of hydrocarbons in this remote desert part of the Arabian Gulf petroleum basin inspite of the lack of favourable surface structures and surface hydrocarbon showings, so far as potential petroleum production is concerned. Proper evaluation of carbonate and clastic reservoirs properties and modeling will contribute to the discovery of new oil and gas deposits.

From the foregoing discussions the following conclusions have arisen :

(1)The Early Cretaceous/ Thamama Group is a major oil-bearing carbonate sequence which represents the economically most important reservoir unit in the studied area.

(2)Most of the oil and /or gas fields are simple domal anticlinal growth structures, which consist of gently folded and faulted carbonate rocks.

(3)The distinctive structural style in the studied area, together with the tripartite development of the source - reservoir - seal has produced in Abu Dhabi (U.A.E.), one of the World's richest petroleum province, which comprises several super-giant Middle East oil fields.

(4)The petroleum fields structural models demonstrate multilevels gas-oil and oil-water contacts which form multiple traps in a successive order within the same anticlinal reservoir model, which can be nominated aggregated reservoirs.

(5)The distribution of petroleum was by feeding of the reservoirs partially from the proposed Cretaceous source rocks. However, the main feeding is proposed from the mature Diyab/ Late Jurassic source rock which was controlled by the distribution of the Hith anhydrite edge or where the Hith seal was not wholly anhydrite, where facies change is locally ineffective, allowing migration Diyab sourced oil up to the overlying Thamama reservoirs to a certain extent.

(6)The Cretaceous carbonate reservoirs are the excellent reservoirs capable of sustainable production followed by second order sandstone reservoirs.

(7)The development of an exploration model for the Thamama reservoirs in Abu Dhabi petroleum province requires understanding of the source, migration cycles, accumulation, and the nature and deposition of potential reservoir and seal units. These subjects are studied and will be published shortly.

(8)The major observed detected seals within the Thamama succession have allowed petroleum fluids to segregate vertically, giving rise to apparently separate reservoir units with identical or closely similar pressure regimes and petroleum-water contacts, i.e. one petroleum pool.

(9)Two petroleum systems are proposed for the Cretaceous petroleum-bearing lithostratigraphic section which have fulfilled the four critical attributes for their essential requirements. The lower petroleum system is the lower Thamama Group which is underlain by Nahr Umr Shale seal, The upper petroleum system overlies

Nahr Umr (coastal shales) till the Simsima Formation/ upper Cretaceous/ Aruma Group.

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