Petroleum Geology of Kuwait

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Abstract

Kuwait has proven conventional oil reserves of about 100 billion barrels which makes it one of the major oil-producing countries worldwide. Most of this reserve is found in Cretaceous and Jurassic with minor quantities in the Paleogene sedimentary successions. Most hydrocarbon production comes from the siliciclastic Burgan Formation which is the most important reservoir in Kuwait. The Jurassic and Lower Cretaceous exhibit good quality source rocks that charged most of the hydrocarbon reservoirs in Kuwait and entered the oil window in Late Cretaceous to Eocene. Most of the hydrocarbon is trapped in very gentle four-way closure structures that are related to the deep-seated fault system of the Arabian Peninsula such as Khurais-Burgan Anticline. Hydrocarbon reservoirs in Kuwait are sealed and capped mainly by shale rocks and to a less extent by evaporites. In the last 15 years, Kuwait Oil Company (KOC) displayed interest in commercially exploiting unconventional hydrocarbon reserves and started laying significant emphasis on the exploration and development of unconventional resources. The aim of this work is to summarize the different petroleum systems of Kuwait including the Paleozoic, Mesozoic, and Cenozoic systems.

6.1 Introduction

After several preliminary surface geological reconnaissances commissioned by the British and Americans early last century, the first oil well spudded in Bahrah, north of Kuwait, in 1936. This well was in the vicinity of oil seepage and close to the center of a gentle anticline that was mapped north of Kuwait Bay. However, this well didn't show huge potential. Then, another location was chosen to drill a new well Burgan-1 (BG-001) at the Burgan oil field and it produced oil from the Cretaceous sedimentary succession. Since the first major oil discovery in 1938 in the Burgan field, Kuwait has become one of the main oil-producing countries worldwide with proven crude oil reserves of about 100 billion barrels (BP Statistical Review of World Energy 2021).

The State of Kuwait is located in the easternmost upper part of the Arabian Peninsula. The tectonic, subsidence histories, and the diagenetic processes that prevailed, on the eastern part of the Arabian Peninsula, are the main drivers for exceptional geological conditions that resulted in the prolific hydrocarbon reserves. These geological conditions are manifested by the widespread geographic distribution of rich, mature source rocks, high-quality reservoir rocks, and highly efficient seal rocks. Along with the formation of large structural traps during or subsequent to oil and gas generation. These geological conditions helped in the formation of multiple petroleum systems in Kuwait, contributing to its enormous oil and gas fields (Fig. 6.1) (Alsharhan and Nairn, 1997). Although multiple petroleum systems of different ages are discovered in Kuwait, only Jurassic, Cretaceous, and Tertiary petroleum systems where the majority of the production is coming from, while deep stratigraphic sections are underexplored yet.

The Paleozoic formations such as Unayzah and Khuff formations are very important hydrocarbon reservoirs in many parts of the Arabian Peninsula (e.g., Laboun, 1987a, b; McGillivray & Husseini, 1992; Al-Jallal, 1995; Alsharhan and Nairn, 1997; Wender et al., 1998; Konert et al., 2001). The Lower Silurian organic-rich "hot shale" of Qusaiba Formation is believed to be the source rock of these Permian reservoirs (Mahmoud et al., 1992; Abu-Ali et al., 1999; Parmijit et al., 2010). However in Kuwait, the Paleozoic section is very deep and remains an exploratory target for decades due to the hostile drilling environment. This deep section contains mainly continental clastic deposits with intercalated shallow shelf carbonates with a maximum

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Fig. 6.1 Major and minor oil fields (onshore) map of Kuwait

thickness of 2000 m (6562 ft) (Alsharhan et al., 2014). Although the primary depositional characteristics of the Paleozoic clastics such as coarse-grained sandstones, good sorting, and low matrix content suggest they had potentially good reservoir quality (e.g., Abdullah et al., 2017; Tanoli et al., 2008), the reservoir potential of the deep Paleozoic section is very poor (Strohmenger et al., 2003). Recent studies are focusing on the evaluation of the Paleozoic source rock, yet the reservoir quality of that deep section is still under exploration. Therefore, we are excluding the Paleozoic reservoirs and seal rocks from this work as more studies are needed to be conducted on that deep section.

The aim of this work is to summarize the different petroleum systems of Kuwait including the Paleozoic, Mesozoic, and Cenozoic (Fig. 6.2). Data is collected from several published literature.

Here, we will discuss the elements of the Kuwait petroleum system from older to younger.

6.2 Source Rocks

6.2.1 Paleozoic Source Rocks

6.2.1.1 Qusaiba Formation

The Lower Silurian organic-rich mudstone of Qusaiba Formation of the Qalibah Group is accepted to be the source rock for most Permian reservoirs in the Arabian Peninsula (Mahmoud et al., 1992; Abu-Ali et al., 1999; Parmijit et al., 2010), and it is also considered as one of the effective Paleozoic source rocks in Kuwait (Al-Khamiss et al., 2012; Alsharhan et al., 2014). The formation unconformably overlies the siliciclastic equivalent deposits of Saq Formation and unconformably overlies the thick siliciclastic sediments of the Tabuk Formation, with a hiatus of Ludlow age (Fig. 6.2).

The productive hot shale unit of the lower part of Qusaiba Formation was deposited within intra-shelf anoxic

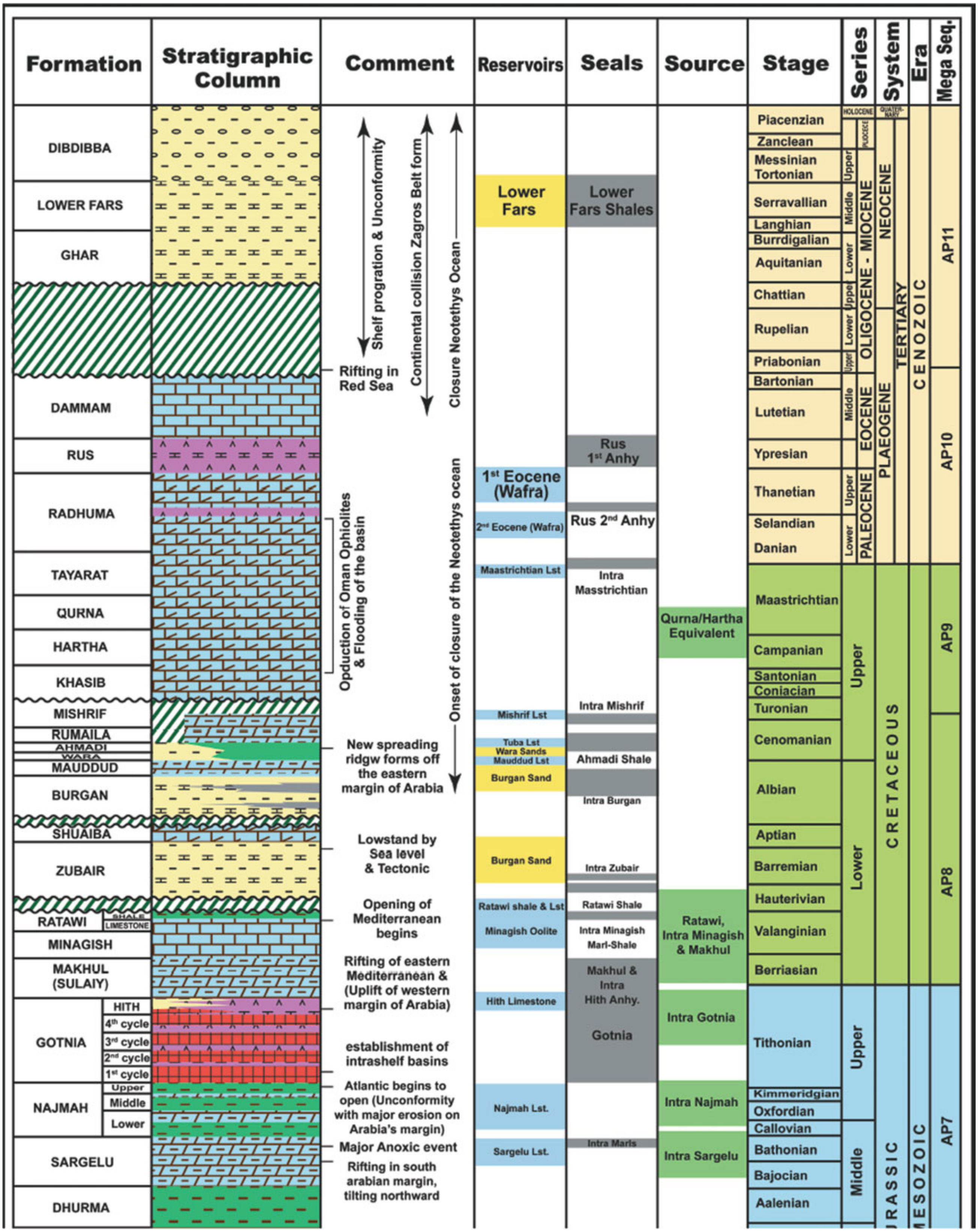

Fig. 6.2 Generalized stratigraphic column of Kuwait along with petroleum system elements and tectonic events (Alsharhan et al., 2014)

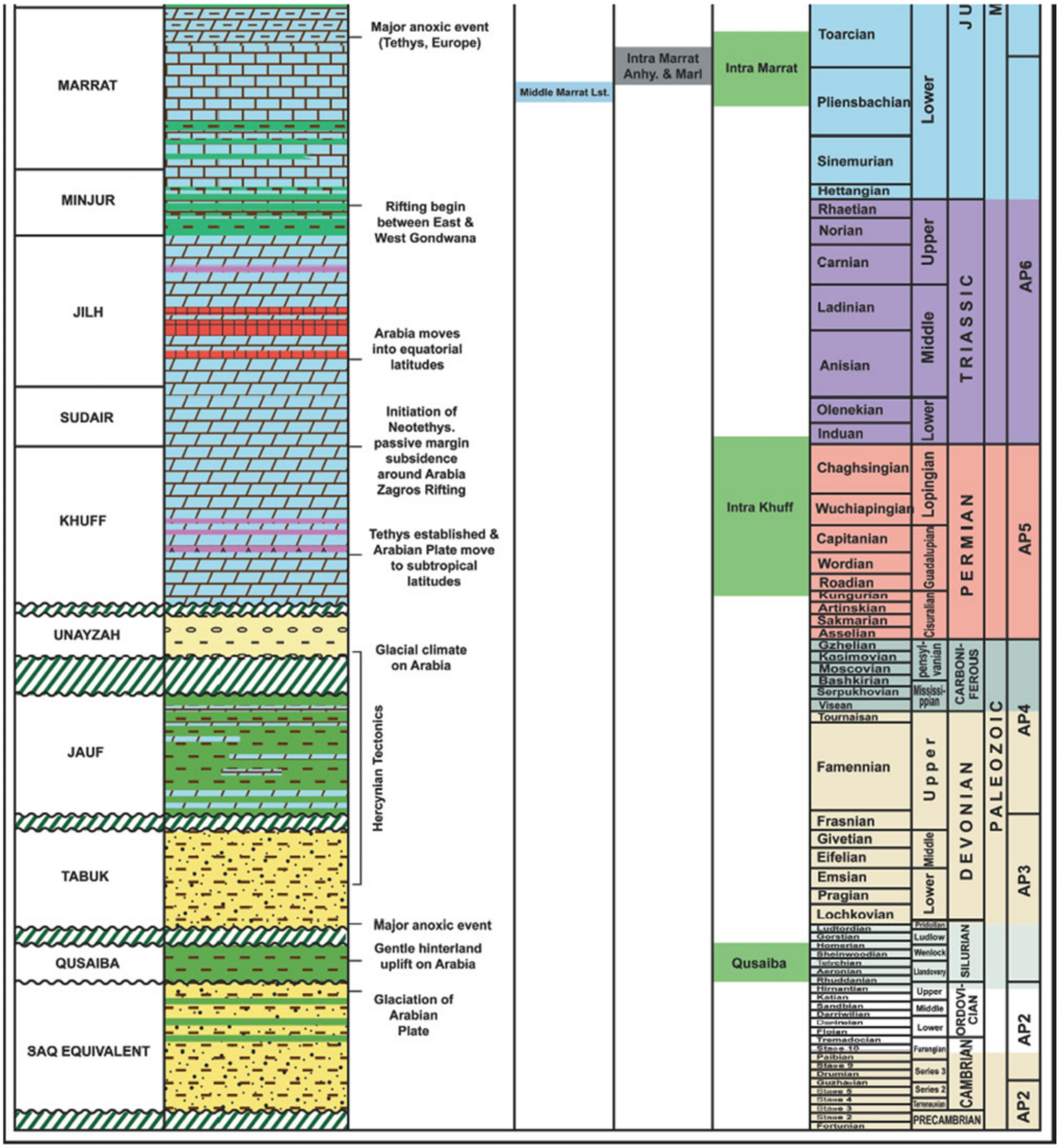

Fig. 6.2 (continued)

depressions during early Silurian in response to major transgression following deglaciation that was observed as maximum flooding surfaces over most of the Gondwana passive margin shelf (Sharland et al., 2001; Inan et al., 2016). Few studies have conducted the burial and thermal history modeling of the Qusaiba shales for testing different burial scenarios to estimate present-day gas potentials. These studies suggest that the formation has reached the oil-generation window around 170 Ma and the gas maturation window around 53 Ma. It is believed that it has expelled all of its potential, and it is overmatured in the present (Al-Khamiss et al., 2012; Alsharhan et al., 2014).

6.2.1.2 Unaizah Formation

The Carboniferous–lower Permian Unayzah Formation and its stratigraphically equivalent deposits are widespread over most of the Greater Arabian Basin (Tanoli et al., 2008). In northern Kuwait, the Unayzah Formation unconformably overlies a thick carbonate succession of the Hormuz Group and is unconformably overlain by a thick carbonate sequence of the Basal Khuff Clastics (Fig. 6.2) (Tanoli et al., 2008). The thickness of the formation varies in value, and it tends to increase westward reaching a maximum depth of ~6334 m (20,780 ft.) while decreasing gradually toward the NE and SE and reaching the minimum depth of 5197 m (17,049 ft.) (Fig. 6.3).

The formation is composed of fine sandstones, siltstones, and claystone cycles with thin beds of argillaceous limestone as shown in Fig. 6.4 (Abdullah et al., 2017). The upper part of the formation has porosity values ranging from 2 to 15%, with water saturation ranging from 65 to 100% reflecting the presence of hydrocarbon concentrations (Abdullah et al., 2017). Based on the neutron and density logs, relatively high gas saturation is recorded at the lower part of the formation in the Raudhatain field, north Kuwait (Fig. 6.5) (Abdullah et al., 2017).

Due to its great hydrocarbon-bearing potential, the formation has great exploration significance in the region (Wender et al., 1998). A recent organic geochemical study conducted on the Unayzah Formation in Kuwait shows a total organic carbon ranging from 0.8 to 3.7 wt. % of a mixture of algal-marine and terrestrial organic matter with the highest TOC values being in the north fields (Abdullah et al., 2021). The thermal maturity data shows that there is a range from oil to overmature with elevated R_o values ranging from 1.85 to 2.57% (Abdullah et al., 2021).

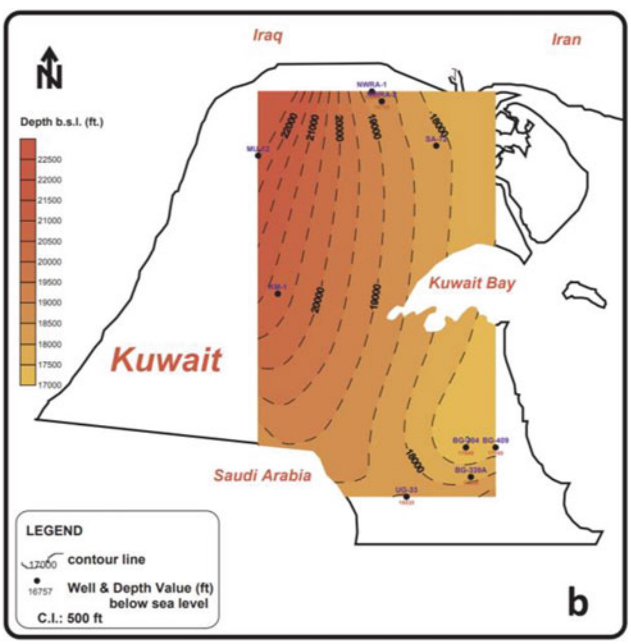

Fig. 6.3 Depth contour maps on the top of the Unayzah Formation (Abdullah et al., 2017)

6.2.1.3 Khuff Formation

The Permian–Early Triassic Khuff Formation in Kuwait occurs at greater depth in comparison to adjoining regions where it reaches more than 4572 m (15,000 ft.) deep (Strohmenger et al., 2003), and it is fully penetrated only in the wells located over the Kuwait Arch (Husain et al., 2011). The formation depth varies in values, and it tends to increase westward reaching a maximum depth of ~6271.6 m (20,576 ft.) while decreasing gradually toward the NE and SE and reaching the minimum depth of ~4727.8 m (15,511 ft.) as shown in Fig. 6.6. The formation unconformably overlies Unayzah Formation and underlines the Lower–Middle Triassic Sudair Formation (Fig. 6.2).

The formation is divided into the Lower Khuff of Middle Permian and the Upper Khuff of the Late Permian at its base to Early Triassic at its top, and they are separated by the Median Anhydrite (Husain et al., 2011). The formation is composed mainly of dolomite and anhydrite interbeds with few limestone and shale deposited in evaporitic low-energy inner to middle ramp setting (Abdullah et al., 2017; Husain et al., 2011) (Figs. 6.7 and 6.8). The formation has low porosity of 2% and low permeability that decreases with clay and anhydrite content and no remarkable hydrocarbon saturation (Abdullah et al., 2017).

A recent organic geochemical study conducted on the Khuff Formation in Kuwait shows a total organic carbon ranges from 0.6 to 2.8 wt.% of a mixture of algal-marine and terrestrial organic matter with the highest TOC values being in the north fields (Abdullah et al., 2021). The thermal maturity of Khuff Formations shows similar values of Unayzah Formation with a range from oil to overmature with elevated R_o values ranging from 1.85 to 2.57% (Abdullah et al., 2021).

6.2.2 Mesozoic Source Rocks

The petroleum system of Kuwait contains excellent source, reservoir, and seal rocks of the Mesozoic carbonate and clastic sequences. Detailed organic geochemical investigations of crude oil and source rocks and extensive reservoir characterization and basin modeling indicated that hydrocarbons trapped in the Lower Cretaceous sandstone and carbonate reservoirs were generated from organic matter-rich Upper Jurassic to Lower Cretaceous carbonate source rocks (Abdullah, 2001; Abdullah et al., 2005; Alsharhan et al., 2014).

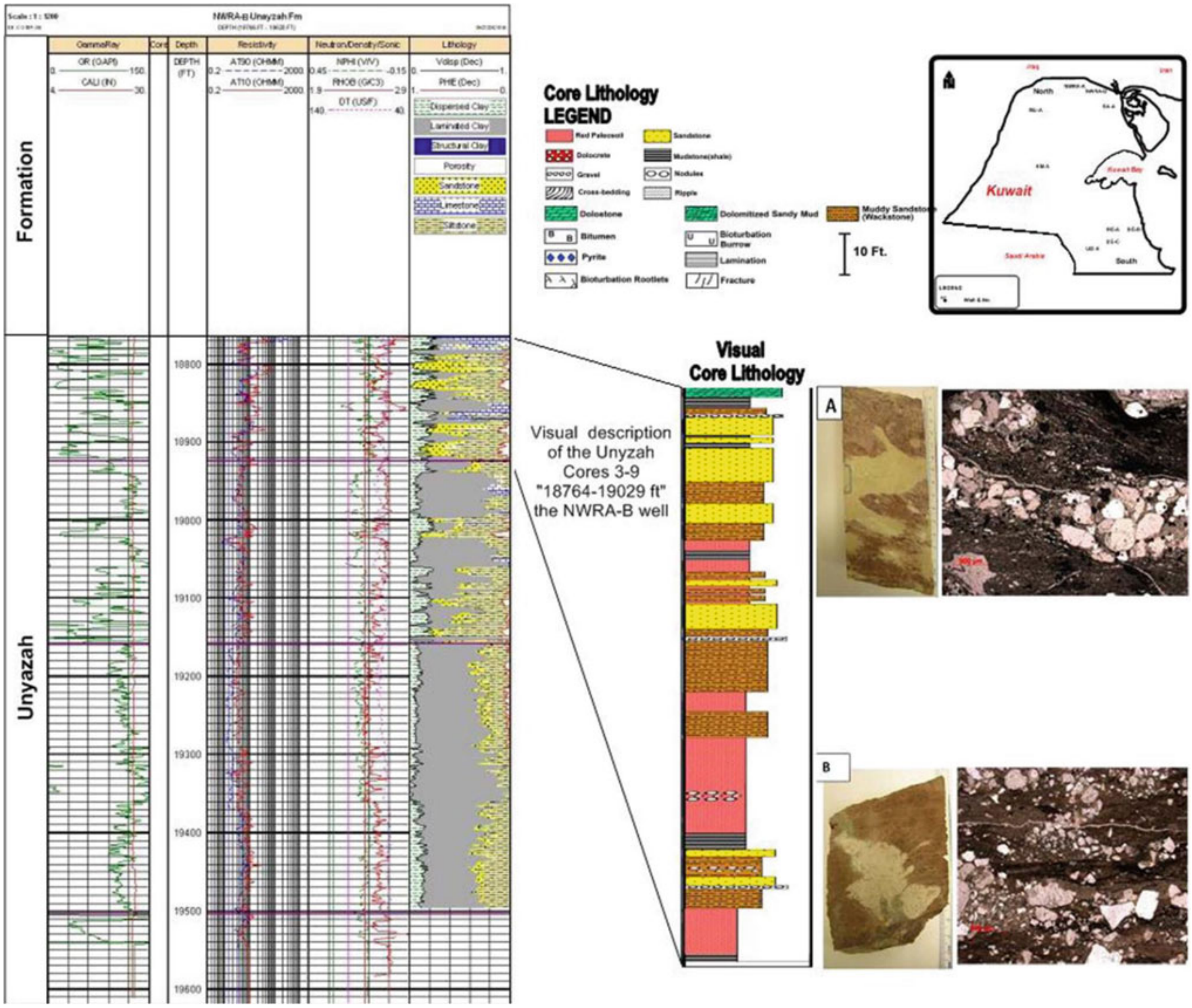

Fig. 6.4 Correlation of the well logging interpreted lithologies with the visual core lithology of the Unayzah Formation in Raudhatain field, north Kuwait (Abdullah et al., 2017)

The type and maturity level of organic matter in the Makhul (Sulaiy) and Minagish Formations in NW Kuwait indicate that they are the most probable Cretaceous source rocks and were probably responsible for generating a proportion of the oil which has accumulated in Kuwait oil fields. Moreover, the Middle Jurassic Najmah-Sargelu are significant contributors to Kuwait's Jurassic and Cretaceous hydrocarbon accumulations (Abdullah, 2001; Al-Bahar et al., 2019).

6.2.2.1 Triassic Source Rocks

The Triassic section in Kuwait comprises the Upper Khuff, Sudair, Jilh, and Minjur formations. The section is under-explored due its depth and poor-quality seismic data. However, a few exploration wells in west Kuwait produced small quantities of condensates and gas in two oil fields (Mutriba and Kra Al-Maru) (Husain et al., 2009). The hydrocarbon shows were from a layer locally named Kra Al-Maru found between underlying Sudair and overlying Jilh formations. The lower clayey carbonate section of Kra Al-Maru is believed to be the source rock. It has TOC of 3–4% and Hydrogen Index of 300–500. It reached the oil window in Middle Cretaceous and the wet gas window during Late Cretaceous. Andriany and Al-Khamiss (2011) based on a crude oil assessment concluded that the source rock is a carbonate of Permo-Triassic age that deposited in an anoxic marine depositional environment.

6.2.2.2 Jurassic Source Rocks

The Jurassic sequence of Kuwait which constitutes one of the most important petroleum systems of the Arabian Gulf

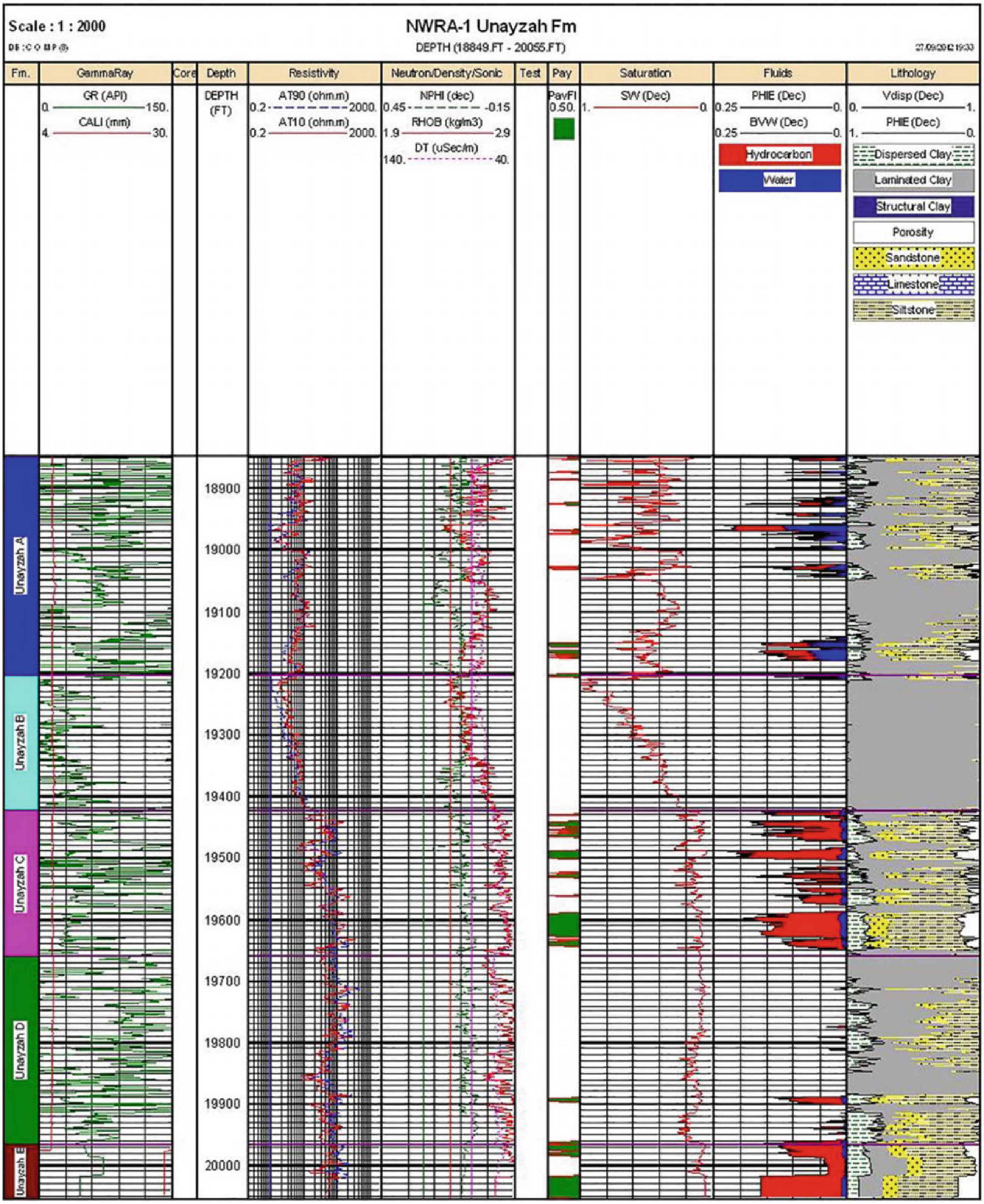

Fig. 6.5 Lithosaturation crossplot of the Unayzah Formation in Raudhatain field, north Kuwait (Abdullah et al., 2017)

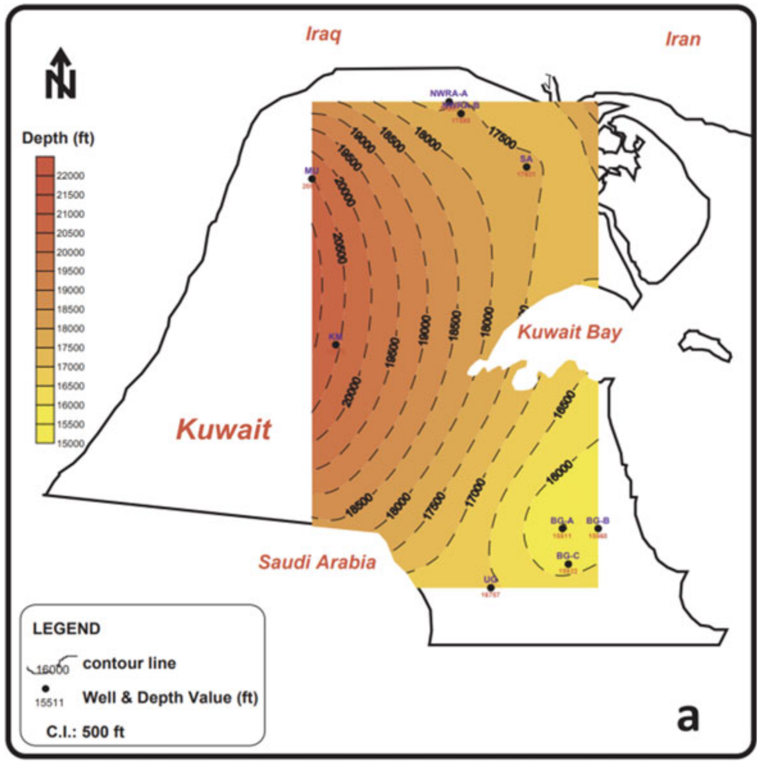

Fig. 6.6 Depth contour maps on the top of the Khuff Formation (Abdullah et al., 2017)

Region is composed of Lower Jurassic Marrat Formation, Middle Jurassic Dhruma, Sargelu, and Najmah Formations, and Upper Jurassic Gotnia and Hith Formations. In the south and southwest of Kuwait, the thickest Jurassic rocks are found and gradually thinned toward the north (Hawie et al., 2021). Organic geochemical analysis of the Jurassic source rocks Marrat, Dhruma, Sargelu, and Najmah Formations which are mainly limestones and calcareous shales shows the significant potential for oil generation in Kuwait (Abdullah, 2001).

Marrat Formation

The Marrat Formation was first defined in the Minagish oil field in the west of Kuwait at a depth between 13,515 ft (4120 m) and 15,350 ft (4679 m), with an average of 2000 ft (610 m). The Marrat Formation has been classified into the Lower Marrat (lime mudstone and dolomite, interbedded with anhydrite and shale), Middle Marrat (limestone), and Upper Marrat (limestone interbedded with shale and dolomite and calcareous shale) members—mainly—based on the presence of argillaceous sediments in the Lower and Upper members. The Marrat Formation conformably overlies the Triassic–Lower Jurassic Minjur Formation in Kuwait (Al Wazzan, 2021). Total organic carbon (TOC%) content in Marrat Formation from several fields in Kuwait show a range of 0.35–5.5%, indicating good source potential. In particular, the dark-colored, fine-grained sediments contain kerogen type II and type III with higher maturity levels as indicated by the kerogen elemental analysis and vitrinite reflectance (0.8–0.9 R_o) of bitumen (Fig. 6.9) (Alsharhan et al., 2014).

Dhruma Formation

Dhruma Formation, overlying Marrat and underlying Sargelu Formation, is composed of calcareous shale interbedded with limestone. Analysis of source potential for samples collected from the Burgan and Minagish fields shows ranges of TOC from 0.30 to 2.50% wt., with higher concentrations in laminated shales. The type of kerogen is amorphous marine kerogen types II to III with the abundance of some oxidized and biodegraded terrestrial particles (spores and woody particles) which as a result lowered their level of maturity (Fig. 6.9). Organic matter maturity level was interpreted as the very first stage of oil generation as indicated by ranges of 0.4–0.5 Ro of vitrinite reflectance (Alsharhan et al., 2014).

Sargelu Formation

Sargelu Formation consisting of Lower and Upper carbonate members with overlying Najmah fractured limestones comprises important hydrocarbon sources for the producing reservoir in the south and east Kuwait oil fields (Al-Enezi, 2019). Organic geochemical results of samples taken from southern oil fields show fair to good source potential of Sargelu Formation with TOC ranges from 0.40 to 5.5% wt and averages about 2.0%. The elemental analysis

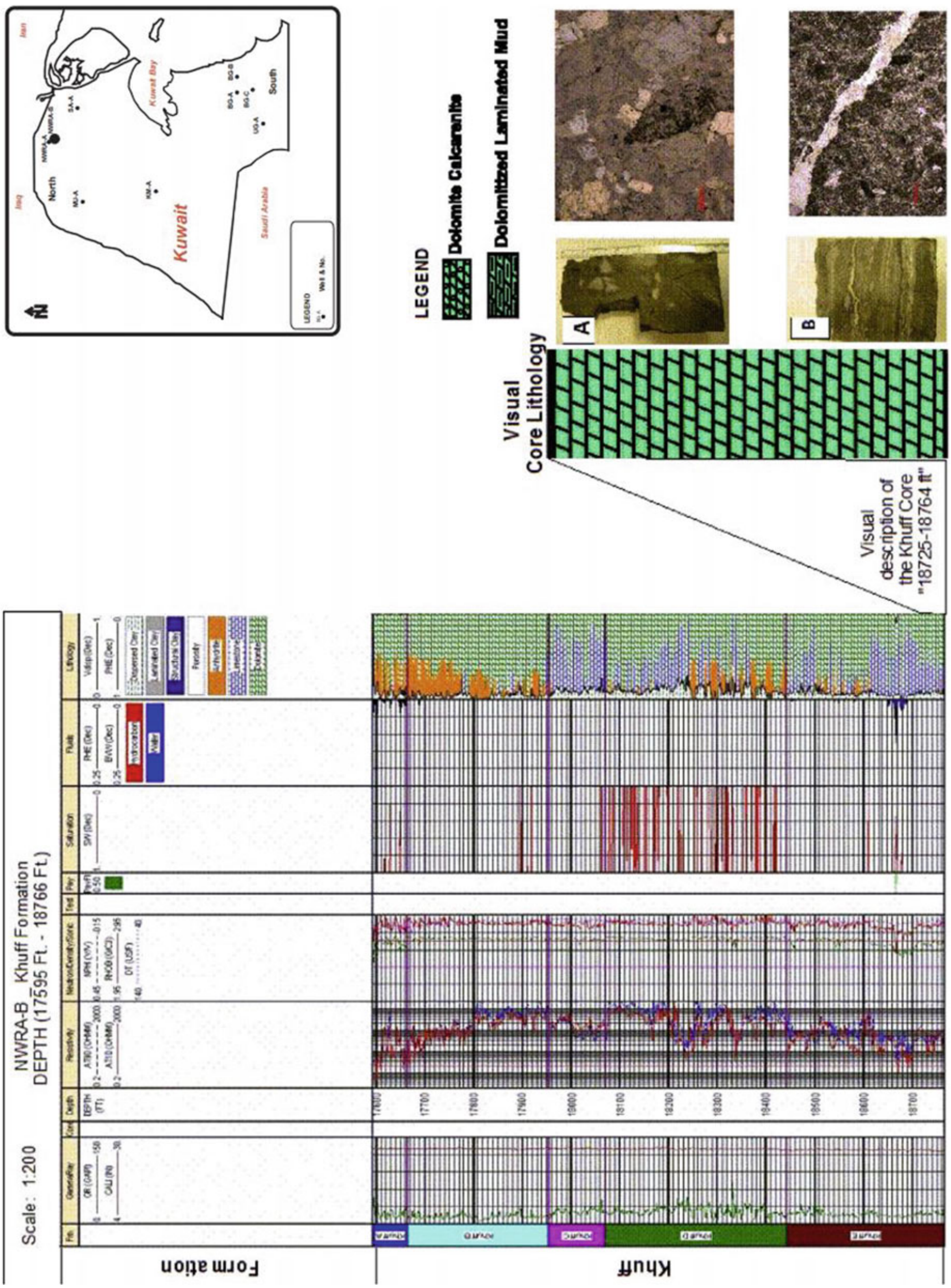

Fig. 6.7 Correlation of the well logging interpreted lithologies with the visual core lithology of the Khuff Formation in Raudhatain field, north Kuwait (Abdullah et al., 2017)

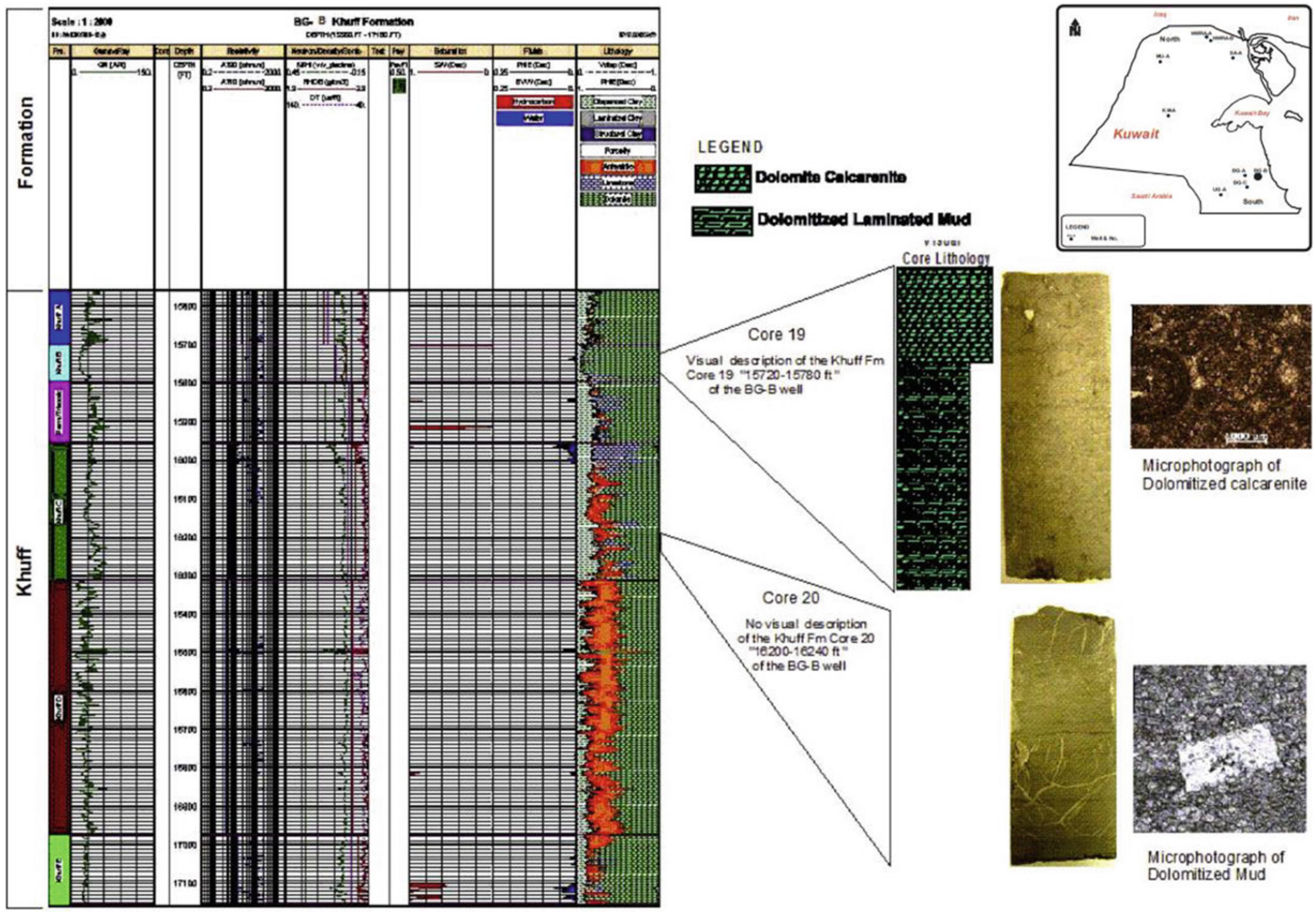

Fig. 6.8 Correlation of the well logging interpreted lithologies with the visual core lithology of the Khuff Formation in Burgan field, south Kuwait (Abdullah et al., 2017)

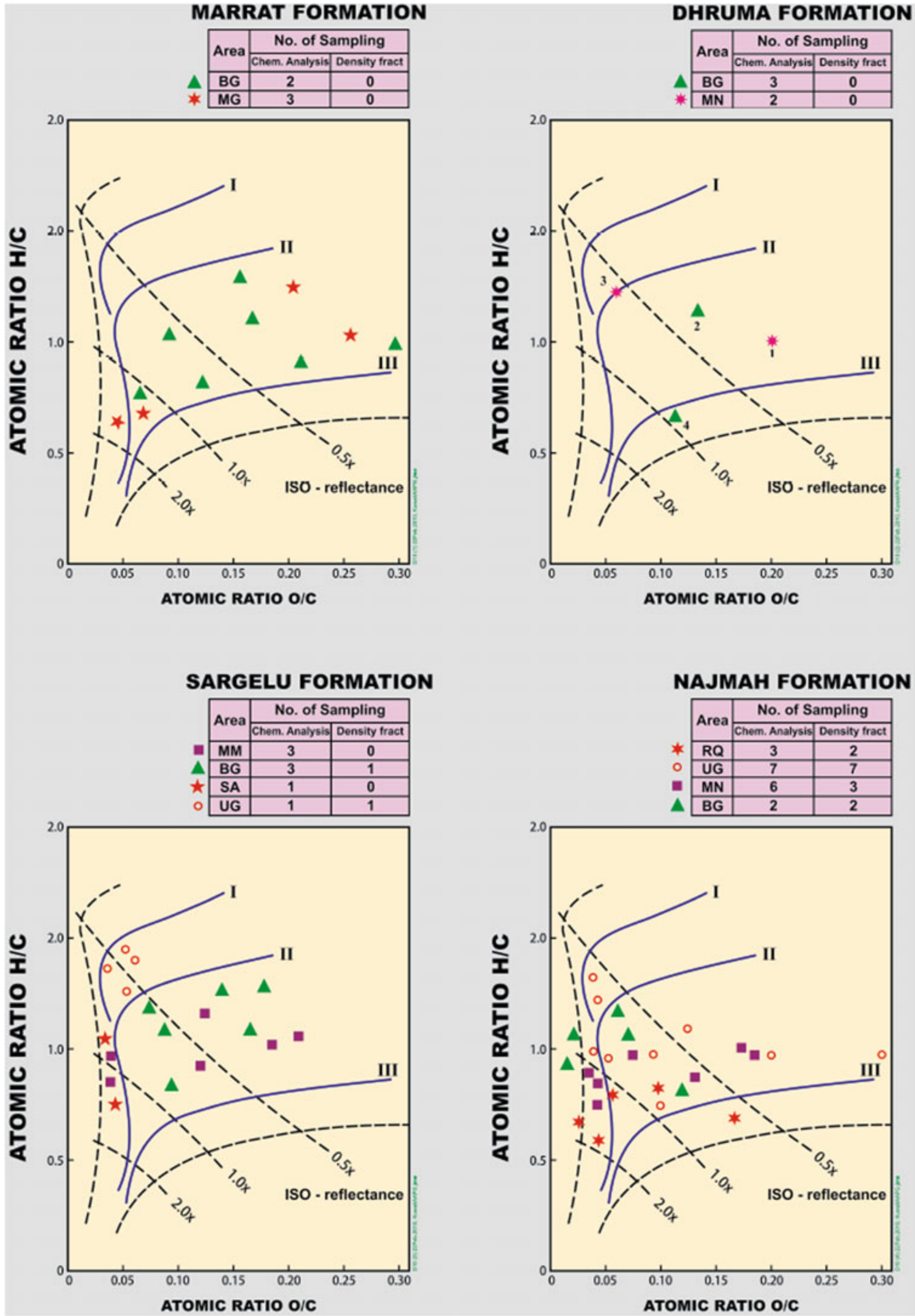

Fig. 6.9 Kerogen type and thermal maturation of the Jurassic source rocks in Kuwait fields (After Alsharhan et al., 2014)

of kerogen indicates type II or types II–III amorphous marine organic matter as well as terrestrial oxidized woody materials that lowered their source potential (Fig. 6.9). Sargelu carbonates are at the onset of oil generation in both Minagish and Umm Ghudair fields as indicated by the vitrinite reflectance (0.6 Ro) and the kerogen dark color. The lowest kerogen maturity is shown by samples from the Burgan field because Sargelu Formation is found at the shallowest depths of 3215–3165 m (10,548–10,384 ft), concluding the early maturity stage of organic matter (Alsharhan et al., 2014).

Najmah Formation

The contribution of Jurassic Najmah-Sargelu Formations to the petroleum system in Kuwait and NE of the Arabian Gulf region has been significantly discussed by many authors (Aqrawi & Badics, 2015; Al-Murakhi, 2019; Grader et al., 2019). Najmah Formation, composed of organic-rich bituminous shales and carbonate, is considered as the prolific major source rock for the main Jurassic Najmah, Sargelu, and Middle Marrat reservoirs. The excellent source beds of Najmah with TOC of 7% on average have generated light oil and condensate from North Kuwait and medium oil from west and south Kuwait (Al-Enezi et al., 2018). Organic richness is concentrated in the laminated Najmah carbonates at the Ratqa field in north Kuwait where the level of maturity is the highest and kerogen is mainly of type II amorphous sapropelic (Fig. 6.9). In contrast, the level of maturity and quality of kerogen decrease in the southern oil field (Minagish and Umm Ghudair) as a result of biodegradation (Alsharhan et al., 2014).

Cretaceous Source Rocks

The source rock characteristics of the Cretaceous formations in Kuwait have been investigated by many authors (Abdullah and Kinghorn, 1996; Abdullah et al., 1997, 2005; Alsharhan et al., 2014; Al Bahar et al., 2019) who concluded their significance as part of the petroleum system of Kuwait. The type of kerogen (type III) and its maturity state indicate that the Cretaceous Formations such as Ratawi, Mauddud, and Ahmadi may have generated oil and gas at a very low maturity level. Oil may also originate from deeper source rocks or may have migrated laterally from other areas in the Arabian Gulf Basin.

Makhul (Sulaiy) Formation

Lower Cretaceous Makhul or Sulaiy Formation is a potential source rock in the Mesopotamian Foredeep (Iraq and Kuwait) and in the Zagros Fold Belt Basins (Iran). Source rock potential of Sulaiy Formation in Kuwait and central and southern Iraq with its basal Garau equivalent in western Iran is well documented (Alsharhan et al., 2014; Aqrawi & Badics, 2015). The formation consists of basinal bituminous shale intercalated with dark gray argillaceous limestone, in which TOC values range from 0.40 to 2.70%. Results of H/C and O/C kerogen elemental analysis of samples from the Raudhatain field show less maturation at shallower depths with the presence of type II kerogen and a higher level of maturation as depth increases where type I amorphous, dark-colored organic matter is present and corresponds to the onset of the oil-generation zone (Fig. 6.10).

Minagish Formation

The Makhul (Sulaiy) Formation is overlain by Minagish Formation which consists of three members: Lower Minagish Member Peloidal–bioclastic, occasionally dolomitic limestone, Middle Minagish Member of medium- to very coarse-grained oolitic-pelletal grainstone and Upper Minagish Member of massive, oolitic, fossiliferous limestone. The oolitic units show higher TOC ranges (from 1.30 to 1.95% wt.) than the Lower member that has a TOC range

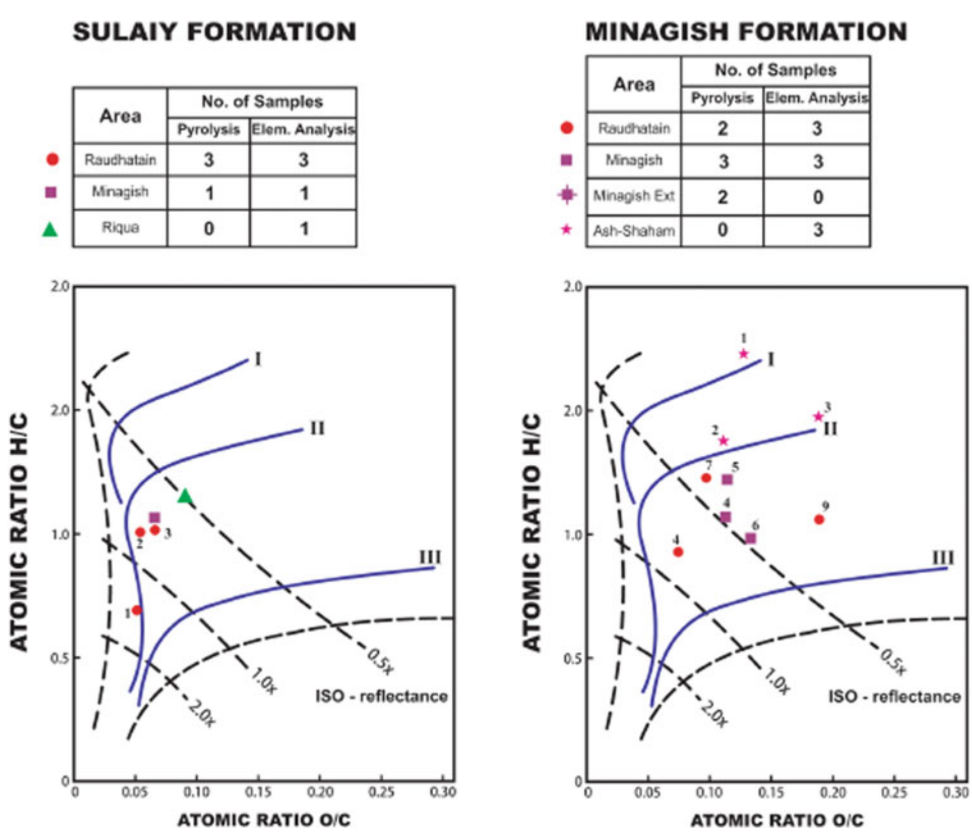

Fig. 6.10 Kerogen elemental analysis plot of the Lower Cretaceous Makhul (Sulaiy) and Minagish Formations showing the type organic matter and level of maturity of the source rocks in Kuwait fields (after Alsharhan et al., 2014)

of 0.3–0.55% wt, indicating the more organic richness of the oolitic parts of the Minagish Formation. The quality of organic matter is better in the oolitic units than in the biodegraded non-oolitic member as indicated by the presence of very low dense, algal amorphous kerogen of marine origin (Fig. 6.10). The level of maturation of the oolitic Minagish Members as indicated by the pyrolysis results for the hydrogen index (HI) and Tmax with an average of 550 mg HC/g to 355 mg HC/g and 435 °C, respectively, suggests the onset of the oil-generation stage (Abdullah et al., 1997) (Figs. 6.11 and 6.12).

Ratawi Formation

The Ratawi Formation consists of two members the Lower Ratawi Member, consisting of limestone thinly bedded with shale and the Upper Ratawi shale Member which is mainly calcareous shale with intercalated sandstone and siltstone. Organic geochemical analyses at the Raudhatain and Minagish fields show poor to fair TOC with an average of 0.55% wt. in the Lower Ratawi member and a range from 0.45 to 3.25% wt in the Upper Ratawi shale.

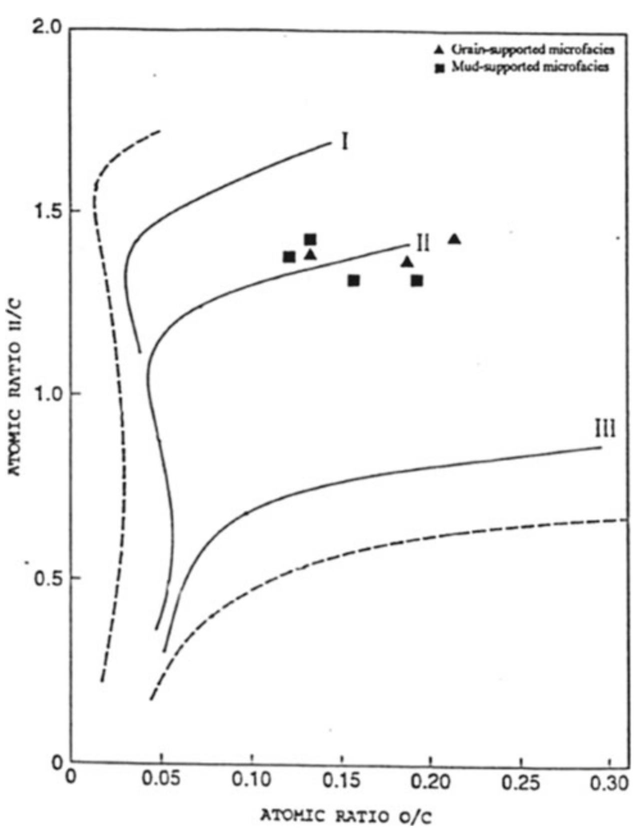

Fig. 6.11 Type of kerogen of the oolitic and non-oolitic samples in the Lower Cretaceous Minagish Formation (after Qabazard et al., 2000)

The type of organic matter is type II kerogen of marine origin as indicated by the abundance of foraminifera, dinoflagellates, and acritarchs. However, biodegradation and the presence of spores, cuticle and woody tissues, terrestrial organic components lowered the quality of this organic matter to type III kerogen. The overall level of maturity is immature or just entering the oil-generation stage as indicated by Tmax (430–435 °C), the Production Index (0.05–0.15), Thermal Alteration Index (TAI) of 2 + and 3–, and a vitrinite reflectance of 0.70% R_o results (Alsharhan et al., 2014).

Mauddud Formation

The Mauddud Formation is mainly composed of limestone interbedded with marl and fine, greenish-brown glauconitic sandstones, and contains abundant microfossils and some pyrite.

The Mauddud Formation which is considered as one of the major Cretaceous oil reservoirs varies in thickness between zero in the south and about 100 m (328 ft) in the north of Kuwait.

The average Total Organic Carbon (TOC) in the carbonate facies is 2.5 wt.% and the highest values (8.0 wt.%) are in the northern fields. The clastic intervals in the northern fields show higher total organic matter (1.3 wt.%) relative to the southern fields (0.6 wt.%). The total Production Index is higher in the carbonate (0.6) than in the clastic section (0.3). The kerogen type in the formation is immature types II–III and III, suggesting that oil accumulated in the reservoir might be largely related to migrated oil from mature deeply buried source rocks such as the Early Cretaceous Sulaiy Formation and the Upper Jurassic Najmah Formation (Abdullah et al., 2005) (Fig. 6.13).

6.3 Reservoir Rocks

6.3.1 Mesozoic Reservoir Rocks

There are many stratigraphic intervals of good-quality reservoirs in Kuwait mainly in the Mesozoic Era. The most famous reservoir is the siliciclastic reservoir of Burgan Formation which contribute to most of the hydrocarbon production in the state of Kuwait along with other several Cretaceous reservoirs which accounts for about 80% of hydrocarbon production in Kuwait (Alsharhan et al., 2014). The approximated production contribution of the Jurassic reservoirs (Marrat, Sargelu, and Najmah Formations) accounts for about 20% of the recoverable oil and gas reserves, while only 1% of recoverable oil and gas was found in the Miocene age (Alsharhan et al., 2014).

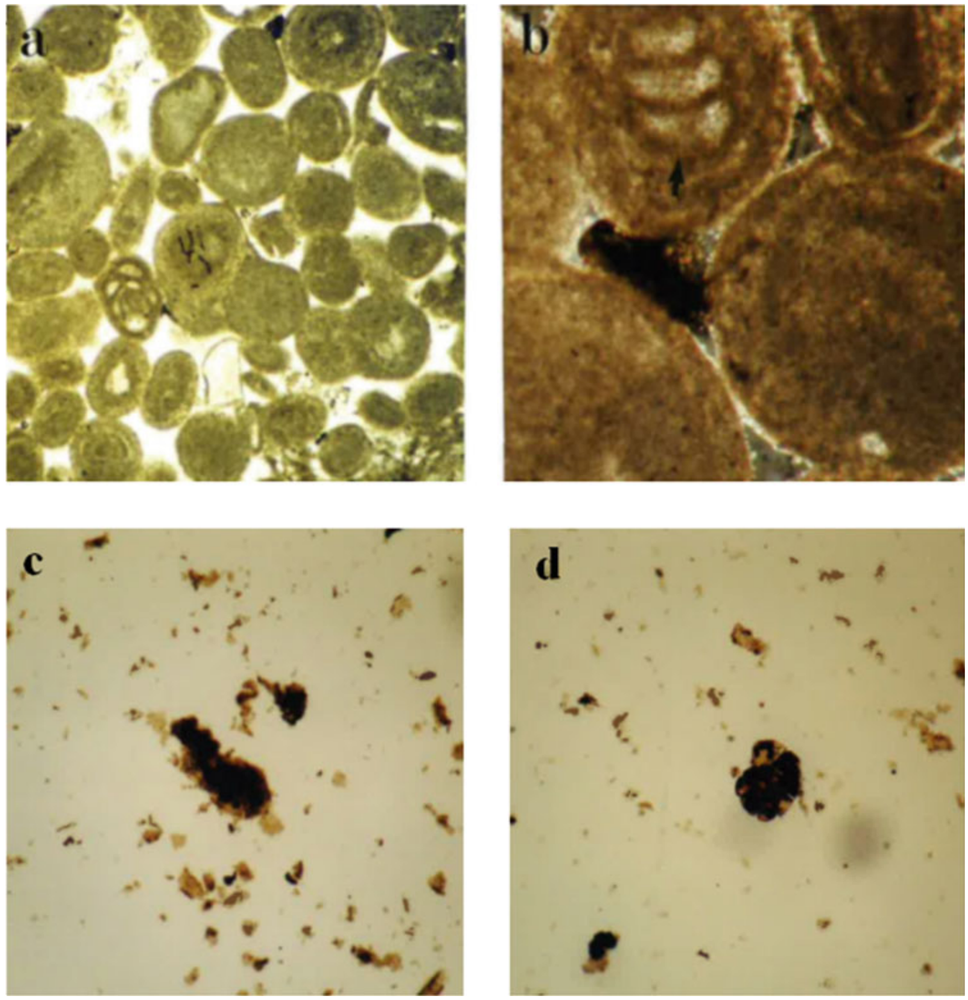

Fig. 6.12 Thin section Photomicrographs showing the oolitic Middle Minagish limestones (**a** and **b**) and the organic matter isolated from the samples (**c** and **d**) from the Minagish field. **a** Typical oolitic grainstone (ppl, 5 mm), **b** A close view of micritized ooids with a nucleus of foraminifera (xpl, 1 mm), **c** Amorphous marine organic matter with sapropelic particles, macerated from the oolitic sample (ppl, 1 mm), and **d** Marine organic matter indicated by the foraminiferal test lining (ppl, 1 mm) (after Qabazard et al., 2000)

6.3.1.1 Triassic Reservoirs

Reservoirs in the Triassic section are very limited. In western Kuwait, the Kra Al-Maru unit which is underlain by Sudair and overlain by Jilh formation presents a potential reservoir with low conventional reservoir quality. This unit comprises cyclical packages of dolomudstones, laminated to bedded anhydrites and dolomitic shales (Husain, et al., 2009). Most matrix porosity is reduced by anhydrite, and matrix permeability values are less than 0.01 mD. The more brittle dolomudstone section is characterized by a fracture network and its related porosity range up to 3.3 mD.

6.3.1.2 Jurassic Reservoirs

Marrat Formation

The Lower Jurassic Marrat Formation is one of the most important carbonate reservoirs in north, west, and south Kuwait fields. Production from Marrat in the Greater Burgan field started in 1984 and has free gas production from the north fields (Raudhatain, Sabiriya, and Bahra) since 2008. The reservoir is classified as tight heterogenous with natural fractures and an average permeability of about 17 md (Snasiri et al., 2015). Marrat Formation has a thickness of about 2400 ft and is subdivided into three members, Lower Marrat, Middle Marrat, and Upper Marrat. The main oil-producing unit is the Middle Marrat member which consists of dolomitized oolitic grainstone to packstone facies, representing high-energy inner-mid ramp shoals. The Lower Member of Marrat is an inner ramp dolostone and micritic limestone facies intercalated with anhydrite and the Upper Marrat Member is a transgressive complex of lime mudstones/wackestone deposited in a mid-outer ramp setting (Hawie et al., 2021). Typically, the Marrat reservoir quality was verified in the high-energy shoal packages and was enhanced by dolomitization (Chakrabarti et al., 2011).

6.3.1.3 Sargelu Formation

The significance of Najmah Sargelu carbonate self-sourced reservoirs has been widely investigated (Siddiqui et al., 2008; Nath et al., 2012). The Najmah Sargelu tight carbonates are considered as naturally fractured, organic-rich prolific reservoirs in west Kuwait (Al-Failakawi et al., 2018;

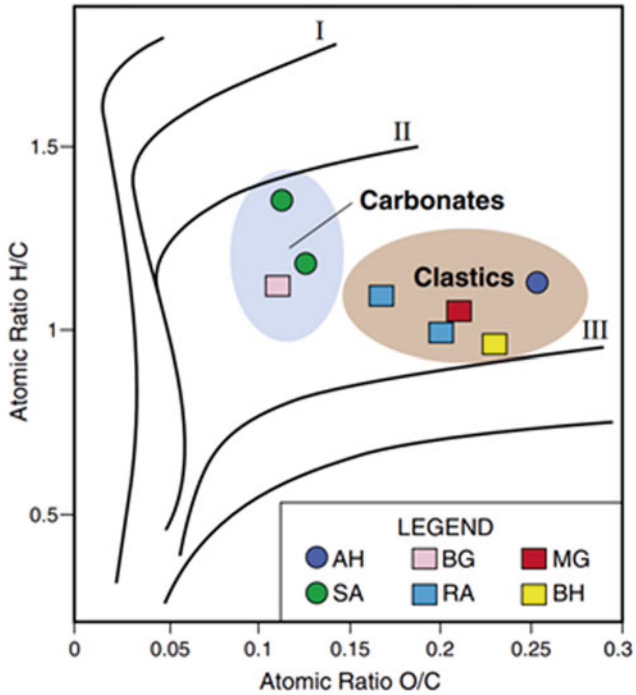

Fig. 6.13 Type of Kerogen in Mauddud Formation samples from Ahmadi (AH), Burgan (BG), Magwa (MG) southern fields and Sabiriya (SA), Raudhatain (RA), and Bahra (BH) northern fields in Kuwait (after Abdullah et al., 2005)

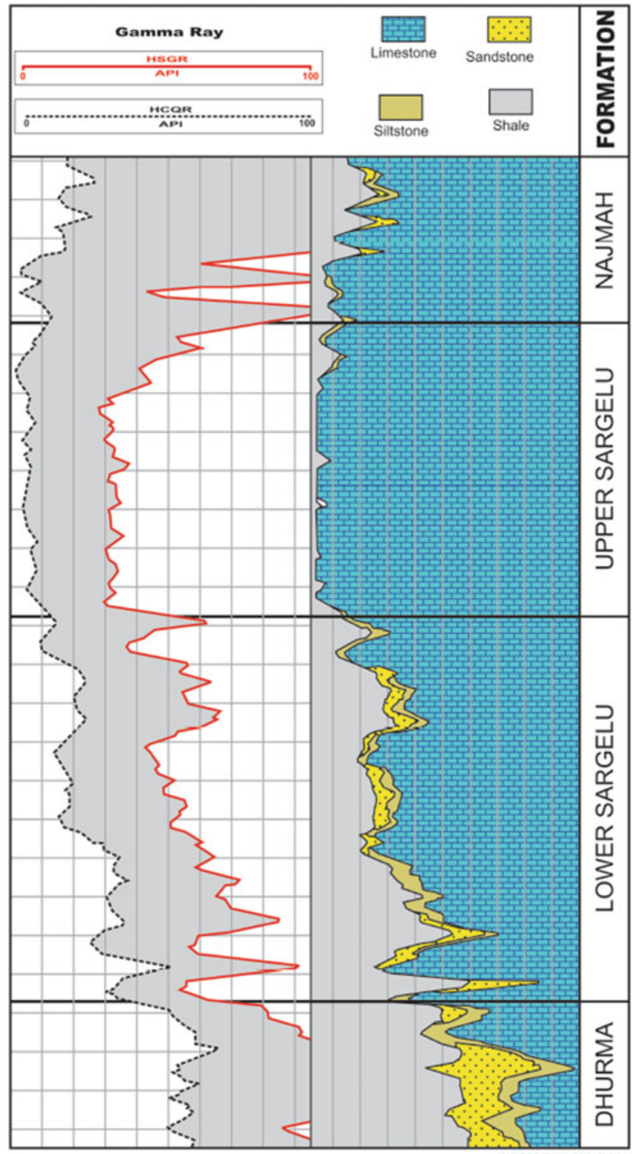

Fig. 6.14 Composite log of Dhruma, Sargelu, and Najmah Formations (after Alsharhan et al., 2014)

Al-Murakhi, 2019) as well as the north fields (Siddiqui et al., 2008; Al-Eidan et al., 2010). The Sargelu Formation overlies Dhruma calcareous shale formation which is an excellent cap rock for the Marrat Formation. The Sargelu Formation can be divided into a lower unit of mudstone and wackestone facies and an upper unit varying from wackestone to packstone facies with rare grainstone facies (Fig. 6.14). The shallowing upward sequence with the dominance of algal, skeletal, and peloidal packstones represents a typical shallow marine setting. The top of Sargelu Formation and the overlying Najmah are found to be similar to some extent in their composition of dark laminated mudstone to pelagic-pelecypod packstones, representing deeper facies accumulated in stagnant and restricted marine (Alsharhan et al., 2014).

Najmah Formation

The Upper Jurassic Najmah Formation is a black, oil-stained, naturally fractured, highly overpressured argillaceous mudstone and calcareous shale which was subdivided into two members: Upper Najmah limestone member and Lower organic-rich shale member (Rabie et al., 2014). The Najmah organic-rich shale is overlain by impermeable Salt and Anhydrite of the Gotnia and Hith Formations and underlain by the Middle Jurassic Sargelu Limestone and Dhruma Shale formations (Fig. 6.15). The Najmah Formation is a complex heterogenous tight carbonate reservoir in which porosity and permeability are essentially enhanced by high-density fracture and vuggy porosity (Nath et al., 2012, Al-Failakawi et al., 2018). The porosity percentage and distribution in the Najmah Formation are controlled by the lithofacies types and show good relation to permeability. The average porosity is about 2 to 10% mainly of fracture type and the permeability ranges 0.01–10 mD. Consequently, Najmah Formation is considered as a good commercial unconventional resource in Kuwait in spite of its low matrix porosity and ultra-low permeability (Nath et al., 2012).

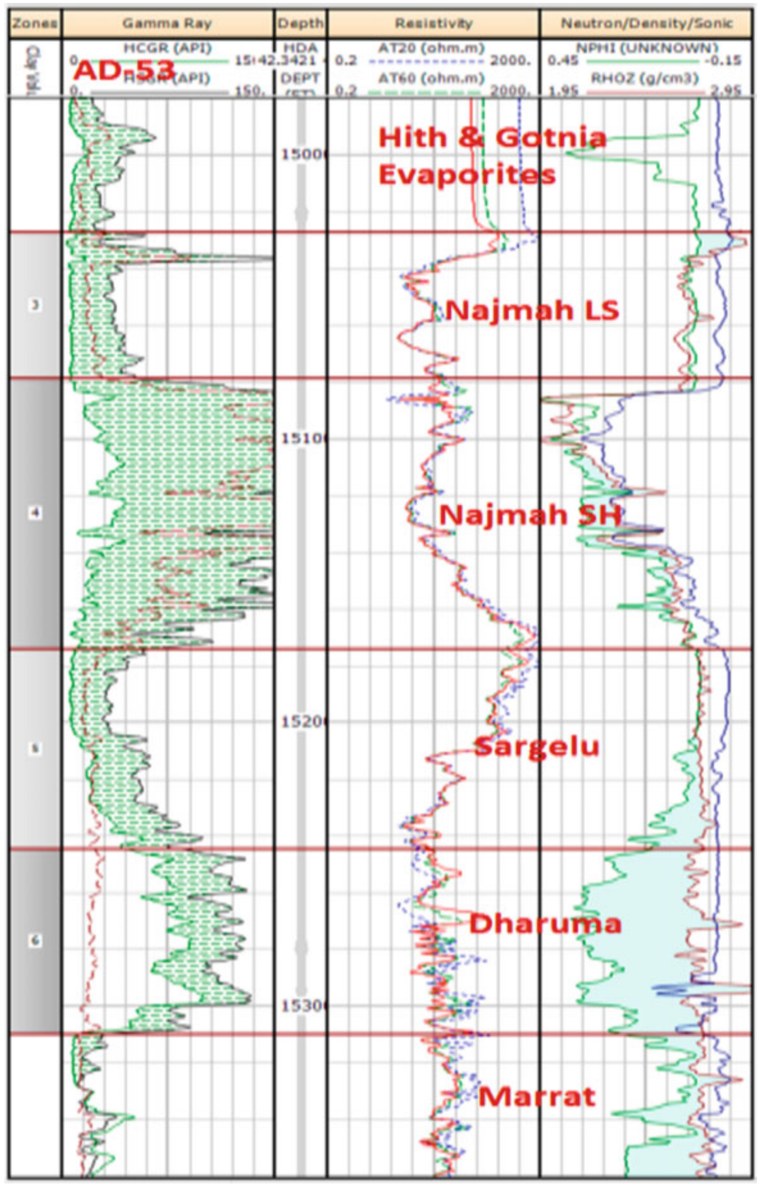

Fig. 6.15 Composite Log of Najmah Formation (Rabie et al., 2014)

6.3.1.4 Cretaceous Reservoirs

Minagish Formation

The Minagish Formation is divided into 3 members where the top and bottom are relatively tight lime mudstone and wackestone separated by the middle bioclastic Oolitic grainstone member—Minagish Oolite (Nath et al., 2014). The latter is the primary reservoir in the Minagish Field and a significant contributor to Umm Gudair, South Um Gudair, and Greater Burgan field. The formation overlays the non-reservoir Makhul (Sulaiy) Formation and is underlying the Ratawi Limestone.

The lower Minagish Member is composed of Peloidal–bioclastic, occasionally dolomitic limestone with 22% porosity and nearly 500 md permeability. The middle Minagish Member is composed of medium to very coarse - grained oolitic grainstone with occasional pellets, bioclastic leaching, and common development of vugs. The uppermost part of this member is mainly a well cemented, peloidal limestone and calcareous and argillaceous limestone.

The middle Minagish resembles a good quality reservoir, for example in Burgan field, porosity ranges 17–30% and permeability typically ranges 300–1000mD with average water saturation (S_w) of 14% (Nath et al., 2014). In the North of Kuwait, the Oolitic member is absent and commonly consists of fractured limestone with some fractures filled with calcite (Alsharhan et al., 2014). The upper Minagish Member is composed of massive, oolitic, fossiliferous limestone cemented with varying amounts of microcrystalline and sparry calcite (Alsharhan & Nairn, 1997).

A zone of heavy and dark, tarry oil (known as tar mat) is present near the oil–water contact in the Minagish field with thickness variation from 10 to 30 m. The continuity of this tar mat throughout the reservoir forms a seal isolating the reservoir from the underlying aquifer. Al-Ajmi et al. (2001) investigated the occurrence and the genesis of this tar mat and suggested that the formation of this tar mat is due to de-asphalting rather than gravity segregation.

Ratawi Formation

Ratawi Formation is considered as a minor reservoir in Kuwait while it is one of the major reservoirs in the Arabian Peninsula region. It is subdivided lithologically into Lower Ratawi and Upper Ratawi Members. The Lower Ratawi Limestone (Ratawi Oolite or Ratawi Limestone Member) consists mainly of limestone with thin shale laminations. It has a uniform thickness of about 90 m (295 ft) throughout Kuwait (Alsharhan et al., 2014). There are packstone and grainstone facies present in the Limestone Member with porosities up to 25% in southern and offshore Kuwait with good oil quality (28–46° API) (Al-Tendail et al., 2012).

The upper Ratawi member is also known as the Ratawi Shale member which is mainly composed of marine shale/claystone, interbedded by siltstone and fine-grained sandstone, and limestone streaks (Arasu et al., 2012). The origin of the sandstone is attributed to the uplift and erosion of the Arabian Shield (Al-Fares et al., 1998; Sharland et al., 2001). Thick coarser sandstones are encountered in the south of Kuwait, however, they are discontinuous in the north.

Major oil discoveries were found in the lower part of the Ratawi Limestone Member at Wafra and Umm Gudair fields since the 1950s. However, in the last 10 years, Kuwait Oil Company has shifted its exploration efforts to the Ratawi Shale Member where it tested oil in the Umm Gudair Field in the south, Rugae in the southwest, and Sabriyah, Raudhatain, and Abdali fields in north Kuwait (Arasu et al., 2012. And Al-Tendail et al., 2012). In north Kuwait, oil was produced from the sands and limestone streaks within Ratawi Shale Member where the hydrocarbon is entrapped stratigraphically.

A study was carried out in 2007 to evaluate the hydrocarbon potential of the Ratawi Limestone Member and consequently identified multiple factors which negatively affected the hydrocarbon potential of the Ratawi Limestone Member (Al-Tendail et al., 2012). Its diagenetic history records up to 11 periods of porosity reduction by calcite and other cements. Accordingly, it suggested that oil migration might have occurred during late diagenesis following the precipitation of the cement.

Burgan Formation

Burgan Formation (lower to middle Albian) is the most prolific oil-bearing sandstone reservoir throughout the Greater Burgan field (Burgan, Magwa, and Ahmadi fields) in the southeast and Raudhatain and Sabiriyah fields in the north of Kuwait (Fig. 6.1). It was named after Burgan hills in south Kuwait. The thickness of Burgan Formation varies from north to south, where in the north (Raudhatain and Sabiriyah fields) it is about 900 ft (275 m) and approximately 1250 ft (380 m) in the south (Greater Burgan field) (Bou-Rabee, 1996).

The formation is divided into Upper, Middle, and Lower Burgan. However, Kuwait Oil Company divides the formation into two members: Fourth and Third Sand. Generally, the formation is more sand prone to the south and southwest and increases in shale percentage toward the east and northeast of Kuwait.

It is composed of medium to coarse grained sandstone, well-sorted, rounded, grading upward into alternating fine-grained sandstone and siltstone (Al-Eidan et al., 2001).

Burgan Formation reservoir quality is highly related to the interpreted depositional environments (Strohmenger et al., 2006). The main reservoirs in Burgan Formation are fluvial and tidal deposits (Fig. 6.16). The best reservoir quality is associated with fluvial-dominated sandstones, where it has an average porosity of 25% and permeability of 1600 mD. The tidal-dominated sandstone displays moderately reservoir quality with average porosity and permeability values of 23% and 270 mD, respectively. The poorest reservoir quality presents in the marginal-marine deposits where the average porosity is about 19% and significantly lower permeability of about 10 mD.

Mauddud Formation

Mauddud Formation forms an important reservoir that extends over the Arabian Plate. It is characterized by rudist buildups with an improvement of reservoir quality by meteoric diagenesis. It was deposited in a broad ramp system ranging from the distal zone of clastic deltaic settings to the marine carbonate system to the outer ramp/basinal environment (Boix et al., 2014).

It is one of the main producing reservoirs in northern Kuwait with a minimal contribution in the south and southwest. Mauddud Formation thickness varies from north to south of Kuwait, where in the north of Kuwait, at Abdali, Raudhatain, and Sabriyah fields, it is approximately 140 (459 ft) and a few feet at Greater Burgan field (Bou-Rabee, 1996). Mauddud Formation can be divided into a lower part which is a mixed clastic and carbonate system, and an upper part which is carbonate-dominated (Fig. 6.17). Porosity

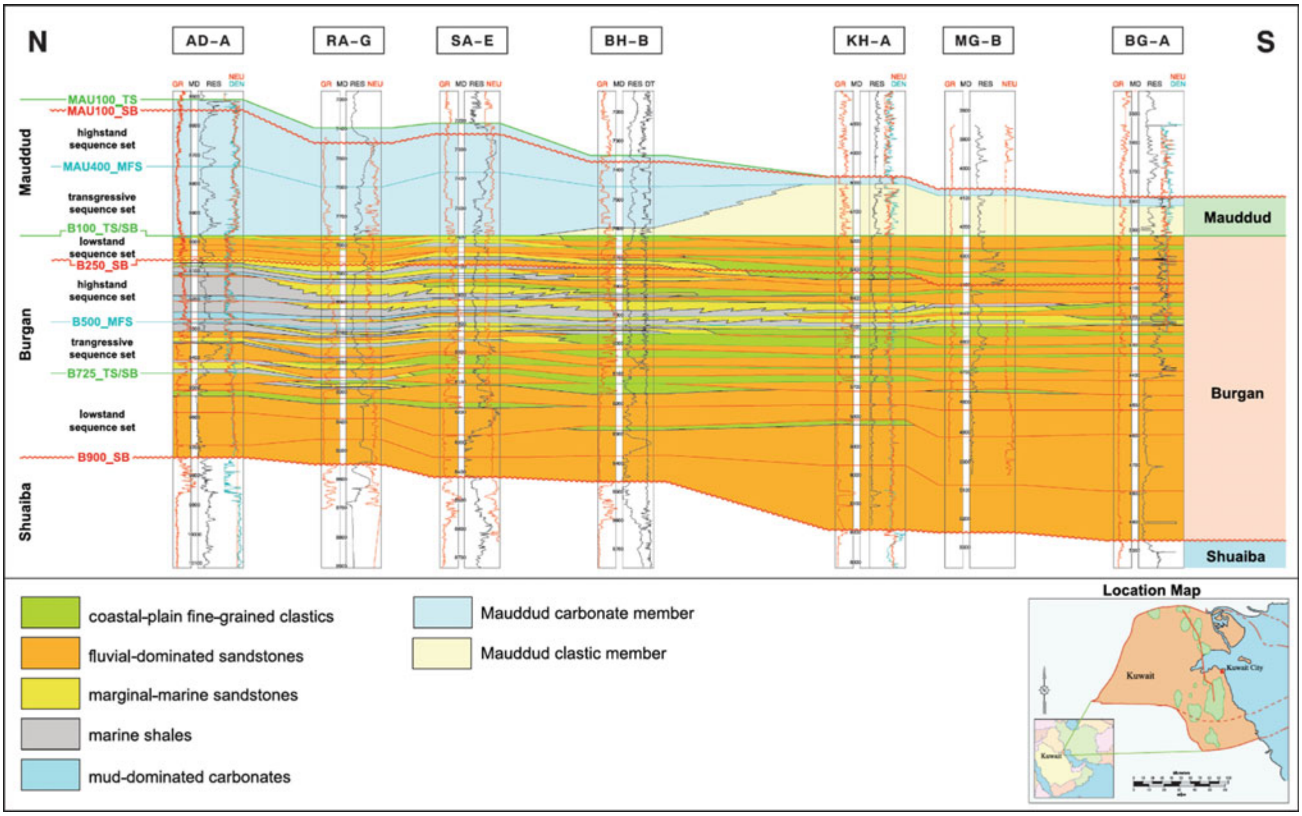

Fig. 6.16 Regional chronostratigraphic correlation from north to south of Kuwait showing facies distribution of Burgan Formation (after Strohmenger et al., 2006)

ranges from 15 to 20%, oil saturation (S_w) from 50 to 90% (Behbehani & Hollis, 2015), and permeability from 1.04 to 22.4 mD (Al-Awadi et al., 2017).

Behbehani and Hollis (2015) investigated the petrophysical properties of Mauddud Formation in Bahrah and Sabriyah fields, north of Kuwait. They found that reservoir quality of Mauddud Formation degrades from Sabriyah to Bahrah oil field. They alluded to this lower reservoir quality in Bahrah due to many factors rather than only facies variability. The reservoir performance (porosity and permeability) is partly affected by depositional facies, its diagenetic processes, structural deformation (tectonism), and timing of oil charge (Behbehani & Hollis, 2015).

Wara Formation

The upper Cretaceous Wara Formation is one of the main reservoirs in Greater Burgan field where oil production represents approximately 10% of the Burgan oil field communitive production (Al-Enzi and Hsie, 1999). It is also a major clastic reservoir in the south of Kuwait at the Wafra oil field. It is separated vertically from the Burgan reservoirs by extensive carbonate, and shale interval of Mauddud Formation and Wara Shales unit, respectively.

In south Kuwait, based on log analysis and well correlation, Wara is divided into three stratigraphic units: Lower, Middle, and Upper (Masarik et al., 2012). The middle Wara represents the best quality reservoir unit which is comprised of interbedded fine to medium-grained sandstone, siltstone, and shale with average porosity of 26%, net permeabilities ranging from 500 to 3000 mD, and average water saturation (S_w) from 18 to 20%, while the Upper and Lower units compose of shales, coals, shaley sandstone, and glauconitic sandstones. Wara reservoir forms a sequence of channel sands (fluvial/tidal) forming stacked channel sandstone, mouth bars, and tidal bars (Fig. 6.18).

The thickness of Wara Formation in Greater Burgan field ranges from 40 to 50 m of which up to 60% of the total thickness comprises sandstones (Alsharhan et al., 2014). In the cleaner sand sections, porosities can reach up to 30% with an average of 24% and permeabilities that can reach up to thousands of millidarcies.

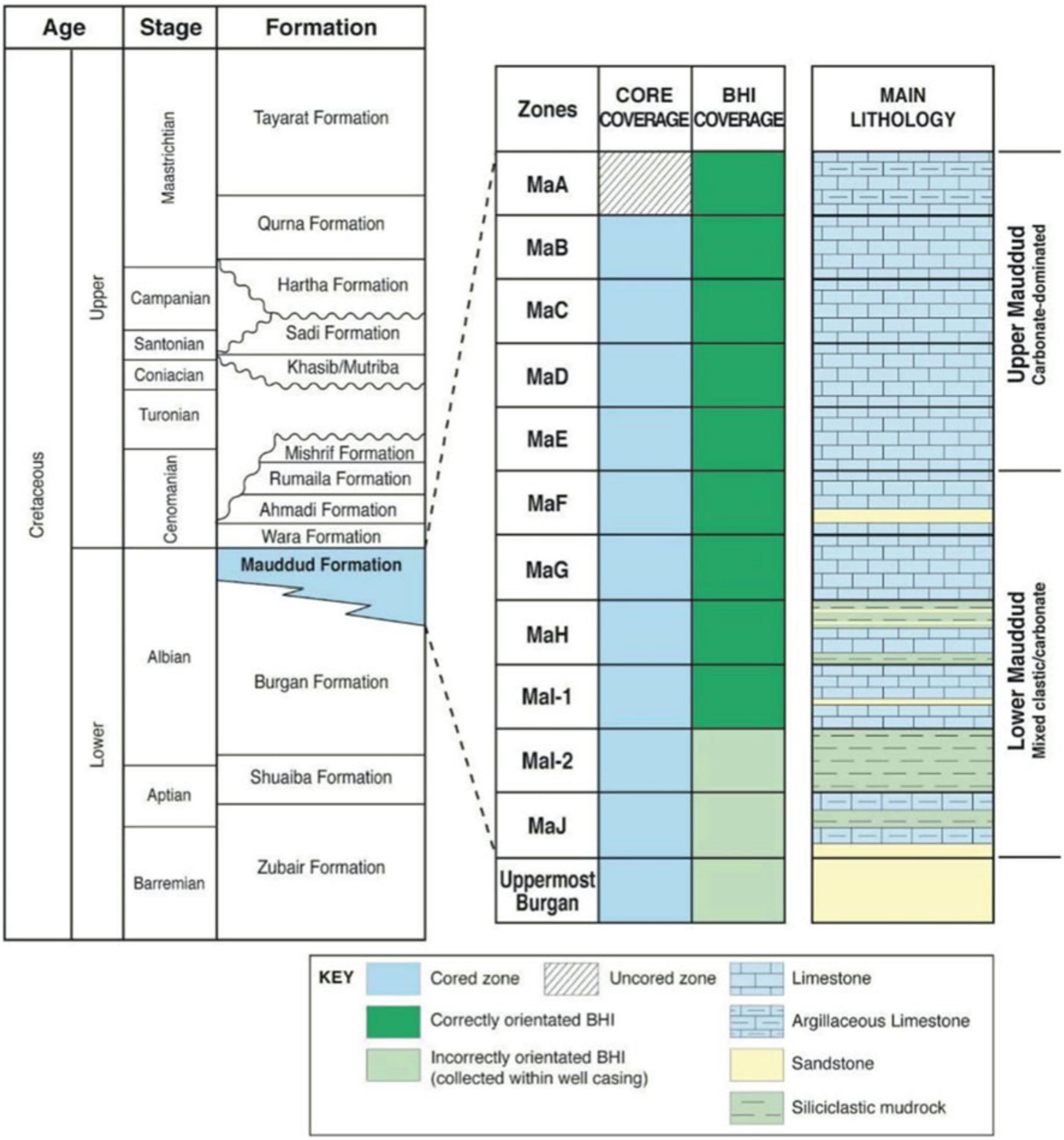

Fig. 6.17 The Late Albian Mauddud Formation reservoir zones of north Kuwait (after Al-Awadi et al., 2017)

6.3.2 Cenozoic Reservoir Rocks

Cenozoic sedimentary succession in Kuwait is divided into upper and lower units, Kuwait and Hasa groups, respectively. Kuwait group comprises a major reservoir, the Miocene Lower Fars sandstone formation, and Hasa Group comprises Paleogene–Eocene Umm Radhuma carbonate Formation.

6.3.2.1 Umm Er Radhuma Formation

The first discovery of heavy oil took place in 1954 in Umm Er Radhuma Formation which is informally referred to as the First, Second, and Third Eocene reservoirs (Fig. 6.19). This formation range in thickness from 424 to 500 m (Alsharhan and Nairn, 1997). The Wafra oil field, in the Divided Zone between Kuwait and Saudi Arabia, is the only field that produces from this reservoir. The First and Second Eocene reservoirs are the main reservoirs in the Wafra oil field, and both are capped by Anhydrite units (Fig. 6.19), Rus Formation (First Anhydrite) and Second Anhydrite of Paleocene age (Saller et al., 2014).

The First Eocene is composed of dolomite with minor, but locally abundant, gypsum and anhydrite. Diagenesis has played a major role in modifying depositional pore types. The First Eocene reservoir is characterized by high porosity values that range 30–50% which might be related to early

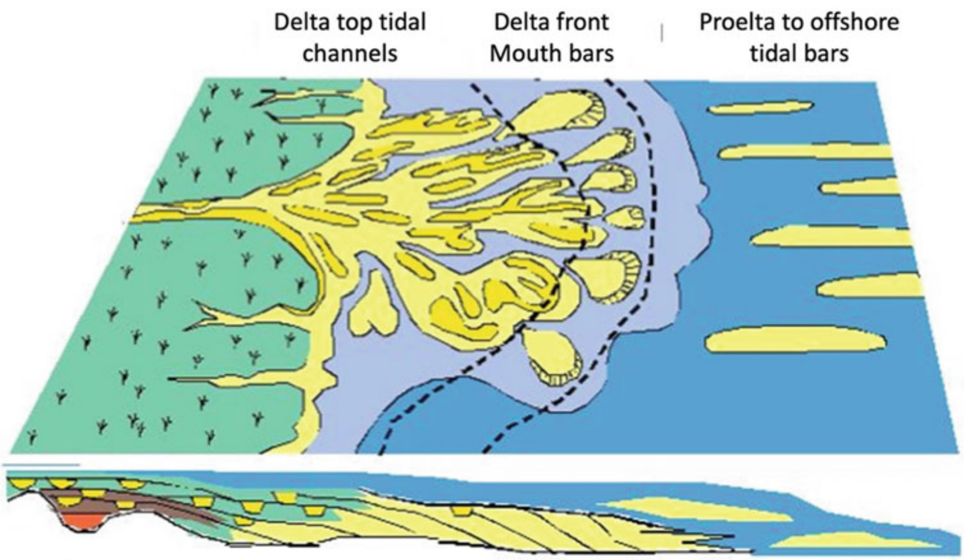

Fig. 6.18 Depositional model for Wara reservoir in Wafra oil field, south of Kuwait (after Masarik et al., 2012)

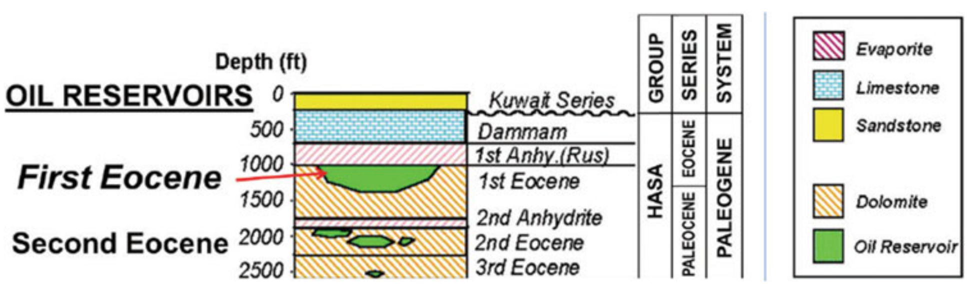

Fig. 6.19 Stratigraphic column for the Wafra Field showing reservoir at the Wafra Field. Contour interval is 20 ft (6 m) location of oil reservoirs (modified after Saller et al., 2014)

dolomitization, shallow burial, and early heavy oil emplacement, while permeability is commonly 100-2000md (Saller et al., 2014). The oil gravity is 19° API, with a 4.43% sulfur content (Nelson, 1968).

The Second Eocene reservoir is composed of dolomites, anhydritic dolostone, and anhydrite and generally shows high porosity values around 30% on density-neutron porosity logs and 20–45% from core plugs measurements. Leaching and dissolution processes have enhanced the predominantly intracrystalline pores forming sometimes millimeter to centimeter size vugs. Vuggy porosity is very common in the lower Second Eocene reservoir and may locally contribute to the high porosity values. Permeability is good to excellent and usually in the 10–100 s of millidarcies range (Wani and Al-Kabli, 2005). The oil gravity is 20° API, with a 4.43% sulfur content (Nelson, 1968).

6.3.2.2 Lower Fars Formation

The Miocene sandstone reservoir, Lower Fars Formation, is a long-established productive reservoir of heavy oil in northern Kuwait. The formation is under development in the Ratqa oil field, and it shows great potential in other oil fields north of Kuwait such as Raudhatain, Sabiriyah, Bahrah, and Mutriba oil fields (Fig. 6.1). The formation is divided into 2 sandstone layers F1 and F2 separated by a thin layer of shaly sandstone (Fig. 6.20). The two reservoir units F1 and F2 refer to the first and second Lower Fars reservoir sand, respectively (Abdul Razak et al., 2018). The upper reservoir unit F1 is found at shallow depths between 400 and 800ft. The F1 layer is composed dominantly of fine to coarse, poorly sorted, thinly laminated fluvial channel sandstone interbedded with silty shale and very fine to medium sandy bioturbated shale and minor argillaceous and bioturbated sandstone. While the F2 layer consists of fine to medium, subtly fining upward, moderately well-sorted sandstone (Abdul Razak, et al., 2018).

The Lower Fars reservoir has a uniform gross thickness in the Ratqa oil field of about 150ft with a total net thickness that ranges 10-100ft. The average recorded API of F1 units ranges 12–18° API, while the F2 unit has a lower average

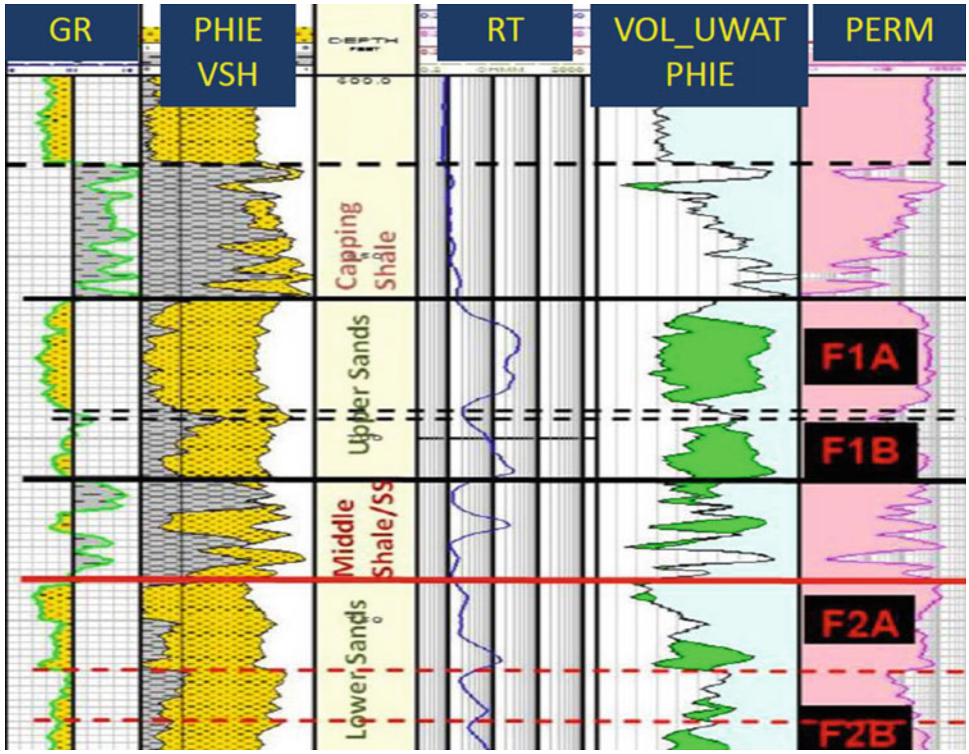

Fig. 6.20 Type log of Lower Fars reservoir from north of Kuwait showing the subdivision of Lower Fars into upper unit F1 and lower unit F2 separated by thin shale layer and capped by capping shale (After, Abdul Razak et al., 2018)

API of 11–15° API. The average computed porosity ranges from 25 to 35% which is in close agreement with core measured porosity. The reservoir is characterized by average permeability that ranges 1–4 Darcy (Al-Ali et al., 2017).

6.4 Seal Rocks

Most of the hydrocarbon in Kuwait oil fields are sealed and capped mainly by shale rocks (e.g., Burgan and Minagish reservoirs) and a few reservoirs by evaporites (e.g., Jurassic Najmah/Sargelu and Eocene Umm Er Radhuma reservoirs). The hydrocarbon potential of the Paleozoic section, in Kuwait, is limited so it will not be discussed. Here, we discuss the major seal rocks of the main hydrocarbon reservoirs of Mesozoic and Cenozoic ages.

6.4.1 Mesozoic Seal Rocks

6.4.1.1 Kra Al-Maru and Jilh Formations

The small quantity of hydrocarbon that is found in the Triassic section in Kuwait (Kra Al-Maru reservoir) is sealed locally by the intraformational halite and anhydrite, while the salt unit in middle Jilh acts as a regional seal for the Triassic system (Husain et al., 2009).

6.4.1.2 Dhruma Formation

This formation seals the oil and gas accumulations of the underlying carbonate reservoirs of the Upper Marrat play. It is composed of argillaceous limestone and fossiliferous shale (Husain et al., 2018a).

6.4.1.3 Gotnia and Hith Formations

Both Gotnia and Hith Formations mark the end of the Jurassic section in Kuwait. The Gotnia Formation (Kimmeridgian age) deposited in a hypersaline, very shallow and semi-confined lagoonal basin that extended from southern Iraq to the Rimthan structure, toward the southwest border between Kuwait and Saudi Arabia. It consists of 4 cycles of halite and anhydrite with occasional occurrences of limestone streaks encapsulated between halite and/or anhydrite (Ali, 1995; Yousif and Nouman 1997). It acts as a regional seal for Upper Jurassic Najmah and Sargelu reservoirs in Kuwait.

In the Arabian Peninsula region, Hith Formation caps the largest conventional carbonate reservoir worldwide, the Arab Formation. Hith Formation (Tithonian age) was deposited in an evaporitic pool and composes of massive anhydrite interbedded and intermixed with argillaceous limestone with minor shales. In the west of Kuwait, Hith Formation reaches a thickness more than 1100 ft and thins to approximately 200 ft toward northeast of Kuwait.

Al-Hajeri (2017) have discussed the integrity of Gotnia and Hith Formations, in Kuwait, based on formation water geochemistry study and suggested that the anomalously abnormal Na-rich formation water in the Cretaceous rocks might be attributed to the vertical migration of saline water from Gotnia and/or pre-Gotnia formations. This might indicate that both Gotnia and Hith Formations are breached by reactivated faults by the Late Cretaceous tectonism.

6.4.1.4 Lower Makhul Shale

Makhul Formation overlies the Jurassic Hith formation. The lower part of Makhul, which consists of heavily bioturbated organic-rich lime mudstone and shale, provides an effective regional top seal for the carbonate reservoirs in the Hith play.

6.4.1.5 Ratawi Formation

Ratawi Formation is divided into 2 members, Lower Ratawi limestone and Upper Ratawi shale. The upper shale member seals the sandstone and limestone streak reservoirs within Ratawi Shale member. It also seals off the major hydrocarbon accumulation in the lower Ratawi limestone and the early Cretaceous Minagish limestone reservoir (Alsharhan and Nairn, 1997).

6.4.1.6 Zubair Formation

This formation is interpreted as a complex section of deltaic origin evolving to estuarine settings with tidal influence. It is dominated by interbedded sand and shale units. The shale act as a good seal for hydrocarbon in the sand reservoirs.

6.4.1.7 Burgan Formation

Despite being the largest oil reservoirs in Kuwait, the interbedded shale within Burgan Formation efficiently plays as a seal for the two major sandstone reservoirs (Third and Forth sand members) (Alsharhan et al., 2014).

6.4.1.8 Wara Formation

The Lower Wara unit, defined as the "Wara Shales", consists of extensive shale interval deposited in marine settings that provide good sealing capacities. This shaley unit provides a regional seal for the underlying Mauddud Formation (Alsharhan et al., 2014).

6.4.1.9 Ahmadi Formation

Ahmadi Formation is the regional seal for the giant hydrocarbon accumulation in Burgan, Mauddud, and Wara reservoirs in Kuwait. It comprises brown shale and limestone (Alsharhan et al., 2014). Its thickness varies across Kuwait, where in the north it reaches 420 feet and about 165 feet in the south. It is divided into Upper member dominated by shale and Lower member which is carbonate-dominated.

6.4.2 Cenozoic Seal Rocks

6.4.2.1 Rus Formation

As discussed earlier in the chapter, there are two reservoirs in the Cenozoic rocks of Kuwait, Umm Er Radhuma (locally known as first and second Eocene reservoirs) and Lower Fars. First Eocene reservoir is capped by Rus Formation (also locally known as first Anhydrite) which consists of anhydrite, subordinate limestone, shale, and marl (Alsharhan and Nairan, 1997). This formation considered to be highly effective in south of Kuwait in the Wafra oil field. The Second Eocene reservoir is capped by this layer of Anhydrite.

6.4.2.2 Lower Fars Formation

The two main reservoir intervals of the Lower Fars Formation contain heavy oil in north Kuwait and are capped by a thick shale unit, and it seems to act as a regional seal for the reservoir. This is indicated as no commercial hydrocarbons are reported above this unit in Kuwait (Abdul Razak et al., 2018).

6.5 Unconventional Petroleum System of Kuwait

Conventional and unconventional resources are fundamentally different in that the traditional components of source, seal, reservoir, and trap must be present for conventional "discontinuous" hydrocarbons to be accumulated. Timing of trap formation relative to the generation of hydrocarbon in the source, migration from source to reservoir, and final entrapment is critical and must be juxtaposed. On the other hand, unconventional resources are continuous, organic-rich mud rocks or carbonates, consisting of self-sourced hydrocarbons trapped within fine-grained, low permeability. As a result of the combined effects of high petroleum viscosity and low matrix permeability, unconventional resources cannot be produced without stimulation (Ma & Holditch, 2016).

Kuwait Oil Company (KOC) displayed interest in commercially exploiting unconventional hydrocarbon reserves and started laying significant emphasis on the exploration and development of unconventional resources. Despite the relatively higher cost of production from unconventional resources and the availability of enormous conventional reserves, the rise in global demand for natural gas and the significant potential of unconventional prospects in Kuwait derived the plan of exploitation toward unconventional oil and gas. However, opportunities for commercial development of unconventional resources, such as fractured carbonates, in Kuwait must be balanced with the technological, environmental, and economic challenges. In

May 2008, Kuwait Oil Company started free gas production from the Jurassic naturally fractured carbonate reservoir which produces sour gas and light oil (API = 48). The main development challenges of the Jurassic gas field are the depth of the reservoir, its high pressure (10,000 psi) and temperature (275 °C), and low porosity and permeability, in addition to the high H_2S (5%) and CO_2 (5%) concentration of the well fluids (Al Qaoud, 2012). The Middle Jurassic Najmah-Sargelu Formations and the Lower Cretaceous Makhul Formation are among the most important unconventional targets in recent exploration efforts in Kuwait (Al Bahar et al., 2019; Husain et al., 2018b). The unconventional shale oil/gas potential within the Najmah Formation was detected West of Kuwait in Dharif, Abduliyah, Minagish, and Umm Gudair Fields (Al Murakhi, 2019).

Recently, the unconventional resources in Kuwait have been classified into 3 categories (Al Baher et al., 2019) based on organic geochemical properties of source and crude and reservoir parameters (Fig. 6.21).

Class-I Unconventional Kerogen: Defines organic-rich/Kerogen prospects that are further subdivided into two subcategories: Class IA: Self-sourced kerogen/organic-rich intervals including Makhul, Najmah, and Base Gotnia kerogen; and Class IB: Kerogen and Limestone intercalations of Lower Najmah, developed currently as a fractured limestone.

Class-II Unconventional Tight: incorporates tight clastic or carbonate formations with low organic material content, for example the Marrat tight limestone. Permeability is less than 0.1 millidarcy (mD).

Class-III Unconventional Viscous Oil: it involves both immobile and mobile oil subdivided into Class IIIA: Mobile: it relates to mobile viscous oil of less than or equal to 10,000 centipoise viscosity, current development of Lower Fars under production appraisal; and Class IIIB: Immobile: it relates to immobile viscous oil exceeding 10,000 centipoise viscosity and it includes tar mat and bitumen (e.g., Tayarat Formation).

6.6 Hydrocarbon Thermal Maturation, Generation, Migration, and Entrapment

As discussed earlier, the Jurassic Najmah and Lower Cretaceous Sulaiy (Makhul) Formations are believed to be the main source rocks in Kuwait. Maturity levels of Jurassic source rocks vary throughout Kuwait due to their depth variations. Generally, maturity levels in the south of Kuwait (e.g., Burgan oil field) are lower than in northern oil fields (e.g., Ratqa oil field) because of the difference in burial depths (Abdullah, 2001). The shallowest formation in the north of Kuwait is in the oil-generation phase while in the south, Jurassic source rocks are at the early stage of oil generation.

Abdullah et al. (1997) and Abdullah (2001) evaluated the burial and thermal history of the main Cretaceous and

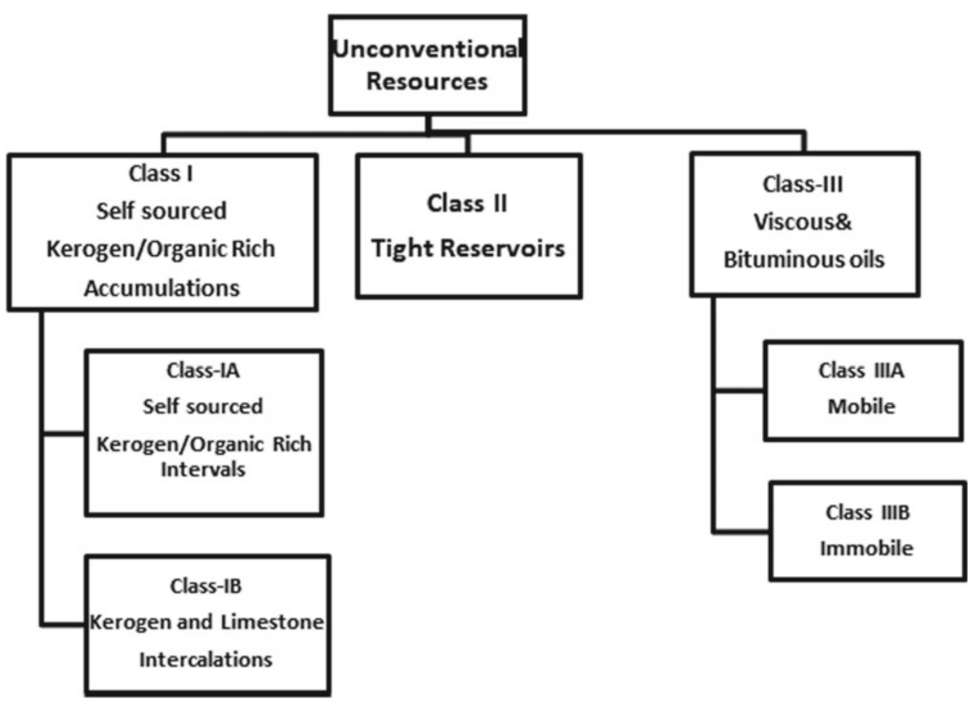

Fig. 6.21 Classification of unconventional resources (after Al-Bahar, et al., 2019)

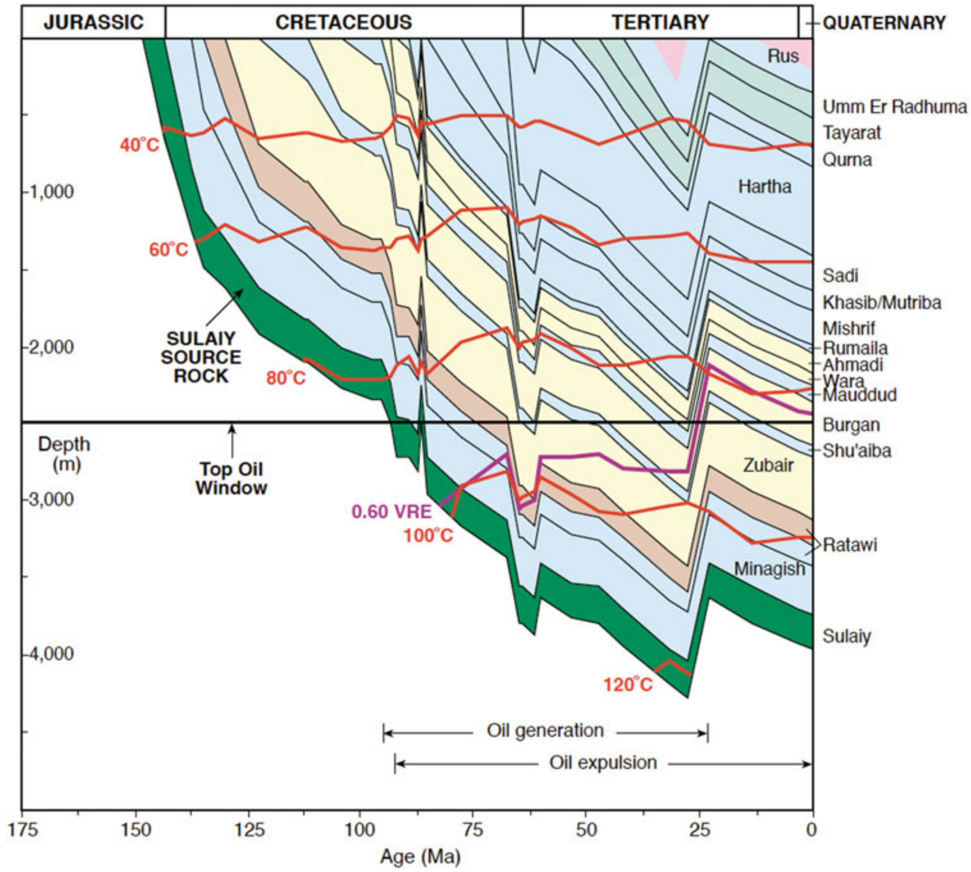

Fig. 6.22 The burial history curve shows that most oil generation of Sulaiy Formation occurred during Late Cretaceous and Early Paleogene and most oil expulsion during Paleogene (After Abdullah et al., 1997)

Jurassic source rocks in Kuwait, respectively. The study concluded that most oil generation occurred during Late Cretaceous and Early Paleogene, while oil expulsion took place during Paleogene. Figure 6.22 shows that Sulaiy source rock reached its peak oil generation around 75 Ma (Late Cretaceous) at a temperature of 100° and a depth of around 3,000 m. And it reached its peak expulsion during Paleocene (62 Ma).

The Jurassic source rocks of Kuwait began oil generation in Late Cretaceous to Eocene. A study based on samples from the Burgan oil field showed that deeper Jurassic horizons (Marrat Formation) began to generate oil around 110 Ma (Late Cretaceous), while Najmah Formation (shallowest Jurassic formation) started generating oil around 45 Ma (Eocene) (Fig. 6.23) (Abdullah, 2001). Jurassic source rocks are capped by thick anhydrite and evaporite sections of Gotnia and Hith Formations which might have prevented vertical migration to Cretaceous reservoirs. However, results from oil analysis of Cretaceous and Jurassic reservoirs of Kaufman et al. (1998) showed similar characteristics which might suggest that both were charged by the same source or from a different source of very similar compositions. A study by Al-Hajeri (2017) concluded that Gotnia and Hith Formations might be breached by fracture systems during Late Cretaceous tectonism which might have facilitated vertical migration of Jurassic hydrocarbon to Cretaceous reservoirs.

Since peak oil expulsion took place during Late Cretaceous and Early Paleogene (Table 6.1) synchronously with Zagros Orogeny, these tectonic stresses along with micro-fracturing of source rock due to intensive oil generation might have enhanced the migration of hydrocarbon out of the source rocks (Abdullah & Connan, 2002). The synchronous events of oil expulsion and trap formation during Late Cretaceous and Early Paleogene could be one of the main reasons for the huge hydrocarbon reserves in Kuwait.

6.7 Conclusions

The first commercial oil discovery in the state of Kuwait was made in 1938 in the Burgan oil field. Since then, several oil fields were discovered which made Kuwait one of the major oil-producing countries worldwide with proven crude oil reserves of about 100 billion barrels (BP Statistical Review of World Energy 2021).

Several geological factors are responsible for the prolific hydrocarbon reserves in Kuwait. The tectonics, subsidence histories, and the diagenetic processes that prevailed, on the

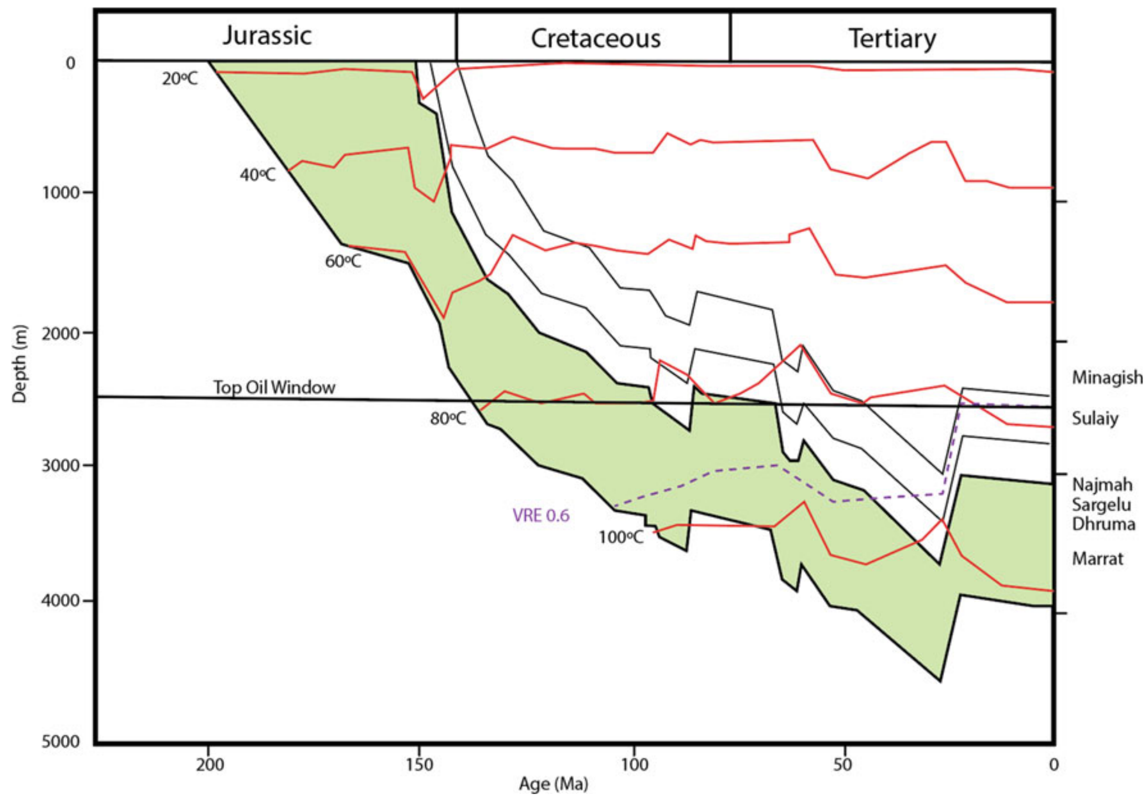

Fig. 6.23 Burial history diagram for one of Burgan oil field wells. The shaded area represents the Jurassic source rocks (modified after Abdullah, 2001)

Table 6.1 hydrocarbon generation and expulsion of Najmah/Sargelu and Sulaiy (Makhul) source rocks in Kuwait (after Alsharhan et al., 2014)

Formation	Hydrocarbon generation	Hydrocarbon expulsion
Najmah/Sargelu	Around 100 Ma (Cenomanian)	Expulsion becomes efficient at 60 Ma to 50 Ma (Selandian–Lutetian)
Sulaiy (Makhul)	Around 60 Ma (Selandian)	Expulsion of oil is expected at 40–30 Ma (Bartonian–Rupelian)

eastern part of the Arabian Peninsula during its geological history, are the main drivers for the exceptional geological conditions. These geological conditions are manifested by the widespread geographic distribution of rich, mature source rocks, high-quality reservoir rocks, and highly efficient seal rocks. Along with the formation of large structural traps during or after oil and gas generation, which helped in the formation of multiple petroleum systems in Kuwait. There are more than 20 oil fields across the country, however, most of the hydrocarbon production comes from the Greater Burgan field. These fields resemble very gentle four-closure anticlines interpreted as drape structures over deep-seated faults or as growth structures related to salt tectonics.

There are many stratigraphic intervals of good-quality reservoirs in Kuwait mainly from the Mesozoic Era. Most of the Cretaceous reservoirs are sealed by interbedded and overlying Cretaceous shales, while the Jurassic reservoirs are sealed regionally by salt and anhydrite of Gotnia and Hith Formations. The most famous reservoir is the siliciclastic reservoir of Burgan Formation which contributes to most of the hydrocarbon production in the state of Kuwait along with other several Cretaceous reservoirs which accounts for about 80% of hydrocarbon production in Kuwait.

Although source rocks are well distributed along the stratigraphic column of Kuwait, from Silurian up to Cretaceous, the richest source rocks are dominant in Jurassic and Lower Cretaceous. Types of kerogens from these source rocks are types II and II–III, a mixture of marine and terrestrial organic matter with TOC values ranging from moderate to excellent. Organic geochemical analysis of the Jurassic and Cretaceous source rocks which are mainly composed of limestones and calcareous shales shows the significant potential for oil generation in Kuwait. Oil generation of the Jurassic and Cretaceous source rocks started in Late Cretaceous–Early Tertiary synchronously with structure trap formation.

Kuwait Oil Company (KOC) displayed interest in commercially exploiting unconventional hydrocarbon reserves. The Middle Jurassic Najmah-Sargelu Formations and the Lower Cretaceous Makhul Formation are among the most important unconventional targets in recent exploration efforts in Kuwait.

References

Abdullah, F. H. A. (2001). A preliminary evaluation of Jurassic source rock potential in Kuwait. *Journal of Petroleum Geology, 24*(3), 361–378.

Abdullah, F. H. A., & Connan, J. (2002). Geochemical study of some Cretaceous rocks from Kuwait: Comparison with oils from Cretaceous and Jurassic reservoirs. *Organic Geochemistry*, *v. 11*, 125–148.

Abdullah, F. H. A., & Kinghorn, R. R. F. (1996). A preliminary evaluation of Lower and Middle Cretaceous source rocks in Kuwait. *Journal of Petroleum Geology*, *v. 19*, 461–480.

Abdullah, F. H. A., Peter, J. R., Ormerod, M. P., & Kinghorn, R. F. (1997). Thermal history of the Lower and Middle Cretaceous source rocks in Kuwait. *GeoArabia, 2*(2), 151–164.

Abdullah, F. H., Carpentier, B., Kowalewski, I., Buchem, F., & Huc, A. (2005). Organic matter identification in source and reservoir carbonate in the Lower Cretaceous Mauddud Formation in Kuwait. *GeoArabia, 10*(4), 17–34.

Abdullah, et al. (2017). Petrophysics and hydrocarbon potential of Paleozoic rocks in Kuwait. *Journal of Asian Earth Sciences*, *v. 148*, 105–120. https://doi.org/10.1016/j.jseaes.2017.07.057

Abdullah, F. H., Shaaban, F., Al-Khamis, A., Khalaf, F., Bahman, F., & Akbar, B. (2021). Evaluation of Paleozoic source rocks in Kuwait. *AAPG Bulletin, 105*(4), 721–748.

Abdul Razak, M. H., Al-Jenaie, J., & Moubarak, H. (2018). Understanding the Reservoir Architecture of Lower Fars Formation in North Kuwait through Seismic Reservoir Characterization, Adapted from oral presentation given at the GEO 2018 13th Middle East Geosciences Conference and Exhibition, Manama, Bahrain. (5–8 Mar 2018).

Abu-Ali, M. A., Rudkiewicz, J. L. L., McGillivray, J. G., & Behar, F. (1999). Paleozoic petroleum system of Central Saudi Arabia. *GeoArabia, 4*, 321–336.

Al-Ajmi, H., Brayshaw, A. C., Barwise, A. G., & Gaur, R. S. (2001). The Minagish field tar mat, Kuwait: Its formation, distribution and impact on water flood. *GeoArabia, 6*(1), 7–24.

Al-Ali, Y., Wang, G., Al-Mula, Y., Hussein, M., Choudhary, P., & Ahmed, F. (2017). Evaluation of the first cycle of steam stimulation in North Kuwait heavy oil thermal pilots, SPE 186182-MS.

Al-Awadi, M., Haines, T., Bertouche, M., Bonin, A., Fuchs, M., Deville De Periere, M. (2017). Predictability of the sedimentological make-up and reservoir quality in the Mauddud formation using FMI Logs-a case study from a North Kuwait field, SPE-187630-MS.

Al-Bahar, M., Vandana Suresh, V., Al-Sahlan, G., & Al-Ajmi, M. A. (2019) Classifications of Unconventional Resources in Kuwait. Search and Discovery Article #80657. Adapted from extended abstract based on oral presentation given at the GEO 2018 13th Middle East Geosciences Conference and Exhibition, Manama, Bahrain. (5–8 Mar 2018).

Al-Eidan, A. J., Wethington, W. B., & Davies, R. B. (2001). Upper Burgan reservoir distribution, northern Kuwait: Impact on reservoir development. *GeoArabia*, *v. 6*(2), 179–208.

Al-Eidan, A. J., Narahari, S. R., Al-Awadi, M., Al-Ajmi, N. H., Pattnaik, C., Al-Ateeqi, K., Al-Houli, M. M., Kidambi, V. K., De Keyser, T. (2010). Jurassic tight carbonate gas fields of North Kuwait: Exploration to early development. In *Paper presented at the SPE Deep Gas Conference and Exhibition*, Manama, Bahrain. https://doi.org/10.2118/130914-MS.

Al-Enezi, K., & Hsie, J. (1999). Modeling and scale up of a heterogeneous reservoir, Wara Sand, Greater Burgan Field, SPE 53206.

Al-Enezi, S.A., AlAli, S., AlKamiss, A. (2018). The Jurassic petroleum system of Kuwait. AAPG Datapages/Search and Discovery Article #90319 at GEO 2018 13th Middle East Geosciences Conference and Exhibition, Manama, Bahrain. (5–8 Mar 2018).

Al-Enezi, B. (2019). Geological description for unlocking potential of Najmah-Sargelu reservoir in greater Burgan Field. In *European Association of Geoscientists & Engineers, Conference Proceedings, Third EAGE WIPIC Workshop: Reservoir Management in Carbonates, Nov 2019* (Vol. 2019, pp. 1–8).

Al-Failakawi, F., Al-Muraikhi, R., Al-Shamali, A., Al Qattan, A., Belgodere, C., Marti, F., & Quttainah, R. (2018). Fracture characterization of Najmah-Sargelu tight carbonates reservoir using geomechanical attributes in Minagish field, West Kuwait Search and Discovery Article #20447 (2019) Posted January 14, 2019. Adapted from oral presentation given at the GEO 2018 13th Middle East Geosciences Conference and Exhibition, Manama, Bahrain. (5–8 Mar).

Al-Fares, A. A., Bouman, M., & Jeans, P. (1998). A new look at the middle to Lower Cretaceous stratigraphy, offshore Kuwait. *GeoArabia, 3*(4), 543–560.

Al-Hajeri, B. (2017). Application of formation water geochemistry to assess seal integrity of the Gotnia Formation, Kuwait. *Arabian Journal of Geosciences*, *v. 10*(3), 1–10. https://doi.org/10.1007/s12517-017-2842-2

Ali, M. A. (1995). Gotnia salt and its structural implications in Kuwait. In M. I. Al-Husseini, (Ed.), *Middle east petroleum geosciences, GEO'94: Gulf PetroLink, Bahrain* (Vol. 1, pp. 133–142).

Al-Jallal, A.I. (1995). The Khuff Formation—its reservoir potential in Saudi Arabia and other Gulf countries. In Al-Husseini, M.I. (Ed.), *Middle East Petroleum Geosciences Conference Geo-94, Gulf Petrolink, Bahrain* (Vol. 1, pp. 103–119).

Al-Khamiss, A., AdulMalik, S., & Abdel Hameed, W. (2012). Compositional basin model of Kuwait–leads for yet to find potential. In *Abstract, AAPG Search and Discovery Article AAPG Hedberg Conference Petroleum Systems*. Modeling the Past, Planning the Future, Nice, France. (1–5 Oct).

Al-Murakhi, R. (2019). West Kuwait unconventional hydrocarbon potential evaluation of the Najmah formation - phase 1 project summary. Search and Discovery Article #80658 (2019) Posted January 14, 2019. In *Adapted from oral presentation given at the GEO 2018 13th Middle East Geosciences Conference and Exhibition, Manama, Bahrain* (5–8 Mar 2018).

Al-Qaoud, B. N. (2012). Challenges in Sour Gas handling for Kuwait Jurassic Sour Gas. Paper presented at the SPE Middle East Unconventional Gas Conference and Exhibition, Abu Dhabi, UAE, January 2012. SPE-154452-MS.

Alsharhan, A. S., Strohmenger, C. J., Abdullah, F. H., Al Sahlan, G. (2014). Mesozoic stratigraphic evolution and hydrocarbon habitats of Kuwait. In L. Marlow, C. Kendall, & L. Yose, (Eds.), *Petroleum systems of the Tethyan region: AAPG Memoir* (Vol. 106, pp. 541–611).

Alsharhan, A. S., & Nairn, A. E. M. (1997). Sedimentary basins and petroleum geology of the Middle East (p. 942). Elsevier Publishing Company. ISBN 0-444-82465-0.

Alsharhan, A. (1994). Albian clastics in the Western Arabian gulf region: A sedimentological and petroleum-geological interpretation. *Journal of Petroleum Geology, 17*(3), 279–300. https://doi.org/10.1111/j.1747-5457.1994.tb00135.x

Al-Tendail, S. B., Taal, A., Al-Adwani, T., Abu Ghneej, A., Arasu, R., Barr, D., & Clews, P. (2012). Reviving a classic exploration play in Kuwait: The lower cretaceous Ratawi formation, search and discovery Article #10436.

Al-Wazzan, H. (2021). 3D forward stratigraphic modelling of the Lower Jurassic carbonate systems of Kuwait. *Marine and Petroleum Geology*, *123*, 104699–.https://doi.org/10.1016/j.marpetgeo.2020.104699

Andriany, R., & Al-Khamiss, A. (2011). Permo-triassic source rock assessment by inherited of the triassic oils in Kuwait, Third Arabian Plate Geology Workshop Permo-Triassic (Khuff) Petroleum System of the Arabian Plate Kuwait City, Kuwait, 28 Nov-1 Decr 2011

Aqrawi, A. M., & Badics, B. (2015). Geochemical characterisation, volumetric assessment and shale-oil/gas potential of the Middle Jurassic-Lower Cretaceous source rocks of NE Arabian Plate. *GeoArabia, 20*(3), 99–140.

Arasu, R. T., Nath, P. K., Khan, B., Ebrahim, M., Rahaman, M., Bader, S., & Abu-Ghneej, A. F. N. (2012). Stratigraphic Features Within the Ratawi Shale Member of the Lower Cretaceous Ratawi Formation and Their Hydrocarbon Prospectivity in Sudai –Abdali Area, North Kuwait.˵ Paper presented at the 2012 SEG Annual Meeting, Las Vegas, Nevada. (Nov 2012).

Behbehani, S., & Hollis, C. (2015). Controls on petrophysical properties of the Mauddud formation, Bahra and Sabriyah Fields, Kuwait, IPTC-18511-MS.

Boix, C., Di Simone, S., Deville De Periere, M., et al. (2014). New insights on the Mauddud formation (Upper Albian): Characterisation of sedimentology, diagenesis and reservoir quality. Abstract presented at the AAPG ICE, Istanbul. (14–17 Sept 2014).

Bou-Rabee, F. (1996). Geologic and tectonic history of Kuwait as inferred from seismic data. *Journal of Petroleum Science and Engineering*, *16* (pp. 151–167).

Chakrabarti, B., Al-Wadi, M., Abu Hebiel, H., Al-Enezi, A. (2011). Diagenetic controls on carbonate reservoir quality of Jurassic Middle Marrat formation in Burgan Field, Kuwait. Search and Discovery Article #20121 (2011) Posted November 28, 2011. Adapted from extended abstract prepared in conjunction with poster presentation at AAPG International Conference and Exhibition, Milan, Italy. (23–26 Oct 2011).

Grader, A., Al-Jallad, O., Kayali, A. (2019). Micro porosity within the organic matter and its impact on assessment of unconventional potential of a Kerogen rich Najmah formation in Kuwait. Presentation at the Abu Dhabi International Petroleum Exhibition & Conference held in Abu Dhabi, UAE. (11–14 Nov 2019).

Hawie, N., Al-Wazzan, H., Al-Ali, S., Al-Sahlan, G. (2021). De-risking hydrocarbon exploration in lower Jurassic carbonate systems of Kuwait through forward stratigraphic models. *Marine and Petroleum Geology*, *123*. ISSN 0264-8172.

Husain, R., Sajer, A., Al-Khamiss, A., Iqbal, M., & Al-Zeabout, N. (2009). Triassic petroleum system of Kuwait, AAPG Search and Discovery Article #90090©2009 AAPG Annual Convention and Exhibition, Denver, Colorado. (7–10 Jun 2009).

Husain, R., Khan, D., Sajer, A., Alammar, N. (2011). Khuff formation in Kuwait: an overview: Conference paper, Third Arabian Plate Geology Workshop Permo-Triassic (Khuff) Petroleum System of the Arabian Plate Kuwait City, Kuwait. (28 Nov–1 Dec 2011).

Husain, R., Al-Wadi, M., Al-Ali, S., Al-Abdullah, M., Al-Fadhli, H., (2018a). Unlocking the potential of unconventional oil and gas resources in Kuwait. Paper presented at the Abu Dhabi International Petroleum Exhibition & Conference, Abu Dhabi, UAE. SPE-192604-MS. (Nov 2018a).

Husain, R., Al-Owihan, H., Mulyono, R., Ahmed, S. M., Al-Fadhli, H., Al-Kandari, A., Al-Ali, S., Al-Wadi, M. (2018b). Hydrocarbon seals in Jurassic carbonate and evaporite sequences in Kuwait: Implications for exploration, second EAGE/AAPG Hydrocarbon Seals of the Middle East Workshop, Abu Dhabi, UAE. (17–19 Apr 2018b).

Inan, S., AbuAli, M. A., Qathami, S., Hakami, A. A., & Shammari, S. H. (2016). Hydrocarbon potential of the Silurian Qusaiba Shales of Saudi Arabia in a regional context of the Paleozoic Shales in the Arabian Platform. In *Conference paper, AAPG GTW The Source Rocks of the Middle east, Abu Dhabi–UAE*. (Jan 2016).

Konert, G., Afifi, A. M., Al-Hajri, S. A., & Droste, H. J. (2001). Paleozoic stratigraphy and hydrocarbon habitat of the Arabian Plate. *GeoArabia, 6*, 407–442.

Kaufman, R. L., Kabir, C. S., Abdul-Rahman, B., Quttainah, R., Dashti, H., Pederson, M. S., & Moon, M. S. (1998). Characterizing the Greater Burgan field using geochemical and other field data. In *SPE 49216 Annual Technical Conference and Exhibition, New Orleans, Louisiana*.

Laboun, A. A. (1987a). Unayzah formation: A new permo-carboniferous unit in Arabia. *The American Association of Petroleum Geologists Bulletin, 71*(1), 29–38.

Laboun, A. A. (1987b). Unayzah formation-a new permian-carboniferous unit in Saudi Arabia. *American Association of Petroleum Geologists Bulletin, 71*, 29–38.

Ma, Y. Z., & Holditch, S. A. (2016). Unconventional oil and gas resources handbook evaluation and development. *Gulf Professional Publishing*. https://doi.org/10.1016/C2014-0-01377-9

Mahmoud, M. D., Vaslet, D., & Al-Husseini, M. I. (1992). The Lower Silurian Qalibah Formation of Saudi Arabia—An important hydrocarbon source rock. *American Association of Petroleum Geologists Bulletin, 76*(10), 1491–1506.

Masarik, C., Gonzalez-Mieres, R., Jamil, F., Buza, J. (2012). Identifying new opportunities in a mature reservoir: Wara formation, Wafra Field, Saudi Arabia/Kuwait Partitioned Zone, SPE 160873.

McGillivray, J. G., & Husseini, M. I. (1992). The Paleozoic petroleum geology of Saudi Arabia. *American Association of Petroleum Geologists Bulletin, 76*, 1473–1490.

Nath, P. K., Sunil Kumar Singh, S. K., Abu Taleb, R., Prasad, R., Badruzzaman Khan, B., & Bader, S. (2012). Characterization and modeling of tight fractured carbonate reservoir of Najmah-Sargelu formation, Kuwait search and discovery Article #41059 (2012) Posted October 29, 2012. Adapted from extended abstract prepared in conjunction with oral presentation at AAPG International Convention and Exhibition, Singapore. (16–19 Sept 2012).

Nath, P. K., Singh, S. K., Ye, L., Al-Ajmi, A. S., Bhukta, S. K., Al-Otaibi, A. H. (2014). Reservoir characterization and stratistructural play of Minagish Formation, SE Kuwait. In *International Petroleum Technology Conference*. OnePetro.

Nelson, P. H. (1968). Wafra field, Kuwait-Saudi Arabia Neutral zone. SPE 2nd Region. In *Technical Symposium Proceedings, Dhahran, Saudi Arabia* (pp. 101–120).

Parmjit, S., Husain, R., Sajer, A., Al-Fares, A. M. (2010). Estimating pre-Khuff thickness and delineating basement configuration in Dibdibba Trough, Kuwait-An integrated model based study, Paper presented at the 2010 SEG Annual Meeting, Denver, Colorado, October 2010.

Qabazard, S. A., Al Tameemi, A., & Abdullah, F. H. (2000). Petrographical, mineralogical and geochemical studies of the Quaternary carbonates, Al Khiran area, southern coast of Kuwait & Lower Cretaceous Middle Minagish Formation, Kuwait southern oil fields. A Thesis in Geology. 2000.

Rabie, A., Husain, R., & Al-Fares, A. M. (2014). Unconventional Petrophysical Workflows for Evaluation of Shale Plays: A Case Study from Kuwait. Search and Discovery Article #80370 (2014) Posted March 31, 2014 *Adapted from extended abstract prepared in conjunction with poster presentation at GEO-2014, 11th Middle East Geosciences Conference and Exhibition. (10–12 Ma 2014).

Saller, A. H., Pollitt, D., & Dickson, J. A. D. (2014). Diagenesis and porosity development in the First Eocene reservoir at the giant Wafra Field, Partitioned Zone, Saudi Arabia and Kuwait. *AAPG Bulletin*, *98*(6), 1185–1212.

Sharland, P. R., Archer, R., Casey, D. M., Davies, R. B., Hall, S. H., Heward, A. P., Horbury, A. D., & Simmons, M. D. (2001). Arabian Plate sequence stratigraphy: GeoArabia Special Publication 2, Gulf Petrolink, Manama, Bahrain (p. 371).

Siddiqui, M. A., Al-Omair, F. S., & Al-Salali. Y. Z. (2008). Production from Najmah-Sargelu Reservoirs: A Formation Damage Perspective. AAPG Search and Discovery Article #90077 at GEO 2008 Middle East Conference and Exhibition, Manama, Bahrain.

SinghaRay, D., Mukherjee, P., Matar, S., Alessandroni, M., Joussineau, G., Erwan Perfetti, E., Maux, T. L., Al-Sammak, I., & Al Matar, B. (2015). Characterization and modeling of natural fractures in a tight Najmah-Sargelu formation, Dharif-Abduliyah Field, Kuwait. In *Conference: 77th EAGE Conference and Exhibition, Madrid* (1–4 June 2015).

Snasiri, F., Abdulrazzaq, E., Tirkey, N., Kotecha, R., Gazi, N.H., Al-Othman, M., Al-Sabea, S., & Ali, F. (2015). Excellent stimulation results in deep carbonate reservoir in Marrat formation in Magwa structure in Greater Burgan Field Kuwait. Paper presented at the SPE Kuwait Oil and Gas Show and Conference, Mishref, Kuwait, October 2015. Paper Number: SPE-175342-MS.

Strohmenger, C. J., Al-Anzi, M. S., Pevear, D. R., Ylagan, R. F., Kosanke, T. H., Ferguson, G. S., Cassiani, D. H., & Douban, A. F. (2003). Reservoir quality and K-Ar age dating of the pre-Khuff section of Kuwait: GeoArabia. *Bahrain, 8*(4), 601–620.

Strohmenger, C. J., Patterson, P. E., Al-Sahlan, G., Mitchell, J. C., Feldman, H. R., Demko, T. M., Weller, R. W., Lehmann, P. J., McCrimmon, G. G., Broomhall, R. W., & Al-Ajmi, N. (2006). Sequence stratigraphy and reservoir architecture of the Burgan and Mauddud formations. In P. M. Harris, & L. J. Weber, (Eds.), Giant hydrocarbon reservoirs of the world: From rocks to reservoir characterization and modeling (Vol. 88, pp. 213–245). AAPG Memoir 88/SEPM Special Publication, Boulder.

Tanoli, S. K., Husain, R., Sajer, A. A. (2008). Facies in the Unayzah Formation and the basal Khuff clastics in subsurface, northern Kuwait. *GeoArabia*, *13*(4), 15–40.

Wani, M. R., & Al-Kabli, S. K. (2005). Sequence stratigraphy and reservoir characterization of the 2nd Eocene Dolomite Reservoir, Wafra Field, Divided Zone, Kuwait-Saudi Arabia, Paper SPE 92827 presented at the SPE Middle East Oil and Gas Show and Conference, Bahrain. (12–15 Mar 2005).

Wender, L. E., Bryant, J. W., Dickens, M. F., Neville, A. S., & Al-Moqbel, A. M. (1998). Paleozoic (Unayzah) hydrocarbon geology of the Ghawar area, eastern Saudi Arabia. In: Al-Husseini, M.I. (Ed.), *Middle East Petroleum Geosciences Conference Geo-97*, (Vol. 3, pp. 273–301). Gulf Petrolink.

Yousif, S., & Nouman, G. (1997). Jurassic geology of Kuwait. *GeoArabia, 2*(1), 91–110. https://doi.org/10.2113/geoarabia020191