

## **Late Permian to Holocene Paleofacies Evolution of the Arabian Plate and its Hydrocarbon Occurrences**

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### **ABSTRACT**

A series of 19 paleofacies maps have been generated for given time intervals between the Late Permian and Holocene to reconstruct the depositional history of the Arabian Plate. The succession of changing lithological sequences is controlled by the interplay of eustacy and sediment supply with regional and local tectonic influences. The Mesozoic paleofacies history of the Plate is, in its central and eastern portion east of Riyadh, strongly influenced by an older N-trending, horst and graben system that reflects the grain of the Precambrian Amar Collision and successively younger structural deformations. The late Paleozoic Hercynian orogenic event caused block faulting and relative uplift and resulted in a marked paleorelief. This jointed structural pattern dominated the entire Mesozoic and, to some extent, the Cenozoic facies distribution. The relationship between producing fields and the paleofacies maps illustrates the various petroleum systems of particular times and regions.

### **INTRODUCTION**

The lithostratigraphic units of the Arabian Plate have been described in outcrop and subsurface from the Mediterranean to the Gulf of Oman and from the Red Sea to the Zagros Mountains. Serious variations in nomenclature exist regionally and between the surface and subsurface. Various authors, for example, Beydoun (1988), Alsharhan and Nairn (1997), and Christian (1997) have published regional lithostratigraphic reviews in attempts to comprehend this vast amount of stratigraphic information. Most recently, Sharland et al. (2001) published the first chronostratigraphic interpretation of the rock units of the Arabian Plate.

Most of the previous lithostratigraphic studies have presented paleofacies, interpreted environments, and associated petroleum systems, in separate discussions. This study reconstructs paleofacies for time intervals from the Late Permian to the Holocene, each reconstruction being shown with its associated oil and gas fields. The study helps to illustrate the close relationship between lithofacies, depositional environments, and petroleum reservoirs. It also highlights active structural elements and the influence of relative sea-level changes interpreted from the paleofacies variations.

This review of the Arabian Plate benefited from its association with the International Geological Correlation Program (IGCP) Project 369, 'Comparative Evolution of the Peri-Tethyan Rift Basins', which in turn is affiliated to the Peri-Tethys Program. The Project's aim was to integrate geological and geophysical data in a study of the evolution of the rift and wrench basins located along the northern and southern Tethyan margins and adjacent platforms. Paleoenvironmental maps of the Peri-Tethyan domain from the Urals to the Atlantic Ocean and from the Baltic Shield to Equatorial Africa were produced. The Muséum National d'Histoire Naturelle, Paris published the results as Memoir No. 6 (Ziegler et al, 2001). The results are accessible on the Internet ([http://www-sst.unil/igcp\\_369/default369.htm](http://www-sst.unil/igcp_369/default369.htm)) and are also available as a CD-ROM (Stampfli et al., 2001).

For ease of reference between this paper and the sequence stratigraphic study by Sharland et al. (2001) that describes the sedimentary architecture using Genetic Stratigraphic and Depositional Sequences, I have placed in square brackets equivalent dated surfaces referred to in their publication. These are interpreted Genetic Stratigraphic Sequences (GSS) bounded by Maximum Flooding Surfaces (MFS) identified by Period [Jurassic J10 dated at 185 Ma] and Arabian Plate (AP) Tectonostratigraphic Megasequences [base of AP7 dated at 182 Ma].

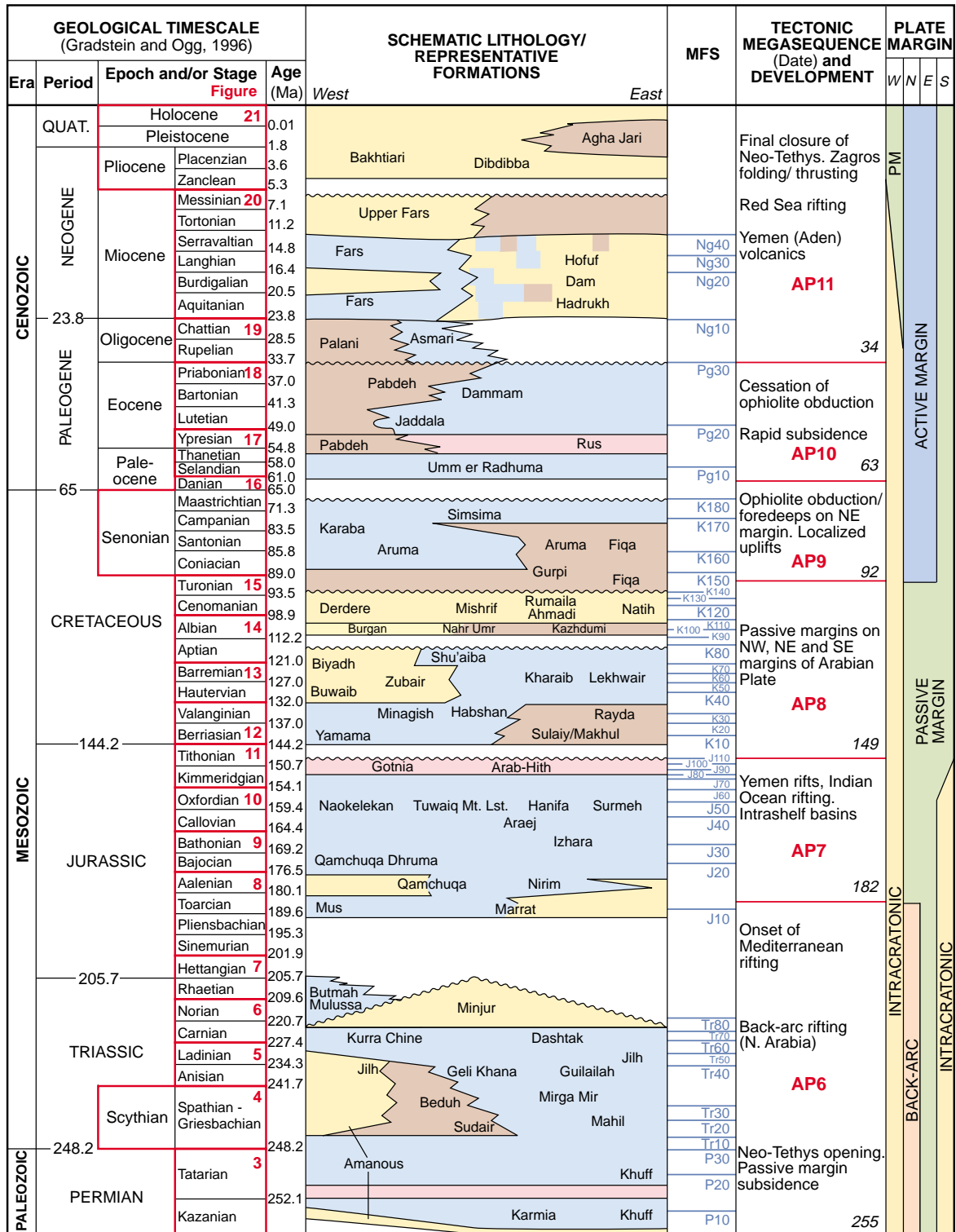


Figure 1: Stratigraphic column from the Late Permian to the Holocene modified from Figure 1.2 of Sharland et al. (2001); with a representative selection of the major stratigraphic units mentioned in the text.

Figure 1 is a stratigraphic column from Late Permian to Holocene based on Figure 1.2 of Sharland et al. (2001). It shows the MFSs, AP boundaries and a representative selection of the major stratigraphic units mentioned in the text.

## STRUCTURAL TRENDS

Figure 2 is a structural interpretation of the Arabian Plate as it relates to the distribution of the Upper Permian to Holocene paleofacies patterns. Their distribution appears to be influenced by N-, NW- and NE-trending fault systems.

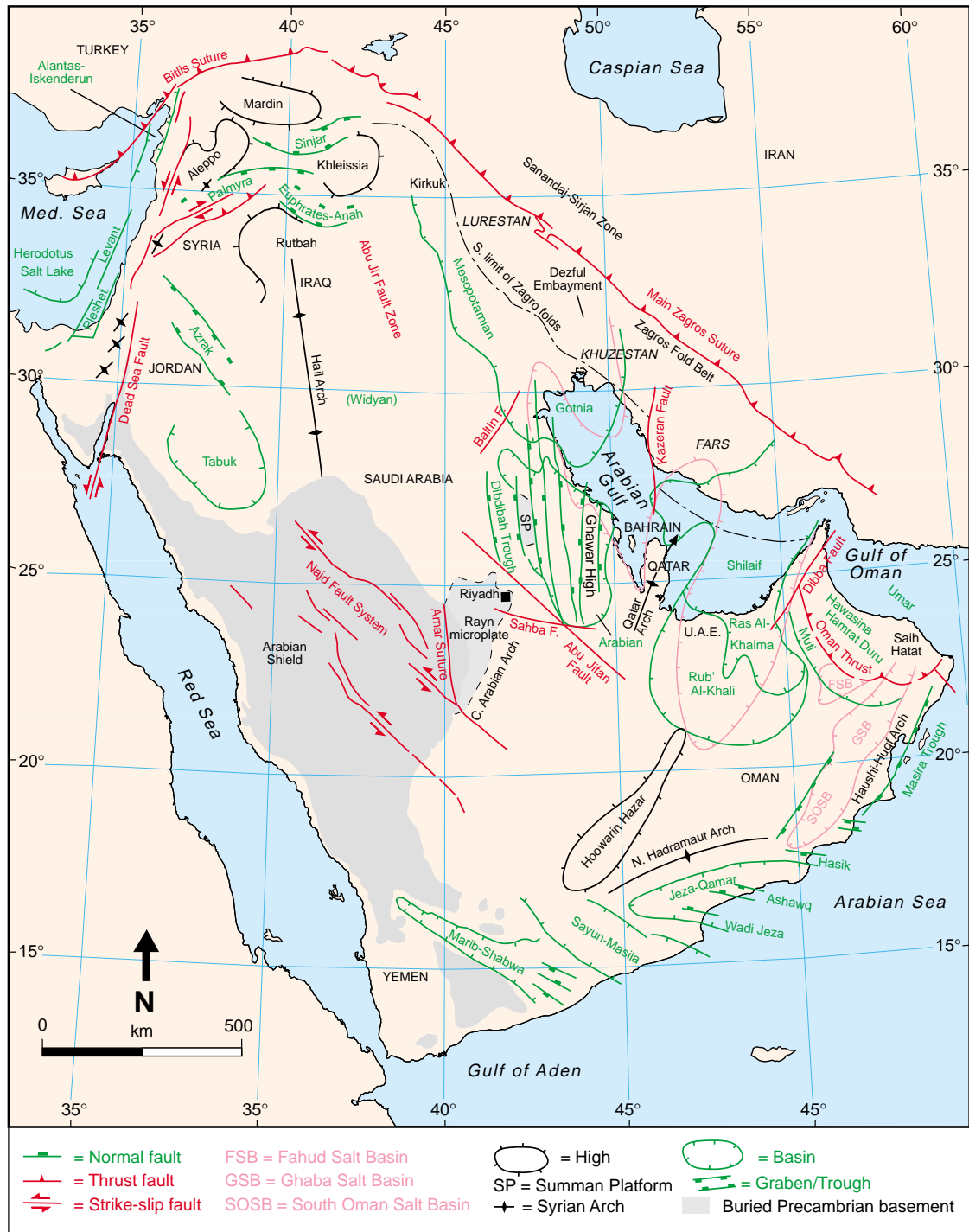
- The regularly spaced, northerly trends that comprise the Central Arabian Arch are interpreted as reflecting the Precambrian basement architecture. The structures along the Arch may have originated during the Amar Collision (640–620 Ma) of the Rayn Plate (in the east) with the Arabian-Nubian Craton (in the west), and the ensuing Najd Rift (570–530 Ma) (Al-Husseini, 2000). Some of the well-known northerly structural trends are the Summan Platform, Dibdibah Trough, Khurais-Burgan Anticline, En Nala (Ghawar-Safaniya) Anticline, and the Qatar Arch.
- The northwesterly grain is visible in the Arabian Shield as the Najd Faults, and is interpreted as bounding the Arabian Plate along the Zagros Suture.
- The northeasterly trend corresponds to the Dibba Fault, Oman salt basins, and the Wadi al Batin lineament, and appears to control the distribution of Infracambrian salt basins of the Arabian Gulf and Oman (Husseini, 1988; Husseini and Husseini, 1990; Loosveld et al., 1996; Al-Husseini, 2000).

The intersection of these three fault trends results in a jointed basement fabric that has been reactivated by successively younger deformations governed by the interplay of local and far-field stresses related to large-scale plate tectonic processes. The different structural orientations of these faults resulted in marked mechanical inhomogenities that reacted differently to external plate events. Nearly all the paleofacies maps show evidence of these older structural grains, particularly in central Saudi Arabia.

Of particular relevance to this study is the late Paleozoic (?Late Devonian to Late Carboniferous) structural uplift that followed a phase of comparative stability during the early Paleozoic. This uplift is evident from regional isochron thinning measured between the Lower Silurian and Permian seismic reflections in central Saudi Arabia (McGillivray and Husseini, 1992; Wender et al., 1998). The tectonic event is referred to as the 'Hercynian' orogeny, a term more properly applied to Europe. During this orogeny, the Arabian Plate was rotated through 90° in an anticlockwise direction (Konert et al., 2001), and central Arabia was uplifted, tilted down eastward, and deeply eroded. A series of N-trending basement structures were uplifted along the Central Arabian Arch (McGillivray and Husseini, 1992; Wender et al., 1998). Extensive erosion of lower Paleozoic rocks took place over the Hercynian paleohighs on the Arch during the mid-Carboniferous and Early Permian. South of Riyadh, low relief structures formed due to Hercynian movements (Simms, 1995, Evans et al., 1997) but erosion over their crests was less than in the north over the Arch. Fluvial to alluvial clastics (e.g. the Unayzah Formation of Saudi Arabia), were deposited over the Hercynian relief.

During the Late Carboniferous and Early Permian, glaciation occurred in Oman (Al Khlata Formation), southern Saudi Arabia and Yemen, and periglacial and fluvial conditions existed in central Arabia. In Oman and Yemen, tillites rest directly on glacially striated Precambrian basement. Hughes Clarke (1988) interpreted the glaciation as having been restricted to south of present-day 20°N.

With the exception of the Neogene Dead Sea Transform Fault, which formed in two phases as a left-lateral, strike-slip dislocation of about 100 km (Garfunkel, 1998, Walley, 1998b), and the Maradi fault zone in Oman, most of the tectonic features on the Arabian Plate show only minor wrench motion. Eustatic sea-level fluctuations combined with minor fault movements may have predisposed certain seaways that allowed deep-marine branches of the Neo-Tethys to penetrate into the Craton, forming intrashelf basins. Under restrictive conditions, such as during the Late Permian to Jurassic, these basins became anoxic or hypersaline (e.g. the Gotnia and Rub' Al-Khali basins of the Middle and Late Jurassic). Subsequently, in the Early Cretaceous, the Mesopotamian Basin was a depositional site for continental clastics. The shelf basins were frequently rimmed by biogenic build-ups and coral



**Figure 2: Structural interpretation of the Arabian Plate as it relates to the distribution of the Late Permian to Holocene paleofacies.**

reefs, as in the Arabian Basin (Powers et al., 1966; Le Nindre, Manivit and Vaslet 1990, 1990a), or rudist banks, as in the Rub' Al-Khali Basin. Bahamas-type lime-sand belts and biogenic shoals were frequently developed on the platform-shelf margins.

### PALEOFACIES MAPS

The 19 time frames shown here are those proposed by the IGCP (Figure 1), according to the Geological Time Scale of Gradstein and Ogg (1996). The reservoir rocks of oil fields (green) and gas fields (red)

on a particular figure belong to that time interval. The interpreted lithofacies definitions were selected by the ICGP project. They are based on an idealized bathymetric profile of a plate margin that differentiates the lateral sequence of depositional environments into the following four major groups:

1. Continental environments corresponding to dunes, lacustrine, fluvial, alluvial, and coastal plain deposits (e.g. *Continental deposits*).
2. Neritic environments comprising supratidal and intertidal deposits, inner- and outer-shelf sediments, including deeper-water deposits that occur in association with significant intrashelf basins (e.g. *Marginal-marine/coastal/deltaic deposits*; *Shallow-marine carbonate platform*; *Open marine carbonate shelf*; *Shallow-marine clastics*).
3. Bathyal environments reflecting the continental slope and continental rise, and the resulting deposits characterized by hemipelagic sediments, turbidites and debris flows (e.g. *Deep-marine carbonates*; *Deep-marine clastics*).
4. Abyssal environments represented by the predominance of mudstones with a pelagic fauna (e.g. *Deep-marine clastics*).

These depositional environments are color-coded and distinguish between predominantly siliciclastic and carbonate sediments. Formation names are placed on the maps in the areas to which they relate. However, on maps that cover a long time span there is a recognized problem of how to show the most relevant formations. In these instances, the longest-ranging formations are generally shown.

### **Late Permian: Kazanian to Tatarian (256–248.2 Ma) (Figure 3)**

#### ***Regional Setting***

This time period spanned the deposition of the lower and lower upper Khuff (Arabian Peninsula) [MFS P20 to intra-Tr10], Karmia (Levant), and Amanous (Syria) formations, and their regional equivalents. The Khuff was deposited on the new northeastern passive margin with Neo-Tethys. A major Late-Permian unconformity occurred within P20.

In the Late Permian, continental rifting and spreading took place along the present-day Zagros Suture and Gulf of Oman as the Neo-Tethys Ocean started to form [base of AP6 at 255 Ma]. Short-term sea-level oscillations caused recurrent shoaling pulses that culminated in the establishment of evaporite sabkhas and salinas particularly over the Central Arabian Arch. The carbonates represent a shallow-shelf to a coastal-plain depositional environment. In general, a weakly prograding terrigenous to shallow-marine clastic shoreline existed. Sharland et al. (2001) interpreted three MFS in the Permian Khuff [P20, P30, and P40] and correlated them over most of the Arabian Plate.

#### ***Paleofacies***

The Khuff sequence varies in thickness from 80 m near the onlap margin along the Arabian Shield, to over 800 m in the Arabian Gulf. Although no marked thinning of the Khuff units is evident over older structures, the cumulative thickness of coastal sabkha deposits over the Hercynian structures of the Central Arabian Arch suggests that they formed subtly positive blocks (Al-Jallal, 1995).

In general, the lower Khuff in the Gulf region was transgressive before becoming regressive and culminating in a marked sea-level lowstand (Haq et al., 1988) toward the end of Khuff deposition [intra-Tr10 unconformity]. As a result of this lowstand, the sediments consisted of shallow-water carbonates and rapidly expanding coastal evaporite sabkhas in central Saudi Arabia and the Gulf. Coastal complexes that rimmed the western and southern uplands were lined with significant amounts of sandstones and shales.

Le Nindre, Manivit, and Vaslet (1990) illustrated this transition between the western upland and the shallow-marine environments, west of Riyadh. At the Khuff locality, an embayment of at least 100 km extended southwestward from Neo-Tethys into the Arabian Shield. The western Gondwana hinterland appeared to have been drained by low-energy rivers that discharged siliciclastics onto the sabkhas and intertidal flats to form a mixed carbonate-clastic fringe. These mixed facies gave way eastward to shallow-marine carbonates (dolomites and dolomitic limestones), containing algal material.

Late Permian: Kazanian to Tatarian (256–248.2 Ma)

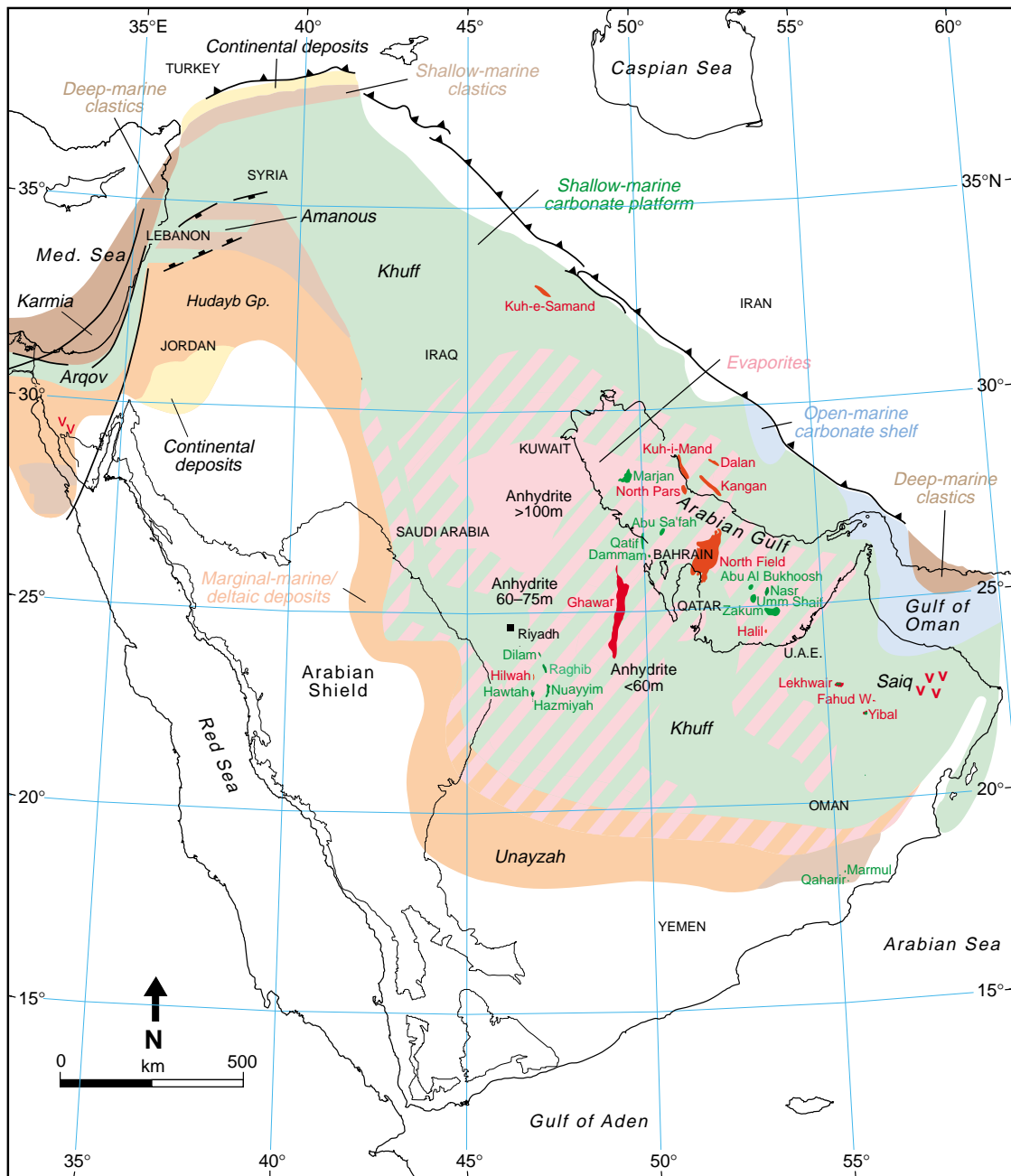


Figure 3: Paleofacies of the Late Permian. This time period spanned the deposition of the Khuff, Karmia, and Amanous formations, and their regional equivalents [MFS P20 to intra-Tr10]. The Khuff was deposited on the new northeastern passive margin with Neo-Tethys. A major Late-Permian unconformity occurred within P20. With information from: Al Jallal (1995); Andrews (1991, 1992a); Béchenec et al. (1989); Garfunkel (1989); Guiraud et al. (2001); Koop and Stoneley (1982); Le Métour et al. (1995); Le Nindre, Manivit et al. (1990); Murris (1980); Szabo and Kheradpir (1978); and unpublished Saudi Aramco Miscellaneous Report 913 (W.J. Koop, 1982).

The location of the drainage system at the southern spur of the Arabian Shield was significant, specifically in the context of the Precambrian basement high beneath Riyadh (McGillivray and Husseini, 1992). Mainly shallow seas were widespread and true abyssal conditions in the Neo-Tethys developed only in southeastern Iran and the Gulf of Oman.

Al-Jallal (1995) depicted a cyclic deposition of shallow-water carbonates that shoal upward and develop widespread, multiple evaporite sabkhas. In the Gulf region, the total evaporite thickness exceeds 100 m and is thickest in the Dibdibah Trough, possibly indicating increased subsidence. The main anhydrite accumulation appears to be confined to south of the Wadi al Batin Fault. This implies that the central Arabian horsts ceased to exist as positive, paleomorphological features.

Farther east, and offshore from the Arabian Arch along the “shallow shelf break” (Al-Jallal, 1995), a curvilinear trend passes from the Rub’ Al-Khali, first east and then north of Qatar. It shows expanded carbonate sections and, in the Upper Permian Khuff C and B, repeated reservoir developments and minor evaporite accumulations. This feature may represent a deeper-water environment reflecting an approximate N-trending sag, presumably bounded by the Qatar Arch to the west. No hydrocarbon accumulations have been located in this zone, which apparently lacks a suitable caprock.

Offshore along the outer shelf break, higher energy calcarenites formed. The outer belt that marked the Arabian Plate margin was laced with reefoid, coral-algal, and detrital carbonates. Abyssal (hemipelagic) carbonates developed in Fars and on the Gulf of Oman-Makran slope.

In the Late Permian, a shallow-marine carbonate platform (Khuff and Saiq formations) was established over most of Oman. This transgression was the result of subsidence of the northeastern Oman margin that resulted from Neo-Tethys protorifting. Near Muscat, a rifted shelf margin with horst and graben structures developed. Condensed carbonate successions are present on the horsts, whereas thick melanges of clastics, conglomerates, and olistoliths occur in the troughs (Le Métour et al., 1995). Volcanic rocks are present in two intervals. The lower one consists of tuff and tuffites at the base of the carbonate suite, whereas the younger interval (basalt, trachyandesite and rhyodacite) is in the middle of the carbonate succession (Le Métour, 1987; Béchenec et al., 1989).

In the Levant, transform faults controlled the coastline. Deep-water carbonates (Karmia Formation) separated a western basement high (Helez Uplift) from a narrow shelf on the northwestern edge of the Arabian Plate (Hirsch et al., 1995). A NNE-trending transcurrent fault from the area of the present-day Gulf of Aqaba appears to have predated the Palmyra Trough. During the subsequent period of subsidence, the Amanous shales were deposited. In central Syria, the Amanous is an intercalated sandstone-argillite sequence containing rare plant fragments and some algal limestones. It has been dated by its foraminiferal and ostracode content.

## **Early Triassic: Scythian (248.2–241.7 Ma) (Figure 4)**

### ***Regional Setting***

This time period spanned the deposition of the Sudair (Saudi Arabia, United Arab Emirates, Oman), Mahil (Oman), Amanous (Jordan, Syria), Beduh and Mirga Mir (Iraq) formations, and their regional equivalents [MFS Tr10 to intra-Tr40]. The Arabian Plate persisted as a relatively peneplaned ENE-sloping passive margin platform [AP6]. In the eastern Mediterranean, faulting and rifting took place in the mid-Late Triassic, and transform faults separated a narrow continental margin in the east from a deep-water basin to the west. A rift splay branched off to the northeast and created the Palmyra and Sinjar basins in a rift that underwent thermal subsidence during the mid-Late Triassic and Jurassic.

### ***Paleofacies***

The facies pattern represents the mid-Scythian [c.Tr30 at 245 Ma] conditions of the Arabian Plate. A pronounced sea-level lowstand at the end of the Khuff deposition is expressed by a wide apron of coastal and shallow-marine clastics around the stable landmass of the Arabian Shield, and an even wider belt of shallow-marine silty shales (Sudair Shale) on the Arabian Shelf. West of Riyadh, evaporites are associated with shallow-marine shales (Le Nindre, Manivit and Vaslet, 1990). A shallow-water



**Figure 4: Paleofacies of the Early Triassic.** This time period spanned the deposition of the Sudair, Mahil, Amanous, Beduh, and Mirga Mir formations, and their regional equivalents [MFS Tr10 to intra-Tr40]. With information from: Andrews (1992a); Guiraud et al. (2001); Makhoul et al. (1996); Murris (1980); Sawaf and Tarek (1996); Szabo and Kheradpir (1978); Walley (2001).



carbonate platform with localized paper shale and evaporites also occurred in the northern Gulf and Zagros Mountains areas (Szabo and Kheradpir, 1978). In the Rub' Al-Khali, gypsiferous shales predominated (Sudair Formation) and gave way eastward to shallow-marine carbonates (Mahil Formation of Oman). The eastern shelf-break remained the flexure developed in the Late Permian Saih Hatat horst and graben structures.

In the Levant, Hirsch (1991, 1992) described an Early Triassic transgressive-regressive cycle that formed an alternating sequence of shallow-marine sands containing plant remains, shales and marly limestones (Yamin and Zafir formations) with a characteristic pelecypod fauna of *Pseudomonotis* sp. (*Claraia*) and myophorids. Hirsch interpreted this as an open-marine environment, typical of the 'Werfen-type' facies from the Austrian Alps. The same lithologies extend into Jordan and Syria as the Amanous shales. Hirsch (1992) related the two Scythian onlap cycles of the Yamin and Zafir formations to two eustatic cycles and considers them as a probable response to a renewed phase of Neo-Tethyan sea-floor spreading. The source of the clastic influx during this time was probably from the Arabian-Nubian massif to the southeast (Druckman, 1974). Hirsch compared the sands (Gevanim Formation) with the Buntsandstein of the western Mediterranean. A shallow-marine connection with the northern Zagros Basin probably existed through the Palmyrid Trough.

### **Middle Triassic: Anisian to Ladinian (241.7–227.4 Ma) (Figure 5)**

#### ***Regional Setting***

This time period spanned the deposition of the Jilh (Arabian Peninsula), Gulailah (eastern Gulf) and Geli Khana (Iraq) formations, and their regional equivalents [MFS Tr40 to intra-Tr60]. In general, the Middle Triassic facies patterns in the Arabian Gulf region are a continuation of those of the Early Triassic, accentuated by a Ladinian subsidence event (Sharland et al., 2001).

#### ***Paleofacies***

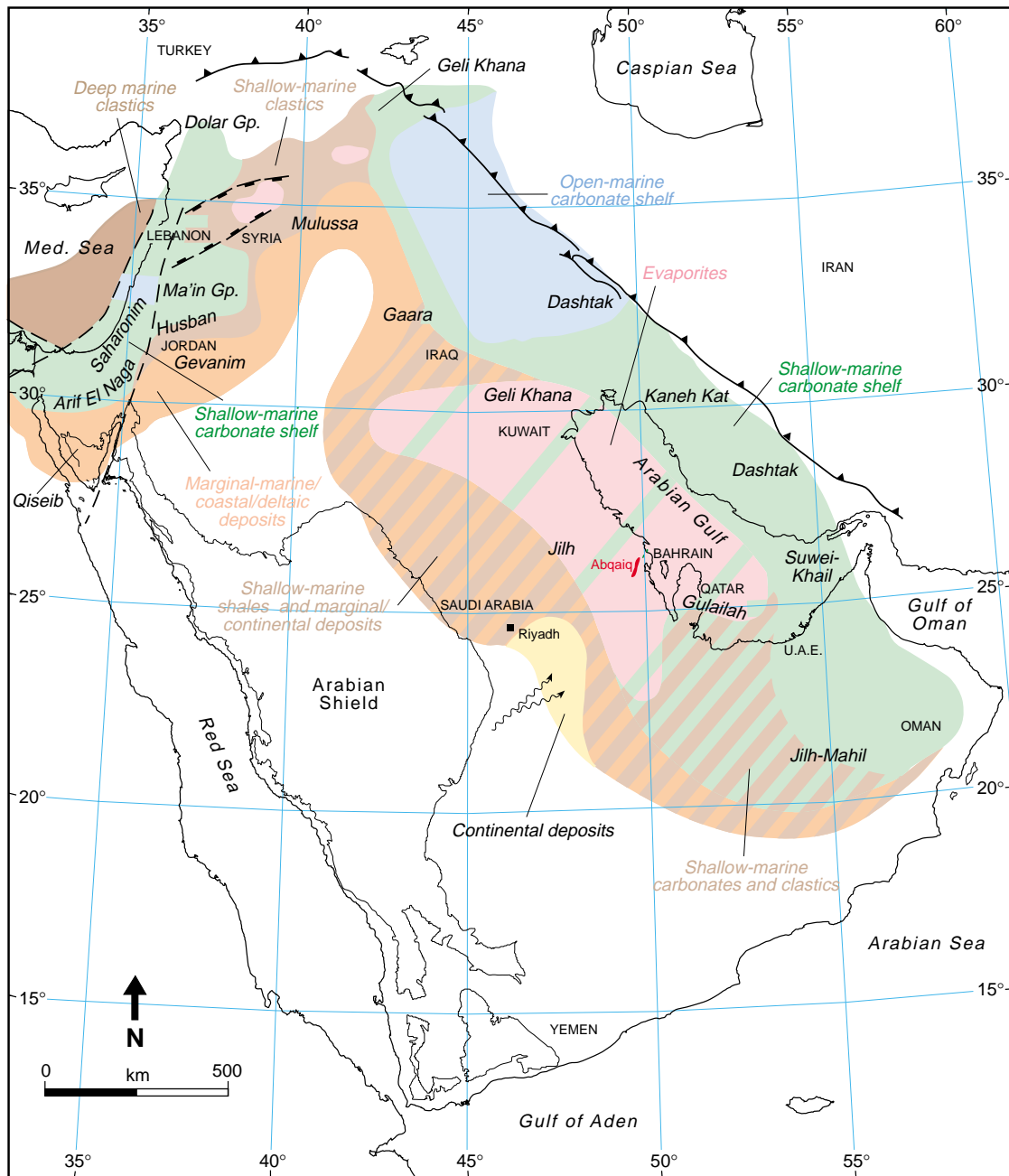
Along the western outcrop belt of Saudi Arabia, the Jilh Formation was deposited as a continental to shoreline complex (Sharief, 1986). Alluvial fans from the western uplands spilled over coastal lagoons onto a platform that had restricted marine conditions (Le Nindre, Manivit and Vaslet, 1990). Large evaporite salinas were formed in the area between Kuwait and the southern Gulf. Southward toward the Rub' Al-Khali Basin, the evaporites grade into dolomitic mudstones and fine-grained clastics of the Gulailah Formation. The pronounced input of sand from the southwest relates to an earlier hinterland uplift. In the Zagros foreland, the limestone/dolomite Geli Khana Formation consists of two shoaling-upward cycles that each ended in emergence. Solution breccias in the lower part of the Formation indicate once-present evaporites.

The area north of the Arabian Arch was relatively poor in siliciclastics. The Hercynian horst and graben structures appear to have had only a minor influence on the distribution of the evaporite flats in the northern Gulf region. The Rutbah-Khleissia High was poorly defined, but the presence of coastal to shallow-marine sands indicates the existence of the Ha'il Arch.

The central and eastern Rub' Al-Khali Basin was an area of restricted deposition of shallow-marine shales and carbonates that grade distally into shallow-marine platform dolomites. On the southeastern flank of the Arabian Shield, a flood of siliciclastics was carried into the shallow sea by a major fluvial system (Le Nindre, Manivit and Vaslet, 1990). The clastic discharge took a northeasterly direction and may reflect the buried horst/graben structure of the Central Arabian Arch.

In the Levant, platform carbonates (Ra'af and Saharonim formations) were deposited (Hirsch, 1992) as an onlapping sequence of open-marine Muschelkalk-type facies that existed until the end of the Ladinian. The clastic-evaporitic, coastal to deltaic deposits of the Gevanim Formation rimmed the northern edge of the Arabian Plate. Farther west, offshore 'Alpine Muschelkalk', and reefoid (Reifling-type) limestone indicate open-marine environments by the occurrence of *Daonella* pelecypods, ceratid ammonites and conodonts. In the Palmyra Trough, shallow-marine shales and evaporites accumulated locally. Similar conditions seemed to exist for the early Sinjar Trough.

**Middle Triassic: Anisian to Ladinian (241.7–227.4 Ma)**



**Figure 5: Paleofacies of the Middle Triassic.** This time period spanned the deposition of the Jilh, Gulailah, and Geli Khana formations, and their regional equivalents [MFS Tr40 to intra-Tr60]. With information from: Andrews (1992a); Guiraud et al. (2001); Koop and Stoneley (1982); Le Nindre, Manivit et al. (1990); Makhlouf et al (1996); Murriss (1980); Sawaf et al. (2001); Szabo and Kheradpir (1978).

## Late Triassic: Carnian to Norian (227.4–209.6 Ma) (Figure 6)

### **Regional Setting**

This time period spanned the deposition of the Minjur (Arabian Peninsula), Mulussa (Syria), Kurra Chine (Iraq), Dashtak (Iran) formations, and their regional equivalents [MFS Tr60 to intra-J10]. These sediments were partly deposited during a second Triassic infilling-subsidence event. The early Carnian 'Saharan salinity crisis' is a clear indication of a sea-level lowstand at 223 Ma.

### **Paleofacies**

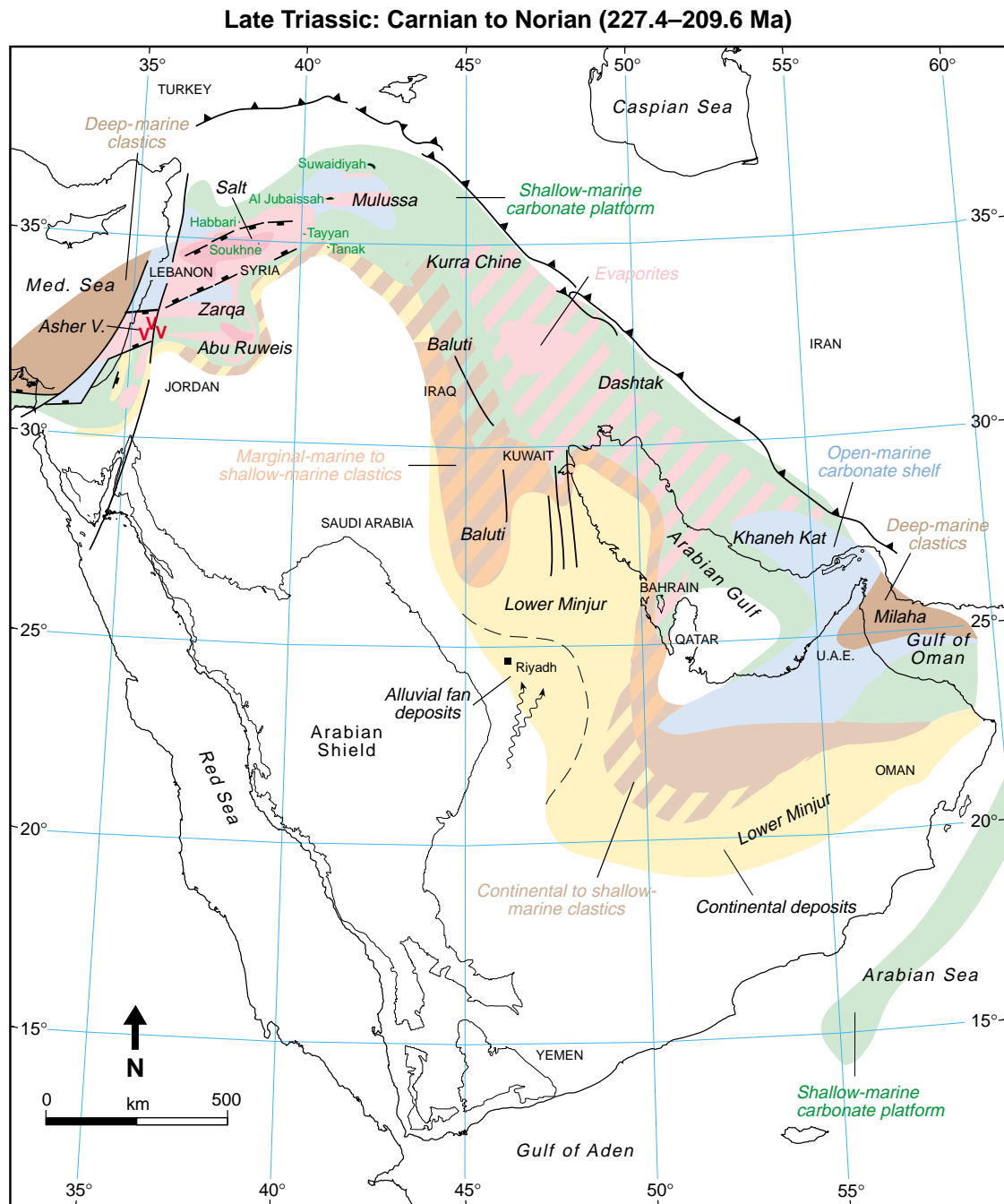
The most striking feature in the Gulf region is the continuation from Middle Triassic times of the massive eastward spread across the Arabian Arch of continental to deltaic clastics derived from the southern edge of the Arabian Shield (Le Nindre, Manivit and Vaslet, 1990). The clastics are a monotonous succession of light-colored, cross-bedded sandstones with variegated shale intercalations and lenses of conglomerates (lower Minjur Formation). These sediments represent alluvial plain and, farther eastward, inundation-plain environments. Ripple marks, mud cracks, sand-bar structures and features resembling fossil dunes, were recognized by Powers et al. (1966) as littoral to continental deposits. No marine fossils have been recorded, but several forms of plants and wood debris were found that indicated a middle Keuper flora of Carnian age similar to that of Central Europe. Variegated gypsiferous shales occur throughout the section. An embayment of inter- to infratidal sediments west of the Summan Horst and the Dibdibah Trough possibly influenced its localization. The southernmost extension of the embayment contained a marsh facies east of Buraidah (Le Nindre, Manivit and Vaslet, 1990).

The Iranian Zagros region (Szabo and Kheradpir, 1978) was occupied by shallow-marine carbonates, and multiple evaporite intervals occur in the area northwest of the Qatar Arch. Szabo and Kheradpir (1978) and Koop and Stoneley (1982) noted a marked erosional truncation of the Sefida dolomite member in the Fars, central Arabian Gulf, and Qatar regions. The Dashtak dolomite and evaporite sequence has been eroded in this area, or may have changed facies across the Fars province. The Khaneh Kat Formation is a shallow-water deposit with indications of intermittent subaerial exposure surfaces, such as mud cracks, stromatolites, and solution breccias, as well as light-colored limestones containing gypsum pseudomorphs. The erosional surfaces suggest paloe karst conditions that, accompanied by soil developments and brecciation, indicate a series of hiatuses. In Iraq, the limestone/dolomite/evaporite Kurra Chine Formation represents, like the Middle Triassic Geli Khana, a succession of shoaling-upward, shallow-water to inner-neritic, euxinic, to near-shore deposits.

Le Métour et al. (1995) reported that a second phase of Neo-Tethyan extensional tectonics occurred in the eastern part of the Arabian Platform during this period. This caused drowning of the northeastern margin, and localized volcanic activity on the continental slope. This second subsidence event had an important effect on the restructuring of the Hawasina Basin and it is assumed that the basement of the Hawasina Basin was thinned continental crust rather than oceanic crust (Le Métour et al. 1995).

The northern and western parts of the Arabian Plate (Rutbah High and Ha'il Arch), were exposed and a 200- to 300-km-wide shallow-marine carbonate shelf surrounded the exposed Shield. Areas with tendencies for preferential subsidence, such as the Sinjar and Palmyra troughs and the Jordan Embayment (Harrat er Rujeila), accumulated large amounts of evaporites (e.g. Mulussa Formation). The Palmyra Trough can be traced westward into the Levant where it is offset by the present-day Dead Sea Transform Fault.

Early in the Carnian, a very pronounced relative drop in sea level was recorded throughout the circum-Mediterranean region. This 'salinity crisis' (Hirsch, 1992) expressed itself in the epicontinental regions as a typical lowstand evaporite sequence dominated by halite and sulfate deposition, continental sands, marls and shales. Concurrent with the opening of new Tethyan rift zones in the Eastern Mediterranean was the deposition of pillow lavas (Asher volcanics), continental sands, and deep-water radiolarites and *Halobia*-limestones. The facies and faunal distribution in late Carnian to Rhaetian allowed the distinction into continental platform and reef-bank and deeper-marine facies (Hirsch, 1992, 1995). This type of lateral facies substitution extended westward from the Arabian Plate toward the Helez uplift in the Levant.



**Figure 6: Paleofacies of the Late Triassic.** This time period spanned the deposition of the Minjur, Kurra Chine, and Dashtak formations, and their regional equivalents [MFS Tr60 to intra-J10]. These sediments were partly deposited during a second Triassic infilling-subsidence event. The early Carnian ‘Saharan salinity crisis’ is a clear indication of a sea-level lowstand at 232 Ma. With information from: Andrews (1992a); Béchenec et al. (1989); Beydoun and Habib (1995); Garfunkel (1989); Makhlouf et al. (1996); Le Nindre, Manivit et al. (1990); Murris (1980); Ponikarov et al. (1966); Sawaf and Tarek (1996); Sawaf et al. (2001); Szabo and Kheradpir (1978); and unpublished Saudi Aramco Miscellaneous Report 913 (W.J. Koop, 1982).

## Triassic to Jurassic Transition: Rhaetian to Hettangian (209.6–201.9 Ma) (Figure 7)

### **Regional Setting**

This time period spanned the deposition of the upper Minjur (Saudi Arabia, United Arab Emirates), Mulussa (Syria), and Butmah (Iraq) formations, and their regional equivalents [GSS J10]. Rocks of Hettangian age are generally absent from much of the Arabian Plate as are many of Rhaetian age. Erosion and non-deposition was caused by structural uplift (onset of Mediterranean rifting) combined with a lowstand in sea level.

### **Paleofacies**

The Arabian Gulf region was still influenced by the central Arabian horst and graben system. The northerly directed supply of deltaic to coastal sands (Minjur) gave way to evaporitic, shallow-marine shales (e.g. the Butmah Formation in Iraq and the Mulussa in Syria). The sands were possibly derived from the southern edge of the Arabian Shield or, more probably, supplied by meandering river systems from further southwest in Yemen (Le Nindre, Manivit and Vaslet, 1990).

The facies distribution seems to have been controlled by deep-seated tectonic lineaments that had been in existence since the Permian. To the west, between the Arabian Shield and the horst and graben system, a mixed facies of carbonates and shallow-marine shales was deposited in a shallow-marine reentrant that probably corresponded to the Paleozoic Widyan Basin (Al-Laboun, 1986). The marine shales mixed with spill-over sands from a possible braided river system that drained the hinterland to the south and southwest. At this location, about 100 km south of Riyadh, ophiuroid remains were found (Le Nindre, Manivit and Vaslet, 1990; D. Vaslet, personal communication, 2000).

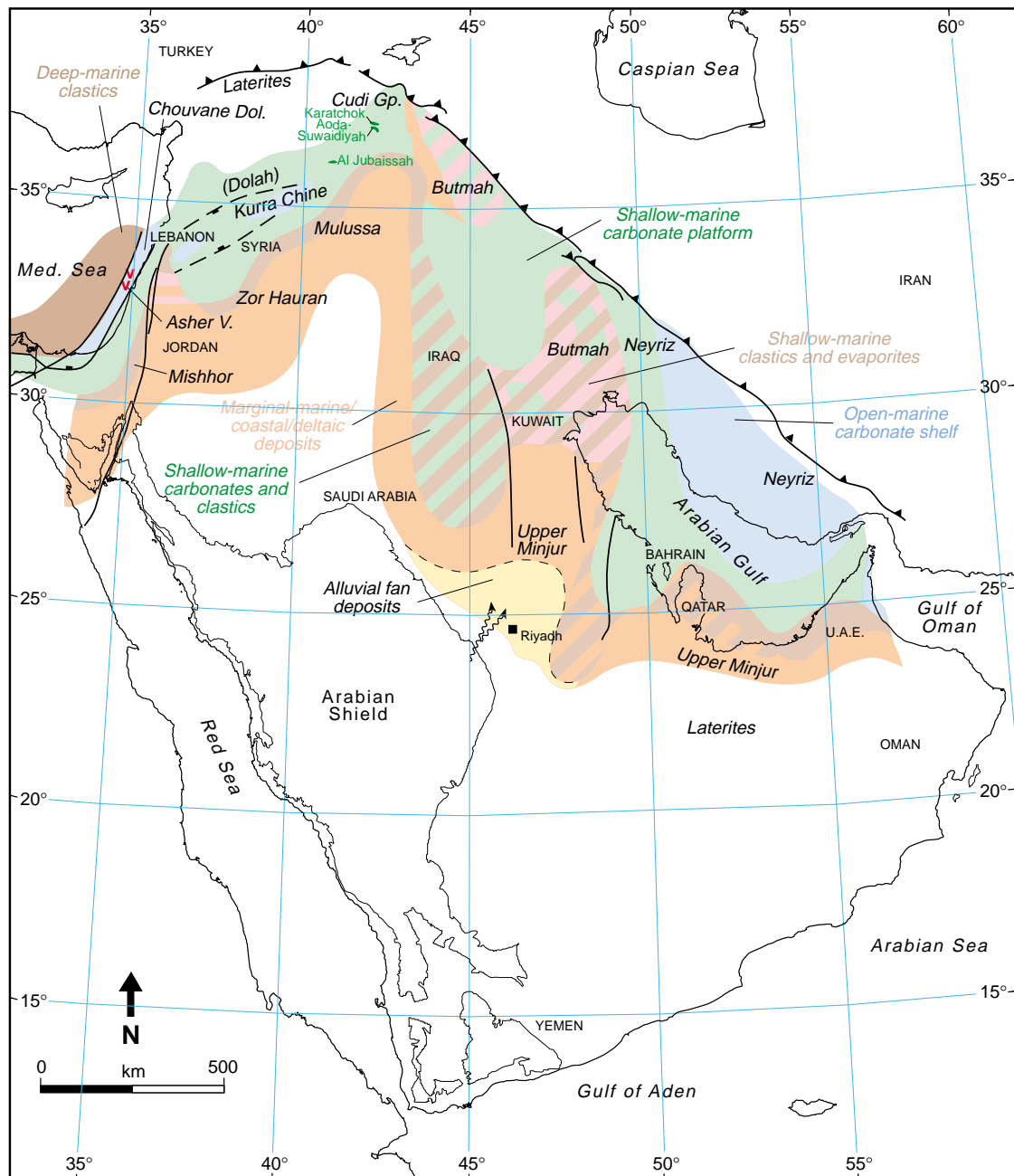
The top of the Hettangian is truncated and marks a stratigraphic gap until the transgression of the lower to middle Toarcian [TST leading to MFS J20]. The southern Qatar Arch was still exposed and upper Minjur sands were eroded from its flanks. Laterally, a transition into shales and mixed shelf carbonates (Neyriz Formation of Iran) took place (Murriss, 1980).

The limestone sequence of the Cudi Group in southeastern Turkey has a poorly defined age ranging from Late Triassic to Jurassic, and possibly even Early Cretaceous. In general, the Hakkari area of easternmost southeastern Turkey belongs to the transition from the peri-Gotnia Basin to the Tethys. The succession starts with limestone/dolomite, passes up through phases of exposure and intense weathering into agitated shallow-marine, shelf-marginal carbonates. Arac and Yilmaz (1990) have reported evidence of slumping from the edge of the Mardin shelf

Hirsch and Picard (1988) and Hirsch (1992) discussed in detail the transition from the Triassic to the Lower Jurassic in the Levant. The contact between the Triassic and Liassic corresponds to the globally recognized drop in sea level (Haq et al., 1988) that left large areas of the eastern Mediterranean and Arabian Plate exposed to lateritic weathering (Mishhor Formation of the Levant). In the Negev, deep weathering and karstification of Upper Triassic rocks took place. At the same time, basalts of the Asher volcanics were extruded in the Mount Carmel area and are as much as 2,000 m thick at Atlit, 30 km south of Haifa. According to Hirsch and Picard (1988), these basalts are related to intracratonic fracturing that was probably associated with the opening of the eastern Mediterranean. Garfunkel and Derin (1985) attributed the volcanics to the rifting and opening of the Erez offshore oceanic graben. From the middle Lias, a marine transgression occurred in the Negev. It began with the deposition of paralic to deltaic sands that passed laterally into gypsiferous lagoonal carbonates of the lower Nirim Formation. Dark laminites and collapse breccias of the lower Kesrouane Formation (Chouane dolomite member) occur in Lebanon (Walley, 1998b).

In Syria, shallow-marine carbonates containing dark, fetid limestones and papery shales (Dolaa group) were deposited in the relic Palmyra depression. The Zor Hauran Formation (Rhaetian) deposited around the northern Rutbah High is the time-equivalent of the Mishhor Formation in the Levant. The Mishhor is characterized by gypsiferous marls, dolomites, and limestones that grade upward into conglomerates with indurated ferruginous crusts. The ferruginous crusts indicate post-Rhaetic emergence and soil formation (Buday, 1980), most likely due to a eustatic fall in sea level (Haq et al., 1988).

### Triassic to Jurassic Transition: Rhaetian to Hettangian (209.6-201.9 Ma)



**Figure 7: Paleofacies of the Triassic to Jurassic Transition.** This time period spanned the deposition of the upper Minjur, Mulussa, and Butmah formations, and their regional equivalents [GSS J10]. Rocks of Hettangian age are generally absent from much of the Arabian Plate as are many of Rhaetian age. Erosion and non-deposition was caused by structural uplift (onset of Mediterranean rifting) combined with a lowstand in sea level. With information from: Andrews (1992a); Guiraud et al. (2001); Hirsch and Picard (1988); Le Nindre, Manivit et al. (1990); Le Métour et al. (1995); Murriss (1980); Walley (2001).

The Rub' Al-Khali Basin was filled for the most part by a sand-shale sequence of the upper Minjur Formation. A thinly bedded dolomite-shale succession, overlain by siltstones and argillaceous lime mudstones (the Neyriz Formation in Iran), indicates deeper-marine conditions toward the eastern Plate margin in the Zagros Fold belt. The sediments appear to be almost devoid of macrofossils, but from regional correlation the Formation is considered to be of Liassic age (James and Wynd, 1965).

### **Early Jurassic: Sinemurian to Aalenian (201.9–176.5 Ma) (Figure 8)**

#### ***Regional Setting***

This time period spanned the deposition of the Mus (Iraq), Marrat (Kuwait, Saudi Arabia, United Arab Emirates), Qamchuqa (Syria) and Nirim (Levant) formations, and their regional equivalents [MFS J10 to intra-J20; the late Toarcian unconformity marks the base of AP7 at 182 Ma]. The eastern Mediterranean opened during this period to create a new passive margin.

#### ***Paleofacies***

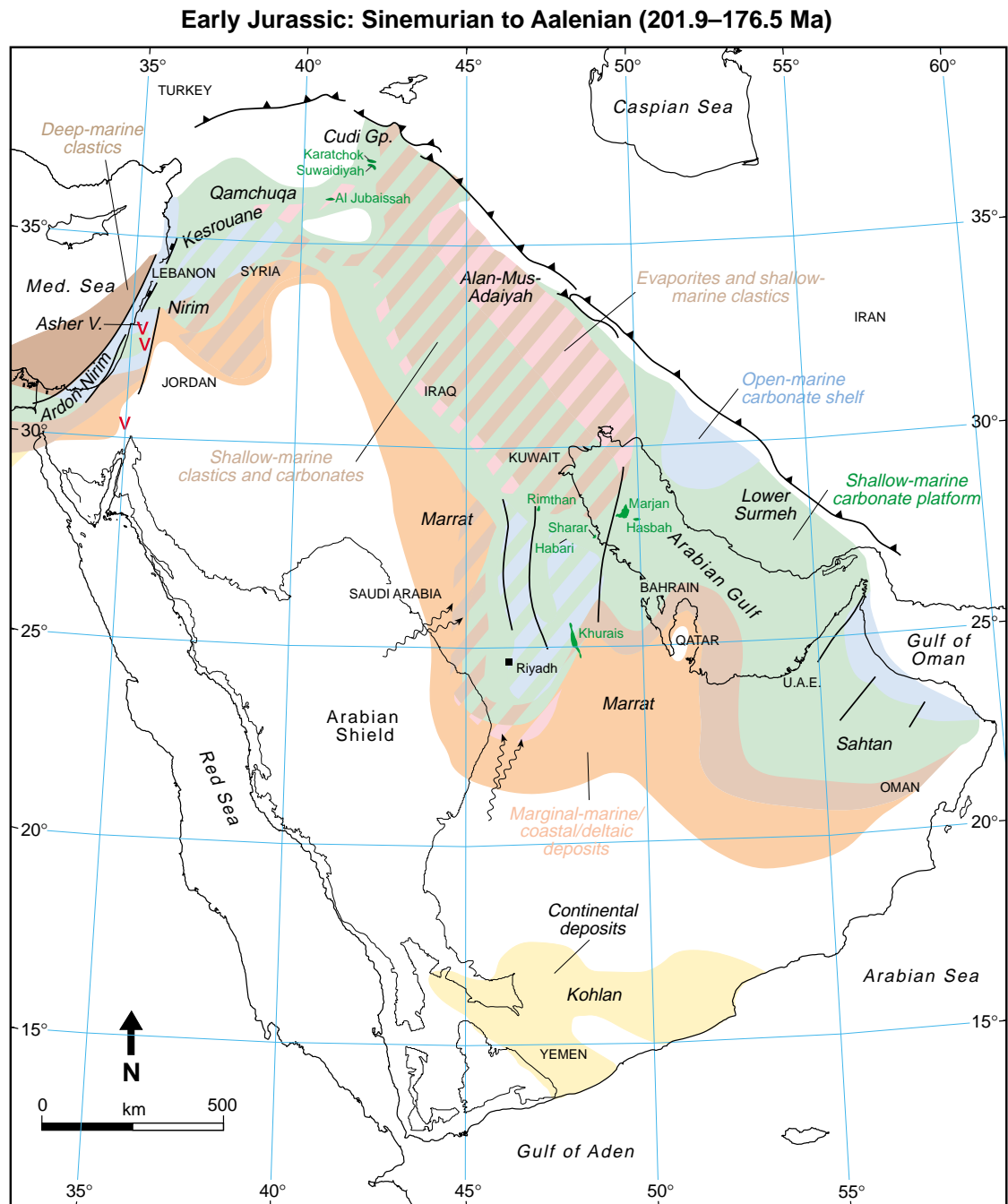
In the Arabian Gulf region, a reversal of the depositional pattern of the Triassic to Jurassic transition occurred at this time. Where previously there had been a structural uplift of the Arabian Arch combined with a lowstand in sea level, there now appeared to have been relaxation and the marked subsidence of the Summan Platform. The pronounced northerly trend of the Platform and the observed facies pattern suggest an underlying tectonic control that probably corresponds to the Hercynian 'basement grain'. These trends extend northward into Iraq and toward the Plate margin. Argillaceous limestones and shallow-marine shales were deposited, together with interbedded evaporites (Alan, Mus and Adaiyah formations), on the edge of the Mesopotamian (Gotnia?) Basin. South of the Arabian Arch, the lower Marrat Formation changed from a carbonate to a clastic sequence and appears to have been eroded in outcrop. In the Rub' Al-Khali Basin, the sandy Marrat is difficult to separate from the Late Triassic upper Minjur clastics, although a significant hiatus—probably due to the global Early Jurassic lowstand of Haq et al. (1988)—is likely to separate them.

In the United Arab Emirates, the Marrat is a mixed facies of terrigenous clastics and shallow-marine, peloidal to bioclastic limestones in its lower part, and an upper sequence of interbedded micritic sandstones and sandy limestones and dolomites. These sediments represent a slowly deepening sedimentary sequence from flood plains, through tidal flats to shallow-marine, and finally to deeper, quieter-water environments. This sequence is the Hamlah Formation (Alsharhan, 1989). On the Qatar Arch (by now only weakly expressed), the Hamlah or Marrat formations rest unconformably on the Middle Triassic Jilh and Gulailah, probably as a result of a global Early Jurassic lowstand (Haq et al., 1988).

In Oman, the long-lasting Sahtan group was a gradually shoaling carbonate sequence that had a thin, basal transgressive succession of mixed terrigenous clastics and carbonates of Pliensbachian age (Le Nindre et al., in press). The lower Surmeh Formation of Iran is a similarly ill-defined long-lasting sequence of massive to thick-bedded crystalline dolomites that includes the basal Liassic *Lithotis* (pelecypod) bed (James and Wynd, 1965).

In the southwestern quadrant of the Arabian Plate, erosional lows or sags occur on a peneplaned topography. These depressions in southern Yemen and the Hadramaut accumulated terrestrial and fluvial conglomerates and sands of the diachronous and transgressive Lower to Middle Jurassic Kohlan Formation (Beydoun, 1997).

In southern Levant, the clastic upper Inmar Formation dominates the central Negev and northern Sinai area. In Ramon, southwest of the Dead Sea, cross-bedded sandstones, interbedded with kaolinitic, coaly, and flinty clays, were deposited in deltaic to lower-estuarine environments (Hirsch and Picard, 1988). Laterally, the sands pass into the shaly Rosh Pinna subfacies and finally into the Nirim Formation. The Nirim is a sequence of limestones, dolomites, and gypsum that is equivalent to the thick and long-lasting Haifa or Kesrouane formations. According to Hirsch (1992), the stacking of the various subfacies appears to reflect repeated sea-level oscillations.



**Figure 8: Paleofacies of the Early Jurassic.** This time period spanned the deposition of the Mus, Marrat, Qamchuqa, and Nirim formations, and their regional equivalents [MFS J10 to intra-J20; the late Toarcian unconformity marks the base of AP7 at 182 Ma]. The eastern Mediterranean opened during this period to create a new passive margin. With information from: Andrews (1992a); Guiraud et al. (2001); Hirsch and Picard (1988); Koop and Stoneley (1982); Le Nindre, Manivit et al. (1990); Murriss (1980); Ponikarov et al. (1966); Walley (1998b, 2001); and unpublished Saudi Aramco Miscellaneous Report 913 (W.J. Koop, 1982).



The Lower and Middle Jurassic rocks of Syria belong to the diachronous Qamchuqa Formation that ranges in age from Sinemurian to mid-Oxfordian in northwest Syria and from Toarcian to Callovian in eastern Syria. The farther north and east, the later the marine transgression occurred. It represents a shallow-shelf to protected lagoonal dolomitic limestone/dolomite sequence (Alsharhan and Nairn, 1997) in a low-energy environment. Interspersed evaporites occur, particularly in the Sinjar area. Due to pronounced post-Jurassic erosion, no sediments younger than Oxfordian are known from this area.

### **Middle Jurassic: Bajocian to Bathonian (176.5–164.4 Ma) (Figure 9)**

#### ***Regional Setting***

This time period spanned the deposition of the Izhara (Qatar), Araej (Qatar, United Arab Emirates) and Dhurma (Saudi Arabia) formations, and their regional equivalents [MFS J20 to intra-J40]. These sediments were deposited in an open-marine environment, as the Arabian Plate now had passive margins to Neo-Tethys to the northeast and north.

#### ***Paleofacies***

This time slice represents a phase of general sea level rise (Haq et al., 1988) and with it the westward transgression of marine environments far onto the Arabian Craton. Coastal and nearshore environments are represented by coastal sands that pass eastward into shallow-marine shales and then into shallow-marine detrital carbonates. Examples are the Dhurma (Saudi Arabia, Oman), Izhara/Araej (Qatar and United Arab Emirates), and the lower Surmeh (Iran) formations.

In Saudi Arabia, the area located over the Precambrian basement high at the southwestern end of the Central Arabian Arch, began to undergo a differentiated subsidence, as did the southern Summan horst-graben tract, to form the Arabian Basin of Ayres et al. (1982). Subsidence continued to collect shales and deeper-marine carbonates ('Mid-Dhurma shales') [J20 at 175 Ma]. The eastward clastic discharge from the hinterland seems to have been reduced and fed only the western Rub' Al-Khali Basin; minor run-offs were mapped by Le Nindre, Manivit and Vaslet (1990) about 200 km northwest of Riyadh. The Arabian Basin and the Gotnia Basin were separated by an approximately 100 km-wide sill (the 'Rimthan Arch') cross-cut by a set of N-trending Hercynian faults. A northwesterly fault-trend appears to have controlled the shape of the Sargelu (Gotnia Province) basin-sill.

In Oman, the shallow-water limestones of the Middle to Late Jurassic Sahtan Group were deposited in the eastern part of the Rub' Al-Khali Basin. The present-day shore of the Gulf of Oman, corresponds roughly to the Middle Jurassic paleoslope that passed into the Al Ayn subbasin (Hawasina Basin) off the continental margin (Cooper, 1990). The slope has a fringe of submarine-fan sands.

In Yemen, incipient graben systems (with typical Najd alignment) began to form and were filled with terrestrial sand/shale sequences of the Kohlan Formation. Local limestone intercalations indicate a local gradual shift from continental/littoral to transgressive, shallow-marine environments. Ellis et al. (1996) interpreted the succession as a prerift package.

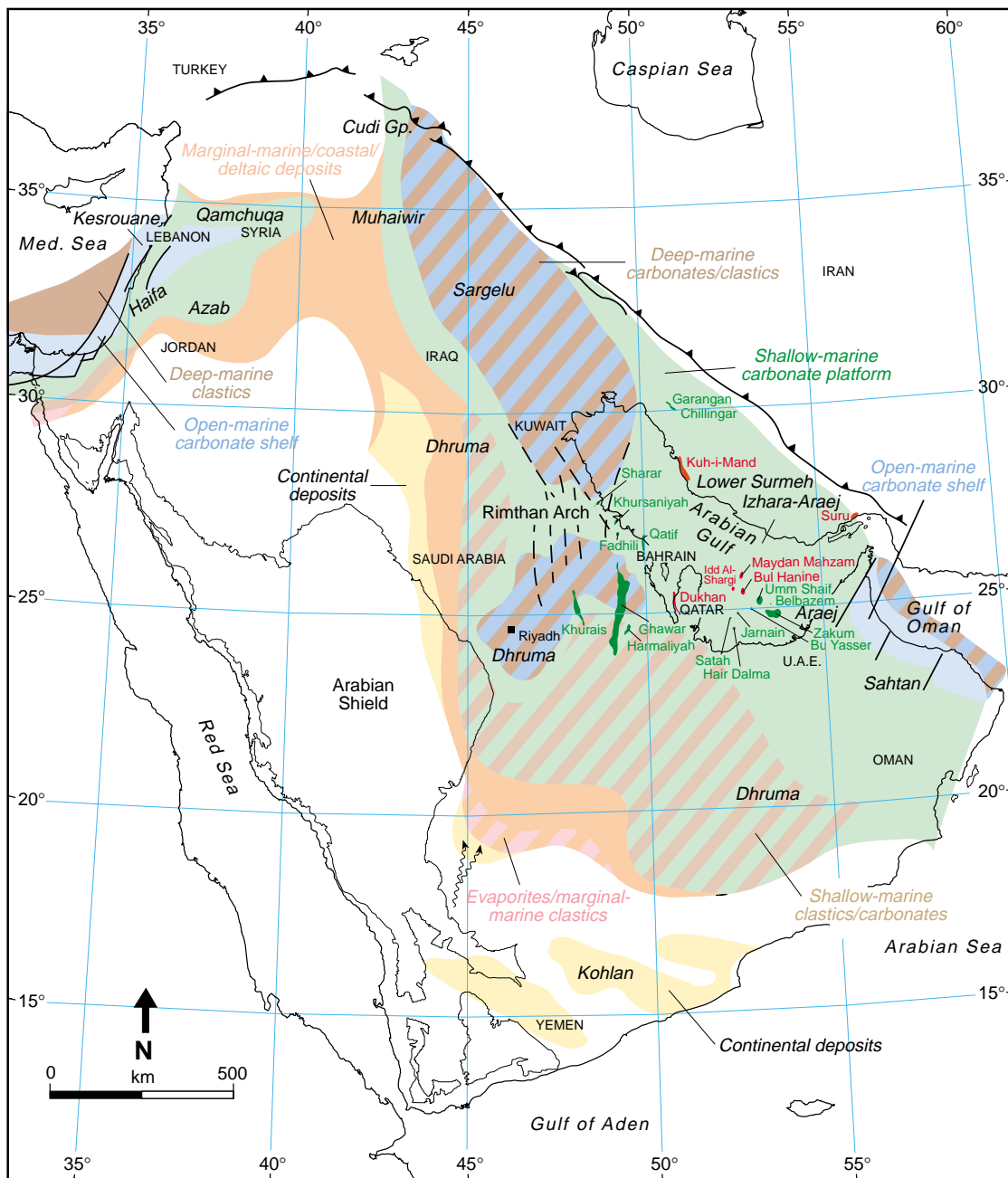
A narrow marine shelf existed in the northwest of the Arabian Plate. It was covered with shallow-water carbonates (Haifa Group) and with deeper-water facies farther offshore. In Lebanon, the thick (1,500–2,000 m) cliff-forming limestones of the Kesrouane Formation form a prominent morphological feature in the Mount Lebanon range (Walley, 1997). The Formation was deposited in a middle- to outer-shelf depositional environment. The interior of the former Palmyra Trough hosts the Qamchuqa argillaceous limestones of the widespread Dolaa Group. North of the Rutbah High, a connection through the future Euphrates-Anah Graben might have existed to link up with the northern Mesopotamian sag (Sargelu Formation) of van Bellen et al. (1959).

### **Late Middle Jurassic: Callovian to Oxfordian (164.4–154.1 Ma) (Figure 10)**

#### ***Regional Setting***

This time period spanned the deposition of the carbonate Upper Dhurma and Tuwaiq Mountain Limestone of Saudi Arabia, the Upper Araej of the Gulf (and equivalents in Lebanon), the clastic

**Middle Jurassic: Bajocian to Bathonian (176.5–164.4 Ma)**



**Figure 9: Paleofacies of the Middle Jurassic.** This time period spanned the deposition of the Izhara, Araej, and Dhruma formations, and their regional equivalents [MFS J20 to intra-J40]. These sediments were deposited in an open-marine environment, as the Arabian Plate now had passive margins to Neo-Tethys to the northeast and north. With information from: Andrews (1992a); Garfunkel (1998); Hirsch and Picard (1988); Le Métour (1995); Le Nindre, Manivit et al. (1990); Murris (1980); Walley (1998b); and unpublished Saudi Aramco Miscellaneous Report 911 (M.A. Ziegler, 1982).

Hanifa, and Naokelekan formations of the Gulf, Syria and Iraq, and the Surmeh dolomite of Iran [MFS J40 to J60]. Differential intraplate subsidence led to the development of intrashelf basins.

### ***Paleofacies***

Although a relative lowstand in sea level prevailed during most of this time interval (Haq et al., 1988), widespread carbonate sediments indicate a shallow-marine environment. Four intrashelf basins have been identified in the southern Arabian Gulf (Rub' Al Khali and Ras al Khaima basins), central Arabia (Arabian Basin) and at the head of the Arabian Gulf (the Gotnia Basin). The northward-trending extensions of the Arabian Arch fault blocks penetrated the 'Rimtham Arch' and controlled the architecture of the platform basins. Substantial amounts of organic-rich source-rock shales, which formed under anoxic conditions, accumulated in the basins. These are the rich source rocks analyzed by Ayres et al. (1982) and Bordenave and Burwood (1990) (e.g. the Hanifa and Naokelekan shales and the Diyab of Qatar and the southern Gulf).

The creation of these intrashelf basins appears to have been based on rejuvenated N-trending Hercynian tectonic structures between the Arabian and Gotnia basins. The southern Gulf Basin, however, was probably controlled by the Dibba fault zone. The 'V'-shape of this basin partly reflects the trend of the Arabian Arch (Rayn trend of Al-Husseini, 2000) and partly that of the Dibba fault system.

The western platform between the Arabian Basin and the silty-shaly coastal-fringe deposits was occupied by coral-algal and bioclastic lime sand deposits. Clastic input derived from the southwestern hinterland was still guided by the southern edge of the Arabian Shield toward the Arabian Basin (Le Nindre, Manivit and Vaslet, 1990). An unconformity at the top of the Callovian Tuwaiq Mountain Limestone defined by hardground and weathering phenomena, was overlain and overlapped by late Oxfordian Hawtah shales at the base of the Hanifa Formation. A similar relationship was described by Hirsch et al. (1995) for the eastern Mediterranean.

Jurassic volcanic rocks from the Batinah coastal plain and Sumayni area of eastern Oman are interpreted as a sign of tectonic instability caused by the incipient breakaway of India and Madagascar along the eastern margin of the Afro-Arabian Plate. Volcanic activity also occurred on the continental slope of the Hamrat Duru Basin, where the Buwayfah Formation (clayey, turbiditic calcarenite) is interbedded with alkaline basalt and andesite (Le Métour et al., 1995). In the Late Jurassic to Early Cretaceous, intermittent uplift, coincident with the easterly tilt of the Oman plate margin, occurred due to incipient rifting and spreading in the Indian Ocean, with continental separation occurring at the end of the Jurassic (Loosveld et al, 1996).

During the Early Jurassic, extensional tectonism started in Yemen. The developing troughs were characterized by shallow-marine carbonates of the first marine transgression (transgressive system tract (TST) of Toland et al., 1995). The J40 MFS of Sharland et al. (2001) occurs in the upper part of the Shuqra Formation. The Formation is composed of well-bedded, fossiliferous limestones with sand-shale intercalations. This intracratonic rifting culminated during the Late Jurassic (Kimmeridgian-Tithonian).

In the Levant, the shallow-marine carbonate shelf at the eastern end of the Mediterranean became markedly smaller, and a more abrupt transition into the Pleshet Basin occurred. Here, the Haifa Formation shows the development of bioherms containing corals and nerineid gastropods. According to Hirsch and Picard (1988) and Hirsch et al. (1995), there is evidence of a short-lived emergence at the end of the Callovian (combined with widespread marine erosion) in eastern Lebanon (Mount Hermon) and at the Djebel Maghara in Sinai (Al-Far, 1966). As a result, sediments of middle and upper Callovian age are missing over large areas and hardground and karstification mark the emergence (Buchbinder et al., 1984). Transgressive shales of the early Oxfordian Kidod Formation, and equivalents, overlie this surface. Late Oxfordian vitreous tuffs (Devorah volcanics) occur on eastern Mount Carmel. Walley (2001) reported extensive late Oxfordian to Barremian block-faulting and alkali-basalt magmatism in Lebanon. Shelf carbonate deposition (Kesrouane Formation) ended at this time.

At the northern extremity of the Arabian Plate, a shallow seaway joined the eastern Mediterranean with the northern extension of the Gotnia Basin. The Qamchuqa Formation was deposited here as an

Late Middle Jurassic: Callovian to Oxfordian (164.9–154.1 Ma)

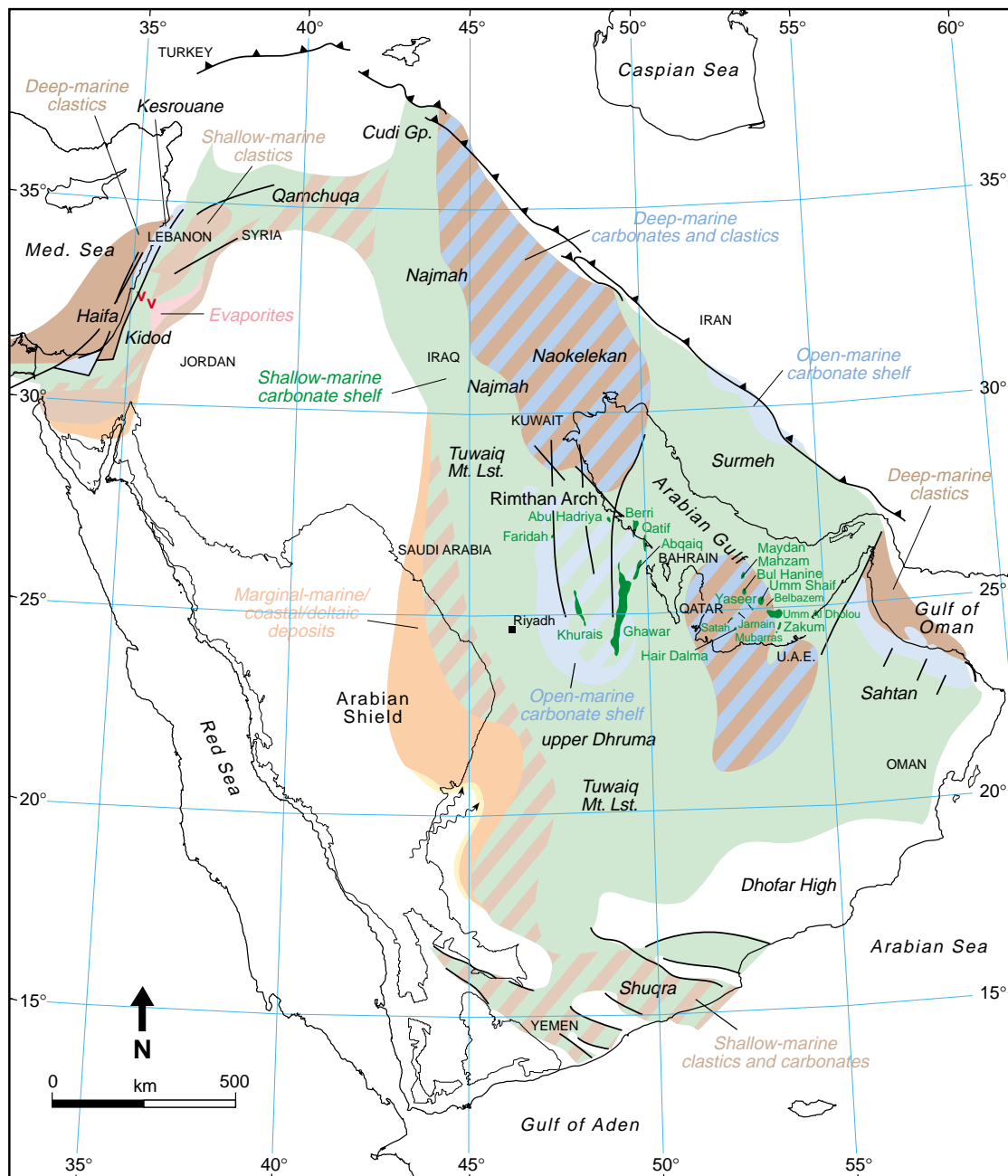


Figure 10: Paleofacies of the late Middle Jurassic. This time period spanned the deposition of the upper Dhurma, Tuwaiq Mountain Limestone, upper Araej, Hanifa, Naokelekan, and Surmeah formations, and their regional equivalents [MFS J40 to J60]. Differential intraplate subsidence led to the development of intrashelf basins on the Arabian Plate. With information from: Andrews (1992a); Guiraud et al. (2001); Hirsch and Picard (1988); Le Métour et al. (1995); Le Nindre, Manivit et al. (1990b); Murris (1980); Walley (1998b); and unpublished Saudi Aramco Miscellaneous Report 911 (M.A. Ziegler 1982) and 913 (W.J. Koop, 1982).

alternating sequence of shallow-marine shales and limestones. The deposition represented a gradation from open-marine massive limestones on the Levant coast, to a restricted oncolithic and micritic interior shelf facies (Haifa Formation).

### **Late Jurassic: Kimmeridgian to Tithonian (154.1–144 Ma) (Figure 11)**

#### ***Regional Setting***

This time period spanned the deposition of the Arab and Hith (Saudi Arabia, Qatar, United Arab Emirates) and Gotnia (Iraq, Kuwait) formations, and their regional equivalents [MFS J70 to K10; base of AP8 at 149 Ma]. Deposition of evaporites was widespread. According to Sharland et al. (2001), the base of AP8 corresponds to a plate-wide late-Jurassic unconformity. A new passive margin developed along the southeastern coast of Oman following continental rifting and sea-floor spreading between the Afro-Arabian and Indian plates.

#### ***Paleofacies***

This time interval corresponded to an overall progressive rise in sea level, and a corresponding widespread deposition of predominantly shallow-marine carbonates. With apparent regularity, shoaling-upward cycles formed a complex system of infratidal carbonates to arid, supratidal evaporites. These cycles represent the Arab Formation, with its four Members (A to D), and the capping Hith Anhydrite. A dashed line on Figure 11 indicates the extent of the Hith Anhydrite, which was the last and most widespread anhydrite unit. Shales for the most part replaced coastal clastics along the margin of the Arabian Shield. Shallow, subtidal oolitic and peloidal, and algal and stromatolitic carbonate/evaporite rhythmites were deposited on a regional scale.

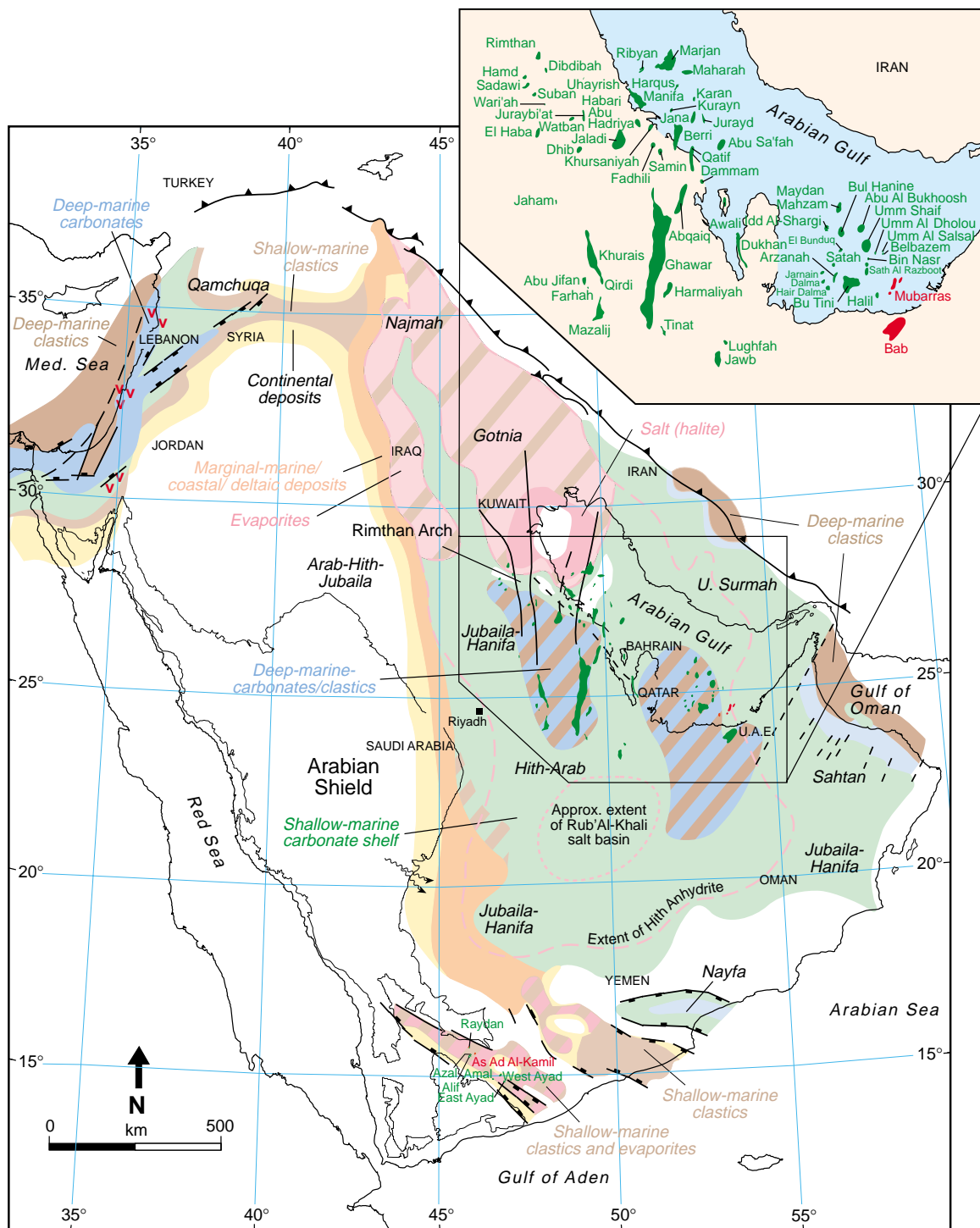
The sediment types and distribution indicate a Bahamas-type depositional model. In such a model, shelf margins with high-energy regimes allowed for the production of calcarenites, whereas protected shelves with pellet-grapestone sediments were associated with algal mats and the creation of spreading islands. These in turn accommodated beaches, tidal and evaporite flats, and other coastal environments. Alternatively, a model of brine concentration in an epeiric sea is possible. The shoaling-upward cycles show strong sulfate replacements that have totally obliterated the depositional textures in some places. Relic textures indicate typical shallow-marine shelf carbonates.

The Arabian and southern Gulf basins with partly anoxic biotopes (Hanifa shales) still existed, but appear to have been filled-in progressively by actively prograding, interior shelf-edge calcarenites. The prograding units downlap into the Arabian Basin and change facies to argillaceous, deep-water deposits. The edge of the Arabian Basin was intensely dolomitized and locally shows evidence of subaerial exposure (karstification and brecciation) with geopetally arranged, internal silt deposits. These marked hiatus surfaces were formed during the late Tithonian. Canyons were incised along the Levant coast during this sea-level lowstand (Hirsch, 1991).

In the Rimthan field on the northern extension of the Summan Platform, numerous stacked erosional surfaces and algal mats and crusts are present (M.A. Ziegler, unpublished Saudi Aramco Miscellaneous Report 911, 1982). Similar features are known from the Saudi offshore area around the Marjan field. On the Fuwaris trend there is pervasive dolomitization up to 1,000 m thick. It is likely that this diagenetic process in near-subaerial conditions occurred close to the major sequence boundary either at end Rayazanian or end Portlandian (Malm) (Haq et al., 1988). This corresponded to uplift relating to continental rifting and sea-floor spreading.

South of the 'Gotnia Rim', four shoaling cycles of interbedded calcarenite and anhydrite units developed. They are the A to D Members of the Arab Formation. Throughout the 250-km-wide Arabian Basin, they show a remarkably uniform development in fabric and thickness. The facies change across the Gotnia margin to shale-sulfate-halite rhythmites appears to correlate with the southern carbonate-evaporite cycles of the Arabian basin. The overlying Hith Anhydrite is thickest in the Arabian Basin. It thins northward into the Gotnia Basin where organic-rich, argillaceous, thinly bedded micritic limestones overlie the evaporites. It is probable that this lithofacies was deposited in a shallow, protected marine environment that was undergoing slow but continuous subsidence.

## Late Jurassic: Kimmeridgian to Tithonian (154.1–144 Ma)



**Figure 11: Paleofacies of the Late Jurassic.** This time period spanned the deposition of the Arab, Hith, and Gotnia formations, and their regional equivalents [MFS J70 to K10; base of AP8 is at 149 Ma]. Deposition of evaporites was widespread. A new passive margin developed along the southeastern coast of Oman following continental rifting and sea-floor spreading between the Afro-Arabian and Indian plates. With information from: Ellis et al. (1996); Guiraud et al. (2001); Hirsch and Picard (1988); James and Wynd (1965); Koop and Stoneley (1982); Le Métour et al. (1995); Le Nindre, Manivit et al. (1990b); Murriss (1980); Ponikarov et al. (1966); and unpublished Saudi Aramco Miscellaneous Report 911 (M.A. Ziegler, 1982) and 913 (W.J. Koop, 1982).

Detailed spectrochemical correlations in various transects from the Arabian Basin into the Gotnia domain revealed that the Tuwaiq Mountain Limestone is progressively missing northward, and even the Dhurma Formation has been markedly truncated with about 300 m of section missing (M.A. Ziegler, unpublished Saudi Aramco Miscellaneous Report 911, 1982).

Sadooni (1997) reported a wide areal distribution of the Najmah Formation into Iraq, markedly farther than the general Cretaceous erosional limit. He suggested that the reactivation of basement faults during the Late Jurassic was responsible for widespread erosion and associated diagenesis. Solution porosities in the southern Gotnia subbasin suggest postdepositional exposure. Shallow-water carbonates of the Formation in the Ribyan field show well-developed columnar stromatolites attached to reworked, angular pebbles of calcarenitic limestone containing rare *Mangashtia viennoti* Henson. These foraminifera have an age range of upper Oxfordian to lower Kimmeridgian and are diagnostic of the upper Hanifa Formation. The base of the overlying evaporite/halite sequence in the Gotnia intrashelf basin can therefore be dated as post-Hanifa.

The active hinge line that controlled the truncation may be located on the northern dip of the Summan Platform, near the Rimthan and Uhayrish fields in Saudi Arabia. The fault alignment relates to the Najd fault system and seems to correspond approximately to the Abu Jir Fault Zone of Iraq. It appears that the Abu Jifan trend has been affected by the N-trending Summan Platform lineament (M.A. Ziegler, unpublished Saudi Aramco Miscellaneous Reports 896 and 911, 1980, 1982). Similar fault interference patterns for central Arabia and the Gulf coast in the Kuwait-Saudi Arabia Partitioned Neutral Zone were suggested by Christian (1997) in the framework of the regional Cretaceous structure. Milner (1998) recognized comparable trends that provide the structural framework for the distribution of source rocks in the southern part of the Arabian Plate.

In offshore Saudi Arabia and Kuwait, four halite cycles are recognized. The lowest salt layer appears to model the northern extension of the 'Khafji Graben' and the eastern boundary of the Gotnia Evaporite Province. The westerly salt pod follows the trend of the 'Minagish Graben' that is located between the Summan Platform and the Burgan trend. The half-grabens are shown on the pre-Unayzah (Upper Carboniferous to Lower Permian) subcrop map of McGillivray and Hussein (1992). The youngest Paleozoic strata within them are of Devonian age. Al-Husseini (2000) related the underlying basement grain to structures within the Rayn microplate that were caused by the Amar collision during the late Precambrian.

Yousif and Nouman (1997) have recorded a similar salt distribution for onshore Kuwait. They located the onlap/downlap of the basal and second salt layer from the west against the Burgan Arch. Along the southern rim of the Gotnia, the remaining upper three salt layers can be correlated across the head of the Gulf. The well-defined cycles typically show repeating couplets commencing with fetid paper shales [high-frequency MFS of Sharland et al., 2001], followed upward by nodular anhydrite that gives way to pure halite before reverting to nodular anhydrite. The next cycle begins with paper shales. This kind of sequence repeats itself three times over the entire southern Gotnia Basin, and four times in the eastern and western parts of the southern basin (M.A. Ziegler, unpublished Saudi Aramco Miscellaneous Report 911, 1982). The salt distribution in the basin appears to be extremely fine-tuned with respect to the Hercynian lineaments branching out from the Arabian Arch.

It is possible that distant plate motions may have reactivated fault-bounded rift blocks that locally appear to have undergone minor uplift and erosion, or tilting, in order to create local intrashelf basins or troughs. Pratt and Smewing (1993a,b) envisage these tectonic influences to be responsible for the flexing and blockfaulting of the eastern margin of the Arabian Plate. A general westward tilt of the Plate, as suggested by Murriss (1980), could have triggered these events. In view of the basement grain, as indicated by Al-Husseini (2000), a complementary interaction of the Rayn, Batin and Abu Jifan fault sets may have occurred.

It seems probable that the marine replenishment of this 'sink' was from the Neo-Tethys to the north. This contrasts with Al-Husseini's (1997) suggestion of a water source to the east, with increasing brine concentrations in a westerly direction toward the Gotnia sedimentary province, (or away from the Neo-Tethys). It appears that the Arabian basin was filled-in rapidly by organic detritus and shelf-

marginal calcarenite wedges (clinoforms) that produced the prolific Middle Eastern oil reservoir facies of the Hanifa, Jubaila, Arab and Manifa formations. Most of them prograde and wedge-out into the Arabian and Rub' Al-Khali basins, or at least thin out (downlap) markedly toward their centers.

In Oman, the NE-trending Dibba Fault clearly separates the western Gulf province from the complexly structured margin of the Hamrat Duru and Umar basins to the southeast. Here, high-energy, well-oxygenated sediments such as reefs and detrital calcarenites, characterize the plate margin. Various types of debris flows covered the continental slopes of Neo-Tethys, typically majolica facies with tintinnids and radiolarian cherts, and Cooper (1990) recorded exotic limestones.

The widespread occurrence of conglomerates in Oman at the end of the Jurassic indicates a regional destabilization of the shelf edge associated with the rifting of India from Arabia. With a possibly still moderately rising sea level, the rapid drowning of the northeast platform seems to have outpaced the vertical carbonate production and led to the accumulation of deeper-water, mud-dominated, chert-rich facies.

In Yemen, the synrift graben systems contain anoxic shales and evaporites that are comparable with the eastern shelf of the Arabian Plate. The greatest marine constriction seems to have occurred in the Marib-Shabwa Basin (Madbi Formation) and to a lesser degree in the Sayun-Masila Basin. Normal marine carbonates (Nayfa Formation) are present in the easternmost Jeza-Qamar Basin, which appears to have been a prerift sag (Redfern et al., 1995; Ellis et al., 1996; and Beydoun, 1997).

In the Levant and eastern Mediterranean region, intensive uplift, rifting, and volcanism correspond to the top of AP7 (Sharland et al., 2001) at 149 Ma (Tithonian). The earlier Jurassic paleogeographic pattern of highs and lows in the Negev and northern Levant was replaced by the Pleshet Basin (Cohen et al., 1988). This event subdivided the Levant region into a structured shelf with numerous fault blocks, generally parallel to the Mediterranean plate margin. Cohen et al. (1988) differentiated the plate margin in the following manner:

1. a western platform province along the Gevar-Am trough, related to the Pleshet Basin (subsiding along the present-day Levant coastline); and
2. an eastern platform province on the margin of the exposed and eroding Arabian-Nubian massif.

Fault activity is marked by 'Tayasir' volcanics (vitreous tuffs) at Devorah (Hirsch and Picard, 1988). In Syria, a shallow seaway connected the Syrian Platform with the Gotnia Basin to the southeast between the Aleppo High (Mardin Shelf) and the Rutbah High. Along its western margin were deposited mainly shales (Qamchuqa Formation) and terrigenous sands.

## **Very Early Cretaceous: Berriasian to Valanginian (144–132 Ma) (Figure 12)**

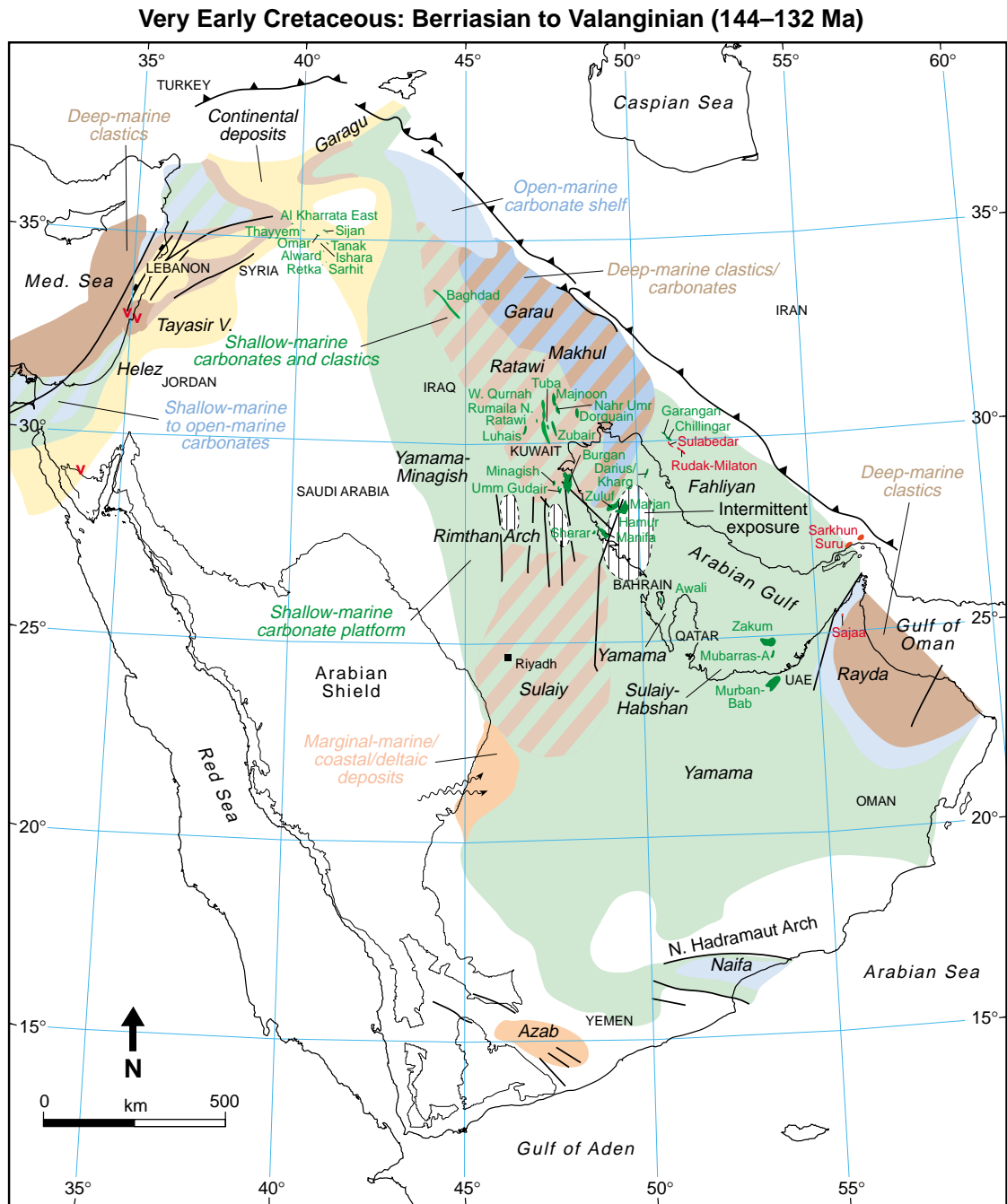
### ***Regional Setting***

This time period spanned the deposition of the Yamama, Minagish, Habshan, and Rayda formations, and their regional equivalents [MFS intra-K20 to intra-K40]. Relatively continuous sedimentation took place in Oman, but most other parts of the Arabian Plate were affected by a late Valangian unconformity. Al-Fares et al. (1998) related a major sedimentary hiatus of Valanginian to early Hauterivian age in offshore Kuwait to far-field stresses induced by the opening of the South Atlantic that may have reactivated older structures. The sediments were deposited on open platforms and within intrashelf basins of the Arabian Plate that was surrounded to the north, east, and south by passive margins with Neo-Tethys. They correspond to the first Early Cretaceous second-order depositional sequence of Sharland et al. (2001).

### ***Paleofacies***

This interval is characterized by a moderately high, but falling, eustatic sea level (Haq et al., 1988). The eastern shelf platform of the Arabian Plate was covered by shallow-water carbonates (Yamama, Minagish, and Habshan formations), with the exception of the areas of the former Gotnia Province





**Figure 12:** Paleofacies of the earliest Cretaceous spanning the deposition of the Yamama, Minagish, Habshan, and Rayda formations, and their regional equivalents [MFS intra-K20 to intra-K40]. Relatively continuous sedimentation took place in Oman but most other parts of the Arabian Plate were affected by a late Valangian unconformity. Sediments were deposited on open platforms and within intrashelf basins of the Arabian Plate. With information from: Béchenec et al. (1989); Ellis et al. (1996); Hirsch (1990); James and Wynd (1965); Le Métour et al. (1995); Murriss (1980); Sawaf and Tarek (1996); Walley (1998b, 2001); and unpublished Saudi Aramco Miscellaneous Report 911 (M.A. Ziegler, 1982) and 913 (W.J. Koop, 1982).

and the residual Arabian Basin, where argillaceous limestones of the Sulaiy/Makhul formations were deposited. However, from the flanks of the now actively subsiding Gotnia Trough, shallow-water pelletal and peloidal, mainly mud-supported limestones, prograde into the basin eastward and accumulated as the Ratawi Formation reservoir rock.

In the north of the Arabian Plate, a terrigenous, sand-dominated environment is suggestive of active uplifting, rifting, and volcanism (Tayasir Volcanics). West of the present-day coastline of the Levant, the Pleshet Basin opened through the subsidence of the northerly oriented Gevar-Am trough, which collected mainly clastic sediments. The source of the Helez sandstones was the land masses to the southeast, as well as a western basement high possibly on an old rift shoulder (Rosenfeld et al., 1998), about 50 km offshore from the present coastline.

A possible marine connection might have existed across Syria between the eastern Mediterranean and northern Iraq where sediments indicate shallow-marine to shoreline and coastal environments. In eastern Iraq and adjacent Iran, a similar alternating shale-limestone sequence is present (the Gadvan Formation of Iran). The shale facies indicate somewhat deeper-water intrashelf conditions with a normal marine fauna containing abundant crinoids and echinoids. These rocks appear to grade laterally into the long-lasting Garau Formation (Early Cretaceous to Coniacian) that consists of gray-black carbonaceous shales and argillaceous limestones. The occurrence of a radiolarian fauna and planktonic foraminifera indicate the proximity of deep, open-marine conditions adjacent to Neo-Tethys farther to the north and east.

The northern Rub' Al-Khali/Ras al Khaimah Basin appears to have lost its former expression as a result of infill by shelf carbonates and evaporites. Pratt and Smewing (1993a,b) suggest the occurrence of Late Jurassic block faulting along the northeastern Oman plate margin. Variable rates of thermal subsidence and tranpressive forces were translated onto this margin by oceanic plates in the Neo-Tethys. These forces caused local minor uplift and erosion. With the termination of this stress regime, the Hamrat Duru Basin came into existence as a large downwarp. The platform sediments of the Arabian Plate withdrew southwestward and pelagic-type sediments uniformly covered the old continental slope and the drowned plate margin (Le Métour et al., 1995). The clastic source was pushed back southwestward, so that an essentially pelagic sediment regime covered both the old continental slope and the Hamrat Duru Basin. In the proximal parts of the Basin, the turbiditic succession of the Guwyza Formation is covered by radiolarian chert and silicified micrites of the lower Sid'r Formation and by Wahrah radiolarian chert.

In the interior of Oman, the Middle to Late Jurassic shallow-water limestones of the Sahtan Group are overlain unconformably by thin-bedded, cherty lime mudstones of the Rayda Formation. The Rayda represents a deep-marine facies and contains pelagic microfossils, such as silicisponges, radiolarians, and saccocoma (crinoid) ossicles. This porcellanitic limestone extends across central Oman, into the eastern United Arab Emirates, and as far north as the eastern Musandam Peninsula.

In the Hawasina Basin of northeastern Oman, cherty sediments characterize the sequence from Tithonian through Hauterivian. However, the Hamrat Duru Basin with a high carbonate generation rate contains hemipelagic limestones, whereas radiolarian cherts prevail predominantly in the proximal, shale-rich Al Ayn subbasin and the distal Duru subbasin (Cooper, 1990). The flanking platform of the Al Ayn sag had mainly shallow-shelf environments with reefs, winnowed oolitic and peloidal grain-limestone belts, and a lagoonal to platform interior environment with mud-supported lithologies (Alsharan and Nairn, 1997).

In Yemen and southern Oman, tectonic stresses caused not only flexuring and drowning of the Jurassic platform but also uplift, such as the North Hadramaut Arch. A shallow-marine carbonate province developed in the Say'un-Masila and Jeza-Qamar basins whereas the Marib-Shabwa Basin appears to have been more isolated from marine circulation. It accumulated predominantly shallow- to transitional-marine shales (Azab Formation) and terrigenous sands (Harshiyat Formation). The Naifa Formation in the Jeza-Qamar Basin is an important source rock (Richardson et al., 1995).

## Early Cretaceous: Hauterivian to Barremian (132–121 Ma) (Figure 13)

### **Regional Setting**

This time period spanned the deposition of the Aarda (Jordan), Zubair, Buwaib, and Biyadh (Iraq, Kuwait, Saudi Arabia), and Lekhwair, and Kharab (United Arab Emirates, Oman) formations, and their regional equivalents [MFS K40 to intra-K70]. It was a period of low sea levels with minor subcycles and a later moderate rise of the sea (Haq et al., 1988). Sediments were deposited in shallow-marine shelf and intrashelf settings on the Arabian Plate passive margin with Neo-Tethys, and were influenced by the strong clastic sediment supply from the Zubair delta to the west.

### **Paleofacies**

In the Levant, extensive freshwater ('Wealden facies') and continental deposits, interbedded with Tayasir basaltic volcanics, are reported by Rosenfeld et al. (1998) for the Negev, Galilee High and Mount Lebanon area (Walley, 1998b). This indicates a clear uplift of the northwestern plate margin concurrent with a marked marine regression. Offshore in the Gevar-Am Trough are deeper-marine shales and pelitic to chalky sediments of the Talme Yafe and Abeih formations.

The northern part of the Arabian Plate was covered by shallow-marine shales and occasional evaporite sabkhas and salinas of the Areban, Cherrife, and Mdarej formations (Syria, Iraq) and of the lower Mardin Group of southeast Turkey. The interior-shelf, coastal-fringe shales grade northeastward toward the plate margin into sandy limestones, which by their faunal content (algae, oncoids and oysters) indicate some restriction in marine circulation.

The wider Gulf Basin was fringed toward the Arabian Shield by an extensive transgressive sand-shale apron of the Biyadh, Buwaib, and Zubair formations. The lateral transition illustrates a gradual change from continental fluvial systems, through shallow-marine sandbars and subtidal shales to a carbonate ramp system farther offshore. West of the N-trending Dibdibah Trough, a shallow-marine embayment resulting from carbonate suppression may explain the nannofossil finds about 150 km northeast of Buraydah (Le Nindre, Manivit et al., 1990).

The Gotnia Basin contains about 800 m of dark, deep-marine shales and fine-grained cherty limestones of the Balambo and Garau formations (van Bellen et al., 1959; James and Wynd, 1965). In contrast, shallow-marine Fahliyan limestones composed of oolitic, pelletal and brecciated calcarenites, formed a shallow shoal passage from the Fars province of Iran to the Ras al Khaima Basin in the southern Gulf and United Arab Emirates. The Basin is marked by a predominantly deeper-marine, fine-grained argillaceous mudstone, with pelletal, bioclastic lime packstones in Qatar (Lekhwair Formation overlain by Kharab Formation). In offshore Abu Dhabi, Boichard et al. (1995) described a micrite sequence interspersed with peloidal to rudistid grainstones that they attributed to a broad carbonate-ramp setting. The depositional environment appears to have alternated between an inner-outer, proximal-outer, to deep-outer ramp conditions. The rudistid Thamama zones II and IIIA of the Kharab Formation indicate general shoaling phases reflecting an inner-ramp environment.

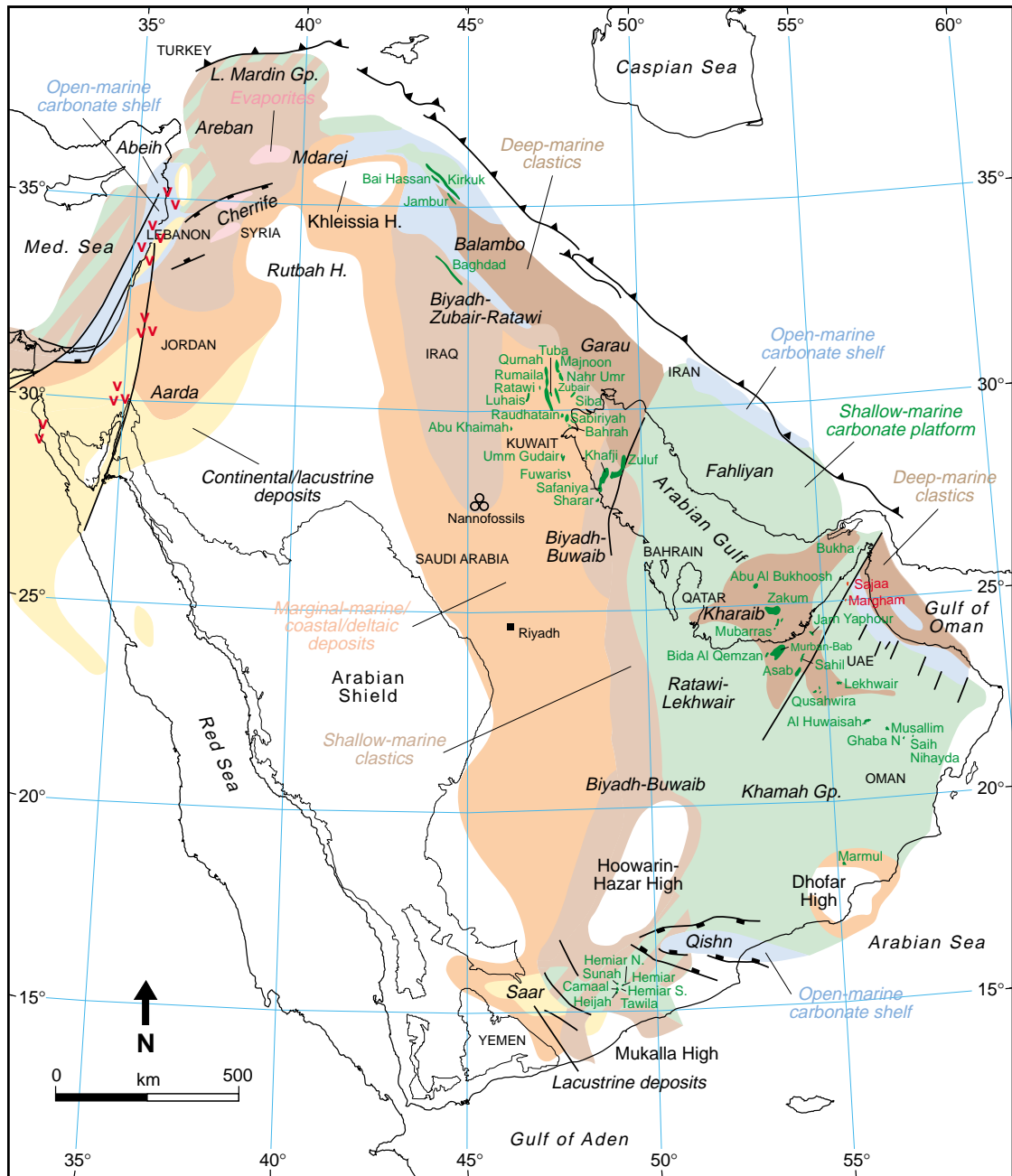
In the south of the Arabian Plate are located the large positive structures of the Hoowarin-Hazar High in northern Hadramaut and the Dhofar High in Oman. Shoreline and shallow-marine clastics fringe the structures. In Yemen, the two eastern basins of Sayun-Masila and Jeza-Qamar belong to the shallow-marine setting (Qishn Formation), whereas the Marib-Shabwa Basin appears to have been an isolated basin in which lacustrine sediments of the Saar Formation accumulated.

## Late Early Cretaceous: Aptian to Albian (121–98.9) (Figure 14)

### **Regional Setting**

This time period spanned the deposition of the Shu'aiba, Biyadh, Nahr Umr, and Burgan (Arabian Peninsula), and Kazhdumi (Iraq, Iran) formations, and their regional equivalents [MFS K70 to intra-K120]. A marked late-Aptian regional unconformity and sedimentary hiatus separates rocks of Aptian age (e.g. Shu'aiba Formation) from those of Albian age (e.g. Nahr Umr). This break probably coincided

Early Cretaceous: Hauterivian to Barremian (132–121 Ma)



**Figure 13: Paleofacies of the Early Cretaceous.** This time period spanned the deposition of the Aarda, Zubair, Buwaib, Biyadh, Lekhwair, and Kharairb formations, and their regional equivalents [MFS K40 to intra-K70]. Sediments were deposited in shallow-marine shelf and intrashelf settings on the Arabian Plate passive margin with Neo-Tethys, and were influenced by the strong clastic sediment supply of the Zubair delta to the west. With information from: Andrews (1992b); Ellis et al. (1996); Guiraud et al. (2001); Hirsch (1990); Holden and Kerr (1997); Koop and Stoneley (1982); Murriss (1980); Ponikarov, et al. (1966); Roger et al. (1998); Sawaf et al. (2001); Walley (1998b); and unpublished Saudi Aramco Miscellaneous Report 826 (D.W. Hagen, 1975), 849 and 911 (M.A. Ziegler, 1976, 1982).

with a worldwide lowstand in sea level (Haq et al., 1988) and was followed by a gradually rising sea level that culminated in maximum flooding by end Albian [K110 MFS at 101 Ma]. Al-Fares et al. (1998) interpreted the pre-Albian unconformity as the result of far-field stress consequent on the opening of the central Atlantic Ocean. This caused uplift of the western part of the Arabian Craton and the shedding of deltaic sands and transitional marine clastics from the west and southwest. Well-defined salt domes in the southern Gulf are attributed to halokinetic movements of the Precambrian Hormuz salt and evaporites that began with salt pillowing in the late Aptian-Albian due to structural reactivation.

### ***Paleofacies***

The transgressive Albian deposits reflect a rise in sea level. The gradually rising sea level that followed the pre-Albian unconformity caused the oscillating deposition of shale and carbonate. In general, by late Albian times, the Arabian Platform was widely inundated by shallow seas in which were deposited shallow- to progressively deeper-marine carbonates in various subbasins around the plate margin. These are as follows:

1. The shallow Palmyra intrashelf basin in the north;
2. The Lurestan intrashelf basin, east of Baghdad;
3. The Khuzestan intrashelf basin, east of Basra;
4. The Rub' Al-Khali, Ras al Khaimah and Fars intrashelf basins in the southern Gulf;
5. The Jeza-Qamar intrashelf basin of eastern Yemen (Hadramaut).

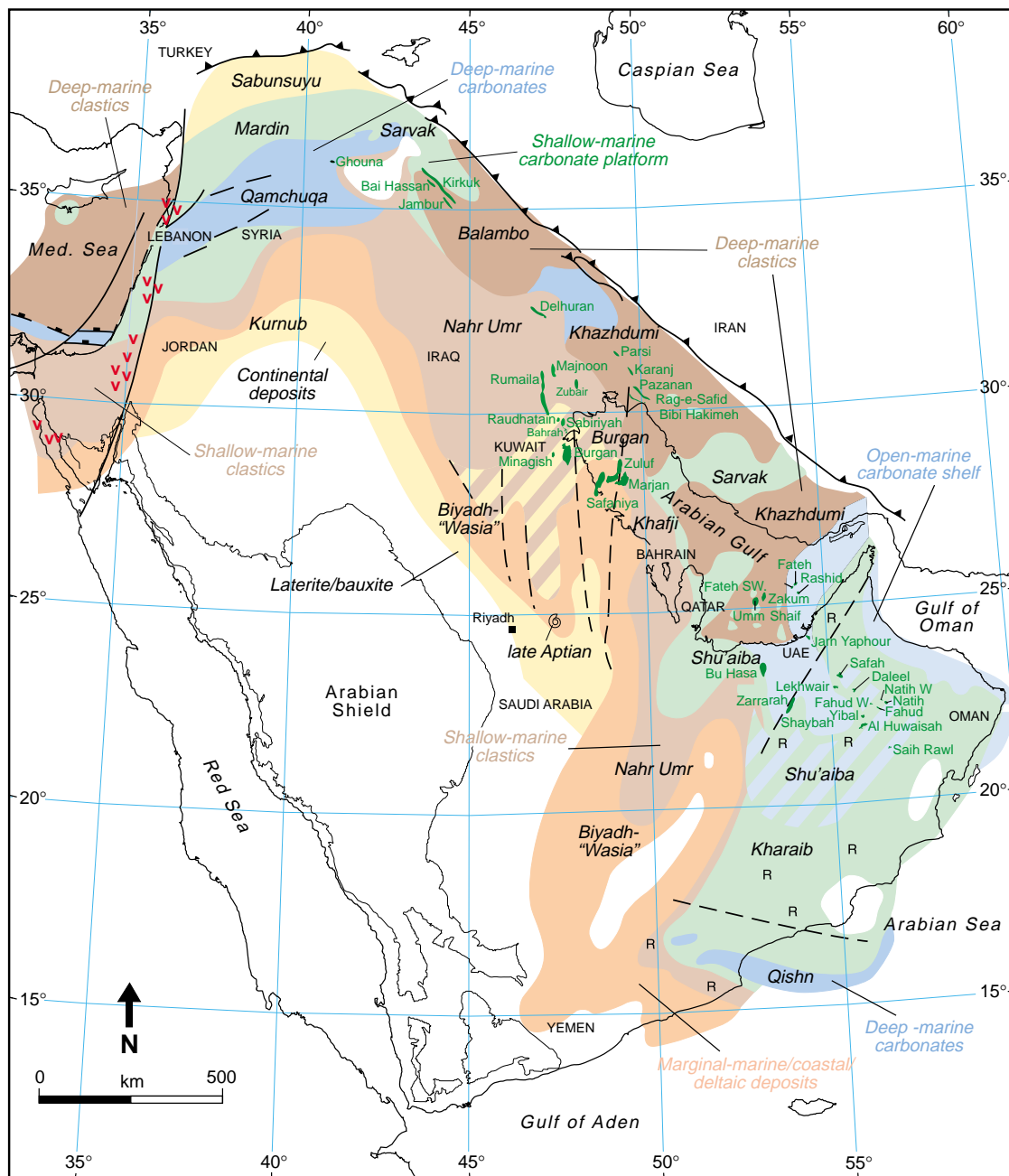
Dark organic-rich shales and argillaceous limestones of the Kazhdumi and Balambo formations characterize the eastern plate intrashelf basins of Iraq and Iran. The presence of ammonites and a foraminiferal-oligosteginid fauna indicate a deeper-marine depositional setting and connection with Neo-Tethys.

Shallow-water platform limestones with fringing rudist reefs are present along the hinge line of the eastern Mediterranean shelf margin (Bein, 1976). Westward, the platform sediments pass rapidly into thick, fine-grained slope and cherty basinal facies. The platforms that separate the various intrashelf basins are the sites of shallow-water carbonate deposition (e.g. the Sarvak Formation of Iran). These bioclastic skeletal lime grainstones are the 'rudist limestones' of James and Wynd (1965). In part, they are composed of rudistid banks (reefs) and aprons of large-scale, cross-bedded bioclastic debris and brecciated limestones.

Hughes (2000) subdivided the early Aptian Shu'aiba Formation of the Shaybah field of Saudi Arabia. He recognized three stacked units on the basis of distinct micro- and macro-biofacies. The Shu'aiba, at a location in the southern Rub' Al-Khali Basin, evolved from a moderately deep-water platform into a rudist-rimmed plateau that may be a spur of the Dibba Fault of Oman. The distinct biofacies belts allow subdivision into an open marine/basinal environment, followed by platform-rimming rudist banks, and finally back-bank to lagoonal environments. The lagoons are indicated by the presence of dasyclad algae and encrusting *Lithocodium* sp. aggregates. The tripartite vertical sequence consists of an early unsculptured, shallow-marine platform at the base, adjacent to open-marine conditions. In the middle Shu'aiba, rudist mounds began to thrive [MFS K80], and the upper part shows a general tendency toward shoaling and a spread of lagoonal biofacies that may be suggestive of a sequence boundary [MFS K90]. The basinal shoals and internal paleoshelf margins hosted Shu'aiba rudistid banks. Their various skeletal and grain-supported textures provide excellent primary and secondary porous reservoir lithologies.

In the Shaybah field, the Shu'aiba Formation shows signs of weathering with deep invasion of late Aptian Nahr Umr shales into the carbonate reservoirs (M.A. Ziegler, unpublished Saudi Aramco Miscellaneous Report 849, 1976; Hughes, 2000). At outcrop in Saudi Arabia, Aptian sedimentation ends with the Sallah Member of the Biyadh Formation. This shallow-marine sand-shale represents a maximum flooding event that is dated by a late Aptian ammonite discovery near Riyadh (Le Nindre, Manivit et al., 1990). The marine ingression onto the Arabian Shield suggests that the Hercynian structures of the Arabian Arch allowed a narrow seaway to extend far across the Arabian Plate. The top of the Biyadh Formation was exposed and weathered during the Albian and lateritic clay and

## Late Early Cretaceous: Aptian to Albian (121–98.9 Ma)



**Figure 14:** Paleofacies of the late Early Cretaceous spanning deposition of the Shu'aiba, Biyadh, Nahr Umr, Burgan, and Kazhdumi formations, and their regional equivalents [MFS K70 to intra-K120]. A marked late-Aptian regional unconformity and sedimentary hiatus separates rocks of Aptian age (e.g. Shu'aiba Formation) from those of Albian age (e.g. Nahr Umr). Well-defined salt domes in the southern Gulf are attributed to halokinetic movements of the Precambrian Hormuz Salt due to structural reactivation. With information from: Andrews (1992b); Guiraud et al. (2001); Hirsch (1990); Holden and Kerr (1997); Koop and Stoneley (1982); Le Métour et al. (1995); Lutfi (1996); Murriss (1980); Pascoe et al. (1995); Roger et al. (1989); Sawaf and Tarek (1996); and unpublished Saudi Aramco Miscellaneous Report 913 (W.J. Koop, 1982), 826 (D.W. Hagen, 1975), 849 and 911 (M.A. Ziegler, 1976, 1982). R=Rudist reefs.

bauxite developed, as at Az Zabirah north of Buraydah in central Saudi Arabia (Le Nindre, Manivit et al., 1990; Collette and Grainger, 1994).

Over the Arabian Arch, continental sands and conglomerates (Biyadh Formation in Saudi Arabia) gave way northward to littoral and shallow-marine environments in Kuwait. There, the Early Cretaceous Aptian sands (Zubair Formation) are fine grained with intercalated shales, and the later Albian Burgan sands are typical of deposition in a littoral to delta-front setting. It appears that the former N-trending Hercynian grain was directing the sediment discharge as far north as southern Iraq, where delta distributaries took on a northeasterly direction (Al-Fares et al., 1998) that may be related to the former Batin Fault lineament (Al-Husseini, 2000).

Fluviatile and continental sands of the upper Kurnub Group occur in the vicinity of the Rutbah High. In the interior of the Arabian Plate, Andrews (1992b) described poorly dated fluviodeltaic environments in southeastern Jordan, typified by freshwater algae and coaly, wood fragments, that indicate deposition close to shore. Similar continental environments appear to have existed in the Al Jawf region of northern Saudi Arabia.

Along the eastern plate margin, as far as the southern Gulf region, organic-rich Kazhdumi shales were deposited. They contain subordinate argillaceous limestone beds that have an open-marine basinal biota of planktonic foraminifera, radiolarians, and sponge spicules (James and Wynd, 1965). Southward, the Fars intrashelf basin extended into the lobate intracratonic Rub' Al-Khali Basin whose filling is of an open-marine, off-bank nature containing planktonic foraminifera (*Hedbergella* ssp.) and skeletal debris that fines away from the bank/fore-bank sediment source areas (Hughes, 2000).

The Hoowarin-Hazar Ridge of Yemen and the southern Rub' Al-Khali is a prominent feature conspicuously aligned with the Dibba Fault. It shed clastics into the Rub' Al-Khali Basin as far as the southern United Arab Emirates (Pascoe et al., 1995). The shelf east of Hoowarin was a marly orbitolinid carbonate platform with numerous rudist patch reefs (Kharai Formation). The rift troughs in Yemen had, for the most part, ceased to exist by this time. Only the easternmost Jeza-Qamar Basin was still in existence as shown by the deposition of deep-marine carbonates of the Qishn (Fartaq) Formation.

## **Early Late Cretaceous: Cenomanian to Turonian (98.9–89 Ma (Figure 15)**

### ***Regional Setting***

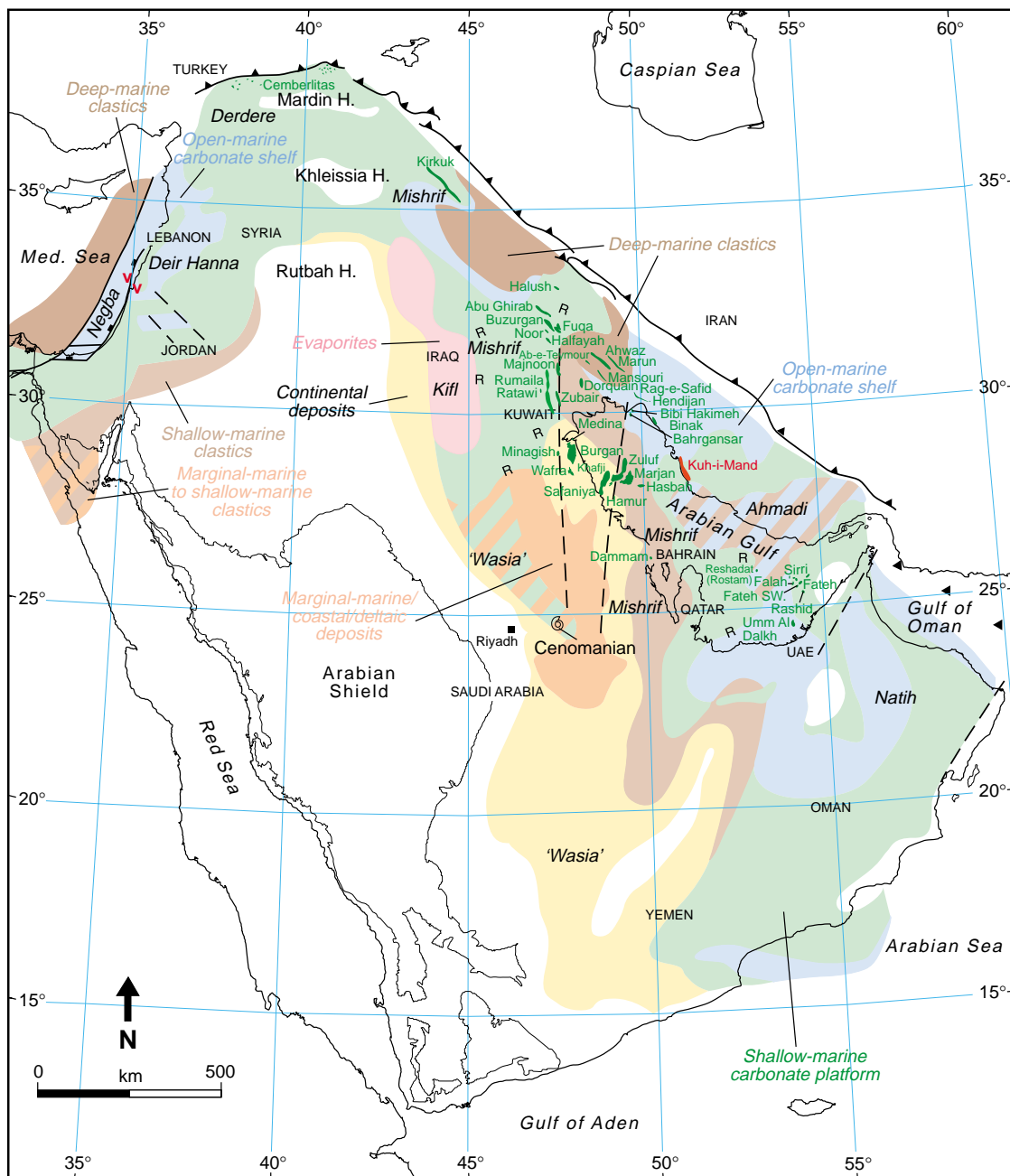
This time period spanned the deposition of the Mishrif, Ahmadi, and Rumaila (Arabian Peninsula), Natih (Oman), and Dardere (SE Turkey) formations, and their regional equivalents [MFS K120 to intra-K150; base of AP9 dated at 92 Ma]. Base AP9 corresponds to the Plate-wide mid-Turonian unconformity resulting from the start of ophiolite obduction along the eastern margin of the Arabian Plate. The sediments were deposited on platforms and within intrashelf basins on the passive margin of the Plate.

### ***Paleofacies***

A maximum global coastal onlap for this time interval has been proposed by Haq et al. (1988) and, in Arabia, the sedimentary record indicates the presence of widespread shallow-marine platform carbonates (Mishrif Formation). The repetitive interbedding of limestones with silty shales and shales (Rumaila, Ahmadi, and Natih formations of the Wasia Formation of Saudi Arabia) indicate a reduced input of terrigenous clastics from the hinterland to the west. Generally, the succession becomes pure limestone toward the late Cenomanian (e.g. Mishrif Formation). Detrital limestones with rudistid remains and coralline algae are present in Kuwait and southwestern Iraq. The late Cenomanian to Turonian Mishrif Formation of Kuwait contains coral and rudist bioherms with a chalky limestone fabric. The Nasiriyah Embayment of southern Iraq was still in existence, but was probably not as prominent as before. Marine deposits of late Cenomanian age (Mishrif Formation) in central Arabia were followed by a marked hiatus until the late Campanian (D. Vaslet, BRGM, personal communication, 2000). This hiatus is the mid-Turonian unconformity that occurred at the base of AP9 (Sharland et al., 2001).



## Early Late Cretaceous: Cenomanian to Turonian (98.9–89 Ma)



**Figure 15: Paleofacies of the early Late Cretaceous spanning deposition of the Mishrif, Ahmadi, Rumaila, Natih, and Derdere formations, and their regional equivalents [MFS K120 to intra-K150; base of AP9 dated at 92 Ma]. Sediments were deposited on platforms and within intrashelf basins on the passive margin of the Arabian Plate. With information from: Andrews (1992b); Azzam (1995); Béchenec et al. (1995); Bender (1968); Burchette (1993); Cater and Gillcris (1994); Guiraud et al. (2001); Hirsch (1990); Le Métour et al. (1995); Makhlof et al. (1996); Murriss (1980); Ponikarov et al. (1988); Roger (1989); Walley (1998b); and unpublished Saudi Aramco Miscellaneous Report 826 (D.W. Hagen, 1975). R=Rudist reefs.**



The shelf breaks of the shallow Rub' Al-Khali Basin and Lurestan intrashelf basin of Iran are marked by carbonate shoal deposits that merge basinward into bioclastic micrites with oligosteginid and pelagic foraminifera. The shelf break shows an increase of bioclastic detritus and is marked by the occurrence of thick-walled, limid and ostreid bivalves (Alsharhan and Nairn, 1993). The crest and immediate back shoal area have an increased rudist content, in places with biostromal attitudes. The crests of these build-ups were strongly bioturbated, to the extent that no bedding traces are preserved. The sheltered lagoonal beds are laden with benthonic foraminifera. The Hoowarin-Hazar High was still shedding detrital material into the Rub' Al-Khali Basin (Azzam, 1995; Pascoe et al., 1995).

Rudist facies are recorded from most of the fields west of Basra in Iraq, and also from Majnoon and the Buzurgan area. Similar facies are present all around the northern end of the Gulf. From the Rutbah High westward, facies changes from shallow-marine carbonates to hypersaline lagoons and continental deposits took place. Dunnington (1958) recorded erosional truncations and weathering effects in northern Iraq. West of Baghdad is an extensive evaporite pan (Kifl Formation) that is presumed to be located over a broad and stable Hercynian block and could be related to the Abu Jir fault zone of Lovelock (1984).

On the northern edge of the Arabian Plate, shallow-marine conditions prevailed in which carbonates were deposited. The lower part of the Derdere Formation of southeast Turkey consists of transgressive open-marine skeletal calcarenite units that shoal progressively upward into a shallow-marine environment. The capping units of the Derdere Formation are essentially transgressive, although vugs and fissures indicate intermittent high-frequency subaerial exposure (Cater and Gillcrist, 1994). Over the Mardin uplift, vuggy dolomites pass laterally into deeply karstified sequences. The Khleisia High of eastern Syria and northern Iraq appears to be separated from the Rutbah High by a shallow seaway that later became the Euphrates Graben.

In the Levant, a rudist-reef barrier marks the shelf break south of Mount Carmel and may be traced into northern Sinai according to Bein (1976) and Hirsch (1991). Open-marine Negba chalks characterize the Pleshet Basin in offshore Levant. Shallow-marine shales occur in the southern Negev and Sinai. The Azrak Graben in Jordan contains basal deep-water chalky limestones that are equivalent to the Deir Hanna and Negba formations of the Levant (Hirsch, 1991). The Fuluk and Siwaqa graben-bounding faults restricted the limestone development.

## **Late Cretaceous to Early Paleocene: Senonian to Danian (89–60.9 Ma) (Figure 16)**

### ***Regional Setting***

This time period spanned the deposition of the Shiranish, Gurpi (Iraq, Iran), Aruma and Simsima (Kuwait, Saudi Arabia, United Arab Emirates), and Fiqa (United Arab Emirates, Oman) formations, and their regional equivalents [MFS K150 to intra-Pg10]. It approximates to the interval of AP9 (92 to 63 Ma). The pre-Cenozoic unconformity at 63 Ma (Sharland et al., 2001) is the base of AP10 and marks the cessation of ophiolite obduction along the eastern margin of the Arabian Plate. The sediments were deposited within a compressive foreland basin setting following onset of mid-Turonian ophiolite obduction along the eastern margin of the Plate.

### ***Paleofacies***

Figure 16 illustrates the depositional features during the late Senonian (Campanian-Maastrichtian) and shows the approximate extent of the early Senonian erosional limit onto the shallow platform (Murriss, 1980). Koop and Stonely (1982) indicated truncation and onlap on a pre-Late Cretaceous unconformity [middle Turonian unconformity, base AP9 dated at 92 Ma]. In the deeper intrashelf basins (such as the Lurestan Basin), continuous sedimentation occurred across this marked hiatus. Tectonic uplift and the rejuvenation of former N-trending structures coupled with erosion occurred as far north as the Zagros range of Lurestan.

A narrow NW-trending foredeep formed west of the rising orogen as a result of ophiolite obduction. The erosional products from the orogenic front were shed as flysch deposits into the foredeep where deeper-water marine conditions were present (e.g. Simsima and Shiranish formations). Oceanic

## Late Cretaceous to Early Paleocene: Senonian to Danian (89–60.9 Ma)

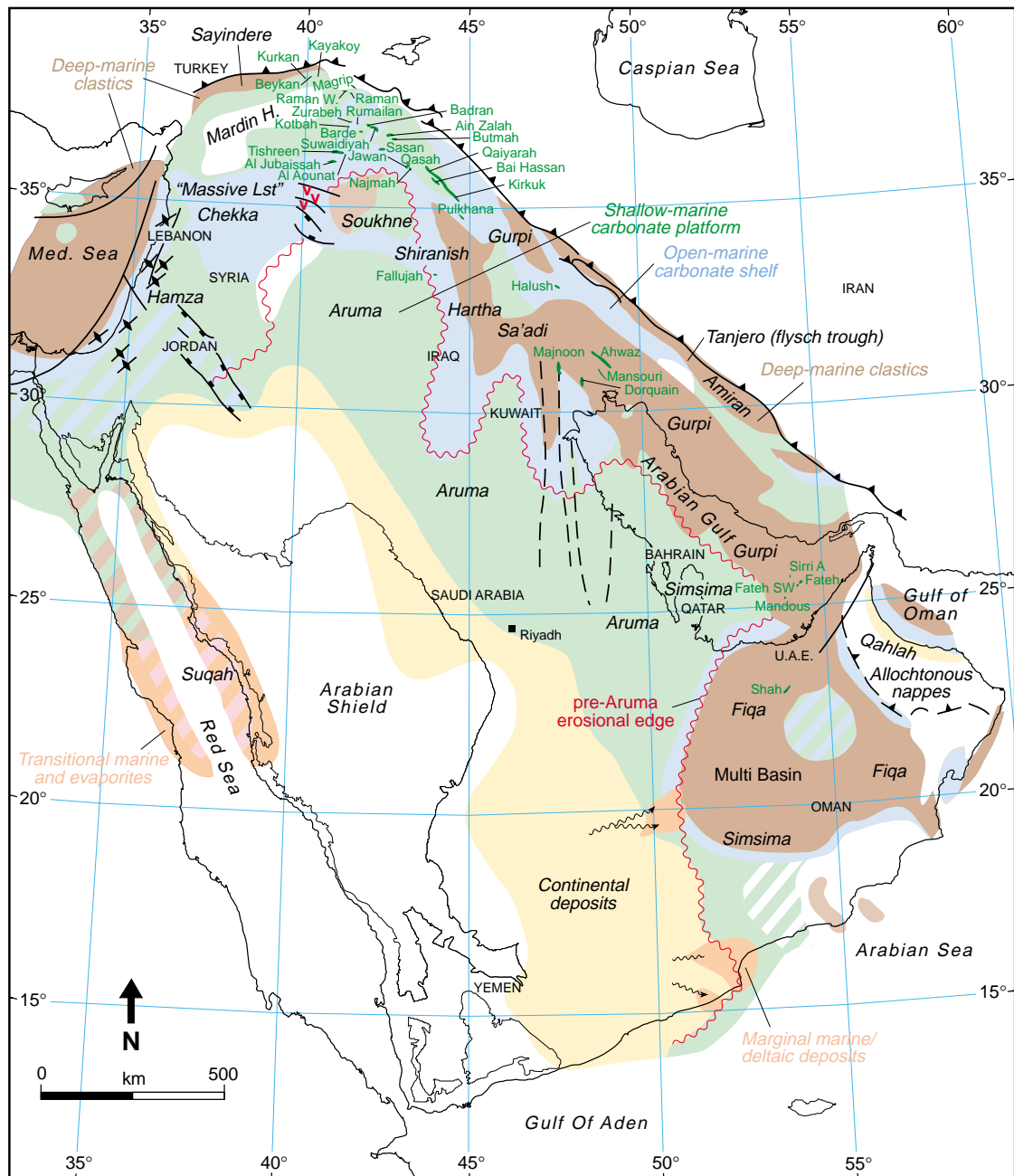


Figure 16: Paleofacies of the Late Cretaceous to Early Paleocene spanning deposition of the Shiranish, Gurpi, Aruma, Simsim, and Fiqa formations, and their regional equivalents [MFS K150 to intra-Pg10]. The sediments were deposited within a compressive foreland basin setting following onset of mid-Turonian ophiolite obduction along the eastern margin of the Plate. With information from: Andrews (1992b); Azzam (1995); Béchenec et al. (1995); Cater and Gillcrst (1994); Ellis et al. (1996); Filbrandt et al. (1990); Gilmour and Mäkel (1996); Guiraud and Bosworth (1997); Hirsch (1990); Koop and Stoneley (1982); Litak et al. (1997); Murriss (1980); Nolan et al. (1990); Ponikarov et al. (1966); de Ruiter and Lovelock (1995); Roger et al. (1989); Sawaf and Tarek (1996); Walley (1998b); and unpublished Saudi Aramco Miscellaneous Report 913 (W.J. Koop, 1982).

sediments (radiolarites) and ophiolites were emplaced onto the Oman continental margin. At the same time, a shallow-water carbonate platform formed over the interior of the Arabian Shield.

Haq et al. (1988) proposed a generally slow sea level fall during this period. In contrast, based on evidence from the Arabian Plate, Harris et al. (1984) consider a relative rise in sea level that was the highest of the whole Cretaceous. It is likely that a foundering of the eastern part of the Plate caused a widespread and progressive westward onlapping of a shallow sea. For the Levant area, however, an early Senonian uplift is postulated, with evidence of inversion of older structures and a first phase of Syrian Arc deformation. These movements were probably an effect of the closure of the Neo-Tethys (Guiraud and Bosworth, 1997; Walley, 2001).

A reduction in the exposed landmass occurred during the late Senonian and a broad shallow-marine shelf developed on which were deposited limestones of the Aruma Formation. The former intrashelf basins (Lurestan and Khuzestan in Iran) had by now been consolidated to form one long, relatively narrow foredeep trough along the future Zagros Fold Belt. Deeper-marine shales of the Shiranish, Sa'adi and Gurpi formations in part represent source rocks (Gurpi) or caprock (Shiranish). Close to the Zagros main thrust, silt and sandstones of the Amiran and Tanjero flysch formations were deposited in the foredeep. This clastic detritus heralded uplift, or compression, which resulted in folding and erosion farther east during the continuing ophiolite obduction onto the eastern margin of the Arabian Plate (Hooper et al., 1995). Ophiolite nappes were emplaced along the Zagros Main Thrust in Iran, in Oman (Hawasina), and in the Troodos Mountains of Cyprus.

The Levant underwent a radical change in the sedimentary regime at this time (Hirsch, 1991). The Syrian Arc influenced the paleotopography so that the crests of the anticlines formed a cluster of small islands, whereas the synclines formed small basins in which chert and phosphate sequences (Mishash Formation) accumulated. Intercalations of limestone and chalk of the Ein Zeitim-Chekka formations cover most of the area.

The compressive stresses exerted on the Arabian Plate are evident in the en-echelon alignment of fold structures in the Levant (Walley, 1998), the accentuation of the Azraq Graben, and the complex structures of the Euphrates Graben. Additional evidence is the emplacement of the Campanian Tayarat basaltic extrusives in the Euphrates Graben (de Ruiter et al., 1995). At the same time, the Sinjar and Anah grabens were forming in Iraq. The easterly oriented graben system in the Sinjar-Abd el Aziz area of Syria began to subside in the late Campanian–Maastrichtian (Brew et al., 1999). The prominent Sinjar Basin was structurally related to the Palmyra Basin until the late Mesozoic. After the prerift uplift and concurrent erosion over the northern margin of the Arabian Plate, a brief magmatic event in the Euphrates Graben marked the maximum extension. This phase was followed by postrift subsidence during the late Cretaceous (Senonian) and Paleogene (de Ruiter et al., 1995). Consequently, the deposition of more than 1,600 m of marly limestones (Shiranish and Aaliji formations) took place in an open-marine setting.

In the course of the collision of the Arabian Plate with Eurasia, the elongate Kastel Trench of southeast Turkey was formed at the northern extremity of the Plate and was rapidly filled with fine-grained, deep-water sediments containing planktonic foraminifera. Persistent tectonic movements ahead of the advancing ophiolite nappes changed the depositional conditions (Gilmour and Mäkel, 1997). In this new tectonic environment, large gravity-slide complexes of platform carbonates (Karadur Complex), ophiolites, and submarine lavas (Kocali Complex) from the Taurus fold belt were emplaced into the foredeep.

In southeast Turkey, the Karababa Formation of Turonian (Alsharhan and Nairn, 1997) to Coniacian to early Campanian age (Cater and Gillcrust, 1994), represents a renewed transgressive cycle with intervening phases of exposure and weathering that formed caverns and collapse structures. At the northernmost extremity of the Arabian Plate, debris flows indicate slope instability. According to Cater and Gillcrust (1994), the rich planktonic fauna of the mid-Campanian Sayindere Formation represented a deep-water to pelagic depositional environment that indicated the final collapse of the carbonate platform. They suggested that the rapid subsidence of the plate margin was related to the advance of the Kocali ophiolite complex and the Kastel basinal formation in front of the uplifting Late

Cretaceous thrust sheets of the Taurus orogenic belt. The overlying Maastrichtian to Late Paleocene Germav Formation on the northern plate margin is composed of a lower transitional nearshore to shallow-marine conglomerates; a middle, shallow-marine limestone sequence with ephemeral rudistid and coral build ups; and a thick upper flysch succession that grades basinward into pelagic limestones.

In the Gulf region, older Hercynian lineaments were reactivated: for example, the Burgan and Khafji arches. In Oman during the early Campanian, this compressive tectonic phase led to the overthrusting and emplacement of the Sumeini and Hawasina nappes and the obduction of the Semail Ophiolite Nappe onto the eastern margin of the Arabian Plate (Le Métour et al., 1995). Subsequently, the Oman Platform became submerged and a series of transgressions resulted. This setting lasted through the Maastrichtian with deposition of the Aruma and Simsima formations. The Aruma unconformably overlies early Turonian rocks [mid-Turonian unconformity; base AP9 dated at 92 Ma].

The emplacement of the nappes caused the downflexing of the Oman Margin and the formation of the Muti Basin southwest of the newly formed mountain belt. Through isostatic readjustment, the foreland basin was locally subject to uplift and erosion; for example, in the Zumul and Lekhwair structures (Béchennec et al., 1995; Le Métour et al., 1995). The Muti Basin initially underwent rapid subsidence and deposition of more than 1,000 m of hemipelagic mudstones, chalk and shales of the Campanian to Maastrichtian Fiqa Formation. The Fiqa is overlain conformably by the shallow-water Maastrichtian limestones of the Simsima Formation. In the western Oman Mountains in early Maastrichtian time, fanglomeratic to alluvial fan deposits of the Qahlah Formation appear to intertongue with upper Fiqa shales in a nearshore position. Cessation of orogenic activity is marked by the transgression of the Qahlah detrital clastics over the Semail Ophiolites and the onlap of the Simsima Formation onto the allochthon of the Oman Mountains (Nolan et al., 1990).

The discovery of marine vertebrates from northern Saudi Arabia (Thomas et al., 1999) led to an age revision of the Lina Member, previously the uppermost unit of the Aruma Formation. The Lina had formerly been assigned a Maastrichtian age. However, based on the stratigraphic and paleontologic study of the marine vertebrates (mainly selachian fishes and a primitive dermochelid sea turtle), a Late Paleocene to Early Eocene age was proposed. The revised position of the Lina member emphasizes the existence of an important sedimentary hiatus [pre-Cenozoic unconformity, base AP10 dated at 63 Ma] of about 10 My at the top of the Aruma. The hiatus coincides with the Cretaceous-Tertiary boundary in Arabia (Thomas et al., 1999). This important break has been noted throughout central and northern Arabia, and in Qatar, the Rub' Al-Khali Basin, and Oman.

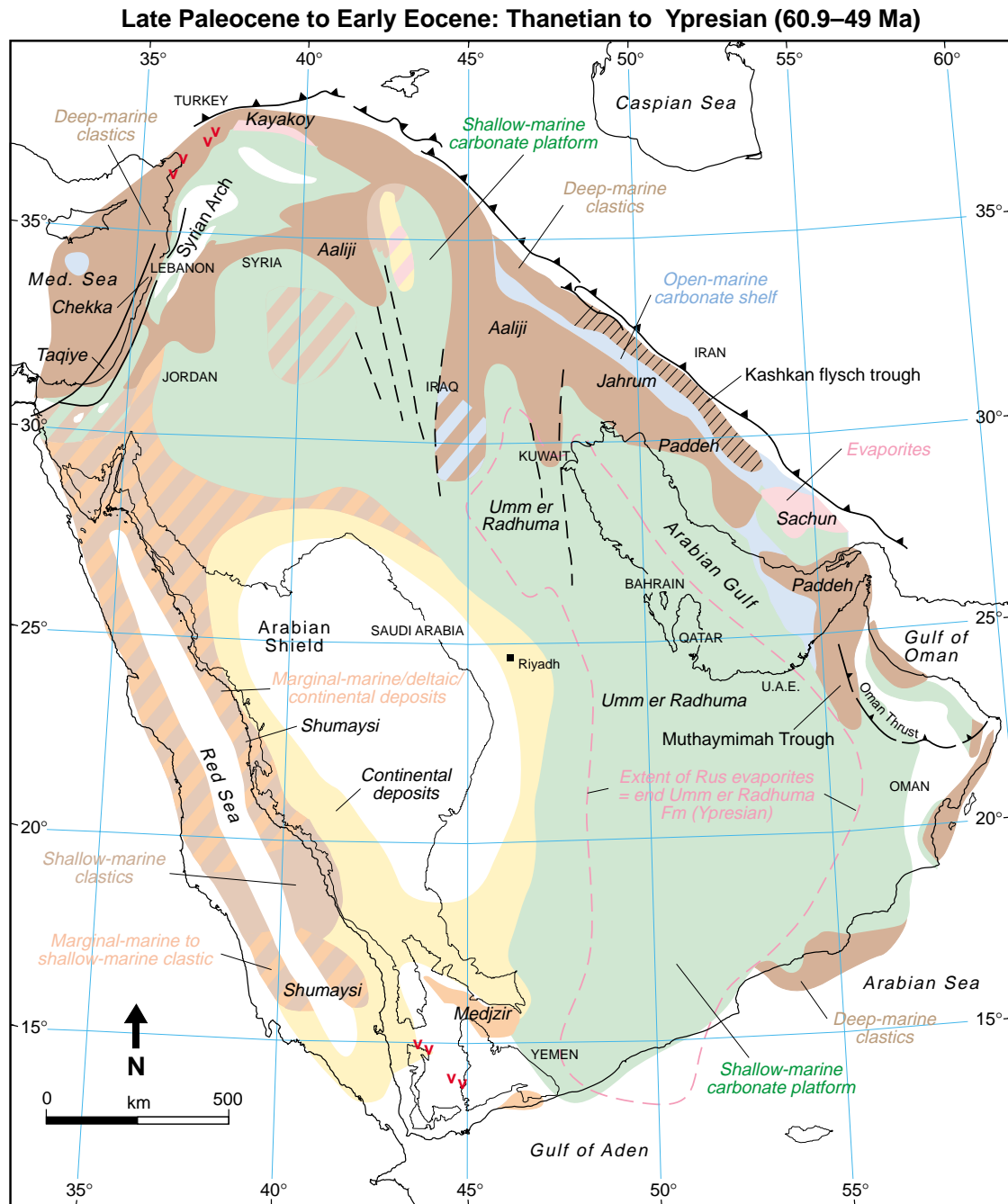
It is possible that the southeastward tilt of the Arabian Plate was a precursor to the rifting of the northern Red Sea. Only the downthrown and collapsed southeastern plate margin in Oman gives evidence (Aruma shales) for continuous Danian deposition (Roger et al., 1992; Platel and Roger, 1989; Roger et al., 1989). Shallow-marine to intertidal marls and evaporite prerift deposits in the northern Red Sea trough (Suqah group) indicate an initial marine ingression from the north along the depression of the proto-Red Sea. Interbedded basalts occur locally.

## **Late Paleocene to Early Eocene: Selandian to Ypresian (60.9–49 Ma) (Figure 17)**

### ***Regional Setting***

This time period spanned the deposition of the Rus and Umm er Radhuma (Arabian Peninsula) and Pabdeh (Iran) formations, and their regional equivalents [MFS Pg10 to intra-Pg20]. Active compression ceased. Sediments were deposited within a 'remnant' foredeep-setting during rapid erosion, lowering, and subsidence of the emergent ophiolite and sedimentary structures along the eastern margin of the Plate. This time period essentially represents the first 'second-order' depositional sequence within AP10 of Sharland et al. (2001).

In the northern part of the Arabian Plate, the earlier Cretaceous foredeep began to deform and generated structural inversion. It coincided with the formation of the Syrian Arc (Goff et al. 1995). The N-trending embayments in southern Iraq and northern Kuwait were still present and the origin for the alignment appears to have been the Hercynian grain of the Arabian Arch.



**Figure 17: Paleofacies of the Late Paleocene to Early Eocene spanning deposition of the Rus, Umm er Radhuma, and Pabdeh formations, and their regional equivalents [MFS Pg10 to intra-Pg20]. Sediments were deposited within a ‘remnant’ foredeep setting during rapid erosion, lowering, and subsidence of the emergent ophiolite and sedimentary structures along the eastern margin of the Plate. With information from: Andrews (1992b); Filbrandt et al. (1990); Gilmour and Mäkel (1996); Goff et al. (1995); James and Wynd (1965); Koop and Stonely (1982); (Kraig and Kozlu (1990); Le Métour et al. (1995); Nolan et al. (1990); Murriss (1980); Ponikarov (1966); Roger et al. (1989); and unpublished Saudi Aramco Miscellaneous Report 913 (W.J. Koop, 1982).**

### ***Paleofacies***

During this time interval, eustatic sea level was generally high with high-frequency regressive events (Haq et al. (1988. The Umm er Radhuma Formation [above MFS Pg10] indicates a major change in the environment, marked by the disappearance of rudist-bearing marine-platform carbonates. A new depositional cycle began with transgression toward the end of the Paleocene. Shallow-marine carbonates overlapped far onto the Arabian Craton and maximum flooding [Pg10] was reached in the Early Eocene. Light-colored foraminiferal, aphanitic to calcarenitic limestones and dolomites were deposited. Regionally, from south to north, a progressive, yet patchy, replacement of limestones by dolomite occurred.

On foraminiferal evidence, the Umm er Radhuma Formation in Saudi Arabia was dated as Late Paleocene to Early Eocene (Powers et al., 1966). The fauna suggest that the carbonates belong to the sublittoral to neritic bathymetric zone. The wide variety of pelecypods and gastropods (naticids, cerithids and strombids) indicate more specifically a protected to lagoonal depositional environment. The Umm er Radhuma depositional environment eventually shoaled to become a restricted lagoonal to supratidal sabkha setting in which the Rus Formation was deposited [HST of Pg10]. These near-shore facies prograded basinward. West of the Rutbah High in Iraq, a wedge-out of the Umm er Radhuma occurred toward the uplift (Alsharhan and Nairn, 1997). In this area, the Formation became marly, phosphatic, and cherty, and a nearshore to lagoonal depositional setting was interpreted.

Deeper-water environments within the remnant foredeep were only reached close to the eastern Plate margin. The Aaliqi Formation of Syria and Iraq is composed of basinal clastics and carbonates. This foredeep extended into the Muthaymiah Trough of the Oman Mountains (Le Métour et al., 1995). Fine grained, clastic-to-shale units alternate with thin argillaceous limestone beds that represent turbidite flysch sequences from the Zagros. Based on its chert content, the upper shale member is considered to have been deposited in deep water (James and Wynd, 1965). Hertig et al. (1995) reported calciturbidites in the Muthaymiah Trough that originated from the southeastern Oman Shelf. The Pabdeh shale formation of Iraq and Iran changes facies westward into platform-interior carbonates (Umm er Radhuma equivalent). Southward in the Fars Province, foredeep sediments grade into a mixed Pabdeh (shale) and Jahrum (limestone) facies. The Jahrum appears to be directly comparable with the Umm er Radhuma Formation of the platform interior. The Sachun Formation is a dolomite and sulfate sequence about 150 m thick in Fars (James and Wynd, 1965).

In the south, the Rub' Al-Khali Basin had disappeared but the presence of the Muthaymiah Trough, as a western foredeep of the Oman Mountains, indicated ongoing extension that existed until the Early Eocene. In the foredeep, debris flows and turbiditic slope sediments were mixed with fine-grained basinal sediments. Basinal shales also accumulated in the Mahdi Basin, southeast of the Hausi-Huqf uplift, and in the Abal Trough (east of Muscat) where hemipelagic mudstones were deposited (Le Métour et al., 1995).

The Hadramaut region of Yemen remained a depositional area for shallow-marine carbonates whereas, to the south and west, shallow-marine sands (Medjzir Formation) and shales were deposited. Farther north, in the Red Sea Graben, deltaic to shallow lacustrine shales dominate the Suqah group; the presence of charophytes provide evidence for brackish to freshwater depositional environments (Hughes and Filatoff, 1995). Oolitic ironstones in the Shumaysi formation west of Jeddah (Moore and Al-Rehaili, 1989) indicate a lacustrine to soil type depositional environment (D. Vaslet, personal communication, 2000).

In the Levant, a shallow shelf was the site of deposition of chalky and cherty limestones and marls of the Taqiye Formation and an unnamed, but similar, formation in Lebanon. The Taqiye is conformable on paleosols on the Syrian Arc ridges (Hirsch, 1991) and, similarly, central and eastern parts of Lebanon were exposed as a result of uplift along the Arc. The Palmyra Trough appears to have formed a narrow, deep seaway on the eastern Plate margin, where the Neo-Tethys was closing. In southeastern Turkey, the imbricated fore-bulge of the compressed platform margin caused intertidal to supratidal conditions that favored the deposition of hypersaline evaporites. On the northern extremity of the Arabian Plate, the Mardin High shows similar evaporitic developments (Kayaköy Formation) to the Sachun Formation in the Iranian Fars Province. The upper part of the Maastrichtian to Late Paleocene

Germav Formation in Turkey is a thick flysch succession that grades basinward into pelagic limestones. Rapid facies changes within the Kayaköy Formation point to a series of relative sea-level changes that are associated with the continual tectonic interaction between the Arabian and Eurasian plates. The evaporites give way to detrital red-bed deposits that originated from the erosion of ophiolite nappes in front of the Bitlis Suture zone (Gilmour and Mäkel, 1996).

### **Middle to Late Eocene: Lutetian to Priabonian (49–33.7 Ma) (Figure 18)**

#### ***Regional Setting***

This time period spanned deposition of the Jaddala (Syria, Iraq), Dammam (Arabian Peninsula), and Pabdeh (Iran) formations, and their regional equivalents [GSS Pg30]. It essentially represents the second 'second-order' depositional sequence within AP10 of Sharland et al. (2001). The sediments were deposited in a structural setting comparable to those of the underlying succession.

#### ***Paleofacies***

The eustatic sea-level curve of Haq et al. (1988) indicates a gradually falling sea level. Consequently, it is possible that only a relatively small part of the Arabian Shield was exposed, at least at the beginning of the depositional sequence.

The Zagros foredeep and the Muthaymiah Trough of Oman appear almost unchanged from the earlier time period and the sediment types (Pabdeh Formation) are basically the same as in the Late Paleocene (Hertig et al., 1995). However, conditions favoring the formation of the Sachun evaporite flats in the Fars Province of Iran changed, and the influence of flysch deposition seems to have lessened due to significantly reduced sediment supply. This implies a stabilization of the margin and a progressive infilling of the foredeep. Further compression at the northeastern margin of the Arabian Plate resulted in a basinward shift of the facies belts toward the craton.

The wide eastern shelf of the Plate was covered by the Dammam Formation [deposited above MFS Pg20] of limestone and dolomite, marl and shale that is about 30 m thick in Saudi Arabia. The base of the Dammam represents an open-marine environment [MFS Pg20], whereas the upper part indicates a shallow-marine environment and a siliciclastic influence from the west. The Dammam contains nummulites and has been dated as upper Ypresian to Priabonian from its foraminiferal content. The contact with the overlying Oligocene deposits appears to be unconformable [base of AP11 at 34 Ma].

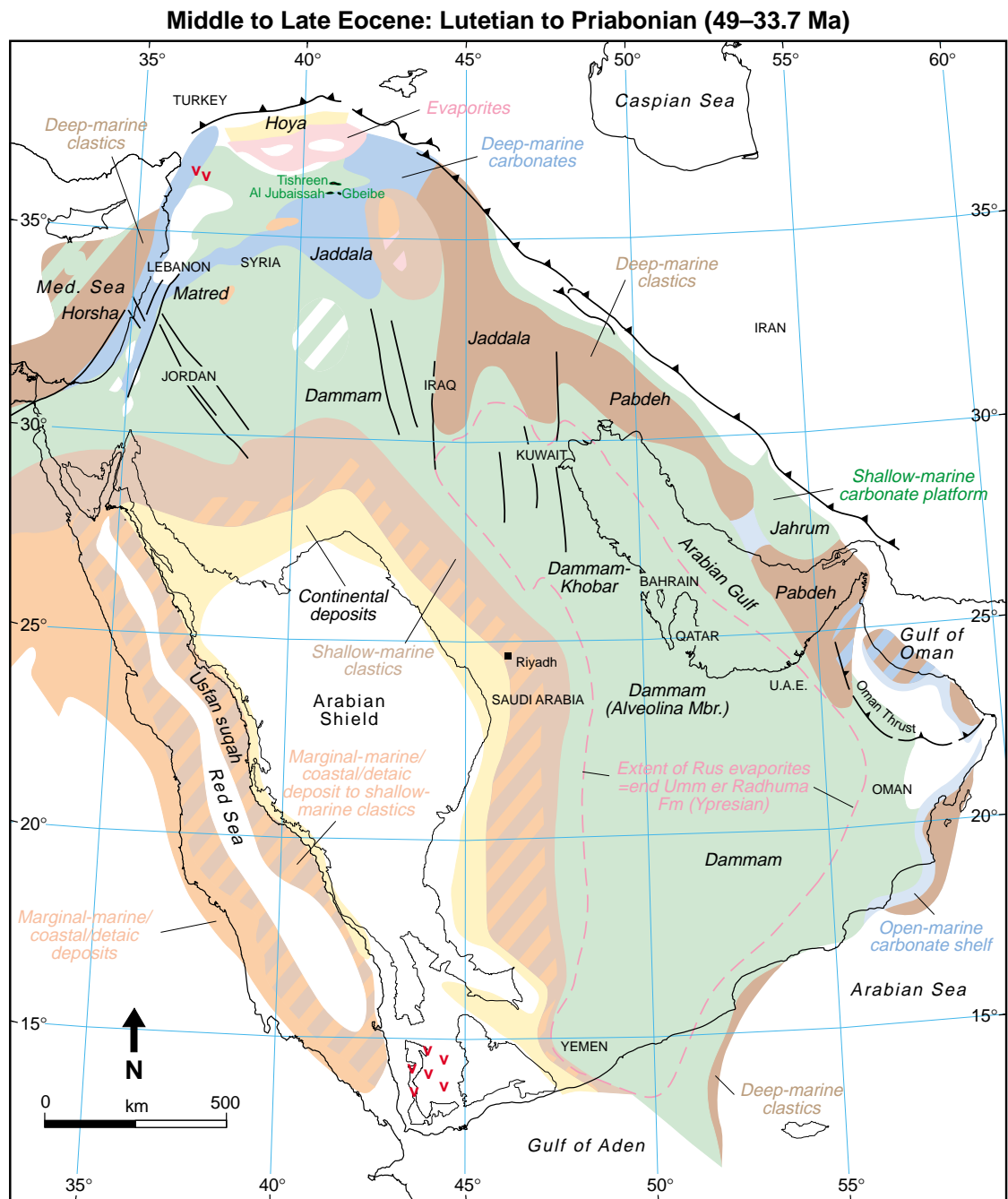
In western Yemen, the Aden Trap basalts were extruded over large areas and indicate the thermal doming of the Afar Triangle (Richardson et al., 1995; Morrison et al., 1997). In the prerift Red Sea depression, non-evaporitic shales, and lacustrine, deltaic and coastal clastics (e.g. the Suqah group of the Jeddah region; Moore and Al-Rehaili, 1989), were deposited on the edges of the basin.

The Lower and Middle Eocene in the Levant is a twofold division of mainly transgressive carbonate cycles. Pelagic chalks containing radiolarians and foraminifera (Sara/Zora and Horsha formations) interfinger with shallow-marine, nummulitic limestones (Mizzana and Matred formations) that were deposited on a broad, shallow shelf at the northern edge of the Arabian Plate. In the Late Eocene, a second phase of tectonism affected the Syrian Arc (Walley, 1998a, 2001), and in Galilee a discordance was noted by Hirsch (1991) between the Middle and Upper Eocene that may be due to either eustasy or tectonism. The Late Eocene coral-bearing Har Aqrav limestone barely reached onto the Arabian Craton as its lateral extent was limited by uplift. At the same time, the broad shallow shelf of Syria and Iraq was covered by neritic or shallow-marine carbonates (Jaddala Formation) formed during the transition to the detrital, molasse-type Gerçus Formation deposited in front of the Taurus-Zagros orogenic front (Gilmour and Mäkel, 1996).

### **Oligocene: Rupelian to Chattian (33.7–23.8) Ma (Figure 19)**

#### ***Regional Setting***

This time period spanned the deposition of the Pabdeh-Chilou (Palani) formations (Iran, Iraq) and their regional equivalents [MFS Pg30 to Ng10]. A major unconformity and sedimentary hiatus [base



**Figure 18: Paleofacies of the Middle to Late Eocene spanning deposition of the Jaddala, Dammam, and Pabdeh formations, and their regional equivalents [GSS intra-Pg30]. The sediments were deposited in a structural setting comparable to those of the underlying succession. With information from: Andrews (1992b); Filbrandt et al. (1990); Gilmour and Mäkel (1996); Goff et al. (1995); Guiraud et al. (2001); Hertig et al. (1995); Koop and Stoneley (1982); Kraig and Kozlu (1990); Le Métour et al. (1995); Nolan et al. (1990); Ponikarov et al. (1966); Roger et al. (1989); and unpublished Saudi Aramco Miscellaneous Report 913 (W.J. Koop, 1982).**



of AP11 dated at 34 Ma] affected much of the Arabian Plate. The sediments were deposited in a compressive foreland setting during the early stages of continental collision between the Arabian and Eurasian plates. On the western side of the Plate, the Red Sea was in a rifting stage prior to the advent of sea-floor spreading and the splitting of the Afro-Arabian Plate.

The late Paleogene-Neogene evolution of the south-central Turkey triple junction near Maras at the northwestern extremity of the Arabian Plate, represents a complex kinematic interplay between the Anatolian Plate (Tauride Arc) in the northwest and the Arabian Plate to the southeast. Kraig and Kozlu (1990) suggested that strike-slip motion rather than thrust tectonics was dominant. The strike-slips created extensional and compressional components that varied with time and space to form a series of small troughs that were mainly filled with clastic sediments.

### ***Paleofacies***

The map reflects the pronounced fall in sea level during the Oligocene to expose almost the entire Arabian Plate. The Neo-Tethys was closing rapidly and the Zagros foredeep along the northeastern plate margin once more became a narrow trench in which mainly limestones were deposited along its margins. In the central part of the foredeep, Pabdeh-type sedimentation (Palani Formation) continued with silty to sandy shales alternating with argillaceous limestone intercalations. In the Late Oligocene, the limier Taleh Zang Formation was deposited. In the deepest part of the narrow basin, Goff et al. (1995) recorded a condensed pelagic sequence that is locally characterized by a lacuna. Farther east toward the High Zagros, the deposition of the variegated marly to silty, in part calcareous, Razak Formation indicated uplift and erosion of the eastern Plate margin. The flanking shelves of the Zagros foredeep are composed of light-colored, well-jointed, micritic and foraminiferal limestones with nummulites and miliolids that form the well-known reservoir rocks of the Asmari Formation.

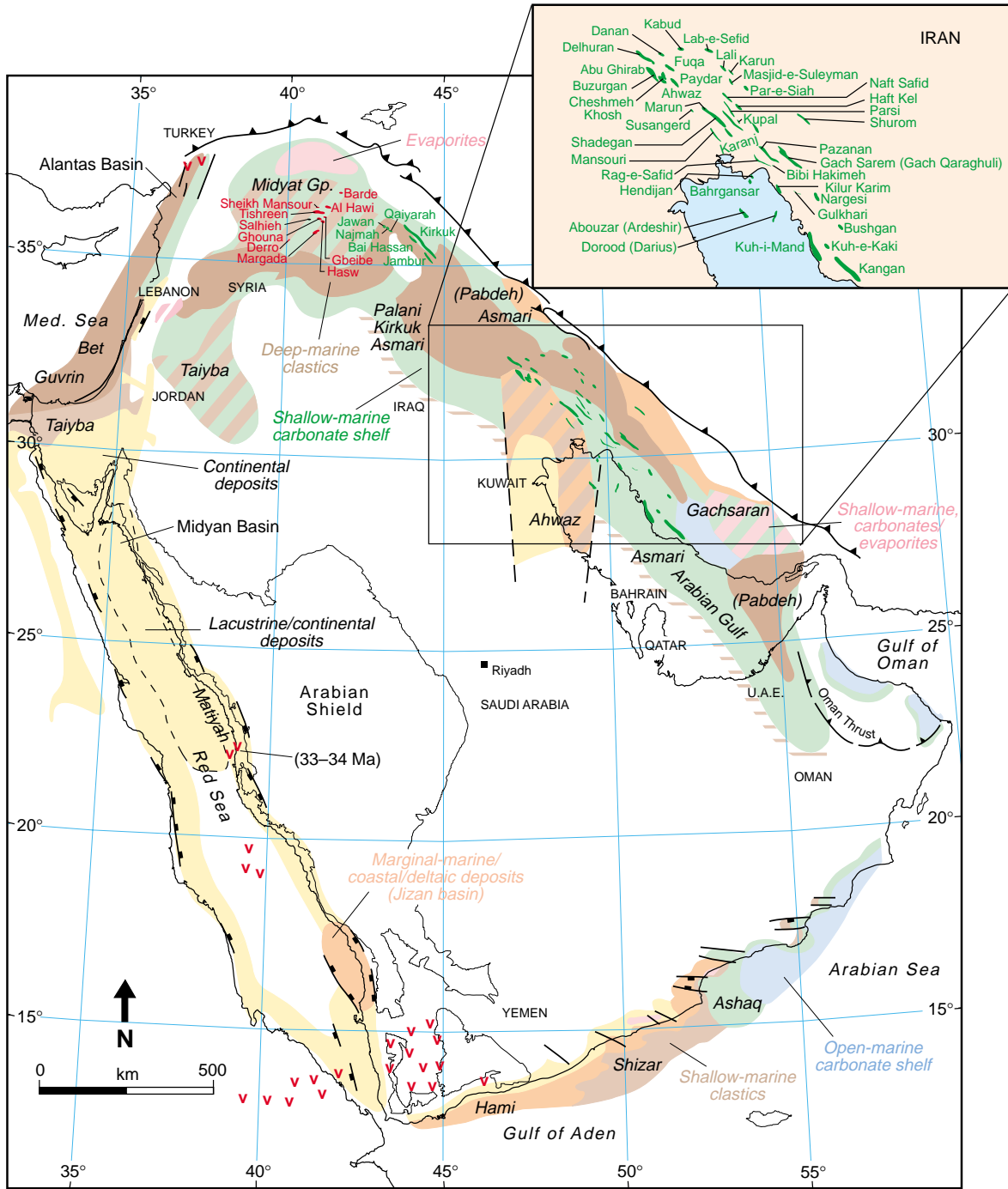
In the center of the Zagros foredeep, the lower Asmari limestones change to calcareous sandstones (the Ahwaz sandstone member) that have a subordinate marine shale component (James and Wynd, 1965). Alshahran and Nairn (1997) considered the Asmari sandstone to be correlative with the Ghar Formation in Kuwait. The sediment supply appears to have been derived from the prerift uplift of the Red Sea to the west. The localization of the Ghar/Ahwaz delta of southern Iraq and western Iran was probably influenced by deep-seated 'Hercynian'-age lineaments that extended north from the Central Arabian Arch.

In the south, the Gulf of Aden was about to rift. A series of small E-trending troughs (Hasik and Ashawq grabens), opened in Dhofar during the Rupelian (Platel and Roger, 1989; Roger et al., 1989; Roger et al., 1992). Deeper-marine carbonates (Mughsayl Formation) off Dhofar gave way toward the Afar region at the southern end of the Red Sea to shallow-marine shales and eventually to coastal, shallow-marine clastics (Hami Formation). In southwest Yemen, the Aden volcanics were extruded, as well as vast outpourings of intraplate volcanics in Ethiopia (Beydoun and Sikander, 1992). In southwestern Saudi Arabia, four small basaltic lava fields (*harrats*) occur near to the eastern edge of the incipient Red Sea rift. This volcanic activity was the earlier of two phases of volcanism associated with the rifting and opening of the Red Sea.

The Red Sea was in a thermal uplift prerift status. The entire protorift was marked by terrestrial to fluviolacustrine sediments and coastal to shallow-lacustrine clastics. Variegated siltstones interbedded with basalt flows and lacustrine sediments with charophytes (Matiyah Formation) were reported by Hughes and Filatoff (1995). The volcanics have been dated radiometrically at 33–34 Ma (earliest Oligocene) [base of AP11].

Similar conditions are found in the Levant. The Dead Sea Transform Fault was not yet active, as continental detritus (red beds of the Taiyba Formation) was discharged from the Arabian Craton onto the Sinai and Negev plains (F. Hirsch, personal communication, 1999). Walley (2001) suggested further inversion of older Levantine extensional structures. The Aleppo High, and its southern continuation into Lebanon, were exposed land on which lacustrine and continental sediments accumulated in major synclines. Shallow-marine conditions, including some evaporite flats, still persisted from the Eocene on the Mardin High.

Oligocene: Rupelian to Chattian (33.7–23.8 Ma)



**Figure 19: Paleofacies of the Oligocene spanning deposition of the Pabdeh-Chilon (Palani) formations and their regional equivalents [MFS Pg30 to intra-Ng10]. A major unconformity and sedimentary hiatus [base of AP11 dated at 34 Ma] affected much of the Arabian Plate. The sediments were deposited in a compressive foreland setting during the early stages of continental collision between the Arabian and Eurasian plates. On the western side of the Plate, the Red Sea was in a rifting stage prior to the advent of sea-floor spreading and the splitting of the Afro-Arabian Plate. With information from: Andrews (1992b); Ellis et al. (1996); Goff et al. (1995); Guiraud et al. (2001); Koop and Stoneley (1982); Kraig and Kozlu (1990); Le Métour et al. (1995); Nolan et al. (1990); Ponikarov et al. (1966); Roger et al. (1989, 1992); and unpublished Saudi Aramco Miscellaneous Report 913 (W.J. Koop, 1982).**

## Miocene: Aquitanian to Messinian (23.8–5.3 Ma) (Figure 20)

### **Regional Setting**

This time period spanned deposition of the Hadruk, Dam, Hofuf (Saudi Arabia), and Fars, Agha Jari and Gachsaran (Iran) formations, and their regional equivalents, together with massive salt deposits [MFS Ng10 to post-Ng40]. The sediments were deposited within the Zagros foredeep and foreland. Strong compression now occurred as Arabia separated from Africa and was driven into Eurasia.

During this period the Burdigalian phase of the European Alpine Orogeny occurred. The Gulf of Aden had opened and the Red Sea rift began to separate Arabia from Africa. Complex strike-slip deformations along the Dead Sea Transform Fault resulted in uplift and faulting along the Syrian Arc. Through collision of Arabia with Eurasia, inversion in the Palmyrides and the Sinjar uplift occurred as well as minor transpression in the Euphrates Graben (de Ruyter et al., 1995; Brew et al., 1999; Sawaf et al., 2000). On the eastern flank of the Arabian Plate, the thrusting of the Sanandaj-Sirjan zone onto the Plate is evidence of the continental collision with Asia. As a result, a massive supply of continental to deltaic clastics occurred and shallow-marine shales accumulated in the rapidly subsiding Zagros foredeep. Post-Asmari Miocene to Recent sediments reached a thickness of over 5,000 m in the Dezful Embayment of the Zagros Basin (Koop and Stoneley, 1982).

Volcanic activity was widespread and prolonged in western Arabia beginning at about 12 Ma (Camp and Roobol, 1991; Roobol and Camp, 1991). This was the second phase of volcanic activity associated with the opening of the Red Sea. Historical eruptions (e.g. at Al Madinah in AD1256) show that volcanism is still in progress. The basaltic lava fields (harrats) extend intermittently from Yemen, through western Saudi Arabia and Jordan, and as far north as southern Turkey. They have a total surface area of about 180,000 sq km and constitute one of the world's largest basalt provinces.

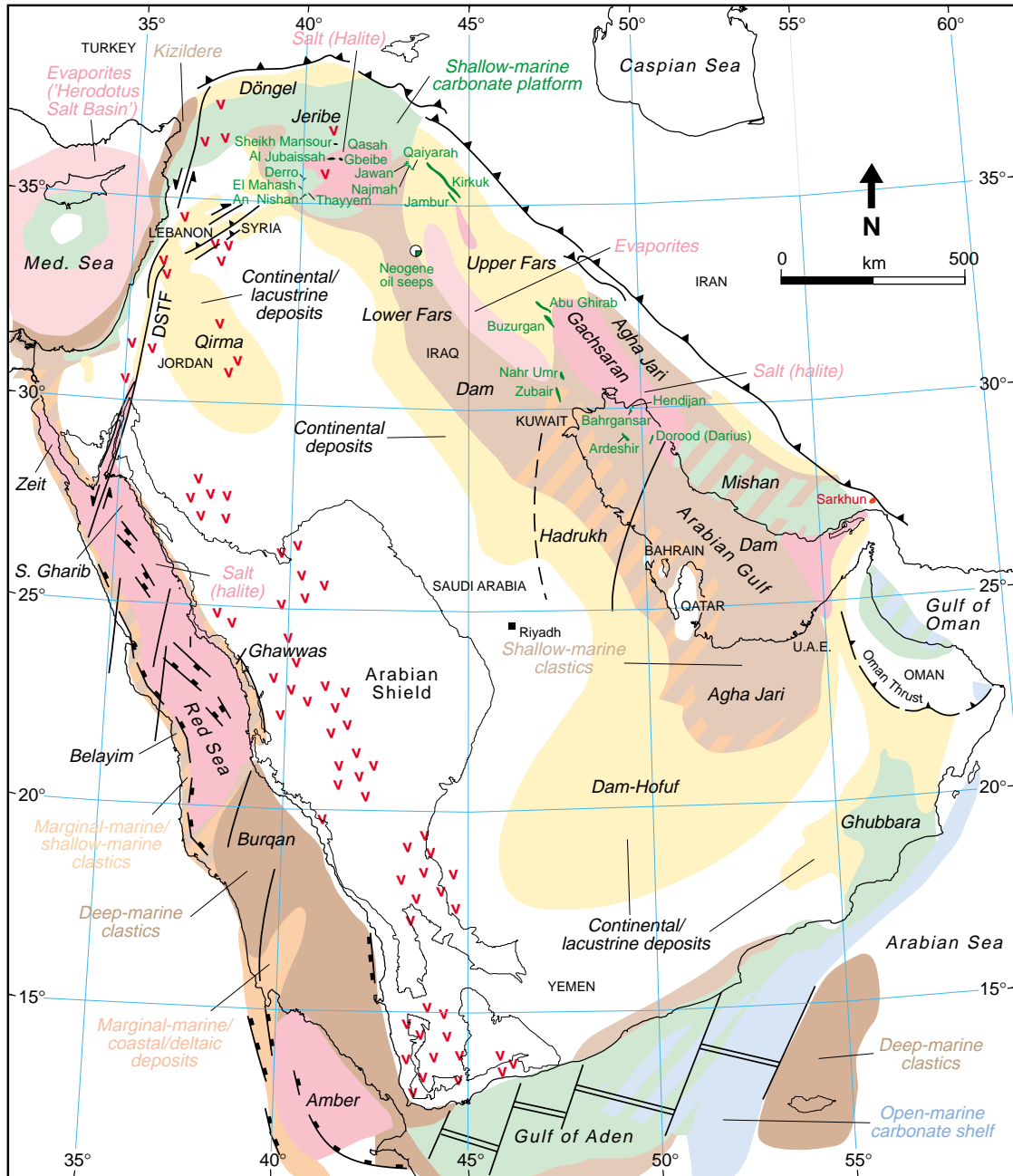
### **Paleofacies**

The N-trending Hercynian lineaments of the Central Arabian Arch extend far north into the Zagros foredeep. They separate on the western (Iraqi side), the massive wedge of the Lower Fars clastics and evaporites from the eastern Gachsaran salt marshes of the Khuzestan Province, (Agha Jari and Dam formations) and shallow-marine carbonates (Guri Formation) in the Fars Province. The hypersaline deposits relate to a relative fall in sea level at the end of the Oligocene. The marine connection, or 'Tethyan Seaway' of Goff et al. (1995), became obstructed along the narrow foreland basin so that basinal evaporites began to precipitate in the former foredeep.

Around the Arabian Arch, a halo of mainly continental (Hadruk Formation) to transitional-marine sediments (Dam Formation) were deposited. In the interior of the Arabian Plate, age-equivalent lacustrine sediments belong to the Hofuf Formation. The Hadruk consists of calcareous to silty sandstones and sandy limestones with chert concretions. The Dam is composed of variegated marl and shales, with some chalk, limestone and coquina beds. In Saudi Arabia, the Hofuf Formation is essentially a sandy, marl-limestone sequence (lower part), with some calcareous sandstones and gravel beds. *Charophytes*, *corbicula* sp., *planorbis* sp., and *Thiara* sp. gastropods suggest freshwater depositional conditions (Powers et al., 1966). Due to uplift of the western part of the Arabian Shield, rapid erosion and denudation of the interior occurred and vast amounts of gravel become incorporated into the Hofuf Formation. The clastic components are primarily quartz and igneous and metamorphic rocks, but sedimentary rocks (particularly from the Jabal Tuwayq escarpment), also occur.

The Gulf of Aden was by now a shallow sea with carbonate deposition. The Red Sea was periodically isolated and this resulted in the deposition of thick evaporite deposits during the Middle Miocene in its northern half (Zeit, South Gharib, and Belayim formations). A marine depositional environment is indicated by the presence of dinoflagellate cysts in the intra-evaporite shale units. In addition, the abundant pyrite-impregnated amorphous kerogen suggests an anoxic setting. The Early Miocene Burgan Formation in the southern Red Sea is a deep-marine clastic unit characterized by the presence of the foraminifera *Globigerina*. The Late Miocene is expressed by coarse to fine-grained siliciclastic sediments of transitional, shallow-marine nature, with occasional sabkha deposits (e.g. the Ghawwas Formation) (Hughes and Filatoff, 1995; Beydoun et al., 1998). The connection of the Red Sea to the

**Miocene: Aquitanian to Messinian (23.8–5.3 Ma)**



**Figure 20: Paleofacies of the Miocene spanning deposition of the Hadruk, Dam, Hofuf, Fars, Agha Jari, and Gachsaran formations, and their regional equivalents, together with massive salt deposits [MFS Ng10 to post-Ng40]. The sediments were deposited within the Zagros foredeep and foreland. Strong compression occurred as Arabia separated from Africa and was driven into Eurasia. With information from: Gilmour and Mäkel (1996); Goff et al. (1995); Guiraud et al. (2001); Hirsch (1990); James and Wynd (1965); Koop and Stoneley (1982); Kraig and Kozlu (1990); Le Métour et al. (1995); Nolan et al. (1990); Ponikarov et al. (1966); Walley (1998b).**

eastern Mediterranean is questionable and at best a shallow marine sill may have existed. The Mediterranean formed a deep basin that was completely shut off from the open sea during the Late Miocene (Messinian). During this 'Messinian salinity crisis', thick evaporite sequences were deposited in the 'Herodotus Salt Lake'.

The northern Arabian Plate was covered by shallow-marine sediments with the exception of the tectonically affected zones along the northern and eastern margins of the Plate. In the Maras area on the northwestern edge of the Plate, red beds and basalt flows pass upward into terrestrial conglomerates and sandstones of the Kizildere and Döngel formations. In the Aslantas-Iskenderun Basin, the sedimentary sequence begins with shales and turbidites, followed upward by shales and fine to coarse clastics, comparable to the Kizildere Formation. The equivalent sequence on the Anatolian Block consists of terrestrial sands and conglomerates deposited in front of the Taurid Arc (Kraig and Kozlu, 1990). With renewed nappe activity in southern Turkey, Selmo to upper Fars red-bed clastics spilled onto the shallow-marine platform carbonates (Silvan-Germik formations) that are located over the imbricated Mardin High in front of the Bitlis Suture. Toward the close of the Miocene, most of the northwestern edge of the Plate appears to have been exposed and subject to erosion. Lacustrine and molasse-type sediments were formed between the Syrian Arc structures.

### **Pliocene to Holocene: Zanclean to Present Day (5.3 Ma to 0 Ma) (Figure 21)**

#### ***Regional Setting***

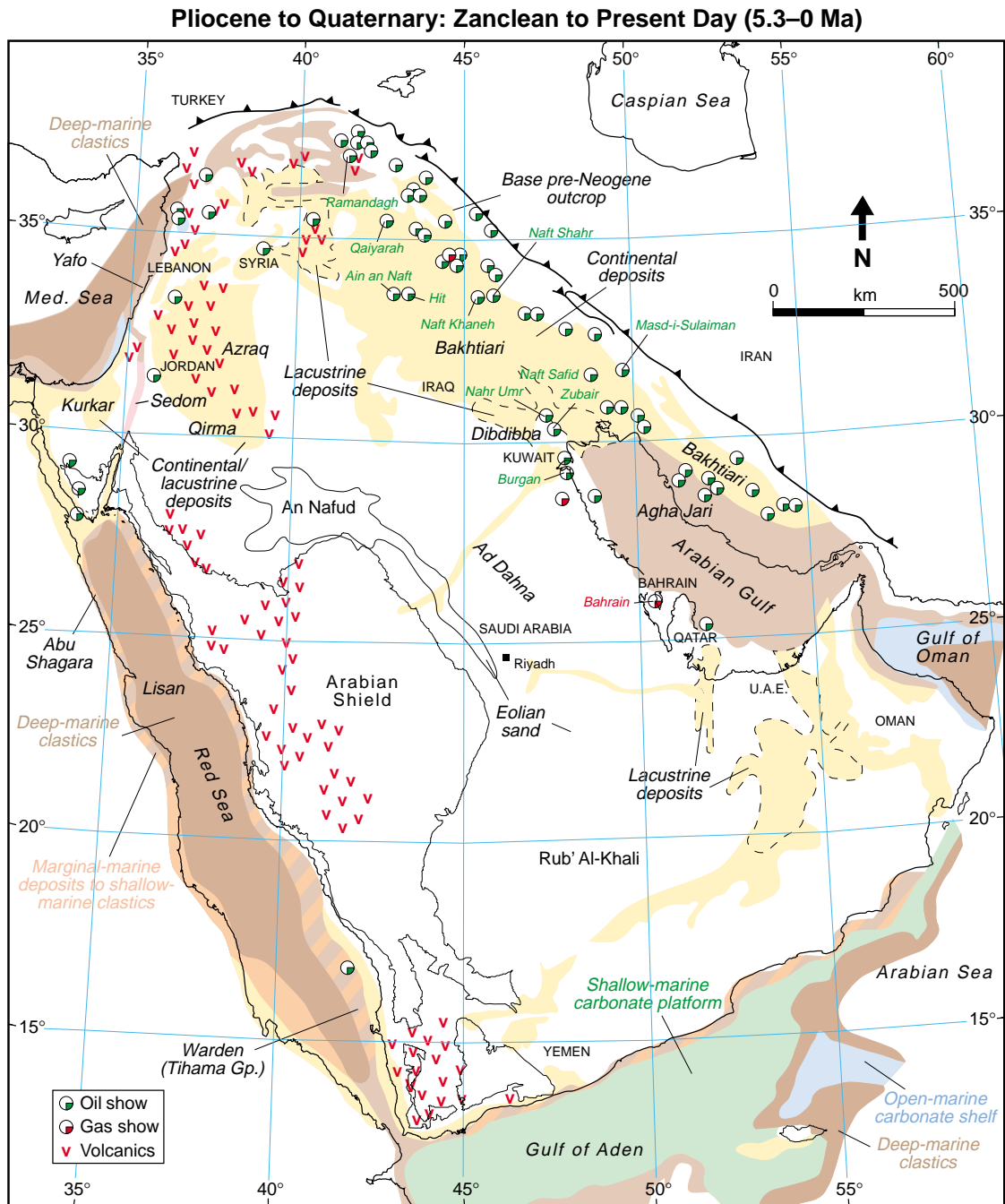
According to the eustatic sea-level chart of Haq et al. (1988), an extreme lowstand with short-term cycles occurred during this period. With the exception of the area of the Arabian Gulf (Agha Jari Formation) most of the Arabian Plate was exposed. As the continent-to-continent collision between Arabia and Eurasia continued, the Zagros orogeny intensified and thrusts and fold belts migrated southwestward to their present position in the Gulf region. Phases of compression led to the formation and deformation of the Zagros foredeep in front of the Zagros mountain belt. In places, the youngest sediments overstep Neogene deposits and rest directly on Cretaceous rocks (Goff et al., 1995).

At the end of the Pliocene, sea level was probably about 150 m higher than at present (Haq et al., 1988), and the strandlines of this time are visible on the Arabian mainland. During the Late Pleistocene glaciation, the proto-Gulf basin was exposed due to glacial 'drawdown' of the oceans. Drainage channels and erosional terraces can be mapped into the Gulf of Oman (Sarntheim and Walger, 1973). After this drawdown, sea level rose once again to about its present-day position (Kassler, 1973; Seibold et al., 1973). Initially shallow-marine shales (Agha Jari) were deposited in the Arabian Gulf basin, but as the climate became increasingly arid a predominantly carbonate depositional environment developed, particularly on the shallow southern margin of the Gulf. Weijermars (1998) suggests that the Arabian Platform was under significant collisional stress until the Quaternary, as expressed by the NNE-trending Batin and W-trending Sahba strike-slip faults. The Hercynian horst-graben structures seem to terminate within Weijermars 'East Arabian Block'.

The northern margin of the Arabian Plate exhibits a continuation of the Miocene tectonic patterns with a phase of thrusting, uplift, and inversion (Kent and Hickman, 1997). This had started in the Levant with dog-leg deflections in the Dead Sea Transform Fault system (Walley, 2001) and transpressive effects with significant inversions in the Palmyrid and Sinjar troughs (Lovelock, 1984; de Ruiter et al. 1995; Brew et al., 1999; Sawaf et al., 2000).

#### ***Paleofacies***

The Zagros foredeep (or 'Mesopotamian Basin') roughly corresponds to the zone between the Mesozoic unstable shelf to the west and the limit of the Zagros fold belt to the east. Into the foredeep was poured a massive (2.5 to 3-km-thick) flood of terrigenous clastics and boulder conglomerates that formed the Bakhtiari Formation. Subsidence is interpreted as having been driven primarily by structural loading of Zagros thrust sheets. The pronounced area of subsidence lay to the west of the central Arabian N-trending lineaments of the Rayn anticlines (Al-Husseini, 2000). The lower contact of the Bakhtiari Formation with the 2,000-m-thick Miocene upper Fars Formation is gradational and its localization seems to be governed by the same structural trends. The Dibdibba Formation of southern



**Figure 21: Paleofacies of the Pliocene to Holocene and location of oil and gas seeps. An extreme lowstand with short-term cycles occurred during this period. With the exception of the area of the Arabian Gulf (Agha Jari Formation) most of the Arabian Plate was exposed. As the continent-to-continent collision between Arabia and Eurasia continued, the Zagros orogeny intensified. Phases of compression led to the formation and deformation of the Zagros foredeep in front of the Zagros mountain belt. With information from: Al Naqib (1967); Al Sayari and Zötl (1978); Bender (1968); Guiraud et al. (2001); Kent and Hickman (1997); Link (1952); Litak et al. (1997); Ponikarov et al. (1966); Walley (1998b).**

Iraq and Kuwait extended from the Late Miocene into the Pliocene. It has the same characteristics as the Late Miocene Hofuf Formation and is considered to be of similar fluvial origin. In the Arabian Gulf, sedimentation continued through from the Miocene (Agha Jari Formation).

Tectonic activity along the northwestern margin of the Plate formed basins in which lacustrine deposits accumulated. A major basin evolved into the Azraq Graben in present-day Jordan (Qirma Formation). In the Dead Sea Graben, Usdom (Sedom) evaporites precipitated in rhombochasms. In the eastern Mediterranean, pelagic sandy shales of the Yafo Formation represent the Pliocene transgression. Here, the littoral facies is made up of terrigenous clastics in the Pleshet Basin and finally by dunes and paleosols of the Kurkar Formation.

The Red Sea, in a renewed rift/drift phase (Hughes and Filatoff, 1995) received sediments from a variety of coastal to marine transitional environments. Collectively they make up the Lisan Formation that is equivalent to the supra- to intertidal siliclastic Warden and Khulaysiyah formations on the flanks (Tihama Group), the shallow-marine carbonate Shagara Formation on the narrow shoulders of the rift, and deep-marine (upper bathyal) sediments within the rift basin. The inner trench contains typically subalkaline basalts. The Gulf of Aden had by now opened widely. It contains essentially shallow-marine carbonates but undifferentiated shales have been drilled off Socotra Island (Richardson et al., 1995). Volcanism on the western margin of the Plate that began in the Miocene has continued into historical times.

Fluvial and eolian processes are eroding the interior of the Arabian Plate. Some areas, particularly on the Arabian Shield, are bare windswept bedrock (*hammada*). Elsewhere, coarse sand and angular, up to pebble-sized, lag deposits remain. Major sand seas (Rub' Al-Khali, An Nafud, Ad Dahna) have characteristic wind-sculpted morphologies. The coastal regions have extensive tidal flats characteristic of an arid climate. The Arabian Gulf, Red Sea, and Levant coasts are typical of mediterranean seas with low tidal-flooding influences other than by seasonal winds. Only the shores of Oman are influenced by significant oceanic tides and waves.

Ephemeral lacustrine salt flats form in the eastern Rub' Al-Khali (Umm as Samim) where the southerly monsoonal run-off from the Oman mountains annually transforms the interdune areas into salt marshes. Lacustrine deposits are also present in the mouth of the Euphrates (Shatt al Arab), where vertical tectonic movements are continuing (Kassler, 1973).

## REGIONAL SUMMARY

1. During the Late Permian to Middle Triassic (Figures 3–5) a new passive margin developed with Neo-Tethys. The Arabian Plate is interpreted as an essentially peneplaned ENE-dipping platform. With the northward drift of the Plate, low-latitude warming occurred. Shallow-marine and arid-evaporitic environments developed and a regional carbonate regime spread over the eastern Arabian Platform. This deposited the Late Permian Khuff Formation and its regional equivalents (Figure 3).
2. During the Late Triassic to Early Jurassic, (Figures 6–8), rifting occurred at the northern end of the Plate. A new northern passive margin with Neo-Tethys was created. The southern part of the Plate and the southeastern edge of the Arabian Shield were uplifted and contributed massive floods of terrigenous clastics toward the northeast (Minjur and equivalent). It is probable that the Hercynian horst-blocks and grabens channeled the sands into southern Iraq and as far as Khuzestan in Iran. West of the Summan Platform, a N-trending seaway developed, possibly a successor of the Paleozoic Widyan Basin.
3. During the Early to late Middle Jurassic (Figures 8–10), the N-trending Gotnia Basin became established across the head of the Arabian Gulf, possibly separated by the 'Rimthan Arch' from its southern extension, the Arabian Basin. The Gotnia Basin allowed direct access for the open marine Neo-Tethys far across the Arabian Platform. The Rimthan Arch has a northwesterly Najd trend, or an even older trend relating to the Rayn microplate (Al-Husseini, 2000). In the late Middle Jurassic, a carbonate regime was dominant throughout the region, and even the western shelf of the Arabian Basin hosted reefal limestones and buildups (upper Dhurma Formation and the Tuwaiq Mountain



Limestone). In the Middle Jurassic (Bajocian-Bathonian), incipient graben systems with a northwesterly Najd trend developed at the southern margin of the Arabian Plate. They began as a terrestrial to continental infill of erosional lows or pre-rift structural depressions, and culminated in the Late to Middle Jurassic (Callovian-Oxfordian) as rift troughs containing shallow-water carbonates of the Shuqra Formation. In the Levant, limited Palmyrid-trend rifting occurred and the extrusion of the Devora volcanics was concurrent with the tectonic activity.

4. The Late Jurassic (Figure 11) was a tectonically active period in southern Yemen, with clearly expressed rifting related to the separation of India from the Afro-Arabian Plate. Significant rift-shoulder uplift characterized the southeastern continental margin of Oman, whilst the northeastern margin remained remarkably stable and accumulated typical shelf-margin carbonate sediments. Instability only occurred in the distal Hawasina Basin. In central Arabia, slow but progressive infill of the intrashelf basins took place through repetitive shoaling-upward carbonate cycles. These cycles usually culminated in subaerially exposed evaporite flats (sabkhas). The Gotnia and Arabian basins may have been intermittently connected by Najd- and Hercynian-trending seaways across the southern Gotnia rim.

The Levant region also shows uplift and rifting coincident with massive Tayasir volcanism. The Arabian-Nubian Shield was to a considerable extent exposed and eroded. Sedimentation was largely controlled by tectonocrustal influences. Similar conditions existed in the Arabian and Gotnia basins.

5. At the beginning of the Cretaceous (Figure 13), global sea level was relatively high and consequently most of the Arabian Plate accumulated almost exclusively shallow-marine carbonates. The major exception was the remnant of the Gotnia Basin that underwent rapid subsidence in the eastern part along Hercynian lineaments to form a narrow deeper-marine intrashelf basin in which the Balambo shales of Iraq and the Garau of Iran accumulated. The Arabian Basin was rapidly infilled, first by carbonates and later by terrigenous clastics (Buwaib and Biyadh formations). The southeast Oman plate-margin segment was foundering accompanied by the establishment of open-marine, deep-shelf deposits.

In the late Early Cretaceous (Figure 14), extensive rudist banks colonized the shelf breaks to the intrashelf basins, such as the Shilaif Basin in the southern Gulf, and in the Levant. Following the opening of the central Atlantic Ocean, a distinct change in motion of the Arabian Plate has been postulated by Al Fares et al. (1998). Far-field stresses are thought to have resulted in the uplift and erosion of the western part of the Arabian Craton and the supply eastward of large amounts of terrigenous clastics and shallow-marine sands. The plate stress, combined with sufficient sediment loading, served to trigger the growth of salt structures in the area of the southern Arabian Gulf over which numerous rudist banks developed.

In the early Late Cretaceous (Figure 15), a renewed spread of rudist growth (Mishrif Formation) occurred to the east, northeast and northwest of the Arabian Plate (the Shilaif Basin, Khuzestan Province, and Pleshet Basin).

6. Neo-Tethys became compressive and began to close during the Late Cretaceous (Turonian) to Early Paleocene (Figure 16). Ophiolite that was obducted onto the Arabian Plate margin may be observed in Oman, at many places along the NE Zagros margin, and in the Troodos Mountains of Cyprus. Flysch-type turbidites accumulated in the foredeep in front of the advancing allochthon along the eastern Plate margin. Hercynian-trend lineaments extended northward from the Central Arabian Arch into the Zagros foredeep.

Early Senonian uplift and inversion of older structures occurred in the Levant. This caused deformations along the Syrian Arc and the onset of faulting in the Azraq Graben in Jordan. Shallow-marine carbonates were deposited southward across Sinai into the depression that marked the proto-Red Sea rift. The deposition of shallow-water and lacustrine sediments occurred as far south as the Jiddah region.



7. Global sea level during the Late Paleocene to Early Oligocene (Figures 17–19) was relatively high and only in the Late Oligocene was there a marked drop (Haq et al., 1988). At the time of high sea level, a shallow epeiric sea inundated the eastern platform of the Arabian Plate. The sea periodically shoaled to emergence, which caused the formation of transitional coastal sabkhas. The Hercynian structural trends of the Central Arabian Arch continued to modify the morphology of the foreland basin. This became progressively narrower as it was filled in, until it became structurally neutralized.

From the late Middle Eocene to Early Miocene (Figures 18–20), the Arabian Plate began to impact southern Asia, and the Zagros Orogeny began. The western part of the Plate was emergent and only on the subsided margins (e.g. the Gulf of Aden), did marine sedimentation continue. The Priabonian and Oligocene-Miocene deposits of southern Dhofar and the Hadramaut record the early stages of rifting and progressive opening of the Gulf of Aden. Western Yemen at this time was part of the thermally doming Afar Triangle. As a consequence, vast amounts of volcanic rocks were erupted in the hinterland of Aden and the southern Red Sea. Although early rifting in the Red Sea region has been dated as Early Oligocene, the first phase of sea-floor spreading did not begin until the Early Miocene, and lacustrine to continental sedimentation prevailed in the pre-rift depressions.

On the northern margin of the Arabian Plate, molasse and flysch-type clastics were discharged into the foredeep of the Taurus orogenic belt (the Aslantes-Iskenderun Basin) and onto the shallow shelf of the Mardin High. In the Levant, clastic detritus from the Arabian Craton was discharged onto the Sinai plains and indicates that the Dead Sea Transform Fault was not yet active, although basaltic extrusives are present along and adjacent to the incipient fault; volcanics were also extruded in the eastern Mediterranean. A new tectonic phase affected the Syrian Arc and Galilee, and the Palmyrids and Sinjar inversion structures.

8. The Miocene to Pliocene (Figures 20–21) was the time of maximum compression between Arabia and Asia, coeval with the Late Alpine Orogeny in Europe. During this period, the Arabian Plate began to separate from Africa, the Gulf of Aden opened, and the Dead Sea Transform Fault acted as a complex sinistral strike-slip fault. The second phase of sea-floor spreading in the Red Sea began about 10 Ma and is continuing. The Syrian Arc, through collision of the Arabian Plate with Eurasia, continued to undergo inversion. Along the Red Sea margin of the Plate, basaltic lavas were extruded to form a series of large lava fields (*harrats*). Major N-trending faults appear to have controlled the emplacement of these volcanics. Where this fault zone meets the Red Sea, the character of the rift sediments changes from constricted marine salina evaporites (Maqna Group) in the north, to globigerinid, deep-marine shales (Burqan Formation) in the south.

The N-trending Hercynian lineaments occur as far north as the Zagros Foredeep, on the western side of which a great thickness (>4,000 m) of continental sediments was discharged into the rapidly subsiding Lurestan (foredeep) Province of Iran. To the east, salt marsh evaporites (Gachsaran Formation) and shallow-marine carbonates and shales were deposited.

The eastern Mediterranean was cut off from open-marine circulation at this time, and the Late Miocene (Messinian) salina evaporites are proof of the resultant 'salinity crisis'.

9. During the Pleistocene, sea level was low (Haq et al., 1988) and, as a consequence of uninterrupted collision and erosion along the northern Arabian Plate margin, a large thickness (>1,000 m) of conglomerates and sands was deposited at the northeastern edge of the Craton. Inversion and uplift continued in the Palmyrid and the Sinjar basins.

East of the Arabian Arch, the shallow epicontinental Arabian Gulf began to take its present shape. Initially, shallow-marine shales were deposited but, as changes to more arid conditions took place, the Gulf established itself primarily as a carbonate province, particularly on the shallow shelf along its southern and southwestern coasts. At the end of the Pliocene, sea level stood about 150 m higher than today and the subsequent drop in sea level to that of the present day has made visible old strandlines and erosional terraces. Kassler (1973) reported high-level terraces in Oman. During the Late Pleistocene glaciation, the sea-level drawdown was such that the entire Gulf basin became exposed as far as the Gulf of Oman.

The axis of the Gulf changed from a central position in its Western Basin (toward the head of the Gulf), to a northward-skewed position in the Eastern Basin (Central Basin of Purser and Seibold, 1973). This axial shift was due to the southward bulge of the Zagros fold belt, east of the Kazerun strike-slip fault. The western axis is situated in front of the Zagros belt, whereas the axis in the Eastern Basin is part of the Zagros fold belt. Along the Iranian coast and at the head of the Gulf, ongoing vertical movements of the Zagros Mountains have been observed in the form of elevated river terraces and renewed incisions by younger drainage systems; also canals and other artifacts have been affected by rising anticlines.

The Gulf of Aden continues to open and is underlain by oceanic crust. It reaches bathyal depths and is rimmed by a narrow marine shelf. The Red Sea is also a spreading center and now forms a 1,900-km-long trench that has a maximum depth of 2,220 m in the Discovery Deep. For the most part, an extremely narrow shelf parallels the rift. Subalkaline basalts are accumulating in the southern part of its inner trench. The Dead Sea Transform Fault is active and several 'rhomboclasts' have formed, some of which became isolated basins, as evidenced by lacustrine and hypersaline depositional environments. The Mediterranean reestablished normal marine conditions following the Messinian salinity crisis, with bathyal depths close to the Levant shore.

A striking feature has been the progressive desertification of much of the region during the Pleistocene-Holocene. Most parts of the Arabian Peninsula are strongly affected by wind erosion and the accumulation of wind-blown sand. Large areas are rock deserts or deflation plains (*hammada* or *najd*). Elsewhere, huge volumes of loose sand are being piled up by the prevailing winds in the deserts of the Rub' Al-Khali of eastern Arabia, An Nafud of northern Saudi Arabia, and Ad Dahna desert of eastern Saudi Arabia. In southeastern Arabia, monsoon influences result in sediment transport by seasonal flow in wadis. Similarly, ephemeral lacustrine conditions prevail in parts of the eastern Rub' Al-Khali and Yemen due to monsoonal flow from the mountains. The Levant is influenced by seasonal winter rainfall. Under hot, arid conditions, and in wind-sheltered locations with a relatively stable sea level, the shorelines of the Arabian Gulf are prograding, and saline supratidal flats (*sabkhas*) are spreading basinward.

## HYDROCARBON OCCURRENCES

1. The Permo-Triassic Khuff non-associated gas accumulations (Figure 3) are critically dependent on the distribution of Lower Silurian source rocks (Qusaiba 'hot shale') and the presence of an effective caprock in the form of Khuff evaporites and Lower to Middle Triassic shales (Sudair and Jilh formations). The primary reservoir lithology is microcrystalline dolomite.

Mahmoud et al. (1992) depicted a regional Qusaiba 'hot shale' isopach map of central Arabia. It is thickest (>75 m) south of the Central Arabian Arch and thins in a northeasterly direction toward Bahrain. The isopach map illustrates a northerly grain. Toward the Kuwait-Saudi Arabia Partitioned Neutral Zone, a more 'layer cake' shale thickness of 30 m is suggested although this is unconstrained by well penetrations. In Iran, the equivalent Early Silurian Gahkum shale sources the non-associated gas in equivalent Permian reservoirs (Alsharhan and Nairn, 1997). In the Fahud and Ghaba salt basins of Oman, Precambrian to Cambrian carbonates and shales of the Huqf Supergroup (Terken, 2000), as well as the Silurian Sahmah Formation (Droste, 1997), provide source rocks for the Khuff oil and gas reservoirs.

The Khuff evaporite intervals act as intraformational caprocks for the numerous gas fields that are mainly present south of the Arabian Arch. The Khuff contains the world's largest accumulation of non-associated gas—the North Field/South Pars of Qatar and Iran (500–600 TCF). Notable accumulations are also found in Khurais and Ghawar in Saudi Arabia.

2. Petroleum production from Jurassic reservoirs (Figures 8–11) is mostly concentrated around the intrashelf basins (Arabian, Rub' Al-Khali, and Ras al Kaimah basins), but is also derived from Late Jurassic sediments in the Marib and Sayun-Masila basins of southern Yemen.

The extent of the Late Jurassic Arab/Hith anhydrite (Figure 11) and the presence of mature source rock in the intrashelf basins control the present-day distribution of the many oil fields in the southern and western Arabian Gulf region. The Dhurma, Arab, and Hith (Hanifa) formations are the main producing units. The chief hydrocarbon source is the anoxic shales of the intrashelf basins in central Arabia, or the Sargelu and Naokelekan formation in the early Gotnia Basin of Kuwait, Iraq, and Iran. The source rock can be of Bajocian to Bathonian age (Dhurma and Sargelu formations) or Callovian to Oxfordian age (Hanifa-Diyab, Najmah and Naokelekan formations). The cap rocks are formed by the regionally widespread Arab-Hith evaporites that extend from Iraq to the southern Rub' Al-Khali Basin and into the Fars Province of Iran.

In Saudi Arabia, the distribution of Middle Jurassic fields (Figure 9) is controlled by the occurrence of shelf-calcareous reservoirs, exemplified by Ghawar the largest oil field in the world (80–100 billion barrels total recoverable reserves). In Qatar, the Araej Formation contains considerable gas reserves in the Uwainat Member. The production is from interbedded pelletal lime grainstones and packstones, and dense limestones with moderate moldic to vuggy porosity generated by leaching during high-frequency hiatuses. Good porosity, however, is often handicapped by poor permeability. The Middle Jurassic production of the United Arab Emirates stems from the Upper Araej Formation, a mainly grain-supported limestone with good porosity and permeability values. Oil and gas fields in Iran produce from the lower Surmeh limestones.

In the Marib-Shabwa basin of Yemen (Figure 11), the Madbi Formation (containing shales and fossiliferous platform limestones indicating restricted water circulation) is late Oxfordian to Kimmeridgian. The overlying Lam Formation typically represents thick basinal shales that are interbedded with distal turbidites and thin limestones. The sequence was deposited during the main precursor-rifting phase prior to the separation of India from Arabia. The shales of both formations are source rocks and are widespread in the Marib-Shabwa and Sayun-Masila basins. The open-marine shale sequence is capped by a stacked, braided-stream succession that gives way to organic shales, together with anhydrite and halite. In the Marib-Shabwa Trough, production has been established around the central high and at the edges of the graben where fluvial sands are overlain by, and interbedded with, evaporites.

3. Production from Cretaceous reservoirs (Figures 12–16) shifted northward and eastward to the Gotnia and Rub' Al-Khali basins. During the Early Cretaceous, widespread flooding of the Arabian Craton took place and shallow-marine carbonates were deposited. The production is again concentrated on the edges of the carbonate shelf, mainly in the western ramp of the Gotnia Basin. During Hauterivian to Turonian time (Figure 13–15), considerable amounts of clastics derived from the western hinterland were shed into the Zagros (Gotnia) Basin. They make up most of the oil reservoirs in Kuwait and southern Iraq. Beyond the reach of clastic input, rudistid banks occupy the shelf breaks around the Rub' Al-Khali and Zagros basins. Shallow-marine shelf limestones and detrital carbonates host the many (mostly small) reservoirs of the Zagros Basin in Iran and Iraq, and in the Sinjar Trough of Syria.

The distribution of Early Cretaceous oil and gas fields in the Gulf region can be broadly subdivided into a shallow-marine shelf carbonates setting, and more intrashelf deposits (Figure 13).

Shallow-marine shelf-carbonate reservoirs are the upper Ratawi of Saudi Arabia and Bahrain and the Habshan and Lekhwair formations of the United Arab Emirates. In Iran, the corresponding reservoirs are in the Fahliyan Formation, a massive oolitic-peloidal limestone with some fracture porosity. Other fields belong to the Khami Group, a succession of massive, thin-bedded limestones of which the Fahliyan Formation is part. In Syria, oil fields are present in the Euphrates Graben in the Cherrife (Rutbah) Formation of shales, sandstones, and carbonates deposited in a shallow, transitional-marine environment close to the Rutbah High.

Shelf-slope reservoirs are mainly found in the southern Gotnia Basin that had become accentuated since the beginning of Cretaceous. In general, an interbedded sequence of transgressive and

regressive shelf carbonates were deposited in reaction to eustatic sea-level changes; oolitic, peloidal, and locally dolomitic lime grainstones alternate with dense, argillaceous micrites on a generally passive margin.

North of the Arabian Arch, notable Early Cretaceous reservoirs (Zubair in Kuwait and southern Iraq) occur in the siliciclastic Hauterivian to Barremian Biyadh Formation. The younger Albian Wasia Formation of the northern Gulf hosts the Safaniya/Khafji reservoirs and the cyclic sands of the Burgan reservoir. Vast amounts of oil accumulated in these reservoirs in Saudi Arabia, Kuwait, Iraq, and Iran. Smaller fields occur in the continental to shallow-marine Rutbah/Biyadh sands in the precursor depression of the Euphrates Graben. At the northern end of the former Gotnia Basin, oil fields were developed over, and adjacent to, the Kirkuk High.

The Chia Gara and Makhul-Garau shales of the confined (Gotnia) Zagros Basin are considered to be the source rocks for Early Cretaceous ramp carbonate reservoirs, such as the Yamama Formation of Saudi Arabia and Kuwait. The source rocks for the Biyadh and Wasia sand wedges were probably shales of the Garau, Balambo, and Kazhdumi formations. The Khatiya Formation in the Rub' Al-Khali Basin is a potential source rock. Faults and fractures may connect some older Jurassic source rocks, such as the Sargelu and basinal Naokelekan, with Cretaceous reservoirs.

Late Early Cretaceous oil fields (Figure 14) are mainly localized in the shallow-marine rudist and associated carbonates (Shu'aiba Formation) along shelf breaks and above salt pillows/ domes in the southern Gulf and the Rub'al Khali Basin, and are sealed by the overlying Nahr Uhr shales. The reservoirs have formed mainly in accumulations of biogenic detritus in a forebank position. Various types of primary and secondary rudistid porosities were created through extensive porosity and permeability enhancement by leaching and karst weathering. In Iran, similar reservoirs were created in the Albian-Turonian Sarvak carbonates in the Khuzestan Basin, and in Iraq on the Kirkuk High in the Zagros foothills. In Syria, the Albian Qamchuqa Formation at the southern edge of the Sinjar Trough produces from a dolomitic (marly) limestone shelf.

4. Late Cretaceous and early Tertiary production (Figure 16) is clustered around the northern Zagros foredeep and the Sinjar Trough mainly in shallow-water neritic carbonates. Deep-marine shales of the Shiranish, Sa'adi and Gurpi formations in part represent source rocks (Gurpi) or caprock (Shiranish). Shoals at Garzan (southern Turkey) and the Kirkuk High host bioclastic to reefal limestones that accommodate small fields in the northern Zagros Basin.

Most of the production from southern Turkey is from fossiliferous, shallow-water carbonates of the middle Mardin Group. Other production is from fractured reefoidal limestones of the Late Cretaceous Raman Formation. Minor production in Syria is from the 'Massive Limestone' (micrites and argillaceous dolomites), Soukne sandstones, and the Shiranish Formation (marly limestone, in parts reefoid) in the Euphrates Graben and the Sinjar Trough. The source rocks are considered to be basinal equivalents.

Production in Iraq is from the Kometan and Shiranish formations in the Kirkuk and Mosul areas and from shallow-water carbonates of the Hartha Formation in southern Iraq. In Iran, production in the Khuzestan Province is from the Sa'adi/Ilam formations for which the Gurpi shales are the source rock. United Arab Emirates production is from the Ilam and Halul formation and the Simsima shallow-water carbonates sourced by the Laffan (Gurpi) shales.

5. Oligocene to Early Miocene production (Figures 19–20) is from the widely distributed Asmari Formation, a shallow- to marginal-marine limestone of the Zagros Basin. Localized siliciclastic input from the western hinterland formed the Ahwaz/Ghar sand reservoir in southern Iraq and western Iran. The Asmari limestone is generally a dense mud-supported limestone with a rich foraminiferal fauna in its lower segment. In spite of its low porosity, the Asmari micrite has a very effective permeability due to fracturing of the brittle limestone. Two fracture generations occur. An earlier N-trending, very fine fracture set seems to be linked to older, basement-induced configurations, whereas the younger NW-trending set coincides with the present-day anticlinal

stress patterns (McQuillan, 1985; 1991). The source rocks for the Asmari (Ahwaz) play are the Pabdeh shales of the Zagros foredeep.

The Early Miocene hydrocarbon development along the northern Zagros foredeep is to a large extent controlled by the distribution of evaporitic caprocks of the Lower Fars and Gachsaran formations. The extensive Gachsaran salt and evaporite deposits are the seal to the Asmari oil accumulations in the Khuzestan-western Fars region of southwestern Iran.

Miocene oil and gas accumulations in Syria are associated with the vast foreland evaporite flats of the Lower Fars Formation. They are located in front of large outwash fans in the Jeribe Formation of the Sinjar Trough. In Iraq, fields of this age are located at the head of the Gulf in the sand-shale intercalations of the Hadruk and Dam formations. Production in Iran is from the upper Asmari and Mishan formations. In the Strait of Hormuz, minor amounts of gas are produced from the Mishan shallow-marine platform carbonates.

6. Surface indications of natural oil and gas seeps (Figure 21) are often recognized by local names such as *naft*, which is Arabic for oil; for example, Naft Khaneh and Naft Shahr, in western Iran, and Ain an Nafat, west of Baghdad. Man has used the tar and oil seeps since early historical times.

Oil and gas seeps, as illustrated by Link (1952), are mostly located in the frontal part of the Zagros fold belt. This area is the mobile belt of the Mesopotamian Basin where folding and the destruction of earlier oil pools took place (Beydoun et al., 1992). The seeps are related to breached and faulted anticlines. Through crestal leakage of the fractured Asmari limestone reservoir, the oil and gas have reached the surface. In other cases, leakage is related to low-angle thrust faults originating in ductile cover-rock sequences, such as salt and anhydrite of the Lower Fars Formation. These seeps generally occur to the south and some distance away from the oil-bearing subsurface structures.

Asphalt seeps occur over the Burgan structure of Kuwait and southern Iraq on the Arabian Craton. The surface structures represent gentle folds, but faults accommodating drape over underlying basement-induced horsts acted as hydrocarbon migration pathways. A stringer of bitumen about 5 cm thick occurs in the Late Jurassic anhydrite at Dahl Hit, about 40 km southeast of Riyadh. This represents the only unroofed pinch-out trap on the Arabian homocline. Other oil impregnations have been found along the Dead Sea Transform Fault and in the Palmyrids.

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## ABOUT THE AUTHOR

**Martin A. Ziegler** retired in 1989 after a long and distinguished career in Middle East geology. He was awarded his PhD in 1961 from Zürich University, Switzerland, for a study of Late Jurassic facies changes between the Paris Basin and the interior Helvetic Shelf of the Tethys Basin. Then followed five years with Shell International studying carbonates in Qatar and rudist mounds in Switzerland and Oman. From 1968 until his retirement in 1989, he worked for the Exxon Corporation, first in the Carbonate Facies Group at EPRCO in Houston and later in various postings in the Middle East and Europe. Martin was seconded for nine years to Saudi Aramco where he was engaged in carbonate studies, such as the rudist play in the Shaybah area of the Rub' Al-Khali Basin and the Late Jurassic to Early Cretaceous stratigraphy of the Gotnia Rim and the Arabian Basin. Since retirement, he has acted as a consultant on carbonate plays and Middle East geology in general.



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