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Chapter R2

REGION 2 ASSESSMENT SUMMARY—MIDDLE EAST AND NORTH AFRICA

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Loosveld and others (1996).

Figure R2-3. -- Generalized paleolatitude curve for Oman and southeastern Arabian Peninsula from Precambrian to Tertiary showing major glaciation stages illustrating and the affect of latitude on depositional facies. Modified from Beydoun (1991). MYBP, million years before present; TRIAS., Triassic; SILUR., Silurian.

Figure R2-4.--Generalized outline of the three major intrashelf sub-basins formed during the Late Jurassic on the eastern Arabian sub-continent that were centers for basinal, organic-rich source rocks. Modified from Murris (1980) and Alsharhan and Kendall (1986).

INTRODUCTION

The major landmasses of the world and the offshore areas (most to 2,000-m water depths) were divided into 937 geologic provinces and ranked by known petroleum volume (Klett and others, 1997). Ninety-five percent of the known petroleum volume was found to exist in 76 provinces exclusive of the U.S, and they were designated as priority provinces for resource assessment. Other provinces, designated as boutique, also were examined because of perceived viable future petroleum resource. Total Petroleum Systems (TPS) and their subdivisions, Assessment Units (AU), were defined for each priority and boutique province to evaluate undiscovered petroleum resource potential.

Sixteen of the 76 priority provinces are in Region 2 (Middle East and North Africa), and they contribute about 44 percent of the world's total known petroleum volume, with more than 90 percent of that volume from eleven Middle East provinces within or adjacent to the Arabian Peninsula (table R2-1). Descriptions of the USGS Middle East provinces (fig. R2-1) are in Pollastro, Karshbaum and Viger (1999), Pollastro, Persits, and Steinshower (1999) and Persits and others (1997). Region 2 priority provinces are listed in table R2-1, along with their ranking relative to other provinces and their percent contribution to the world's total known petroleum volume, exclusive of the U.S. Thirty-one geologic provinces from Region 2 contained AU that were quantitatively assessed for the USGS World Petroleum Assessment 2000, and they are shown on figure R2-1.

Region 2, Middle East and North Africa, contributes 764.7 billion barrels of oil (BBO) (58 percent) of the total 1326.4 of known oil volume for the 76 priority provinces, of which 706.3 BBO (53 percent of the total) is exclusively from provinces in the Middle East (Klett and others, 1997). Region 2 makes an enormous contribution to the world's known volume, and is estimated to contain the major volume of the world's undiscovered petroleum. This assessment benefited from discussions with members of the World Energy Consortium (AK) and from utilization of proprietary databases and supporting projects, which included USGS petroleum migration modeling studies. USGS staff also met with national oil companies of the region and private consultants and experts from private industry.

TOTAL PETROLEUM SYSTEMS AND ASSESSMENT UNITS

Middle East—Eastern Arabian Subcontinent

Overview

An estimated two-thirds of the world's ultimately recoverable oil is in the Arabian-Persian Gulf Region and in the Greater Arabian and Greater Oman Basins (Beydoun, 1991; Cole Carrigan, and others, 1994; Cole, Abu-Ali and others, 1994; Alsharhan and Nairn, 1997). Most oil is generated and produced from Jurassic carbonates; however, Cretaceous, Paleozoic, and Infracambrian petroleum systems account for production in numerous giant oil fields in reservoirs of equivalent age. This area of the Middle East is rich in petroleum because it comprised an areally extensive depositional platform along a pre-Mesozoic passive margin of Gondwana. Subsequent development of intraplatform basins, extensive source-rock deposition within these basins, and multiple tectonic stages of compression and extension, produced large subtle structural closures coincident with peak oil generation and migration. Moreover, the large resource base was secured by efficient horizontal hydrocarbon migration into traps underlying thick, regionally extensive evaporite seals.

Four, overlapping mega-TPS are identified in eight of the priority provinces located on the eastern half of the Arabian Peninsula. This locale encompasses the area east of the Arabian Shield, along the Arabian-Persian Gulf, eastward to the Zagros Fold Belt and Oman Mountains and in eastern Saudi Arabia, Kuwait, Qatar, United Arab Emirates, Oman, Yemen, and Iran. Combined, this region comprises the Greater Arabian and Greater Oman Basins. The four major TPS of this area are of

Infracambrian, Paleozoic, Jurassic, and Cretaceous age. Geographically extensive source, reservoir, and seal rocks characterize each of these prolific hydrocarbon-producing systems.

The Infracambrian TPS is geographically centered in major subsiding rift salt basins that formed during Infracambrian and Early Cambrian time (Gorin and others, 1982; Husseini and Husseini, 1990; Mattes and Conway-Morris, 1990). Oterdoom and others (1999) report that, in Oman, this rifting period is represented by the Infracambrian Huqf Supergroup that was deposited between about 570 and 530 Ma. These rift salt basins formed by extension from left-lateral, strike-slip (rifting and wrenching) movement of the Najd transform fault system (fig. R2-2), which ultimately moved the Arabian plate with a cumulative strike-slip component some 300 km eastward (Schmidt and others, 1979; Loosveld and others, 1996; Oterdoom and others, 1999). The rift salt basins are approximately perpendicular to the Najd Fault Zone and the orogenic collision front and are related to escape tectonsim (Molnar and Tapponier, 1975; Stern, 1994).

In the eastern Arabian subcontinent, these Infracambrian rift salt basins include, but are not restricted to, the North and South Gulf (Hormuz) Salt Basins of the Arabian-Persian Gulf and the Ghaba, Fahud, and South Oman (Ara) Salt Basins of Oman (fig. R2-2). Smaller-scale Infracambrian rift basins of similar origin and sedimentary fill recently have been recognized on seismic profiles in the central and eastern portion of the Rub ‘al Khali Basin and along the main Najd fault trend (Dyer and Husseini, 1991; Faqira and Al-Hawuaj, 1998; Blood, 2000) (fig. R2-2).

The sedimentary section of these Infracambrian, rift salt basins includes rocks ranging from Proterozoic to Recent age (Hughes-Clarke, 1988; Droste, 1997). In the type section of Oman, clastic rocks compose most of the lower Paleozoic part of the section, whereas Permian through Tertiary rocks (fig. R2-3) are predominantly carbonate and reflect climatic variations due to the changing paleolatitude of the Arabian plate through geologic time (Beydoun, 1991). In the northern part of the

Arabian Peninsula in Kuwait, Saudi Arabia, and Iraq, significant clastic deltaic systems prograded northeasterly from the Arabian Shield, resulting in major reservoirs in the Lower Cretaceous (Barremian-Aptian) Zubair Formation and the Middle Cretaceous (Albian) Burgan Formation. In the uppermost part of the stratigraphic section along the Arabian-Persian Gulf, Middle Cretaceous clastic deposits are replaced by carbonates because of sea level fluctuations in the Zagros foredeep as the Zagros Mountains rose.

Outside the rift basins, basement structures beneath the Greater Arabian Basin have substantially controlled sediment deposition and subsequent structural growth. Several north-south trending anticlinal axes, especially Ghawar, reflect this primary structural grain (fig. R2-4) inherited from east-west compressional movements associated with microplate island-arc accretion during the Late Precambrian Idsas Orogeny about 680 Ma (Loosveld and others, 1996; Wender and others, 1998; Oterdoom and others, 1999). A secondary northwest-southeast structural element is related to, and parallel to, the Najd wrench-fault system, which formed the Infracambrian rift basins and controlled later Mesozoic deposition in Yemen and elsewhere. Major episodic tectonic events, particularly the Carboniferous Hercynian Orogeny, Triassic Zagros rifting, and the First (Cretaceous) and Second (Tertiary) Alpine Events that formed the Oman Mountains and foredeep (Wender and others, 1997), reactivated basement structures and promoted halokinesis. The timing and movement of these distinct, multiple tectonic stages controlled sediment deposition and created numerous, subtle, structural undulations ideal for trapping large accumulations of hydrocarbons.

Infracambrian TPS

The Infracambrian TPS is sourced within the Huqf Supergroup, the type section of which is in Oman (Hughes-Clark, 1988; Edgell, 1991). The Huqf Supergroup contains multiple carbonate and shale source rocks of exceptional quality. Pollastro (1999) identified two Huqf petroleum subsystems in North Oman for the assessment of the Ghaba Salt Basin (2014) and Fahud Salt Basin (2016) provinces. A more general 'North Oman Huqf'-type oil is dominant in the Fahud Salt Basin. Oils in the Ghaba Salt Basin are linked to at least two distinct Huqf source-rock units based on oil geochemistry, a general North Oman Huqf-type source and a more dominant 'questionable unidentified-source' or 'Q'-type Huqf source (Grantham and others, 1988, 1990; Al-Ruwehy and Frewin, 1998). These Huqf-sourced oils are commonly found mixed in reservoirs throughout north-central Oman.

The characteristics of the giant Oman Huqf system, as well as reports of rift systems in the Oman and Saudi Arabian portions of the Rub 'al Khali Basin (Dyer and Husseini, 1991; Faqira and Al-Hawuaj, 1998; Blood, 2000), support the hypothetical extensions of a similar Infracambrian TPS westward in the Rub' al Khali Basin Province (2019). In this study, a hypothetical Infracambrian TPS in the Rub' al Khali Basin was assessed with the Silurian-Paleozoic TPS (201903).

The Cambrian Ara Formation is a carbonate-evaporite sequence with salt as thick as 1,000 m. Ara evaporites were deposited in geographically restricted basins during periods of low relative sea level where stratified, anoxic conditions periodically prevailed and organic-rich sediments and salt were deposited (Mattes and Conway-Morris, 1990; Edgell, 1991). Hydrocarbons generated from Huqf sources in the Ghaba and Fahud Salt Basins are produced from a variety of reservoir types and ages ranging from Precambrian to Cretaceous. The North Oman Huqf/'Q'-Haushi TPS (201401) and Ghaba-Makarem Combined Structural AU (20140101) were identified for the Ghaba Salt Basin Province. The main oil reservoirs are clastics of the Permian-Carboniferous Haushi Group (Gharif and Al-Khlata Formations). A North Oman Huqf -- Shu'aiba TPS (201601) and Fahud-Huqf Combined Structural AU (20160101) were defined for the Fahud Salt Basin Province. Here, the Lower Cretaceous Shu'aiba and Middle Cretaceous Natih limestones account for most of the production. In both Huqf TPS and AU units, deep gas is produced mainly from Middle Cambrian to Lower Ordovician clastic reservoirs of the Haima Supergroup. Traps in nearly all hydrocarbon accumulations of these TPS are mainly structural and were formed by one or more mechanisms, thus the term “combined structural” is used in the AU name.

Paleozoic TPS

The Paleozoic TPS is comprised of a regionally extensive, Silurian source facies that can be locally partitioned into subsystems along a north-south trend across the eastern Arabian subcontinent (Husseini, 1991; Mahmoud and others, 1992; Jones and Stump, 1999). In addition, names of the subsystems were determined by the equivalent local (country) formation names. Early Silurian deglaciation resulted in a major sea level rise and the widespread deposition of the upward-coarsening, progradational Qalibah Formation. The Qalibah Formation consists of a lower Qusaiba Shale Member and upper sandstones, siltstones, and shale of the Sharawra Member. The base of the Qusaiba Member contains regionally correlative, organic-rich shale with a distinctive high gamma-ray signal on geophysical logs; this high gamma-ray interval is generally referred to as the “hot shale” (Abu-Ali and others, 1991; Milner, 1998; Jones and Stump, 1999). The organic-rich hot shale was deposited in a broad, anoxic, marine shelf environment of Gondwana, which included the greater part of present Arabia and North Africa (Beydoun, 1991; Husseini, 1991; Mahmoud and others, 1992; McGillivray and Husseini, 1992).

The Lower Silurian, basal hot shale is a dark-gray to black, euxinic shale as thick as about 75 m and with as much as 8 weight percent TOC. The hot shale averages 3 to 4 weight percent TOC in Saudi Arabia (Cole, Abu-Ali, and others, 1994; Jones and Stump, 1999) and 6 weight percent in Iraq (Aqrawi, 1998) and is considered the principal source rock for hydrocarbons of the Silurian-Paleozoic petroleum system throughout the Arabian Platform and Zagros Fold Belt (Bishop, 1995; Cole, Abu-Ali, and others, 1994; Jones and Stump, 1999). Locally, the Qusaiba Member is absent due to uplift and erosion during the Late Devonian to Carboniferous Hercynian Orogeny. Qusaiba absence is particularly evident in central Saudi Arabia along the Central Arabian Arch and Arabian Shield, and along the eastern flank of the Rub’ al Khali Basin in western Oman and Yemen; thus, the Paleozoic TPS was subdivided here into four regional TPS reflecting the influence of the Central Arabian Arch and Arabian sub-basins.

In the northeastern Arabian Plate and within the Widyan Basin-Interior Platform Province (2023) and the Mesopotamian Foredeep Basin Province (2024) of Iraq, Syria, and Jordan, the Lower Silurian "hot shale" is about 65 m thick. The Qalibah Formation of Saudi Arabia is referred to as the Akkas Formation in Iraq, the Mudawwara Shale in Jordan, and the Tanf Formation in Syria (Aqrawi, 1998). In the subsurface of Saudi Arabia, the organic-rich hot shale rarely exceeds 50 m and is usually about 9 to 31 m thick (Jones and Stump, 1999).

For the current USGS assessment of the Arabian subcontinent portion, three separate Paleozoic subsystems are described to more accurately represent local variations in the more regional-extensive, Paleozoic TPS. A northern subsystem, designated as the Paleozoic Qusaiba/Akkas/Abba/Mudawarra TPS (202301), encompasses the area in Saudi Arabia north of the Central Arabian Arch and Hercynian unconformity, the western and southwestern deserts of Iraq, and eastern portions of Syria and Jordon. In this area, super-light, high (43°-56°) API gravity, low-sulfur crude oil and natural gas occur in north-trending, block-faulted anticlines that formed over reactivated basement blocks (Horst/Graben-Related Oil and Gas AU (20230101). In this area, highly mature hydrocarbons migrated vertically along basement-rooted faults and fracture zones in structures into fluvial and eolian, quartzose sandstones of the Carboniferous to Early Permian Unayzah Formation. In Iraq, high gravity oils and sweet gas are produced from sandstones of the Ordovician upper Khabour and Silurian Akkas Formations.

In Saudi Arabia and Qatar, a second Paleozoic subsystem is recognized centered on the Greater Ghawar Province (2021) and designated as the Central Arabia Qusaiba Paleozoic TPS (202101). While covering all the Greater Ghawar Uplift Province, the Central Arabia Qusaiba-Paleozoic subsystem extends over just the central part of the Interior Homocline-Central Arch (2020), the western flank of the Qatar Arch

(2022), the northern edge of the Rub ‘al Khali Basin (2019) and the southeasternmost parts of the Widyan Basin-Interior Platform (2023) and Mesopotamian Foredeep Basin (2024) Provinces. The western boundary of the Central Arabia Qusaiba Paleozoic TPS (202101) is defined by the absence of the Qusaiba source rock due to Hercynian uplift and erosion (Bishop, 1995; Milner, 1998; Jones and Stump, 1999). In Central Arabia, this subsystem is divided into two AU. A southern, onshore unit is referred to as the Central Arch Horst-Block Anticlinal Oil and Gas AU (20210101). A primary north-south structural grain characterizes this AU where anticlines formed by draping of sediments over reactivated basement horst blocks. Sourced by the basal hot shale of the Qusaiba Formation, light sweet oils with high (44°-52°) API gravities are produced in the Central Arabian fields along the western edge of the AU. Production is from alluvial and (or) fluvial sandstones of the Lower Permian Unayzah Formation and shallow marine shelf sandstones of the Devonian Jauf Formation; some production is also from Ordovician sandstones. The primary regional seal combines basal shales, low permeability (“tight”) carbonates, and anhydrite of the Permian Khuff Formation. These oils migrated westward and updip from a more thermally mature eastern source area. Gas is also produced in several fields throughout the AU.

A second AU in the Central Arabia Qusaiba-Paleozoic TPS, designated as the North Gulf Salt Basin Structural Gas AU (20210102), encompasses the area in the northeast half of the TPS that is underlain by the Hormuz Salt. This AU is mostly offshore in USGS Province 2023 (Mesopotamian Foredeep). Structures are mainly domes over salt diapirs and salt-assisted or -enhanced horst-block anticlines. Here, the Qusaiba basal hot shale is mostly in the main gas generation window. Reservoirs are the cyclic dolomitic shelf carbonates of the Late Permian Khuff Formation, with production controlled mainly by distribution and amount of anhydrite. Some fields produce sour gas.

The third Paleozoic TPS is recognized for the greater Rub ‘al Khali Basin Province (2019) and is designated the Silurian Qusaiba TPS (201903). In this TPS, two AU are specified. The Khuff Carbonates in Salt Structures AU (20190301) encompasses the northeastern Rub' al Khali Basin where shelf carbonates of the Upper Permian Khuff Formation are the predominant reservoirs in salt-related structures of the Infracambrian Hormuz Salt Basin. Source rocks are "hot shales" of the basal Qusaiba Member of the Lower Silurian Qalibah Formation, which occurs throughout the Rub al Khali Basin. Qusaiba mudstones in this AU have passed through the zone of oil generation and are in the zone of dry gas generation throughout much of the area (Milner, 1998; Jones and Stump, 1999). Migration of Qusaiba hydrocarbons in this AU was mainly from an easterly direction, up regional dip and into the crestal portion of the Qatar Arch, forming the supergiant North and South Pars fields. Vertical migration occurred along the flanks of numerous salt structures. Reservoirs are mainly shelf carbonate grainstones and reef carbonates of the Upper Permian Khuff Formation. Traps are mainly structural and are related to salt domes and other salt structures in the Infracambrian Hormuz Salt Basin, which encompasses this area of the southern Arabian Gulf. Seals are predominantly anhydrites within the Permian Khuff interval.

The Paleozoic Reservoirs AU (20190302) encompasses most of the Rub' al Khali Basin in Saudi Arabia, and along its eastern flank in parts of Oman and Yemen. Here, structures are related to extensive regional wrench fault systems and faults related to salt structures. Qusaiba mudstones in this AU are in the zone of dry gas generation over much of the central part of the basin, but are in the oil and wet gas generation zone along the western, southern and eastern basin margins. Migration of Qusaiba hydrocarbons is considered to be mainly vertical in basement-involved structures in the central part of the basin, and moderate- to long-distance lateral migration is inferred along the basin margins with Unayzah sandstones as the major carrier beds. Reservoir rocks are mainly alluvial, fluvial, and eolian sandstones of the Permian Unayzah Formation and the basal Khuff Formation (Al-Jallal, 1995; Evans and others, 1997). Potential reservoirs might also occur in fluvial and deltaic sandstones of the Cambro-Ordovician section. Porosity in Unayzah sandstones is as high as 30 percent and permeabilities are as high as 4 darcies. Traps range from stratigraphic and structural traps along the margins of the basin to structural traps related to major basin-wide fault systems in the central part of the basin. Seals are mainly anhydrites of the Khuff Formation, but seal quality may degrade to the south along the basin margin.

In Iran and within the Zagros Fold Belt, the Paleozoic-Permian/Triassic TPS (203002) with the Northern Qatar Arch Extension AU (20300201) was designated to include an area that sources the giant and supergiant gas fields of Pars, Kangan, Nar, Aghar, Banubast, Dalan, Asaluyeh, Dhanul, and Varavi. The speculative gas source is deep Silurian shales of the Qusaiba or equivalent in the Zagros foreland, although some consideration is given to a possible Permian source rock. Reservoirs are Upper Permian (Dalan Formation) and Lower Triassic (Kangan Formation) dolomites, dolomitic limestones, and oolitic limestones. The Qatar Arch is the primary regional structure that contributes to hydrocarbon charge in the AU. Anhydrite of the Permian-Triassic Khuff Formation is the primary regional seal in this area.

Jurassic TPS

Passive margin conditions along the Arabian Plate during the Jurassic through Late Cretaceous Periods produced a broad, stable shelf environment. Flooding of this platform in warm equatorial latitudes allowed for continued deposition of shallow-marine carbonates over the Greater Arabian Basin (Murris, 1980; Al-Husseini, 1997). In particular, Jurassic geologic conditions of the Arabian subcontinent resulted in deposition of the following ideal sequence of primary petroleum system elements: thick oil-prone source rocks, extensive reservoir facies, and excellent seals. Widespread Early and Middle Jurassic marine transgression deposited a thick sequence of shallow-marine shelf carbonates and platform evaporites. Late Jurassic (Oxfordian and early Kimmeridgian) differential subsidence and sea level rise resulted in the formation of broad, intrashelf sub-basins (fig. R2-4). These intra-shelf sub-basins were depocenters for the main Jurassic source rocks (Upper Jurassic Hanifa and equivalents), as well as several important reservoirs. Three primary depocenters, the northern Gotnia Sub-basin, the central Arabian sub-basin, and southeastern South Arabian Gulf sub-basin (fig. R2-4), define the major Jurassic petroleum systems of the eastern Arabian subcontinent and also include the dominant petroleum system in Yemen.

Late Jurassic (Tithonian) eustatic variations of the Arabian platform resulted in deposition of carbonate-anhydrite cycles that constitute the dominant reservoirs and caprocks (Arab Formation carbonates and Arab Formation and Hith Formation evaporite seal rocks). Late Tithonian evaporitic conditions on a vast platform produced the Hith anhydrite and formed inland salt lakes in the western Rub 'al Khali and Gotnia Basins (Al-Husseini, 1997). Significant loss of hydrocarbons generated within these petroleum systems was prevented by the regionally extensive, overlying evaporite seals; thus, only limited vertical migration occurred. In the northernmost Arabian Gulf, and sourced within the Jurassic Gotnia sub-basin, oil and gas accumulated in Middle to Upper Jurassic, high-energy calcarenites and oolites of bar or shelf-margin origin. These reservoirs are cyclic and interbedded with organic-rich (2 to 5 weight percent TOC), muddy lime source rocks that were deposited under anoxic and dysoxic conditions in the restricted, intrashelf Gotnia sub-basin (fig. R2-4). The Gotnia/Barsarin/Sargelu/Najmah TPS (202302) is identified in the northern area and consists of the following two AU: (1) the proven Platform Horst/Graben-Related Oil AU (20230201) and (2) the hypothetical Basinal Oil and Gas AU (20230202) .

Encompassing the entire Greater Ghawar Uplift Province (2021) and the southern part of the Mesopotamian Foredeep Basin Province (2024) in the North Arabian Gulf Region, the current USGS assessment designates the Arabian Sub-Basin Tuwaiq/Hanifa-Arab TPS (202102). This TPS includes Ghawar field, the world's largest oil field, as well as several other supergiant oil fields of the North Gulf region, such as Berri, Abqaiq, Abu Sa'fah, Khurais, Khursaniyah, and Dukkan. In this area, the Tuwaiq Mountain Formation is the primary source rock where it reaches about 150 m in thickness and averages about 3.5 weight percent TOC. The Hanifa

Formation also sources the system, forming the “Tuwaiq/Hanifa Superfamily” of oils (Cole, Abu-Ali, and others, 1994). In central Arabia, the Hanifa source rock is less than 30 m thick and averages about 2.6 weight percent TOC; however, the Hanifa is the primary Jurassic source rock southward and eastward in the Greater Rub’ al Khali Basin.

The primary reservoirs are 10- to 30-m thick, cyclic shallow-water, platform carbonate grainstones of the Upper Jurassic Arab Formation (Arab A, B, C, D). Arab D is the primary reservoir with an average porosity of about 25 percent. A latest Jurassic restricted-shelf, evaporitic environment resulted in the deposition of the regionally extensive, massive Hith Formation evaporite, which forms the primary regional seal for the Jurassic TPS.

Two AU are described for the Arabian Sub-Basin Tuwaiq/Hanifa-Arab TPS. A Horst-Block Anticlinal Oil AU (20210201) encompasses the onshore portion of the petroleum system and is characterized by a primary north-south structural grain formed by basement fault blocks from island arc accretion (Precambrian Idsas Orogeny). It includes the Ghawar and Abqaiq fields. Anticlines formed by sediments draping over horst blocks that subsequently moved upwards. A second AU, the Salt-Involved Structural Oil AU (20210202), encompasses the northern half of the TPS that is underlain by the Hormuz Salt and where halokinetic structures are the primary traps (that is, salt domes, diapirs, and salt-assisted or enhanced horst-block anticlines).

The Jurassic Hanifa/Diyab-Arab TPS (201902) is designated for the Rub’ al Khali Basin Province (2019) of Saudi Arabia, U.A.E., Qatar, eastern Oman, and northeastern Yemen. Here, Jurassic reservoirs were assessed separately, recognizing possible overlap with Cretaceous, Paleozoic, and a hypothetical Infracambrian TPS. In the Jurassic Hanifa/Diyab-Arab TPS, the organic-rich, argillaceous limestone facies of the Upper Jurassic Hanifa Formation (formally the Diyab Formation in U.A.E.) is the primary source rock. The regionally extensive, Upper Jurassic Arab

Formation cyclic carbonate rocks are the primary reservoirs. Intraformational, cyclic, Arab and overlying Hith Formation evaporites form the seals.

Similar to the central Jurassic Tuwaiq/Hanifa TPS of the North Gulf-Central Arch area, two AU are described here in the southern Arabian Gulf and Rub' al Khali Basin area, based on the structural trapping types and extent of underlying Infracambrian salt. The Jurassic Reservoirs in Northwest Desert Anticlines AU (20190201) extends into the central Rub 'al Khali Desert and incorporates a limited number of known oil and gas fields. The Hanifa source rock is in the zone of gas generation over a large areal portion of this AU and adjacent to Kudan North and Kudan South fields, which produce Jurassic gas. The Jurassic Reservoirs in South Gulf Suprasalt/Qatar Arch Structural AU (20190202) is designated for the portion of the TPS that is underlain by the Hormuz Salt. In this suprasalt structural AU, giant fields such as Umm Shaif, Nasr, and Ghasha produce Jurassic oils from Upper Jurassic Arab carbonate rocks in salt-related structures.

Cretaceous TPS

Cretaceous rocks of the Greater Arabian Basin incorporate several TPS along the eastern portion of the Arabian subcontinent (Christian, 1997). Along the Zagros Fold Belt Province (2030), bordering the eastern edge of the Arabian subcontinent, Cretaceous carbonate and clastic rocks produce within the Zagros fold system and foreland. The Zagros Mesopotamian Cretaceous-Tertiary TPS (203001) is designated for this region, and it has been separated into AU on the basis of the following reservoir ages: (1) Cretaceous Reservoirs AU (20300101) and (2) Tertiary Reservoirs AU (20300102). Although both AU produce from carbonate and clastic rock reservoirs, the Cretaceous Reservoirs AU is dominated by clastic rocks (deltaic), and the Tertiary Reservoirs AU is dominated by rocks formed in carbonate bank, shoal, and reefal deposits. The deltaic deposits of the Lower Cretaceous Zubair and Middle Cretaceous Burgan Formations are the main reservoirs in many fields in Kuwait and Iraq. For example, the second largest oil field in the world, Burgan, produces from these Cretaceous deltaic reservoirs, as do many surrounding giant oil fields in the northern Arabian Peninsula.

Several Cretaceous source-rock intervals are recognized in the Zagros Mesopotamian Cretaceous-Tertiary TPS. Most source rocks in the TPS are shales of Early Cretaceous age, including beds in the Sulaiy and Minagish Formations of Kuwait, the Ratawi Shale, and the Zubair Formation of the North Arabian Gulf region. Carbonate source rocks of the Shu'aiba Formation also provide hydrocarbons for much of the Arabian Gulf region. The middle Cretaceous Burgan (Nahr Umr), Mauddud, Rumaila and Mishrif Formations are also important source rocks in the Zagros Fold Belt and foreland basin areas. Peak generation occurred in Middle Miocene time. This timing is coincident with Zagros collision and a thick accumulation of orogenic clastics in the Zagros foredeep. The middle Cretaceous Nahr Umr Shale is a major regional seal for Cretaceous reservoirs; whereas, Eocene and Miocene salt and evaporite beds are primary seals for Tertiary reservoirs in the Zagros Fold Belt.

The Cretaceous Thamama/Wasia TPS (201901) is designated for the southern Arabian Gulf region and within the Rub' al Khali Basin Province (2019); this system also extends into a small southeast portion of the Qatar Arch Province (2022). Similar to the Hanifa/Diyab-Arab TPS of the Rub 'al Khali Province, Cretaceous reservoirs are assessed separately, recognizing possible overlap with Jurassic and Paleozoic TPS. Also, similar to the Jurassic system in this area, the Cretaceous TPS is divided into two AU where underlying Hormuz Salt is present or absent.

The organic-rich, basinal facies of the Shu'aiba Formation, a series of argillaceous dense layers in the Lower Cretaceous Thamama Group, and argillaceous basinal facies of the middle Cretaceous Shilaif (Khatiyah) Formation of the Wasia Group are the primary source rocks. These source rocks contain Types I and II organic matter and as much as 10 weight percent TOC (2.0 weight percent average). Jurassic oils also mix with Cretaceous oils along the eastern edge of the Hith evaporite. Primary reservoirs are the cyclic, shallow-water, platform and shelf carbonate grainstones and packstones of the Lower Cretaceous Shu'aiba Formation and bioclastic shoal buildups of the middle Cretaceous Mishrif Formation. Some fields might produce Silurian-sourced gas from the Permian Khuff Formation.

The Cretaceous Reservoirs in Northwest Desert Anticlines AU (20190101) encompasses an area where the Shu'aiba source-rock facies is present and mature for oil generation (R_o = 0.65) along the Rub 'al Khali basin axis, as defined by Milner (1998). Cretaceous oils within the AU range from 26° to 45° API gravity. More mature oils are produced from Asab and Shah fields adjacent to the Falaha syncline where Thamama source rocks are presently in the zone of gas generation. Shu'aiba source rocks started generating oil as early as Eocene (65 Ma) with major expulsion of petroleum from the Falaha syncline and Oman foreland basin commencing about 40 Ma (Taher, 1997). Traps are mainly structural and most are anticlinal (crest and flank traps), with combination structural and stratigraphic traps along a north-southeast trending, secondary-leached shelfal limestone.

The Cretaceous Reservoirs in South Gulf Suprasalt Structural AU (20190102) is defined mostly by the geographic extent of the underlying Hormuz Salt. The northern two-thirds of the AU is offshore. The southern one-third is onshore and bounded to the southsoutheast by the Dibba transform fault, to the west by the Qatar Arch, to the east by the Omani Foredeep, and to the north by the Zagros Fold Belt. Structural traps are anticlines or salt domes and diapirs (crest and flank traps) with some combination structural/stratigraphic traps in leached shelfal limestone.

Red Sea Basin and Yemen

Overview

The Red Sea Basin and Yemen provinces of the western and southern Arabian Peninsula, respectively, are rift basins of different ages with Mesozoic and Cenozoic

TPS, regional salt seals, and modern structural trends inherited from events as old as Precambrian.

The 600,000-km^2 Tertiary-rifted Red Sea Basin Province (2071) includes parts of the countries of Egypt, Sudan, Eritrea, Saudi Arabia, and Yemen. The northwesternmost Egyptian Gulf of Suez Basin is a shallow-water, abandoned rift of Miocene age, and is the most densely explored and productive part of the province. The northeasternmost Gulf of Aqaba is a younger, deep-water, left-lateral wrench basin with no wells. The remaining Red Sea Basin is an active rift of Oligocene origin, where sea-floor spreading has occurred for the last 5 m.y. and established production and well penetrations are sparse and primarily limited to the basin margins.

Major Red Sea crustal fault systems were established in Precambrian and early Paleozoic time, associated with cratonization and continental breakup events. Parts of the Paleozoic and Mesozoic rock records were eroded or not deposited, and only Cretaceous and Jurassic seas ever covered the region. Cretaceous seas transgressed southward across the Gulf of Suez and into the northwesternmost Red Sea area, and Jurassic seas transgressed north and westward into only the southern part of the Red Sea. Cenozoic subsidence, extensional rifting, and igneous emplacements resulted from magmatic expansion and the episodic and segmented movement of the Arabian Peninsula away from Africa. Later thermal re-equilibration slowed the subsidence, and evaporitic conditions existed until a full connection to the Indian Ocean was established during the Pliocene. Upper Miocene salt (post-rift in the Gulf of Suez; syn-rift in the remaining Red Sea Basin) forms a major regional seal for the province, and salt tectonism affects the youngest part of the stratigraphic section. More extensive geologic discussion and appropriate references can be found in Lindquist (1998).

The Red Sea Basin Province contains two major TPS, both with onshore and offshore components (Lindquist, 1998). The Sudr-Nubia TPS (207101) (30,500 km^2) is oil dominated with pre-rift, marine carbonate Cretaceous source rocks and pre- to post-rift continental to marine reservoir rocks of variable age. A second system, the Miocene-sourced Maqna TPS (207102) (400,000 km^2), is gas dominated, with syn- and post-rift, marine to marginal marine reservoir rocks and shale source rocks. Both TPS are characterized with local shale and regional salt seals, dominantly block faulted anticlinal traps, and vertical to short lateral migration paths for hydrocarbons. Additionally, Maqna contains halokinetic traps.

The Ma 'Rib-Al Jawf/Masila Basin Province (2004) of Yemen and the southernmost tip of Saudi Arabia is part of a complex graben system that formed during the Precambrian Najd Orogeny (Husseini and Husseini, 1990; Bosence, 1997). The Ma 'Rib-Al Jawf Graben is interpreted as a series of minor linked grabens or half grabens that contain a Kimmeridgian source rock and are sealed by Jurassic (Tithonian) salt (Bosence, 1997; Beydoun and others, 1998). A number of oil and gas fields are in the southeastern half of the province and in the Ma'rib Graben (Brannan and others, 1999). The graben contains more than 2 km of Precambrian to Lower Jurassic rocks (predominantly clastics) that were deposited prior to major Middle Jurassic (Kimmeridgian-Tithonian) rifting. Some argue that pre-rift Jurassic sediments also contain hydrocarbon source rocks (Brannan and others, 1999).

Cretaceous TPS (Red Sea)

The densely explored, pre-rift Sudr-Nubia TPS (207101) has Upper Cretaceous to Eocene oil-prone, uniform marine carbonate source rocks (TOC average 2.6 weight percent, Type II kerogen, tens of meters thick). There are at least 111 oil and gas fields and discovery wells, largely in Tertiary fault-block traps and in Paleozoic through Tertiary siliciclastic and carbonate reservoirs of continental to marine origin. The Sudr-Nubia TPS (207101) is located in the Gulf of Suez Basin and extends southeastward a short distance into the Red Sea Basin proper. Known Sudr-Nubia ultimate recoverable reserves exceed 11 BBOE (Petroconsultants, 1996), with 60 percent of this total produced through 1995. The median size of known fields is 9.5 MMBOE and the mode is 5 MMBOE. Sudr-Nubia hydrocarbon generation occurred within the last 10 m.y. Seals are local shales, dense carbonate rocks, and a regional Upper Miocene salt.

Three AU characterize the risk variability in the Sudr-Nubia TPS. The Gulf of Suez Block-Fault Fairway AU (20710101), with both onshore and offshore zones in the northern Gulf of Suez (48 percent of the TPS area), is densely drilled and contains the major portion of established production. The onshore Gulf of Suez Qaa Plain AU (20710102) on the eastern side of the province (6 percent of the TPS area) is hypothetical with no established production, few well penetrations, and significant geologic risk. The Southern Gulf of Suez AU (20710103), with both offshore and onshore areas in the southern Gulf of Suez and the northwestern Red Sea (46 percent of the TPS area), is a frontier AU with limited production and well penetrations, and an expectancy to be slightly more gas prone than the Gulf of Suez Block-Fault Fairway (20710101).

Tertiary TPS (Red Sea)

The sparsely explored, syn- and post-rift Maqna TPS (207102) has Lower to Middle Miocene oil- and gas-prone, marine to marginal marine shale source rocks (TOC average 1-2 weight percent, Types II to III kerogen, variable thicknesses and lateral extents). There are 18 oil and gas fields and discovery wells in Tertiary siliciclastic and carbonate reservoir rocks. The Maqna TPS covers much of the Red Sea Basin but excludes the deep and young axial rift area, the Gulf of Aqaba, and the northern Gulf of Suez. There are approximately 18,000 km^2 overlap with Sudr-Nubia TPS along a 300-km distance in the southern Gulf of Suez. Known Maqna ultimately recoverable reserves are 1 BBOE (Petroconsultants, 1996), with just 2.4 percent produced through 1995. The median size of known fields is 5.8 MMBOE and the mode is 10 MMBOE. Hydrocarbon generation occurred within the last 10 m.y. Seals are local shales and regional Upper Miocene salt.

Two AU characterize the risk variability in the Maqna TPS. The Red Sea Coastal Block Faults AU (20710201) with onshore and offshore components (27 percent of the TPS area) provides the outer margin of the TPS, contains all the known but limited TPS production, and has block-fault traps similar to those in the Sudr-Nubia TPS. The offshore Red Sea Salt Basin AU (20710202) (73 percent of the TPS area) is hypothetical with no established production, has structural and stratigraphic traps formed by halokinesis, and has the higher thermal gradients in the TPS.

Jurassic TPS (Yemen)

The Mabdi-Amran/Qishn TPS (200401) contains the Ma 'Rib Al Jawf/Shabwah/Masila AU (20040101). Although the Mabdi-Amran/Qishn TPS is centered in the Ma'rib Al Jawf/Masila Basin Province, it encompasses most of the adjacent Shabwah Basin (2006) and Masila-Jeza (2009) Provinces. The principal source rocks for Mesozoic hydrocarbons of these Yemen provinces are syn-rift, deep marine, organic-rich shales of the Late Jurassic (Kimmeridgian) Madbi Formation. The Madbi interval contains a thick succession of pelagic marls and claystones, with turbidites and coarse clastics located along the rift margins. Sediments were deposited in a rapidly subsiding basin with pervasive anoxic bottom conditions that resulted in blooms and preservation of organic matter (Bosence, 1997; Beydoun and others, 1998). Reservoirs are dominantly Upper Jurassic (Tithonian) clastics of the Amran Group that prograded from the northwest part of the Ma 'Rib al Jawf Basin. Salt of the Upper Jurassic Shabwa Member and evaporites of the Avad and Nayfa Formations form the main seals in the Shabwah Basin. Eastward in the Masila-Jeza Basin, Lower Cretaceous sandstones of the Qishn Formation are the primary reservoirs, and carbonates of the Qishn Formation are seals in the absence of Jurassic salts. Earliest generation occurred in the central rift basin during Late Cretaceous time, and oil and gas migrated vertically along faults to adjacent horst blocks, such as the Central Masila high.

North Africa (excluding Red Sea area)

Overview

Regional stratigraphy is continuous across many North African basins, but petroleum generation, migration, and entrapment in each TPS has been controlled by the different tectonic histories of the basins. The main deformational events occurred in Precambrian to early Cambrian (Pan African event), Late Silurian to Early Devonian, Late Devonian (Frasnian event), Carboniferous to Permian (Hercynian event), Early Jurassic, Early Cretaceous (Aptian, Austrian event), Late Cretaceous, and Tertiary (Eocene to Miocene, Pyrenean event) (Aliev and others, 1971; Peterson, 1985; Boudjema, 1987; van de Weerd and Ware, 1994). Other minor Phanerozoic deformational events are recorded by unconformities reflecting basin tilting, uplift, and erosion of intracratonic structural axes.

Throughout most of the Paleozoic Era, North Africa was a single depositional basin on the northern shelf of the African craton (Aliev and others, 1971; van de Weerd and Ware, 1994). This passive-margin basin generally deepened northward where deposition and marine influence were greater (Daniels and Emme, 1995). Some low-relief and areally extensive structures existed here throughout Paleozoic time, and affected the thickness of the overlying sediments (Aliev and others, 1971; van de Weerd and Ware, 1994). Many of the preserved basins and uplifts were initially developed from earlier structures during the Late Silurian and Early Devonian Periods when Laurasia separated from Gondwana and caused minor deformation, uplift, and local erosion (Peterson, 1985; Aliev and others, 1971; Boote and others, 1998). In Middle to Late Devonian time, collision of Laurasia and Gondwana resulted in further erosion and modification of pre-existing structures (Boote and others, 1998). Structures then remained relatively undeformed until the Hercynian event of Late Permian to Early Triassic time. Silurian and Late Devonian major flooding events were responsible for the deposition of source rocks (Aliev and others, 1971; Boudjema, 1987). Many of the prograding fluvial, estuarine, deltaic, and shallow marine sandstones that were deposited during these transgressive-regressive cycles are now reservoirs (Aliev and others, 1971).

The Hercynian orogeny, which records the collision between Laurasia and Gondwana, caused regional uplift, folding, and erosion (Aliev and others, 1971;

Boote and others, 1998). Paleozoic basins delineated by earlier tectonic events were modified, resulting in the development of several intracratonic sag and foreland basins (Aliev and others, 1971; van de Weerd and Ware, 1994; Boote and others, 1998). An early phase of petroleum generation occurred during the Carboniferous Period in deeper portions of the basins. Subsequent uplift caused generation to cease (Tissot and others, 1973; Daniels and Emme, 1995; Makhous and others, 1997), and post-Hercynian erosion probably removed or dispersed petroleum that had accumulated in some areas (Boote and others, 1998).

In post-Hercynian time, extension caused by the opening of the Tethys and Atlantic Oceans caused a cratonic sag, the Triassic Basin, to develop. This younger depocenter was superimposed on the northeastern margin of the Paleozoic basins (Aliev and others, 1971; Boudjema, 1987). Triassic fluvial sandstones were deposited in the sag basin and were superseded by a thick Triassic to Jurassic evaporite section overlain by carbonate rocks (Aliev and others, 1971; Boudjema, 1987). Fluvial sandstones are major reservoirs, and the overlying evaporites provide a regional seal (Aliev and others, 1971). Tertiary sedimentation was limited except in the Pelagian Basin and Sirte Basin areas (Aliev and others, 1971; Peterson, 1985; Boudjema, 1987). Much of the petroleum present in Saharan Africa was generated in Cretaceous and early Tertiary time (Daniels and Emme, 1995; Makhous and others, 1997).

Transpressional movements (wrenching) during Austrian deformation reactivated older structures, causing local uplift and erosion (Claret and Tempere, 1967; Aliev and others, 1971). Austrian-related, middle to Late Cretaceous rifting and subsidence occurred in the Pelagian and Sirte regions (Peterson, 1985; Guiraud, 1998). Initial stages of the Africa-Arabia and Eurasia collision during Late Cretaceous to middle Tertiary time caused compression and uplift that inverted basins near the present-day Atlas Mountains (Aliev and others, 1971; Peterson, 1985; Guiraud, 1998). In a few areas, such as in the Pelagian and Sirte Basins, subsidence and sedimentation occurred throughout Mesozoic and Tertiary time

(Burollet, 1991) where the lithology is dominantly carbonate. Much of the petroleum was generated in the middle to late Tertiary Period (Entreprise Tunisienne d'Activites Petrolieres, 1999).

Mesozoic and Tertiary TPS

Sirte Basin

The Sirte Basin is a Late Mesozoic and Tertiary continental rift province along the northern margin of Africa. The Sirte Basin Province extends offshore into the Mediterranean Sea and is characterized by one major TPS designated here as Sirte-Zelten (204301). Horst and graben structures in the onshore portion have been extensively explored; however, little exploration and no discoveries characterize the deeper offshore portion (>200 meters water depth). The Upper Cretaceous Sirte Shale of the Rakb Group is the dominant hydrocarbon source rock of the Sirte-Zelten TPS. Speculative source rock intervals that range in age from Silurian through Tertiary have also been proposed (Burwood, 1997; Futyan and Jawzi, 1996; Gumati and others, 1996). Onshore fields produce low-sulfur, high gravity oils; however, in deeper grabens such as the Sirte Graben, the Sirte Shale is thermally mature for gas generation. Complex tectonics and repeated structural inversion produced multiple episodes of both deposition of reservoir rocks and petroleum charging of reservoir in adjacent horst blocks. Reservoir rocks range in age from Cretaceous to Eocene with clastic reservoirs more common to the Cretaceous and carbonates rock reservoirs dominating the Tertiary.

The Sirte-Zelten TPS is subdivided into four AU, two proven and two hypothetical. The Southeast Sirte Clastics AU (20430101) refers to an area that produces from Cretaceous and older rocks (including the giant Messla, Sarir, Amal, and Abu Attifel fields) in the eastern onshore portion of the Sirte Basin Province where fluvial and alluvial clastics of Early Cretaceous age (Nubia and Serir sandstones) are the primary reservoirs. Combination structural-stratigraphic traps characterize these Cretaceous reservoirs in Sarir and Messla fields. The Central Sirte Carbonates AU (20430102) is designated for a mostly onshore portion of the central Sirte Basin, where syn-rift carbonates of Late Cretaceous through Eocene age produce in fields on horst blocks and major structural platforms (for example, Beda and Zelten Platforms).

Two hypothetical AU were designated and risked as part of the current USGS assessment, the Offshore Sirte Hypothetical AU (20430103) and the onshore Southeast Sirte Hypothetical AU (20430104). Offshore Sirte Hypothetical comprises the offshore area of the Gulf of Sirte at water depths between 200 and 2,000 m where some hydrocarbon shows have been recorded, and it includes potential carbonate and clastic rock reservoirs. In the Southeast Sirte Hypothetical AU, numerous wildcats have been drilled with no significant shows. Potential reservoirs are mainly Cretaceous marine bar sandstones that might be oil- or gas-charged by long-distance lateral migration along faults that extend into the deeper parts of the grabens, such as the Sirte Graben to the north.

Pelagian Basin

The Pelagian Basin Province is primarily an offshore region of the Mediterranean Sea, located off eastern Tunisia and northern Libya, and extending slightly into Italian and Maltese waters. The Pelagian Basin Province contains more than 2.3 BB of known (estimated total recoverable, including cumulative production plus remaining reserves) petroleum liquids (mostly oil) and approximately 17 TCF of known natural gas (Petroconsultants, 1996). The Pelagian Basin Province contains the giant Bouri oil field that produces from the Bou Dabbous-Tertiary TPS (204801).

Two composite TPS were identified in the Pelagian Basin, the Bou Dabbous-Tertiary (204801) and the Jurassic-Cretaceous Composite (204802). The Bou Dabbous-Tertiary TPS coincides with the presence of mature Eocene source rocks, and the Jurassic-Cretaceous Composite similarly matches the area of Jurassic and Cretaceous source rocks. Only one AU was defined for each TPS. All AU boundaries (20480101, 20480201) coincide with TPS boundaries.

The primary source rock of the Bou Dabbous-Tertiary TPS is dark-brown marl and mudstone of the Lower Eocene Bou Dabbous Formation (Bishop, 1988; Macgregor and Moody, 1998; Entreprise Tunisienne d'Activites Petrolieres, 1999). The source rock matured in Miocene to Pleistocene time (Entreprise Tunisienne d'Activites Petrolieres, 1999), and petroleum migrated laterally into adjacent or juxtaposed reservoirs and vertically along faults or fractures. Known reservoir rocks are shallow-marine limestones and sandstones (Bishop, 1988; Entreprise Tunisienne d'Activites Petrolieres, 1999). Petroleum accumulations are in fault blocks, low-relief anticlines, high-relief anticlines associated with reverse faults, wrench-fault structures, and stratigraphic traps (Bishop, 1988; Entreprise Tunisienne d'Activites Petrolieres, 1999). Seals include Eocene and Miocene mudstone and carbonate rocks (Entreprise Tunisienne d'Activites Petrolieres, 1999).

The primary source rocks of the Jurassic-Cretaceous Composite TPS are Jurassic and Cretaceous argillaceous and calcareous mudstones and marls (Bishop, 1988; Entreprise Tunisienne d'Activites Petrolieres, 1999; Macgregor and Moody, 1998). Peak petroleum generation occurred in Miocene and Pliocene time, and petroleum migrated laterally into adjacent or juxtaposed reservoirs and vertically along faults or fractures (Entreprise Tunisienne d'Activites Petrolieres, 1999). Known reservoir rocks are shallow-marine limestones and sandstones (Bishop, 1988; Entreprise Tunisienne d'Activites Petrolieres, 1999). Most known accumulations are in fault blocks, low-relief anticlines, high-relief anticlines associated with reverse faults, wrench-fault structures, and stratigraphic traps (Bishop, 1988; Entreprise Tunisienne d'Activites Petrolieres, 1999). Seals include Jurassic and Cretaceous mudstone and carbonate rocks (Entreprise Tunisienne d'Activites Petrolieres, 1999).

Silurian and Devonian TPS

Algerian Basins

Three provinces were analyzed for assessment in this area. First, the Trias/Ghadames Basin Province, located in eastern Algeria, southern Tunisia, and westernmost Libya, generally coincides with the Mesozoic-aged Triassic Basin. This basin is partly or wholly superimposed on the Paleozoic-aged Melrhir Basin, the Ghadames or Berkine Basin, and the Oued Mya Basin. Second, the Illizi Basin Province is located in eastern Algeria and extreme western Libya. Third, the Grand Erg/Ahnet Basin Province is located primarily in western Algeria, but extends slightly into Morocco. The Grand Erg/Ahnet Basin Province contains the Timimoun Basin, Ahnet Basin, Sbaa Sub-Basin, Mouydir Basin, Benoud Trough, Béchar/Abadla Basins, and part of the Oued Mya Basin.

Several TPS might exist in each of these geologic provinces; however, data available for this study permit recognition of only "composite" TPS (GL), each of which may contain one or multiple petroleum systems. Composite TPS identified in the Trias/Ghadames, Illizi, and Grand Erg/Ahnet Provinces include the following: Tanezzuft-Oued Mya (205401), Tanezzuft-Melrhir (205402), Tanezzuft-Ghadames (205403), Tanezzuft-Illizi (205601), Tanezzuft-Timimoun (205801), Tanezzuft-Ahnet (205802), Tanezzuft-Sbaa (205803), Tanezzuft-Mouydir (205804), Tanezzuft-Benoud (205805), and Tanezzuft-Béchar/Abadla (205806). Tanezzuft refers to the Silurian Tanezzuft Formation, which is the oldest major source rock in these TPS. The second name refers to the basins in which the TPS exist. Only one AU was defined for each TPS. All AU boundaries coincide with TPS boundaries.

Primary source rocks in all these TPS are the Silurian Tanezzuft Formation and Middle to Late Devonian mudstone (Tissot and others, 1973). Peak generation occurred from Middle Jurassic to Eocene time (Tissot and others, 1973; Daniels and Emme, 1995; Makhous and others, 1997). In the southern and western areas (Ahnet, Timimoun, Mouydir, and parts of the Illizi Basins), generation from both

Silurian and Middle to Late Devonian source rocks probably started and peaked in the Carboniferous Period but was halted by the Hercynian event (Tissot and others, 1973; Daniels and Emme, 1995; Logan and Duddy, 1998). Petroleum is believed to have migrated laterally into adjacent or juxtaposed reservoirs and vertically along faults or fractures (Daniels and Emme, 1995; Boote and others, 1998). Reservoir rocks are Paleozoic fluvial, deltaic, and marine sandstone, and Triassic fluvial sandstone (Aliev and others 1971; van de Weerd and Ware, 1994; Petroconsultants, 1996). Most known accumulations are in anticlines, faulted anticlines, fault blocks, and combination traps (Aliev and others 1971; Petroconsultants, 1996; Echikh, 1998). Triassic to Jurassic evaporites, mudstone, and carbonate rocks as thick as 500 m provide a regional top seal for reservoirs in the Ghadames (Berkine), Oued Mya, Benoud, and Melrhir Basins (Aliev and others 1971). Intraformational Paleozoic marine mudstones provide the seal where salt is absent, such as in the Grand Erg/Ahnet and Illizi Provinces (Aliev and others 1971).

The Trias/Ghadames Basin Province contains more than 16 BB of known (estimated total recoverable, including cumulative production plus remaining reserves) petroleum liquids (approximately 15 BBO and 1 BBNGL) and approximately 25 TCF of known natural gas (Petroconsultants, 1996). The Trias/Ghadames Basin Province contains the giant Hassi Messaoud oil field that produces from the Tanezzuft-Oued Mya TPS (205401). The Illizi Basin Province contains approximately 4.6 BB of known petroleum liquids (approximately 3.7 BBO and 900 MMBNGL) and approximately 45 TCF of known natural gas (Petroconsultants, 1996). The Illizi Basin Province contains the giant Tin Fouye-Tabankort and Zarzaitine oil fields. The Grand Erg/Ahnet Basin Province contains more than 5.5 BB of known petroleum liquids (approximately 500 MMBO and 5 BBNGL) and approximately 114 TCF of known natural gas (Petroconsultants, 1996). The Grand Erg/Ahnet Basin Province contains the giant Hassi R'Mel gas field.

ASSESSMENT RESULTS

The assessment results are shown at the TPS, AU, Province and Region level (see Assessment Output Tables). Eighty-four AU from 28 TPS, present in 31 provinces, were assessed for Region 2. The USGS estimate of 229.9 BBO for mean total undiscovered recoverable oil in the Middle East and North Africa indicates that Region 2 has the greatest undiscovered oil potential, representing 35.4 volume percent of the world's total estimated undiscovered oil resource of 649 BBO (exclusive of the U.S.). Region 2 ranks second globally in undiscovered gas potential with 1,370 TCF, which is 29.3 volume percent of the world's total estimated undiscovered natural gas resource of 4,669 TCF (exclusive of the U.S.). Finally, the Middle East and North Africa region ranks first in mean undiscovered NGL with 81.7 BBOE, which is 39.5 volume percent of the world's total estimated undiscovered NGL.

The second largest area for oil potential is Region 1, the Former Soviet Union, with a mean undiscovered estimated at 106 BBO. However, the Former Soviet Union Region ranks first in undiscovered, recoverable natural gas with a mean estimate of 1,611 TCF. Similarly, the Former Soviet Union ranks second in undiscovered NGL with a mean estimated at 55 BBOE. Combined, the remaining six world regions have 20 BBOE NGL. Overall, Region 2 contributes 44 percent of the world's known petroleum volume, but only 30 percent (540 BBOE) of the world's total undiscovered petroleum volume (1808 BBOE) as estimated in this assessment.

SIGNIFICANCE OF ASSESSMENT

Results from the USGS World Petroleum Assessment 2000 show that Region 2 ranks first in undiscovered oil and undiscovered NGL and second in undiscovered nonassociated gas. Although the Middle East and North Africa will remain the most prolific petroleum region in the world, the USGS World Petroleum Assessment 2000 illustrates that undiscovered petroleum volumes are distributed more globally than known petroleum volumes. Without considering field growth, about two thirds of the world undiscovered petroleum (oil, natural gas, and NGL) is dispersed throughout the remaining seven USGS world regions.

Results of the USGS World Petroleum Assessment 2000 were compared to the 1994 USGS world assessment (Masters and others, 1994; summarized and updated in the Oil and Gas Journal as Masters and others, 1997)with the following results: In 1994, the assessed world petroleum volume for Region 2 was less than that estimated in the current study in all categories of undiscovered resources. Overall, the current USGS assessment estimates are 46.5 percent greater for oil (229.9 BBO versus 156.9 BBO), 28.3 percent greater for natural gas (1,370 TCF versus 1067.4 TCF), and 496.7 percent greater for NGL (81.8 BBOE versus 16.4 BBOE) than those of 1994.

Current estimated undiscovered petroleum resources are greater in Algerian provinces than in the 1994 USGS assessment (Masters and others, 1994, 1997). Estimates are 374 percent higher for oil (10.1 BBO versus 2.7 BBO) and 229 percent greater for gas (55 TCF versus 24 TCF). However, in the Pelagian Province of Tunisia, undiscovered petroleum resources are estimated to be 76 percent less (1.3 BBO versus 5.5 BBO) for oil and 66 percent less for gas (6 TCFG versus 17 TCF). The volume of known gas in the Pelagian Province is correspondingly greater in the current assessment than in the 1994 USGS assessment (17 TCF versus 3 TCF), indicating that much of the previously undiscovered gas has now been discovered. Known oil volumes reported in the current and the 1994 USGS assessments are similar in the Pelagian and Algerian provinces, and known gas volumes are similar in the Algerian provinces.
For the Sirte Basin of Libya, the current USGS estimates declined 29 percent for oil (6.85 BBO versus 9.6 BBO) and 37 percent for gas (15 TCF versus 23.9 TCF). The Murzuk Basin of Libya, where there have been recent petroleum discoveries from a Silurian TPS, was not included in this assessment. In contrast, current USGS estimates of undiscovered petroleum resources in the Red Sea Basin increased from those of the 1994 USGS assessment previously published by

Masters(1994) for the Gulf of Suez portion of the basin. Oil increased 144 percent (5.2 BBO versus 3.6 BBO) and gas increased 1111 percent (60 TCF versus 5.4 TCF). The current USGS estimates for the Arabian Peninsula ("Middle East") increased about 146 percent for oil (206.5 BBO versus 141 BBO) and about 122 percent for gas (1235 TCF versus 1014 TCF) from the1994 USGS assessment. Masters (1994) did not include Yemen in the previous USGS assessment.

In summary, the 1994 and 2000 USGS assessments differ in the following ways: (1) The current assessment has identified and assessed a significant undiscovered gas resource (348 TCF at the mean) from Silurian source rocks in the Rub' al Khali Basin Province (20190302) that was not previously recognized. (2) The estimated resource for the Silurian TPS of the Arabian Peninsula increased, partly due to new discoveries. (3) Considerably larger oil resources in Iraq, Saudi Arabia, and Iran in all TPS are recognized, because of access to new and updated databases, prospect maps, and geochemical data and because of improvements in petroleum migration modeling. (4) Co-product ratios are documented, thereby accounting for most NGL increases. And (5) Associated gas resources in the Red Sea and petroleum resources in Yemen, not considered previously, are accounted for.

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Table R2-1.--Rank and known petroleum volume (in percent) of world oil and gas priority provinces exclusive of the United States, USGS Region 2, Middle East and North Africa. [Data from Klett and others (1997)]

World Ranking (exclusive of U.S.)	USGS Province No.	USGS Province Name	Location	Percent of World Total Known Petroleum Volume (excluding U.S.)
2	2024	Mesopotamian Foredeep Basin	Middle East	13.8
3	2021	Greater Ghawar Uplift	Middle East	7.7
4	2030	Zagros Fold Belt	Middle East	7.6
5	2019	Rub' al Khali Basin	Middle East	4.9
6	2022	Qatar Arch	Middle East	3.7
13	2043	Sirte Basin	North Africa	1.7
19	2058	Grand Erg/Ahnet Basin	North Africa	1.0
21	2054	Trias/Ghadames Basin	North Africa	0.8
23	2023	Widyan-Interior Platform	Middle East	0.8
32	2056	Illizi Basin	North Africa	0.5
39	2071	Red Sea Basin	Middle East	0.4
45	2020	Interior Homocline/Central Arch	Middle East	0.3
47	2016	Fahud Salt Basin	Middle East	0.3
55	2048	Pelagian Basin	North Africa	0.2
57	2014	Ghaba Salt Basin	Middle East	0.2
61	2004	Ma 'Rib-Al Jawf Basin	Middle East	0.2
			Total	44.1

Middle East and North Africa Region 2

2004 Ma'Rib-Al Jawf/Masila Basin
2006 Shabwah Basin
2009 Masila-Jeza Basin
2010 Ghudun-Khasfeh Flank Province
2011 South Oman Salt Basin
2013 Huqf-Haushi Uplift
2014 Ghaba Salt Basin
2015 Central Oman Platform
2016 Fahud Salt Basin
2019 Rub Al Khali Basin
2020 Interior Homocline-Central Arch
2021 Greater Ghawar Uplift
2022 Qatar Arch
2023 Widyan Basin-Interior Platform
2024 Mesopotamian Foredeep Basin
2025 Hail-Ga'Ara Arch
2028 Rutbah Uplift
2029 Wadi-Surhan Basin
2030 Zagros Fold Belt
2043 Sirte Basin
2048 Pelagian Basin
2054 Trias/Ghadames Basin
2055 Illizi Basin
2058 Grand Erg/Ahnet Basin
2071 Red Sea Basin
2074 Khleisha Uplift
2075 Euphrates/Mardin
2089 Anah Graben

Figure R2-1.--Assessed provinces of Region 2, Middle East and North Africa.

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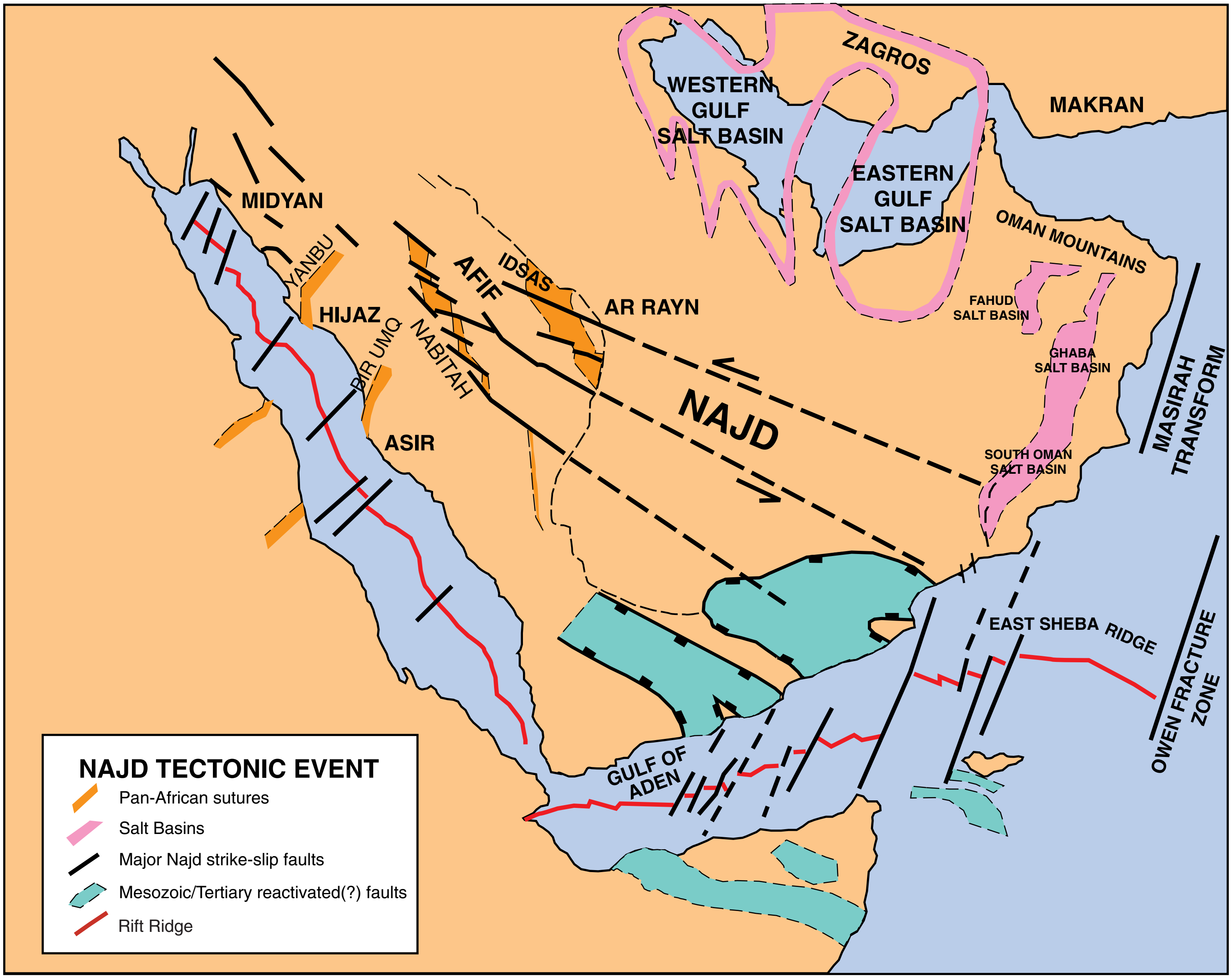

Figure R2-2.--Major fault systems and rift salt basins of the Arabian Peninsula formed during the Infracambrian Najd Tectonic Event. Modified from Loosveld and others (1996).

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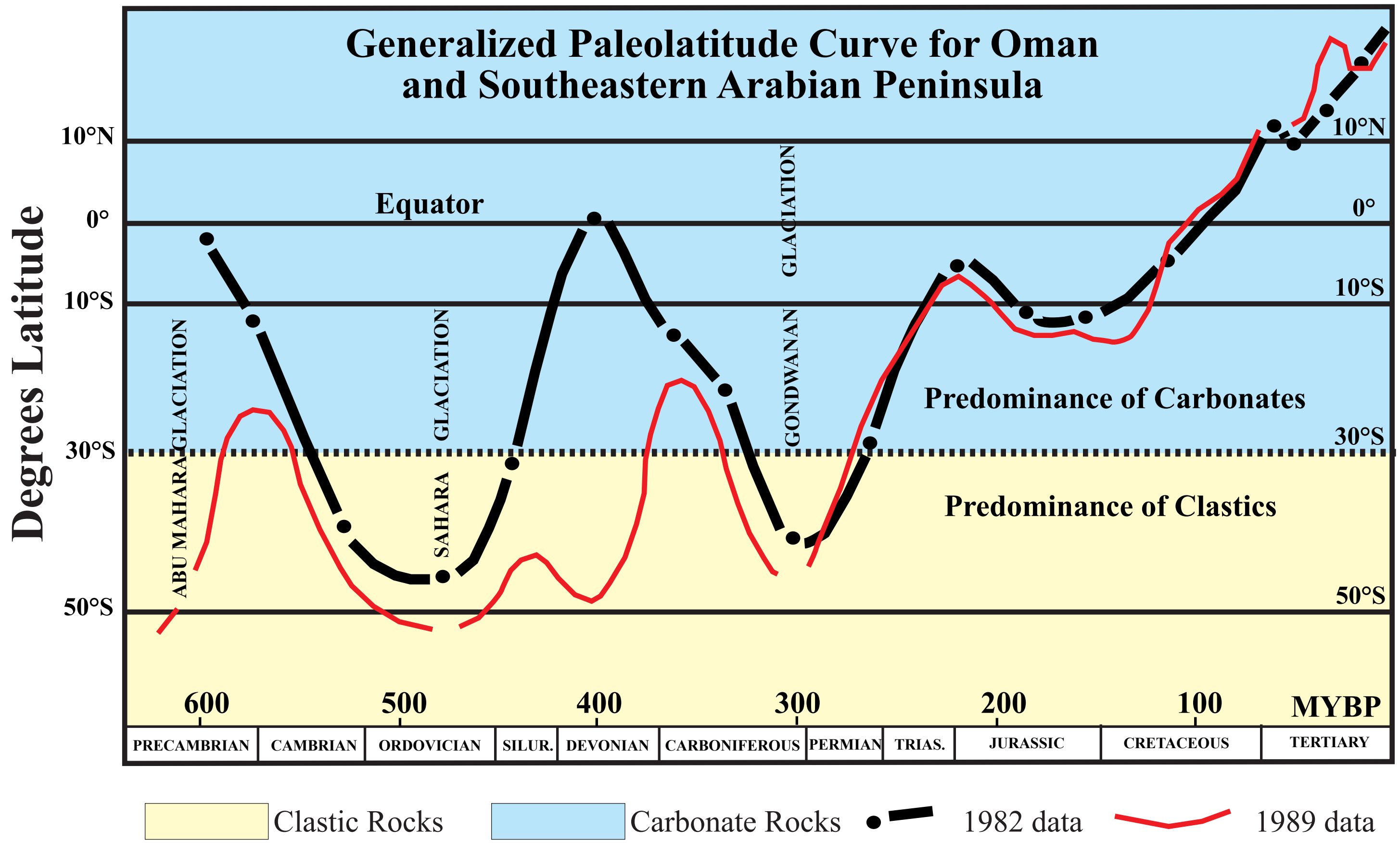

Figure R2-3. -- Generalized paleolatitude curve for Oman and southeastern Arabian Peninsula from Precambrian to Tertiary showing major glaciation stages illustrating and the affect of latitude on depositional facies. Modified from Beydoun (1991). MYBP, million years before present; TRIAS., Triassic; SILUR., Silurian.

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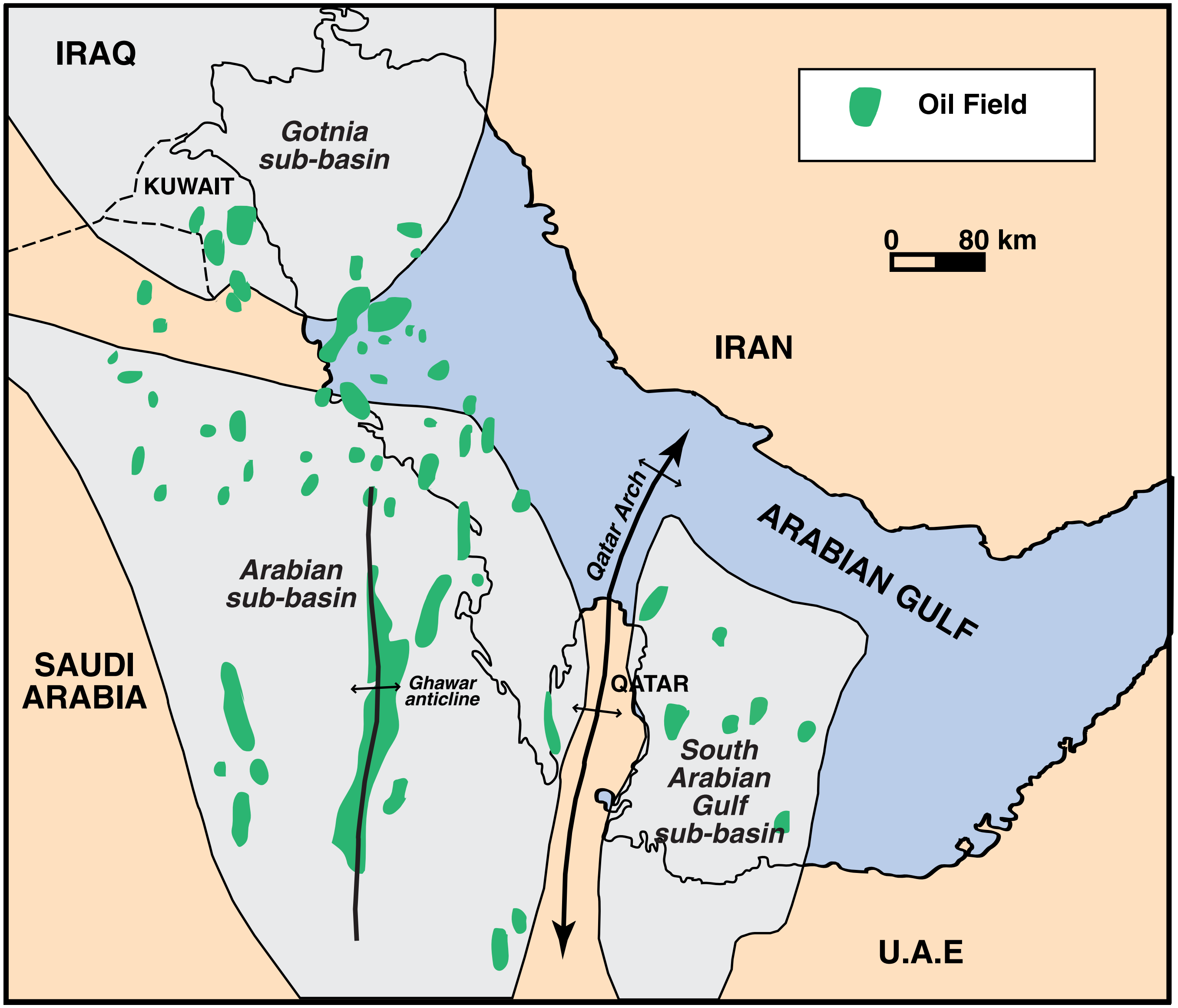

Figure R2-4.--Generalized outline of the three major intrashelf sub-basins formed during the Late Jurassic on the eastern Arabian sub-continent that were centers for basinal, organic-rich source rocks. Modified from Murris (1980) and Alsharhan and Kendall (1986).

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