Petroleum Geology and Total Petroleum Systems of the Widyan Basin and Interior Platform of Saudi Arabia and Iraq

By James E. Fox *and* Thomas S. Ahlbrandt

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Foreword

This report was prepared as part of the World Energy Project of the U.S. Geological Survey. For this project, the world was divided into eight regions and 937 geologic provinces, which were then ranked according to the discovered oil and gas volumes within each (U.S. Geological Survey World Energy Assessment Team, 2000). Of these, 76 "priority" provinces (exclusive of the U.S. and chosen for their high ranking) and 26 "boutique" provinces (exclusive of the U.S. and chosen for their anticipated petroleum richness or special regional economic importance) were selected for appraisal of oil and gas resources. The petroleum geology of these priority and boutique provinces is described in this series of reports.

The purpose of the World Energy Project is to assess the quantities of oil, gas, and natural gas liquids that have the potential to be added to reserves within the next 30 years. These volumes either reside in undiscovered fields whose sizes exceed the stated minimum-field-size cutoff value for the assessment unit (variable, but must be at least 1 million barrels of oil equivalent) or occur as reserve growth of fields already discovered.

The total petroleum system constitutes the basic geologic unit of the oil and gas assessment, and is defined as including all genetically related petroleum that occurs in shows and accumulations (discovered and undiscovered) that (1) has been generated by a pod or by closely related pods of mature source rock, and (2) exists within a limited mappable geologic space, along with the other essential mappable geologic elements (reservoir, seal, and overburden rocks) that control the fundamental processes of generation, expulsion, migration, entrapment, and preservation of petroleum. The minimum petroleum system is that part of a total petroleum system encompassing discovered shows and accumulations along with the geologic space in which the various essential elements have been proven by these discoveries.

An assessment unit is a mappable part of a total petroleum system in which discovered and undiscovered fields constitute a single, relatively homogeneous population such that the chosen methodology of resource assessment based on estimation of the number and sizes of undiscovered fields is applicable. A total petroleum system may equate to a single assessment unit, or it may be subdivided into two or more assessment units if each unit is sufficiently homogeneous in terms of geology, exploration considerations, and risk to assess individually.

A graphical depiction of the elements of a total petroleum system is provided in the form of an events chart that shows the times of (1) deposition of essential rock units; (2) trap formation; (3) generation, migration, and accumulation of hydrocarbons; and (4) preservation of hydrocarbons.

A numeric code identifies each region, province, total petroleum system, and assessment unit. These codes are uniform throughout the World Energy Project and identify the same type of entity in any of the publications. The code is as follows:

Example	
Region, single digit	**2**
Province, three digits to the right of region code	20**23**
Total petroleum system, two digits to the right of province code	2023**01**
Assessment unit, two digits to the right of petroleum system code	202301**01**

The codes for the regions and provinces are listed in U.S. Geological Survey World Energy Assessment Team (2000), and in Klett and others (1997).

Oil and gas reserves quoted in this report are derived from Petroconsultants' Petroleum Exploration and Production database (Petroconsultants, 1996) and other area reports from Petroconsultants, Inc., unless otherwise noted.

Figure(s) in this report that show boundaries of the total petroleum system(s), assessment units, and pods of active source rocks were compiled using geographic information system (GIS) software. Political boundaries and cartographic representations were taken, with permission, from Environmental Systems Research Institute's ArcWorld 1:3 million digital coverage (1992), have no political significance, and are displayed for general reference only. Oil and gas field centerpoints, shown in these figures, are reproduced, with permission, from Petroconsultants, 1996.

Abstract

Two total petroleum systems are associated with the Widyan Basin–Interior Platform Province in northern Saudi Arabia and western Iraq. In the Paleozoic Qusaiba/Akkas/Abba/Mudawwara Total Petroleum System, which consists of one assessment unit—the Horst/Graben-Related Oil and Gas Assessment Unit—high-gravity, low-sulfur crude oil, as well as natural gas, occurs in horst/graben-related traps that formed prior to, during, and after Hercynian deformation (Carboniferous). The source of oil and gas is from organic-rich marine shale at the base of the Silurian sedimentary sequence (Qusaiba, Akkas, Mudawwara, and Abba Formations) that was deposited under dysoxic to anoxic conditions in an intra-shelf basin located north of the Central Arabian Arch. Onset of oil generation in Iraq began about 250 million years ago (Ma) and in eastern Saudi

[1]South Dakota School of Mines and Technology, Rapid City, S.Dak.

Arabia about 160 Ma, reaching peak generation, expulsion, migration, and entrapment during the Jurassic Period. In Saudi Arabia, petroleum migrated into fluvial and eolian quartzose sandstones of the Carboniferous-Early Permian Unayzah Formation that overlies the Hercynian unconformity, filling in rifts and half-grabens to thicknesses ranging to more than 400 meters. Combined stratigraphic-structural traps exist where the Unayzah Formation is the reservoir, as is the case in central Saudi Arabia. Oil and gas are sealed in those reservoirs by overlying tight carbonate-evaporite strata, and by subunconformity pinchouts of Pre-Unayzah clastic reservoir units against impermeable facies. In Iraq, reservoirs are sandstones of the Ordovician Upper Khabour and Silurian Akkas Formations. Over most of the Southwestern Desert of Iraq, Lower Silurian shale is a seal for hydrocarbons in the underlying Ordovician Khabour Formation.

The Jurassic Gotnia/Barsarin/Sargelu/Najmah Total Petroleum System has two assessment units: the Platform Horst/Graben-Related Oil Assessment Unit and the Basinal Oil and Gas Assessment Unit. All reservoirs are in the Upper Jurassic Najmah Limestone and Gotnia Formation in Iraq, and the correlative Arab Formation in Saudi Arabia, occurring as lenses of marine bar or shelf-margin calcarenites, calcarenitic limestone, and dolomite. These strata grade eastward into organic-rich source rocks that were deposited under anoxic and dysoxic conditions in three restricted intra-shelf basins—from north to south, the Gotnia, Arabian, and Southern Arabian Gulf Basins. Maturation of the Upper Jurassic source-rock formations (Sargelu and Naokelekan Formations in Iraq) began around 90 Ma; peak generation took place from 85 to 13 Ma. With time, the oil migrated updip and was trapped in calcarenite lenses. Later, oil remigrated and was trapped in anticlines that began to form in Early Cretaceous time. Younger Jurassic shale and anhydrite seal rocks are distributed throughout the total petroleum system.

The Widyan Basin–Interior Platform Province (2023) ranks 17th in the world, exclusive of the United States, with 62.5 billion barrels of oil equivalent of total petroleum endowment (cumulative production plus remaining petroleum plus estimated mean undiscovered volumes). Mean estimates of undiscovered petroleum for the province, which includes both Paleozoic and Jurassic petroleum systems as well as portions of three additional total petroleum systems from adjacent provinces, are 21.22 billion barrels of oil, 94.75 trillion cubic feet of gas (15.8 billion barrels of oil equivalent), and 6.85 billion barrels of natural gas liquids. The Paleozoic total petroleum system is dominantly gas prone, whereas the volumetrically larger Jurassic total petroleum system is oil prone—resulting in the characterization of the province as an oil province. The discovery maturity for the province is a relatively low 31 percent, meaning that much of the province petroleum potential lies in the future.

Geology of the Widyan Basin–Interior Platform Province (2023)

Structural Setting

The stable platform interior of the Arabian plate is surrounded by tectonically active margins (fig. 1). Compressional terranes define the northern and eastern margins of the plate and form the Taurus thrust suture zone of southeastern Turkey and the Zagros thrust suture zone that trends from Iraq to Oman. The southern and western margins are rift basins of the Mediterranean Sea, Red Sea, and Gulf of Aden. Structural provinces of the Arabian Peninsula include the Arabian Shield, surrounded by the Arabian shelf and Arabian platform. Various basins and uplifts of these provinces are shown in figure 1.

The focus of this report is on the Widyan Basin-Interior Platform Province (2023) and its two associated total petroleum systems—the Paleozoic Qusaiba/Akkas/Abba/Mudawwara Total Petroleum System (202301) and the Jurassic Gotnia/Barsarin/Sargelu/Najmah Total Petroleum System (202302). The province is situated on the Arabian Peninsula (fig. 2), adjacent to, and east and north of, the Interior Homocline–Central Arch Province (2020). Undiscovered resources allocated to this province are shown in table 1.

The Widyan Basin is separated from the Tabuk Basin on the west by the low-lying Arabian Shield area and the Ha'il-Rutbah Arch (fig. 1). Paleozoic rocks ranging in age from Cambrian through Late Permian crop out and subcrop in an offlap manner away from the Arabian Shield.

To the north, the stable shelf zone of Iraq is a continuation of the Widyan Basin. It includes a large area referred to as the Western and Southwestern Deserts (fig. 3) (Agrawi, 1998). This zone occupies more than one-third of the area of Iraq, including the Khieisia and Rutbah-Ga'ara Uplifts and the Anah Graben. Target reservoirs in the stable shelf zone are primarily of Paleozoic age. Eastward, the structural style changes into the Mesopotamian Basin, the folded, and the thrust zones. These structural zones are not within the area defined as the Widyan Basin–Interior Platform Province. The surface of the Mesopotamian Basin zone is flat and covered by Quaternary fluvial-plain deposits of the Tigris and Euphrates Rivers, marsh and lacustrine sediments of southern Mesopotamia, and eolian sediments. It constitutes the richest petroleum basin in Iraq, with more than two-thirds of the country's total hydrocarbon reserves, mostly contained in Cretaceous reservoirs.

The folded zone (fig. 3), formed during the Late Cretaceous and Tertiary, occupies the northern and northeastern mountainous areas of Iraq. It is contiguous with the Alpine fold belts of the Taurus and Zagros Ranges of Turkey and Iran, respectively. The folded zone has been subdivided into the high-folded and low-folded (foothill) zones (Buday, 1980; Al-Sakini, 1992; Agrawi, 1998). The low-folded subzone has thick sedimentary cover; its long anticlinal folds are arranged in narrow belts separated by broad flat synclines. Outcropping rocks are younger than Neogene age. In contrast, the high-folded subzone is characterized by extensive exposures of sedimentary rocks as old as Jurassic, particularly in some high-amplitude folds and overturned structures. The thrust zone is a restricted narrow strip along the northern and northeastern borders of Iraq.

Petroleum Occurrence

Two large hydrocarbon-producing areas occur in Saudi Arabia, divided by the Central Arabian Arch. Nearly all of the discovered oil reserves of Saudi Arabia and adjacent countries

Figure 1. Structural provinces of Arabian Peninsula (modified from Al-Laboun, 1986). Coordinates are approximate.

are to the north of the arch, and on the Interior Platform (figs. 1, 2). A minor amount is present at the lower edge of the Interior Homocline bordering the Interior Platform. The structural features that control the accumulation are a series of north-south-trending anticlines.

Within Saudi Arabia, more than 90 percent of the total petroleum reserves lies in structures of the Ghawar field area (fig. 4). A second trend of accumulation is about 100 km (kilometers) to the west and parallel to Ghawar field. The southern part of this trend is within Province 2023 and includes Khurais field and several smaller fields, namely Mazalij, Farhah, Qirdi, and Abu Jifan.

About 90 km to the northwest is a third north-south trend of small oil fields on short north-south aligned anticlines (fig. 4). Between Jaham field on the south to Rimthan field on the north, a distance of about 300 km, are the Faridah, Al Haba, Wari'ah, Suban, and Dibdibah fields.

The three principal trends of petroleum accumulation just discussed may represent concentrations of calcarenite lenses that were deposited under bar or shelf margin conditions to form reservoirs, while contemporaneous muddy lime deposition took place to the east in the deeper part of the basin to form source rocks. With increased burial and compaction, oil was expelled from the muddy lime facies and trapped in the calcarenite lenses. Later, the oil was concentrated in the anticlines by structural growth beginning probably in Early Cretaceous time and extending into the Tertiary. Structural growth was probably completed by Miocene time.

As discussed by Ayres and others (1982), the large reserves of oil that accumulated on the Arabian shelf in Jurassic reservoirs can be attributed to several factors: (1) widespread development of thermally mature organic-rich facies underlying or juxtaposed with a carbonate-evaporite shelf containing laterally extensive reservoir units with high porosities and permeabilities;

Figure 2. Widyan Basin–Interior Platform Province (2023) (outlined in bold red); Paleozoic Qusaiba/Akkas/Abba/Mudawwara Total Petroleum System (202301) (outlined in dark purple); Horst/Graben-Related Oil and Gas Assessment Unit (20230101) (lighter purple).

(2) a cycle of deposition that concluded with a major regression in which the intra-shelf basins and adjacent shelves were covered by continuous evaporite seals; and (3) tectonic activity that created large structural traps, but was not strong enough to disrupt oil migration paths or the evaporite caps.

Murris (1980) attributed the richness of this habitat to the extraordinary horizontal extent of the basins, structural traps, and lithologic units. As a result, horizontal hydrocarbon migration was extremely efficient, and traps with access to rich source rocks were filled because they drained large source areas.

Paleozoic Qusaiba/Akkas/Abba/Mudawwara Total Petroleum System

The Paleozoic Qusaiba/Akkas/Abba/Mudawwara Total Petroleum System (202301) of the Widyan Basin–Interior

[MMBO, million barrels of oil. BCFG, billion cubic feet of gas. MMBNGL, million barrels of natural gas liquids. MFS, minimum field size assessed (MMBO or BCFG). Prob., probability (including both geologic and accessibility probabilities) of at least one field equal to or greater than the MFS. Results shown are fully risked estimates. For gas fields, all liquids are included under the NGL (natural gas liquids) category. F95 represents a 95 percent chance of at least the amount tabulated. Other fractiles are defined similarly. Fractiles are additive under the assumption of perfect positive correlation. Shading indicates not applicable]

Table 1. Widyan Basin–Interior Platform, Province 2023, Assessment Results Summary—Allocated Resources.

Figure 3. Major tectonic regions and petroleum fields of Iraq. Widyan Basin includes Western and Southwestern Deserts of Iraq (shown in yellow), the only region of Iraq included in this report (modified from Agrawi, 1998).

Platform Province (2023) has one assessment unit, identified as the Horst/Graben-Related Oil and Gas Assessment Unit (20230101) (fig. 2), and assessed undiscovered resources are shown in table 2.

Stratigraphy

Cambrian to Devonian nonmarine clastic sedimentary rocks crop out along the edge of the Arabian Shield and were deposited prior to the breakup of the eastern platform into a series of north-trending horsts and grabens during the Hercynian Orogeny (Al-Laboun, 1986). Carboniferous and Lower Permian clastics of the Unayzah Formation then covered the eroded and truncated edges of older Paleozoic strata (fig. 5). Permian carbonates of the Khuff Formation then blanketed the region, reflecting tectonic stability. During the Mesozoic and early Cenozoic, the region remained tectonically stable.

The sedimentary sequence thickens from west to east across the Arabian Plate, ranging from the erosional edge along the Precambrian outcrop to more than 15,000 m (meters) in central Iran. Strata also thicken to the north to more than 7,000 m.

Buday (1980) subdivided the Paleozoic sedimentary column of Iraq into three major sedimentary cycles (fig. 5): Cambro-Ordovician to Silurian, Devonian to Lower Carboniferous, and Upper Carboniferous to Upper Permian. Of particular interest are hydrocarbon source rocks of the Silurian Mudawwara-Akkas-Qalibah Formations, clastic reservoir rocks of the Ordovician Risha Formation in Iraq, clastic reservoir rocks of

Figure 4. Major petroleum fields in western Arabian Gulf region (modified from Al-Husseini, 1997).

the Carboniferous Unayzah-Ga'ara Formations of Saudi Arabia, and widespread seals in carbonates and evaporites of the Permian Khuff and Chia Zairi Formations.

Source Rocks

Stratigraphy

Lower Silurian clastic sediments of the Qalibah Formation were deposited on a broad continental shelf of Gondwana during sea-level rise that resulted from melting of the Gondwana polar ice cap (Al-Husseini, 1991). The basal Qusaiba Member in central and south Arabia accumulated in a trough that subsided from Late Ordovician through Early Devonian time. Abundant graptolites in the Qusaiba Member indicate an Early to Middle Llandoverian age for the lower Qusaiba (fig. 6; Mahmoud and others, 1992).

The general paleogeographic pattern is that of a major rapid transgression during the early Llandoverian followed by a regression (Al-Husseini, 1991), as reflected in a depositional sequence consisting of, in ascending order, organic-rich shale, sandy and shaly micaceous gray siltstone, and gray to dark-gray

Table 2. Paleozoic Qusaiba/Akkas/Abba/Mudawwara, Total Petroleum System 202301—Assessment Results Summary.

[MMBO, million barrels of oil. BCFG, billion cubic feet of gas. MMBNGL, million barrels of natural gas liquids. MFS, minimum field size assessed (MMBO or BCFG). Prob., probability (including both geologic and accessibility probabilities) of at least one field equal to or greater than the MFS. Results shown are fully risked estimates. For gas fields, all liquids are included under the NGL (natural gas liquids) category. F95 represents a 95 percent chance of at least the amount tabulated. Other fractiles are defined similarly. Fractiles are additive under the assumption of perfect positive correlation.
Shading indicates not applicable]

Figure 5. Paleozoic stratigraphic column of Jordan, Southwestern Desert of Iraq, and northern Saudi Arabia (modified from Agrawi, 1998). Correlations queried where uncertain.

and black fissile micaceous shale with black carbonaceous organic matter (fig. 6). The overlying Sharawa Member of the Qalibah Formation is siltstone and sandstone that is generally coarser than the underlying Qusaiba Member of the Qalibah Formation.

Cole, Halpern, and Aoudeh (1994) have recognized three distinct gamma-ray response zones (cool, warm, and hot) on well logs through the Qusaiba Member of the Qalibah Formation. Cool zones with low gamma-ray response are not considered to be a source rock and were deposited under oxic

Figure 6. Subsurface composite reference section for the Qalibah Formation in central Saudi Arabia, showing lithology, biostratigraphy, and gamma ray-density-neutron well-log patterns (modified from Mahmoud and others, 1992). Note “hot shale” unit of basal Qusaiba Member. NEUPOR. %, neutron log porosity in percent.

conditions. Moderate gamma-ray response zones (warm zones) contain moderate to excellent source-rock quality of dysoxic origin. “Hot shales,” of dysoxic to mainly anoxic origin, are excellent source rocks for the Paleozoic Qusaiba/Akkas/Abba/Mudawwara Total Petroleum System.

Qusaiba Member source rocks occur primarily in two subbasins, being thickest and most widespread in the southern basin south of Ar Riyad and thinner and less widespread in the northern Tabuk Basin (Jones and Stump, 1999). The Qusaiba Member in northern Saudi Arabia is as much as 1,200 m thick in the Widyan Basin (Agrawi, 1998). The “hot shale” is at least 60 m thick in the southern basin, south of Ar Riyad. In the Tabuk Basin the maximum thickness is about 30 m. The maximum thickness of age-equivalent strata in western Iraq (Akkas

Formation) is about 2,000 m. In the Akkas-1 and Khiesia-1 wells (fig. 3), the Silurian "hot shale" has an average thickness of about 65 m.

Petroleum Geochemistry

The "hot shale" source rock in the Tabuk Basin area, separately assessed as the Jafr-Tabuk Basin Province (2026) (fig. 2), has total organic carbon content (TOC) that exceeds 3 percent and has mixed oil/gas-prone to oil-prone potential (Alsharhan and Nairn, 1997). Microscopic study of "hot shale" source rocks by Monnier and others (1990, written commun.) identified primarily oil prone amorphous Type-II organic material. A marine shale origin is demonstrated by high rearranged to regular sterane ratios, tricyclic terpane distributions typical of marine shales, and relatively high diahopane to hopane ratios. Silurian-sourced oils from Saudi Arabia are isotopically light.

At Akkas-1 and Khiesia-1 wells the Silurian "hot shale" has TOC values as much as 16.6 percent, and a hydrocarbon yield of 49 kg (kilograms) per ton of rock, one of the highest yields in the world (Al-Gailani, 1996). Petrographic analysis of the kerogen extracted from these shales reveals a marine origin, rich in organic components such as algae, graptolites, and chitins.

Geochemical analysis of kerogens from the "hot shale" of the Western Desert revealed that the saturated and aromatic hydrocarbons exceed 96 percent of their components, which characterizes them as having low molecular weights (C3-C20) and limited amounts of asphaltic materials (about 3.89 percent). They are almost free of H_2S. Similar characteristics are reported for both the extracts of the Silurian "hot shales" and the hydrocarbons being produced from the Paleozoic reservoirs of Central Saudi Arabia and Jordan.

Maturation

Silurian "hot shale" source rocks began generating hydrocarbons possibly during the late Paleozoic in the region of northern Arabia into Iraq, and during the Triassic in the region of the present-day Arabian Gulf (fig. 7; Bishop, 1995). Peak generation, migration, and entrapment occurred through the Jurassic and ended in Early Cretaceous. As the rate of oil generation declined, gas saturation continued to form. Folding that developed during the late Tertiary when Arabia and Eurasia collided caused gas to displace oil that was already trapped in reservoirs. Major gas yield and entrapment ended in the deep basin of eastern Iraq and northeastern Saudi Arabia by early Neogene, but gas is still presently generated in updip regions (fig. 8). Silurian source rocks are presently immature at shallow depths.

In the Western Desert area, Silurian strata at Akkas-1 and Khiesia-1 wells are currently in the oil-generating zone. Agrawi (1998) (fig. 9) showed a burial history model of the Akkas-1 well in which the Silurian "hot shale" source rock entered the oil zone in late Paleozoic and remains there today.

Migration

As discussed by McGillivray and Al-Husseini (1992), the Qusaiba Shale subcrops beneath the Unayzah reservoir in central Saudi Arabia (fig. 10). The overlying Unayzah is an effective reservoir and provides a potential migration route for transport of hydrocarbons from the structurally deeper mature source-rock areas. Permeability enhancement is evident locally in sandstones below the pre-Unayzah unconformity and updip from the Qusaiba subcrop. Possible, but much less likely, is that subcropping pre-Qusaiba reservoirs could be charged from the overlying Unayzah. In both Iraq and Saudi Arabia the direction of migration is toward the west (Cole, Halpern, and Aoudeh, 1994).

In Iraq, along the eastern flank of the Akkas field, Al-Habba and Abdullah (1989) concluded that hydrocarbons migrated downward from the Lower Silurian source into the Ordovician upper Khabour fractured sandstone reservoir. Paleozoic reservoirs of trapped oil that followed similar migration pathways are expected in Saudi Arabia, and the Southwestern Desert of Iraq.

Reservoir Rocks

Unayzah Formation

In north-central Saudi Arabia, the primary Paleozoic reservoirs are the correlative Unayzah and Ga'ara Formations of Early Permian–Carboniferous age (fig. 5), which are bounded by two regional unconformities—the underlying pre-Unayzah (Hercynian) and the overlying pre-Khuff unconformity. The Unayzah Formation progressively overlaps, from east to west approaching the Arabian Shield, older inclined strata below the pre-Unayzah (Hercynian) unconformity, and fills in rifts and half-grabens.

Thickness of the Unayzah Formation is variable, ranging from less than 2 m on the west end of the Central Arabian Arch to more than 400 m in the Widyan Basin (Al-Laboun, 1987). The Unayzah is predominantly fluvial and alluvial fine- to coarse-grained quartz sandstone, flood-plain and distal fan siltstone, and varicolored flood-plain, distal fan, and playa claystone that contains stringers of carbonate in the upper part. It grades upward from alluvial fan conglomerate at the base into numerous braided channel fills, and is capped by distal fan and playa facies. Eolian sandstone beds are also present. Reservoir facies are predominantly sandstone beds that are fine to coarse grained and poorly cemented to friable. Thus, primary porosity and permeability are highly variable, and are reduced locally by kaolinite and illite. Polkowski (1997) noted the presence of authigenic clay minerals within the Unayzah reservoir rock that cause adverse effects during well drilling, completion, production, and (or) injection. Generally, porosity exceeds 20 percent and permeability may be several darcys.

During compaction and hydrocarbon generation, fluids rich in hydrocarbons and organic acids were expelled from shale

Figure 7. Time at which significant volumes of oil were generated from Lower Silurian strata (modified from Bishop, 1995). Note that this was possibly Carboniferous and late Paleozoic in northern Arabian Peninsula, and Triassic to the south in Arabian Gulf area. Queried boundaries indicate uncertain extent. Coordinates are approximate.

units of the Qusaiba Formation. These fluids migrated into Unayzah reservoir rocks and enhanced reservoir quality by leaching pore throats, corroding framework grains, and removing carbonate cement (Aktas and Cocker, 1995).

Pre-Unayzah Formations

Reservoir continuity may exist in dipping strata such as the Qusaiba and underlying reservoirs such as the Sarah, Qasim, and Saq Formations (fig. 5). These units are truncated by the pre-Unayzah unconformity and are in contact with the overlapping Unayzah or basal Khuff sandstone. Few data are available on pre-Unayzah Paleozoic potential reservoirs below the transgressive Khuff and Unayzah Formations. Such rocks are mainly clastics, and their reservoir quality may have been enhanced by weathering during the development of the Hercynian unconformity. The thickness of pre-Unayzah clastic rocks is as much as 1,000 m in the Widyan Basin (Al-Laboun, 1986).

The main Paleozoic reservoir rocks in the Western Desert of Iraq and East Jordan (Risha field) are sandstones of the Ordovician Upper Khabour and Silurian Akkas Formations (fig. 5). In the Akkas field, the Akkas-1 well contains high gravity oil (42° API) from the Silurian Akkas sandstone, and sweet gas from the upper sandstones of the underlying Ordovician Khabour Formation (Agrawi, 1998). Thirty to forty percent of all

Figure 8. Present-day levels of thermal maturity of Lower Silurian source rock in Arabian Peninsula (modified from Bishop, 1995). Note areas that are currently mature for oil and gas generation in northern Saudi Arabia and western Iraq. Level of maturity (LOM) values shown. Coordinates are approximate.

known reservoirs in Iraq occur within 600 m of the surface, and most of the remaining are within 3,000 m of the surface. The recent Paleozoic discovery at Akkas was at a depth of about 3,650 m (Agrawi, 1998).

Hydrocarbon Traps

Structural Traps

Structural features that control accumulation of petroleum are north-trending block-faulted anticlines reactivated above Precambrian basement fault blocks (fig. 10). Major structural growth occurred during the Late Devonian to Carboniferous Hercynian Orogeny (Simms, 1995). Paleozoic traps are moderate-relief, fault-generated structures with 30 to 100 m of closure. Prominent high-angle reverse faulting in the older Paleozoic section does not extend above the Carboniferous-Permian Unayzah Formation, and gentle drape folds occur in the overlying strata. Strata younger than early Eocene do not reflect deeper structures and there is little or no topographic expression of these long linear folds. Ghawar oil field is located on one of these structures, which has a total length of about 370 km (fig. 4). Two other north-trending structural features are present about 100 km and 200 km west of the Ghawar field. In addition to these

Figure 9. Burial history model of Akkas-1 well of western Iraq (modified from Agrawi, 1998). Basal Silurian "hot shale" source rock is shown to have remained in the oil generation window since the late Paleozoic. Location of the Akkas-1 well shown in figure 3.

major anticlines, many shorter ones are scattered over the Arabian shelf, most showing generally north south orientation.

Within Iraq, 526 structures have been identified and classified as potential hydrocarbon prospects with demonstrable closures (Al-Gailani, 1996). Most of these structures are elongated anticlines that range in length from 1 to 110 km. However, about one-third of the 526 structures are oval to circular in outline. Iraq has been divided into four tectonic settings with characteristically different structures (fig. 3) (Agrawi, 1998). These include thrust zone, folded zone, Mesopotamian Basin zone, and stable shelf zone (Western and Southwestern Desert).

The area of Iraq included in this assessment, the stable shelf zone, has about 155 prospects that range in length from 1 km to 46 km, with seven longer than 20 km. All of the exploration targets involve Triassic and Paleozoic formations in prospects with variable shape and size. Only 10 wells have been drilled in the stable shelf zone. Among the major field discoveries are Abu Khema, Diwan, Samawa, Ekhaidher, and Akkas. The major discovery in Paleozoic strata at Akkas is on a structure that is more than 27 km long and is the result of basement faulting. High gravity oil (42° API) is present in the Silurian Akkas sandstone reservoirs, and sweet gas occurs in the upper sandstones of the Ordovician Khabour Formation.

Stratigraphic Traps

Stratigraphic traps and combined stratigraphic-structural traps have also been identified in central Saudi Arabia; they

Figure 10. Diagrammatic model for migration of hydrocarbons generated from basal Qusaiba "hot shale" in central Saudi Arabia (modified from McGillivray and Al-Husseini, 1992). Note that petroleum (red) migrates upward to the Hercynian unconformity (wavy line) and laterally into the Unayzah Formation, which acts as the conduit for updip migration. This model may be applicable to a similar situation in the Widyan Basin to the north.

typically are updip pinchouts of Unayzah sandstone. The vertical closure mapped in many of these fields is insufficient to account for the observed hydrocarbon column, indicating a stratigraphic component. Evans and others (1997) studied the recent discovery of Arabian super light oil (49° API) in the Usaylah-1 well at Usaylah field (fig. 4). Production is from an updip pinchout of an upper Unayzah eolian dune sandstone unit. A second well at Usaylah field was drilled in a wadi fill channel of the equivalent-age dune sands at the Usaylah-1 well. Wells drilled into the finer grained Unayzah facies have poor production rates. Similar types of traps in the Unayzah are anticipated to occur within the Widyan Basin–Interior Platform Province.

Seals and Overburden Rocks

The most effective cap is the regional salt and evaporite seal, either within the Permian Khuff reservoir of Saudi Arabia and the age-equivalent Chia Zairi reservoir of Iraq (fig. 5) or in Triassic strata. Also, local seals may consist of tight, nonfractured dense limestone within the Khuff and Chia Zairi Formations. Local seals formed as a result of several cycles of shelf carbonate and evaporite deposition on the passive margin platform in what is now the foreland portion of the Arabian/Iranian Basin. Also, Lower Silurian shale regional seals extend from northern Saudi Arabia over most of the Southwestern Desert of Iraq (Agrawi, 1998).

Timing and Critical Events

The sequence of favorable events leading to the entrapment of petroleum include (1) truncation of Paleozoic sandstone reservoirs against faults, (2) drape of Unayzah clastics as reservoir and carrier beds, overlain by Upper Permian Khuff or Triassic tight formations, and (3) maturation and migration of hydrocarbons in the Triassic and Jurassic. Lower Silurian source rocks

Figure 11. Timing of events critical to petroleum accumulation in the Paleozoic Qusaiba/Akkas/Abba/Mudawwara Total Petroleum System of the Widyan Basin–Interior Platform Province (modified from Wender and others, 1998). Unayzah clastics were deposited on horst and graben features that formed during the Hercynian disturbance. Traps resulted where uplifted fault blocks formed anticlines into which petroleum migrated and was trapped by impermeable beds in the Khuff Formation or overlying Triassic strata.

entered the oil window as early as the Triassic and continued generating oil until the Tertiary. These same units entered the gas window during the later Jurassic and remain in the gas window at present (Wender and others, 1998) (fig. 11).

Jurassic Gotnia/Barsarin/Sargelu/Najmah Total Petroleum System

The Jurassic Gotnia/Barsarin/Sargelu/Najmah Total Petroleum System (202302) of the Widyan Basin–Interior Platform Province (2023) has two assessment units. These are the Platform Horst/Graben-Related Oil Assessment Unit (20230201), and Basinal Oil and Gas Assessment Unit (20230202) (fig. 12, table 3).

Source Rocks

Stratigraphy

Most of the petroleum is sourced from cyclically bedded Jurassic shales and carbonates (Callovian-Oxfordian-Kimmeridgian ages) that accumulated in three restricted intra-shelf basins (fig. 13). These basins—from north to south, the Gotnia, Arabian, and Southern Arabian Gulf Basins—formed on the passive margin platform of the Tethys sea after Permo-Triassic rifting. They were separated from each other and from the open Tethys sea to the east by shoals of calcarenite grainstones (Ayres and others, 1982).

In the Gotnia Basin, the largest and deepest of the three, source rocks are primarily bituminous limestone and shale of the Sargelu Formation (Middle Jurassic) (fig. 14). Similarly, source rocks in the Arabian and Southern Arabian Gulf Basins are primarily organic rich, thin-laminated peloidal carbonate of the Tuwaiq Mountain Formation (Upper Jurassic) and overlying Hanifa (Diyab/Dukhan) Formation. The richest source rocks in all three basins occur primarily as condensed sections deposited in the early phase of transgressive cycles. Circulation was restricted, allowing for preservation of large quantities of organic matter, mostly algal, under periodically anoxic bottom conditions in the basin centers. Source-rock facies of Callovian and Oxfordian ages in the Arabian Basin of eastern Saudi Arabia, with total organic carbon (TOC) $\geq$ 1.0 wt. percent, may reach a thickness of more than 90 m. In contrast, higher energy shallow-water grainstone and dolomitic limestone (the reservoir facies) accumulated at the basin margins. Evaporitic facies formed the seal for the hydrocarbons that accumulated in the high-energy shoal deposits, charged from the organic-rich shale and mudstone in the basin center. In latest Jurassic (Tithonian age) the seas eventually became shallower and evaporation rates increased, resulting in precipitation of evaporites that covered the organic-rich source and reservoir facies.

Figure 12. Widyan Basin–Interior Platform Province (2023) (outlined in bold red); Jurassic Gotnia/Barsarin/Sargelu/Najmah Total Petroleum System (202302) (outlined in green); Platform Horst/Graben-Related Oil Assessment Unit (20230201) (blue); Basinal Oil and Gas Assessment unit (20230202) (purple).

Petroleum Geochemistry

In the Gotnia Basin of Iraq, Upper Jurassic source rocks of the Sargelu, Naokelekan, and Gotnia Formations (Qara Chauq-1 well) and Naokelekan, Barsarin, and Chia Gara Formations (Kirkuk-109 well) have TOC values that range from about 2 to 5 percent of Type-II kerogen (Sadooni, 1997).

Cole, Carrigan, and others (1994) have reported on Upper Jurassic source rocks in the Arabian and Southern Arabian Gulf Basins, specifically at Khurais, Al Haba, Ghawar, and Abu Hadriya fields (fig. 4). Oil in these fields has API gravity of 25° to 35°. At Khurais field in eastern Saudi Arabia, the Tuwaiq Mountain Formation, the primary source rock, is 142 m thick. For the four oil fields just listed, source rocks of the Hanifa,

Table 3. Jurassic Gotnia/Barsarin/Sargelu/Najmah, Total Petroleum System 202302—Assessment Results Summary.

[MMBO, million barrels of oil. BCFG, billion cubic feet of gas. MMBNGL, million barrels of natural gas liquids. MFS, minimum field size assessed (MMBO or BCFG). Prob., probability (including both geologic and accessibility probabilities) of at least one field equal to or greater than the MFS. Results shown are fully risked estimates. For gas fields, all liquids are included under the NGL (natural gas liquids) category. F95 represents a 95 percent chance of at least the amount tabulated. Other fractiles are defined similarly. Fractiles are additive under the assumption of perfect positive correlation. Shading indicates not applicable]

Figure 13. Gotnia, Arabian, and Southern Arabian Gulf Basins in which Jurassic hydrocarbon source rocks accumulated (modified from Alsharhan and Kendall, 1986). Sawteeth on upthrown block of Zagros thrust suture zone.

Tuwaiq Mountain, and Dhruma Formations (fig. 14) were compared by Cole, Carrigan, and others (1994); they reported TOC averages as follows: Hanifa 2.60 percent, Tuwaiq Mountain 3.52 percent, and Dhruma 1.80 percent. Source rocks are composed primarily of amorphous Type-II kerogen (from blue-green algae), which makes them capable of generating large amounts of petroleum, particularly oil (hydrogen indices exceed 600 mg (milligrams) of hydrocarbons per gram (g) of TOC).

Figure 14. Correlation of Jurassic strata of western and southern Arabian Gulf region (modified from Al-Husseini, 1997).

Pyrolysis yields average 22.2 mg hydrocarbons/g rock. Most of these source rocks are within the oil-generating window and thus have excellent petroleum generation potential.

Oil to Source Rock Correlation

Based on selected chromatographic, carbon isotopic, and biomarker parameters studied by Cole, Carrigan, and others (1994), a clear correlation exists between Jurassic Hanifa and Tuwaiq Mountain source rocks and Arab and Hanifa Formation oils. Arab and Hanifa oils are high-sulfur (1–4 percent), aromatic-intermediate oils that are consistent with a marine-carbonate source. Comparison of gas chromatograms between Arab oil and Hanifa source-rock extract from the same field show great similarity. Alsharhan and Nairn (1997) also compared C 27–29 regular steranes from Upper Jurassic oils with Hanifa and Tuwaiq Mountain source-rock extracts. Their similarity also supports the interpretation that the Tuwaiq Mountain and Hanifa are the source of Jurassic oil.

Maturation

Maturation of the Upper Jurassic source-rock formations in Iraq (Sargelu and Naokelekan Formations) began around 90 Ma, with peak generation from 85 to 13 Ma (fig. 15; Murris, 1981). Generally, trap growth in Iraq took place through most of the Mesozoic, although Late Cretaceous and Miocene to Recent are the principal periods of growth. Ayres and others (1982) have estimated the degree of maturation of the kerogen within the Gotnia and Arabian Basins from atomic hydrogen/carbon (H/C) ratios, and from calculated maturity based on Lopatin's time-temperature index (TTI) method; from these data, they interpreted that maturation and migration of oils from Jurassic source rocks began in early Tertiary time.

Because of a slower rate of deposition in the Arabian and Southern Arabian Gulf Basins than to the northeast in Iraq, petroleum generation and migration from the Hanifa Formation in the Arabian and Southern Arabian Gulf Basins were not widespread until about 55 Ma.

Figure 15. Burial history of the Hanifa and Sargelu Formations (modified from Murris, 1981). Mature zone is colored yellow. VR/E, calculated maturity in vitrinite reflectance equivalent units. Periods of uplift and erosion shown (dashed line); corrected burial history curve shown (wavy red line).

Migration

Petroleum generated from Jurassic source rocks in the Gotnia Basin migrated updip to the west and south into basement-related, block-faulted structures that moved periodically since Precambrian. Ayres and others (1982) stated that the relatively large number of oil reservoirs implies extensive vertical migration of oils from a more limited number of rich source rocks. For example, evidence in the Ghawar field suggests that the Hanifa reservoir is in hydraulic continuity with the Arab D reservoir, probably maintained through vertical fractures. Presence of oil in the upper Arab reservoirs implies that, at least locally, the Arab anhydrite interbeds were absent or in communication through fractures or fault offsets with underlying carbonate rocks. The Hith Anhydrite appears to be an effective seal everywhere except in the northeast offshore area.

Reservoir Rocks

Hanifa Formation, Tuwaiq Mountain Formation, and Arab Formation

Jurassic reservoirs are almost exclusively cyclic interbedded calcarenite, calcarenitic limestone, dolomite, and organic-rich carbonate source rocks (fig. 14). The best reservoirs are in the high-energy calcarenite-grainstone facies that accumulated around the Gotnia, Arabian and Southern Arabian Gulf Basins (Alsharhan and Kendall, 1986).

The Hanifa, Tuwaiq Mountain, and Arab Formations exhibit similar cyclic sedimentation—transgressive-regressive depositional cycles that consist of a shallowing-upward marine carbonate sequence overlain by anhydrite. Each carbonate cycle concludes with an ooidal-pelletoidal grainstone. These grainstones contain most of the oil in Jurassic reservoirs (Arab A, B, C, D; Lower Kimmeridigian to Tithonian) in Saudi Arabia. They are cyclical calcarenites (grainstone, coarse lime sand to gravel, oolitic and peloidal), aphanitic limestone, anhydrite, and dolomite. A typical depositional cycle began with regression of the sea that resulted in lateral shift of reservoir grainstone facies basinward (Cole, Carrigan, and others, 1994). Further regression exposed the shelf surrounding the intra-shelf basins where water became euxinic and source rocks were deposited. As sea level rose during the next transgression, euxinic conditions ended and reservoir grainstones (high energy) were deposited on intra-shelf basinal source rocks. This type of cyclic stratigraphy was ongoing throughout the Middle to Late Jurassic.

Most Jurassic reservoirs lie at depths ranging from 1,400 to 3,750 m (Alsharhan and Nairn, 1997). Primary porosity in the reservoir grainstones has been reduced by secondary recrystallization and dolomitization. Porosity and permeability are variable

Figure 16. Distribution of the Jurassic Tithonian evaporite seal lithofacies (in shades of pink to purple) in Arabian Gulf region (modified from Murris, 1981). Queried boundaries shown.

in the Arab Formation reservoirs, ranging from 1 to 30 percent and from about 0.1 millidarcy (mD) to greater than 5,000 mD, respectively.

Sargelu Formation, Naokelekan Formation, and Najmah Formation

In the Gotnia Basin, source rocks are organic-rich beds within the Sargelu, Naokelekan, and Najmah Formations (fig. 14). However, where porous and permeable interbeds exist with a local seal, they can also be a minor oil reservoir, such as at Hamrin and Alan fields (fig. 3). Generally, the Najmah Limestone is the primary reservoir; this unit consists of oolitic limestone, dolomite, and anhydrite that were deposited in a shallow marine and transitional marine setting of lagoons and shoals, similar to the Arabian and Southern Arabian Gulf Basins. Locally, oolitic and sandy, marly, argillaceous limestone reservoir facies of the Sargelu and Najmah Formations are laterally juxtaposed to argillaceous limestone marl and shale source-rock facies of the Sargelu. As the seas regressed, the basin was covered with seal rocks of anhydrite intercalated with limestone and dolomite.

The overlying Gotnia Formation consists of evaporite, anhydrite, oolitic limestone, and bituminous shale that were

Figure 17. Events chart for that part of the Jurassic Gotnia/Barsarin/Sargelu/Najmah Total Petroleum System (202302) that lies in Arabian Basin (modified from Cole, Carrigan, and others, 1994).

deposited in an evaporite basin and lagoonal setting. The Gotnia is locally a minor oil reservoir. The anhydrite is a cap rock. Oil tested in Fallujah-1 well in Fallujah field comes from the interbedded subordinate limestone units. In the Gotnia Basin, the Gotnia Formation is nearly isochronous with the Arab Formation (fig. 14) but has thicker evaporite cycles (Yousif and Neuman, 1997).

Hydrocarbon Traps

The Jurassic Gotnia/Barsarin/Sargelu/Najmah Total Petroleum System (202302) has two assessment units, the Platform Horst/Graben-Related Oil Assessment Unit (20230201) and the Basinal Oil and Gas Assessment Unit (20230202). Their boundaries are shown in figure 12, and their assessed undiscovered volumes are shown in table 3. Both assessment units have traps that formed on reactivated basement fault blocks with a drape component resulting in elongate and broad anticlinal structures. Additionally, the Basinal Oil and Gas Assessment Unit contains oil and gas that accumulated in folds resulting from plate collision and nappe abduction that began in the Late Cretaceous. Generally, trap growth took place through most of the Mesozoic, although Late Cretaceous and Miocene to Recent are the principal periods of growth. Reservoir rocks and seals are similar for both assessment units.

Platform Horst/Graben-Related Oil Assessment Unit (20230201)

The main producing areas of Saudi Arabia are located on the northeastern part of the Central Arabian Arch. The basement of Arabia was broken into blocks during Precambrian time. These blocks were reactivated in several stages: (1) the Hercynian Orogeny, (2) following Permo-Triassic rifting, (3) during Late Cretaceous plate collision and nappe abduction, and (4) during late Miocene to recent.

In the Widyan Basin, traps are on fault-block anticlines, with elongated generally north south trends, that occur over reactivated, deep-seated Precambrian/Hercynian faults with some “drape” compaction (Ayres and others, 1982; Christian, 1997). The anticlines have flat tops and long linear flanks with relatively steep dips in the upper beds (as much as 10°). Ghawar oil field, east of this assessment area, is on one such structure that has a total length of about 370 km. The region to the north of the western Widyan Basin and extending to the Tigris/Euphrates drainage area may have good source and reservoir facies but limited continuity of evaporite seal facies. Numerous prospects and structures have been identified in Iraq, and many of them have irregular forms. In addition to major anticlines, there are many shorter anticlines scattered over the Arabian shelf, all showing generally north south orientation.

Basinal Oil and Gas Assessment Unit (20230202)

Numerous prospects and structures have been identified in Iraq. Oil and gas are trapped in elongate north-south-trending fault-block anticlines over reactivated, deep-seated faults in the Mesopotamian Basin region. Also, there may have been early entrapment when Zagros folds were beginning to form during Late Cretaceous and Tertiary, coincident with peak petroleum migration. Later (during the Miocene-Pliocene) oil generation may have been renewed, associated with thick molasse deposition to the east. Tectonic elements of the Mesopotamian Basin, Zagros Fold Belt, and Zagros Thrust Zones, along with the northwest-trending compressive folds accompanying the Zagros collision zone, may contain significant volumes of petroleum that were derived from Jurassic source rocks.

Hanifa source rocks were in the oil window and migration occurred by Tertiary time (fig. 15). Source rocks to the north in the Sargelu Formation of the Gotnia Basin passed into the oil window during the Early Cretaceous. If oil migrated southward from this basin into the region of Province 2023, an additional 35 million years of migration and accumulation may have occurred, but this would have to predate the folding that took place during Campanian time in the early Zagros collisional zone. Previously trapped oil in the Gotnia Basin may have been remobilized and migrated into Zagros-related folds.

Seals and Overburden Rocks

The regional seal of the Arabian shelf is the Upper Jurassic Tithonian Hith Anhydrite, a massive 90- to 120-m-thick anhydrite that formed when the south margin of the Tethys sea broke up (fig. 16). Where the anhydrite pinches out in the southern Arabian Gulf region, upward and lateral leakage of hydrocarbons took place from below into younger reservoirs. Upward seepage through the salt caps is facilitated only where permeability is enhanced, resulting from fracturing, faulting, or facies changes. The Upper Jurassic Hanifa and Jubaila Formations have interbedded shale and carbonate reservoirs, with the shale beds providing seals to trap hydrocarbons in the carbonate reservoirs. In central Saudi Arabia, local seals are tight anhydrite and dolomite in the Arab Formation. The thin layers of anhydrite that separate the four units of the Arab Formation were deposited in restricted intra-shelf depressions on a silled shelf in an arid, low-latitude location.

To the north in Iraq, the Najmah and Gotnia-Barsarin are less cyclic. There, the Gotnia Formation is about 200 m of anhydrite with subordinate shale and limestone, and forms a tight seal for local oil and gas accumulations in the underlying Najmah Limestone.

Timing and Critical Events

Critical events are summarized in figure 17. The northern Gotnia source basin was buried deeper during the Cretaceous than the Arabian platform and therefore passed into the oil window in Early Cretaceous, some 35 million years before the Hanifa of the Arabian Basin (fig. 15). By Tertiary time, the Hanifa was in the oil window, and perhaps a second migratory phase or the original migratory phase began.

The Tuwaiq Mountain Formation source rock reached early-stage maturity for oil generation at about 75 Ma and attained peak oil expulsion in the deeply buried areas by Late Cretaceous and early Tertiary; hydrocarbons then began to accumulate in broad, gentle structures. By 25 Ma, most of the hydrocarbons generated in the Tuwaiq Mountain and Hanifa Formations north and south of the basin center had also begun to migrate into basin margin structures (Alsharhan and Nairn, 1997; Cole, Carrigan, and others, 1994). There are presently large areas of active oil-generation.

Petroleum Assessment

Within the boundary of the Widyan Basin–Interior Platform Province (2023), portions of five total petroleum systems contribute to the petroleum assessment of this province. Two of these total petroleum systems are dominant in the province and are described in this report, that is, the Paleozoic Qusaiba/Akkas/Abba/Mudawwara TPS and the Jurassic Gotnia/Barsarin/Sareglu/Najmah TPS. Portions of three other petroleum systems are also found within the province. Portions of two petroleum systems allocated to the Greater Ghawar Uplift Province (2021) extend into Province 2023, including the Central Arabia Qusaiba Paleozoic TPS and the Arabian Sub-Basin Tuwaiq/Hanifa-Arab TPS. The Zagros-Mesopotamian Cretaceous-Tertiary TPS assigned to the Zagros Fold Belt Province (2030) also extends into Province 2023. Allocations were made to Province 2023 from these three TPS whose areal extent crosses into Province 2023 (table 1).

Previous assessments of Saudi Arabia by Masters and others (1994) did not include estimates for the Paleozoic Total Petroleum System; thus direct comparisons are not made with that assessment. The significant discoveries of Paleozoic hydrocarbons, particularly in Iraq at the Akkas field, significantly alter the petroleum potential for this province. Petroleum-migration modeling studies were undertaken to understand the hydrocarbon potential for both Paleozoic and Jurassic Total Petroleum Systems in the province. These modeling studies (Steinshour and others, 2001) coupled with proprietary prospect information were critical to clarification of the undiscovered potential of these systems.

Known petroleum volumes of 18.7 BBOE (17.4 BBO, 7.4 TCF gas or 1.23 BBOE, and <0.1 BBNGL) give the province a ranking of 23rd in the world, exclusive of the United States (Klett and others, 1997). The recent U.S. Geological Survey assessment estimated the total petroleum endowment (cumulative production plus remaining reserves plus estimated mean undiscovered volumes) for this province at 62.54 BBOE (38.7 BBO, 102.1 TCF gas or 17.1 BBOE, and 6.84 BBNGL; U.S. Geological Survey World Energy Assessment Team, 2000). This petroleum volume gives the province a ranking of 17th in the world exclusive of the U.S. It is classified as an oil province (Ahlbrandt and others, 2000).

The estimated mean undiscovered volumes of the Paleozoic Qusaiba/Akkas/Abba/Mudawwara TPS (202301) are 2.63 BBO, 64.51 TCF gas or 10.75 BBOE, and 5.08 BBNGL. Recent data from Paleozoic reservoirs of this TPS, particularly in Jordan and Iraq, indicate relatively high thermal maturity, which is also reflected in dominance of gas and natural gas liquids within the system (table 2).

The mean estimates of undiscovered volumes of the Jurassic Gotnia/Barsarin/Sargelu/ Najmah TPS (202302) are 6.60 BBO, 22.94 TCF gas or 3.82 BBOE, and 1.11 BBNGL (table 3). This system is dominantly oil, reflecting the lower thermal maturity of the Jurassic source rocks of this TPS when compared to Silurian source rocks of the Paleozoic system. Mean undiscovered oil estimates for the province, which include both Paleozoic and Jurassic petroleum systems as well as portions of the other three TPS allocated to the Widyan Basin–Interior Platform Province (2023) (U.S. Geological Survey World Energy Assessment Team, 2000), are 21.22 BBO, 94.75 TCF gas (15.8 BBOE) and 6.85 BBNGL (table 1).

The province discovery maturity of 31 percent demonstrates that much of the province's petroleum potential for both oil and gas lies in the future (Ahlbrandt and others, 2000).

Summary

The Paleozoic Qusaiba/Akkas/Abba/Mudawwara Total Petroleum System has one assessment unit in the Widyan Basin–Interior Platform Province, identified as the Horst/Graben-Related Oil and Gas Assessment Unit. High-gravity crude oil and natural gas occur in horst/graben-related traps that formed prior to, during, and after the Hercynian Orogeny (Carboniferous). Petroleum is sourced from organic-rich marine "hot shale" at the base of Silurian strata (Qusaiba, Akkas, Mudawwara, and Abba Formations) that were deposited under dysoxic to anoxic conditions in an intra-shelf basin located north of the Central Arabian Arch. Onset of oil generation in Iraq began about 250 Ma and in eastern Saudi Arabia about 160 Ma, reaching a peak with accompanying migration and entrapment through the Jurassic. By the early Tertiary maturation had largely ceased. The Zagros collision of the Arabian and Eurasian plates in the Miocene resulted in reactivation of maturation and generation, and increased trap capacity.

In Saudi Arabia, fluvial and eolian quartzose sandstones of the Carboniferous–Lower Permian Unayzah Formation overlie the Hercynian unconformity and were deposited in rifts and half-grabens. In Iraq, reservoirs are in sandstones of the Ordovician Upper Khabour and Silurian Akkas Formations.

Structural features that control accumulation of petroleum in Saudi Arabia are moderate-relief, fault-generated structures with 30–100 m of closure in north-trending block-faulted anticlines (horsts and grabens) that were reactivated over Precambrian basement blocks during the Late Devonian to Carboniferous Hercynian Orogeny. Hydrocarbons migrated vertically along reactivated basement-rooted faults or associated fracture zones along the flanks of these structures. Combined stratigraphic-structural traps may also exist where the Carboniferous–Lower Permian Unayzah Formation is the reservoir, as is the case in central Saudi Arabia.

Petroleum is sealed in the Unayzah reservoirs by overlying tight carbonate-evaporites within the Upper Permian Khuff Formation or in overlying Triassic strata, and by sub-unconformity pinchouts of pre-Unayzah clastic reservoir units against impermeable facies. Lower Silurian shale extends over most of the Southwestern Desert of Iraq and acts as a seal for hydrocarbons in the underlying Ordovician Khabour Formation.

The Jurassic Gotnia/Barsarin/Sargelu/Najmah Total Petroleum System in the Widyan Basin–Interior Platform Province has two assessment units: (1) Platform Horst/Graben-Related Oil, and (2) Basinal Oil and Gas. Reservoirs are developed in the Upper Jurassic Najmah Limestone and Gotnia Formation (in Iraq), and equivalent Arab Formation (in Saudi Arabia) as lenses of marine bar or shelf margin calcarenites, calcarenitic limestone, and dolomite. These grade eastward into organic-rich muddy limestone hydrocarbon source rocks that were deposited under anoxic and dysoxic conditions in three restricted intra-shelf basins—from north to south, the Gotnia, Arabian, and Southern Arabian Gulf Basins. Maturation of the Upper Jurassic source-rock formations (in Iraq named Sargelu and Naokelekan) began around 90 Ma, with peak generation from 85 to 13 Ma. Oil was first trapped in calcarenite lenses, then was concentrated in anticlines by structural growth that may have begun in Early Cretaceous time and completed by Miocene time. Younger Jurassic shale and anhydrite seal rocks are distributed throughout the total petroleum system.

Major factors contributing to the large reserves of oil in Jurassic reservoirs on the Arabian shelf are (1) a carbonate-evaporite shelf containing extensive high porosity and permeability reservoirs adjacent to widespread and thermally mature organic-rich source rocks; (2) cyclic sedimentation in which most cycles are capped with widespread evaporite seals deposited during regressions; and (3) growth of large structural traps coincident with long phases of oil generation and migration.

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