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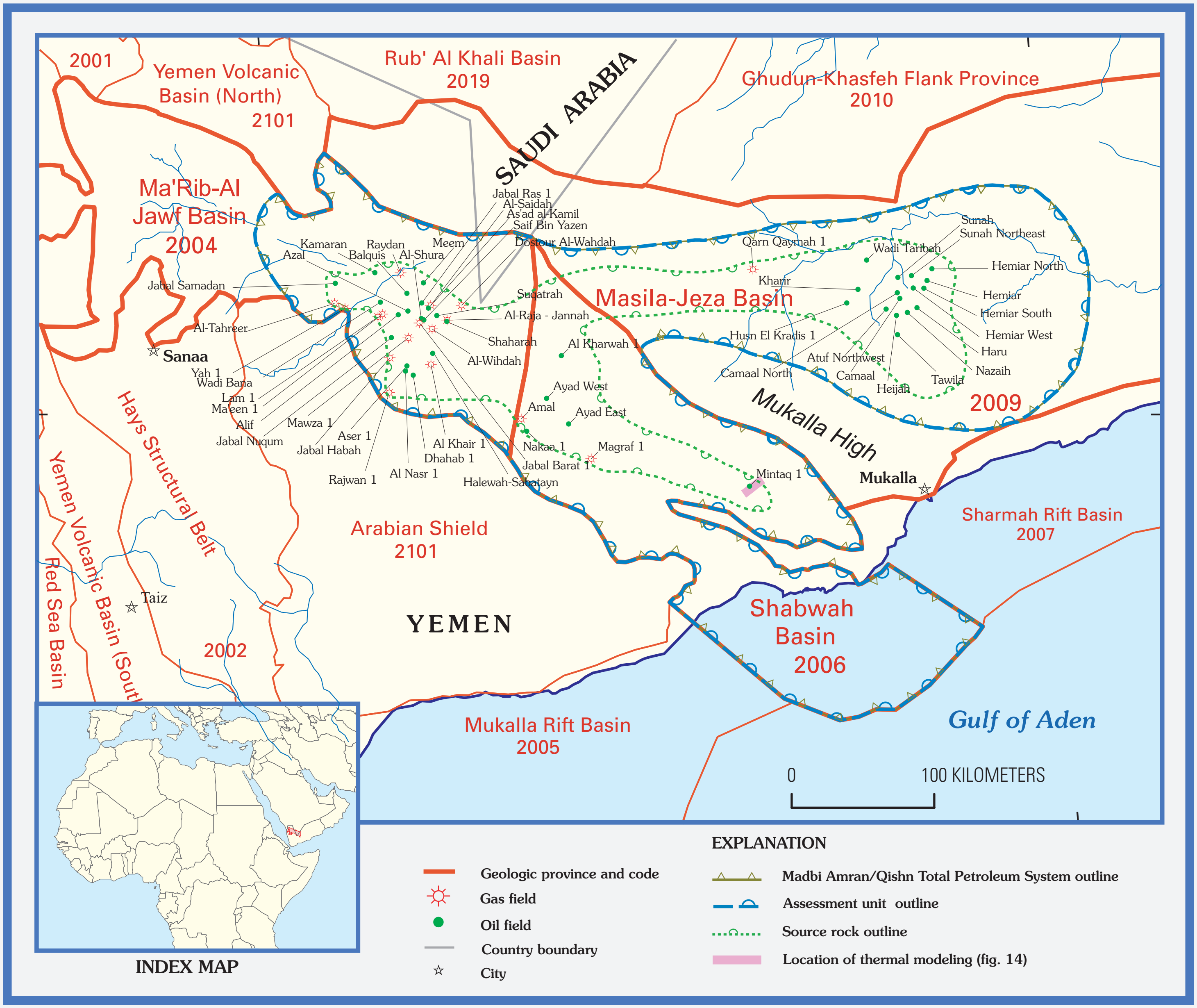
Madbi Amran / Qishn Total Petroleum System of the Ma′Rib–Al Jawf / Shabwah, and Masila-Jeza Basins, Yemen



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Madbi Amran / Qishn Total Petroleum System of the Ma′Rib–Al Jawf / Shabwah, and Masila-Jeza Basins, Yemen

By Thomas S. Ahlbrandt

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Foreword

This report, describing the petroleum resources of a total petroleum system in Yemen, was prepared as part of the World Energy Assessment Project of the U.S. Geological Survey. For this project, the world was divided into 8 regions and 937 geologic provinces, which were then ranked according to the discovered oil and gas volumes within each (Klett and others, 1997). Of these, 76 "priority" provinces (exclusive of the U.S. and chosen for their high ranking) and 52 "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. The total petroleum system includes 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 proved 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 project and will 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	2**004**
Total petroleum system, two digits to the right of province code	2004**01**
Assessment unit, two digits to the right of petroleum system code	200401**01**

The codes for the regions and provinces are listed 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

Since the first discovery of petroleum in Yemen in 1984, several recent advances have been made in the understanding of that country's geologic history and petroleum systems. The total petroleum resource endowment for the combined petroleum provinces within Yemen, as estimated in the recent U.S. Geological Survey world assessment, ranks 51st in the world, exclusive of the United States, at 9.8 BBOE, which includes cumulative production and remaining reserves, as well

as a mean estimate of undiscovered resources. Such undiscovered petroleum resources are about 2.7 billion barrels of oil, 17 trillion cubic feet (2.8 billion barrels of oil equivalent) of natural gas and 1 billion barrels of natural gas liquids. A single total petroleum system, the Jurassic Madbi Amran/Qishn, dominates petroleum generation and production; it was formed in response to a Late Jurassic rifting event related to the separation of the Arabian Peninsula from the Gondwana supercontinent. This rifting resulted in the development of two petroleum-bearing sedimentary basins: (1) the western Ma'Rib–Al Jawf / Shabwah basin, and (2) the eastern Masila-Jeza basin. In both basins, petroleum source rocks of the Jurassic (Kimmeridgian) Madbi Formation generated hydrocarbons during Late Cretaceous time that migrated, mostly vertically, into Jurassic and Cretaceous reservoirs. In the western Ma'Rib–Al Jawf / Shabwah basin, the petroleum system is largely confined to syn-rift deposits, with reservoirs ranging from deep-water turbidites to continental clastics buried beneath a thick Upper Jurassic (Tithonian) salt. The salt initially deformed in Early Cretaceous time, and continued halokinesis resulted in salt diapirism and associated salt withdrawal during extension. The eastern Masila-Jeza basin contained similar early syn-rift deposits but received less clastic sediment during the Jurassic; however, no salt formed because the basin remained open to ocean circulation in the Late Jurassic. Thus, Madbi Formation-sourced hydrocarbons migrated vertically into Lower Cretaceous estuarine, fluvial, and tidal sandstones of the Qishn Formation and were trapped by overlying impermeable carbonates of the same formation. Both basins were formed by extensional forces during Jurassic rifting; however, another rifting event that formed the Red Sea and Gulf of Aden during Oligocene and Miocene time had a strong effect on the eastern Masila-Jeza basin. Recurrent movement of basement blocks, particularly during the Tertiary, rather than halokinesis, was critical to the formation of traps.

Introduction

This report describes the total petroleum system (TPS), the Jurassic Madbi Amran / Qishn of the Ma'Rib–Al Jawf Basin (2004), Shabwah Basin (2006), and Masila-Jeza Basin (2009) provinces (fig. 1). The estimated undiscovered resources of the TPS are all contained within the country of Yemen. In terms of a political entity, Yemen is a relatively young country; and it is also a recent petroleum-producing area, with the first petroleum discovery of oil at Alif field in 1984 (fig. 1). Of the world's 409 geologic provinces that contain hydrocarbons, 3 such provinces are in Yemen and are combined into one total petroleum system with a ranking of total petroleum endowment of 51st in the world. The total petroleum endowment of this TPS is an estimated 9.8 BBOE (billion barrels of oil equivalent) (Ahlbrandt and others, 2000), and with a production of about 405,800 BOPD (barrels of oil per day) from this TPS (International Petroleum Encyclopedia, 2000), Yemen is now recognized as a significant petroleum-producing country. The geologic understanding of Yemen in the last two decades, particularly the last 10 years, has been substantially improved, causing an essentially unexplored area to become an important petroleum-producing area in a relatively short time.

Acknowledgments

This paper benefited from discussions with Dr. David Boote, Occidental Oil Company, and other members of the World Energy Consortium, an advisory group to the World Energy Project. Reserves data are derived from Petroconsultants (1996) and oil data are derived from GeoMark (1998). The Oil and Gas Journal and Dr. Istvan Csato of MOL Hungarian Oil Company gave permission for use of selected figures in this report that is much appreciated. Richard Pollastro and Timothy Klett reviewed the manuscript and made many helpful suggestions.

Province Geology

Province Boundaries

Yemen is located in the southwestern portion of the Arabian Peninsula, bordered by the Red Sea to the west, the Gulf of Aden to the south, and the Arabian Sea to the east. It shares a common border with Oman on the east and a disputed border with Saudi Arabia on the north (fig. 2). Yemen is divided into 10 geologic provinces by the USGS, 3 of which contain petroleum (Klett and others, 1997). These three provinces are Ma'Rib–Al Jawf Basin (2004), Shabwah Basin (2006), and Masila-Jeza Basin (2009) (fig. 1). One total petroleum system, the Madbi Amran / Qishn, encompasses the hydrocarbon potential of Yemen and crosses these three petroleum province boundaries (fig. 1). Subsequently, the geologic understanding of the area permitted combining the three provinces into two basins as described in the total petroleum system section.

Geographic Setting

Yemen is bounded by 1,900 km (kilometers) of coastline of the Red Sea along its western border and the Gulf of Aden at its southern border. A narrow coastal plain adjacent to a mountainous Precambrian terrane to the west gives way to a dissected upland desert plain to the east and merges into the great deserts of the Rub' Al Khali farther to the north and east (figs. 2, 3). The climate ranges from hot and humid in the west to extraordinarily hot in the deserts to the northeast.

The area of Yemen is 527,970 km^2, about twice the size of the State of Wyoming. Yemen claims a 200-nautical mile (or to the edge of the continental shelf) exclusive economic zone.

Political and Exploration History

Politically, Yemen had been divided into two countries—Northern Yemen (the Yemen Arab Republic, YAR), and South Yemen (the former Aden Protectorate and later the People's Democratic Republic of Yemen, PDRY)—until 1990 when they were united to form the Republic of Yemen. North

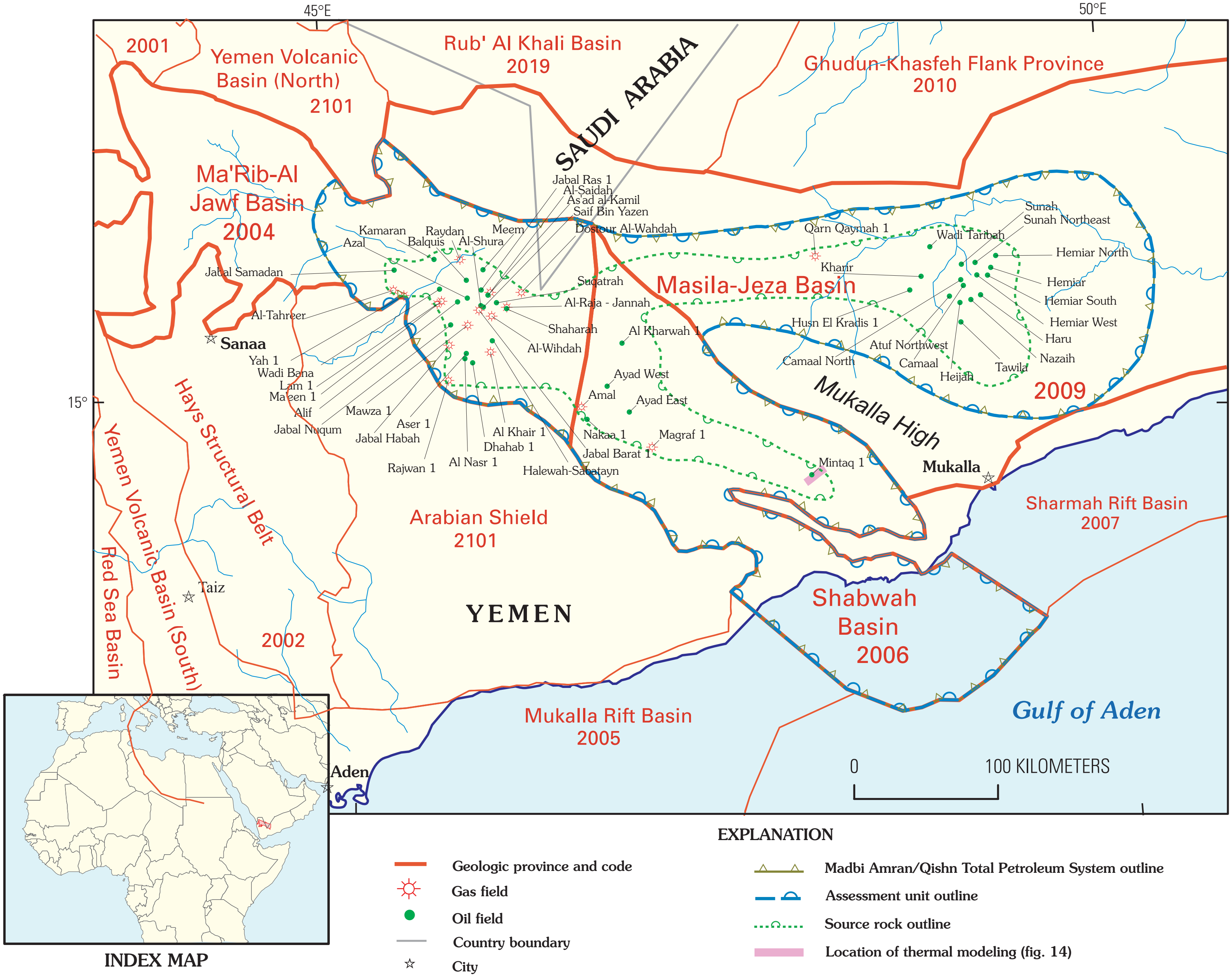
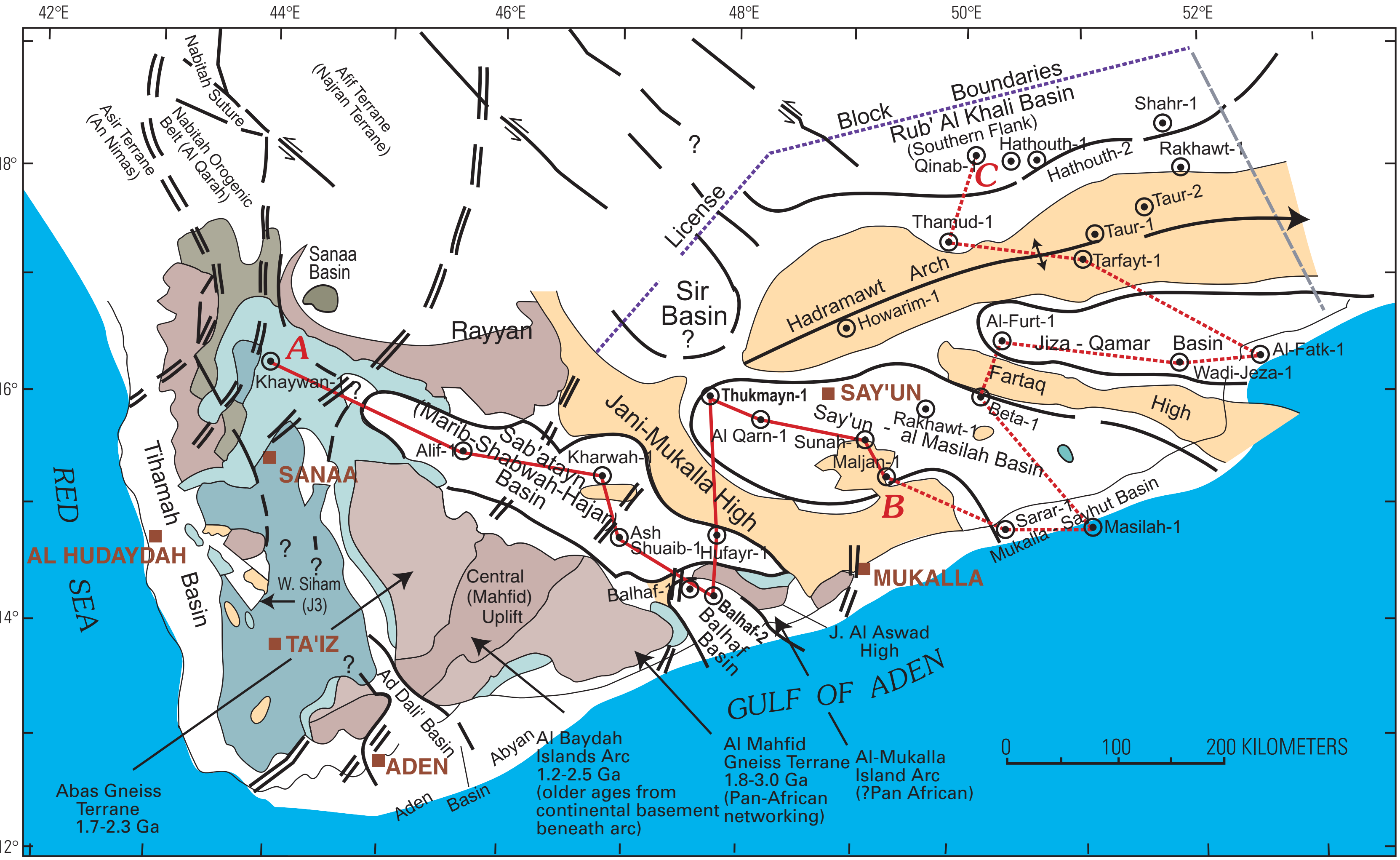


Figure 1. Geologic provinces, Madbi Amran/Qishn Total Petroleum System, assessment unit, and major petroleum basins in and adjacent to Yemen.

Figure 2. Location of cross sections (in red), selected well locations, administrative provinces, and areas of dune sand of Yemen (modified from Beydoun and others, 1998).



EXPLANATION

- Location of exploration wells
- Subsurface Najd faults modified from Dyer and Husseini, 1991; barbs show relative movement
- Approximate limits of various Precambrian terranes
- Basin boundary
- Anticline
- Volcanic (Tertiary Yemen Volcanic Group)
- Jurassic outcrop area (resting on basement except in northwest)
- Basement outcrop area (Archean Late Proterozoic)
- Cretaceous on basement (Jurassic eroded/not deposited)
- Paleozoic outcrop area

Figure 3. Structural elements including basins, highs, faults, and outcrop belts, and cross section locations (red lines) (modified from Beydoun and others, 1998).

Yemen (also called Sanaa) became independent of the Ottoman Empire in 1918, and South Yemen became independent of a British protectorate in 1967. South Yemen (People's Democratic Republic of Yemen, PDRY, or Aden) was a Marxist-dominated government until it merged with North Yemen to form the Republic of Yemen. The unification of the republic and the technological revolution in petroleum exploration brought into the country in the 1980's and 1990's changed the country dramatically in both political and economic terms. Currently, Yemen has a population of about 17.5 million, most of whom are Arabic and of the Muslim faith.

Political turmoil has surrounded Yemen during its history and continues to the present. During the time of separate North and South Yemen countries, 1967–1990, hostilities between the two countries resulted in the migration of hundreds of thousand of Yemenis from the south to the north. Following unification in 1990, a secessionist effort in southern Yemen in 1994 failed, and the country remained a republic. It continues to be an area in dispute particularly along its northern border with Saudi Arabia.

The complex political history of Yemen contributed to a general lack of petroleum exploration until the discovery of Alif field in North Yemen in the Ma'Rib–Al Jawf / Shabwah basin in 1984 (fig. 1) (Beydoun, 1966; Beydoun, 1989; Fairchild, 1992; Schlumberger, 1992; Petroconsultants, 1996; Bosence, 1997; Maycock, 1997). This successful exploration effort, in provinces 2004 and 2006 (fig. 1), was led by Hunt Oil Company and its initial partners from Korea, who formed Yemen Hunt Oil Company (YHOC). This company later merged with Exxon Yemen to form Yemen Exploration and Producing Company. The initial oil discovery at Alif was followed by 11 other discoveries of both oil and gas (figs. 1, 2).

A second petroleum basin area, here referred to as the Masila-Jeza basin (province 2009), lies to the east of the Mukalla High (fig. 1). Oil production was established there in 1991 by a Canadian Oxy-led consortium (CanadianOXY/CCC/Pecten/Occidental); the discovery of oil at Sunah field was rapidly followed by other discoveries at Heijah and Camaal and a dozen other fields (Mills, 1992; fig. 1). Twenty exploration companies are now active in Yemen, mostly independents (International Petroleum Encyclopedia, 2000).

Currently, two state-owned oil refineries operate in Aden with capacities of 170,000 BOPD and a 10,000 barrel per day topping plant in Marib. Two other refineries are in the planning stage including increased capacity (75,000 BOPD) at Aden and a 120,000–200,000 BOPD refinery at Mukalla. A liquefied natural gas plant, to be built by Enron at Ras Omran on the Arabian Sea, is designed to market gas to Asia from the gas fields in the Ma'Rib-Al Jawf / Shabwah area of western Yemen. A 400-km gas pipeline is planned for construction by Enron from the western Yemen gas fields to Ras Omran. The implementation of this 1993 plan to market LNG (liquid natural gas) has yet to be completed. As of 2000, oil reserves were believed to be 4 BBO and gas reserves are given as 16.9 TCF (trillion cubic feet) (International Petroleum Encyclopedia, 2000).

Geologic Setting

Petroleum occurs in two rift basins in Yemen. In western Yemen, petroleum is generated and produced in the Ma'Rib–Al Jawf / Shabwah basin, and in eastern Yemen in the Masila-Jeza basin. These eastern and western basins are largely separated by a structural high known as the Mukalla or Jahi-Mukalla High (figs. 1, 3). The western basin is known by a variety of names such as Sabatayn, Marib-Shabwa-Hajar (Beydoun and others, 1998), and Marib-Shabwa basin (Brannin and others, 1999; Csato and others, 2001). Similarly, the eastern basin is also known as the Sayun al Masilah and Jiza-Qamar basin (Beydoun and others, 1998), Sayun basin, and Sir-Sayun basin (Csato and others, 2001). These basins are part of a system of major rift basins, and various authors have used a variety of names for both the main basins and the sub-basins or grabens that occur within them. The names used herein attempt to represent the major petroleum basins or sub-basins within the three provinces included in the Madbi Amran / Qishn Total Petroleum System.

Although the petroleum-bearing grabens are considered to be of Late Jurassic age, their origins can be traced back to Precambrian fault systems. During Precambrian time, the area underwent a major collision and terrane accretion from about 955 to 615 million years ago (Ma), when older magmatic assemblages (≈2.95–2.55 billion years old) accreted with younger magmatic, volcanic, and plutonic rocks (Husseini, 1989; Whitehouse and others, 1998). However, during the Infra-Cambrian (≈615 to 580 Ma), the southern Arabian peninsula became extensional with intrusions of alkali-rich granites and volcanics as well as development of salt-filled extensional basins. These rift basins were related to major wrench-fault systems such as the Najd, in the western Arabian Shield, which consists of a series of northwest-southeast-trending left-lateral fault zones as much as 1,100 km long and 300 km wide (Husseini and Husseini, 1990; Ellis and others, 1996). The presence of 400 m of Infra-Cambrian syn-rift sediments and metasediments in Yemen (Beydoun, 1997) and the known hydrocarbon occurrence related to Infra-Cambrian salt basins in nearby Oman (Husseini and Husseini, 1990; Pollastro, 1999) led to early exploration efforts that focused on the potential of an Infra-Cambrian petroleum system.

Exploration in the 1980's, however, demonstrated that the Infra-Cambrian sediments were not petroleum bearing, but that petroleum potential existed in rocks, rifts, and structures of Late Jurassic age. The orientation of the Jurassic rifts is likely inherited from the Infra-Cambrian Najd wrench faults, which were reactivated during the Jurassic breakup of the Gondwana supercontinent. The petroleum-bearing grabens of Yemen are interpreted to be the result of a failed arm of a triple junction that occurred in Late Jurassic time (Kimmeridgian) (Greenwood and others, 1980; Husseini, 1989; Jungwirth and As-Sururi, 1990; Schlumberger, 1992; Redfern and Jones, 1995, Csato and others, 2001). Kimmeridgian source rocks and Jurassic-age petroleum systems are important worldwide, particularly within extensional basins such as the North Sea (Ahlbrandt and others, 2000).

Following Jurassic rifting, sediments filled the resulting grabens from earliest Cretaceous (Berriasian) through Late Cretaceous time. A second phase of rifting and associated transpressional and transtensional structures were related to the opening of the Red Sea and the Gulf of Aden during Oligocene and Miocene time (Beydoun, 1989; Haitham and Nanai, 1990; Bott and others, 1992; Crossley and others, 1992; Huchon and others, 1992). During this rifting, sea-floor spreading separated Arabia from Africa and the Arabian plate rotated in a counterclockwise direction. Tertiary petroleum systems of the Red Sea are largely within the rift sequence, whereas petroleum potential in the Gulf of Aden is thought to be largely in the pre-rift sequence. The Gulf of Aden is cut by a series of northeast-trending transform faults that reflect the oblique motion of the Arabian plate from the Gulf of Aden; the Red Sea rift and related structures formed mostly in response to plate movement perpendicular to the ocean spreading center. In Yemen, the southern portion of the Shabwah basin (known as the Balhaf basin) and much of the Masila-Jeza basin (specifically the Hadramawt Arch) are also related to transtensional and transpressional forces during the Tertiary rifting event (Bott and others, 1992; Richardson and others, 1994; Csato and others, 2001) (fig. 3).

Total Petroleum System

The total petroleum system described in this report, the Madbi/Amran/Qishn TPS, is entirely onshore. It is a Jurassic-sourced, and Jurassic- and Cretaceous-reservoired petroleum system. Undiscovered oil and gas resources in this TPS were quantitatively assessed. Two other potential total petroleum systems—the Cretaceous Nayfa (Naifa) petroleum system in eastern Yemen and a possible Tertiary petroleum system in the Gulf of Aden—were not assessed but are briefly discussed.

Petroleum Occurrence

Petroleum is currently produced in two main areas in Yemen; cross sections through the main petroleum-producing areas are located in figures 2 and 3, and shown in figures 4 and 5; structural elements are shown in figure 3. Although the stratigraphic nomenclature is complex, the stratigraphic terminology used by Beydoun (1997) and Beydoun and others (1998) is applied herein. Stratigraphic terminology and spatial relationships of strata are shown for the Phanerozoic in figure 6, for the Paleozoic section in figure 7, the Jurassic section in figure 8, the Cretaceous section in figure 9, and the Cenozoic in figure 10. In figure 6, the general Phanerozoic stratigraphic framework is shown (from west to east) across the Sab'atayn (Ma'Rib–Al Jawf and Shabwah basins of this report, fig. 1), the Say'un Masila basin, and the Jiza-Qamar basin. The latter basin, which is not productive, is included as a sub-basin within the Masila-Jeza basin. The two petroleum-producing basins (Sab'atayn and Sayun Masila) have a common source rock (the Kimmeridgian Madbi Formation; Csato and others, 2001), but the subsequent depositional and structural histories of the two basins are different, as are the ages and quality of their reservoirs and seals.

As shown schematically in figure 11, the combined Ma'Rib–Al Jawf and Shabwah basins (fig. 1) contain a petroleum system that formed in the Late Jurassic. The basal petroleum source-rock interval in the syn-rift sequence is the Madbi Formation, which charges both clastic and carbonate Jurassic reservoirs in the Madbi Formation and Sabatayn Foramation of the Amran Group; these formations are overlain by a salt seal of the Shabwah Member of the Sabatayn Formation (fig. 8). Reservoirs in the Amran Group range from clastic turbidite sequences to strata of alluvial origin that were generally deposited along the margins of the rift or as sediment that filled the basin progressively from the northwest to the southeast. Salt diapirs create additional structures for traps in the western basin (figs. 11, 12); however, the salt seal is absent in the eastern Masila-Jeza basin, and hydrocarbons sourced from the Madbi migrated vertically into the Cretaceous Qishn Formation, where reservoirs are largely contained within a clastic estuarine sequence (fig. 13).

The stratigraphic terminology for the Jurassic rocks of Yemen is shown in figure 8 and for the Cretaceous in figure 9. The maximum extent of the Madbi Amran/Qishn TPS is mapped in figure 1 along with the pod of active source rocks (R_o>0.6 pct). The two basins in Yemen that contain the TPS, the Ma'Rib–Al Jawf / Shabwah basin in the west and the Masila-Jeza basin in the east, are separated by the Mukalla (or Jahi-Mukalla) high (figs. 1, 2, 3, and 11), which is a northwest-southeast-oriented horst block that has undergone recurrent movement and may reflect the Infra-Cambrian Najd fault system. The structural relations between the two basins and this positive feature, which has been a structural high for most of the Mesozoic history of Yemen, are not entirely resolved (Paul, 1990, Putnam and others, 1997; Beydoun and others, 1998; Csato and others, 2001). Csato and others (2001) simplified the structural terminology and discussed two basins separated by the Mukalla high. They interpreted the Mukalla high to be a persistent geologic feature reactivated in the Tertiary rifting but dividing major geologic regimes; to the west extensional features formed, whereas to the east major inversion occurred. These authors believed Hadramawt High or Arch (fig. 3) to be an uplift related to tectonic rebound from the opening of the Gulf of Aden. This rebound was asymmetric; the southern flank tilted southward, resulting in high-angle tilted fault blocks in eastern Yemen (as shown in fig. 13).

Jurassic salt halokinesis created additional structural traps for hydrocarbon accumulations in the Ma'Rib–Al Jawf / Shabwah basin. However, Jurassic salt was not deposited in the Masila-Jeza basin to the east, where structures are indicative of inversion and uplift associated with transtensional and transpressional forces and the more east-west orientation of Tertiary rifting (fig. 11). These Tertiary forces also modified the south end of the Ma'Rib–Al Jawf / Shabwah basin creating the Balhaf basin (fig. 3), which has no recorded hydrocarbon production (Crossley and others, 1992; Beydoun and others, 1998; Csato and others, 2001).

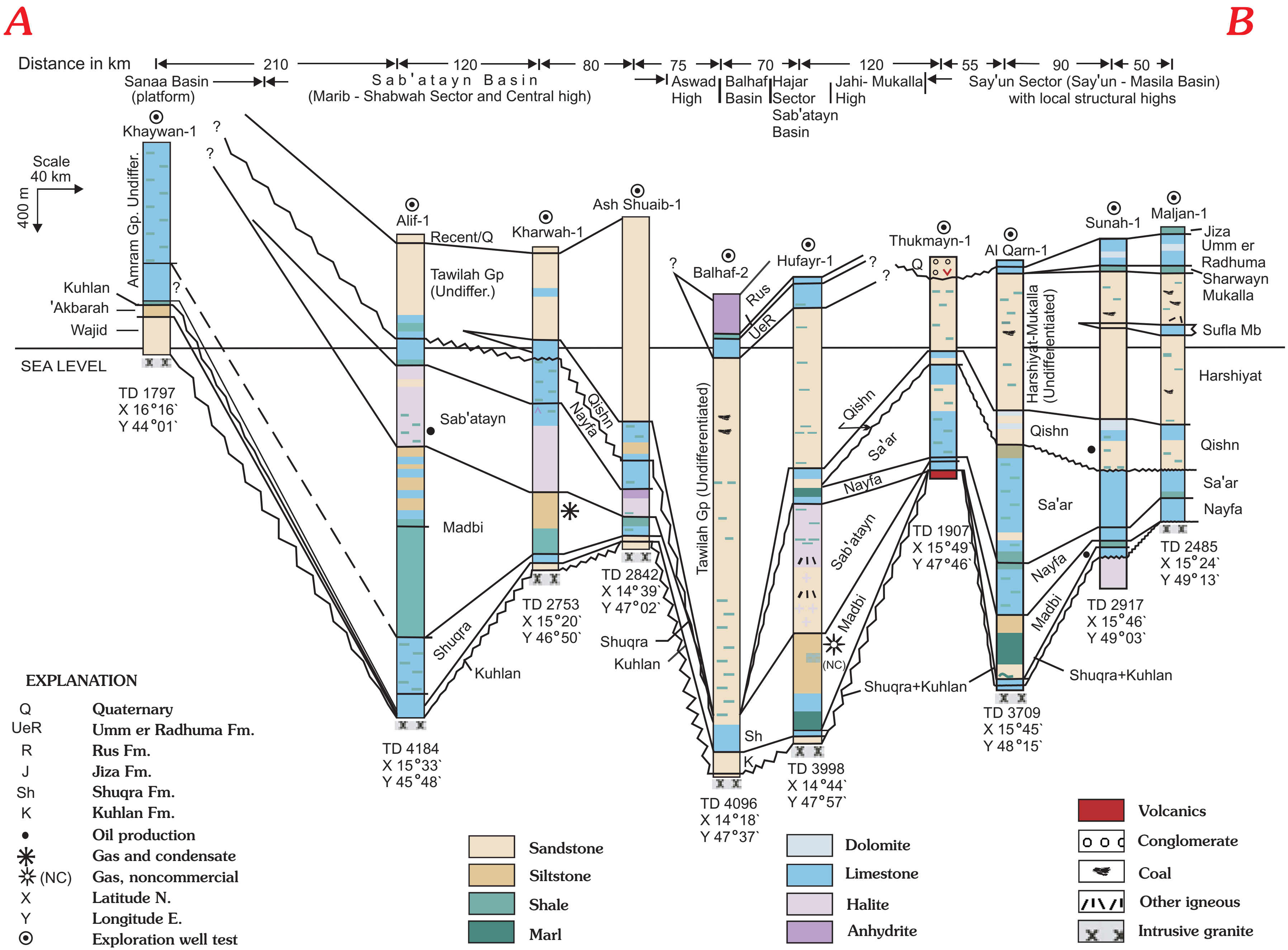


Figure 4. Cross section *A*–*B* across western and central portions of Yemen from Ma'Rib–Al Jawf/Shabwah basin into Masila-Jeza basin (modified from Beydoun and others, 1998). TD, total depth (in meters). Correlations queried where uncertain.

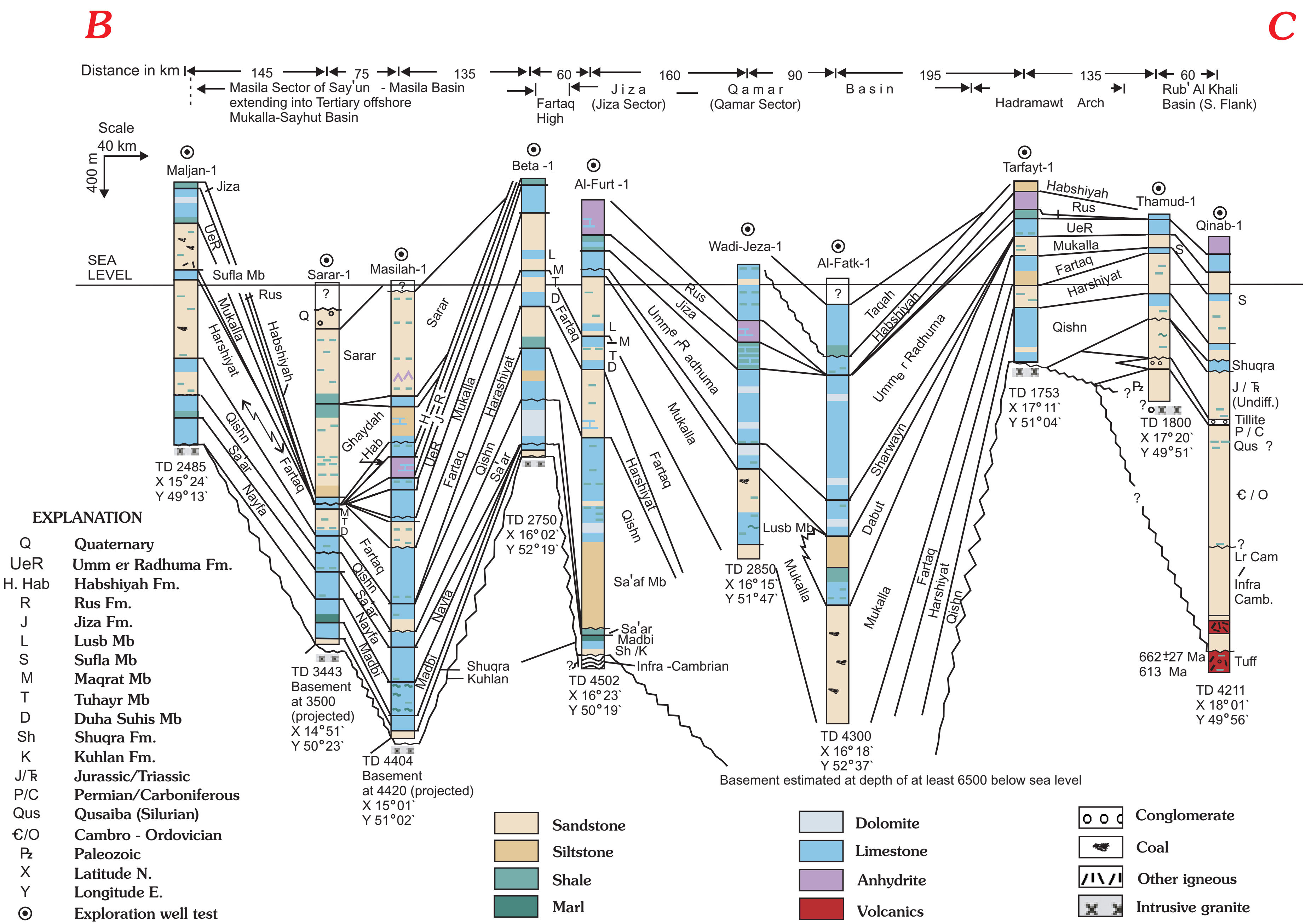


Figure 5. Cross section *B–C* across central and eastern Yemen principally in Masila-Jeza basin (modified from Beydoun and others, 1998). TD, total depth (in meters). Correlations queried where uncertain.

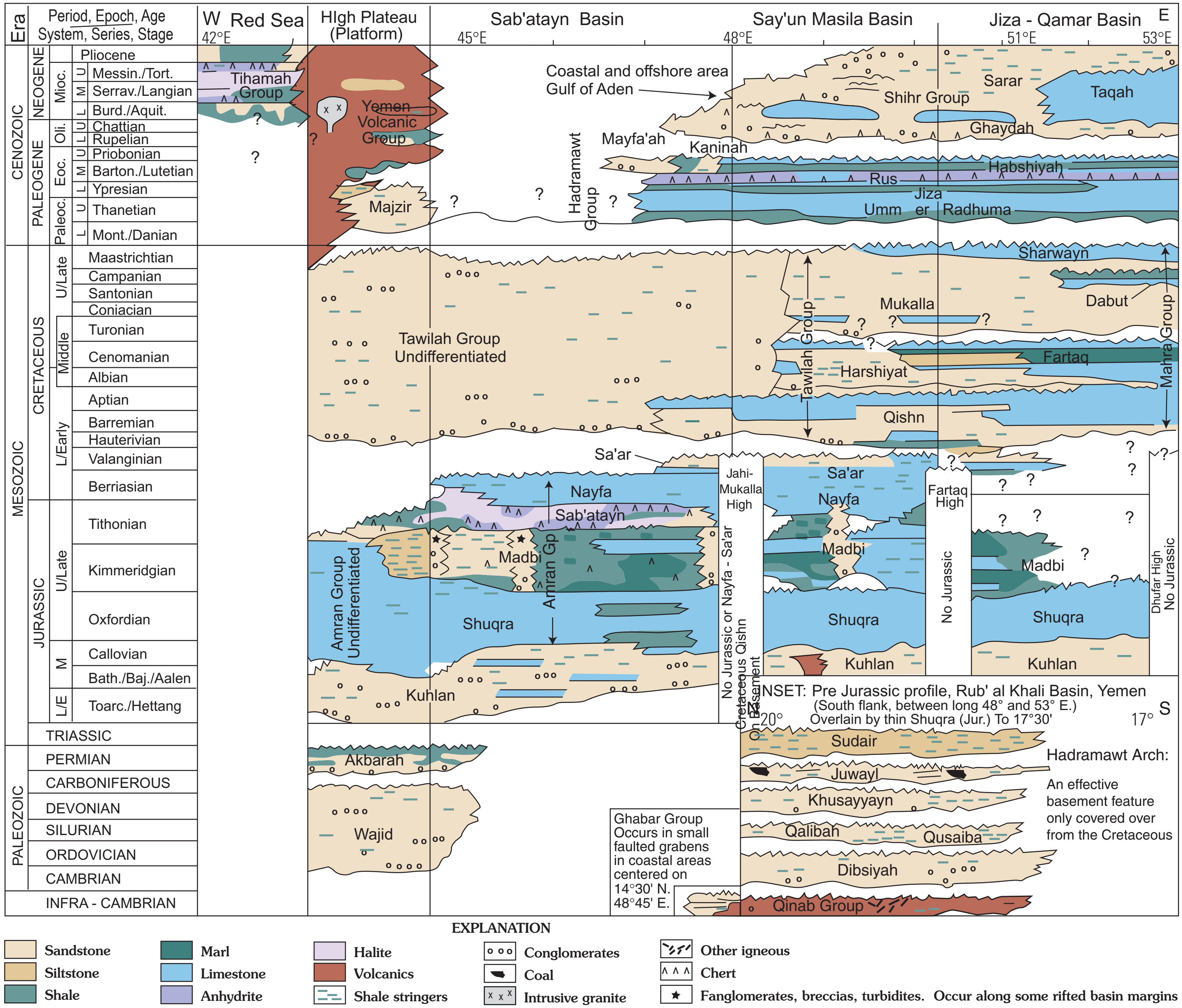


Figure 6. Phanerozoic lithostratigraphy, correlations, and spatial stratigraphic distributions for Yemen (modified from Beydoun and others, 1998). To group and formation status only. Correlation or extent queried where uncertain.

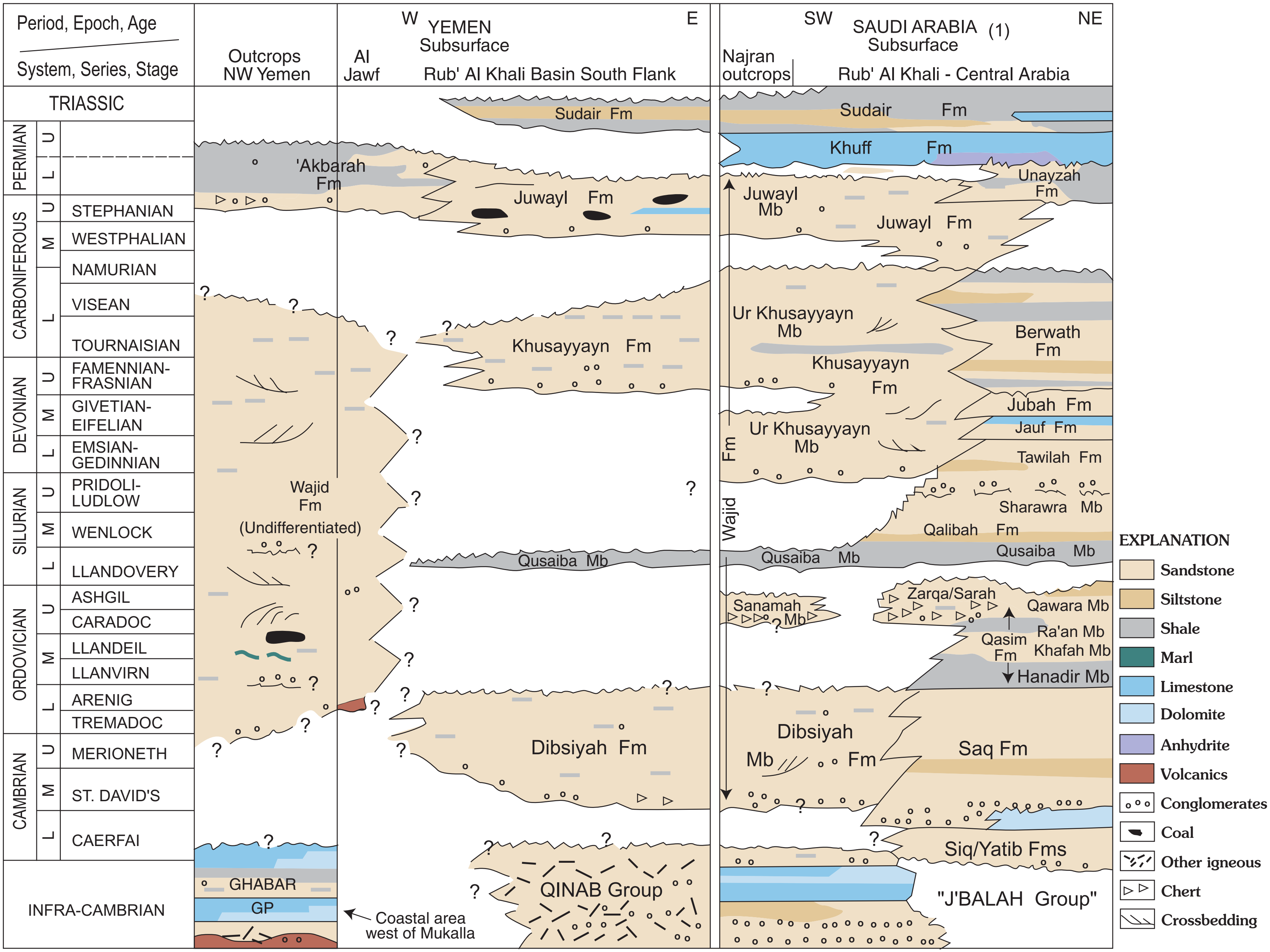


Figure 7. Paleozoic lithostratigraphy, correlations, and spatial stratigraphic distributions for Yemen and adjacent Saudi Arabia (modified from Beydoun and others, 1998). Correlation or extent queried where uncertain.

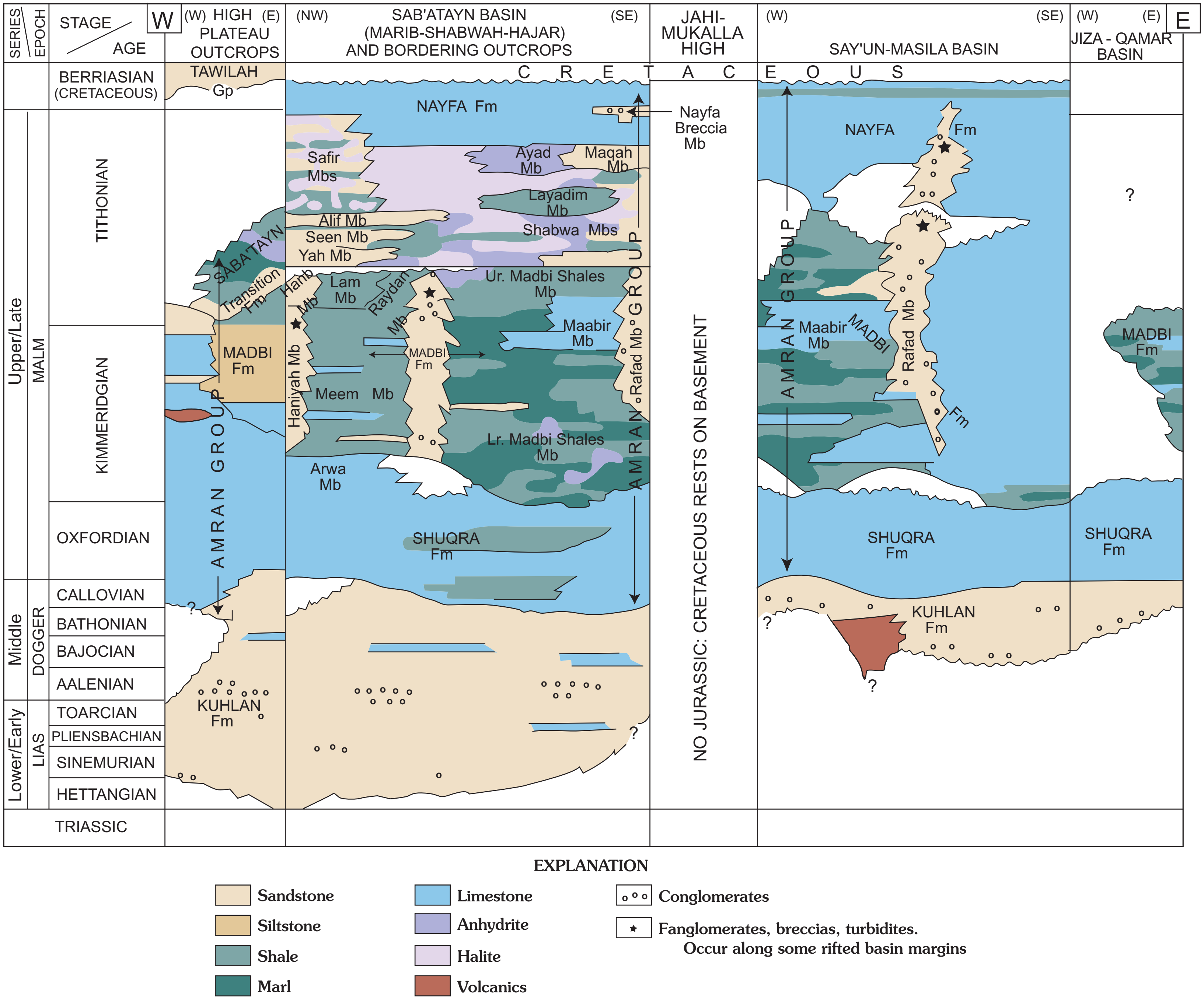


Figure 8. Jurassic lithostratigraphy, correlations, and spatial stratigraphic distributions for Yemen (modified from Beydoun and others, 1998). Queried where uncertain.

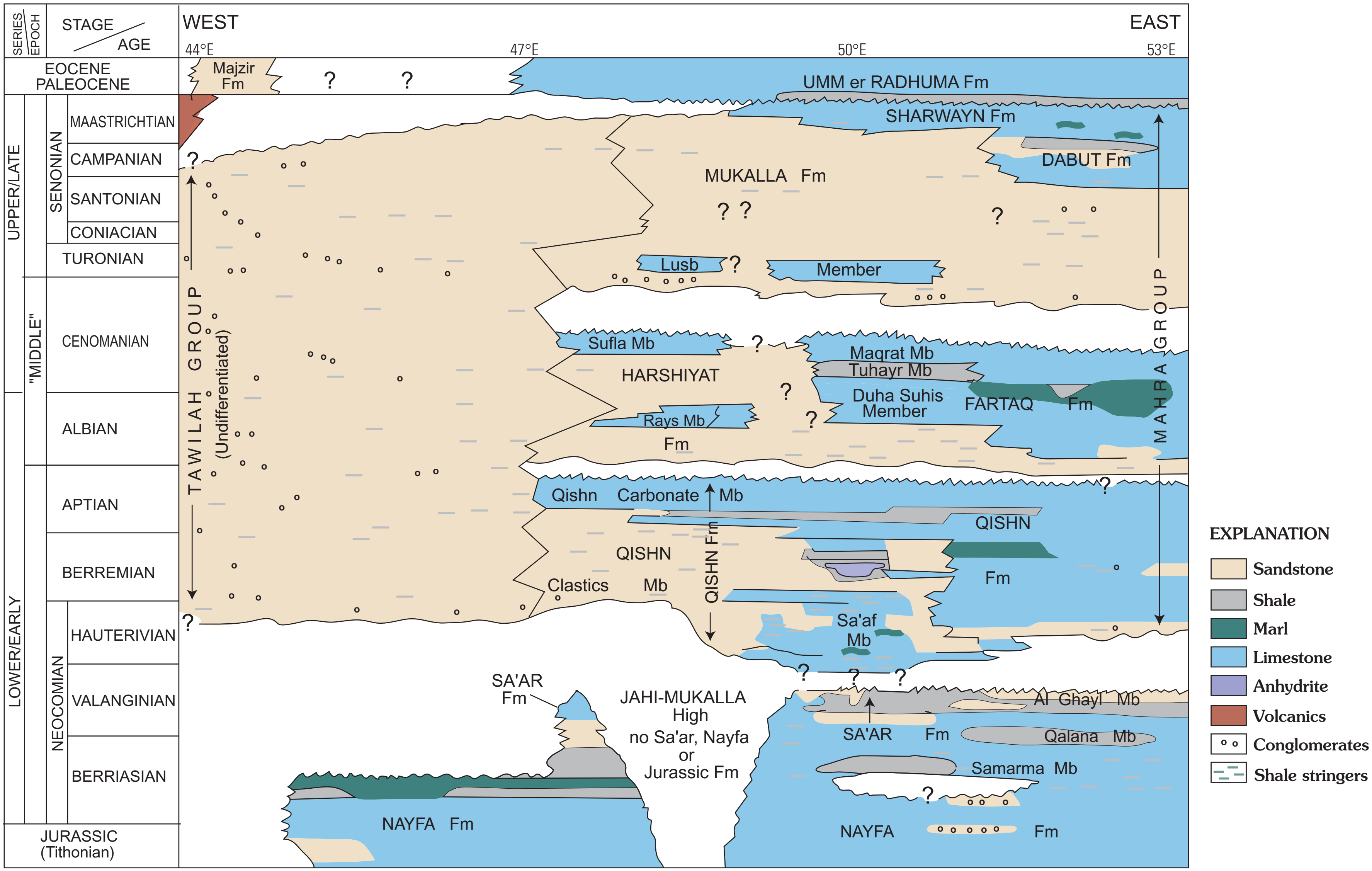


Figure 9. Cretaceous lithostratigraphy, correlations, and spatial stratigraphic distributions for Yemen (modified from Beydoun and others, 1998). Queried where uncertain.

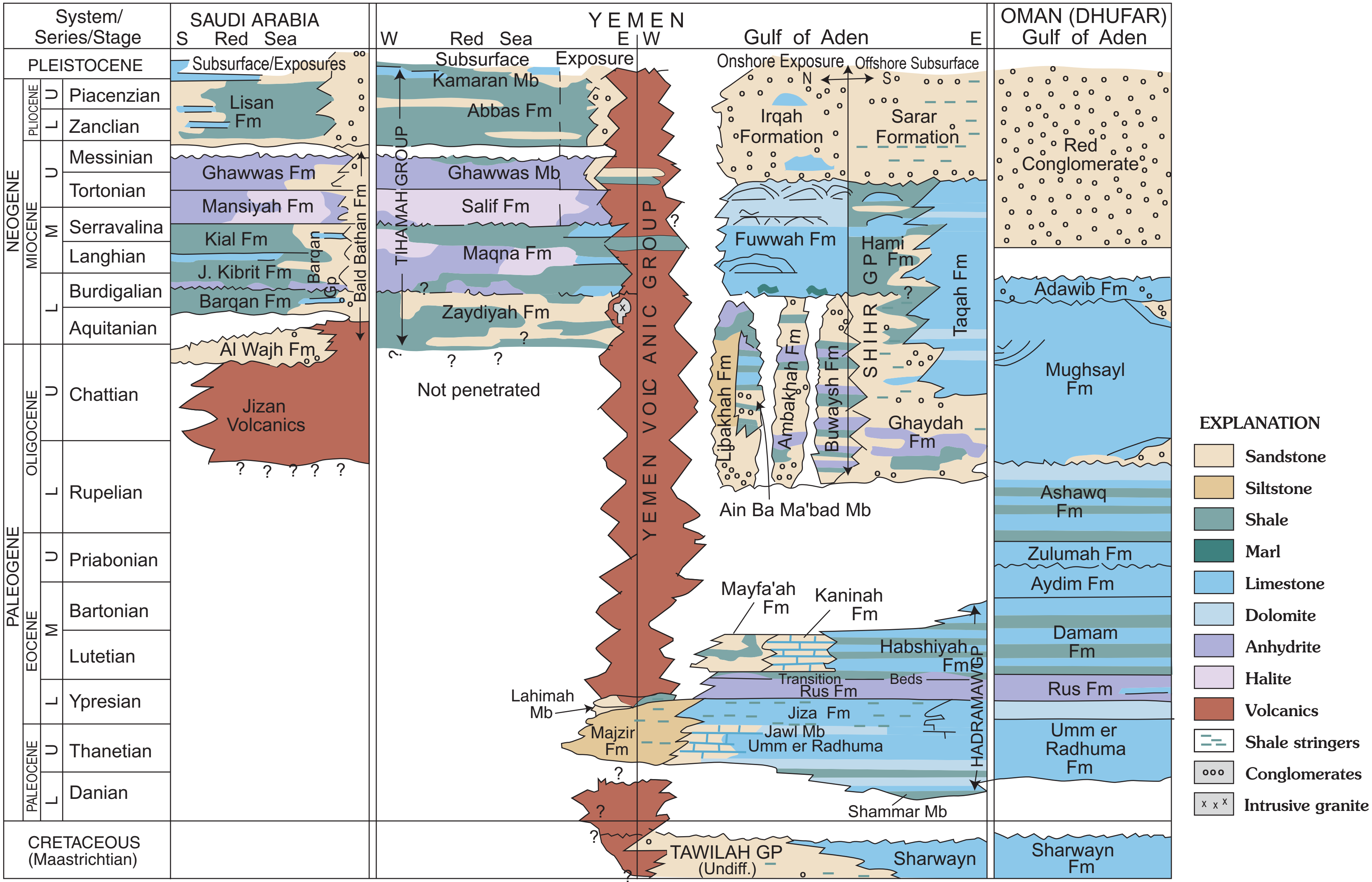


Figure 10. Cenozoic lithostratigraphy, correlations, and spatial stratigraphic distributions for Yemen, Oman, and Saudi Arabia (modified from Beydoun and others, 1998). Queried where uncertain.

The Ma'Rib–Al Jawf / Shabwah basin in western Yemen was initiated during the Jurassic and was related to rifting of the Arabian plate from the Gondwana supercontinent. Pre-rift sedimentation is represented by mostly continental deposits of the Kuhlan Formation (fig. 8); this formation includes fluviatile and arkosic redbeds that grade upward into a shallow-marine facies and represent the early transgressive phases of the Late Jurassic seas. It is essentially absent of fossils; however, in the subsurface some palynomorphs have been recovered indicating a Middle Jurassic (Bathonian to Early Callovian) age (Beydoun and others, 1998). These continental rocks are overlain by shallow-marine fossiliferous carbonates such as the Shuqra Formation of the Amran Group (fig. 8).

During the Late Jurassic, commencing in the Kimmeridgian and continuing through the Tithonian, syn-rift sediments of the Madbi Formation were deposited (Beydoun and others, 1998). The Meem Member of that formation (fig. 8) consists of clastic turbidites and shales that are important source rock as well as reservoirs in the western basin. The middle Maabir Member is largely a carbonate sequence and a petroleum reservoir, and the upper Lam Member is mostly shaly strata. Clastic reservoirs also occur in the Madbi Formation and reflect deep-marine sand deposition along the flanks of grabens or half-grabens. Simultaneously continental sediments filled the grabens from the north end of the western basin along rift margins. In particular, these sediments formed the Safer, Alif, and Yan Members of the Amran Group (fig. 8). Apparently, ocean circulation in the western Yemen basin became restricted during the Late Jurassic, and salts of the Shabwah Member of the Sabatayn Formation were deposited over the syn-rift sequence, thereby providing a seal for the Jurassic petroleum system.

The tectonic history of the Masila-Jeza basin was somewhat different from that of the Ma'Rib–Al Jawf / Shabwah basin. Whereas the basal source rocks of the Madbi Formation were deposited in a syn-rift setting, the overlying sequence was relatively starved for clastic sediment input. A much later Cretaceous transgression of the Qishn Formation was thus required to provide both reservoir and sealing carbonates, as illustrated in figures 11 and 13. In eastern Yemen, ocean circulation remained open during the Late Jurassic and Early Cretaceous, and open marine carbonates and clastics were deposited—but with no Upper Jurassic salt seal (figs. 11, 13). Further, the eastern Yemen basin reflects east-west-oriented Tertiary rift forces, compared to the western Yemen basin, which was dominantly influenced by northwest-southeast-directed Jurassic-age forces, inherited from Infra-Cambrian faulting (fig. 13).

The preferred pre-rift, syn-rift and post-rift sedimentary sequences, as designated in this report, are consistent with those shown by Csato and others (2001) (figs. 12, 13). Brannin and others (1999) considered only the Madbi Formation and what they referred to as the Lam Formation to be syn-rift deposits. (Note that Beydoun and others, 1998, considered the Lam to be a member of the Madbi Formation.) Stratigraphic divisions and correlations advanced by Beydoun and others (1998) made a significant contribution toward clarifying the stratigraphic correlations in Yemen (figs. 6–10). The pre-rift Shuqra Formation, as defined by Beydoun and others (1998), is a neritic limestone with richly fossiliferous marls and does not contain potential source beds. Interestingly, the Shuqra contains crocodile skeletons estimated to be as much as 3 m long. The Shuqra source beds as referred to by Brannin and others (1999) are likely the Lower Madbi Shale Member of Beydoun and others (1998).

The pre-rift sequences are similar in both the eastern and western Yemen basins, but the syn-rift fill in the east has considerably less sandstone (potential reservoirs). Structures in the eastern basin are mostly related to rejuvenation of basin zones of weakness in response to both Jurassic and Tertiary rifting forces, rather than related to salt diapirism, as is evident in the western basin. Both basins have multiple grabens and half-grabens that form stratigraphic traps, particularly along the margins of adjacent horsts.

Only oil fields are found in eastern Yemen, reflecting a lower thermal maturation of the Madbi shales relative to those in the western basin. Thus, vertical migration of Madbi-sourced hydrocarbons charge mostly Jurassic reservoirs beneath the salt seal in the west. In the eastern basin where no salt is present, the hydrocarbons migrate upward, are trapped in the Qishn Formation's fluviatile, estuarine, and tidal sandstone reservoirs, and are sealed by impermeable Qishn carbonates and shales (figs. 11 and 13). The Qishn deposits represent a transgressive marine sequence progressing from east to west across Yemen that grades laterally westward into clastics of the non-petroleum-bearing Tawilah Group (fig. 9).

Source Rock and Oil

Within Yemen, geochemical data from 12 oils are reported in the GeoMark (1998) oil database. Seven oils are from Jurassic reservoirs in the Ma'Rib–Al Jawf / Shabwah basin; of these, six samples are from Alif, Azal, and Shabwah fields, and one sample is from an oil seep. Three oils are from Jurassic and Cretaceous reservoirs in the Masila-Jeza basin (Sunah, Hemiar, and Camaal fields; fig. 1), and two other samples are from Tertiary reservoirs in the Gulf of Aden. Although three groupings of oil were identified, oils from Jurassic reservoirs are dominant in both basins. The nine Jurassic-reservoired oils (seven from the west, two from the east) are genetically similar. API gravities range from 29° to 35°, sulfur content from 0.09 to 0.59 percent, and pristine / phytane ratios from 1.46 to 1.72. Biodegradation is suspected in the seep sample from the western basin due to its low API gravity of 14°, high sulfur content of 6.3 percent, and low pristine / phytane ratio of 0.3. The Cretaceous oil sample from Hemiar field in the eastern basin is distinct from all other oil samples, perhaps due to biodegradation; its gravity is lower (22.2°), and sulfur content is higher (1.23 percent), but its pristine / phytane ratio of 1.69 is within the range of the Jurassic samples. The Gulf of Aden Tertiary oils are also different, in that they have high pristine / phytane ratios, 2.02 to 2.92, and reduced δC^{13} values (<–24) as compared to all other samples whose δC^{13} values range from –26 to –28.3. Some oil from the Gulf of Aden is anomalously high gravity, as much as 43°, as noted by Beydoun (1989). These data indicate that the onshore oils in Mesozoic rocks dominantly belong to one genetic oil family, although biodegradation is suspected in the seep and Hemiar samples. The offshore, Gulf of Aden oils reservoired in Cenozoic rocks are from a different oil family.

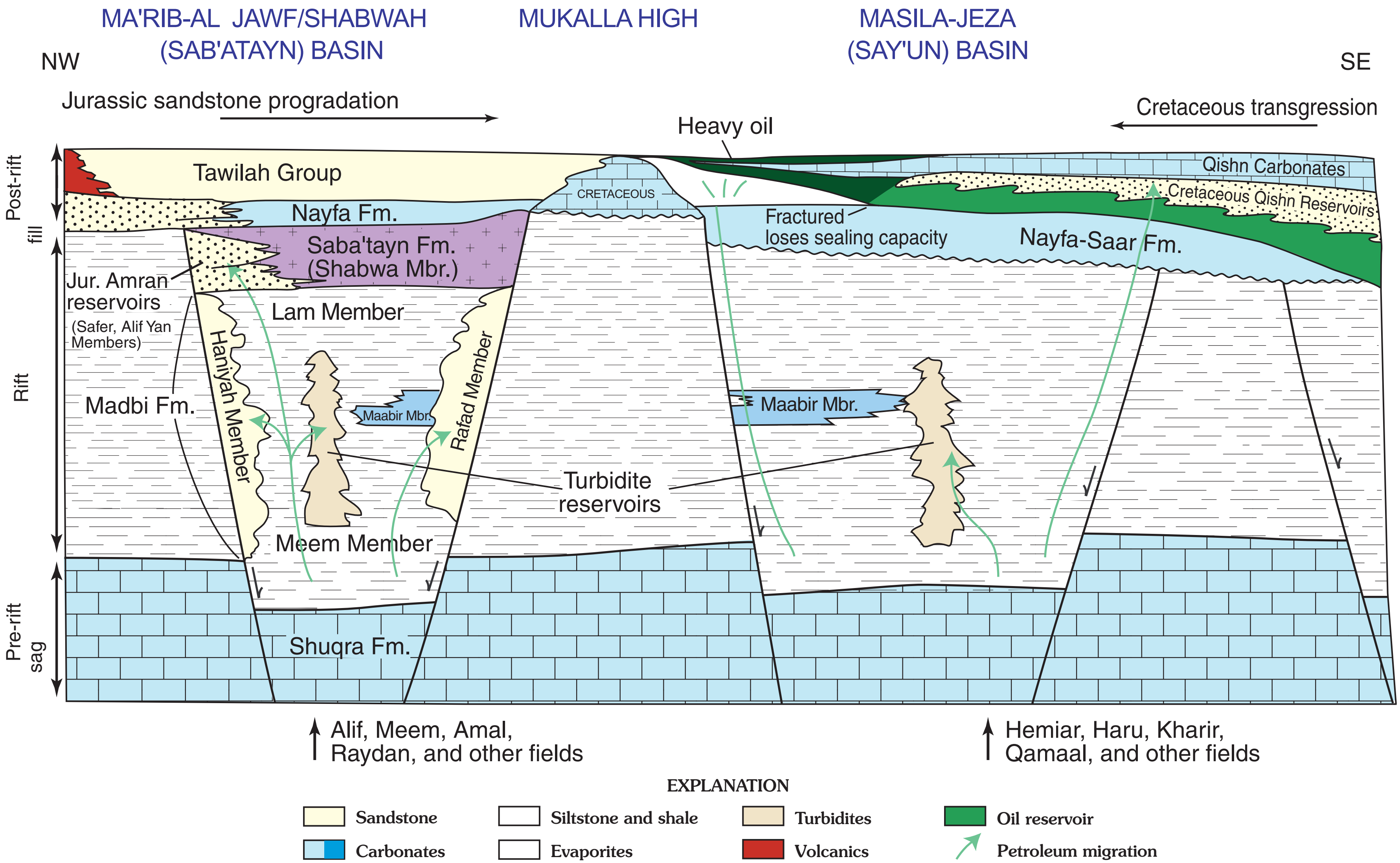


Figure 11. Schematic diagram of total petroleum systems in Ma'Rib–Al Jawf / Shabwah and Masila-Jeza basins, Yemen.

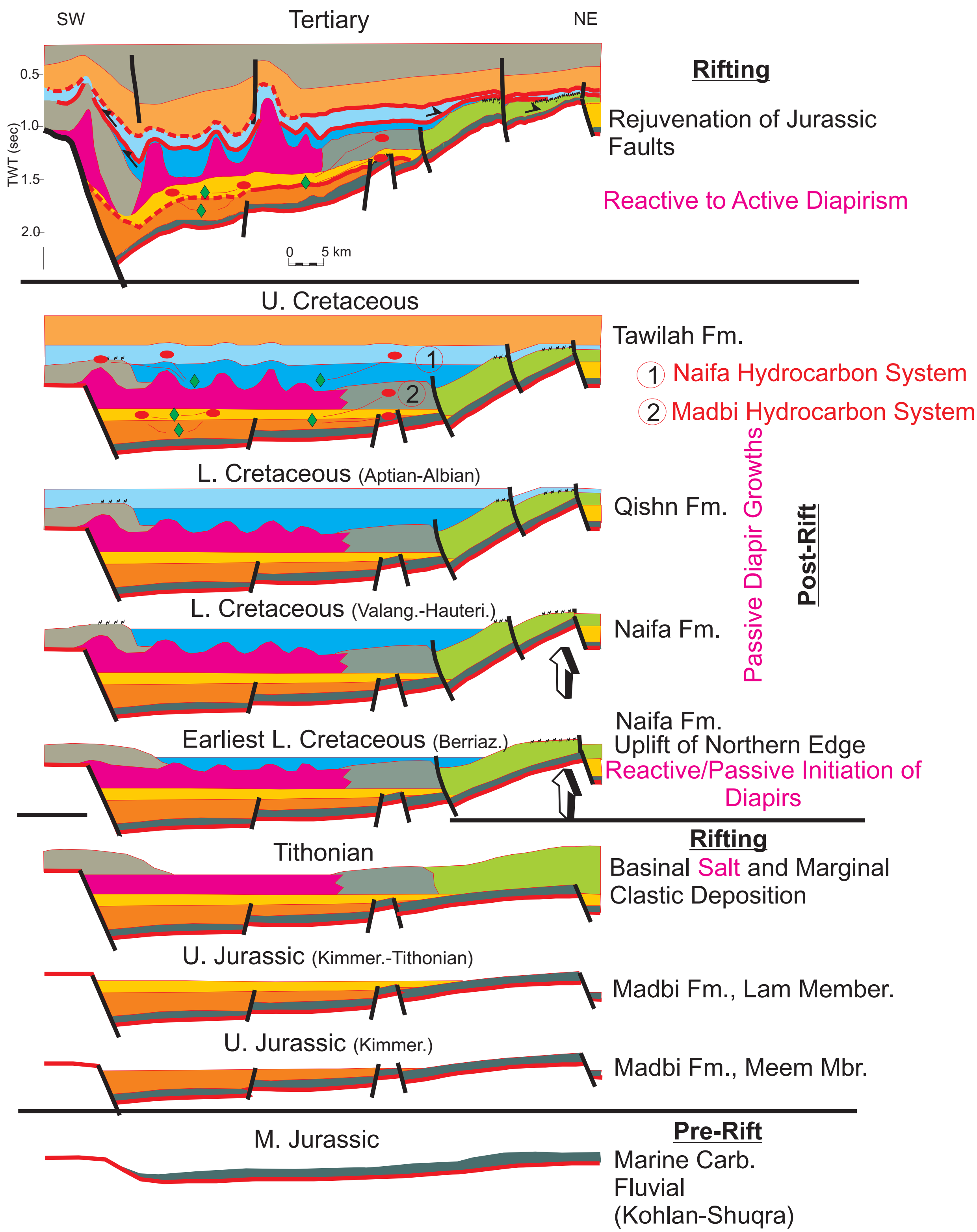


Figure 12. Tectono-stratigraphic, halokinetic, and petroleum generation history model of Ma'Rib–Al Jawf / Shabwah basin, western Yemen (with permission from Csato and others, 2001). TWT, two way time.

The source of hydrocarbons from the Madbi Amran / Qishn TPS is believed to be Upper Jurassic Madbi (Kimmeridgian age) shales (figs. 14, 15). Petroleum-migration modeling in the deeper western basin demonstrates the effectiveness of Madbi source rocks and the thermal immaturity of Tithonian Nayfa (Naifa) source rocks (Csato and others, 2001; fig. 14). Csato and others (2001) reported thermally mature Madbi Formation in the Lam and Maabir-Meem members to contain source rocks with total organic carbon (TOC) ranging from 1.4 to 3.6 weight percent, hydrogen indices (HI) of 180–370 and TMAX values

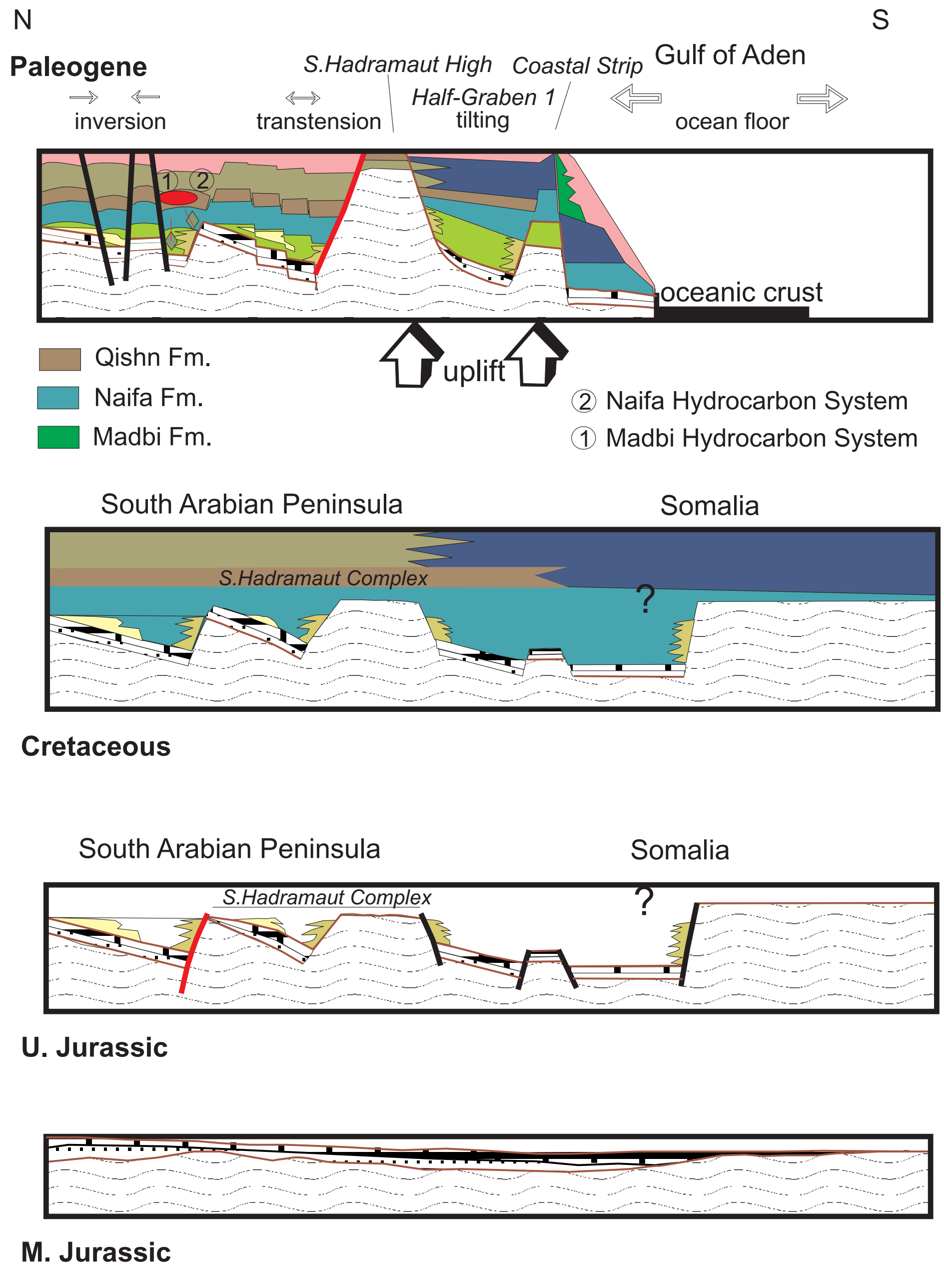


Figure 13. Tectono-stratigraphic and petroleum generation model of Masila-Jeza basin, eastern Yemen (with permission from Csato and others, 2001).

ranging from 224°C to 229˚C. Brannin and others (1999) reported TOC values of 2–5 percent and HI's of 580 for the Madbi Formation in the western Yemen basins, and reported as much as 12 percent TOC (Rock Eval) in the pre-rift Shuqra Formation with HI greater than 300. Thermal maturation of Madbi source rocks is believed to commence with oil generation at about 2,700 m (Csato and others, 2001). Thermal maturation modeling shows that with high heat flow, Madbi source rocks may have expelled oil from 135 to 90 Ma, and with low heat flow, from 85 to 50 Ma (Csato and others, 2001). Both models apply inasmuch as a variety of structural configurations and variable heat flow exist within and among the basins. Essentially, oil generation commenced in the Late Cretaceous following deposition of significant post-rift clastics of the Tawilah Group (figs. 9, 12, 13).

In summary, the Kimmeridgian shales of the Madbi Formation are probably the principal source rocks in both the eastern and western onshore basins of Yemen. One total petroleum system was identified and assessed for both basins (fig. 1).

Reservoir Rock

Reservoirs in the two basins are dependent primarily on the presence or absence of the Upper Jurassic (Tithonian) salt of the Sabatayn Formation (Shabwah Member) (fig. 8). In the western Ma'Rib–Al Jawf / Shabwah basin, reservoirs beneath the salt consist dominantly of clastics deposited either along the margins of the various grabens (Hayniyat and Rafad Members, fig. 8) or as turbidites (Meem and Lam Members) in the deeper

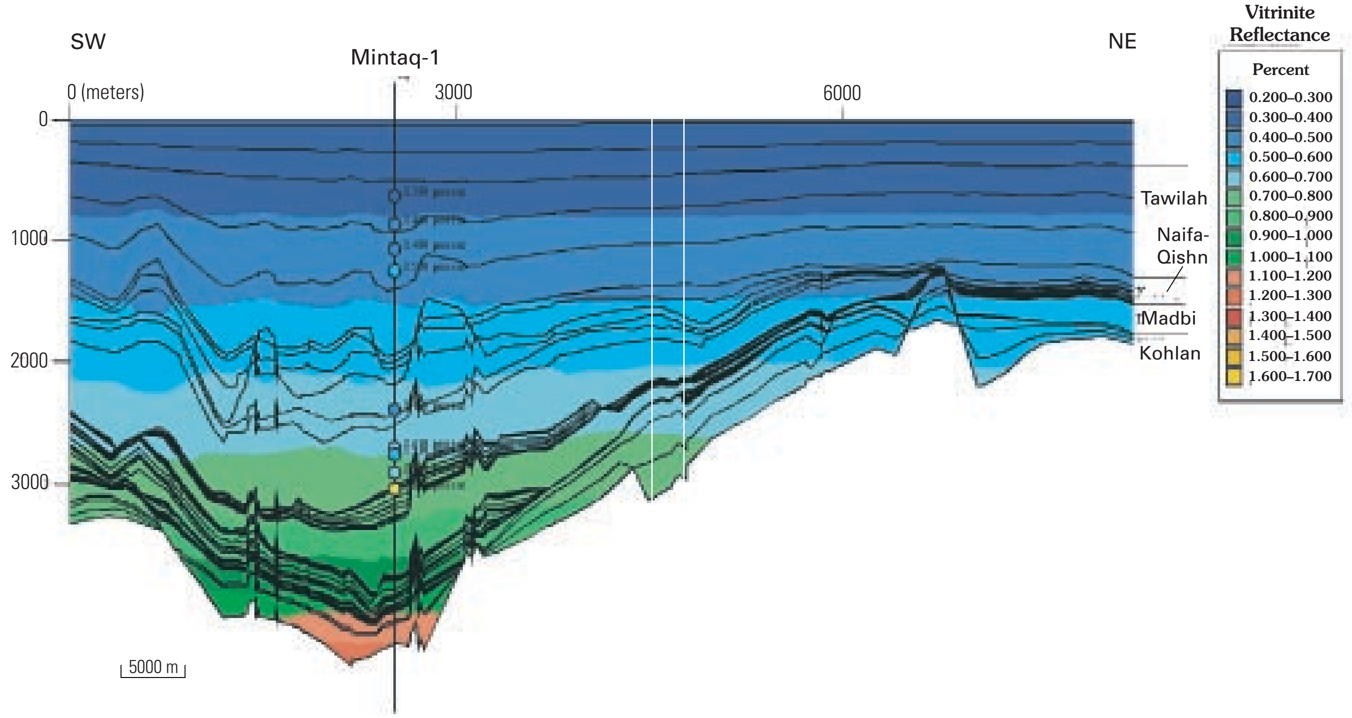


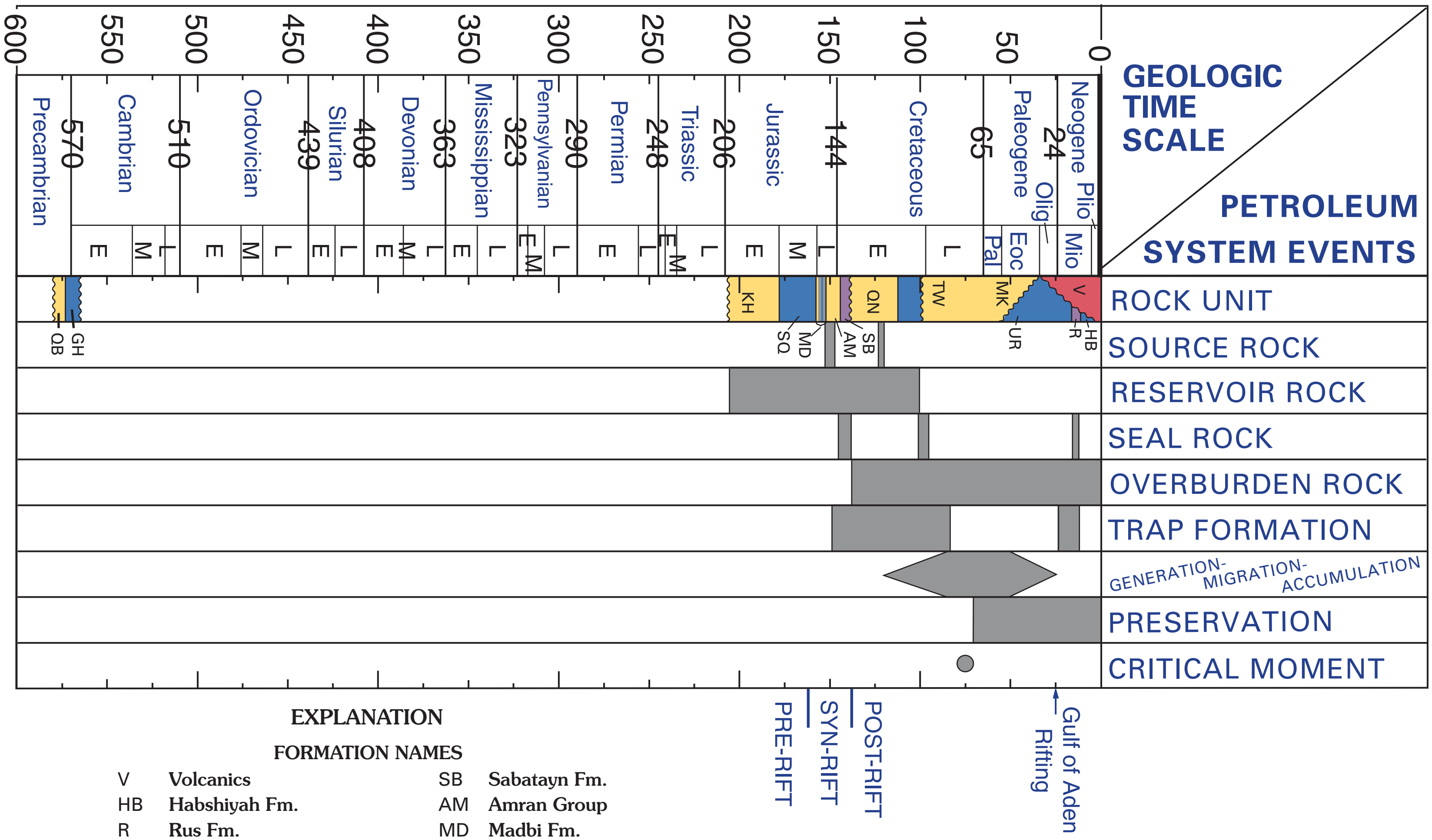
Figure 14. Thermal maturation modeling (PetroMod 4.2) for Ma'Rib–Al Jawf/Shabwah basin, western Yemen (with permission from Csato and others, 2001). Profile location shown in figure 1. Hydrocarbon generation commences at R_0=0.7 percent vitrinite reflectance (green color) or higher.

portions of the grabens (figs. 8, 11). The upper part of the Jurassic Amran Group and its coarser clastic units, Alif, Seen, Yah, and Safir Members of the Sabatayn Formation, are the principal reservoirs in the western basin (fig. 8).

The Madbi Amran / Qishn Total Petroleum System takes its name from the Madbi Formation source rocks and the Amran Formation (Jurassic Tithonian) carbonate and clastic reservoirs in the western basin beneath the salt and the Qishn Formation (Cretaceous Berriasian) clastic reservoirs in the eastern basin where no salt is present (figs. 11, 13). Reservoirs in the western basin are relatively shallow, with depths ranging from 1,829 to 2,286 m (from 6,000 to 7,500 ft) in the west (Petroconsultants, 1996). Initially, much of the production was established in Jurassic carbonate intervals; however, production from sandstones became more dominant as the fields were more fully developed. Porosities for the sandstones generally range from 15 to 28 percent, with permeabilities ranging from 80 millidarcies (mD) to 4 darcies. Most Jurassic sandstones have permeabilities in the several hundred millidarcy range, and commonly in the one-half darcy range (Petroconsultants, 1996). Some reservoirs have lower porosities resulting from halite cement present in the pores, and some production problems are related to salt precipitation and salt production in the western basin reservoirs (Schlumberger, 1992).

Reservoirs in the western basin were charged by vertically migrating hydrocarbons that were trapped beneath a salt seal formed by the Shabwah Member of the Sabatayn Formation (fig. 8). Halokinesis in the western basin commenced in Early Cretaceous time and strongly influenced reservoir distribution there (fig. 12). Thickness of these formations and members changes abruptly, depending upon their position relative to the horsts and grabens in the basins and their relations to salt dynamics (thin over diapirs, thick in salt removal areas). The Jurassic syn-rift fill is as much as 4 km thick in the western basin, and individual coarse clastic intervals along some rift margins are as much as 900 m thick (Brannin and others, 1999). Thus, some individual reservoirs may be several hundred meters thick, but thin abruptly across intervening horsts (figs. 4, 5, 12, 13). Turbidite reservoirs and basin margin clastics are also important syn-rift reservoirs that intercept and trap hydrocarbons generated from the deep marine source rocks of both the Meem and Lam Members of the Madbi Formation. Fractured rocks of the Maabir Member also have produced hydrocarbons, as have the pre-rift successions of the Shuqra (carbonate) and Kuhlan (clastic) Formations. Reservoirs in these latter two formations are secondary and generally of poorer quality relative to the Upper Jurassic reservoirs (Brannin and others, 1999).

In the Masila-Jeza basin, the Upper Jurassic salt is absent and the principal reservoir and trapping conditions exist in the transgressive Qishn Formation (fig. 9), which may be as much as several hundred meters thick. The principal reservoirs occur within a 75-m clastic interval of mixed sands and shales underlying a carbonate facies (Putnam and others, 1997) (fig. 11) that forms a seal for Madbi Formation hydrocarbons migrating vertically as shown in figure 11. The eastern basin reservoirs are shallower than those in the western basin with producing depths of about 1,524 m at Camaal, Heijar, Heimar, Haru, Suna, and Tawila fields (Petroconsultants, 1996; Putnam and others, 1997; fig. 1). Reservoir quality for Qishn clastics is excellent. At Camaal field, all Qishn reservoirs exceed 23 percent porosity with permeabilities exceeding 1 darcy (Putnam and others, 1997). Petroconsultants (1996) also reported high porosity and



EXPLANATION

FORMATION NAMES

V	Volcanics	SB	Sabatayn Fm.
HB	Habshiyah Fm.	AM	Amran Group
R	Rus Fm.	MD	Madbi Fm.
UR	Umm er Radhuma Fm.	SQ	Shuqra Fm.
MK	Mukalla Fm.	KH	Kuhlan Fm.
TW	Tawilah Group	GH	Ghabar Group
QN	Qishn Fm.	QB	Qinab Group

Figure 15. Petroleum system events chart for Madbi Amran/Qishn Total Petroleum System, Yemen.

permeability values for the eastern basin Qishn sandstone wells. In the eastern basin, tectonic rejuvenation related to Tertiary rifting caused remigration and breaching of preexisting Jurassic reservoirs. Extensive leakage must have occurred as heavy oil belts are known to occur on the margins of the Qishn reservoirs (David Boote, oral commun., 2000, illustrated in fig. 11).

Seal Rock

Salt in the Shabwah Member (Tithonian) of the Sabatayn Formation forms the seal for the reservoirs in the Ma'Rib–Al Jawf / Shabwah basin (Seaborne, 1996). Salt sequences as much as 30 m thick have been observed in outcrops, but in places where the bases were not exposed (Beydoun and others, 1998). Brannin and others (1999) reported Sabatayn Formation salts as much as 1,500 m thick in the Amal field (fig. 1). The salt was mobilized shortly after deposition of the Nayfa (Naifa) Formation during Early Cretaceous time (fig. 12). Differential loading on the salt during sedimentation, as well as uplift of the Mukalla high, volcanism on the basin margins, and tilting of fault blocks associated with these activities, contributed to salt instability. The thickness of overlying formations, particularly the Nayfa and Qishn Formations, and Tawilah Group, is dependent on salt movement, thicker where salt withdrew and thinner over diapirs (fig. 12).

In the Masila-Jeza basin, the salt is absent; thus, hydrocarbons generated from the Jurassic rifts migrate upward until they are trapped generally within the Qishn sandstone reservoirs beneath the Qishn carbonate unit (figs. 11, 13). The presence of degraded oils and heavy oils in some of these fields indicates that the seal in the eastern basin is less effective than the salt seal to the west.

Overburden Rock

Overburden rock includes the Cretaceous and younger post-rift fill. The Early Cretaceous Nayfa (Naifa) Formation is thus considered post-rift and the Upper Jurassic salt is considered syn-rift. This interpretation, as shown in figures 11 and 13, is consistent with that of Csato and others (2001). Brannin and others (1999) discussed two post-rift sequences: (1) Ayad, Sabatayn, and Naifa Formations, and (2) the Qishn Formation and Tawilah Group. In this report, the latter is considered to be post-rift and the former as syn-rift deposition. In areas where Tertiary rifting is predominant, as much as 4.5 km of post-rift overburden was deposited, such as in the Balhaf basin on the south end of the Ma'Rib-Al Jawf / Shabwah basin (fig. 3). Clastics of the Tawilah Group are the dominant sediments in these Tertiary rift grabens (figs. 4, 5), and more typical overburden depths are in the 1–2 km range in the western basin and 2–3 km in the eastern basin (figs. 4, 5, 12, 13). The earliest post-rift sediments are the transgressive Nayfa Formation clastics and carbonates that prograded generally from west to east, thinning to the west but crossing both basins. The clastic progradation and infilling of the Tawilah Group, principally from the west to east but including local sediment contributions from highs such as the Mukalla high, account for most of the sedimentary overburden (figs. 4, 5, 12).

Hypothetical Total Petroleum Systems

A Silurian-sourced petroleum system may also exist, particularly in northeastern Yemen. As shown in the Paleozoic stratigraphic column for Yemen (fig. 7), the preservation of Silurian and Infra-Cambrian sediments in the Qinab-1 well (fig. 5), particularly hydrocarbon source rocks, indicates the possibility of a Paleozoic or perhaps Infra-Cambrian petroleum system there. The Silurian Qusaiba source rock that extends over much of Saudi Arabia was identified in outcrop in the Wajid Plateau of southwestern Saudi Arabia, where it is as much as 60 m thick. Qusaiba strata may also have been encountered in Yemen in the Qinab-1 well on the north flank of the Hadramawt Arch on the southern flank of the Rub' Al Khali basin (Stump and van der Eem, 1994; Beydoun and others, 1998) (fig. 5). Although the potential may exist for a Silurian petroleum system in Yemen, the depth and thermal maturity of the Silurian Qusaiba shale for the southern Rub' Al Khali basin indicate that it would be gas-prone (Schenk and Pollastro, 2000). Assessment of the Paleozoic potential for the Rub' Al Khali portion of Yemen was included in the Qusaiba Silurian Total Petroleum System, and allocation of resources was made to Yemen (USGS, 2000).

Immature source-rock intervals were identified in the Jurassic: Sabatayn Formation (Tithonian); the Cretaceous Nayfa (also spelled Naifa, Berriasian), Saar (Berriasian), Qishn (Hauterivian-Barremian), Harshiyat (Albian-Aptian), Mukalla (Coniacian to Maastrichtian); and the Paleocene and Eocene Umm er Radhuma and Jeza Formations (Barnard and others; 1992; Bott and others, 1992; Csato and others, 2001).

Another Tertiary total petroleum system probably exists basinward (coastal and offshore areas) of the onshore Masila-Jeza basin (fig. 13). Hydrocarbons have been produced from Tertiary strata in several wells, and are genetically distinct, with different gravity (both much higher and much lower) and higher sulfur content than the Jurassic-sourced hydrocarbons. This potential Tertiary TPS is evidenced by hydrocarbon shows in wells drilled offshore that tested oil from Oligocene and Miocene reservoirs (Richardson and others, 1994). The Sharmah-1 well in the Gulf of Aden (fig. 2), for example, produced 3,700 BOPD of 43° API gravity oil on a test from a middle Eocene carbonate (Beydoun, 1989). To 2001, however, commercial production has not been established in the Gulf of Aden from this hypothetical TPS. The high heat flow, as much as 26.5°C/100 m near the spreading center, indicates the existence of an oil window starting at depths from 2,438 to 2,743 m (from 8,000 to 9,000 ft) in the offshore of the Red Sea and Gulf of Aden (Beydoun, 1989; Barnard and others, 1992). In the onshore area, oil-prone source rocks of Tertiary age were identified in the Masilah-1 well (figs. 3, 5), but they showed only modest organic richness and fair pyrolysis yields, and were thermally immature (Barnard and others, 1992).

Petroleum Assessment

Production was first established in Yemen in 1984 but was not included in a previous assessment by the USGS (Masters and others, 1994). In the present assessment, only one assessment unit (AU), the Ma'Rib–Al Jawf / Shabwah / Masila AU (20040101), is identified within the Madbi Amran / Qishn TPS (200401) (fig. 1). Because the country and its petroleum provinces do not have a long discovery history, field growth is believed to be especially important for assessing future potential. Known oil reserves as of 1/1/96 were about 2 billion barrels of oil (BBO) (USGS, 2000). Known gas reserves as of 1/1/96 were about 11 trillion cubic feet of gas (TCF). The potential size of discovered fields using a field growth algorithm is shown in figures 16 and 17 as reported in USGS World Petroleum Assessment 2000 (USGS, 2000).

The undiscovered resources estimated in this assessment are reported as probability distributions. It is therefore convenient to describe the results in terms of mean values and F95 and F5 probability levels. The mean estimate of undiscovered oil is 2.7 BBO with a F95–F5 range from 1.0 to 4.7 BBO. The mean estimate of undiscovered natural gas is 17.0 TCF with a F95–F5 range of 6.5 to 30.0 TCF. The mean estimate of undiscovered natural gas liquids (NGL) is 0.9 billion barrels NGL (BBNGL) with a F95–F5 range of 0.4 to 2.2 BBNGL. For known petroleum resource volumes, the Ma'Rib–Al Jawf basin province (province 2004) ranks 61st with 4.3 billion barrels of oil equivalent (BBOE), exclusive of U.S. provinces. When undiscovered potential is added to known reserves, the total petroleum endowment for the Madbi Amran / Qishn TPS rises to 9.8 BBOE, which then ranks Yemen 51st for potential of petroleum resources, exclusive of the U.S. The estimated number and sizes of undiscovered oil and gas fields for the Ma'Rib–Al Jawf / Shabwah / Masila AU (20040101) are shown in figures 18 and 19.

Although Yemen is a relatively immature petroleum-producing country from an exploration standpoint, sizes of discovered fields already show significant decline. However, the undiscovered potential, at the mean, was viewed to be larger than what has been discovered to time of this report. The potential resides principally in combination structural/stratigraphic traps related to the complex interplay of rift-filling sequences within multiple grabens, half-grabens, and horsts. In the Ma'Rib–Al Jawf / Shabwah basin, petroleum traps associated with salt tectonics provide many trapping styles. Intra-salt and supra-salt reservoirs are considered viable plays and are being actively explored. In the Masila-Jeza basin, rejuvenation of basement extensional fault blocks, as well as some transpressional features with associated stratigraphic/structural traps, will likely result in future discoveries.

The potential for undiscovered oil and gas resources in the Mesozoic Nayfa (Naifa) petroleum system was not assessed, but the limited areal extent of potential source rocks and their shallow depth of burial and concomitant immaturity (Csato and others, 2001) make its hydrocarbon potential relatively limited.

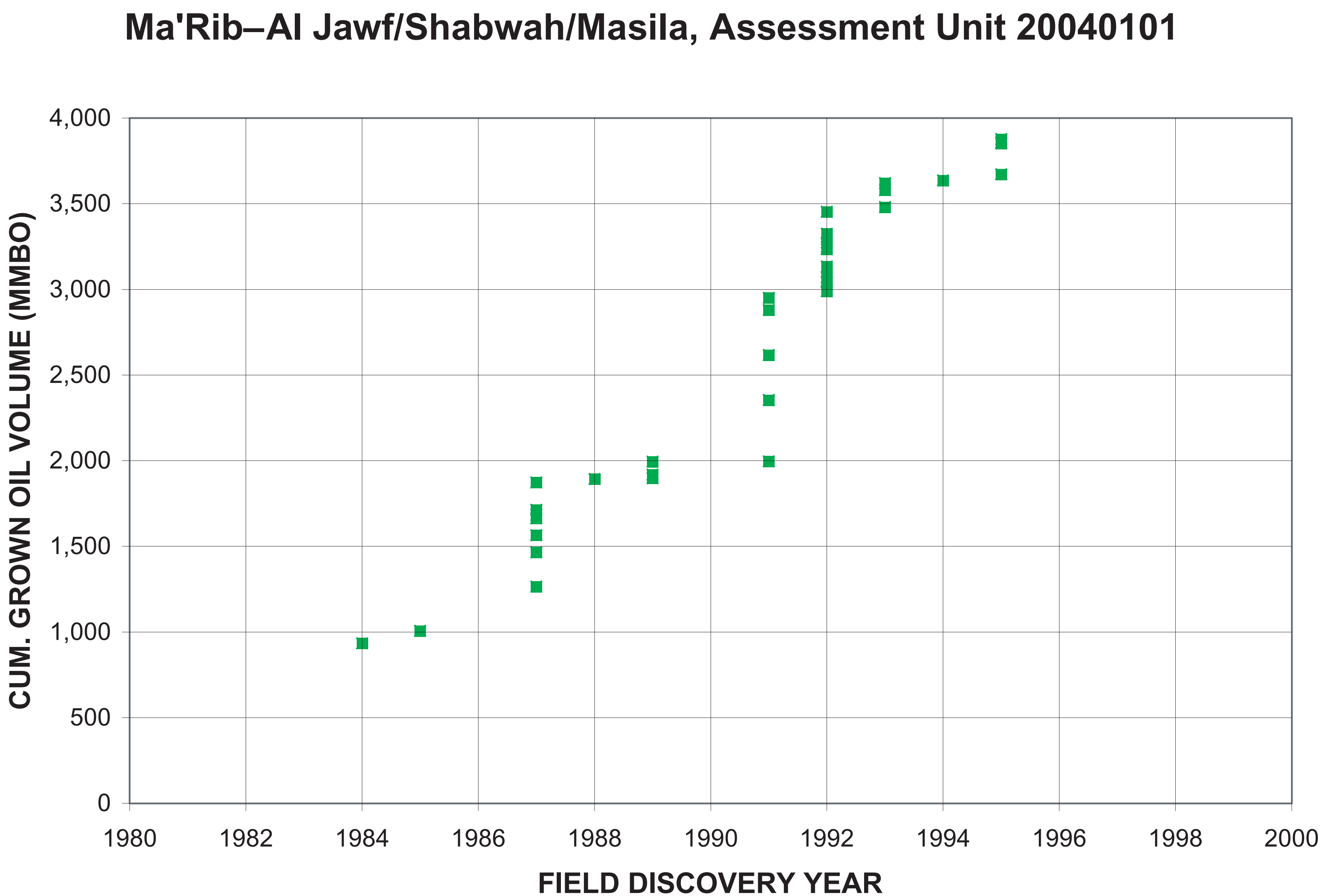


Figure 16. Cumulative grown oil volumes versus discovery year for Yemen assessment unit (from USGS, 2000).

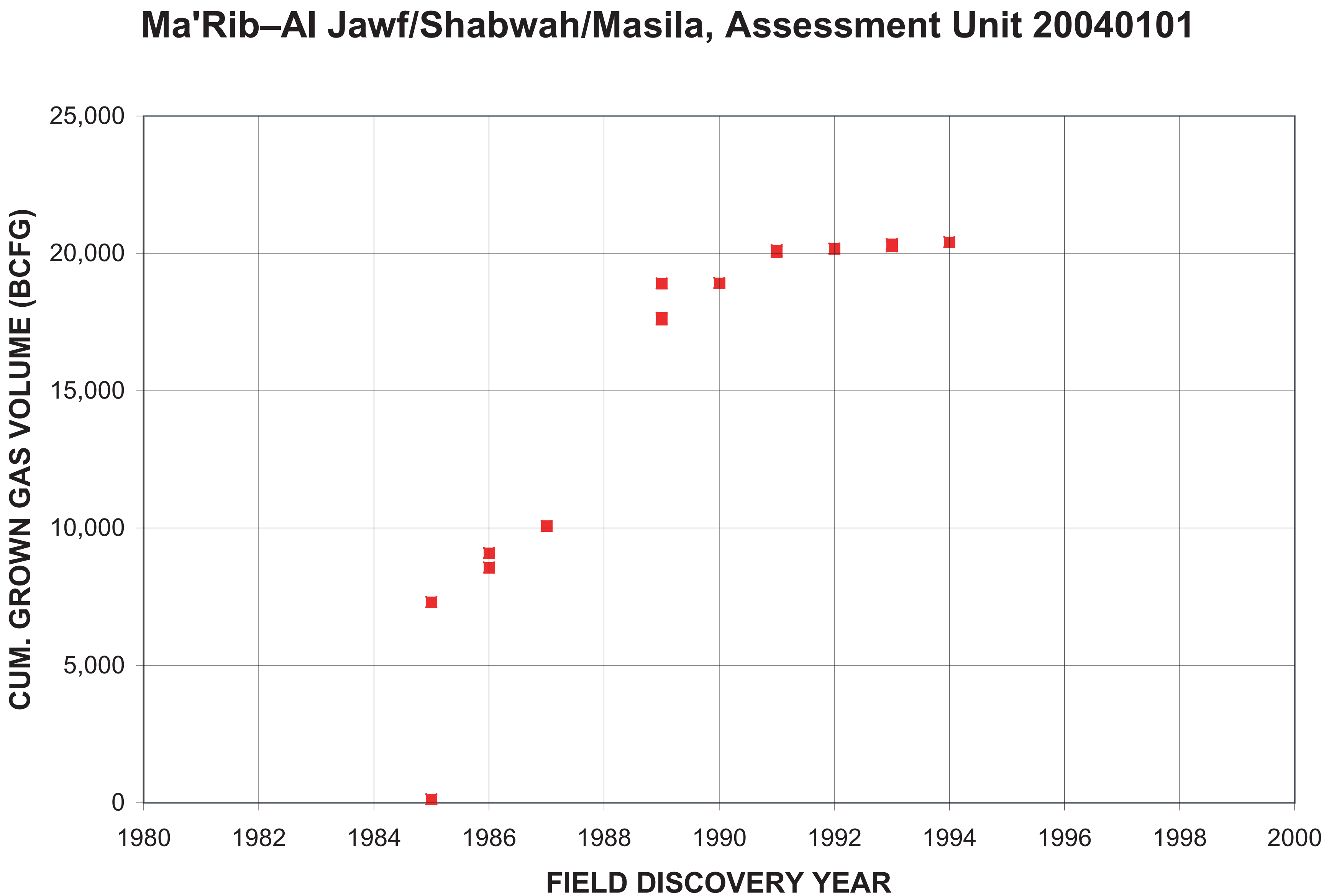


Figure 17. Cumulative grown gas volumes versus discovery year for Yemen assessment unit (from USGS, 2000).

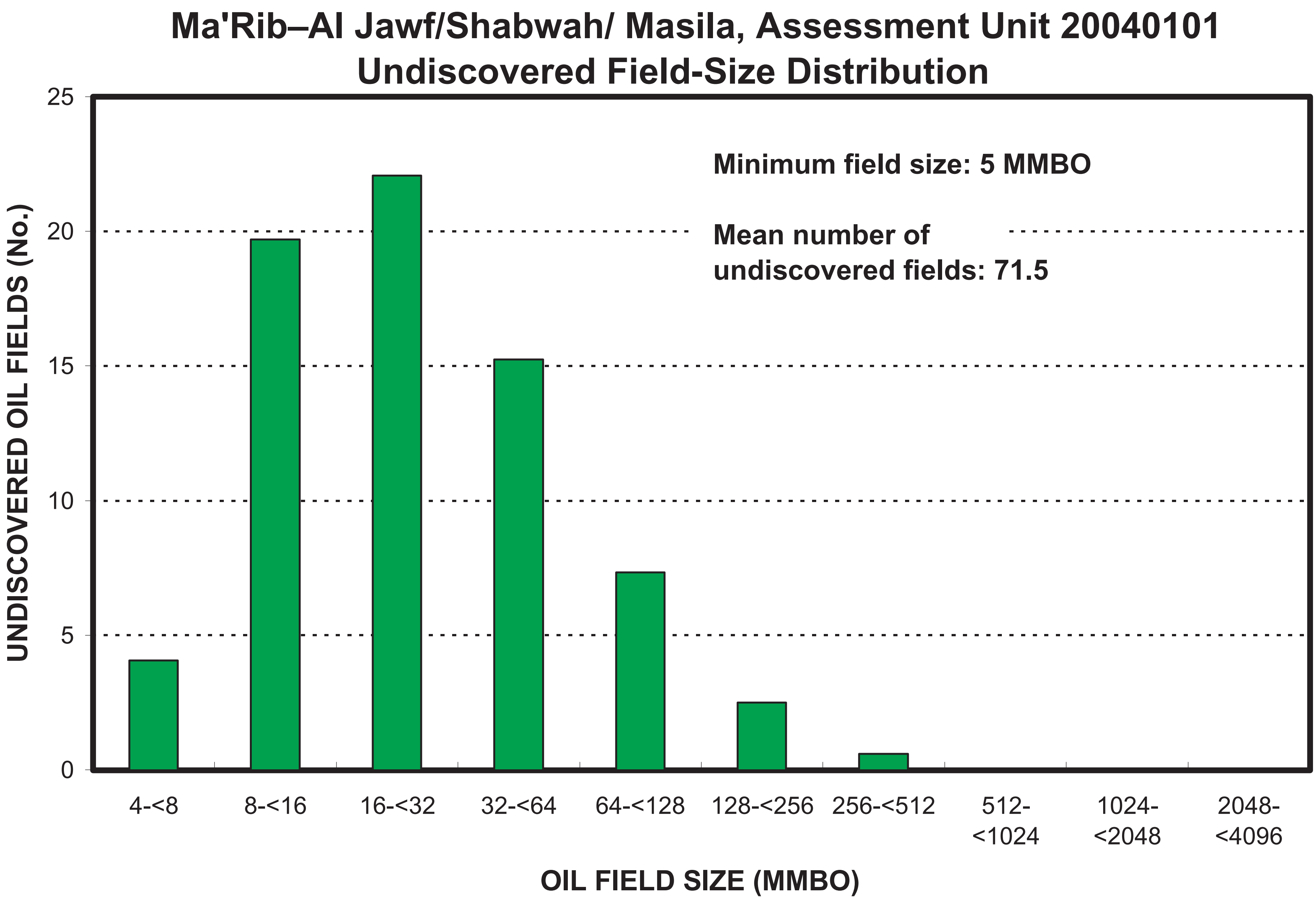


Figure 18. Estimated undiscovered oil field number and size distribution for Madbi Amran/Qishn Total Petroleum System, Yemen (from USGS, 2000).

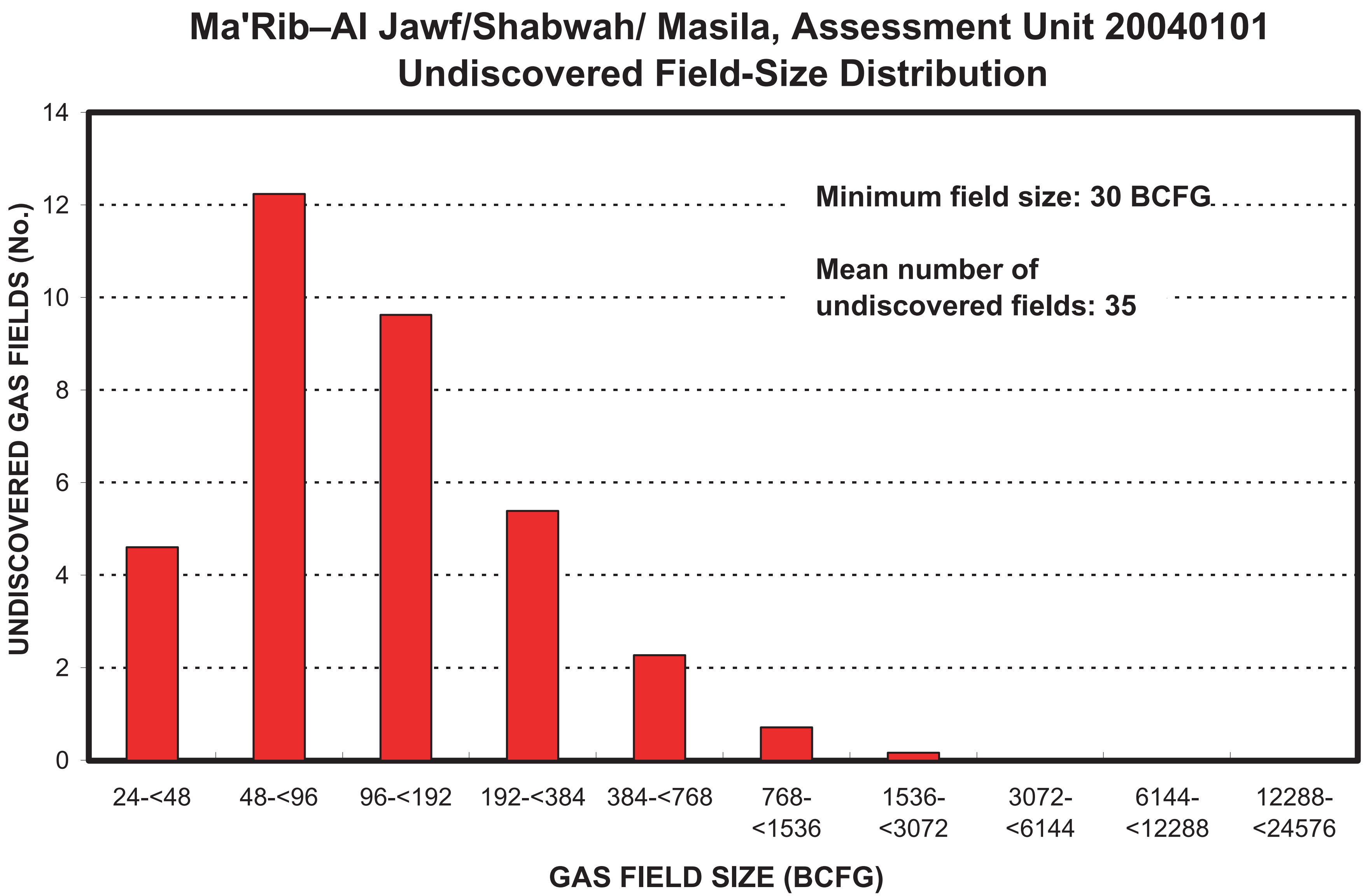


Figure 19. Estimated undiscovered gas field number and size distribution for Madbi Amran/Qishn Total Petroleum System, Yemen (from USGS, 2000).

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