MIDDLE EAST: STRATIGRAPHIC EVOLUTION AND OIL HABITAT[1]

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ABSTRACT

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The post-Hercynian sequence of the Middle East is dominated by carbonate sedimentation on a stable platform flanked on the northeast by the Tethys ocean. Two principal types of depositional systems alternated in time: (1) ramp-type mixed carbonate-clastic units and (2) differentiated carbonate shelves. The first type was deposited during regressive conditions, when clastics were brought into the basin and resulted in 'layer-cake' formations. The second type was formed during transgressive periods and is dominated by carbonate cycles separated by lithoclines, time-transgressive submarine lithified surfaces. Differentiation is marked, with starved euxinic basins separated by high-energy margins from carbonate-evaporite platforms.

The tectonic development of the Middle East can be divided into several stages. The first stage, which ended with the Turonian, was characterized by very stable platform conditions. Three types of positive elements were dominant: (1) broad regional paleohighs, (2) horsts and tilted faults blocks trending NNE-SSW, and (3) salt domes. All three influenced deposition through synsedimentary growth. The subsequent stage, from Turonian to Maestrichtian, was one of orogenic activity, with the formation of a foredeep along the Tethys margin and subsequent ophiolite-radiolarite nappe emplacement. From the late Cretaceous to the Miocene the platform regained its stability, only to lose it again at the close of the Tertiary, when the last Alpine orogenic phase affected the region, creating the Zagros anticlinal traps.

Source rocks were formed in the starved basins during the transgressive periods. Marginal mounds, rudist banks, oolite bars and sheets, and regressive sandstones form the main reservoirs. Supratidal evaporites and regressive shales are the regional seals. The spatial arrangement of these elements and the development of source maturity through time explain the observed distribution of the oil and gas fields.

REGIONAL SETTING AND GENERAL PRINCIPLES

Stratigraphic Frame

The late Carboniferous to Miocene sequence of the Middle East oil province is the world's richest hydrocarbon habitat. The depositional history is dominated by carbonate sedimentation on a very stable, broad platform, bounded on the east by the open Tethys ocean. The carbonates were replaced westward by clastics, which had their source in the uplifted highlands of the Arabo-African continent.

Figure 1 gives a generalized picture of the stratigraphy of the Middle East region and the stepwise evolution of the post-Hercynian sedimentation pattern. From the late Carboniferous to the early Jurassic a very shallow carbonate platform covered large parts of the Middle East region, commonly with evaporitic central depressions and with clastic incursions from the west. From the middle Jurassic to the Turonian the platform became more differentiated, with intrashelf basins breaking up the shallow carbonate platform. Clastics were still coming from the west, reaching their maximum development during the early to middle Albian.

A major change in the depositional system occurred in the late Turonian to early Senonian, related to the Alpine orogeny affecting the Tethyan realm. A shale-filled open-marine foredeep was formed, with flysch-type sediments coming from the rising orogene in the east. After the late Campanian to early Maestrichtian paroxysm resulting in large-scale overthrusting and ophiolite emplacement, stable conditions returned, leaving a stable carbonate platform in the west and a
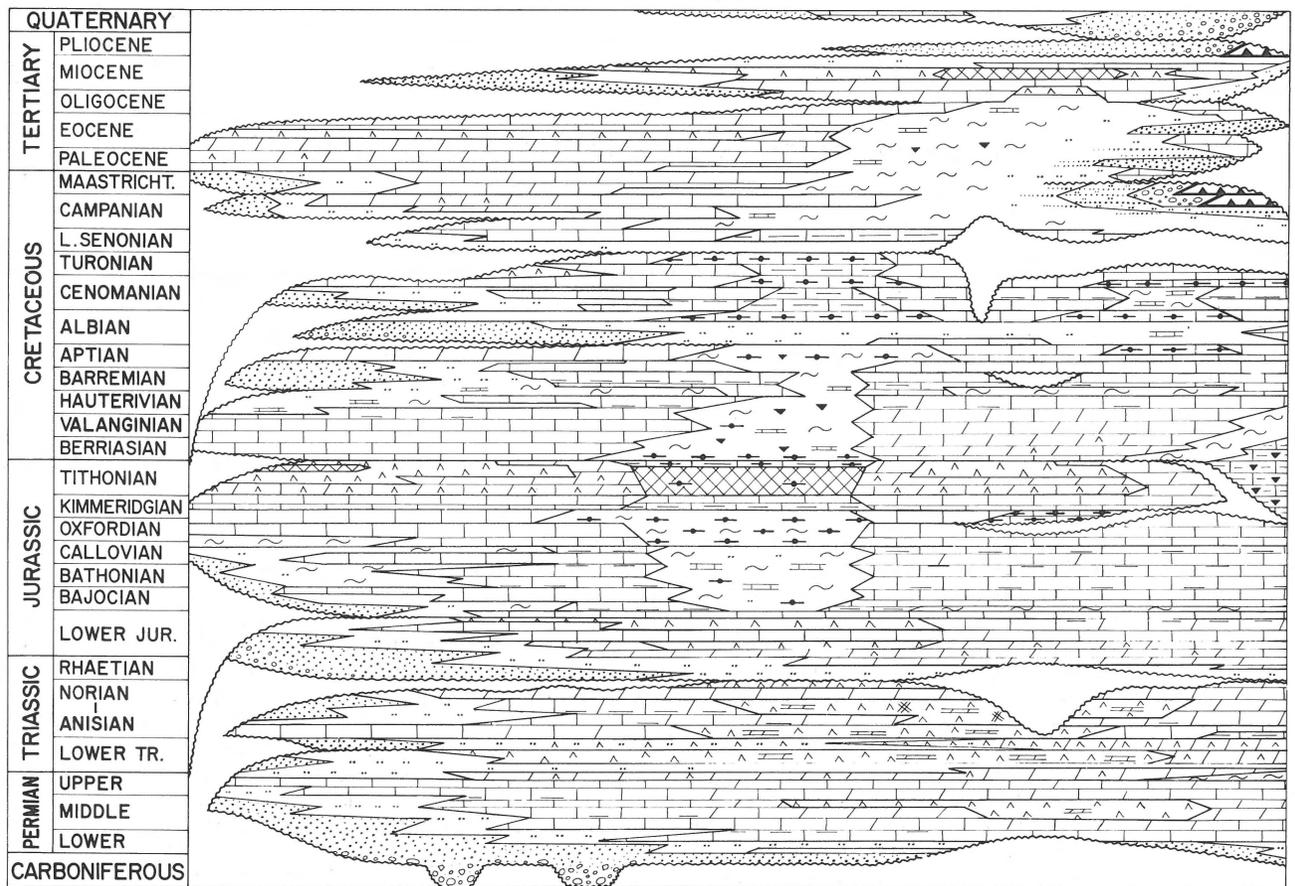

Fig. 1
Generalized stratigraphy of Middle East.

shaly successor basin in the east. Clastic material was then supplied from the isostatically rising orogenic belt on the eastern flank of the basin.

The depositional basin narrowed considerably during the early to middle Oligocene, probably in connection with a pronounced worldwide drop in sea level (VAIL ET AL. 1977). Late Oligocene to middle Miocene carbonate rocks and evaporites covered the basin, to be replaced by clastic rocks during the younger Miocene and the Pliocene. This clastic supply was connected with the late Alpine phase which created the present Zagros and Palmyra foldbelts, with overthrusting evident along the northern part of the Zagros crush zone.

Basic Patterns of Carbonate Deposition

Two basic types of carbonate depositional systems alternated through time: (1) the so-called carbonate ramp (AHR, 1973) and (2) the differentiated carbonate shelf. These two types of carbonate deposition are comparable to those distinguished by BAY (1977) in the Lower Cretaceous of the Gulf Coast. This two-fold subdivision into 'ramp' versus 'differentiated shelf' may well be applicable to other, if not most, shallow-water depositional realms.

Carbonate ramp — The carbonate ramp is characterized by the alternation of more and less clayey units. Each cycle can be correlated over large distances — in the order of hundreds of kilometers — parallel with the depositional strike as well as perpendicular to it. The individual cycles are remarkably constant in thickness and lithology; changes, if any, occur very gradually. The purper carbonate units are typically pelletoidal-bioclastic wacke-packstones with local ooidal grainstones. The more argillaceous units are rich in pyritized pellets to micropellets and grade laterally into marls and shales. Core investigations show that the cycles, 30 to 100 m thick, can be divided into numerous subcycles, each of which can again be correlated over surprisingly wide areas.

Deposition of the ramp-type formations coincided with periods of increased clastic influx onto the carbonate shelf from the western hinterland. The middle Jurassic is a good example of this type of deposition with the concomitant excellent correlatability of the individual cycles, as shown in the lower part of figure 2 (Dhruma Formation).

Differentiated carbonate shelf — The differentiated carbonate shelf conforms more closely to the standard type of carbonate platform described by WILSON (1975, p. 22-27). The formations falling into this category were formed during relatively high
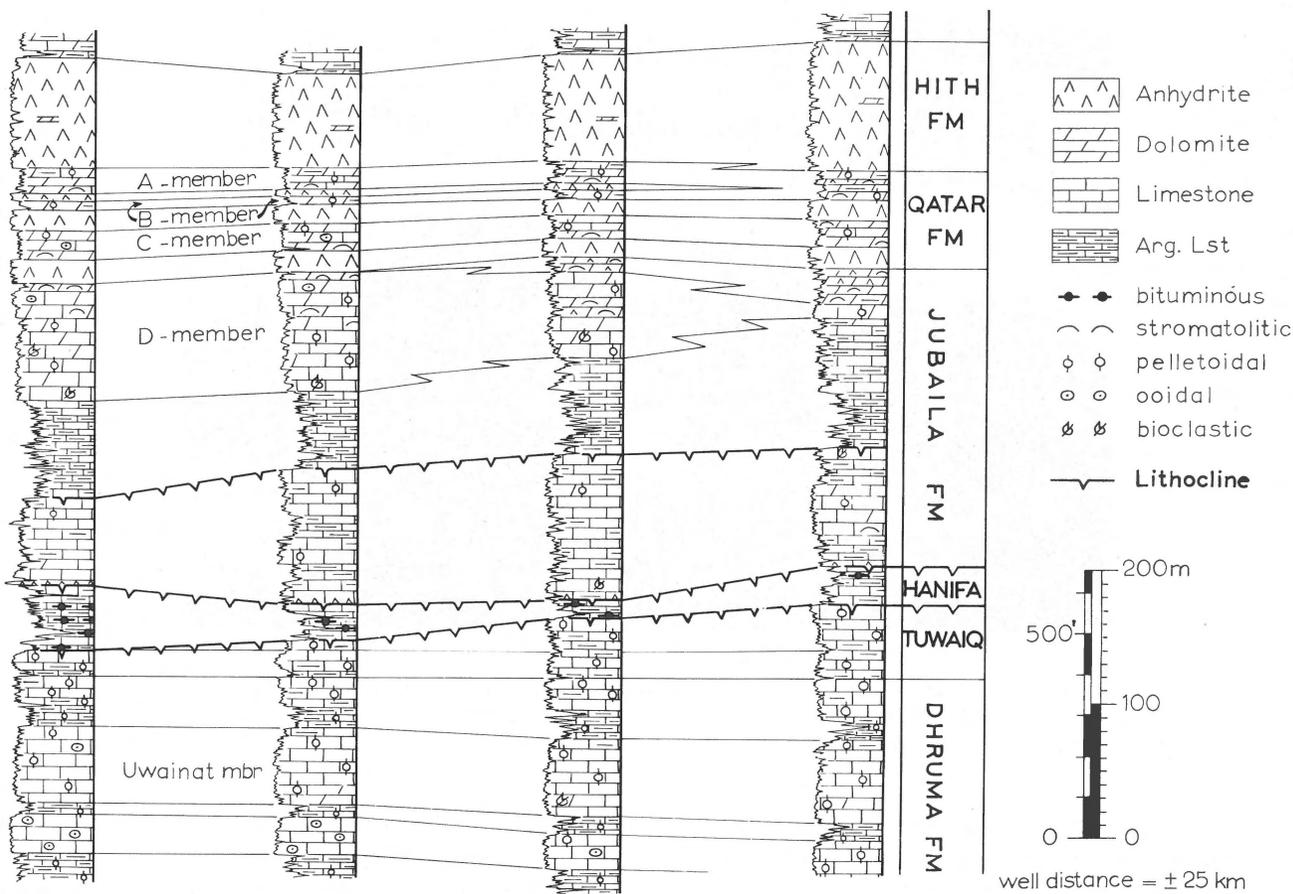
Fig. 2
Carbonate ramp (Dhruma Formation) versus differentiated shelf (Tuwaiq-Hith Formations), Qatar area.

stands of sea level, when clastic supply was pushed far back to the west. On the shallower parts of the platform rather pure carbonates were deposited, typically algal-foraminiferal wacke-packstones and ooidal-pelletoidal pack-grainstones. The deeper parts of the inundated platform became sediment starved, with reduced deposition of lime mud and marl, commonly under euxinic conditions.

Owing to the critical water-depth dependency of carbonate production, the carbonate cycles formed under these conditions are much less constant in thickness and lithology than those of the ramp-type units. Characteristic time-transgressive lithification surfaces (PURSER, 1969, 1972) separate the cycles. These were formed by submarine lithification of the slope in front of shelf margins. When the sea level kept rising, these hardgrounds were progressively covered by basinal muds. At the same time, the shallow shelf margin was gradually drowned and subjected to lithification and sometimes to slope erosion. Depending on the balance between the rate of carbonate production in the shallow waters and the speed of sea-level rise and slope erosion, the carbonate margin was outbuilding, upbuilding, or inbuilding. When outbuilding, the slope prograded with the formation of numerous minor hardgrounds. Under upbuilding and in particular inbuilding conditions, a single well-defined hardground was formed, which is

older in the more basinal part than near the margins. The basinal muds above the lithified surface in the centers of the depressions commonly are demonstrably older than the shallow-water carbonates below the same surface further upslope, which may lead to confusion in regional correlations.

The middle part of figure 2 shows an example of a differentiated shelf with hardgrounds separating the Tuwaiq, Hanifa, lower Jubaila, and upper Jubaila-Hith cycles (Late Jurassic). Figure 3 is a photomicrograph of the lithocline surface separating the high-energy carbonates at the top of the Tuwaiq cycle (below) from the basinal muds of the Hanifa cycle (above).

Climate has been another important factor controlling the lithofacies development in the Middle East. Since Permian time the area was situated in the tropical to subtropical belts as it migrated from the southern latitudes past the equator (Cretaceous) to northern latitudes in conjunction with the northward drift of the Afro-Arabian continent (e.g., reconstruction by SMITH & BRIDEN, 1977). Superimposed on this gradual change due to global position were climatic changes of shorter periodicity, reflected in the alternation of more humid and more arid conditions. These were probably related in a very complex way to global mean-temperature variation, continental configuration, presence of mountain ranges, etc.
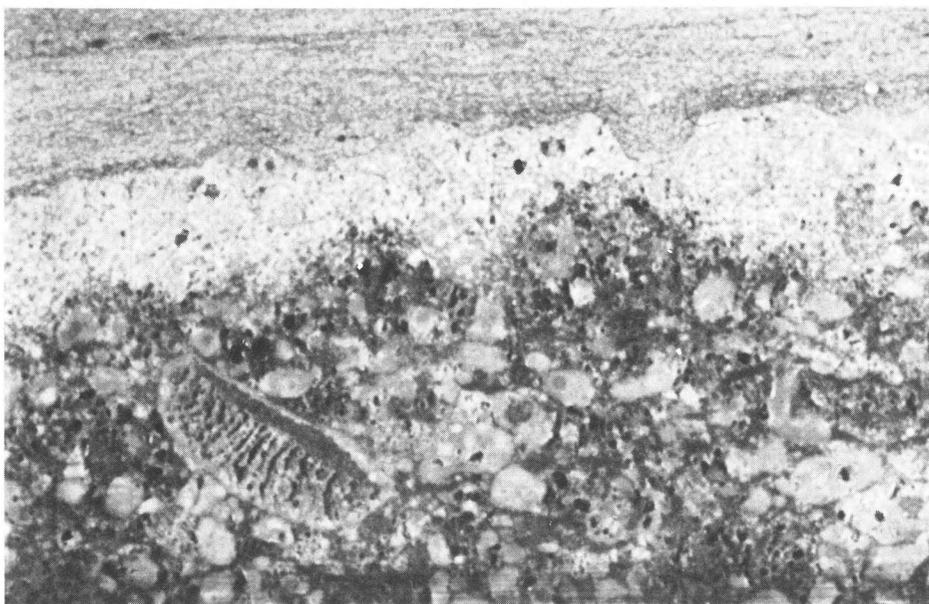
Fig. 3
Photomicrograph of lithoclinal surface between bioclastic - pelletoidal grainstone (Tuwaiq) below and lime - mudstone (Hanifa) above, Qatar area. Large object in lower left - hand quarter is about 3 mm long.

The interplay of changes in sea level, epeirogenetic crustal movements, and climatic variations controlled to a large extent the depositional patterns on the vast carbonate platforms which characterize the Middle East oil province. The relative role each of these factors and the way in which they interact are not fully understood.

Megatectonic Frame

Figure 4 shows the megatectonic frame of the Middle East as it is today. The area is bounded on the northeast by the Zagros 'crush-zone,' a major right-lateral strike-slip fault zone of late Tertiary to recent age, which separates the Zagros foldbelt from the tectonically very complex Hamadan-Sirjan zone of interior Iran. In front of this fairly rectilinear fault system are outposts of nappes created during the two orogenic upheavals which affected the region during the late Campanian to early Maestrichtian and late Miocene to Pliocene.

On the south the crush zone terminates against the so-called Dibba line (1 in Fig. 4), a NNE-SSW-striking lineament which separates continental basement on its west from the oceanic realm of the Gulf of Oman-Makran on the east. This line acted in all probability as an ocean to continent transform fault during the Mesozoic along the boundary between the Afro-Arabian plate and oceanic Tethys. Southeast of the Dibba line the ophiolite-radiolarite nappe complex of the Oman Mountains was emplaced during the late Campanian to early Maestrichtian (GLENNIE ET AL, 1974, p. 393). This complex is bounded on the southeast by another continent to ocean transform fracture zone, the Masirah line (2 in Fig. 4), which

separates the Arabian continent from the Indian Ocean and which is also of Mesozoic origin.

The stable Arabian platform is dominated by two types of structural elements: (1) broad regional highs such as the Jauf-Ga'ara-Mosul arch in the north (a in Fig. 4), the Qatar-South Fars arch in the central Gulf area (b in Fig. 4), and the Huqf-Dhofar arch in the south (c in Fig. 4); and (2) mostly NNE-SSW-striking anticlinical trends and flexures reflecting deep-seated basement faults. All of these structural elements have influenced sedimentation from the early Mesozoic onward, with periods of increased activity alternating with quiet intervals. They were most active from the late Turonian to the early Campanian, the aforementioned period of major change in basin configuration and the first phase of regional compressive tectonics.

Another major structure former is the Infra-Cambrian salt. Four distinct salt basins can be distinguished, from south to north: (1) South Oman-Dhofar, (2) Fahud, (3) the Southern Gulf, and (4) the Northern Gulf. The limits of the first three basins are fairly well known, but the northern extension of the Northern Gulf basin is highly conjectural. The edge of the salt, as determined from outcrops and/or from geophysical records, may be depositional, that is, by a lateral change into a carbonate-anhydrite platform, or owing to later erosion or solution. The Qatar arch and the Central Oman platform between the Fahud and South Oman salt areas are probably examples of intervening carbonate platforms.

The four salt basins each have their own style of halokinesis, probably reflecting differences in original salt thickness and in overburden thickness and lithology. The South Oman-Dhofar
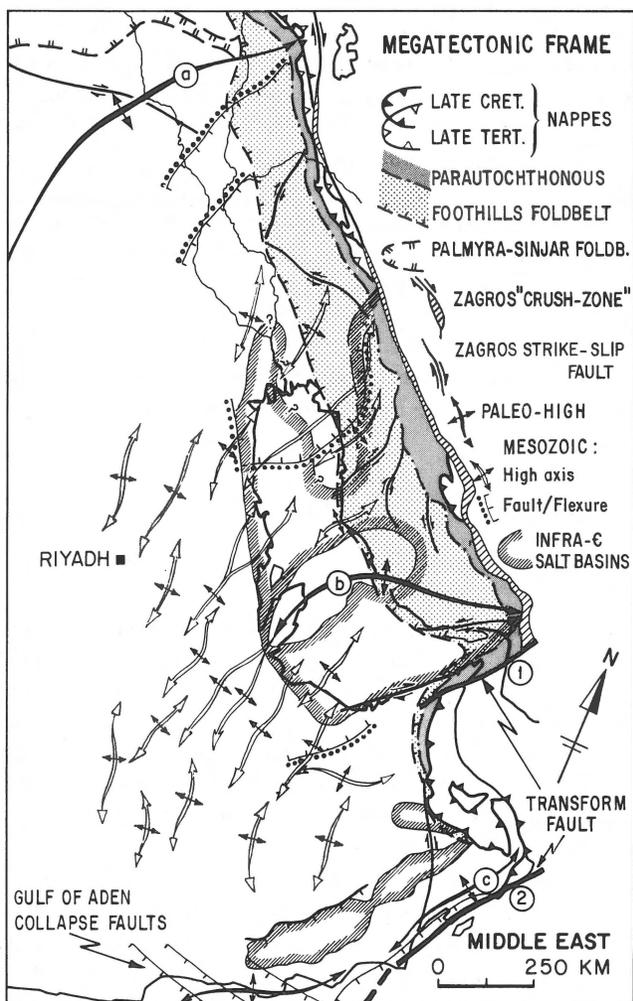
Fig. 4
Megatectonic frame of Middle East; (1) Dibba line, (2) Masirah line, (a) Jauf-Gáara-Mosul arch, (b) Qatar-South Fars arch, (c) Huqf-Dhofar arch.

Gulf salt basin contains very large, elongate pillows and salt swells, such as Dukhan, Bahrain, and Rumailah and only a few piercements. Some of the largest oil accumulations such as Burgan occur in combined halokinetic-basement horst-block structures.

The Zagros foldbelt, with its famous giant 'whale-back' structures, extends between the undisturbed Arabian platform and the nappes or crush zone. Recent deep drilling and seismic work have shown that the rather simple surface folds become much more complex at depth, where the acute space problem is resolved by repeated reverse faulting and even overthrusting. The Infra-Cambrian salt and the principal shale formations such as the Jurassic Sargelu and the Cretaceous Garau and Khazhdumi provide the necessary detachment zones. The shortening of the sedimentary cover is considerable, increasing eastward. In the High Zagros, designated as parautochthonous in figure 4, the shortening may well be two to three-fold or more. Unfortunately data are lacking for a reliable palinspastic reconstruction, which therefore has not been attempted when constructing the layer maps (Figs. 6-23).

The Zagros fold chains are offset by several strike-slip faults of regional significance. These commonly appear to follow preexisting Mesozoic faults which acted during the compressive phases as boundaries between the differentially folded segments. Near the High Zagros, the faults seem to have been rotated dependent on their angle of incidence with the axis of maximum compression which was roughly northeast-southwest. At their southwestern end the faults tend to splay off into reverse faults in front of the anticlinical folds, producing a horsetail pattern.

Not all strike-slip faults are confined to the Zagros belt. On the Arabian platform, and in particular on its northern promontory in Syria, northwest Iraq, and southeast Turkey, dextral and sinistral strike-slip faults and fault zones were formed during the Late Cretaceous orogenic period. These fault zones are commonly accompanied by narrow grabens, with a thick Upper Cretaceous sedimentary fill, which were inverted during the late Tertiary compressive phase, giving rise to en echelon foldbelts.

In the southernmost Arabian Peninsula a fault system is related to the collapse of the Gulf of Aden. Though initiated in Jurassic times, this fault system only became fully active in its present form during the early Tertiary. From the late Oligocene onward major rifting occurred in the Gulf of Aden.

Depositional Environment and Oil Habitat

The depositional patterns resulting from the interplay of sea-level changes, epeirogenetic movements plus rejuvenation of relief, climatic variations, and synsedimentary structural growth have a direct bearing on the regional distribution of habitat-controlling parameters such as source rock, reservoir, and seal, and hence are of great interest to the petroleum geologist. Figure 5 serves as a legend to the layer maps of

basin shows all the classical elements: piercements, domes, pillows, turtlebacks, and rim synclines of different ages. Its southern part is a half-graben bounded on the northwest by the Ghudun-Khasfah fault, a northeast-to-southwest-striking fault zone of early Paleozoic age. The eastern edge of the basin is erosional because of the repeated uplift along the flank of the Huqf-Dhofar high. The small Fahud salt basin contains only a few halokinetic structures, modified in its eastern part by regional tectonics connected with the Oman Mountains.

The large Southern Gulf salt basin is characterized by numerous piercements which are surrounded by Cretaceous to late Tertiary rim synclines. The diapirs are separated by very gentle pillows with flanks generally dipping only a few degrees, many of which contain oil accumulations. No undisputed turtleback structures have been reported. If present, such structures must occur below depths of 4,000 to 5,000 m, where seismic resolution is still insufficient. The Northern

DEPOSITIONAL ENVIRONMENT	LITHOLOGY		SOURCE	RESERVOIR	SEAL
	MAIN	OTHER			
Humid Climate:					
Alluvial - U. Coastal Plain	Sandstone	Silt/Claystone Lignite	(G)	X	
Lower Coastal Plain	Sandstone Siltst/Claystone	Lignite Carbonate	(G)	X	X
Clastic (Shallow Shelf)	Shale	Silt/Sandstone Limestone		(X)	☒
Mixed (Shallow Shelf)	Shale/Marl Limestone	Silt/Limestone		(X)	(X)
Carbonate (Shallow Shelf)	Limestone	Shale/Marl Dolomitic Lst		X	
Clastic (Deeper Shelf — Intrashelf Basin)	Shale/Marl	Siltstone Bituminous Shale	(X)		X
Mixed (Deeper Shelf — Intrashelf Basin)	Shale/Marl Arg. Limestone	Bituminous Lst Siltstone	X		(X)
Carbonate (Deeper Shelf — Intrashelf Basin)	Arg. Limestone Bituminous Lst	Marl/Shale	☒		(X)
Shallow Carbonate Shelf prograding over Basin	Limestone Arg. Limestone	Marl/Shale Bit. Limestone	X	X	
Arid Climate:					
Alluvial - U. Coastal Plain	Sandstone Red-gn Claystone	Siltstone Anhydrite		X	(X)
L. Coastal Plain — Clastic Platform	Red-gn Claystone Siltstone	Anhydrite/Dol. Sandstone		(X)	X
Mixed (Shallow Platform)	Anhydrite/Dolomite Red-gn Claystone	Siltstone Sandstone		(X)	X
Carbonate (Shallow Platform)	Dolomite Dolomitic Limest.	Anhydrite Shale/Marl		X	(X)
Evaporite (Sebkha)	Anhydrite Shale/Marl	Dolomite Rocksalt	(X)	(X)	☒
Evaporite Basin	Anhydrite Rocksalt	Shale (bitum.) Arg. Limestone	X		☒
Deep Open Marine:					
Little/No Clastic Influx	Arg. Limestone Siliceous Lst	Marl/Shale	(X)		(X)
With Clastic Influx	Marl/Shale	Arg. Limestone Siltstone			X
Synorogenic Basin:					
Distal	Shale Siltstone	Sandstone Limestone		(X)	X
Proximal	Breccia/Conglom. Claystone	Olistostromes			

☒ = High quality regional source/seal   (G) = Gas source only

Fig. 5

Key to layer maps, figures 6 through 23. *X,* Well developed, mostly present. *(X),* doubtful, scattered. Square indicates high quality (source/seal only).

figures 6 through 23. It lists the depositional environments present in the Middle East, with the lithologies typical of the various environments. Also indicated is the translation of these lithologic units into habitat terms such as source, reservoir, or seal potential.

Periods of low sea-level stand plus increased clastic influx, when ramp carbonates were dominant, produced good reservoirs in the form of coastal and alluvial sands, whereas coastal and platform shales formed effective regional seals. Within the realm of carbonate deposition moderately good reservoirs were laid down during these periods in the form of pelletoidal-bioclastic packstones and, less commonly, ooidal-pelletoidal grainstones. Seal development within the carbonate realm was modest and resulted in marls and argillaceous limestones with limited sealing capacity, especially in the less gentle structures.

During high sea-level stands and consequently suppressed clastic influx, excellent source beds commonly were formed in the euxinic intrashelf basins, whereas the algal boundstones and ooidal-bioclastic pack-grainstones which commonly cap the cycles form good reservoirs. Under evaporitic conditions, excellent and widespread anhydrite-salt seals were formed, both on the shallow carbonate platforms and in the intrashelf basins. In the latter, however, though the seals overlie or are interbedded with euxinic source rocks, there is little reservoir to seal.

The open marine offshelf realm is not a very favourable oil habitat. Reservoirs and source rocks are few or nonexistent, and the calcareous shales and marls are only moderately effective seals, especially when fractured. The synorogenic and postorogenic clastic sediments of the Zagros contain some reservoirs and seals, but they are restricted to the most disturbed part of the foldbelt and are of limited interest.

BASIN EVOLUTION

Pre-Late Carboniferous

The sequence deposited prior to the Hercynian unconformity will be dealt with briefly here, for data are limited. The sequence does not form part of the rich Middle East oil habitat. Commercial oil fields have been found only on the fringes of the basin (e.g., southern Oman-Dhofar). Elsewhere, the pre-Hercynian sequence is buried below thick upper Paleozoic, Mesozoic, and Tertiary sedimentary rocks, offering therefore only speculative deep gas prospects.

The first unmetamorphosed sedimentary rocks covering the Arabian shield are the carbonates, clastics, and evaporites of the Huqf Group. The salt of this depositional megacycle causes halokinetic structures in parts of the basin (Fig. 4). The age of the salt is somewhat problematic. Well and outcrop evidence suggest a late Precambrian to early Cambrian age, as the salt is separated from dated Middle Cambrian carbonate rocks by a thick red-bed sequence.

Carbonate-evaporite sedimentation of this 'Infra-Cambrian' is followed by a predominantly clastic regime during the early Paleozoic. Vast aprons of terrestrial to very shallow-marine sandstones with subordinate shales and silts were laid down over the entire shields area (HELAL, 1965). Carbonate rocks are rare and restricted to the middle-late Cambrian, early-middle Devonian, and early-middle Carboniferous. Several regional unconformities related to epeirogenetic movements affect the sequence of which the most important are pre-late Cambrian, pre-Devonian, and early Carboniferous. In general the formations become more sandy toward the south, and the unconformities become more pronounced. As a result, the lower Paleozoic along the southern rim of the basin is composed almost exclusively of sandstone and conglomerate formations, separated by unconformities representing wide time gaps.

In late Carboniferous time the Middle East craton was affected by the main phase of Hercynian movements, which is reflected in upwarp and concomitant erosion, locally cutting as deep as the Cambrian or even the Precambrian.
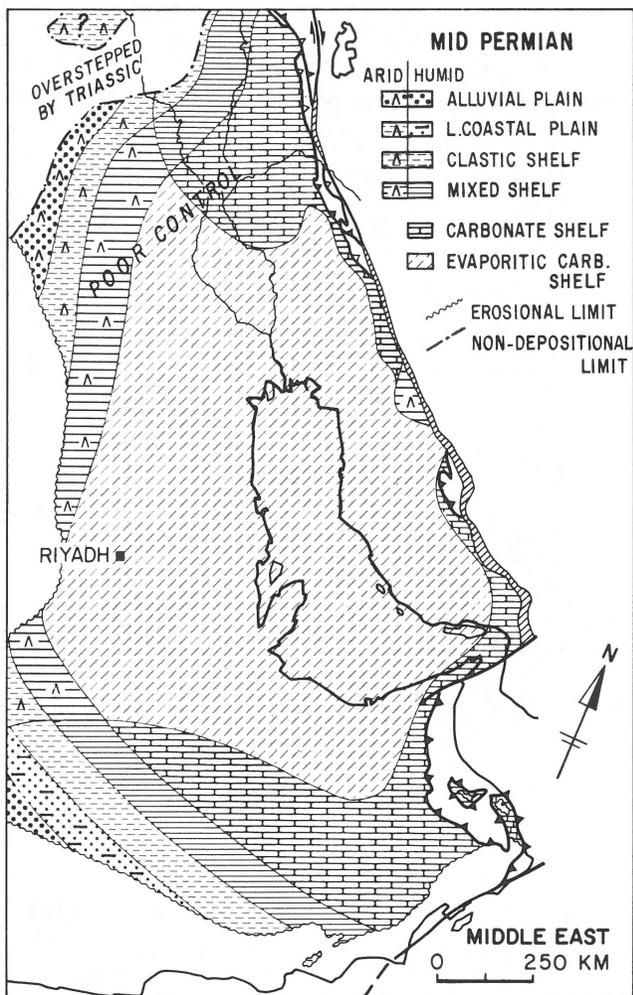
Fig. 6
Mid-Permian environments of deposition.

Fig. 7
Early Triassic environments of deposition.

Late Carboniferous to Liassic

The first sedimentary rocks laid down after the Hercynian epeirogeny are clastics of glacial origin, dated as late Carboniferous to earliest Permian by palynology. HUDSON & SUDBURY (1959) were the first to draw attention to the glacial origin of this formation and HELAL (1969) described similar strata in southern Saudi Arabia. The glacial origin of these beds has been corroborated by subsurface data from southern Oman and Dhofar, where they contain oil accumulations in the Marmul area now under development. The glacial nature of these deposits is firmly established in the south only. In Oman the glacial influence can be seen to decrease northward, and beds of similar age in the Iranian Zagros and in eastern Turkey are nonglacial coastal deposits (SZABO & KHERADPIR, 1978). The late Carboniferous to early Permian glacial beds of the southern part of the Arabian shield belong to the Dwyka glaciation of the Gondwana continent.

During the Permian the climate became gradually warmer and more arid. By mid-Permian time a carbonate platform

was established over most of the region (Fig. 6). Evaporites are present along a central belt, whereas clastic material was mainly provided by the western hinterland, with local supplies from the east in the High Zagros. The latter probably represent local sources in the uplifted Hercynian ranges along the margin of Paleotethys.

In the early Triassic (Fig. 7) hot arid conditions prevailed over the whole basin. Increased clastic influx from the western hinterland is evident, restricting the carbonate-evaporite platform to a rather narrow northwest-southeast-trending belt. There is evidence in the Oman Mountains that the margin with the open Tethys ocean was somewhere in the eastern part of the present mountain range (GLENNIE ET AL, 1974, p. 355-386). The evaporites deposited during this period form, together with younger Triassic evaporites, an effective regional seal to major gas accumulations in the underlying Permian carbonate-rock reservoirs.

Figure 8 shows the situation as it had evolved by Ladinian to Carnian times. During the Anisian a major inundation of the platform had occurred, and clastic influx from the west was
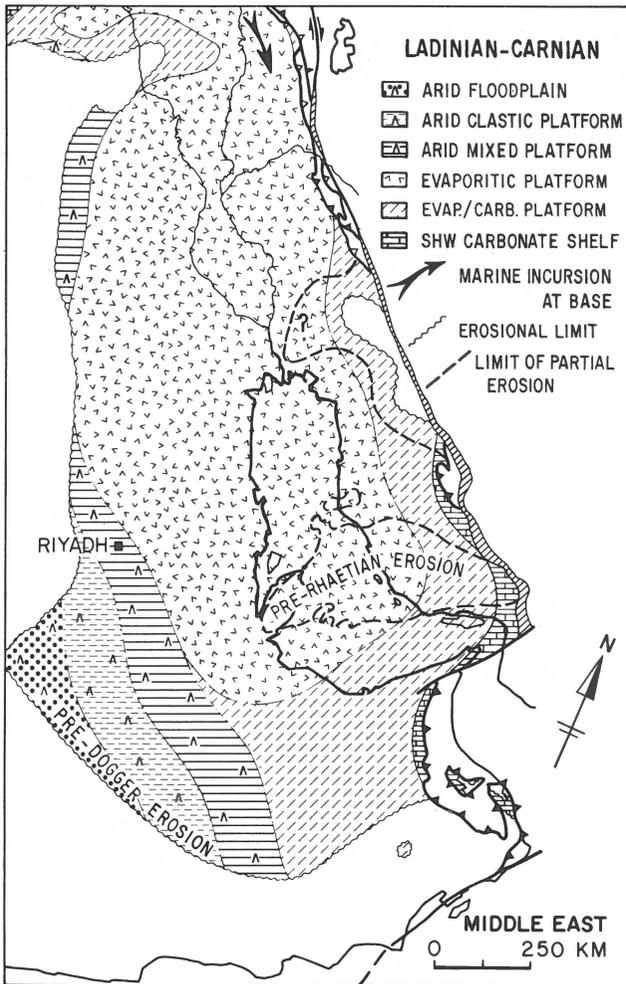
Fig. 8
Ladinian to Carnian environments of deposition.

Fig. 9
Rhaetian environments of deposition.

again much subdued. Most of the basin was occupied by an evaporitic platform with very little differentiation. In the northern tip of the basin more open-marine incursions suggest a connection with Tethys.

Near the close of the Triassic there was a marked change. The climate became less arid, and there was apparently a relative drop in sea level, caused either by a eustatic lowering of the sea or a rise of the shield. That the craton was tectonically active is shown by the activation of regional highs such as the Qatar arch, as witnessed by some erosion of the Triassic (Fig. 8; SZABO & KHERADPIR, 1978). The Rhaetian layer map (Fig. 9) shows the effects of this late Triassic change with restriction of arid conditions to the northern part of the platform, and nondeposition across the Qatar arch. The fluviatile and coastal sandstones belonging to this period have good reservoir properties, but are so far unproductive, probably owing to lack of access to adequate hydrocarbon charge.

During the subsequent early Jurassic, carbonate deposition became gradually more widespread, and by late Liassic time (Fig. 10) there was again a vast carbonate-evaporite platform which, however, still received substantial clastic influx from the west. Evaporitic conditions were limited to the northwestern half of the carbonate platform.
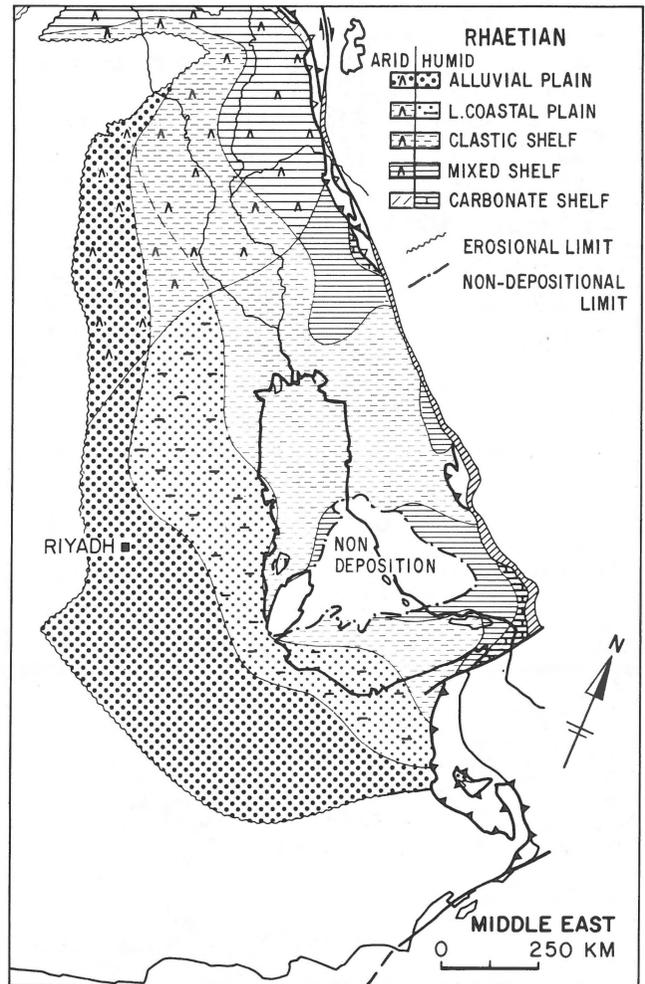
Middle Jurassic to Turonian

Near the end of the early Jurassic a major change in the regional depositional pattern occurred. The climate became more humid, so that the hitherto ubiquitous evaporites became rare, while at the same time a more pronounced tectonic differentiation of the platform led to the creation of an intrashelf depression, the Lurestan basin, in the north.

Figure 11 shows the depositional pattern during the Bathonian – a wide carbonate platform with an intrashelf basin in its northwestern part. Clastic material was supplied from the west and also from the south, where the Gulf of Aden area was an active positive element. The carbonates deposited on the platform during this period are good examples of the ramp model: wide sheets of pelletoidal-ooidal pack-grainstones cyclically alternating with argillaceous pelletoidal-bioclastic mud-wackestones (Fig. 2, Dhruma Formation). The higher energy, cleaner carbonate rocks form oil and gas reservoirs in the central part of the basin.

Sometime during the late Callovian a major inundation of the Middle East platform was initiated, which continued until late Tithonian – earliest Berriasian time. This event had a profound impact on the paleogeography of the area and is
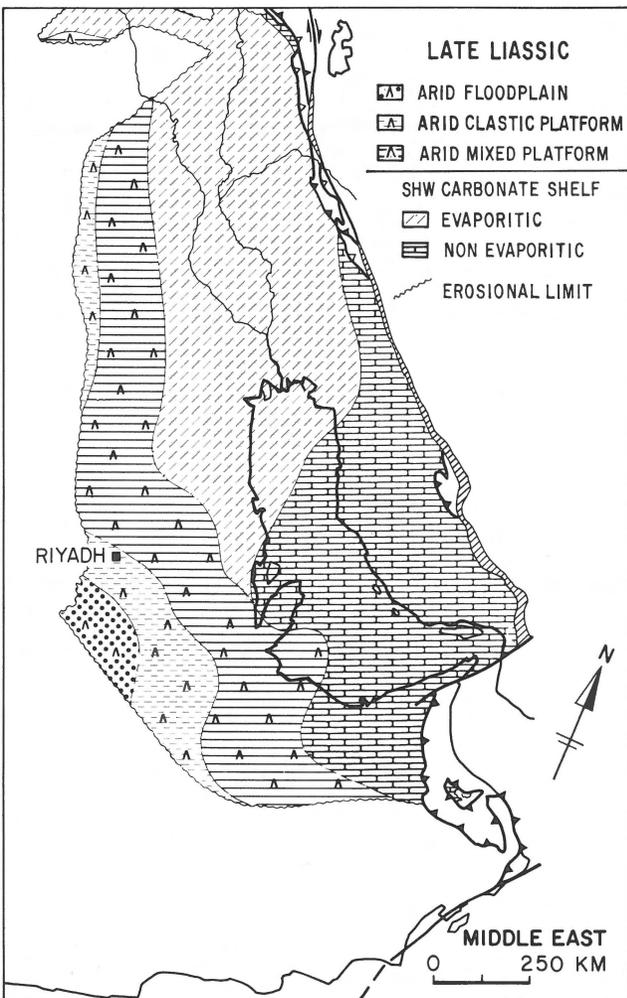
Fig. 10
Late Liassic environments of deposition.

Fig. 11
Bathonian environments of deposition.

responsible for much of the oil found in the central part of the province.

The environments of deposition by late Oxfordian - early Kimmeridgian times are depicted in figure 12. Clastics were absent and the Lurestan basin had been extended southward by flooding of the platform. For the first time the continental margin between platform and open ocean is evident. East of this margin, little or no deposition occurred, and a submarine lithification surface was formed, covered by a thin veneer of pelagic crinoid debris. Under the influence of the steadily rising sea level this margin was gradually eroded back so that, westward, increasingly younger pelagic deposits rest on increasingly younger shelf carbonate rocks: a perfect example of a lithocline. As shown by figure 12, the top of the marginal complex was, near the end of the cycle, subjected to non-deposition and erosion in a high-energy environment, probably in conjunction with a temporary minor drop in relative sea level. Maximum erosion occurred where the Qatar-South Fars arch intersects the marginal complex.

On the flooded platform and in the permanent Lurestan basin with euxinic conditions, laminated bituminous lime muds and marls were deposited, which later became the prolific source of the oil found in the Late Jurassic Arab
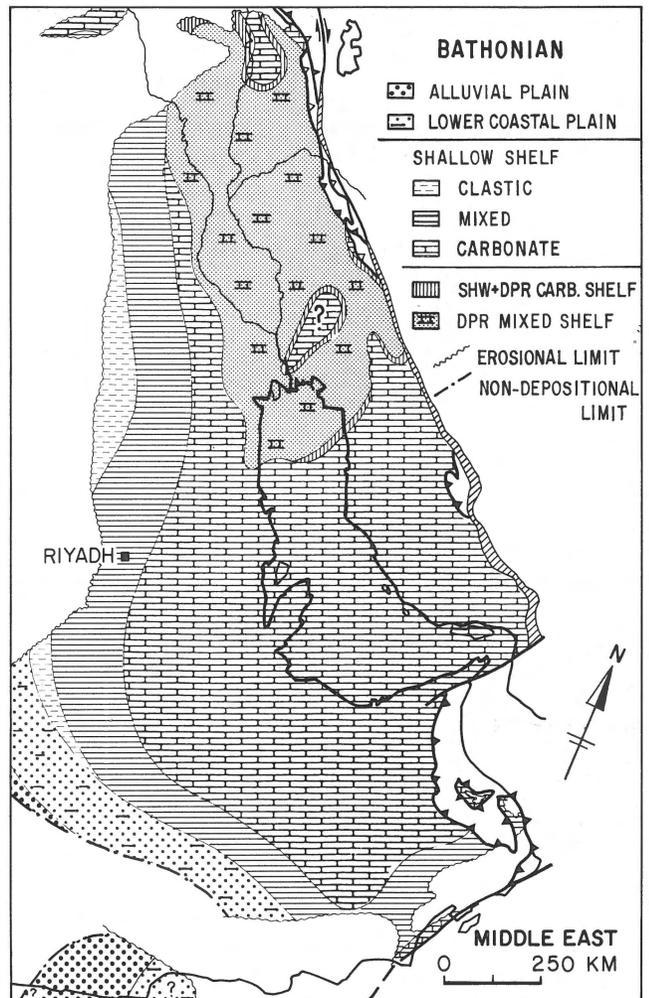
reservoirs. Though the center of the Lurestan basin was by this time several hundreds of meters deep, the starved intrashelf basin on the flooded platform had probably a depth of only a few tens of meters, as reconstructed from the sedimentologic study of cores and from regional isopach and facies data. On the correlation diagram of the Qatar area (Fig. 2) this cycle is represented by the Hanifa Formation, here primarily developed in its basinal facies.

During the remainder of the late Jurassic, sea level appears to have risen steadily, as evidenced by the continued recession of the continental margin. On the platform, however, carbonate deposition kept pace with and finally superseded the flooding, reestablishing very shallow depositional conditions over the southern part of the Middle East. In Tithonian time (Fig. 13) the climate again became arid, so that extensive evaporites were deposited on the very shallow southern platform in a sabkha environment, in the Lurestan basin as basinal salt and laminated anhydrite and shale (Gotnia Formation). Figure 2 indicates the spatial relation of the Hanifa source, Arab A to D reservoirs, and the sealing anhydrites of the Qatar and Hith formations, the result of the sequence of events sketched previously. It is this source-reservoir-seal triplet which constitutes the world's richest single oil habitat,
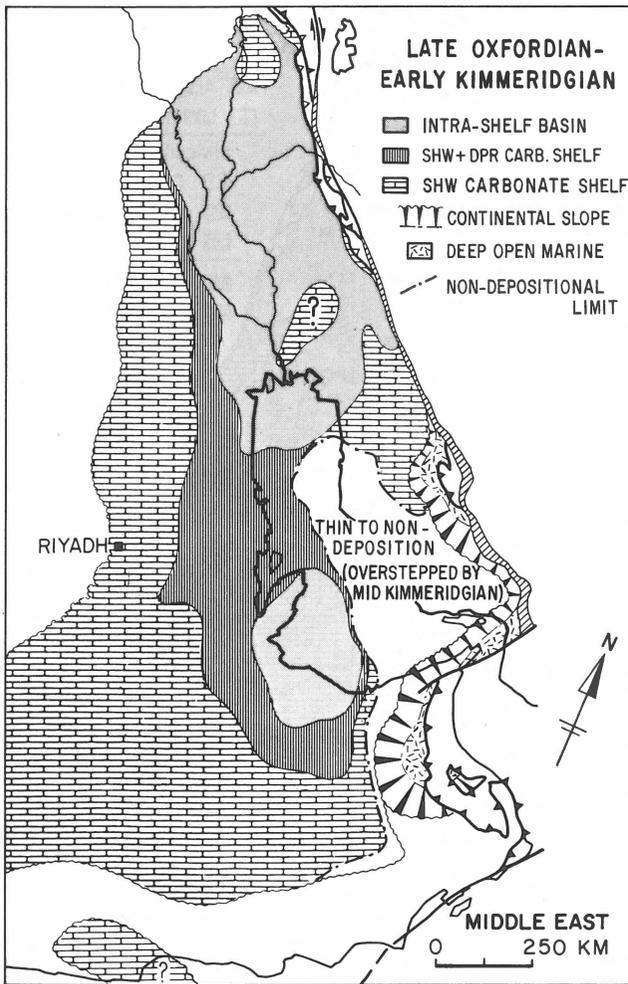
Fig. 12
Late Oxfordian to early Kimmeridgian environments of deposition.

Fig. 13
Tithonian environments of deposition.

containing well over 100×10^9 bbl of recoverable reserves and possibly even as much as several times that amount.

During the early Cretaceous there was a gradual return to a more humid climate, and evaporites disappeared from the record. Relative sea level dropped, and ramp-type carbonate deposition replaced the differentiated shelf. The early-mid-Valanginian layer map (Fig. 14) shows the 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. In the south the Gulf of Aden swell is well expressed as a broad arch with nondeposition and erosion. Clastic influx is still limited, and restricted to the far southwestern corner.

Through the Hauterivian and Barremian the trend toward increased clastic influx continued. By mid-late Barremian time (Fig. 15) 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 with the open Tethys was again located beyond today's mountain front. The Gulf of Aden swell was still evidence, but had apparently been subsiding
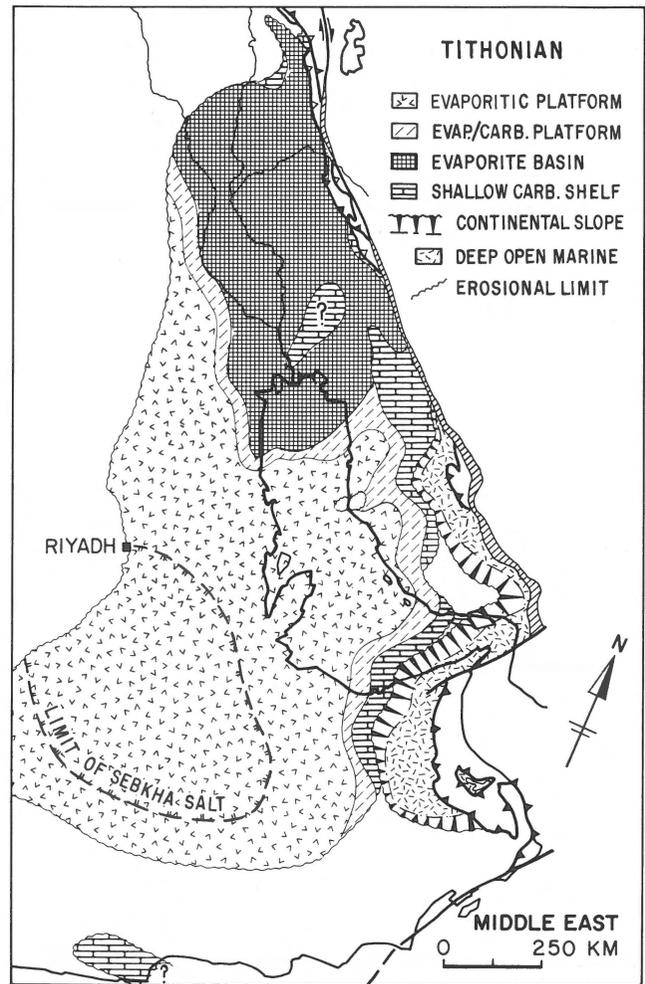
since the earlier Cretaceous, whereas the Qatar arch was now the locus of marked thinning, nondeposition, and even pre-Aptian erosion.

The extensive sheets of pelletoidal-bioclastic pack-grainstones which form the higher energy parts of the cycles contain oil and gas accumulations in the southern part of the Gulf, where they are sealed by the interbedded marls and argillaceous limestones. Farther north, the coastal plain sandstones of the Zubair Formation contain major oil reserves in several fields. 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 (Fig. 16). The Lurestan basin again expanded and a new subbasin was formed in the Khuzestan area of Iran, providing the source for at least part of the oil in the giant Iranian fields. In the southern Gulf another intrashelf basin is evident, occupying about the same location and area as the late Oxfordian-early Kimmeridgian basin (compare Figs. 12 and 16). On the fringing shelf margins rudist 'reefs' grew where conditions
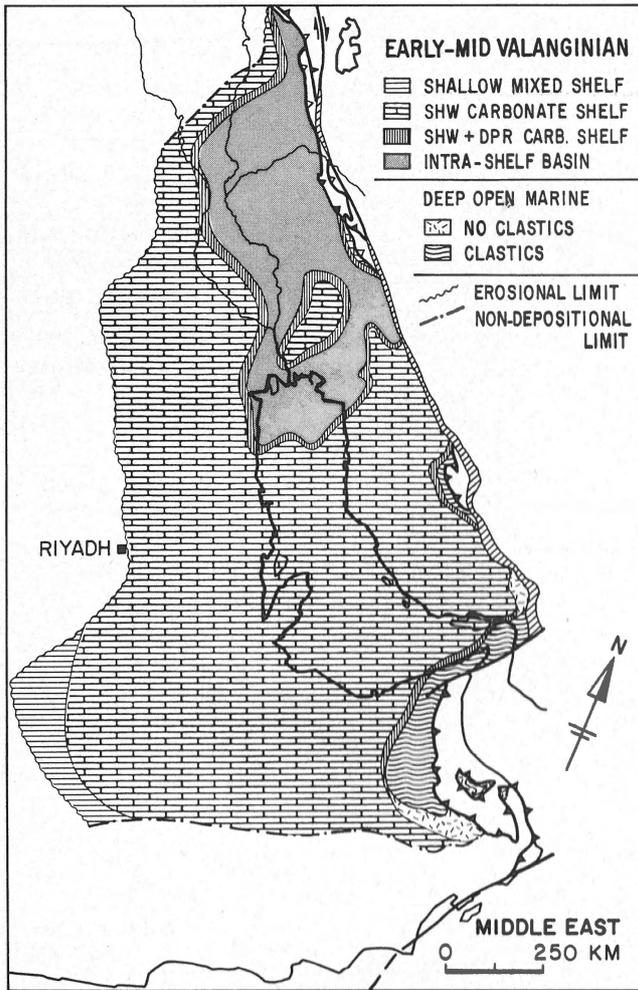
Fig. 14
Early to mid-Valanginian environments of deposition.

Fig. 15
Mid- to late Barremian environments of deposition.

were favorable, creating the prolific Shuaiba reservoirs (see also WILSON, 1975, p. 342-347).

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 such as that on Figures 12 and 13. The climate was also more humid than during the late Jurassic, though evaporites were again deposited on the northern end of the platform.

The temporary flooding during the Apitan was followed by the most pronounced regression since the Rhaetian. As shown on figure 17, by mid-Albian time the classic regime had spread across the whole platform except for a narrow belt in the northeast. The Lurestan basin was now at its smallest, and separated by a shallow mixed-carbonate shelf from the Khuzestan subbasin (K in Fig. 17) which was filled by shales deposited in front of the Burgan delta lobe. 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
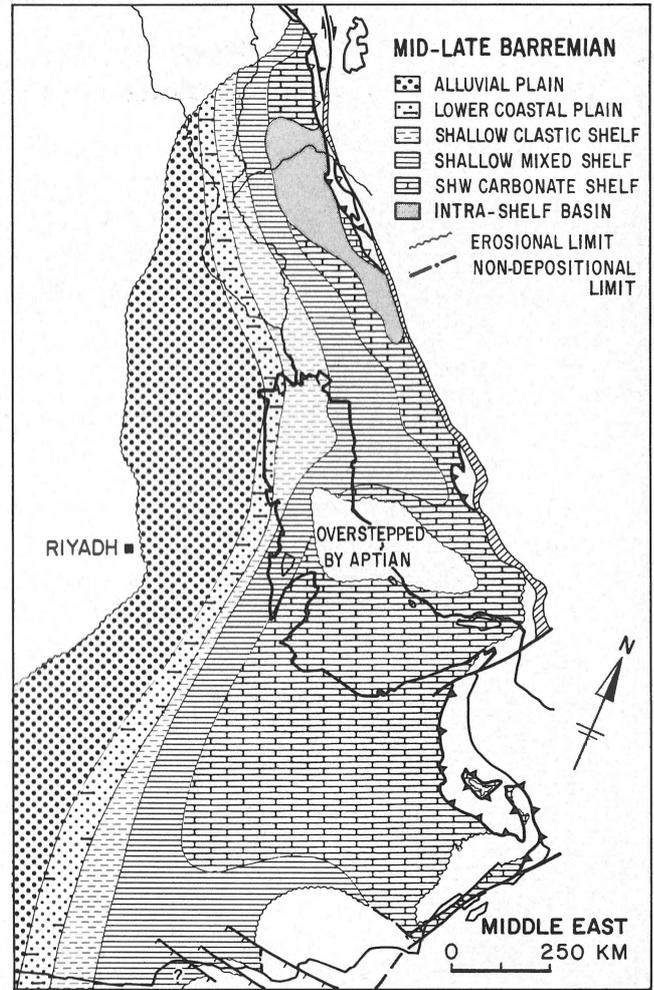
deposits of the Lurestan basin.

Figures 18 to 20, late Albian, early Cenomanian, and late Cenomanian, 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 the 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 the deeper parts), which are potential source rocks. On the shallow shelf, foraminiferal-algal wack-packstones and rudist pack-grainstones were deposited and these now form the reservoirs.

Early Senonian to Recent

Near the end of the Turonian a major change occurred with the onset of the Alpine orogeny. The older Mesozoic structural elements were strongly reactivated, with concomitant erosion and nondeposition during the early part of the new
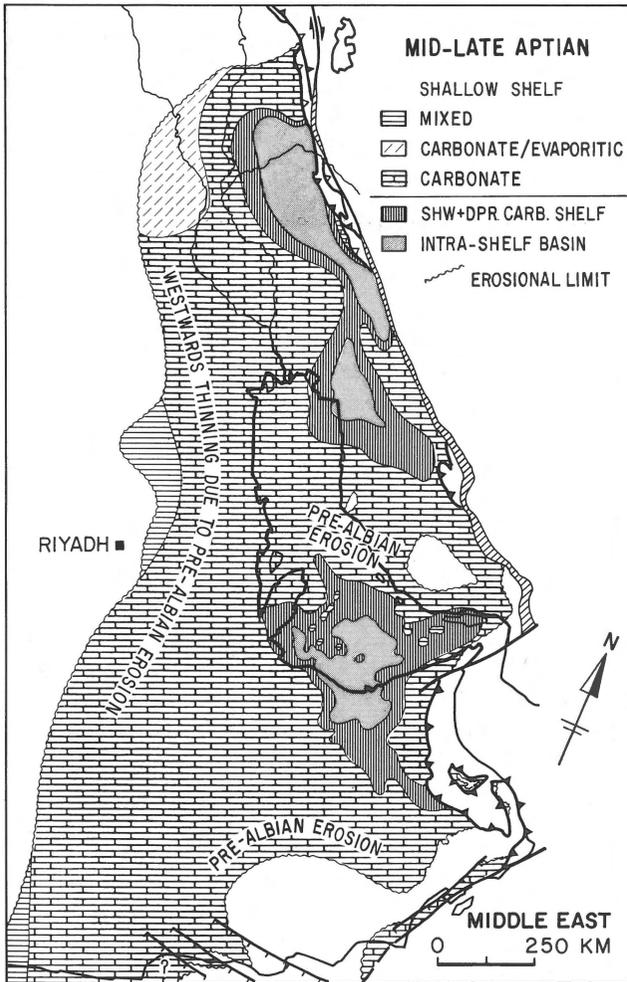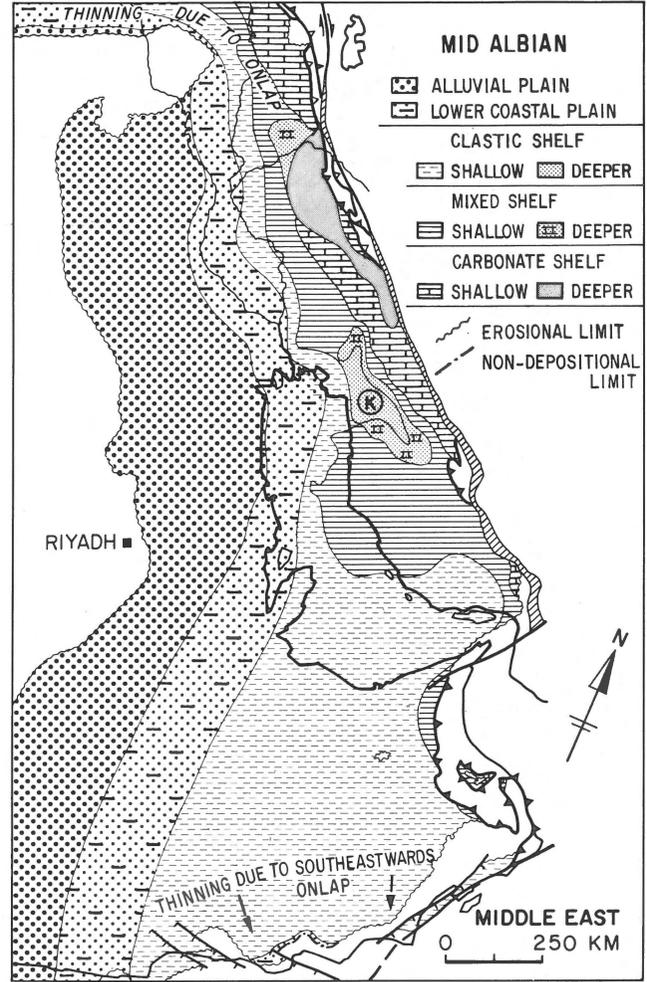
Fig. 16
Mid- to late Aptian environments of deposition.

Fig. 17
Mid-Albian environments of deposition: *K*, Khuzestan subbasin.

megacycle. A foredeep was formed along the rising orogene, trending northwest-southeast, the now dominant direction. Figure 21 shows the situation in late Campanian time. Along the orogenic front in the northeast, nappes were emplaced from northeast to southwest. Where they originated from the open Tethys ocean, they are composed of radiolarites and ophiolites – the Oman Mountain complex (GLENNIE ET AL. 1974) and the southern Zagros salient in the Neyriz area (RICOU, 1974). In the northern Zagros the late Cretaceous nappes are made up of radiolarites and shelf carbonate rocks of Jurassic age, without genuine ophiolites (BERTHIER ET AL. 1974). The lithology, facies relations, and palinspastic reconstructions suggest that these northern nappes represent the old marginal realm of the Arabian plate, underlain by continental crust. There is no evidence for true oceanic conditions such as in the Oman Mountains.

As shown in figure 21, the nappes are accompanied by a fringe of synorogenic deposits in the form of wildflysch-type boulder clays, conglomerates, and olistostromal masses near the nappe front, and as regular shale-silt-sandstone flysch away from it. As usual, the nappes tended to overrun their own preceding debris, and along the thrust front the complica-

tions are manifold and not always resolvable. Seismic data and sedimentologic studies point to an eastern source of the synorogenic deposits, the rising orogene. Between the orogenic front and the shelf in the west was an open-marine basin, in which marls and calcareous shales with globotruncanids and other planktonic forms were deposited. From the shelf in the west shallow-water carbonates prograded over the slope shales into this marine basin.

The shelf had become much more varied. In the south a major source of clastics was present, in the north was a carbonate platform with a central evaporitic pan. In the far north, narrow restricted grabens were formed in conjunction with ENE-WSW-trending wrench-fault systems. The synsedimentary fill is mostly marl and shale with common bituminous limestone, phosphate, and chert beds. At the northeastern end of the plunging Mosul arch in northwest Iraq, near the edge of the area mapped, the presence of Campanian shallow-shelf carbonate rocks with intraformational conglomeratic and brecciated zones was reported from the Kurdistan mountain front area (Hadiena and Bekhme limestones) by DUNNINGTON ET AL (1959). These formations appear to be recemented carbonate slope breccias, later taken
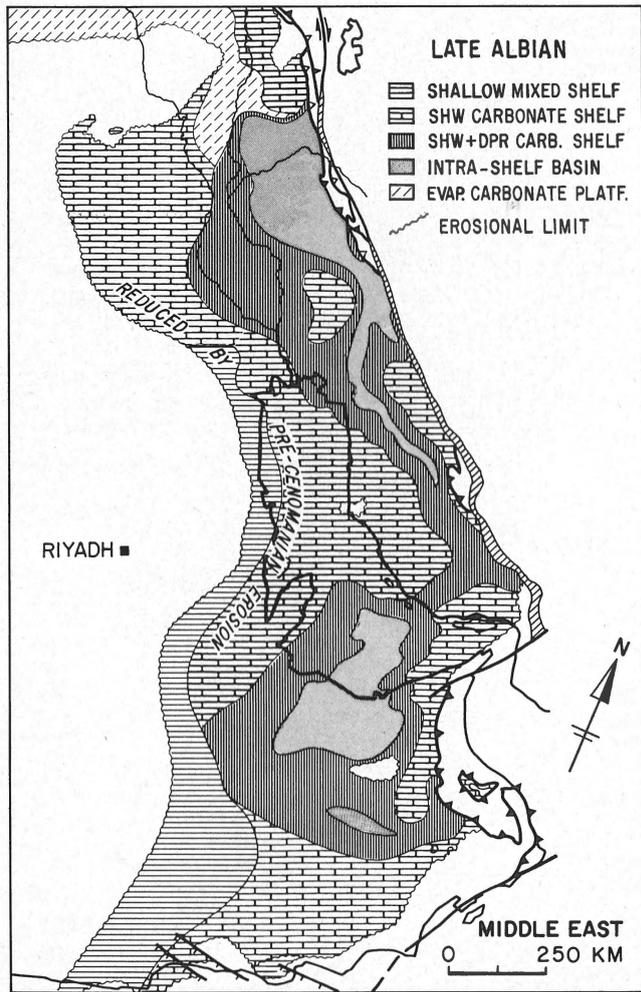
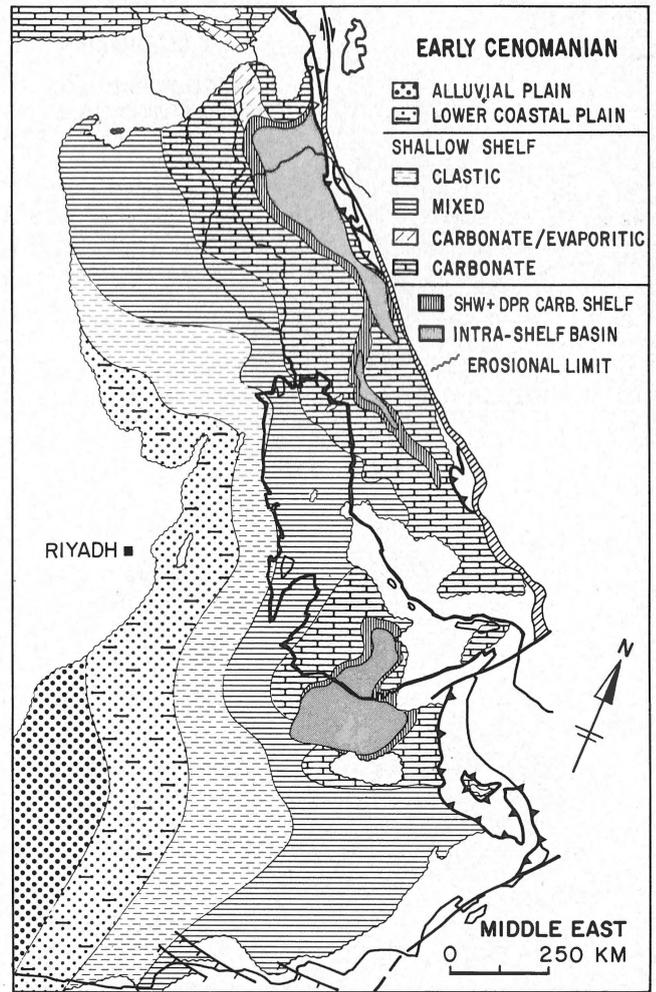Fig. 18
Late Albian environments of deposition.

Fig. 19
Early Cenomanian environments of deposition.

up in the thrust front, and as such are indicated on figure 21 as proximal synorogenic deposits.

By late Maestrichtian time, orogenic upheaval had abated and more quiet depositional conditions returned. The Oman Mountains, loaded with heavy ultrabasic rocks, rose little and were the site of late Maestrichtian shallow-water carbonate deposition. Most of these conditions existed also in the southwestern end of the Zagros thrust belt, but in the north, where ultrabasic rocks are absent and continental crust is present, the orogenic zone started to rise isostatically, producing an apron of clastics which contain reworked radiolarite debris shed by the nappes.

Figure 22 shows the paleogeography in the Paleocene-early Eocene with the open-marine successor basin and the wide shallow evaporitic platform southwest of it separated by a narrow and steep margin. Clastic material came from the rising orogenic belt in the northeast. In the southern Zagros an isolated carbonate island with a central evaporite pan occupied the middle of the open marine basin. This shoal was caused by shallowing along the axis of the Qatar-South Fars arch, which still acted as a regional positive element. In the far south, the east-central part of Gulf of Aden swell started to

collapse, leading to an incursion of the Indian Ocean.

During the remainder of the Eocene the paleogeography stayed nearly the same, though the climate was less arid and evaporites were therefore virtually absent. The open-marine basin was gradually narrowed through progradation of the western carbonate platform and the growing wedge of clastic and shallow-water carbonate material, generated by the rising lands in the northeast. Across the Arabian platform, beds of late Eocene age are missing, which is partly because of nondeposition on the gradually emerging carbonate shelf. In the early and middle Oligocene this trend was accelerated, aided by an apparent major drop in relative sea level. The drop, which is reflected on the platform by extensive leaching and erosion of the Eocene carbonate rocks, is probably correlative with the global mid-Oligocene event (VAIL ET AL, 1977, p. 87), but its precise dating has not been attempted.

Figure 23 shows the situation in Aquitanian time (latest Oligocene to early Miocene). The depositional realm has shrunk as compared to previous maps. Only a rather narrow northwest-southeast-trending evaporitic shelf with central depressions remained, with clastics coming in from the west and east. At the northern tip of the gulf a major source of sand
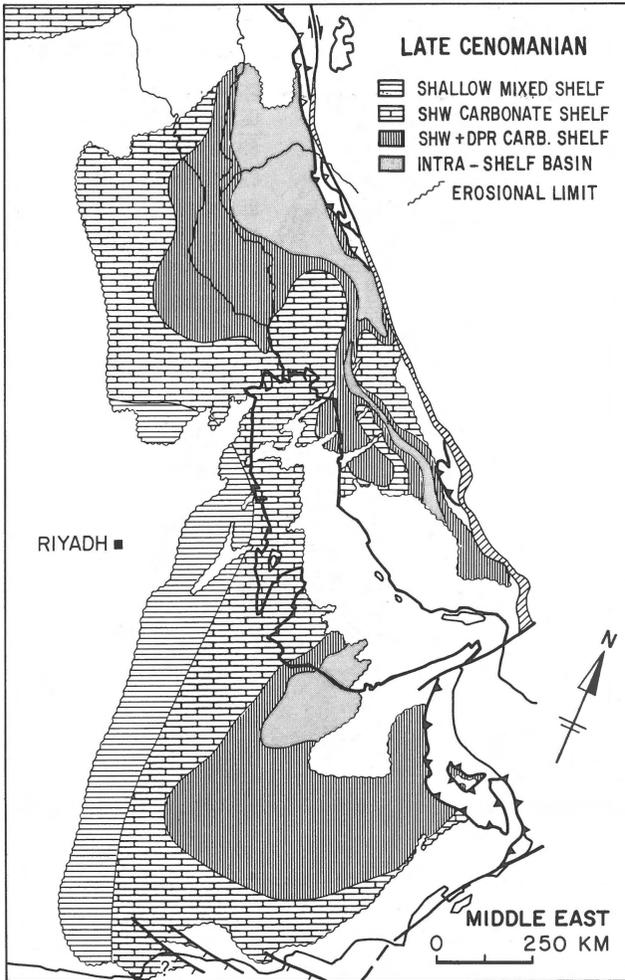
Fig. 20
Late Cenomanian environments of deposition.

Fig. 21
Late Campanian environments of deposition.

was present, forming the Ahwaz delta.

The late Oligocene to early Miocene Ahwaz sandstone and Asmari limestone form the principal reservoirs of the giant Iranian fields. Geologic and geochemical data point strongly to a deep source for this oil, that is, from Cretaceous and Jurassic source rocks deposited in the Lurestan and Khuzestan intrashelf euxinic basins (DUNINGTON, 1967; THODE & MONSTER, 1970; MURRIS & DE GROOT, 1979). As already postulated by DUNNINGTON (1967), Cretaceous carbonate reservoirs thereby commonly served as 'way stations' in which oil started to accumulate as early as the late Cretaceous to early Tertiary, in structures which by then still must have been aligned along the old Mesozoic NNE-SSW trends. During the late Tertiary folding phase, which in the Zagros is much stronger that the late Cretaceous phase, the present northwest-southeast giant anticlinical traps were formed. The Campanian-Oligocene marls and shales which until then formed an effective seal to the Cretaceous reservoirs were fractured and hydrocarbons escaped upward into the Asmari traps, which are capped by the very efficient sealing Gach Saran evaporites of early to middle Miocene age.

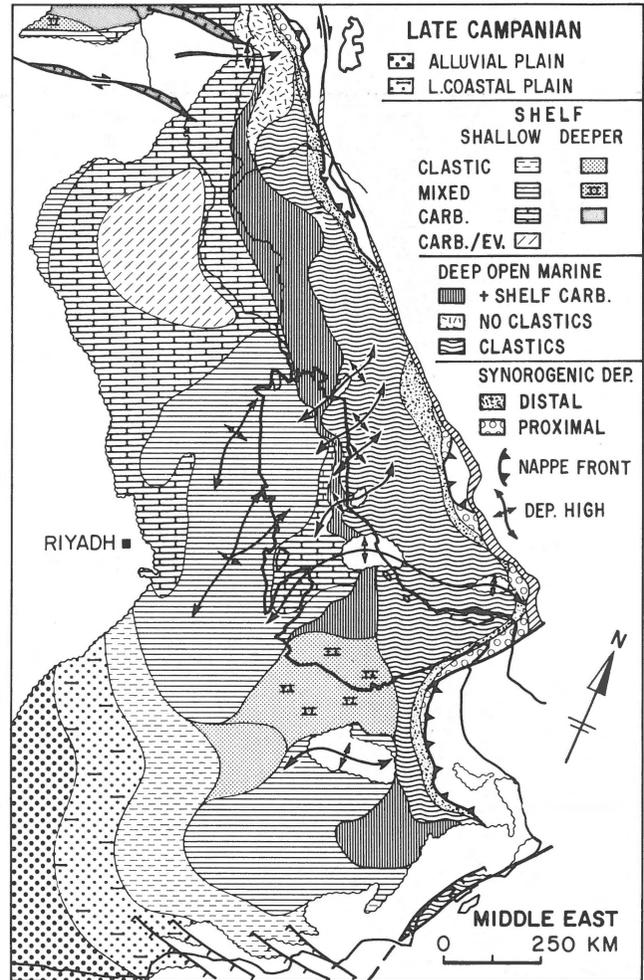The Miocene evaporites and carbonate rocks were suc-

ceeded in the late Miocene and Pliocene by a clastic sequence which gradually coarsens upward and ends with the massive Bakhtiari conglomerates and sandstones, a molasse-type deposit contemporaneous with the later stages of the late Tertiary orogenic event. The Pliocene Zagros folds came into existence and, in Kurdistan and the northern High Zagros, nappe emplacement occurred, which may have started as early as late Miocene (BERTHIER ET AL, 1974).

Today, the center of the successor deep again has shifted farther west and coincides with the axis of the gulf and its northwestern extension, the Mesopotamian depression. The Zagros crush zone which, at least along part of its trace, is a root zone for the late Cretaceous and late Tertiary nappes, now acts as a dextral strike-slip fault (see also BERTHIER ET AL, 1974, p. 97-101). Earthquake epicenter maps of the region show a concentration of foci 0 to 100 km deep along the Zagros foldbelt (NOWROOZI, 1971). In contrast, the zone between the Zagros crush zone and the Elburz is seismically remarkably quiet, which indicates that central Iran is today a stabilized block of which the crush zone forms the southwestern frontal boundary. The seismic data suggest that the crustal shortening caused by the active spreading of the Red Sea and
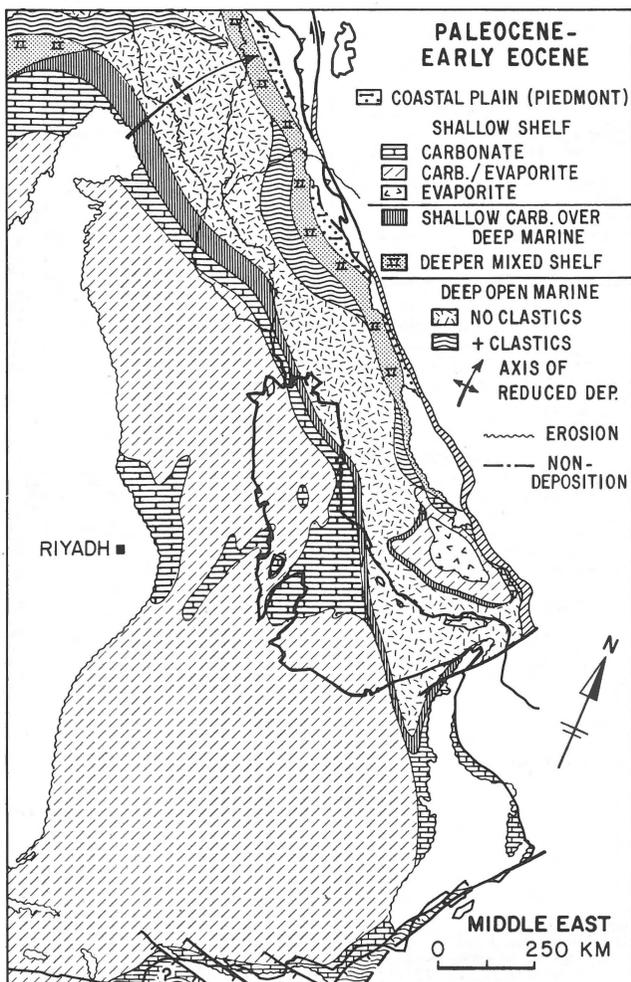
Fig. 22
Paleocene to early Eocene environments of deposition.

Fig. 23
Aquitanian environments of deposition.

the Gulf of Aden is accommodated by an imbrication of the continental crust underlying the Zagros foldbelt. The presence of some very deep foci – more than 100 km – implies that we are not only dealing with a crustal process but that the mantle is involved too.

CENTRAL GULF OIL HABITAT

Bajocian to Albian Sequence

For a clearer understanding of how the depositional environment, in conjunction with structure and maturation through burial, controls the hydrocarbon distribution, a restricted area and section will be described in more detail. Figure 24 depicts the regional development of the Bajocian to Albian sequence in the central Gulf area, around the Qatar Peninsula. The section is about 700 km long, and oriented roughly east-west, with the approximate location of the Qatar Peninsula indicated above it.

The mid-Jurassic Dhruma Formation is the lowermost unit: a typical carbonate ramp, of which the margin with the open
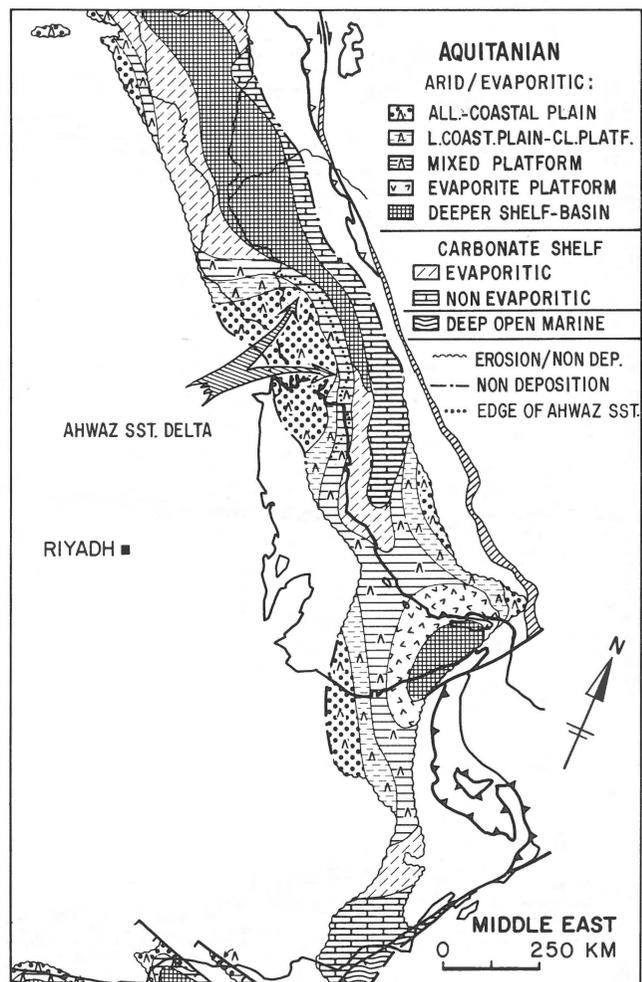
ocean was located well east of the section. This wide flat platform is the substrate for the subsequent differentiated shelf of the late Jurassic, gently backtilted by differential subsidence.

The late Jurassic inundation which started during the late Callovian is very evident in this section. In the east is the inbuilding carbonate margin, separated from the deep open-marine marls and cherty limestones by lithoclinal surfaces. West of the margin is the intrashelf depression, where in late Oxfordian to early Kimmeridgian time euxinic conditions reigned. At the western end of the section, the Tuwaiq (late Callovian-late Oxfordian) and Hanifa (late Oxfordian-early Kimmeridgian) cycles expand upshelf, separated by lithoclinical surfaces. The mid-Kimmeridgian to Tithonian shallow shelf built out into the intrashelf basin, containing tongues of ooidal-pelletoidal grainstones and algal boundstones which represent the very shallow terminal carbonate units. The late Jurassic closed with sabkha evaporites, which at the margin with the open sea are replaced by algal boundstones and oolite sands.

Above the late Jurassic evaporite platform the early Cretaceous carbonate shelf prograded into the open ocean in the
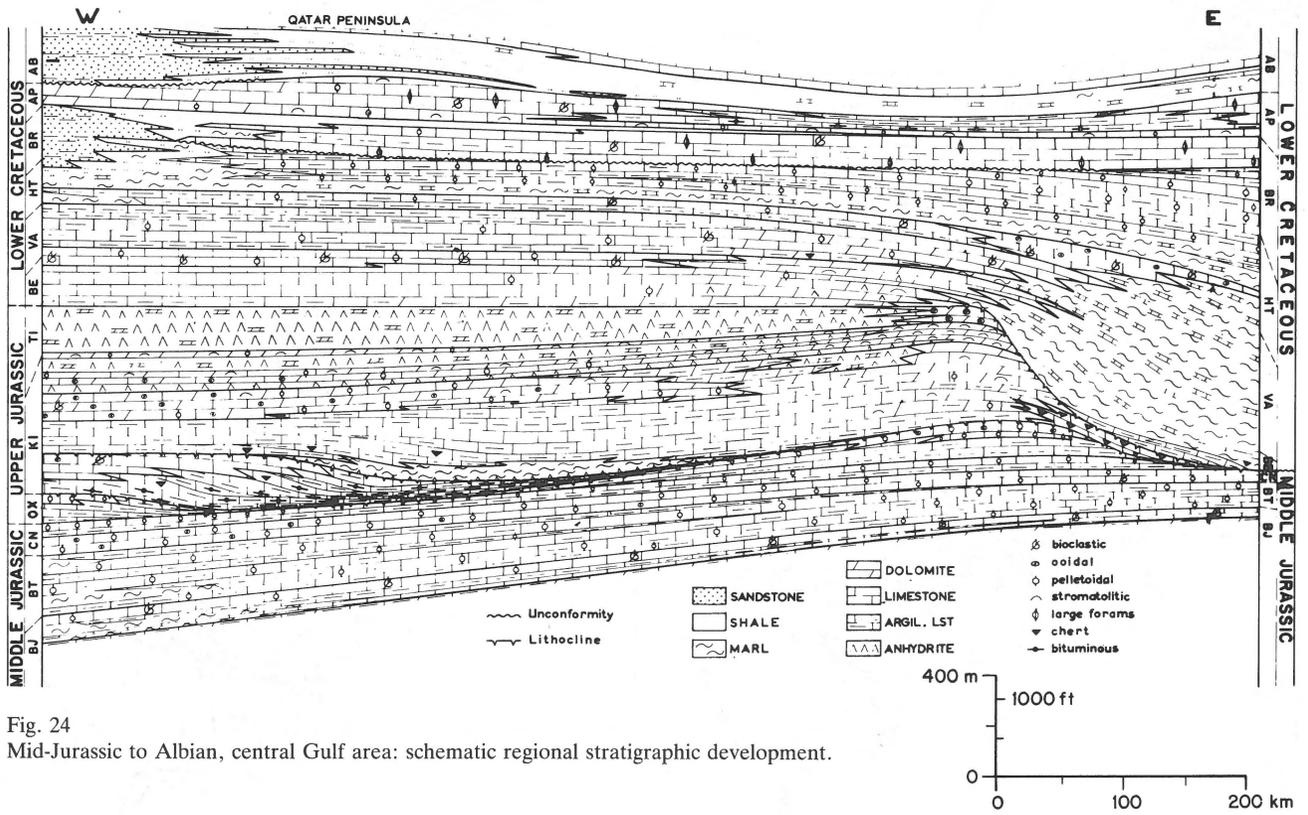
Fig. 24
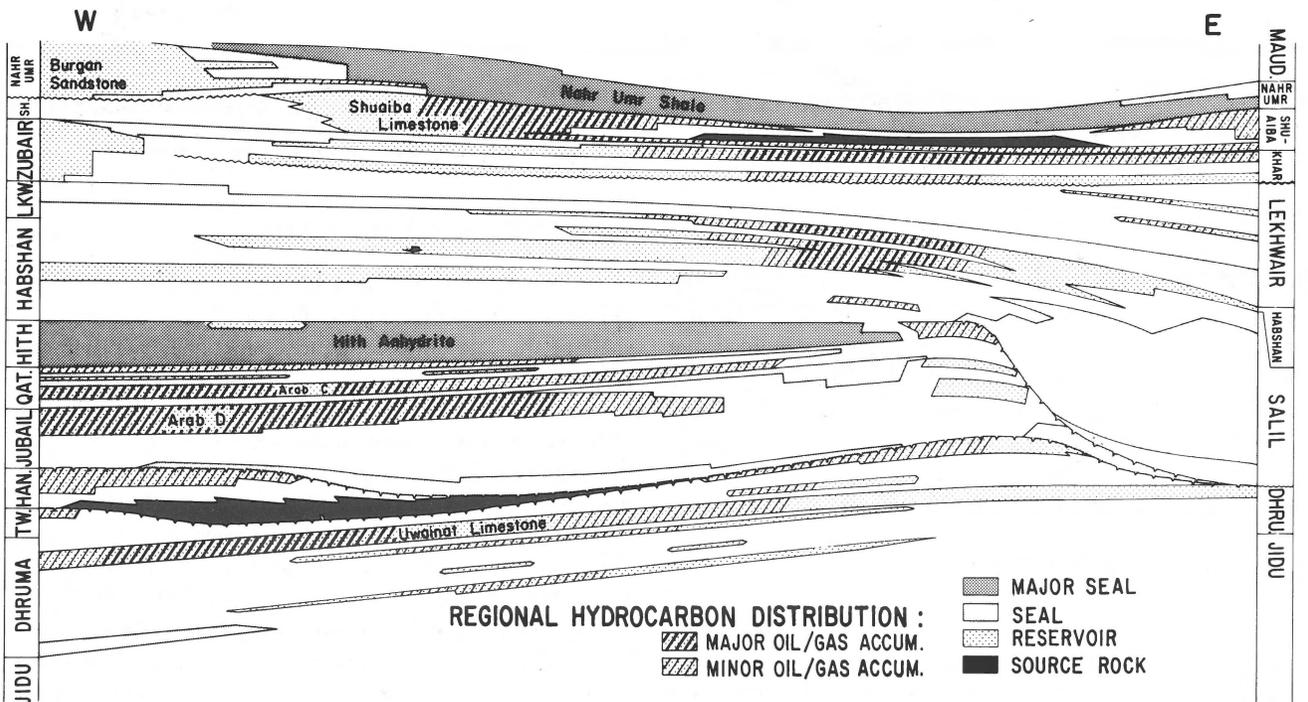Mid-Jurassic to Albian, central Gulf area: schematic regional stratigraphic development.

Fig. 25
Mid-Jurassic to Albian, central Gulf area: habitat parameters and distribution of oil and gas accumulations.

east. Development was cyclical with several shallowing-upward sequences containing ooidal-pelletoidal and bioclastic pack-grainstones as high-energy members. By Barremian time, ramp-type sedimentation prevailed, with carbonate

rocks very much like those of the Middle Jurassic in lithology and correlatability. Associated sands came from the west.

A minor unconformity, latest Barremian to earliest Aptian in age, is present over the Qatar arch. Above it the foramini-

feral limestones of the Kharaib indicate the onset of the basinwide Aptian transgression. By mid-late Aptian time, the platform was flooded and was succeeded by an intrashelf basin flanked by shallow platform carbonate rocks which contain rudist 'reefs' and banks along the margin. The roof of the section is formed by the regressive Albian shales (Nahr Umr Formation), which contain tongues of Burgan sand in the west.

Translation into Oil Habitat

Figure 25 shows how the stratigraphic section of figure 24 can be translated into habitat terms – source, reservoir, and seal – and how these control the oil and gas distribution. It is a generalized scheme (with local exceptions) for a substantial part of the central and southern Gulf area.

Based on Shell's method for rapid source rock identification, two potential source formations have been identified within this sequence: the Upper Oxfordian — Lower Kimmeridgian Hanifa and the Aptian Shuaiba; both where developed in their basinal facies. Regressive shales such as the

Nahr Umr, and the ramp-type marls and argillaceous limestones do apparently not possess source characteristics. The open marine realm is also poor in preserved organic matter and is a marginal local source rock at best.

Of the two potential source formations, the Hanifa is the richest within the central Gulf area. It is a thinly laminated limemudstone, with a clay content less than 10%. Organic carbon content varies between 2 and 6 percent, with some even richer laminae. Oil yield can be as high as 2 volume percent. Figure 26 shows a comparison between gas chromatograms of the saturated hydrocarbons of a typical Arab reservoir oil (above), and the extract of the Hanifa source rock in the same field. The similarity is striking, and also other typing methods, based on diverse geochemical parameters like porphyrins, carbon isotopes, phytane-pristane-N alkane ratio's, and C_{15}/C_{30} ring number distributions show a close correlation between reservoired oils and the Hanifa. The high sulpur content of oils and extracts indicates a euxinic carbonate-evaporite environment of deposition (GRANSCH & POSTHUMA, 1973), which is fully compatible with the

GAS CHROMATOGRAM OF SATURATED HYDROCARBON FRACTION , OIL

GAS CHROMATOGRAM OF SATURATED HYDROCARBON FRACTION OF (MATURE) HANIFA
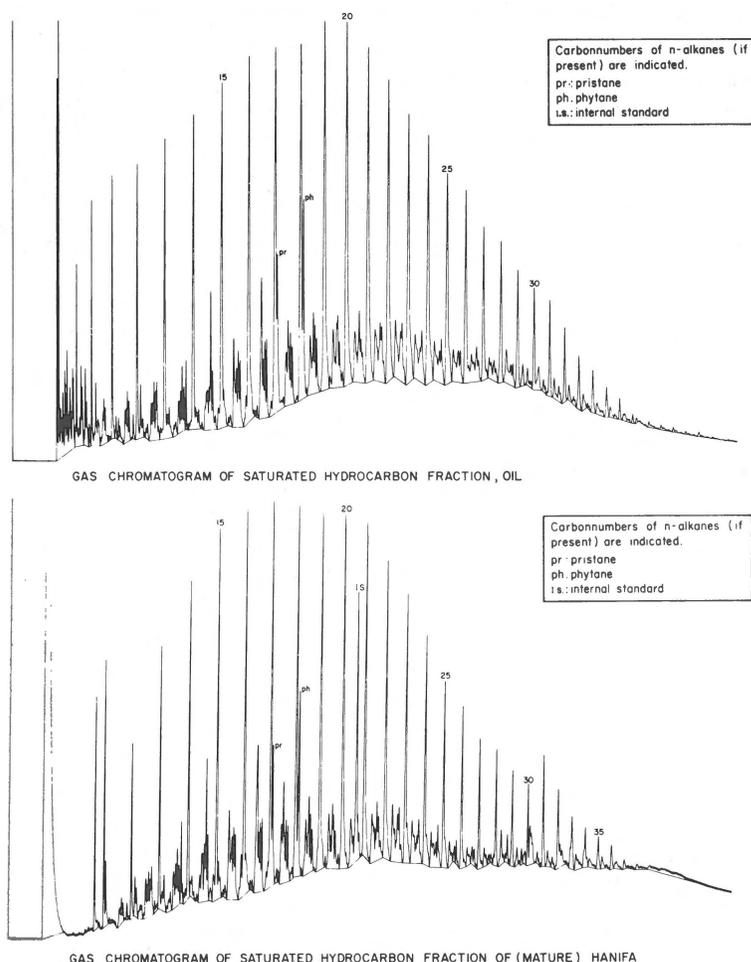
Fig. 26
Gas chromatogram comparison between an Arab reservoir oil (above) and an extract of the Hanifa source rock in the same field.

conditions under which the Hanifa was deposited. The importance for oil generation of the basinwide inundations and the concomitant creation of starved intrashelf basins is obvious.

Reservoirs are present in abundance and are widely distributed through the section. The best reservoirs are formed by the regressive sands and by the high-energy ooidal grainstones terminating the carbonate cycles. Other favorable facies are the rudist 'reefs' and the algal boundstones along the shelf margins. Leaching and cementation processes are important factors in determining the final reservoir quality of the carbonate rocks. Some porosity-creating leaching is apparently related to the lowering of sea level and subsequent subaerial exposure (e.g., early Albian) but there is also evidence for late leaching caused by acids in the formation waters.

There are two principal regional sealing formations, the Hith Anhydrite and the Nahr Umr Shale, which (as shown in Fig. 25) control to a large extent vertical migration and hence oil and gas distribution. The Hith is the ultimate cap rock for the prolific Arab reservoirs. Where it is present, the overlying Lower Cretaceous reservoirs are devoid of charge, as at the western end of the example section. There are exceptions, however, when the Hith is breached through faulting and Arab oil could escape upward (Idd el Shargi, Bahrain). On the oceanic shelf margin the Hith is absent and hydrocarbons generated in the Hanifa source rock could escape upward to be trapped in Lower Cretaceous reservoirs.

Apart from the two main seals, there are other, less widespread but still effective sealing strata. The Hanifa source rock itself can form a good seal to reservoirs of the Dhruma or Tuwaiq Formations. Upper Jurassic argillaceous lime-mudstones hold modest columns in the Hanifa and Tuwaiq reservoirs in several fields. Marls and argillaceous limestones of the upper Hauterivian to Barremian Lekhwair Formation cap substantial reserves in several fields in the southern Gulf, in the zone where the Hith seal is absent and Hanifa charge is therefore available.

Cross-strata migration of the oil from the source beds to the reservoirs through the intervening section that is composed of tight limestones, marls, and thin anhydrites is indicated by occasional shows encountered during drilling. More unambiguously this is done by fluorescence-microscopical investigations performed at Shell's E and P Laboratory in The Netherlands, which show the presence of oilfilled microfractures. In conjunction with the almost identical composition of reservoired oils and source rock extracts, these microscopical observations strongly support the model that oil migrates in the whole phase as thin threads and stringers through fractures, faults and permeable carrier beds.

Maturity, Kitchens and Regional Oil Distribution

Another important controlling factor is the degree of maturation of the source rocks. There is by now overwhelming geologic and geochemical evidence that source rocks of the type dominant in the Middle East start to generate oil when
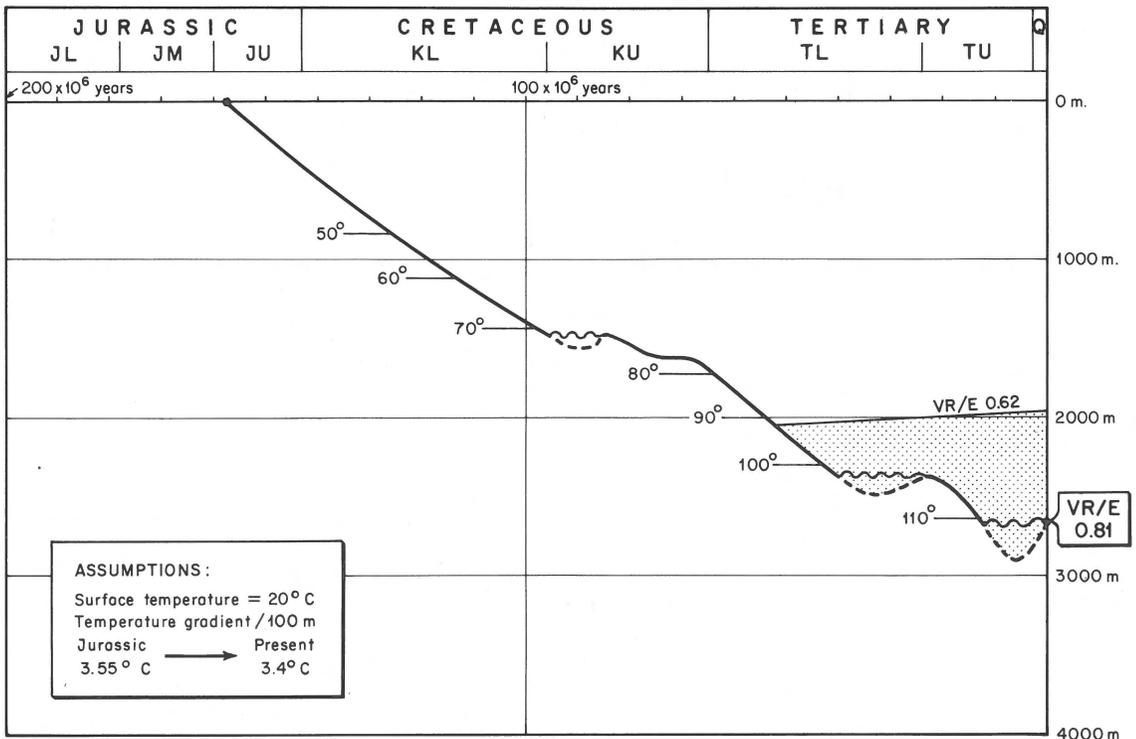

Fig. 27
Example of a burial graph of the Hanifa.
VR/E = calculated maturity in vitrinite reflectance equivalent units; stippled area = mature zone.
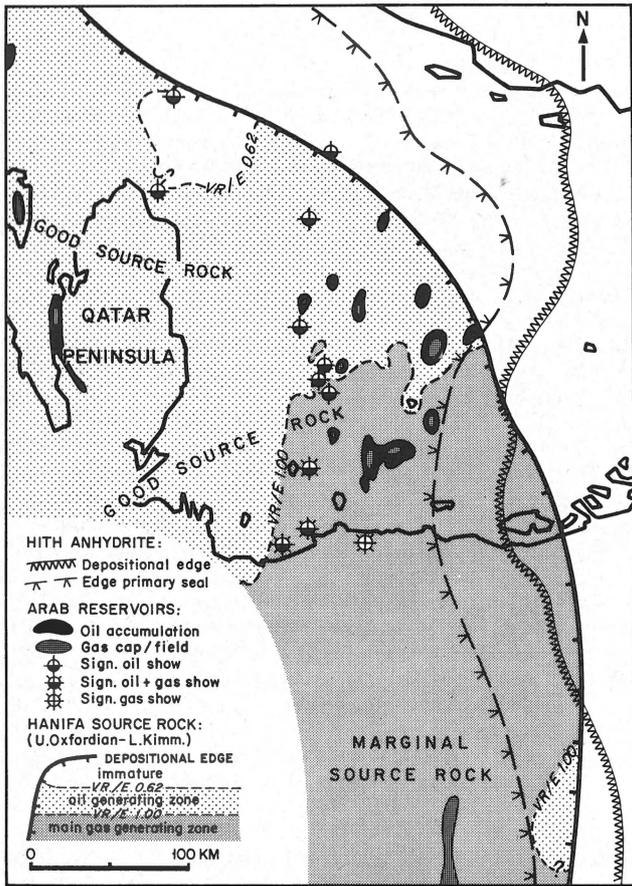
Fig. 28
Central Gulf area: Jurassic accumulations in relation to Hanifa kitchen and Hith Anhydrite development.

Fig. 29
Central Gulf area: Lower Cretaceous accumulations in relation to Shuaiba kitchen and Hith Anhydrite development.

they reach a certain thermal maturity, roughly corresponding to a fixed carbon content of 60% in coals and to a vitrinite reflectance of 0.60 to 0.65 (TEICHMÜLLER, 1971; HOOD ET AL, 1975). In the predominant carbonate environment of the Middle East, reliable vitrinite data are scarce, and the delineation of the mature source rock areas has to based on calculated maturity levels. For this the Lopatin time-temperature method calibrated to a worldwide set of vitrinite data was used, along the lines first published by WAPLES (1980). Figure 27 gives an example of such a calculation for the Hanifa source rock, which at this location has reached a maturity corresponding to a vitrinite reflectance of 0.81, and appears to have reached the generation threshold in the early Tertiary.

The combination of the statigraphic extent and the maturity limits defines the areas of mature petroleum source or 'kitchens', from which the receiving structures and other traps get their proportionate share of the charge depending on the size of their drainage area (NEDERLOF, 1980). Figure 28 shows the regional Hanifa kitchen, as well as the extent of the overlying regional Hith Anhydrite seal. The distribution of the Jurassic accumulations is clearly controlled by mature source and seal, whereby it should be noted that the Jurassic targets are hardly drilled in the southern part of the area, where they are deep and gas-prone. As the map shows, the Hanifa source rock is
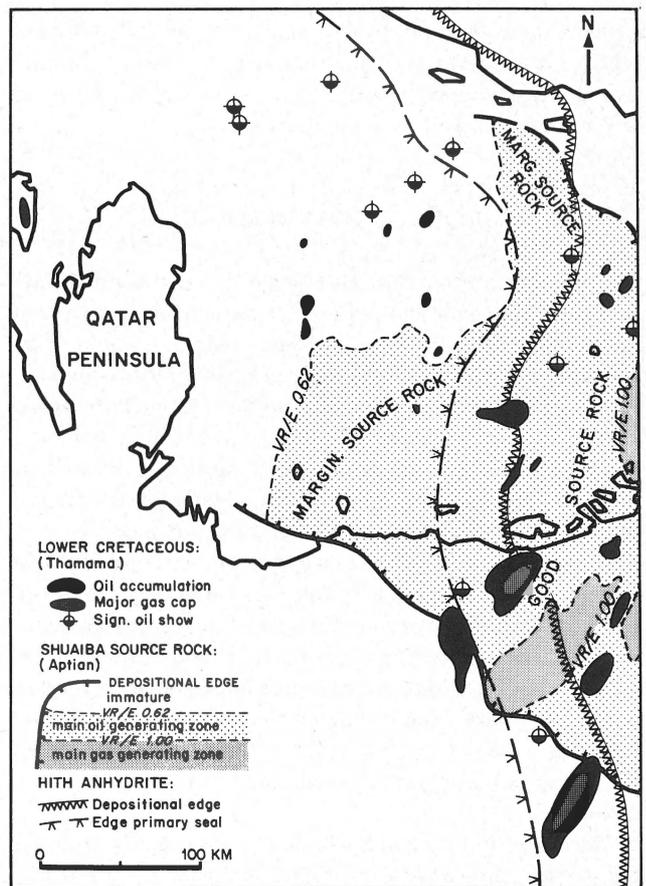
mature over most of the area where it is present, apart from the culmination of the Qatar arch. The absence of sizeable Jurassic-Cretaceous oil discoveries on this broad paleohigh is at least partly due to this lack of maturity within the drainage area of the closure.

Figure 29 shows the kitchen of the Aptian Shuaiba source rock. In the western part of the central Gulf area this potential source formation is poorly developed and not or barely mature. Major Lower Cretaceous oilfields are concentrated in the eastern part, where the Shuaiba source rock is better developed and is in the oil generating zone. Part of the reservoired oil – in particular in the earlier Cretaceous Habshan and Lekhwair formations (see Fig. 25) – may represent Jurassic oil migrated upwards in this zone where the Hith is thin or absent as indicated on figure 29. Detailed geochemical data are as yet lacking to determine in each case what the source of the reservoired oil might be. The oil occurring in lower Cretaceous reservoirs in the northwestern part of the area, outside the Shuaiba kitchen, has in several instances been unequivocally typed to the Jurassic Hanifa source. It can be shown that in these cases the intervening Hith seal is breached through faulting, often leading to a depletion of the Jurassic reservoirs.

As demonstrated with this example of the Upper Jurassic to

Lower Cretaceous of the wider Qatar area, the distribution of oil over the various available reservoirs is closely controlled by the primary development and preservation of source and seal formations, and by source maturity.

CONCLUDING REMARKS

The principles of translating lithologies and depositional environments into hydrocarbon habitat parameters, as given in the example of the Middle Jurassic-Lower Cretaceous of the central Gulf area, can be extended to the other formations and the whole province. Superposition of the layer maps of figures 6 to 23 permits outlining of other source-reservoir-seal triplets, and their regional extent. With thermal-maturity maps these go a long way in explaining the regional distribution of the oil and gas fields in the Middle East province.

The question remains as to why the Middle East is such an exceptionally rich habitat. Source rocks are not exceptionally thick or rich compared to other basins. Reservoirs are abundant and have generally high porosities and permeabilities, enhanced by fracturing in the Zagros folds, but again they are not a class apart when compared to other basins such as the North Sea, Alberta, or the United States Gulf Coast. Seals, without doubt, are very effective, but not unusually thick or abundant.

The horizontal scale of the basin is extraordinary. Whereas the vertical dimensions are rather average, the horizontal dimensions are greater than in most basins. The pre-erosional Mesozoic depositional platform was 2,000 to 3,000 km wide and at least twice as long. Differentiation was minimal and source rocks, reservoirs, and seals have consequently a very wide extent. The structures are also out of scale horizontally, and closures of 1,000 sq km or more are no exception. Because of large horizontal scale, the structures are very gentle, which has a two-fold effect: loss of seal efficiency through fracturing is minimal and large trap volumes are attached to even modest vertical closures or column heights. Finally, because of the wide extent of the lithologic units, horizontal migration is very efficient and the large structures have a high degree of fill because they could drain very large 'kitchens.'

ACKNOWLEDGEMENTS

REFERENCES

Ahr, W. M. 1973 The carbonate ramp – an alternative to the shelf model – Gulf Coast Assoc. Geol. Socs. Trans. 23: 222-225.

Bay, T. A. 1977 Some Lower Cretaceous stratigraphic models from Texas and Mexico. In: Cretaceous carbonates of Texas and Mexico – Univ. Texas Bur. Econ. Geology Rept. Inv. 89: 12-30.

Berthier, F. et al. 1974 Etude stratigraphique, pétrologique et structurale de la région de Khorramabad, Zagros iranien – Thesis Univ. Grenoble, France.

Dunnington, H. V. 1967 Stratigraphical distribution of oilfields in the Iraq-Iran-Arabia basin – Inst. Petroleum J. 53: 129-161.

Dunnington, H. V., R. Wetzel & D. M. Morton 1959 Iraq (Mesozoic and Paleozoic). In: Dubertret (ed.): Lexique stratigraphique international, Asie 10a.

Glennie, K. W. et al. 1974 Geology of the Oman Mountains – Verhand. Kon. Nederlands geol. mijnbouwk. Gen. 31: 423 pp.

Gransch, J. A. & J. Posthuma 1973 On the origin of sulphur in crudes – Adv. Org. Geochem.: 727-739.

Helal, A. H. 1964 On the occurrence and stratigraphic position of Permo – Carboniferous tillites in Saudi Arabia – Geol. Rundsch. 54: 193-207.

—— 1965 Stratigraphy of outcropping Paleozoic rocks around the northern edge of the Arabian shield (within Saudi Arabia) Deutsch. Geol. Gesell. Zeitschr. 117: 506-543.

Hood, A., C. C. M. Gutjahr & R. L. Heacock 1975 Organic metamorphism and the generation of petroleum – AAPG Bull. 59: 986-996.

Hudson, R. G. S. & M. Sudbury 1959 Permian Brachiopoda from south-east Arabia – Notes et Mém. Moyen- Orient. 7: 19-55.

Murris, R. J. & K. De Groot 1979 Oil habitat of carbonate provinces – Cong. Panam. Int. Petr. Mexico Proc. Sec. 1, Paper 5.

Nederlof, M. H. 1980 The use of habitat models in exploration prospect appraisal – 10th World Petr. Congr. Proc. 2: 13-21.

Nowroozi, A. A. 1971 Seismotectonics of the Persian Plateau, eastern Turkey, Caucasus and Hindu – Kush regions Seismol. Soc. America Bull. 61: 317-341.

Purser, B. H. 1969 Syn-sedimentary marine lithification of Middle Jurassic limestones in the Paris basin Sedimentology 12: 205-230.

—— 1972 Subdivision et interprétation des séquences carbonatées France, Bur. Recherches Géol. et Miniére Mém. 77: 679-698.

Ricou, L. E. 1975 L'étude géologique de la région de Neyriz (Zagros iranien) et l'évolution structurale des Zagrides – Thése d'état, Paris.

Smith, A. G. & J. C. Briden 1977 Mesozoic and Cenozoic paleocontinental maps. In: Cambridge earth science series: Cambridge, England – Cambridge Univ. Press: 62 pp.

Szabo, F. & A. Kheradpir 1978 Permian and Triassic stratigraphy, Zagros basin, southwest Iran – J. Petrol. Geol. 1: 57-82.

Teichmüller, M. 1971 Anwendung kohlenpetrographischer Methoden bei der Erdöl- und Erdgasprospektion – Erdöl u. Kohle 24: 69-76.

Thode, H. G. & J. Monster 1970 Sulphur isotope abundances and genetic relations of oil accumulations in Middle East basin – AAPG Bull. 54: 627-637.

Vail, P. R., R. M. Mitchum Jr. & S. Thompson III 1977 Global cycles and relative changes of sea level. In: Seismic stratigraphy – applications to hydrocarbon exploration – AAPG Mem. 26: 83-97.

Waples, D. W. 1980 Time and temperature in petroleum formation etc. – AAPG Bull. 64: 916-926.

Wilson, J. L. 1975 Carbonate facies in geologic history – Springer (New York): 469 pp.