ARABIA AND THE GULF

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Introduction

Arabia consists of two main geological features: the Arabian shield and the Arabian shelf. Charles Doughty, who in 1888 produced the first geological map of Arabia, wrote "the Geology of the Peninsula of the Arabs consists of a stack of plutonic rock, whereupon lie sandstones, and upon the sand-rocks limestones. There are besides great land-breadths of lava and spent volcanoes". These two sentences encapsulate the geology of Arabia, and indeed of the whole of the southern shoreline of Palaeo-Tethys, from the modern Atlantic Ocean to the Arabian Gulf.

The Arabian shield is a Precambrian complex of igneous and metamorphic rocks that occupies roughly one-third of the western part of the Arabian Peninsula. The Arabian shield is a continuation of the adjacent African shield from which it is separated by the Red

Sea rift (*see* **Africa:** Rift Valley). The rocks in West Arabia, Yemen, Aden, and Oman are dated as Precambrian by radioisotopic dating and by the presence of Cambrian fossils in sediments above. Radiometric dates show that the Arabian shield was involved in the Pan-African Orogeny (*see* **Africa:** Pan-African Orogeny). The shield crops out along the east coast of the Red Sea rift, south to Yemen, and extend eastward into central Arabia with varied degrees of exposures.

The Arabian shield dips eastwards beneath some 6000 m of sedimentary rocks of Infracambrian to Recent age. These rocks crop out as belts surrounding the shield that dip gently east and north-east into the subsurface before they crop out again in Oman, United Arab Emirates, and Iran, mostly during the Mesozoic time that brought to surface the famous ophiolites of Oman. The geological formations are generally well exposed, due to a lack of vegetation, and can be traced along their outcrops for hundreds of kilometres. Geologists from Charles Doughty to the present day have noted that the uniform stratigraphy of Arabia can be traced westwards across North Africa to the Atlantic Ocean time (*see* **Africa:** North African Phanerozoic). This uniformity is most marked in the Lower Palaeozoic, and degrades thereafter through time.

Subsequent to the work of Doughty, geological mapping and fieldwork in Arabia in the 1930s was tied to oil exploration and covered more than 1 300 000 km^2. **Figure 1** is the first published geological column of Arabia compiled by Powers and Ramirez in 1963.

During the early days of Aramco, geologists identified, measured, and mapped nearly 6000 m of sediments ranging in age from presumed Infracambrian to Recent. The main rock units have been identified and mapped since 1966 by Aramco and the US Geological Survey (USGS). Through the years much additional work has been performed by Saudi Aramco, USGS, and Bureau de Recherches Geologiques et Minieres (BRGM). Some formation names have changed and some new ones have been introduced in Arabia and the Gulf states, the result being a wealth of information both from outcrops and from the subsurface that has affected our knowledge of the formations, their contacts, ages, and nomenclatures; however, the original stratigraphic framework remains largely intact. This may be seen by comparing **Figure 1** with **Figure 2**, which is the stratigraphic column for Saudi Arabia, recently produced by Aramco.

In central Arabia, the Palaeozoic and Mesozoic rocks crop out as curved belts bordering the Arabian shield, dominated by parallel west-facing escarpments capped by resistant limestone. In eastern Arabia the older sediments are mostly covered by a gently dipping belt of low relief Tertiary and younger deposits that include the Rub al Khali and north-eastern Arabia (Nafud) of Quaternary sands.

In north-western Arabia some 2000 m of largely lower Palaeozoic sandstone is exposed. The lower units of this Palaeozoic sandstone can be correlated into Jordan and across the Arabo-Nubian shield into North Africa. To the east lies a basin of Upper Cretaceous to Tertiary sediments. Volcanic rocks of Tertiary to Recent age cover substantial parts of the shield and adjacent cover. These result from deep crustal tension associated with the development of the Red Sea rift system.

The Stratigraphy of Arabia and the Gulf

The geological section above the Precambrian basement Arabia falls into eight major divisions separated by unconformities (**Figures 1** and **2**). These may be summarized as follows from base to top:

1. Infracambrian and Lower Palaeozoic clastic rocks (Cambrian through Lower Devonian);
2. Carboniferous, Permian, and Triassic carbonate/clastic rocks (Upper Permian through Upper Triassic);
3. Lower and Middle Jurassic clastic and carbonate rocks (Toarcian to Callovian?);
4. Upper Jurassic and early Lower Cretaceous carbonate rocks (Callovian through Valanginian);
5. Late Lower Cretaceous clastic rocks (Hauterivian through Aptian);
6. Middle Cretaceous clastic rocks (Cenomanian through Turonian?);
7. Upper Cretaceous to Eocene carbonate rocks (Campanian through Lutetian); and
8. Neogene clastic rocks (Miocene and Pliocene).

Infracambrian and Lower Palaeozoic Clastic Rocks (Cambrian through Lower Devonian)

Above the igneous and metamorphic basement of the Arabo-Nubian shield the Infracambrian cover consists of sandstone, carbonates, shale, and salts. The Infracambrian shows the oldest fossils. The Infracambrian Huqf Group of Oman contains potential petroleum source rocks. The Huqf Group includes the Mahara, Khufal, Shuram, Buah, and Ara Salt formations, ranging in age from Precambrian to Lower Cambrian. The evaporites are usually referred to as the Hormoz Salts, and have formed many diapiric structures in Oman and throughout the Gulf, many of which are petroliferous. In central Arabia the Precambrian shield is overlain by the Infracambrian

Age				Formation	Generalized lithologic description	Thickness (Type or reference section)	Major stratigraphic divisions
	Quaternary and Tertiary			Surficial deposits	Gravel, sand, and silt		
				Kharj	Limestone, lacustrine limestone, gypsum, and gravel	28m	Miocene and Pliocene clastic rocks
Cenozoic	Tertiary	Miocene and Pliocene		Hofuf	Sandy marl and sandy limestone; subordinate calcareous standstone. Local gravel beds in lower part	95m	
				Dam	Marl and shale; subordinate sandstone, chalky limestone, and coquina	91m	
				Hadrukh	Calcareous, silty sandstone, sandy limestone; local chert	84m	
		Eocene	Lutetian	Dammam	Limestone, dolomite, marl, and shale	33m	Upper Cretaceous to Eocene carbonate rocks
			Ypresian	Rus	Marl, chalky limestone, and gypsum; common chert and geodal quartz in lower part. Dominantly anhydrite in subsurface	56m	
		Paleocene	Thanetian / Montian(?)	Umm er Radhuma	Limestone, dolomitc limestone, and dolomite	243m	
				Possible disconformity			
Mesozoic	Cretaceous		Maestrichtian / Campanian	Aruma	Limestone; subordinate dolomite and shale. Lower part grades to sandstone in northwestern and southern areas of outcrop	142m	
			Turonian(?) / Cenomanian	Wasia (Sakaka Sandstone of north-west Arabia)	Sandstone; subordinate shale, rare dolomite lenses	42m	Middle Cretaceous clastic rocks
			Aptian / Barremian	Biyadh	Sandstone; subordinate shale	425m	Late Lower Cretaceous clastic rocks
			Hauterivian	Buwaib	Biogenic calcarenite and calcarenitic limestone interbedded with fine sandstone in upper part	18m	
			Valanginian	Yamama	Biogenic-pellet calcarenite; subordinate aphanitic limestone and biogenic calcarenitic limestone	46m	Upper Jurassic and Early Lower Cretaceous carbonate rocks
			Berriasian	Sulaiy	Chalky aphanitic limestone; rare biogenic calcarenite and calcarenite limestone	170m	
	Jurassic		Tithonian	Hith	Anhydrite	90m	
				Arab	Calcarenite, calcarenitic and aphanitic limestone, dolomite and some anhydrite. Solution-collapse carbonate breccia on outcrop due to loss of inter-bedded anhydrite	124m	
			Kimmeridgian	Jubaila	Aphanitic limestone and dolomite; subordinate calcarenite and calcarenitic limestone. Lower part sandstone between 20°N and 22°N	±118m	
				Hanifa	Aphanitic limestone, calcarenitic limestone, and calcarenite	113m	
			Oxfordian / Callovian	Tuwaiq Mountain	Aphanitic limestone; subordinate calcarenitic limestone and calcarenite. Abundant corals and stromatoporoids in upper part	203m	
			Callovian(?) / Bathonian / Bajocian	Dhruma	Aphanitic limestone and shale; subordinate calcarenite. Dominantly sandstone south of 22°N, and northof 26°N	375m	Lower and Middle Jurassic Clastic and carbonate rocks
			Toarcian	Marrat	Shale and aphanitic limestone; subordinate sandstone	103m	
	Triassic		Upper	Minjur	Sandstone, some shale	315m	Permian and Triassic clastic rocks
			Middle	Jilh	Sandstone, aphanitic limestone, and shale; subordinate gypsum	±316m	
			Lower	Sudair	Red and green shale	116m	
Palaeozoic	Permian		Upper	Khuff	Limestone and shale; dominantly sandstone south of 21°N	171m	
			Lower	Wajid	Sandstone, gravel, and basement erratics (Recognized only in southwestern Saudi Arabia and northern Yemen	950m Calculated	
	?		Undated				
				Precambrian basement complex			
	Devonian		Lower	Jauf	Limestone, shale, and sandstone	299m	Lower Palaeozoic clastic rocks
	Ordovician and Silurian			Tabuk	Sandstone and shale	1,072m	
	Cambrian			Saq (Umm Sahm, Ram, Quweira, Siq)	Sandstone	+600m	

Precambrian basement complex

Compiled by RW Powers and LF Ramirez, June 3, 1963

Figure 1 The first geological column of Saudi Arabia, compiled by RW Powers and LF Ramirez in 1963. After Powers *et al.* (1966).

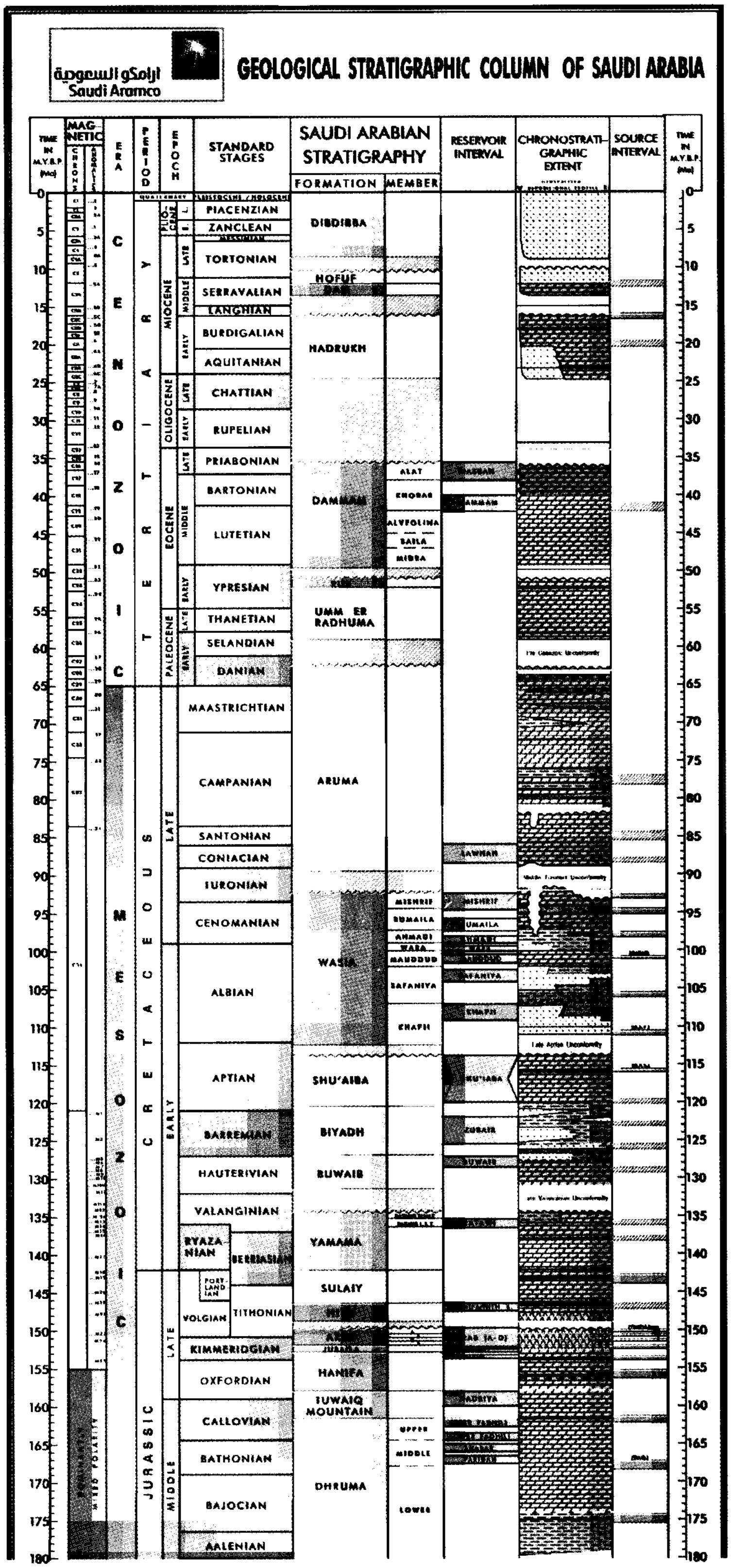

Figure 2 Modern geological stratigraphic column of Saudi Arabia. After Qahtani *et al.* (2004).

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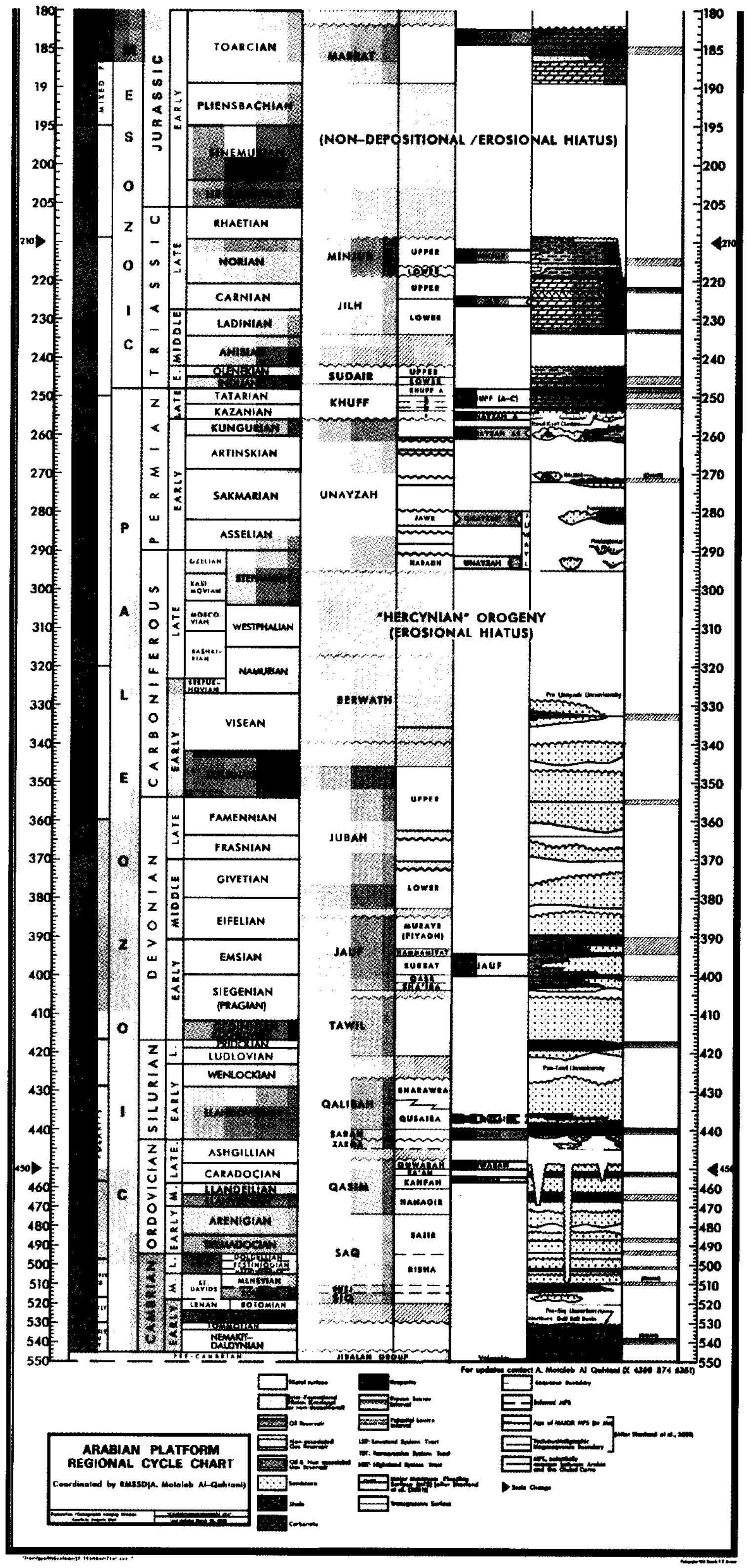

Figure 2 Continued

Jubailah Group, whose biostratigraphy is poorly known, but can be correlated with Huqf Group of Oman. The Lower Palaeozoic rocks are mainly quartz, sandstone, and shale, with some thin carbonate beds in the upper part. They range in age from Cambrian to Lower Devonian. These include the Saq, Tabauk, Tawil, and Jauf formations. Some of these old names have been replaced by newer names. For example, the Tabuk has been replaced by the Qasim. Additional formations have been added, such as the Kahfah and Juba. The 'old' Wajid Sandstone (**Figure 1**) in south-western Arabia has been divided into four new formations. The Cambro-Ordovician Saq and Qasim formations can be correlated with the Haima Group in Oman, which includes the Amin, Andam, Ghudun, and Safiq formations. In Jordan the Saq Sandstone can be divided into four units: the Siq, Quweira, Ram, and Um Sahm. The Siq is probably equivalent to the Yatib Formation of the BRGM in central Arabia. The Burj Formation of Jordan (Middle Cambrian carbonates and shale) was introduced to the Aramco chart in 1992, and Laboun suggested that it be renamed the Farwan Formation in al-Jauf near Jordan. The Burj carbonates overlie the Siq or Yatib in north-western Saudi Arabia. The Saq Sandstone is of mainly fluvial origin, though the presence of *Cruziana* tracks in abandoned shale channels towards the top suggest marine influence. The Saq Formation has two members, the Resha and the Sajir.

The Saq Formation is uncomfortably overlain by the Middle Ordovician Qasim Formation of sandstone with alternating Shale members. These include the Hanadir Shale, the Kahfah Sandstone, the Raan Shale, and the Qawarah Sandstone. The shales contain rare graptolites, of great biostratigraphic significance, and the sandstones locally contain abundant burrows variously termed *'Tigillites'*, *'Sabellarifex'*, and *'Scolithos'*, which are indicative of intertidal conditions.

The Qasim is unconformably overlain by the Zarga and Sarah formations of Late Ordovician and Early Silurian ages; these two formations are famous for their glacial features. The Mid- to Late Silurian age Qalibah Formation follows with its two members, Sharwrah and Qusaiba. Formerly the Qalibah was called the Tayyarat Formation developed by BRGM studies. The Qusaiba Shale is the main source rock for the Palaeozoic gas in the Jauf (Devonian), Unayzah (Permian), and Khuff (Late Permian–Early Triassic) reservoirs.

Sedimentological studies reveal that this Lower Palaeozoic sequence resulted from deposition on alluvial braid plains that passed down-slope into intertidal and shallow marine shelves, which in turn passed into basinal mud. Graptolites in the latter can be used to demonstrate the diachronous progradation of these facies across the Arabian shield. These events were coeval with similar progradational episodes northwards across the Saharan shelf.

The Tawil Formation (Late Silurian and Early Devonian) unconformably overlies the Sharwrah member of the Qalibah Formation. This sandstone is very different from other Palaeozoic sandstones because it contains an abundance of heavy minerals. These give a spiky character to the spectral gamma ray log, which aids subsurface correlation because the Palaeozoic sands commonly lack palynomorphs that can be used for age dating. The Tawil Formation is conformably overlain by the Jauf Formation. The Jauf Formation is remarkably different in character from where it crops out in the north to where it is found in the subsurface of eastern Arabia. Where it crops out near the town of Jauf it is mostly marine limestone, whereas in the subsurface in eastern Arabia it consists of deltaic sandstone. The Jauf Formation is one of the main Palaeozoic gas reservoirs in Arabia. In the Jauf Formation reservoir drilling problems are usually encountered due to considerable amounts of permeability-inhibiting illite. The palynology of the Jauf Formation is more useful for environmental than for stratigraphic analysis (**Figures 1** and **2**).

The Jauf Formation is overlain by the Jubah Formation. This consists of Middle Devonian to Lower Carboniferous cross-bedded sandstone that used to be considered part of the Jauf Formation, but is now separated from it. It is unconformably overlain by the Wasia Formation in the Sakaka area of northern Saudi Arabia. The Jubah Formation can be correlated with the Sakaka Sandstone, whose age was controversial, having once been considered Cretaceous, and equivalent to the Wasia Formation.

The Wajid Sandstone of south-western Arabia has been divided into five members: the Dibsiyah (Cambrian, equivalent to Saq), the Sanamah (Late Ordovician, equivalent to Sarah/Zarga), the Silurian Qusaiba, the Khusyyayn (Devonian–Carboniferous, equivalent to Tawil, Jauf, Jubah, and Berwath) and the Juwayl (Permo-Carboniferous) equivalent to Unayzah and its units. The lower parts of Unayzah has recently been interpreted by Aramco as the equivalent of the Juwayl or Wajid Sandstone and to the Al Khlata Formation of Oman.

Carboniferous, Permian, and Triassic Carbonate/ Clastic Rocks (Upper Permian through Upper Triassic)

Lower Palaeozoic strata are succeeded by some 1000 m of interbedded carbonate and clastic sediment of Upper Permian to Triassic ages, with some basal Permo-Carboniferous rocks. The old stratigraphic terminology included the Berwath (Carboniferous), Khuff, Sudair, Jilh, and Manjur Formations. Of these, only the Berwath has been renamed (**Figures 1 and 2**). The Unayzah Formation was introduced to include the Pre-Khuff clastics. The new formation includes the clastics below the Khuff together with the basal Khuff clastics. The Unayzah is one of main sweet gas reservoirs in the Palaeozoic rocks of Arabia. It is divided into the A, B, and C reservoirs. The age of this formation is still ill-defined. Currently it is believed to span the Carboniferous/Early Permian to Late Permian, usually referred as a Post-Hercynian orogeny event. Many intervals of the Unayzah reservoirs, however, differ from each other and from the lower unit (the Unayzah C). This is more cemented than the overlying B and A units, suggesting a very wide gap in age within the Hercynian period. This in turn led geologists to generate other nomenclatures to separate these sections. The Unayzah rocks are mostly alternating red beds with three sandstone reservoirs. Several depositional environments have been suggested for the Unayzah Formation. These include eolian dunes, meandering streams, incised valleys, deltas and parabolic and coastal plain deposits, and variations of the above. The Berwath Formation, however, is only known in the subsurface, and it has been suggested that the name be discarded. The Berwath rocks are similar to those of the Unayzah Formation. The Unayzah Formation in Saudi Arabia can be correlated with the Gharif and Al Khlata (Houshi group) in Oman and Faragan in Iran, while the Unayzah upper reservoirs (partly A and B) can be correlated with the Gharif Formation and the Unayzah C with the Al Khlata Formation. Debates on the nomenclature and correlation of the stratigraphic units of the Unayzah Formation continue. The Unayzah is one of the main Palaeozoic sweet gas reservoirs in Arabia.

The shallow marine sabkha carbonates and evaporites of the Khuff Formation unconformably overly the Unayzah Formation. The sequence starts with a basal shallow marine clastic unit. The Khuff reservoirs hold large volumes of gas in both Saudi and the Gulf states. The Khuff gas is usually sour due to its sulphur content, which increases northwards with increasing anhydrite. The Khuff reservoirs are normally dolomitized, with lenses of limestone. The reservoirs are heterogeneous, even though the main units are correlatable for long distances. The formation has undergone extensive diagenesis, including leaching, anhydrite cementation, and dissolution, that made it very hard to predict reservoir character. The Khuff Formation is equivalent to the Akhdar Formation of Oman. In the subsurface the Khuff has been divided into seven members: Khuff A, Khuff B, Khuff C, Khuff D, Khuff E, Northern Sandstone/Evaporate Member, and Southern Sandstone/Shale Member.

The Khuff Formation is overlain with local unconformities by the Sudair shale. This marks a change to a more restricted depositional environment from sabkha evaporites to terrestrial red beds. The Sudair Shale is followed by the Jilh Formation, which consists of interbedded sandstone, shale, limestone, anhydrite, and salt. It is often overpressured and hazardous to drill through. The formation has few oil shows in Arabia. The Jilh Formation is conformably overlain by the Minjur Formation (Upper Triassic), which consists mainly of sandstone and shale and is a very good aquifer for central Arabia. These rocks correlate with the lower part of the Sahtan unit in Oman.

Lower and Middle Jurassic Clastic/Carbonate Rocks (Toarcian to Callovian?)

Jurassic rocks are mainly marine shale interbedded with carbonates in central Arabia, grading to sandstone in northern and southern areas. These include the Marrat, Dhruma, and Tuwaiq Mountain Formations (**Figures 1 and 2**). The Marrat Formation unconformably overlies the Minjur Formation. The Jurassic system in central Arabia is dominated by the Tuwaiq Mountains escarpment in the outcrop with coral heads. Marrat and Dhruma are exposed in lower relief structures, marked by the red and green shales that alternate with resistant caps of yellowish limestone. These formations contain few oil reservoirs in Arabia.

The Lower and Upper Jurassic formation names have remained unchanged in Saudi Arabia, but other names have been introduced in other Gulf countries. For example, the Marrat Formation in Kuwait carries the same name, but the Tuwaiq Mountain Formation has been replaced by the Sargelo Formation.

Upper Jurassic and Early Lower Cretaceous Carbonate Rocks (Callovian through Valanginian)

The Upper Jurassic to Lower Cretaceous rocks are mostly cyclic carbonate sands and evaporites that close several stages of the Jurassic. These include the most important oil-bearing Arab formation in Arabia. The formation names are largely unchanged from the earliest days of research (**Figures 1 and 2**). The upper parts of the Tuwaiq Mountain Formation consist of mainly carbonate grainstone and packstone with corals and stromatoporoids, followed by the Hanifa Formation, which is composed of carbonate mudstone, wackestone, and grainstone. The Hanifa is the main source rock of the Jurassic oil of Arabia. This is overlain by the Jubaila Formation, which is composed of mainly mudstone and wacke- to packstone; the famous Arab D reservoir can extend to include the upper parts of the Jubaila.

The Jubaila is succeeded by the Arab Formation (**Figures 1 and 2**), the most famous oil reservoir in Arabia, especially the Arab D unit. The Arab Formation includes four members A, B, C, and D, each of which consists of a carbonate reservoir with an anhydrite cap rock. The reservoirs include alternating ooidal, skeletal, and peloidal grainstone, wackestone, and packstone containing *Cladocropsis*, stromatoporoids, and foraminiferans. They also include some mudstone. The facies indicate shallowing upward sequences from high-energy shoal, through intertidal flat, to supratidal sabkha (salt marsh) and subaqeous anhydrites (*see* **Sedimentary Environments:** Carbonate Shorelines and Shelves). The Arab D Member of the Arab Formation contains most of the oil reserves of the Ghawar Field, the largest oil field in the world, more than 250 km long and 50 km wide.

The Arab Formation is well known in the subsurface by cores and logs, but the outcrop is poorly known from small hilly exposures that show signs of anhydrite karst terrain near Riyadh (*see* **Sedimentary Processes:** Karst and Palaeokarst). The Arab Formation extends into the Gulf states with minor modifications. For example, in Qatar, it is divided into the Fahahil and Qatar formations. The Arab Formation extends into Abu Dhabi where the amount of anhydrite increases offshore. Major facies changes of the Arab Formation occur in Kuwait where the Jubaila and Arab formations of the Gotnia Basin are largely evaporites.

The Jurassic rocks of Yemen are very different yet again, consisting of sandstone and shale with minor carbonates. The Naifa and Hajar formations (Kimmeridgian-Tithonian) are similar to the Arab Formation further north.

In Saudi the Arab Formation is overlain by the Hith Formation, which consists mainly of anhydrite with minor carbonate reservoirs and crops out at Dahl Al-Hith in the Al-Kharj area near Riyadh; elsewhere it has generated karst terrane. The Hith is overlain by the Early Cretaceous Sulaiy Formation, which is composed of fossiliferous chalky limestone with wackestone and packstone, and is overlain in turn by the Yamama Formation (Berriasian-Valanginian) composed of bioclastic and pelletal grainstone, wacke to grainstone and mudstone (**Figures 1 and 2**).

Late Lower Cretaceous Clastic Rocks (Hauterivian through Aptian)

The Late Cretaceous marks a change from predominantly carbonate to terrigenous sedimentation. The sequence commences with the Buwaib Formation, which is a thin basal carbonate composed of mainly bioclastic grainstone and packstone that pass up into sandstone, overlain by sandstone and shale of the Biyadh Formation. This is truncated by an unconformity between the Aptian and Cenomanian stages. In Kuwait, however, the Buwaib and Biyadh Formations are grouped together as the Zubair Formation, while in Abu Dhabi and Oman the Yamama, Buwaib, and parts of the Biyadh Formations are termed the Lekhwair Formation. The Biyadh Formation is overlain by the Shu'aiba Formation (Aptian). This does not crop out at the surface, and like most formations, thickens eastwards from the shield to the shelf. The Shuaiba Formation contains many rudist 'reefs' which are important oil fields, such as the Shaybah field in the Rub Al-Khali (empty quarter) of Arabia and the Bu Hasa field in the United Arab Emirates (*see* **Sedimentary Environments:** Reefs ('Build-Ups')).

Middle Cretaceous Clastic Rocks (Cenomanian through Turonian?)

The Shuiaba Formation is overlain by deltaic sandstone and shale of the Albian–Turonian Wasia Formation (**Figures 1 and 2**). This crops out occasionally as low-lying hills. The Wasia Formation includes the Ahmadi, Moudoud, Khafji, and Safaniyah members in the northern parts of Arabia. The Safaniyah and Khafji members contain huge oil reservoirs in northern Saudi Arabia and Kuwait. In some of the Gulf states the Wasia Formation and its constituent members have been raised to group and formation status, respectively. In Kuwait its equivalent is the Burgan Formation. In Oman its equivalent is the Nahr Umr Formation, a predominantly shaley unit that serves as a source rock and seal to the underlying Shuaiba reservoirs.

Upper Cretaceous to Eocene Carbonate Rocks (Campanian through Lutetian)

Wasia sedimentation culminated in an important regional unconformity of Turonian age, overlain by some 500 m of limestone of the Aruma Formation (**Figures 1 and 2**) that crops out in an escarpment extending northwards from Arabia into Iraq. The Aruma Formation ranges in age from Turonian to Danian, and is composed mainly of carbonate rocks with some shale towards the base and increasing amounts of sand towards the north. It is equivalent to the Fiqa Formation in Oman.

The Aruma Formation is overlain unconformably by the Um er Radhuma Formation (Selandian–Ypresian), which is a highly porous and permeable dolomitic carbonate and an important aquifer in eastern Arabia. This formation is overlain by the Ypresian Rus Formation, which consists of interbedded marls, chalky limestone, gypsum, and anhydrite with quartz geodes. The gypsum and anhydrite usually dissolve to form collapse breccias that create drilling problems and also increase the salinity of adjacent aquifers. The

Rus Formation is overlain by the Dammam Formation, whose type locality is the famous Dammam Dome, on which was drilled the first well to discover oil in Saudi Arabia. This was Dammam well 7, which found oil in the Jurassic Arab Formation in 1933. The Dammam Formation consists of a number of members that include shale and carbonates, are locally reefal, and serve as local aquifers. The formation is truncated by an Eocene–Miocene unconformity.

Neogene Clastic Rocks (Miocene through Pliocene)

Sediments of Neogene age (Miocene–Pliocene) include the Hadrukh, Dam, Hofuf, Kharj, and Dibdibah formations (**Figures 1** and **2**). These comprise alternating limestone, chalky limestone, marly sandstone, gravel, and gypsum. The upper part consists of about 200–600 m of nonmarine marly sand and sandy limestone that crop out across the Rub Al-Khali (Empty Quarter) and northeastern Arabia. The Tertiary in Oman is represented by the Hadhramout and Fars groups.

All of the sediment above is locally covered by unconsolidated Quaternary sand and gravel, which is the major contributor to the Rub Al-Khali sand in southern Arabia, an area of about 600 km^2. These include both eolian dunes in the sand seas and vast plains of fluvial sand and gravel.

The Structural Geology of Arabia and the Gulf

As mentioned in the Introduction, Arabia consists of two main structural elements, the Precambrian shield of igneous and metamorphic rocks in the west, and the shelf whose sediment thickens eastwards towards the great mobile belt of the Taurus, Zagros, and Oman Mountains. The Arabian Plate (**Figure 3**) extends from the eastern Mediterranean to the greater part of Arabia (Arabian shield, Arabian platform, and Arabian Gulf), and the western Zagros Thrust Zone—an area enclosed by latitudes 13° and 38° N and longitudes 35° and 60° E. The natural boundaries of the Arabian Plate are most easily defined to the north and north-east, where the Taurus Mountains pass eastwards into the Zagros Fold Belt, which passes in turn eastwards into the Makran ranges. The structures of the Zagros can be traced into the northern Oman Mountains. The region is bounded to the south by the Owen Fracture Zone in the Indian Ocean and the Gulf of Aden Rift, and to the west by the rift system of the Red Sea and the Gulf of Aqaba and Dead Sea.

The area of the Arabian Plate is more than 3 000 000 km^2. Geologically nearly one-third of the area is composed of Neoproterozoic igneous and metamorphic rocks of the Arabian shield, of which, by far, the greatest part lies within western Saudi Arabia with minor inliers in Yemen. This shield was formed by the accretion of a series of Precambrian volcanic island arcs that can be traced into north-east Africa. The Arabian shield represents a fragment of Gondwana that separated as a result of the Phanerozoic tectonic events that were involved with the demise of the Palaeo-Tethys Ocean. Prior to breakup, Gondwana was an important source of widespread clastic sedimentation in the Palaeozoic (from Cambrian to Mid-Permian) and its spread over the platform/interior homocline. The main structural elements of the Arabian Plate are shown in **Figure 4**.

Sedimentary rocks were deposited over the Arabian Plate from Late Precambrian to Late Cenozoic as a result of a series of major tectonic phases. These began with an intracratonic phase (Late Precambrian to Mid-Permian), followed by a passive margin phase (Mesozoic), and concluded with an active margin phase (Cenozoic). During the Palaeozoic era much of the Arabian Plate lay south of the tropics, and was affected by glaciation in the Late Proterozoic, in the Late Ordovician and in the Carboniferous–Permian. It was dominated by the deposition of clastics, but interrupted by episodes of warm-water carbonate deposition in the Middle Cambrian, the Devonian, and the Upper Permian.

In contrast, during the Late Permian to the Holocene the area lay in subtropical and equatorial latitudes and was dominated by carbonate deposition.

The Arabian Plate experienced a number of events, including the rifting and sea-floor spreading of the Red Sea and Gulf of Aden, collision along the Zagros and Bitlis sutures, subduction along the Makran zone, and transform movement along the Dead Sea and Owen-Sheba fault zones. The Makran and Zagros convergence zones separate the Arabian Plate from the microplates of interior Iran.

The main structural elements in the Arabian platform contain several inherited, mechanically weak trends. These include:

1. North-trending highs as exemplified by the En Nala (Ghawar) anticline and the Qatar Arch;
2. The north-west-trending Mesozoic grabens of Azraq (Wadi Sirhan and Jauf) and Ma'rib; and
3. North-east-trending systems like the south Syria Platform and the Khleissia and Mosul trends.

These trends suggest that rejuvenation of basement discontinuities played an important role in the evolution of Arabia.

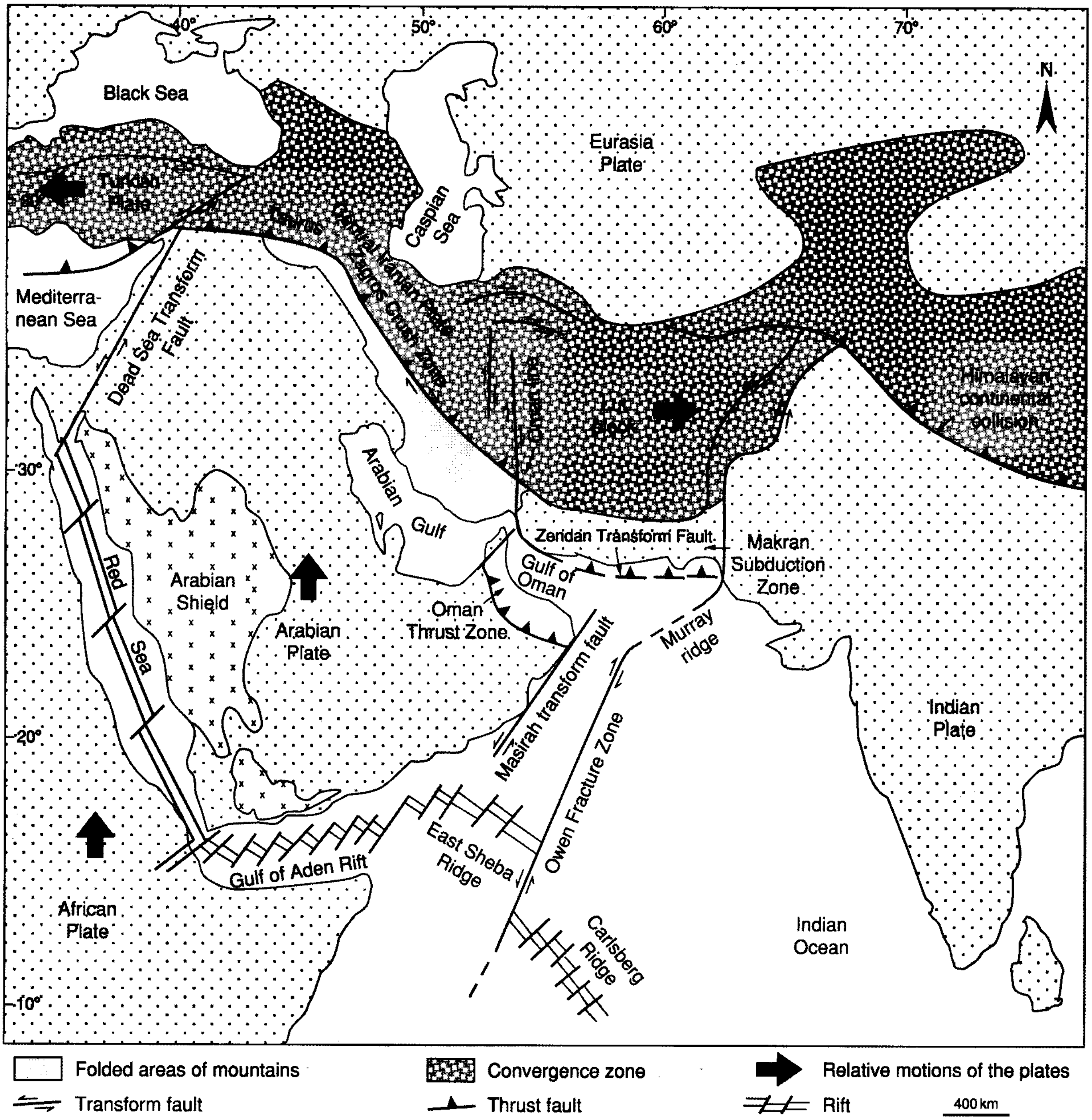

Figure 3 Tectonic setting of the Arabian Plate in relation to adjacent plates.

The Late Precambrian rocks of the Arabian Plate result from the accretion of a mosaic of terranes and ophiolitic sutures (dating to about 870–650 Ma) with later Neoproterozoic intrusions and depositional basins that together formed the basement of Arabia. The basement evolved and consolidated through the coalescence of several island-arc terranes over a long time span in the Proterozoic. Each closure and arc collision resulted in deformation and ophiolite obduction preserved as cryptic sutures.

Faulting in the Najd and the development of rift basins with thick salt sequences, including the salt basins of Oman and the Hormuz in the Arabian Gulf, occurred in the Late Precambrian to Early Cambrian (dated to about 610 to 520 Ma).

A Late Palaeozoic Orogeny is believed to have caused uplift and erosion over most of the Arabian Gulf and some parts of the Middle East Craton. Erosion related to this event tentatively dated as Early Carboniferous cut deeply into Cambrian and Precambrian strata. Following the earlier development of a carbonate shelf along the north and northwest margins in the Early to Middle Cambrian, the plate was covered by continental, deltaic, and

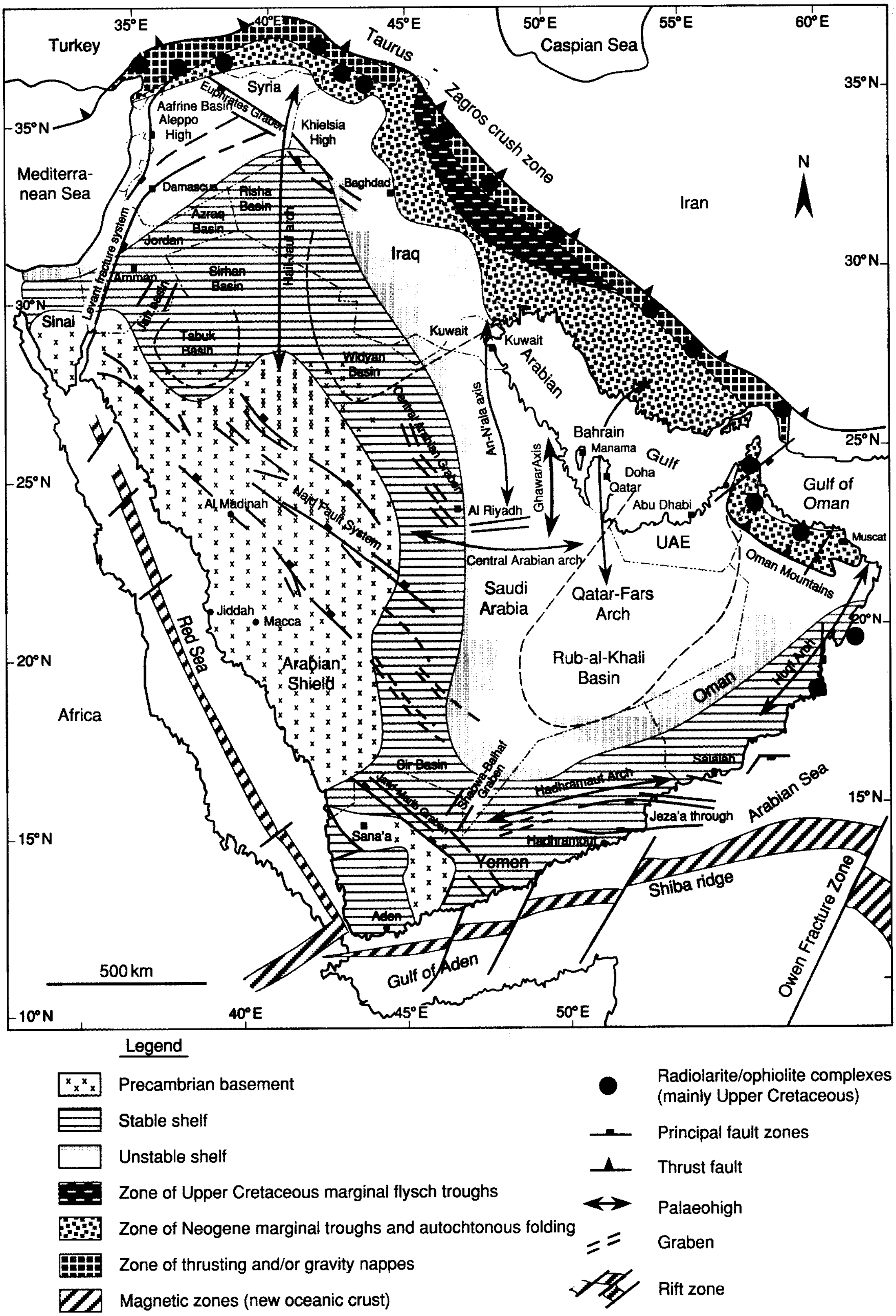

Figure 4 Main structural elements in the Arabian Plate. Reprinted with permission from Alsharhan and Nairn (1997) *Sedimentary Basins and Petroleum Geology of the Middle East.*

shallow-marine clastics. Carbonate deposition continued into the Early Ordovician on the Iranian terraces (**Figure 4**).

During the Late Ordovician and Early Silurian, the central and western parts of the Arabian Peninsula were covered by Saharan glaciers that advanced from the south pole, which was then located in African Gondwana. During this period, nondeposition, erosion, or marginal marine conditions prevailed in eastern and northern Arabia. Deglaciation in the Early Silurian led to a sharp sea-level rise, and the Palaeo-Tethys Ocean transgressed the Arabian and adjoining plates, depositing a thick, widespread, organic-rich shale directly over the glaciogenic and periglacial rocks of Arabia.

There is a general absence of Devonian deposits over the north-eastern Arabian shelf region with the exception of parts of north-eastern Iraq and locally in Oman, and the carbonate deposition reflects a return to lower latitudes. In the Late Devonian to Early Carboniferous the onset of south-west-directed subduction along the former passive margin initiated a phase of back-arc rifting and volcanism. Lower Carboniferous carbonates occur in northern Iraq, but elsewhere the Carboniferous is largely missing, reflecting regional emergence, nondeposition, or erosion.

Following the Hercynian orogeny in Late Carboniferous to Late Permian times the Central Arabian Arch developed as a nondepositional uplift, and the Rub Al Khali became a large nonmarine intracratonic basin. In south and south-east Arabia uplifted areas developed in the Hadhramaut–Huqf and in the vicinity of the present Oman Mountains.

Glaciation occurred in Oman, southern Saudi Arabia, and Yemen, and periglacial and fluviatile conditions existed in central Arabia. In Oman and Yemen tillites rest directly on a glacially striated Precambrian basement.

During the deposition of the Permo-Triassic sequence, back-arc rifting continued at the northern end of the Arabian Plate, and the new north-east passive margin was transgressed by a shallow Permian sea from which was deposited carbonates and evaporates, thickness variations of which indicate syndepositional tectonic activity. Over Arabia the thickness is almost uniform, ranging between 300 and 600 m, but thickens dramatically to more than 1200 m east- and southwards. The main depocentres for the Late Permian carbonates trend approximately north-west–south-east, parallel to the axes of the opening Neo-Tethyan and Hawasina oceans in Oman. There is a general thickening towards the north-east Arabian Gulf and Gulf of Oman and Iran.

A major period of Late Triassic uplift and erosion affected the southern part of the Arabian Gulf and led to the progradation of continental clastic sediment across the southern Arabian Gulf region.

In the Early Jurassic progressive back-arc rifting in the eastern Mediterranean led to the development of a new northern passive margin. During the Jurassic era rift basins in Syria and south-east Yemen were active, and intrashelf basins in the south-western Arabian Gulf, eastern Saudi Arabia, and southern Iraq–Kuwait were well developed. These intrashelf basins formed the main source and reservoir rocks for the large reserves of oil in Arabia.

The Neo-Tethys spreading ridge continued migrating north-eastwards and progressively subducted under Eurasia. This Early Cretaceous sedimentation is dominated by a carbonate sequence related to major flooding of the Arabian Peninsula.

The onset of Late Cretaceous thrusting in the Oman Mountains marks a distinctive change in the pattern of the basin subsidence, and represents the main phase of thrust tectonics in south-east Arabia. The Late Cretaceous thrusting during the closure of the Neo-Tethys is directly related to the change in plate translation (from a south-west to north-east direction) in response to the opening of the South Atlantic Ocean.

Significant and widespread breaks in sedimentation occurred across the Arabian Gulf region in Late Cenomanian and Turonian times. These stratigraphic breaks correspond to major tectonic events in eastern Arabia. In the Late Cretaceous the obduction of a series of ophiolites along the Neo-Tethys margin led to reactivation of some of the basement features in Arabia and localized basin inversions in Syria.

The end of the Cretaceous was marked by a regional unconformity which resulted in the Late Maastrichtian and Danian sediments being absent over most of the Arabian Plate. During the Early Cenozoic subduction of the Neo-Tethys beneath the Sanandaj–Sirjan Terrane along the northern margin of the Neo-Tethys caused the ocean basin to close, a process assisted by the initiation of rifting and opening of the Red Sea. The Late Paleocene–Eocene consists of predominantly shallow marine carbonates and evaporites. The onset of collision between the Arabian and Eurasian continents, which commenced in the Late Eocene, initiated the Zagros orogeny by suturing the Arabian and Eurasian plates. The collision created the Zagros foreland basin on the outer edge of the north-eastern Arabian shelf margin during the final closure of the Neo-Tethys.

Coeval with the Late Alpine Orogeny in Europe, the Neogene was a time of maximum compression between Arabia and Asia. 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.

Economic Geology

The Precambrian basement rocks of Arabia contain a range of mineral deposits, notably gold, anciently mined in the Yemen. Important phosphate deposits occur in a belt that extends from Syria, through Jordan, and along the Palaeo-Tethyan shoreline into Egypt and across the Sahara to the Atlantic Ocean. These are found in Late Cretaceous and Eocene limestone (*see* **Sedimentary Rocks:** Phosphates). A range of evaporite minerals occurs in the Cambrian Hormuz salt, and in modern sabkhas of the Gulf coast, where magnesite occurs in significant quantities (*see* **Sedimentary Rocks:** Evaporites).

It is, of course, for its petroleum reserves that Arabia and the Gulf are best known. This basin is the largest petroleum province in the world. Various figures have been calculated for its reserves, but it is generally agreed (figures vary in time and with author) that it contains some 700×10^9 BOE (barrels of oil equivalent). This is about 40% of the world's petroleum reserves (*see* **Petroleum Geology:** Reserves). Petroleum is produced from reservoirs throughout the stratigraphic column. As a generalizations deep gas comes from Palaeozoic sandstones, and oil from Mesozoic carbonates. Petroleum source beds range from Infracambrian to Cretaceous. Petroleum entrapment is largely stratigraphic, occurring in truncated or onlapped sandstone, and in reefal or shoal carbonate, within which diagenesis in general, and dolomitization in particular, has often played an important part in controlling reservoir quality.

See Also

Africa: Pan-African Orogeny; North African Phanerozoic; Rift Valley. **Petroleum Geology:** Reserves. **Sedimentary Environments:** Carbonate Shorelines and Shelves; Deserts; Reefs ('Build-Ups'). **Sedimentary Rocks:** Dolomites; Limestones; Phosphates. **Shields**.

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