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Sedimentary basins of Yemen: their tectonic development and lithostratigraphic cover

Mustafa Abdullatif As-Saruri · Rasoul Sorkhabi · Rasheed Baraba

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Abstract This paper describes the updated stratigraphy, structural framework and evolution, and hydrocarbon prospectivity of the Paleozoic, Mesozoic and Cenozoic basins of Yemen, depicted also on regional stratigraphic charts. The Paleozoic basins include (1) the Rub' Al-Khali basin (southern flanks), bounded to the south by the Hadramawt arch (oriented approximately W–E) towards which the Paleozoic and Mesozoic sediments pinch out; (2) the San'a basin, encompassing Paleozoic through Upper Jurassic sediments; and (3) the southern offshore Suqatra (island) basin filled with Permo-Triassic sediments correlatable with that of the Karoo rift in Africa. The Mesozoic rift basins formed due to the breakup of Gondwana and separation of India/Madagascar from Africa–Arabia during the Late Jurassic/Early Cretaceous. The five Mesozoic sedimentary rift basins reflect in their orientation an inheritance from deep-seated, reactivated NW–SE trending Infracambrian Najd fault system. These basins formed sequentially from west to east–southeast, sub-parallel with rift orientations—NNW–SSE for the Siham-Ad-Dali' basin in the west, NW–SE for the Sab'atayn and Balhaf basins and WNW–ESE for the Say'un-Masilah basin in the centre, and almost E–W for the Jiza'–Qamar basin located in the east of Yemen. The Sab'atayn and Say'un–Masilah basins are the only ones producing oil and gas so far. Petroleum reservoirs in both basins have been charged from Upper Jurassic Madbi shale. The main reservoirs in the Sab'atayn basin include sandstone units in the Sab'atayn Formation (Tithonian), the turbiditic sandstones of the Lam Member (Tithonian) and the Proterozoic fractured basement (upthrown fault block), while the main reservoirs in the Say'un–Masilah basin are sandstones of the Qishn Clastics Member (Hauterivian/Barremian) and the Ghayl Member (Berriasian/Valanginian), and Proterozoic fractured basement. The Cenozoic rift basins are related to the separation of Arabia from Africa by the opening of the Red Sea to the west and the Gulf of Aden to the south of Yemen during the Oligocene-Recent. These basins are filled with up to 3,000 m of sediments showing both lateral and vertical facies changes. The Cenozoic rift basins along the Gulf of Aden include the Mukalla–Sayhut, the Hawrah–Ahwar and the Aden–Abyan basins (all trending ENE–WSW), and have both offshore and onshore sectors as extensional faulting and regional subsidence affected the southern margin of Yemen episodically. Seafloor spreading in the Gulf of Aden dates back to the Early Miocene. Many of the offshore wells drilled in the Mukalla–Sayhut basin have encountered oil shows in the Cretaceous through Neogene layers. Subcommercial discovery was identified in Sharmah-1 well in the fractured Middle Eocene limestone of the Habshiyah Formation. The Tihamah basin along the NNW–SSE trending Red Sea commenced in Late Oligocene, with oceanic crust formation in the earliest Pliocene. The Late Miocene stratigraphy of the Red Sea offshore Yemen is dominated by salt deformation. Oil and gas seeps are found in the Tihamah basin including the As-Salif peninsula and the onshore Tihamah plain; and oil and gas shows encountered in several onshore and offshore wells indicate the presence of proven source rocks in this basin.

M. A. As-Saruri (✉)
Petroleum Exploration and Production Authority,
San'a, Yemen
e-mail: msaruri@fulbrightmail.org

R. Sorkhabi
Energy and Geoscience Institute, University of Utah,
Salt Lake City, UT, USA
e-mail: rsorkhabi@egi.utah.edu

R. Baraba
Shura Council,
San'a, Yemen
e-mail: rbaraba@yahoo.com

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Introduction

Up until the late 1980s, the geology of Yemen was mainly characterized by only a few tectonic elements based on surface investigations; these included the South Arabian Marginal Swell by von Wissmann (1932) and von Wissmann et al. (1942), the Hadramawt Arch and Jeze Trough by Beydoun (1964, 1966), the Dhufar Huqf Arch by Saint-Marc (1978) and the Coastal Range Arch by Schramm et al. (1986). Gravity and magnetic surveys conducted by Technoexport (a former Soviet Company) and published by Isaev et al. (1984) and Isaev (1987) provided a subsurface framework for divisions of the Mesozoic basins of Yemen. Further attempts to systematize the knowledge of the Mesozoic basins were made by Jungwirth and As-Saruri (1990) using outcrop geologic mapping, and by Redfern and Jones (1995) and Ellis et al. (1996), who elucidated the structural highs and basins based on the 1994 surveys by the Simon Petroleum Technology. Paul (1990) produced a schematic map of structural divisions of the former South Yemen, using unpublished geophysical data. Beydoun (1991) discussed the tectonic elements of the southern Arabia Peninsula. Bosence (1997) studied the structure of the Mesozoic basins based on composite regional seismic sections. Brannan et al. (1997, 1999) discussed the tectono-stratigraphic development of the Qamar basin and geological evolution of the Marib–Shabwah basin. Building upon the work of Beydoun and Bichan (1970), Samuel et al. (1997) described the outcrop geology of the Socotran (Suqatra) island, including its important Triassic section on the eastern part of the island. Beydoun et al. (1996, 1998) and Beydoun and As-Saruri (1998) published the first comprehensive map of the sedimentary basins and highs, integrating all previous outcrop studies and geophysical surveys for the entire Yemen.

In addition to the onshore Mesozoic basins, geologic work has also targeted the Cenozoic rift basins in the Red Sea (e.g., Coleman 1993 and references therein; Davison et al. 1994, 1996, 1998; Ghebreab 1998; McClusky et al. 2010) and the Gulf of Aden (e.g., Haitham and Nani, 1990 based on Agip/Eni's exploration results; Bott et al. 1992, based on British Gas' exploration; Watchorn et al. 1998; Fantozzi and Sgavetti 1998; Huchon and Khanbari 2003; Leroy et al. 2004; Fournier et al. 2007, 2010) from the perspective of rift tectonics or hydrocarbon potential. Burser and Bosence (1998) and Bosworth et al. (2005) present excellent reviews of the sedimentary and structural evolution of the Red Sea and Gulf of Aden regions combined.

Ahlbrandt (2002) published an important USGS study, which included an assessment of the petroleum systems and resources of the two hydrocarbon-bearing Mesozoic basins of Yemen, i.e. the Say'un–Masilah and Jiza'–Qamar basins, which the USGS report grouped as a single 'Masila–Jeza basin' (and employing certain incorrect statigraphic terms). Csato et al. (2001) and Csato (2005) proposed play models for oil exploration in the Sab'atayn basin. Lindquist (1999) reviewed and evaluated the petroleum geology and resources of the Red Sea.

Building upon these and other previous studies as well as subsurface data from the Yemen Petroleum Exploration and Production Authority, this paper presents an updated stratigraphic and tectonic framework for the sedimentary basins of Yemen (Fig. 1) with a discussion on their petroleum systems. In Fig. 2, we present a series of structural–stratigraphic cross-sections along several traverses in Yemen. Figures 3, 4 and 5 show stratigraphic charts for the Paleozoic, Mesozoic and Cenozoic eras, respectively.

Basement tectonics

The Precambrain basement metamorphic and igneous rocks of Yemen represent the southeastern part of the Arabian–Nubian shield. Early reconnaissance works on the basement rocks of Yemen include Lamare (1930), Little (1925), and von Wissmann et al. (1942). Greenwood and Bleackley (1967) worked in the former Western Aden Protectorate, based on photogeological interpretation and reconnaissance fieldwork, and divided the Precambrian rocks into the Aden Metamorphic Group and the Older Gneiss. Beydoun (1964, 1966) and Beydoun and Greenwood (1968) worked in the former Eastern Aden Protectorate and defined the Gharish, Thaniya, Tha'lab and Ghabar Groups. As-Saruri and Wiefel (1998) synthesized data on the basement rocks in central Yemen (Mudiyah–Al-Mukalla) based on a German mapping project. The first investigation of the basement rock on the Island of Socotra (Suqatra) was carried out by Beydoun and Bichan (1970), who divided them into the older Amphibolites Facies group and the younger Weakly Metamorphosed Group (Hadibu series). Recently, Whitehouse et al. (2001) discussed the basement character of Yemen compared to Saudi Arabia to the north and Somalia to the south.

The basement rocks originated as a series of continental basement and subducation volcano-sedimentary arc complexes, or tectono-stratigraphic terranes (Coney et al. 1980) as discussed by various authors (Delfour 1981; Greenwood et al. 1980, 1982; Johnson and Vranas 1984). These rocks formed in various periods during the Precambrian consolidation of the Afro-Arabian cratons; however, our geochro-

Fig. 1 Map of the outcrop geology, major structural highs and sedimentary basins of Yemen

nologic and geochemical knowledge of these rocks in Yemen is not abundant enough to paint a detailed tectonic picture for their formation. Moreover, these terranes have been affected by strike slip movements, thus obliterating their original disposition and field relations with one another.

The Precambrian rocks in Yemen outcrop in the western part of the country as this region experienced basement uplift related to the Red Sea and Gulf of Aden rift events. These Precambrian terranes include: (1) the Asir terrane consisting of basement gneiss and arc-type volcanics (Christmann et al. 1984); (2) the Abas terrane, predominantly geniss and probably 2.7–1.3 Ga in age; (3) the Al-Bayda terrane, mainly meta-volcanics and schist, probably 2.5–1.2 Ga: (4) the Al-Mahfid terrane, mainly granite gneiss of 3.0–1.8 Ga; and (5) the Mukalla terrane, largely meta-volcanics of ~700 Ma (Fig. 1). The geochronlogic data for the terranes are given by Windley et al. (1996).

The basement tectonic 'grains' in Yemen are oriented N–S, NW–SE (and the conjugate NE–SW) and subordinately E–W. These lineaments have influenced the orientation of inter-basin rifting or tectonic swells/highs as differing stress fields were built up in Yemen during various stages of Gondwana break up, commencing with the African Karoo rift in the Early Jurassic (Cannon et al. 1981; Bosellini 1989) that affected the horn of Africa including Socotra (Suqatra) (Bott et al. 1994), and continuing through rejuvenation of the ancient NW–SE Najd faults in Late

Jurassic and Early Cretaceous times, and finally separation of Arabia from Africa in the Neogene along the ENE–WSW Gulf of Aden and NNW–SSE Red Sea trends.

Fig. 2 Regional cross-sections showing the main structural framework and stratigraphy along several traverses in Yemen. Locations of the lines shown in Fig. 1. A–A′, B–B′, C–C′ are modified after Beydoun (1966); D–D′ modified after Jungwirth and As-Saruri (1990) and F–F′ modified after Davison et al. (1998) ▶

Infra-Cambrian sediments

A succession of low-grade metasediments, occurring at the Proterozoic–Cambrian transition, often called the Infracambrian sediments, are preserved in Yemen, but only in the small faulted depressions of the Wadi Ghabar (about 60 km northwest of Mukalla City in Hadramawt Province) and the Wadi Minhamir (1 km northwest of Ma'abir in Wadi Hajr, along the Gulf of Aden). These structurally deformed sediments, described as the Ghabar Group by (Beydoun 1964, 1966) and Beydoun and Greenwood (1968), consist of breccia, conglomerate, siltstone, sandstone, dolomite and tuffaceous material (Fig. 2). The 432-m thick Ghabar Group has been divided into four lithological formations: Minhamir (breccia and conglomerate), Shabb (platy limestone and sandstone), Khablah (dolomite and calcareous sandstone), and Harut (well-bedded sandy dolomite and platy shale).

The subsurface equivalent of Infracambrian sediments are known from Qinab-1 well (drilled in the southern flank of the Rub' Al-Khali basin), and are formally defined as the Qinab Group, consisting of conglomerate, breccia and sandstone with intercalation of volcanic rocks (Fig. 2). The latest Proterozoic ('Pan African') Najd fault system of the Arabian Shield and its extension in Yemen, created Infracambrian to Early Cambrian graben fills as observed on seismic sections in the Rub' Al-Khali basin (Dyer and Husseini 1991).

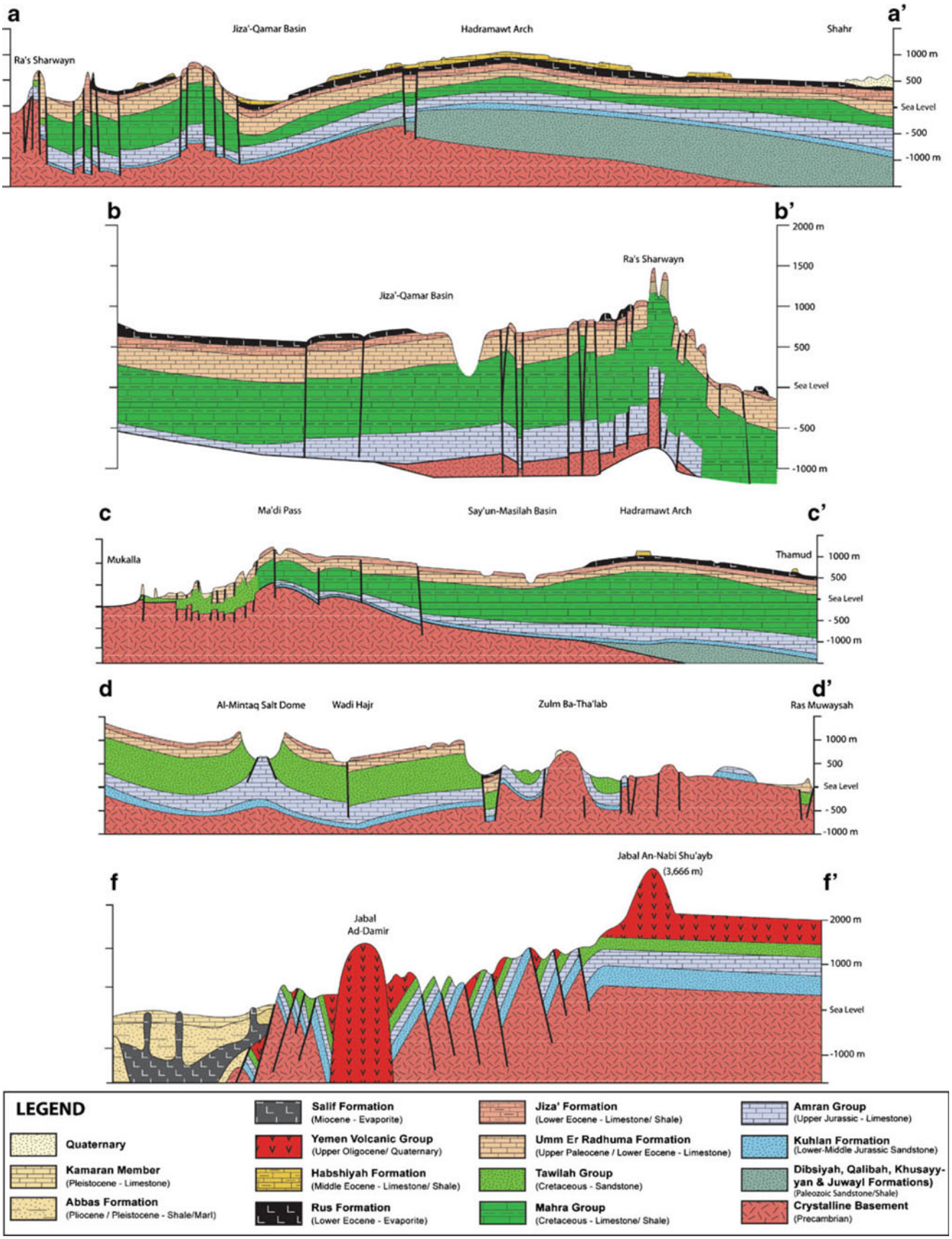
Paleozoic basins

Paleozoic sediments outcrop in northwest Yemen, in the Sa'dah and Hajjah areas, as a thin wedge between the metamorphic basement and the Mesozoic sediments (Fig. 3). They consist mainly of fluvial sandstone of the Wajid Formation (Cambrian–Carboniferous?) resting unconformably on the metamorphic basement, and are, in turn, overlain unconformably by the glacial sediments of the Akbara Formation (Upper Carboniferous/Lower Permian). These sediments outcrop along the northern and western margin of the San'a basin (Figs. 1 and 3) as described by Geukens (1960, 1966) and Kruck and Thiele (1983). The southern extent of the Paleozoic outcrops in this area is little known because they are covered by the Oligocene–Miocene Yemen Volcanic Group (Beydoun et al. 1998).

Subsurface Paleozoic successions have been recorded from several exploration wells drilled in the southern flank of the Rub' Al-Kali basin (ranging in age from the Cambrian through the Permian) in northern Yemen, in the San'a basin and in the Marib sector of the Sab'atayn basin (Cambrian–Permian sediments) in western Yemen, and offshore Suqatra Island (Permian sediments).

The Rub' Al-Khali basin (largely located within Saudi Arabia but its southern flank is shared between Yemen and Oman) constitutes a huge structural down-warp to the north of the Hadramawt Arch, originated as an Infracambrian–Cambrian intracratonic sag within Gondwana, and evolved to a platformal basin on the wide Tethys shelf during Permian and Mesozoic times (Beydoun 1989, 1991; Dyer and Husseini 1991; Husseini 1989; Sykes and Abu Risheh 1989). The southern flank of the Rub' Al-Khali basin along the Hadramawt Arch is more than 650 km long and 70–100 km wide. The Paleozoic–Mesozoic sedimentary fill ranges from a thickness of 2 km near the crest of the Hadramawt Arch to more than 4 km at the Yemeni/Saudi Arabian border, and these sediments generally pinch out toward the Hadramawt Arch. In analogy with central Saudi Arabia, the Silurian Qusaiba Shale in the Rub' Al-Khali basin is probably a productive source rock although extensive exploration of the basin is yet to be carried out (Fig. 3).

The San'a basin stratigraphy has been recorded from *Khaywan-1* exploration well drilled in the northern part of the basin, which encountered less than 400 m of Paleozoic sedimentary cover before terminating at the basement. The Paleozoic sediments, predominantly clastics capped by Permian glacial deposits, are overlain by continental sandstones of the Kuhlan Formation (Bathonian/Callovian), about 100 m thick in the subsurface. The Kuhlan Formation outcrops in the Kuhlan village (70 km northwest of San'a) in a narrow belt, and its maximum thickness is 200 m. The Kuhlan is overlain by more than 1,200-m-thick Jurassic carbonates (Amran Group) and more than 600-m-thick continental clastics interfingered with shallow marine carbonates, which together constitute the Cretaceous Tawilah Group. The sedimentary succession in the second exploration well, *Shuja-1*, is similar to that in *Khaywan-1* and yields a total thickness of 1,936 m sediments, including 370 m of Paleozoic section. According to the results of exploration wells drilled in the San'a basin, there are good source rock units in the marly limestones of the Amran Group, and excellent reservoir quality in the sandstones of the Wajid and Kuhlan formations, sealed by glacial clays of the Akaba Formation and carbonates of the Amran Group. Possible traps include stratigraphic pinch-outs against the basement or


a
Jiza'-Qamar Basin
Hadramawt Arch
Shahr
a'
Ra's Sharwayn
1000 m
500
Sea Level
- 500
-1000 m
b
b'
2000 m
1500
1000
500
Sea Level
- 500
-1000 m
Ra's Sharwayn
Jiza'-Qamar Basin
c
Ma'di Pass
Say'un-Masilah Basin
Hadramawt Arch
c'
Mukalla
Thamud
1000 m
500
Sea Level
- 500
-1000 m
d
Al-Mintaq Salt Dome
Wadi Hajr
Zulm Ba-Tha'lab
d'
Ras Muwaysah
1000 m
500
Sea Level
- 500
-1000 m
Jabal An-Nabi Shu'ayb
(3,666 m)
f
f'
Jabal
Ad-Damir
2000 m
1000 m
Sea Level
-1000 m
LEGEND
Quaternary
Kamaran Member
(Pleistocene - Limestone)
Abbas Formation
(Pliocene / Pleistocene - Shale/Marl)
Salif Formation
(Miocene - Evaporite)
Yemen Volcanic Group
(Upper Oligocene/ Quaternary)
Habshiyah Formation
(Middle Eocene - Limestone/ Shale)
Rus Formation
(Lower Eocene - Evaporite)
Jiza' Formation
(Lower Eocene - Limestone/ Shale)
Umm Er Radhuma Formation
(Upper Paleocene / Lower Eocene - Limestone)
Tawilah Group
(Cretaceous - Sandstone)
Mahra Group
(Cretaceous - Limestone/ Shale)
Amran Group
(Upper Jurassic - Limestone)
Kuhlan Formation
(Lower-Middle Jurassic Sandstone)
Dibsiyah, Qalibah, Khusayy-yan & Juwayl Formations)
(Paleozoic Sandstone/Shale)
Crystalline Basement
(Precambrian)

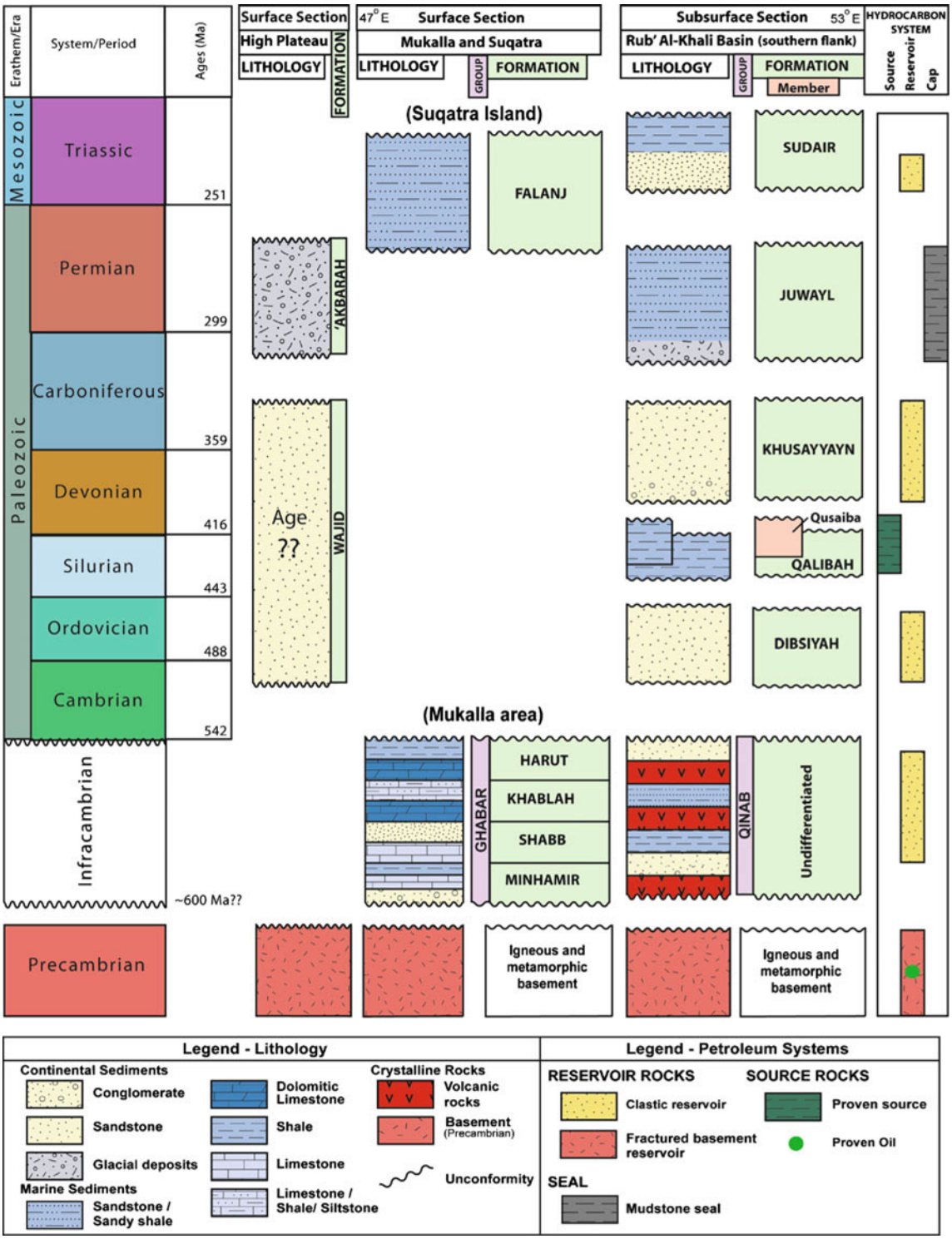


Fig. 3 Paleozoic stratigraphic chart and petroleum systems of Yemen

tilted blocks resulting from the Late Jurassic or Cenozoic rifting events.

The southern parts of the Suqatra Island basin include a sedimentary succession ranging in age from the Permian through the Cenozoic (Beydoun 1966; Beydoun and Bichan 1970; Beydoun and Sikander 1992; Beydoun 1989, 1991; Bott et al. 1994; Brise et al. 1997; Richardson et al. 1994, 1995; Samuel et al. 1997). The first offshore *Samhah-1* well penetrated the granitic basement at a depth of 2,620 m and showed that a clastic succession of Permo-Triassic age

rests unconformably on the basement and is, in turn, overlain by Triassic(?) volcanics (probably related to a rifting event within Gondwana correlatable to the Karoo volcanics). The Jurassic is not widely distributed, but the Lower Cretaceous is represented by the Sa'ar Formation (shale, limestone and sandstone) and the Qishn Formation (conglomeratic sandstone and marly limestone); while the Upper Cretaceous is represented by the Fartaq Formation (limestone) and Sharwayn Formation (marl and limestone). The Paleogene Hadramawt Group (largely carbonate and evaporite) is also well developed in the Suqatra basin, with some lateral facies changes. The Neogene Shihr Group (carbonates overlain by congrlomente) is represented by the outcrop section of the 'Idiyu Formation', which extends to the offshore. Offshore Suqatra thus offers an attractive frontier basin for hydrocarbon exploration.

Mesozoic basins

The Late Jurassic rifting between east Africa and west India also caused extensional tectonics in Yemen (but notably without rift-related volcanism), and sediments began to fill Mesozoic grabens thus developed, including the Siham–Ad-Dali', Sab'atayn, Say'un–Masilah, Balhaf and Jiza'–Qamar basins (Figs. 1 and 4).

The pre-rift sedimentary sequences in these basins are represented by the Kuhlan Formation (Bathonian/Callovian) and the Shuqra Formation (Oxfordian). The Kuhlan Formation consists of a basal transgression unit, poorly sorted coarse sandstone (fluvial sands and conglomerates), filling the topographic lows in the peneplaned basement. The Kuhlan Formation conformably grades up into the platform carbonates of Shuqra Formation, which was part of a wider Tethys shelf on the passive margin of the Arabian plate.

Seismic images, well data, and field observations from the Mesozoic basins of Yemen indicate that the rifting started during early Kimmeridgian in the western part, during middle Kimmeridgian–Lower Tithonian in the central part, and shortly later in the eastern parts of Yemen. Subsequent northeastward separation of the Indian plate is reflected in the easterly and southerly propagation of basin subsidence and sediment fills in Yemen during Tithonian–Valanginian times (Beydoun et al. 1996; Bott et al. 1992). The thickness of the sedimentary succession in the Mesozoic basins is between 1.8 and 3 km in the western parts and 4–6 km in the east parts of Yemen. The location of the Mesozoic rift basins was additionally controlled by the basement grain of NW–SE trending Najd fault system (Fig. 4).

Episodic subsidence of the Mesozoic basins was caused by sporadic, localized and brief pulses of fault activity and erosion which reflects instability in the Kimmeridgian–Tithonian sedimentary record. These localized events affected different sectors of the Mesozoic basins at different times, and gave rise to structural differentiations into sub-basins, half-grabens, and intra-basinal horsts. Within and in-between the Mesozoic basins, major paleo-highs exerted important controls on the distribution and thickness of sedimentary facies. These structural highs include (1) the Mahfid basement uplift separating the Siham–Ad-Dali' and Sab'atayn basins, (2) the Jabal Al-Aswad High between the Hajr sector of the Sab'atayn basin and Balhaf basin, (3) the Jahi–Mukalla High dividing the Sab'atayn and Say'un–Masilah basins and (4) the Fartaq High separating the Say'un–Masilah basin from Jiza'–Qamar basin. The Hadramawt Arch acts as a major divide between the Say'un–Masilah and Jiza'–Qamar basins to the south and the Paleozoic Rub' Al-Khali basin to the north (and this lineament appears to have been a persistent structural barrier with periodic movements since the early Paleozoic).

Upper Jurassic–Early Cretaceous syn-rift sediments in the Mesozoic basins constitute the predominant petroleum plays and production in Yemen. Early syn-rift sediments of the Mesozoic basins are represented by the Madbi Formation, which consists in the surface section of organic-rich marine shale (Lower and Upper Madbi Shales Members), debris flow and breccias (Rafad Member) and well-bedded limestone (Ma'abir Member). In the subsurface section, the Madbi Formation is divided into the rich bituminous shale of the Meem Member in the lower part, and the shale and turbidite of the Lam Member in the upper part. Continued basins subsidence and intra-basinal tectonic uplift brought fluxes of thick turbidites into the structurally deepening rift. The juxtaposition of deltaic sandstones with alluvial submarine fans carbonate breccias in the Madbi Formation reflects tectonic instability in these Mesozoic basins. The turbidites of the Madbi Formation are overlain by the thick evaporites of the Sab'atyan Formation. For long, these evaporates had masked the importance of the Madbi turbidites on seismic images, but recent drillings in the Sab'atayan and Say'un–Masilah basins have revealed the turbidites to be an important petroleum reservoir (Fig. 4). The Barremian-age Qishn Clastics offer another noteworthy reservoir rock, especially in the Say'un–Masilah basin. These sandstones have high porosity and permeability and are free from inhibiting authigenic clay or other diagnetic problems because of their quartz-rich composition and relatively shallow burial depth (Putnam et al. 1997; Leckie and Rumpel 2003; King et al. 2003).

The Sab'atayan evaporites are overlain by platform carbonates of the Nayfa Formation (Upper Tithonian) and deepwater limestone and shale sediments of the Sa'ar Formation (Berriasian–Valanginian). The remaining Cretaceous sediments (mainly shallow marine limestones, marls and sandstone) in the Mesozoic basins are sandwiched between major unconformities at the Hauterivian, Aptian, Cenomanian

Fig. 4 Mesozoic stratigraphic chart and petroleum systems of Yemen

and Danian stages, reflecting transgressions due to eustatic changes or non-deposition/erosion by tectonic uplifts.

Cenozoic basins

The separation of the Arabian Peninsula from Africa was made by the rift-opening of the Gulf of Aden to the south of Yemen and the Red Sea to the west of Yemen. The rifting, that began at ~31 Ma and is still active, is widely believed to be part of the Afar plume impingement beneath the African–Arabian plate associated with a large volume of flood basalts (e.g., Bosworth et al. 2005; Camp and Roobol 1989; Camp et al. 1991, 1992). The Gulf of Aden rift system propagated from the Alula/Ra's Fartaq trend in the east to the Bab Al-Mandab in the west, and thus joined the Owen fracture zone to the Afar hotspot (Courtillot 1980; Fournier et al. 2010; Leroy et al. 2004; Manighetti et al. 1998). The Red Sea rifting propagated from south to north, joining the Dead Sea and Levant strike-slip fault (Bott et al. 1992; Hughes et al. 1991; Hughes and Beydoun 1992). The Red Sea was cut off from India Ocean via Bab Al-Mandab in the late Middle Miocene, giving rise to thick evaporite deposition in the Red Sea during this time. These evaporite deposits (originally 1.5–2.0 km thick) have produced significant salt structures (notably canopies) in the Red Sea sedimentary basin offshore Yemen, which may be favourable sites for petroleum traps (Heaton et al. 1996).

Extensional tectonics in the Gulf of Aden and Red Sea has resulted in rift shoulder uplift (exposing the Precambrian basement in western Yemen) and basin subsidence and sediment fill with a thick succession from fluvial/coastal through shallow marine to deep marine facies. The Aden–Abyan, Hawrah–Ahwar and Mukalla–Sayhut basins along the northern coast of the Gulf of Aden run parallel to the ENE–SWS trend of the Gulf of Aden trend, while the Tihamah basin spans parallel to the NNW–SSE Red Sea trend (Figs. 1 and 5).

The Mukalla–Sayhut basin is largely distributed offshore eastern Yemen and represents an Oligocene-Recent sequence in the Gulf of Aden with a thickness of 3,500–4,500 m. Its syn-rift package includes shale, sandstone and evaporite sediments of the Ghaydah Formation. The Hami limestone and Sarar clastics represent the post-rift package. Pre-rift sediments in the basin are comprised by the Jurassic (equivalent Kuhlan Formation and 'Amran Group), Cretaceous (equivalent Tawilah and Mahra Groups) and Paleogene (equivalent Hadramawt Group) sediments, deposited in a setting similar to that of the onshore Say'un–Masilah basin (Fig. 5).

The offshore Hawrah–Ahwar basin in central Yemen is an extension of the onshore Balhaf basin superimposed by the Gulf of Aden rift sediments. Outcrops of Mesozoic rocks on the western margin of the Balhaf basin consist of the Kuhlan (Middle Jurassic sandstone), Shuqra (Oxfordian limestone and dolomite), Madbi (Kimmerdgian–Tithonian shale and limestone) and Nayfa (Tithonian limestone) Formations. This sequence also probably exists at the deeper levels of Hawrah–Ahwar basin, yet to be penetrated. Drilling in the basin has documented the Tawilah Group (Barremian–Maastrichtian clastics and carbonates) as well as the Hadramawt Group (Upper Paleocene/Middle Eocene carbonates and evaporites). Outcrops of the Oligocene syn-rift sediments are found on the northern margin of the Balhaf basin (Fig. 4), which consists of conglomerate and sandstone in the lower part, alternations of shale and limestone in the middle part, and gypsum in the upper part, and were designated as the Libakhah Formation and Ayn Ba-Ma'bad Member by As-Saruri and Beydoun (1998) and (As-Saruri 1999).

The Aden–Abyan basin contains pre-, syn- and post-rift sediment packages, and in our view, is the offshore extension of the Mesozoic Siham–Ad-Dali basin, further affected by the Gulf of Aden rifting and sediment fill. The pre-rift sediments crop out onshore in the northern margin of the Siham–Ad-Dali basin and include the following succession: The Kuhlan Formation (Bathonian/Callovian), the Shuqra Formation (Oxfordian), the Madbi Formation (Kimmeridgian/Middle Tithonian), the Nayfa Formation (Upper Tithonian/Lower Berriasian), the Qishn Formation (Lower cretaceous) and the undifferentiated Tawilah Group (Lower/Upper Cretaceous). The syn- and post-rift sediments in the Aden–Abyan basin are distributed only in the subsurface section and represented by the Upper Oligocene to Pleistocene sediments as imaged from seismic surveys. These sediments have been intruded and covered by a thick volume of the Yemen Volcanic Group, erupted during various phases of the rifting. The Aden–Abyan basin is divided into the western and eastern parts. The former is extensively injected by the rocks of the Yemen Volcanic Group, while the eastern part is less affected by the volcanism and contains a thick sedimentary succession having hydrocarbon potential to be explored (Trad et al. 1991).

The Tihamah basin on the eastern coastline of the Red Sea includes both onshore and offshore sectors and represents high rates of tectonic extension and deposition of the Neogene Tihamah Group, exceeding 3,000 m in thickness. The Zaydiyah Formation (Lower Miocene sandstone) lies at the base of the Tihamah Group although the base of the formation itself is not penetrated so far. This formation is succeeded by the Maqna Formation (Lower-Middle Miocene shale). Both of these formation represent the lower part of the syn-rift package. The Salif Formation (Middle-Upper Miocene) lies disconformably over the Maqna Formation, and is a thick pile of halite with subordinate shale and limestone, representing the upper

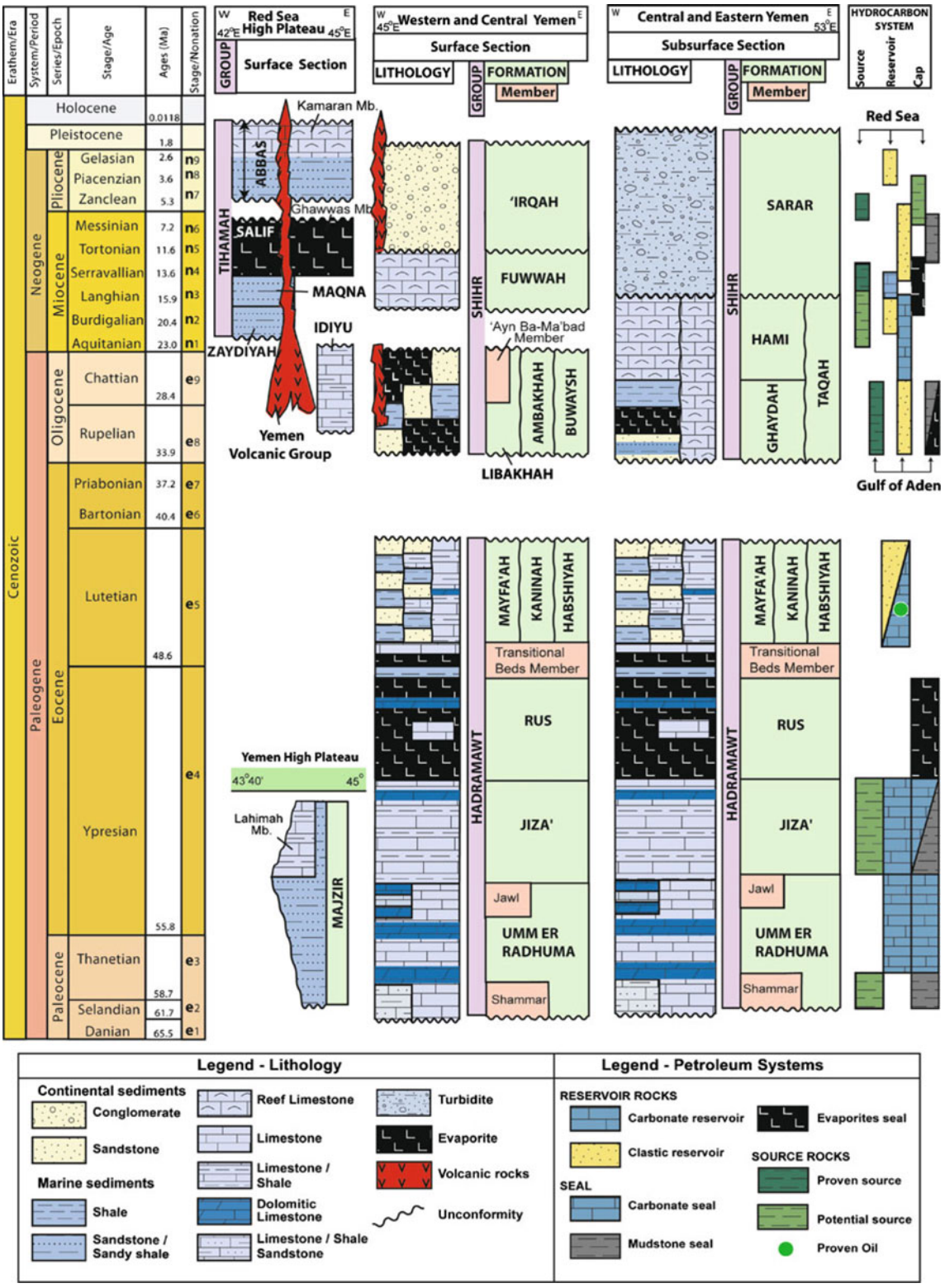


Fig. 5 Cenozoic stratigraphic chart and petroleum systems of Yemen

part of the syn-rift deposits. The uppermost part of the Salif Formation, called the Ghawwas Member (Upper Miocene), is separated from the overlying Abbas Formation (Pliocene–Pleistocene) by a major unconformity. The Abbas Formation represents post-rift clastics, mainly alternations of sandstones and shale. The uppermost part of the Abbas Formation, called the Kamaran Member (Pleistocene), consists of reef carbonates (Fig. 5). The pre-rift sediments in the onshore

Tihamah basin include continental sandstones of the Kuhlan Formation (Bathonian/Callovian), marine sediments of the 'Amran Group (Oxfordian–Lower Berriasian) and clastic sediments of the Tawilah Group (Barremian–Maastrichtian). In the northern part of the onshore Tihamah basin, the sedimentary succession includes the glacial tillites of the 'Akbarah Formation' (Carboniferous/Permian) at its lowermost part. Oil and gas seeps are found in the Tihamah basin including the As-Salif peninsula and onshore Tihamah plain, indicating good potential for hydrocarbon accumulation and discovery in this basin.

Concluding remarks

The geology of Yemen is largely characterized by a passive-margin rift setting throughout the Phanerozoic, resulting in Jurassic–Cretaceous rift basins related to the breakup of Gondwana (separation of India–Madagascar from Africa–Arabia) and Late Oligocene–Pliocene rift basins related to the separation of Arabia from Africa. Paleozoic basins in Yemen were also formed on the passive margin of Gondwana and are represented by the southern flank of the Rub al-Khali basin, the San'a basin and the offshore Suqatra island basin. The Paleozoic and Cenozoic rift basins have been relatively less explored and thus offer attractive hydrocarbon targets.

The two Mesozoic basins of the Sab'atayn and the Say'un–Masilah are currently the only hydrocarbon-producing basins in Yemen. In both of these basins, the Kimmeridgian Lower Madbi Shales Member is the main source rock with high organic carbon content and sufficient burial thermal maturity. Its thickness increases away from the structural highs within or surrounding the basins. The sandstones of the Alif Member of the Sab'atayn Formation are the major reservoirs in the Marib sector of the Sab'atayn basin, whereas hydrocarbon so far discovered in the Shabwah sector of the same basin has come from the pre- and post-salt carbonates or from the fractured granitic basement. Intra-salt clastics of the Yah and Seen Members and Madbi turbidites (Lam Member) have proved to be hydrocarbon bearing. The evaporites of the Sab'atayn Formation constitute the main cap rock in the Sab'atayn basin. In the Say'un–Masilah basin, sandstone units of the Qishn Clastics Member are the main producing interval with high porosity and permeability and capped by the tight Qishn Carbonates Member. Fractured basement, sandstone beds of the Kuhlan Formation, fractured carbonates of the Shuqra Formation, and the carbonate and sandstone of the Sa'ar Formation are also proven reservoirs in the Say'un–Masilah basin.

Three offshore Mesozoic–Cenozoic basins along the Gulf of Aden, i.e. the Aden–Abyan, Hawrah–Ahwar, and Mukalla–Sayhut basins, are categorized as frontier basins, yet to be explored systematically. Noncommercial hydrocarbon in the Mukalla–Sayhut basin (in the fractured limestone of the Middle Eocene Habshiyah Formation) was discovered by Agip (Eni) in 1982. The Cenozoic Tihamah basin, which span onshore and offshore along the southeasten part of the Red Sea, is also a promising hydrocarbon basin according to the presence of seepages as well as oil shows in several exploration wells drilled in the basin.

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