Subsurface Stratigraphy of Kuwait

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Abstract

This chapter reviews the subsurface stratigraphy of Kuwait targeting geosciences educators. The lithostratigraphy and chronostratigraphy of the reviewed formations (association of rocks whose components are paragenetically related to each other, both vertically and laterally) followed the formal stratigraphic nomenclature in Kuwait. The exposed stratigraphic formations of the Miocene–Pleistocene epochs represented by the Dibdibba, Lower Fars, and Ghar clastic sediments (Kuwait Group) were reviewed in the previous chapter as part of near-surface geology. In this chapter, the description of these formations is based mainly on their subsurface presence. The description of the subsurface stratigraphic formations in Kuwait followed published academic papers and technical reports related to Kuwait's geology or analog (GCC countries, Iraq and Iran) either from the oil and gas industry or from different research institutions in Kuwait and abroad. It is also true that studies related to groundwater aquifer systems also contribute to our understanding of the subsurface stratigraphy of Kuwait for the shallower formations. The majority of the published data were covered the onshore section of Kuwait. The subsurface stratigraphic nomenclature description is based on thickness, depositional environment, sequence stratigraphy, the nature of the sequence boundaries, biostratigraphy, and age. The sedimentary strata reflect the depositional environment in which the rocks were formed. Understanding the characteristics of the sedimentary rocks will help understand many geologic events in the past, such as sea-level fluctuation, global climatic changes, tectonic processes, geochemical cycles, and more, depending on the research question. The succession of changing lithological sequences is controlled by three main factors; sea-level change (eustatic sea level), sediment supply, and accommodation space controlled by regional and local tectonics influences. Several authors have developed theoretical methods, established conceptual models, and produced several paleofacies maps to interpret Kuwait's stratigraphic sequence based on the data collected over time intervals from the Late Permian to Quaternary to reconstruct the depositional history of the Arabian Plate in general and of Kuwait to understand the characteristics of oil and gas reservoirs.

2.1 Introduction

Kuwait is located within the depocentre of the Arabian platform carbonates basin and is covered by approximately integrated shallow marine Phanerozoic sedimentary succession with a thickness of more than 35,000 ft (10,688 km). This Phanerozoic section is interrupted by significant episodes of uplift and erosion or non-deposition manifested by well-recognized unconformities (Fig. 2.1). The sedimentary succession is influenced by large, gentle folds of different shapes and sizes associated with differential regional subsidence or uplifting along basement faults. These deep-seated structures cause lateral and vertical variations in sedimentary successions (Al-Sharhan & Nairn, 2003).

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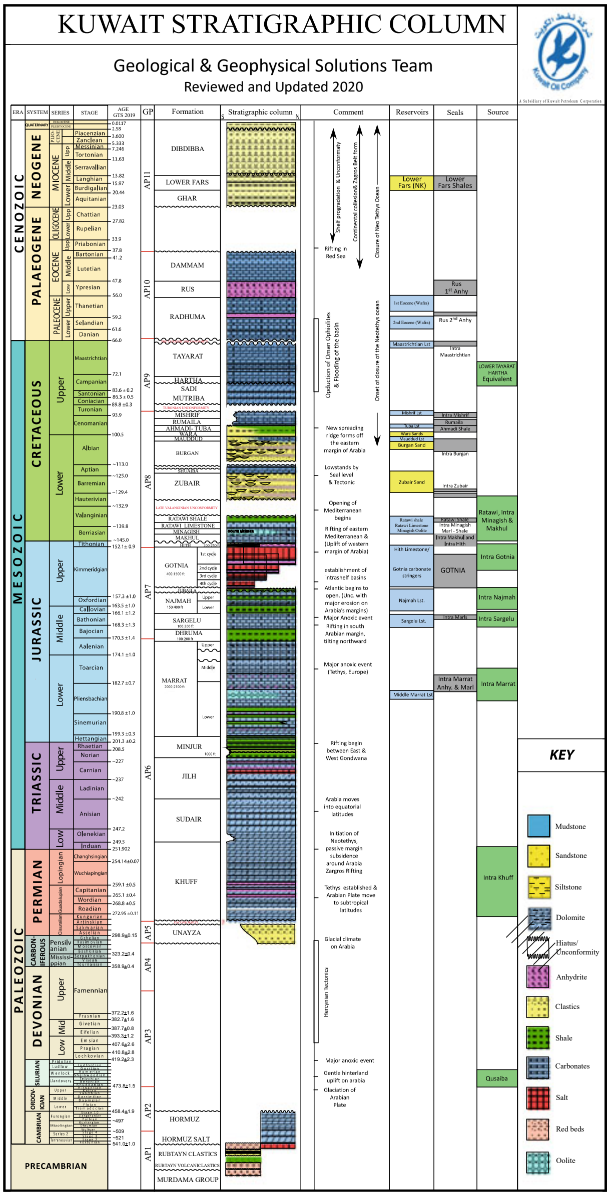


Fig. 2.1 Kuwait chronostratigraphic column. AP refers to the Arabian Plate tectonostratigraphic megasequence, which will not be discussed in this chapter in detail

The Phanerozoic succession is not exposed at the surface in Kuwait; hence, it is relatively poorly documented across its entire thickness. Most of the vital information about the subsurface formations in Kuwait are obtained from the great history of petroleum industry-related hydrocarbon drilling wells in the state of Kuwait (Fig. 2.2). Remarkable information was derived from deep wells drilled onshore, and few wells have reached the ancient basement (Al-Hajeri & Bowden, 2018). Hence, this chapter's authors found some uncertainties and rare information interpreting the Pre-Kuff (Pre-Upper Permian) formations in Kuwait and excluded it from the discussion.

In an attempt to understand the vast amount of stratigraphic information, several authors published regional lithostratigraphic studies. The depositional environment interpretations of the identified sequences are based on sedimentary stacking patterns, core observations, lithology, physical and biogenic sedimentary structures, facies and their associations, facies boundary characteristics, etc. Ziegler (2001) reconstructs the depositional history of the Arabian Plate by generating paleofacies maps for given time intervals between the Late Permian and Holocene. Sharland et al. (2001) published the first chronostratigraphic interpretation of the rock units of the Arabian Plate. Beydoun (1988) and Al-Sharhan and Nairn (2003) have published regional lithostratigraphic reviews to understand the substantial amount of stratigraphic information. Pasyanos et al. (2007) used a limited amount of seismic data from the Kuwait National Seismic Network (KNSN) to estimate the lithospheric structure of Kuwait. They combined surface wave and receiver functions to develop a KUW1 model, presenting a sedimentary cover with (8 km) thick and crustal thickness of 45 km.

2.2 Late Paleozoic–Early Mesozoic

The Late Paleozoic–Early Mesozoic period in this chapter is referred to as the Permian to Triassic time, describing the potential source rocks formations including the oldest Khuff Formation (Late Permian–Early Triassic), Sudair Formation (Early Triassic), Jilh Formation (Middle-Late Triassic), and Minjur Formation (Late Triassic). This Permo-Triassic section in the subsurface of Kuwait is poorly understood, and very limited published reliable data are available. The formations that belong to this section gained less attention in drilling and exploration from oil companies due to the following reasons: The greater depths of these formations, the lack of high-resolution seismic and core data, the lack of hydrocarbon reservoirs within these formations, and most importantly, the higher cost of drilling (Abdullah et al., 2017; Husain et al., 2013; Pöppelreiter & Marshall, 2013; Singh et al., 2013).

2.2.1 Khuff Formation

The Khuff Formation cropped out in Central Saudi Arabia near the Riyadh–Jiddah Road and was named Khuff according to ‘Ayn Khuff (Khuff Spring) (Steineke et al., 1958). The Khuff Formation is considered one of the largest

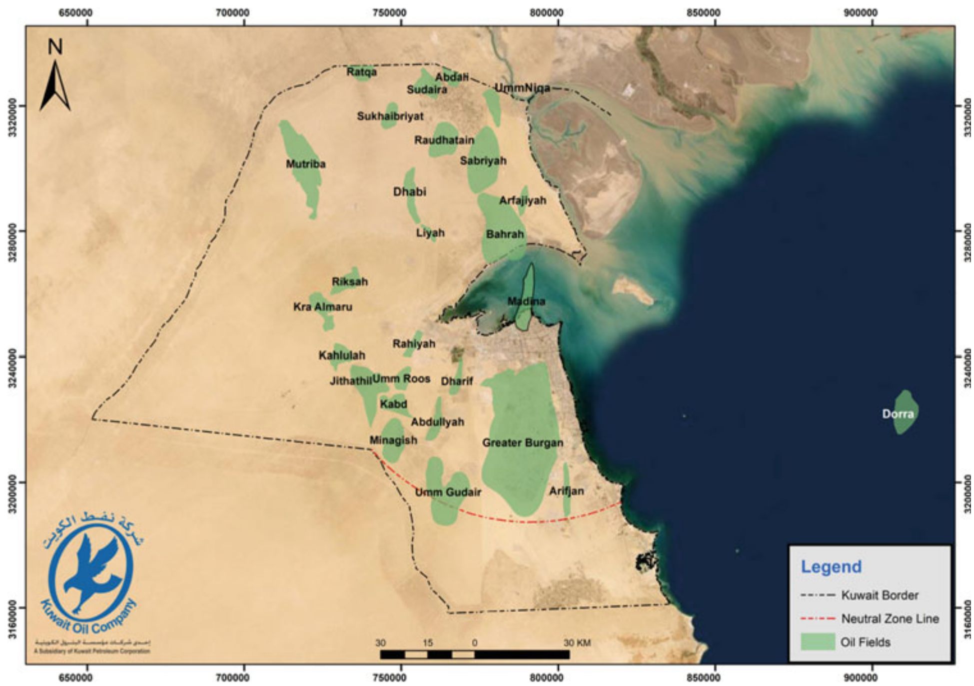


Fig. 2.2 Map illustrating the location of the oil and gas field from which the stratigraphic column of Kuwait was interpreted and constructed

gas reservoirs in the Arabian Gulf region and worldwide. It was deposited in one of the most extensive shallow-water carbonate ramp environments in Earth's history, that extended for 3.7 square million kilometers along the eastern side of the Arabian Plate (the passive northeastern margin of Neo-Tethys) during the Permo–Triassic time (Zieglar, 2001; Pöppelreiter & Marshall, 2013). The Late Permian age is assigned for Khuff Formation due to the presence of foraminifera and algae, a fauna that includes *Globovalvulina vonderschmitti, Pachyphloia* cf. *ovata, Hemigordius* cf. *ovatus, Mizzia velebitana,* algae, echinoids, bryozoa, gastropods, and ostracods (Khan, 1989).

Information about Khuff Formation in Kuwait is deficient due to the greater depths of the formation (ranges between15,000 and 24,000 ft (4572–7315 m)), which increases the drilling operations costs (Abdullah et al., 2017; Husain et al., 2013; Singh et al., 2013). Furthermore, the seismic data resolution for the Khuff Formation and deeper formations in Kuwait's subsurface are limited. Moreover, the presence of better and shallower hydrocarbon reservoirs above the Khuff Formation makes it less desirable for further exploration (Al-Sharhan et al., 2014; Husain et al., 2013).

Very few wells had penetrated entirely the Khuff Formation in Kuwait (six wells in Northwest Raudhatain, Burgan, and Umm Gudair structures) to the top of the Unayzah Formation that underling the Khuff Formation (Abdullah et al., 2017; Al-Sharhan & Nairn, 2003; Husain et al., 2013). Other wells were drilled only up to the upper parts of the Khuff Formation without full penetration (e.g., those in Sabriyah, Mutriba, and Kra Al Maru structures) (Husain et al., 2013).

In Kuwait, Khuff Formation is around 1800 ft (549 m) thick on average, and it underlies the Sudair Formation with uncomfortable to gradational(?) contact (Husain et al., 2013). The lower contact (base of AP6) of the Khuff Formation varies through different locations in Kuwait. In the Raudhatain Field, Khuff Formation lies unconformably on top of the Unayzah Formation, while it overlies a regional well-recognized unconformity consists of a clastic sequence of unknown age elsewhere in Kuwait (Al-Sharhan & Nairn, 2003; Husain et al., 2013; Strohmenger et al., 2003; Tanoli et al., 2008).

The Khuff Formation was divided into; Khuff-A, B, C, and D units (Husain et al., 2013; Singh et al., 2013). Another subdivision is widely used for Khuff Formation in Kuwait, and it subdivides the formation into; Upper Khuff (i.e., Khuff-A, Khuff-B, and Khuff-C) and Lower Khuff (i.e., Khuff-D). The Upper and the Lower Khuff are separated by a distinctive, extensive, and thick layer of anhydrite known as the Median Anhydrite (Husain et al., 2013; Khan, 1989).

Lithologically, Khuff Formation generally consists of dolomite and limestone (dolomudstone, dolowackestone, dolopackstone, and dolograinstone) with minor shale and anhydrite that were deposited in shallow subtidal to intertidal and lagoonal depositional settings (Husain et al., 2013; Khan, 1989; Singh et al., 2013). Both Khuff-D and Khuff-B are carbonates-rich in the lower sections with anhydrite-dominated in the upper sections. In Comparison, Khuff-C and Khuff-A are mainly carbonate-rich throughout their entire section (Husain et al., 2013). The early and late stages of diagenesis (e.g., micritization, dolomitization, cementation, stylolites, leaching, and dedolomitization) extensively affected the formation of lithology (Husain et al., 2013).

2.2.2 Sudair Formation

The Sudair Formation (informally called Sudair shale) is named for Khashm Sudayr in Saudi Arabia, where the lower part of the unit is well exposed (Powers et al., 1966). The Early Triassic Sudair Formation is considered a significant seal for the Khuff Reservoir along the Arabian Plate (Abdul Malek et al., 2005; Pöppelreiter & Obermaier, 2013). Lithology-wise, Sudair Formation consists mainly of shale and fine-grained siliciclastics with dolomite and anhydrite in most parts of the Arabian Plate, but it shows lateral facies variation when it is regionally correlated (Davies et al., 2019; Pöppelreiter & Obermaier, 2013).

Sudair Formation is composed of cycles of dolomudstones, laminated to bedded anhydrites and dolomitic shales deposited in an inner ramp and lagoon environments (Abdul Malek et al., 2005; Al-Sharhan et al., 2014). Despite the lack of oil discovery within the Sudair Formation, it has some potential for oil and gas discovery, especially in the West of Kuwait, where potential gas-condensate discoveries within the Sudair Formation were detected in the Mutriba area (Abdul Malek et al., 2005).

The Sudair Formation is unconformably/gradationally overlying the Khuff Formation and conformably underlies the Jilh Formation. The formation ranges in thickness from 98 ft (30 m) in Sabriyah Field, north of Kuwait, to 1201 ft (366 m) in Kra Al-Maru Field west of Kuwait (Al-Sharhan et al., 2014).

Sudair Formation was divided into three major units (from oldest to youngest) (Khan et al., 2010; Al-Sharhan et al., 2014):

Sudair Unit C: consists of argillaceous dolomite with interbedded shale and thin anhydrite.

Sudair Unit B: comprises dolomite, anhydrite, and minor shale.

Sudair Unit A: consists of dolomudastone, anhydrite, and shale. This unit can be found all over the subsurface of Kuwait, and it pinch-out towards the northeast (Khan et al., 2010).

2.2.3 Jilh Formation

The Jilh Formation was named for Jilh al ʻIshãr, a low escarpment in Saudi Arabia across which the section type was measured (Powers et al., 1966). The Jilh Formation is of Middle Triassic in age (Ladinian to Anisian) according to the presence of *Myophoria* sp. (Sharland et al., 2001; Al-Sharhan & Nairn, 2003). It is conformably overlying Sudair Formation and unconformably underlies the Minjur Formation. The thickness of the Jilh Formation in Kuwait ranges between 803 and 1804 ft (245–550 m) (Khan et al., 2010; Al-Sharhan et al., 2014). The formation is mainly composed of dolomite, anhydrite, minor limestone, and shale. The hypothetical depositional environment suggested hypersaline sabkha-dominated, shallow marine environments and intertidal/subtidal to continental influenced sabkha (Husain et al., 2009; Khan et al., 2010; Al-Sharhan et al., 2014).

The Jilh Formation can be subdivided into three units (from oldest to youngest) (Khan et al., 2010; Al-Sharhan et al., 2014; Arasu et al., 2018):

Jilh Unit C (Lower Jilh Carbonate Unit): Consists of altering various carbonates and dolostone (dolomudstone, dolowackestone, and dolopackstone) with anhydrite that indicates coastal marine and sabkha depositional settings.

Jilh Unit B (Jilh Dolomite): Comprises alternations of dolomudstone to dolowackestone with dolomitic shale and some thin-bedded salt at the top section of the unit. The lithology of this unit indicates a hypersaline shallow marine depositional setting.

Jilh Unit A (Upper Jilh Carbonate Unit): Consists of dolomudstone, anhydrite, with rare dolowackestone and dolopackstone. This unit represents more terrestrial sabkha-dominated depositional settings.

2.2.4 Minjur Formation

The Minjur Formation was named after Khashm al Manjûr in Saudi Arabia, where the upper part of the formation is exposed (Powers et al., 1966). In Kuwait, the Minjur Formation comprises mixed siliciclastics, carbonates, and evaporite deposits. It mainly consists of alternating dolomite, anhydrite, and sandstone with intercalation of siltstone and shale indicating siliciclastic input on top of the shallow Arabian shelf (Khan et al., 2010; Al-Sharhan et al., 2014; Davies et al., 2019).

As stated in Al-Sharhan and Nairn (2003), the Minjur Formation is estimated to have been deposited during the Late Triassic age (Carnian to Rhaetian) in agreement with the microhabitat of *Estheria minuta* Alberti and *Lingula tenuissima* var. *zenkeri* Alberta. The Minjur Formation is conformably overlying the Jilh Formation and unconformably underlies the Jurassic Marrat Formation. In Kuwait's subsurface, the Minjur Formation ranges between 524 and 1066 ft (160–325 m) in thickness and it was classified into five units by Al-Sharhan et al., (2014):

Minjur Unit 5: consists mainly of shale and siltstone with alternating sandstone, dolomite, and anhydrite.

Minjur Unit 4: predominantly composed of siliciclastics. It consists of sandstone with intercalated shale and siltstone.

Minjur Unit 3: consists mainly of dolomite with anhydrite and minor shale, siltstone, and sandstone.

Minjur Unit 2: comprises shale and siltstone with minor alternating dolomite, anhydrite, and sandstone. Signs of an arid environment paleosol were found in this unit's cores, indicating an arid floodplain and palaya depositional environments (Al-Sharhan et al., 2014).

Minjur Unit 1: predominantly consists of dolomite and anhydrite, intercalation of shale and siltstone, with minor limestone and sandstone.

2.3 Mesozoic

Kuwait was part of a carbonate shelf environment during the majority of the Mesozoic (Sharland et al., 2001; Ziegler, 2001). This shelf formed part of the Neo-Tethys Sea, which started during the Late Triassic due to the divergence between the central Iranian plate (s) and Arabian plate (Koop & Stoneley, 1982).

The Mesozoic period of the Jurassic and Cretaceous Kuwait stratigraphic column is well studied as part of oil exploration and production. The subsurface lithostratigraphic units have been described to demonstrate the close relationship between lithofacies, depositional environments, geological structures, and petroleum reservoirs. The reviewed Jurassic and Cretaceous stratigraphic columns in this chapter reflect the summary of these studies.

2.3.1 Jurassic

The Jurassic Formations of Kuwait from oldest to youngest are Marrat, Dhruma, Sargelu, Najmah, Jubaila, Gotnia, and Hith. The Marrat, Dhruma, Jubaila, and Hith formations are identified in surface exposures in Saudi Arabia (Powers et al., 1966), while the Sargelu, Najmah, and Gotnia formations were described in wells and outcrops in Iraq (Bellen et al., 1959).

2.3.1.1 Marrat Formation

The Marrat Formation was named and described in outcrop sections in Saudi Arabia (Powers et al., 1966; Steineke et al., 1958). Yousif and Nouman (1997) first published the term “Marrat Formation” in Kuwait.

The Marrat Formation is barren of nannofossils (Kadar et al., 2015; Al-Moraikhi et al., 2014). However, the deposition age was estimated between Late Sinemurian–Early Bajocian (Early–Middle Jurassic) based on isotope studies done by Al-Sahlan (2005) and Al-Moraikhi et al. (2014).

The Marrat Formation is predominantly composed of Carbonates. It mainly consists of micritic limestones with wackestones, packstones, and oolitic grainstones, interbedded with anhydrite, dolomite, and rare shale (Al-Sharhan et al., 2014; Yousif & Nouman, 1997). It conformably underlies Dhruma Shale Formation and unconformably overlies the Triassic Minjur Formation (Al-Sharhan et al., 2014; Neog et al., 2011). The Marrat Formation can reach up to 2001 ft (610 m) in thickness at Burgan field, where the formation is the thickest (Abdullah, 2001; Al-Sharhan & Nairn, 2003). It was deposited in a shallow marine carbonate platform to peritidal and Sabkha environments (Yousif & Nouman, 1997; Al-Eidan et al., 2009; Neog et al., 2011; Al-Sharhan et al., 2014).

The Marrat Formation was informally subdivided into five units: Unit A, B, C, D, and E by Yousif and Nouman (1997). Later it was subdivided into three members: The Lower, the Middle, and the Upper Marrat Members.

The Lower Marrat Member is composed of mixed lithologies of thinly interbedded carbonate, dolomite, argillaceous carbonates, and anhydrite (Al-Sharhan et al., 2014; Neog et al., 2011). It thickens towards the southeast of Kuwait (Neog et al., 2011). The Lower Marrat Member can be divided into seven sequences. Each of these sequences contains anhydrite that is either scattered through the formation or concentrated in the upper part, indicating peritidal, tidal flat, and sabkha environment settings (Al-Sharhan et al., 2014; Kadar et al., 2015; Neog et al., 2011).

The Middle Marrat Member consists of cleaner carbonates deposited in a tidal flat to open marine settings separated by a high-energy barrier (Kadar et al., 2015; Neog et al., 2011). The middle Marrat Member base consists of argillaceous limestone and debris flow deposits, while massive anhydrites fill the lagoons behind the barriers. The lagoonal deposits were later replaced by tidal flats and sabkha deposits (Al-Sharhan et al., 2014). The uppermost part of the Middle Marrat Member is dominated by carbonates and argillaceous limestone (Kadar et al., 2015). In the North of Kuwait, the Middle Marrat Member can be divided into three major cycles consisting of an alternation between carbonates and evaporites (Kadar et al., 2015; Neog et al., 2011) as follows:

1. Supratidal sabkha deposits of enterolithic anhydrite with thinly laminated carbonate beds interbedded with chicken-wire anhydrites.
2. Lagoonal evaporites of gypsum and anhydrite interbedded with carbonates related to cyanobacteria mats.
3. Shallow basin deposits consist of massive bedded anhydrite with dolomite partings, carbonate, and shale interbedded with layers of enormous halite.

The Upper Marrat Member consists of mixed lithology (generally more argillaceous lithofacies) that contains several thin alternating cycles of sabkha, tidal flat, lagoon, and carbonate platform deposits (Al-Sharhan et al., 2014; Kadar et al., 2015; Neog et al., 2011). The contact that separates the Middle and the Upper Members of the Marrat Formation is marked by a subaerial exposure surface (Davies et al., 2019; Kadar et al., 2015). The thickness of the Upper Marrat Member increases uniformly across the basin from 361 to 558 ft (110 m–170 m), indicating an absence of tectonic activities during the time of deposition (Al-Sharhan et al., 2014). The lower part of the Upper Marrat Member is composed mainly of evaporites (mainly anhydrite), with laminated reddish-brown silty dolomudstone, microbial laminites, argillaceous dolomudstone, and skeletal-peloidal, wavy bedded mudstone and wackestone representing sabkha, tidal flat, tidal channel, and shallow lagoon depositional settings. The uppermost part of the Upper Marrat Member consists of more open marine carbonates deepening upward into shale-dominated Dhruma Formation (Al-Eidan et al.,2009; Neog et al., 2011; Al-Sharhan et al., 2014).

2.3.1.2 Dhruma Formation

The Dhruma Formation was named and described concerning outcrops in Saudi Arabia near the town of Durmã (Steineke et al., 1958; Powers, 1966).

Kadar et al. (2015) analyzed the Dhruma Formation in Minagish-27 Well located in Minagish field; they estimated its lithological thickness of 138 ft (42 m), and they found that it consists of shale and calcareous shale with occasional interbeds of argillaceous lime mudstone and wackestone. The formation is thickening towards the South of Kuwait with a maximum of 175 ft (53 m) and (ca. 60 ft, 18 m) in North Kuwait (Cabrera et al., 2019; Kadar et al., 2015).

Based on calcareous nannofossil identifications, Kadar et al. (2015) estimated that Dhruma Formation was deposited during Middle Jurassic, within the age extending from Middle or Late Aalenian to early Late Bajocian.

The lower boundary of the Dhruma Formation with the Marrat Formation appears to be conformable, and it is usually detected with high gamma-ray (an e-log used to measure the gamma-ray radiation from the rocks). It was delineated where the Dhruma basinal shales replaced the interbedded shale and limestone beds of the Upper Marrat Member, suggesting a gradual upward deepening towards the Dhruma Formation (Kadar et al., 2015). The upper boundary with the overlying Sargelu–Dhruma Transition Member of the Sargelu Formation is conformable and marks a noticeable change to a possible shelf deposition with typical storm beds (Cabrera et al., 2019).

The Dhruma Formation is considered an excellent caprock for the Marrat reservoir (Yousif & Nouman, 1997).

2.3.1.3 Sargelu Formation

The Sargelu Formation was named after surface exposures of the succession in the Surdash Anticline, northeastern Iraq (Dunnington, 1958). Sargelu Formation is the oldest formation of the Riyadh Group that comprises of five members as follows: Sargelu, Najmah, Jubaila, Gotnia, and Hith.

Kadar et al. (2015) studied the Sargelu Formation in Minagish-27 Well between 13,166 ft (4,014 m) and 13,377 ft (4,077 m) and subdivided it into two members, a lower argillaceous member named "Sargelu-Dhruma Transition", and the overlying member named "Sargelu Limestone". The Sargelu Formation is the thickest in the country's southern region, adjacent to the Rimthan Arch near Umm Gudair Field, where it reaches a maximum thickness of more than 220 ft ($\sim$67.1 m). It thins consistently northward, parallel to the Burgan Arch, to less than 60 ft ($\sim$18.3 m) along the border with Iraq (Cabrera et al., 2019).

The Sargelu Formation, as interpreted by Kadar et al. (2015), Cabrera et al. (2019) is predominantly an aggradational sequence. The Sargelu–Dhruma Transition comprises extensively burrowed, interbedded argillaceous limestones and skeletal wackestones, with a decreasing number of calcareous nannofossils. The suggested conceptual model for the Sargelu–Dhruma Transition is an outer-ramp, slope, and basin margin. However, the Sargelu Limestone has been found to contain only thin shale interbeds that shallow upward into packstones consisting of cortoids, coated grains, and skeletal fragments with no Flora in the limestone. The conceptual model of the Sargelu Limestone is an open marine shelf.

Kadar et al. (2015) made the Nannofossil recovery in the Sargelu–Dhruma Transition. It was good and suggested Late Bajocian (Middle Jurassic) age. On the other hand, samples from the Sargelu Limestone were barren of nannofossils. Accordingly, the age was not determined, and they place lower Bathonian MFS (maximum flooding surface) near its base.

The Sargelu Formation conformably overlies the Dhruma Formation. Yousif and Nouman (1997) identified the contact between the Sargelu Formation with the underlying Dhruma Formation by the change from predominantly limestone with subordinate shale interbeds to mainly calcareous shale with subordinate limestone interbeds. The contact with the overlying Najmah Formation is interpreted to be conformable and transitional (Kadar et al., 2015; Yousif & Nouman, 1997).

The Sargelu Formation is one of the main carbonate reservoirs in the Jurassic section in Kuwait that includes Najmah, Sargelu, and Marrat Formations. (Singh et al., 2009).

2.3.1.4 Najma Formation

In Kuwait, the Najmah Formation is equivalent to that drilled on the Najmah–Quayarah Anticline southeast of Mosul located in northern Iraq (Bellen et al., 1959). It is the second formation of the Riyadh Group.

Kadar et al. (2015) divided the lithostratigraphy of the Najmah Formation penetrated in Minagish-27 Well into Najmah Shale and Najmah Limestone with further subdivision of Najmah Shale into three subunits:

1. Barren Najmah–Sargelu Transition.
2. Lower Najmah Shale developed during the middle Jurassic, between Late Bathonian and Middle Callovian.
3. Upper Najmah Shale deposited during Middle Callovian to Middle Oxfordian (i.e., Late middle Jurassic–Early-Late Jurassic).

The Najmah Limestone was interpreted to be deposited during Late Oxfordian (Late Jurassic). Kadar et al. (2015) approximated the thickness of the Najmah Formation ranges from 140 ft (42.7 m) in the north to 220 ft (67.0 m) in the south. The three subdivisions of Najmah Shale have correlated throughout Kuwait stratigraphic sections and were recognized by the sharp contact boundaries detected via electrical well-logs due to the variations in limestone lithofacies of strata that are interbedded with fissile, organic-rich, argillaceous lime mudstones reflecting different environmental settings (Fig. 2.3). (see Kadar et al., 2015 for more details).

The Najmah–Sargelu Transition, according to Kadar et al. (2015) does not contain calcareous nannofossils. Nevertheless, it consists of interbedded microlaminated organic-rich argillaceous lime mudstone (ORAM), skeletal microbial wackestones, and mud-dominated packstone beds with cortoids, coated grains, and various skeletal fragments. Calcareous nannofossils. This accumulation hypothesized transportation downslope from an outer-shelf or ramp environment and the microbial skeletal wackestones believed to signify an oxygen-minimum zone (OMZ) environment along the basin margin (Kadar et al., 2015).

The Lower Najmah Shale, as described by Kadar et al. (2015), is a lithological unit of low diversity of nannofossils. It contains a distinguishing association of filamentous microbial wackestones, tiny articulated bivalves, and juvenile ammonites, interbedded with ORAM. These beds were assumed to have been deposited in-situ in a base-of-slope environment along the basin margin.

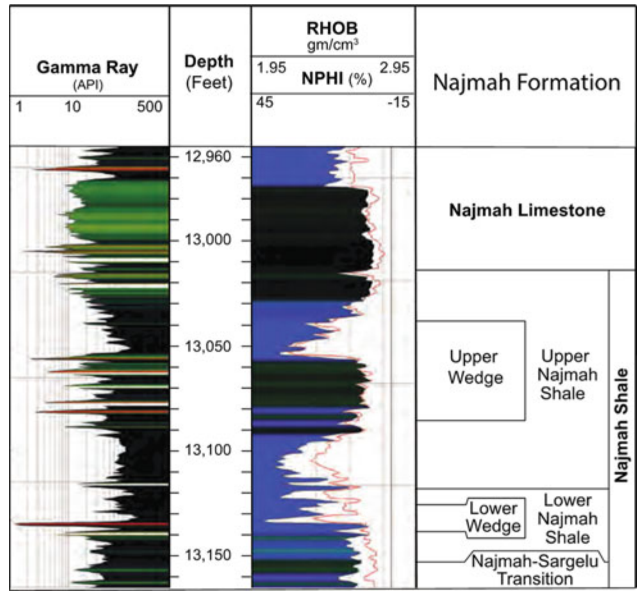


Fig. 2.3 Log display of the Najmah formation in Minagish-27 Well (Modified after Kadar et al., 2015)

Kadar et al. (2015) defined the Upper Najmah Shale as it was lacking burrowing and containing thick accumulations of the pelagic bivalve with abundant calcareous nannofossil assemblies suggesting a more basin-like environment. Furthermore, they found that it consists of predominantly ORAM with a few pure lime mudstone beds that could characterize very distal subaqueous flows.

The Najmah Limestone is characterized by Kadar et al. (2015) by the absence-to-abundance of nannoflora. They also found the basal beds overlie a condensed zone representing an outer shelf to the upper slope. The succession of lithofacies and ichnofacies could suggest shallowing upward and probable progression to the inner shelf or lower shoreface depositional environment.

The underlying boundary of the Najmah Formation with the Sargelu Formation is placed at the highest grain-supported beds. It is transitional, with thin organic-rich (kerogen) beds appearing in the uppermost Sargelu Formation and increasing upward. (Kadar et al., 2015).

The Najmah Limestone lies conformably on the Najmah Shale and unconformably overlain by a thin unit of shale, calcareous shale, and peloidal limestone beds referred to as Jubaila Formation. This unconformity surface has been correlated by Kadar et al. (2015) in eight cores as a minimum, with noticeable karsting and an indication of surface exposure. Erosion induces differences in the thickness of Najmah Limestone at this unconformity (Cabrera et al., 2019; Kadar et al., 2015).

2.3.1.5 Jubaila Formation

The Jubaila Formation type section is defined in Saudi Arabia (Powers et al., 1966). In Kuwait, Kadar et al., 2015 introduce for the first time the name of Jubaila Formation in Minagish-27 Well, referring to the lithological section with 46 ft (~ 14 m) thick and is thinnest towards the north to ca 8 ft (2.4 m) thick in Dhabi area (area in North of Kuwait). In the Sabriyah and Raudhatain Field area, it may be vanished or only a few inches to one or two feet in thickness (Carbrera et al., 2019).

The Jubaila Formation corresponds to the lower part of Najmah Unit 1 that Yousif and Nouman (1997) recognized, and below the fourth Anhydrite unit of the Gotnia Formation. The sediments of the Jubaila Formation are generally dark, reddish-brown to nearly black, and consist predominantly of dolomitic limestone, argillaceous limestone, and calcareous shale (Kadar et al., 2015).

Lithologically, the Jubaila Formation is a sandwich between two surfaces of unconformities that distinguished it from the overlain Gotnia Formation and the underlain Najmah limestone (Fig. 2.1) (Kadar et al., 2015).

Kadar et al. (2015) investigated the lithofacies of the Jubaila Formation across Kuwait. They predicted that the depositional setting in North Kuwait could be peritidal to shallow subtidal environments concerning sediment contents that consist of generally argillaceous, laminated to thin-bedded peloidal and mudstones, mud-dominated packstones, and wackestones. They also noticed that the formation had become more argillaceous and less microbial and had become burrowed with thickenings southward and westward. This type of sedimentation was interpreted to represent an inner ramp/shelf environment.

Kadar et al. (2015) identified extensive calcareous nannofossils in the argillaceous mudstone in some wells located in the south, northwest, and north of Kuwait. They also found Coccospheres within the Jubaila Formation, reflecting a low-energy, open-marine, depositional environment. Kadar et al. (2015) identified nannofossil assemblages in Jubaila Formation related to the Kimmeridgian age.

The high gamma-ray values and the low density between the top of the Najmah and the base of the Gotnia Formation were used to exclude the Jubaila unit from logs, indicating that it could be a source rock (Cabrera et al., 2019).

2.3.1.6 Gotnia Formation

Yousif and Nouman (1997) correlated the salt and anhydrite section penetrated in Burgan-113 Well in Kuwait with the Gotnia Anhydrite Formation in central Iraq in the Awasil-5 Well (Bellen et al., 1959). The Gotnia is equivalent to the Arab Formation in the Kingdom of Saudi Arabia (Cabrera et al., 2019).

The Gotnia Formation consists of alternating layers of cycles of salt and anhydrite units with a maximum of four cycles (Cabrera et al., 2019; Kadar et al., 2015). These anhydrite interbeds are mostly interlaminated with limestones, shales, and bituminous limestones.

The maximum thickness of the Gotnia Formation encountered in southern Kuwait in Minagish Field as it reaches 1,397 ft (426 m) thick (Kadar et al., 2015) and is thinning towards northeast Kuwait due to a gradual pinch out of the basal Gotnia units (Yousif & Nouman, 1997).

Kadar et al. (2015) couldn't date the evaporitic Gotnia and Hith Formations since they were barren of the calcareous nannofossils. However, they depend on Al-Sahlan's (2005) report based on the strontium-isotope analysis in West Kuwait, which assigned that the Hith Formation is of the approximate age of Kimmeridgian–Tithonian, and this would confine the Gotnia Formation to Kimmeridgian.

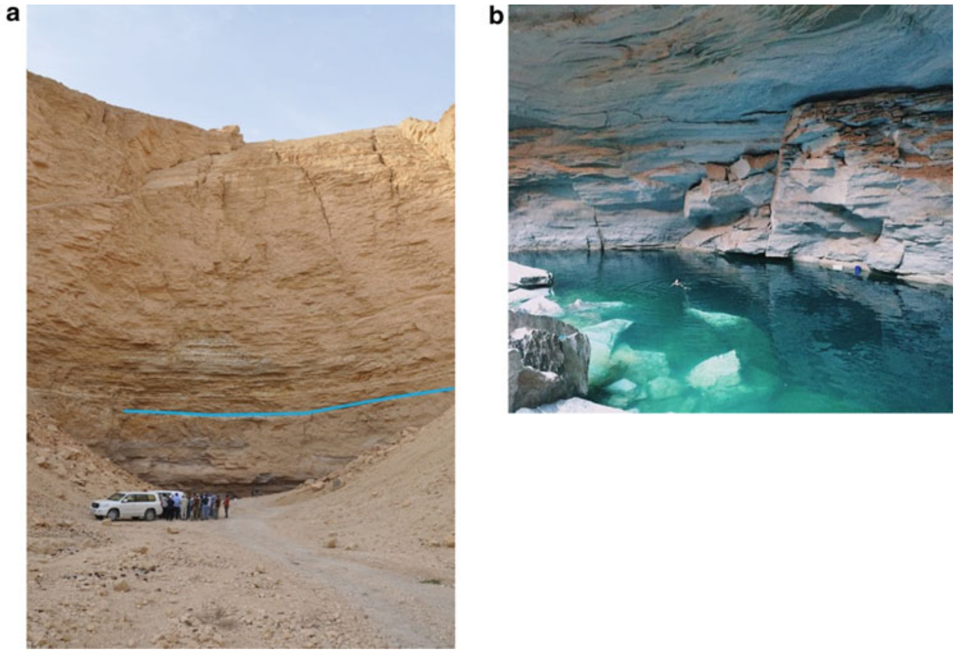
The Gotnia Formation was anticipated to be deposited in the restricted evaporitic Gotnia Basin. The basin was bordered to the south by the NE-trending Rimthan Arch, around the Kuwait–Saudi Arabian boundary (see Fig. 11 in Ziegler, 2001), and to the east by the Burgan Arch (Kadar et al., 2015; Wharton, 2017). This hypersaline environment occurred during the Late Jurassic (see Fig. 2 in Yousif & Nouman, 1997). The limestones and dolomites in the Gotnia anhydrite units are laminated to thin-bedded peloidal and microbial mudstones to packstones. Occasionally, the anhydrites conserve the geometry of stromatolites as well, suggesting deposition under more constrained conditions of a sabkha, tidal flats, or very shallow subtidal environments (Kadar et al., 2015).

Kadar et al. (2015) identified four anhydrite stratigraphic succession of the Gotnia Formation in many localities throughout Kuwait. They recognized that the basal fourth anhydrite unit characterized by microbial, evaporitic, and un-burrowed is unconformably overlain the Jubaila Formation. The upper boundary with the Hith Formation signifies the top of AP7 TMS (seventh Arabian Plate Tectonostratigraphic megasequence) (Fig. 2.1) that is defined by the widespread early Tithonian unconformity hiatus surface, which overlies the Late Jurassic evaporite deposits of the Gotnia and Hith formations (Sharland et al., 2001; Cabrera et al., 2019).

2.3.1.7 Hith Formation

The Hith Formation is the uppermost formation in the Jurassic section and the youngest member of the Riyadh group. The Hith Formation is exposed in a large anhydrite solution cavity called Dahal Heet (Dahl Hit; Ain Heet Cave), situates at the face of Mount Al Jubayl in Wadi As Sulay in a small village called Heet between Riyadh city and Alkharj, Saudia Arabia, Fig. 2.4 (Steineke et al., 1958; Powers et al., 1966; Splendid Arabia website, 2020). The cave sinkholes serve as an entrance to a large groundwater reservoir of Arab Formation (Gotnia Formation in Kuwait) that is

Fig. 2.4 Dahal Heet (Ain Heet Cave), the Blue line delineates the contact between the Hith Formation (below) and the Sulay Formation (up). Photo (**a**), the sinkhole developed due to the dissolution of Hith anhydrite and the collapse of the above Sulay (photo by Dr. Mohammad Al-Mahmood, Ex Geologist in Aramco). Photo (**b**) Copyright https://saudiarabiatours.net/trip-to-heet-cave/ showing the groundwater in Heet Cave



situated under the surface at a great depth, and it is the only place in Saudi Arabia where you can find the exposed Hith Formation (Powers et al., 1966).

Kadar et al. (2015) analyzed the core and interpreted the logs from Minagish-27 Well and described the Lithofacies of the Hith Formation; in such, it is mainly composed of interbedded massive to nodular anhydrite and peloidal to stromatolitic microbial limestones and dolomites; without salt beds and it becomes more carbonate-dominated upward. The Formation was truncated at 11,199 ft (3,413 m) depth with a thickness of 333 ft (101.5 m) in Minagish-27 Well, and it thins northward Kuwait. Hith Formation varies in thickness from 61 m (200 ft) in the North of Kuwait to 335 m (1,100 ft) in the Southwest of Kuwait. (Al-Sharhan & Nairn, 2003).

As in the case of the Gotnia Formation, the Hith Formation is also assumed to be deposited in sabkha, tidal flat, and shallow subtidal environments. (Kadar et al., 2015; Yousif & Nouman, 1997).

The contact between the Hith Formation with the underlying Gotnia Formation, as described by Kadar et al. (2015), is sharp and conformable. While the upper contact, with the Makhul (Sulaiy) Formation, is assumed unconformity, as they notice a profound shift in facies developed from the shallow, confined carbonate-evaporite cycles of the Hith Formation to deep, open-marine, basinal argillaceous mudstones interrupted by thin, probably distal turbidites that defined the Makhul Formation.

Al-Sahlan (2005) delineated the revised ages of formations using new biostratigraphic and strontium isotope data in a figure illustrating a hiatus in the Tithonian separating the Hith Formation from the overlying Makhul Formation. From Sr isotope analysis in West Kuwait, The Hith Formation was assigned an age of about Tithonian/Kimmeridgian, which would confine the Hith–Gotnia section to Kimmeridgian.

The Gotnia and Hith formations are excellent caprocks for the underlying reservoirs (Kadar et al., 2015).

2.3.1.8 Makhul Formation

The Makhul (Sulaiy) Formation was located in Makhul-1 Well of northern Iraq (Bellen et al., 1959). According to Powers et al. (1966), the formation was first defined on the stable shelf in Saudi Arabia (Al-Sharhan & Nairn, 2003). Makhul Formation is the oldest sedimentary sequence of the Thamama Group in Kuwait. The Thamama Group accommodate Makhul, Minagish, Ratawi, Zubair and Shuaiba.

The Makhul Formation lithofacies were divided by Arasu et al. (2012) into upper, middle, and lower zones. The upper zone is an argillaceous lime mudstone/wackestone, interbedded with slightly dolomitic limestone. The middle zone comprises of gray mudstone to wackestone with distinctive packstone. The lower Makhul zone host kerogen-rich layers with alternating laminae of mudstone and wackestone. Arasu et al. (2012) suggested that it can act as a source rock.

The thickness of the formation varies in different locations: in Raudhatain Field (ca. 570 ft, 173,7 m), in northwest Raudhatain Field (ca. 780 ft, 237.7 m), and Minagish Field (650 ft, 198.1 m) (see Fig. 2.2 for locations) (Kadar et al., 2015).

Kadar et al. (2015) interpreted that the Makhul Formation demonstrates a significant deepening upward setting from the Hith Formation and gradually shoals upward to the Minagish Oolite.

The Jurassic/Cretaceous (Tithonian/Berriasian) boundary positioned in the argillaceous mudstone of the Makhul Formation in the Minagish Field was deposited above the Hith anhydrite during the Late Jurassic (late Tithonian)–Early Cretaceous (Early Berriasian) (Arasu et al., 2012; Kadar et al., 2015). The upper contact with the overlying Minagish Formation is described by Kadar et al. (2015) as diachronous.

2.3.2 Cretaceous

2.3.2.1 Minagish Formation

Kuwait Oil Company adopted the Minagish Formation name concerning well Minagish-8 in the Minagish Oil Field (Fig. 2.2) (Al-Sharhan & Nairn, 2003).

The Minagish Formation is the second sedimentary sequence of the Thamama Group in Kuwait overlying Makhul Formation. It is of the Early Cretaceous age (Berriasian–Valanginian), and it was divided into three members: Upper, Middle, and Lower. The Middle Oolitic Member is the main reservoir unit capped with the Upper Member, which comprises carbonate mudstone. The lithofacies of the Middle Member base and the Lower Member are composed of fine-grained, bioturbated, peloidal lime packstones (Abdullah & El Gezeery, 2016). The thickness of the Formation in Kuwait varies from 160 m (528 ft) in the south to nearly 360 m (1,188 ft) in the north. (Abdullah & El Gezeery, 2016).

The Oolitic limestone of the Middle Member composed of peloidal, bioclastic oolitic grainstone and packstone has been deposited on a broad, prograding carbonate ramp (Nath et al., 2014). The Middle Member is confined between a hard, dense, bioclastic micritic limestone. The Minagish Formation is fossiliferous, comprising skeletal fragments, ostracods, miliolids, echinoderms, calpionellids, and benthonic foraminifera, suggesting deposition in a shallow-water carbonate shelf environment characterized by the development of ooid shoals (Al-Sharhan & Nairn, 2003).

The Minagish Formation is one of the major oil reservoirs in South Kuwait (Abdullah & El Gezeery, 2016).

2.3.2.2 Ratawi Formation

The Ratawi Formation overlies the Minagish Formation and underlies the Zubair Formation. The formation was first described in the Ratawi Field in southern Iraq. It is identified in Kuwait, Bahrain, and Qatar, and it is equivalent to Buwaib in Saudi Arabia and Habshan and Lekhwair formations in the U.A.E. and Oman, respectively (Al-Sharhan & Nairn, 2003).

There is uncertainty about the age of the Ratawi Limestone in Kuwait, but it was inferred from Abu Dhabi and Yemen regarding Maximum Flood Surface (MFS) that associated with age diagnostic fauna like the *Salpingoporella pygmaea Biozone* in the upper Habshan Formation of the United Arab Emirates (Aziz & El-Sattar, 1997) and indicates an early Valanginian age (Sharland et al., 2001).

The Ratawi formation was divided into an upper Ratawi Shale Member and a lower Ratawi Limestone Member (Ratawi Oolite), reflecting the proportion of lime mud-wackestone, calcareous shales, and marls in each unit (Al-Fares et al., 1998). The formation varies in thickness from about 951 ft (290 m) in northern Kuwait to 426 ft (130 m) in the south. The upper part shaley unit seals off significant oil and gas accumulations in the lower Ratawi limestone and the underlying Minagish limestone reservoirs. (Al-Sharhan & Nairn, 2003).

The Ratawi Shale Member host three separate sandstone beds deposited as isolated sand bodies of limited extent in a shallow-marine setting. The Ratawi limestone is poorly interbedded with dense intervals of about 20% shale and is suggested to be deposited in intra-shelf and shallow carbonate environments. (Abdullah & Connan, 2002; Al-Sharhan & Nairn, 2003). Ratawi Formation contains benthonic foraminifera, algae, calpionellids, and other skeletal fragments, suggesting deposition on a shallow marine, shelf environment (Al-Sharhan & Nairn, 2003).

The upper boundary of the Ratawi with the Zubair Formation is referred to as the “Late Valanginian Unconformity” (“LVU”). It reflects a significant stratigraphic hiatus and erosion of the late Valanginian and possibly some early Hauterivian strata (Al-Fares et al., 1998). The lower Contact with Minagish formation is less conformable, as delineated from collected well data while drilling.

2.3.2.3 Zubair Formation

The Zubair Formation was deposited with a noticeable unconformity above the top of the Ratawi Shale (Al-Fares et al., 1998). It is almost identical to the Riyadh Formation in Saudi Arabia (Al-Sharhan & Nairn, 2003), and it is roughly equivalent to the lower and middle parts of the Zubair Formation in Iraq (Al-Sharhan & Nairn, 2003; Buday, 1980).

The Zubair Formation is a significant siliciclastic wedge in the Northern Arabian Gulf zone, deposited between the Ratawi Shale and the overlying Shuaiba carbonate formations. The lithostratigraphic successions of the Barremian–Lower Aptian (Early Cretaceous) Zubair Formation thickens from south to north, and it ranges in thickness from 1,158 ft (353 m) in the south to about 1,476 ft (450 m) in the north (Al-Sharhan & Nairn, 2003; Owen & Nasr, 1958).

The Formation predominantly consists of clastic sandstone interbedded with gray to black, thin laminated siltstone, and shale. In some places, a minor amount of limestone is present at the base of the formation (Owen & Nasr, 1958; Al-Sharhan & Nairn, 2003; Nath et al., 2014).

The regional geological correlation and litho-facies investigations designate that the Zubair Formation has been deposited on a fluvial delta complex that episodically displayed an estuarine character to a coastal plain environment with more marine (deeper) influence further eastward (Al-Sharhan & Nairn, 2003; Nath et al., 2015). Abdul Azim et al. (2019) discussed the impact of the depositional environment and the sequence stratigraphy and the structure on developing Zubair reservoirs in North Kuwait.

The shale layer within the Zubair formation forms a good seal for the oil and gas reservoirs in interbedded Zubair sand units. (Al-Sharhan & Nairn, 2003).

2.3.2.4 Shuaiba Formation

The Shuaiba Formation is the youngest unit of the Thamama Group. It was deposited during the Valanginian to Aptian stages (Early Cretaceous) and extended regionally through the Arabian Gulf region (Sharland et al., 2001).

The Shuaiba Formation in Kuwait thickens towards the north from 197 ft (60 m) in the south to 262.5 ft (80 m) in the north. It comprises coarse crystalline, porous, heavily fractured, and cavernous, dolomitized limestone with rare thin shale suggested to be deposited in a low-energy, shallow, lagoonal environment during the Aptian period (Al-Sharhan & Nairn, 2003).

From field observations and the data collected while drilling (i.e., cutting samples or core data) in Kuwait oil fields, the upper and the lower contact of the Shuaiba Formation is confirmable as it is a carbonate sandwich between two clastic formations.

The Shuaiba Formation carbonates are significant hydrocarbon reservoirs in some Arabian Gulf countries (Hohman et al., 2005).

2.3.2.5 Burgan Formation

The Burgan Formation nomenclature accredits the Burgan field, the greatest oil field in Kuwait. The Burgan field was placed on an elliptical-shaped anticline dome transected by multiple radial faults.

Burgan Formation is the oldest member of the Wasia group representing the Middle Cretaceous that overlies the Lower Cretaceous Thamama Group of the Arabian plate. Wasia Group in Kuwait is constructed of six members: Burgan, Mauddud, Wara, Ahmadi, Rumaila, and Mishrif. Burgan Formation was deposited during lower to middle Albian, and it is equal to the Nahr Umr formation of southeastern Iraq (Al-Sharhan & Nairn, 2003).

As described in the Burgan field, the Burgan Formation is composed of siliciclastic sediments characterized by well-bedded, well-sorted, rounded, medium- to coarse-grained littoral sands deposited near a delta front on a gradually sinking shelf (Al-Sharhan & Nairn, 2003). Figure 2.5 represents the present-day Mackenzie delta in Canada, a possible analog to the Burgan paleoenvironment. The Burgan Formation thickness ranges from approximately

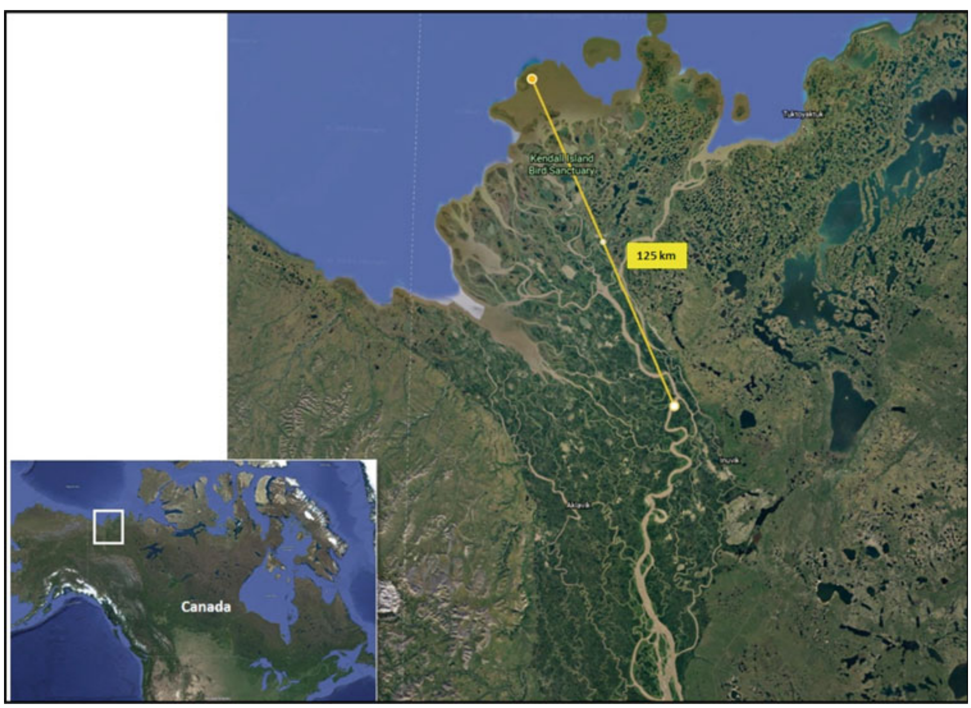


Fig. 2.5 Mackenzie delta in Canada, present-day analog to Burgan paleoenvironment (Google earth V 7.3. Mackenzie delta, Canada. 68° 51′ 11.61″ N, 134° 39′ 12.89″ W, Eye alt 265.16 miles. IBCAO 2021. https://earth.google.com [March 13, 2021])

1250 ft (380 m) at the Greater Burgan field area to nearly 900 ft (275 m) at Raudhatain and Sabriyah fields area (Bou-Rabee, 1996). It is grading upward into alternating fine-grained sandstone and siltstone. The shale is estuarine and contains abundant plant remains, Lignite, amber, and glauconite that exist all over the sequence with no foraminifera (Al-Sharhan, 1994; Brennan, 1990; Owen & Nasr, 1958).

Owen and Naser (1958) distinguished two units in the Burgan formation: the “Third” and “Fourth” Sand units. The “Third Sand Unit” (comparable to the Safaniya Member in Saudi Arabia) is approximately 476 ft (145 m) of glauconitic sand in the lower part, with an upper part of interbedded dark-gray shale. The middle section is almost pure quartz sand with very little secondary cementation and includes amber and lignite traces. The “Fourth Sand Unit” (equivalent to the Khafji Member in Saudi Arabia) has a total thickness of about 675 ft (206 m), of clean, well-sorted sand, with little secondary cementation and some traces of lignite, amber, and plant residues. Since no microfossil content in the sandstone, the Burgan Formation was dated by its apparent time equivalent with the Nahr Umr Formation in Iraq (Al-Sharhan & Nairn, 2003).

Strohmenger et al. (2006) discussed the sequence-stratigraphic framework and reservoir architecture of the Burgan and the overlying Mauddud Formation in Kuwait. The Burgan Formation is the producing reservoir in the Burgan, Ahmadi, Bahrah, Minagish, Raudhatain, and Sabriyah fields in Kuwait (Al-Sharhan & Nairn, 2003).

2.3.2.6 Mauddud Formation

The Mauddud Formation, first identified in Qatar (Sugden & Standring, 1975), is a common term used in the Middle East (Kuwait, Saudi Arabia, the UAE, and Bahrain) to the shallow marine carbonate-dominated succession resulting from the transgression that followed the deposition of the fluvial-deltaic-related clastic-dominated sediments of Burgan Formation (Cross et al., 2010).

To understand Mauddud reservoir heterogeneity, Cross et al. (2010) investigate detailed, integrated sedimentological and biostratigraphic, and dynamic reservoir data collected from Raudhatain and Sabiriyah Fields in northern Kuwait. The average thickness of the formation recorded was about 427 ft (130 m) and comprised a lower, interbedded mixed carbonate and clastic succession overlain by an upper, bioturbated carbonate-dominated interval in which oil is accumulated. The foraminifera (e.g., orbitolina seifini) recorded within Mauddud Formation as recognized by Cross et al. (2010), indicating deposition during the Middle Cretaceous of the Late Albian Age.

The hypothetical depositional model described by Strohmenger et al. (2006) for the Mauddud Formation of north Kuwait as deposition on an open, northward-deepening carbonate ramp or low-angle shelf across which there were intermittent proximal siliciclastic incursions from the retreating Burgan that inhibited carbonate productivity (Cross et al., 2010) (Fig. 2.6).

Siliciclastic incursions punctuate the lower carbonate succession of the Mauddud reservoir assumed to be deposited in a high-energy inner to middle ramp environment. Compared to the Upper Mauddud, it is deposited in low energy inner to middle carbonate ramp (Cross et al., 2010).

Significant post-depositional erosion occurs at the contact between the Mauddud carbonate and the overlying Cenomanian Wara Shale (Strohmenger et al., 2006). On the other hand, Sharland et al. (2001) documented a sharp contrast of the offshore mudrocks and the outer ramp wackestones at the base of the Mauddud Formation with the shoreface

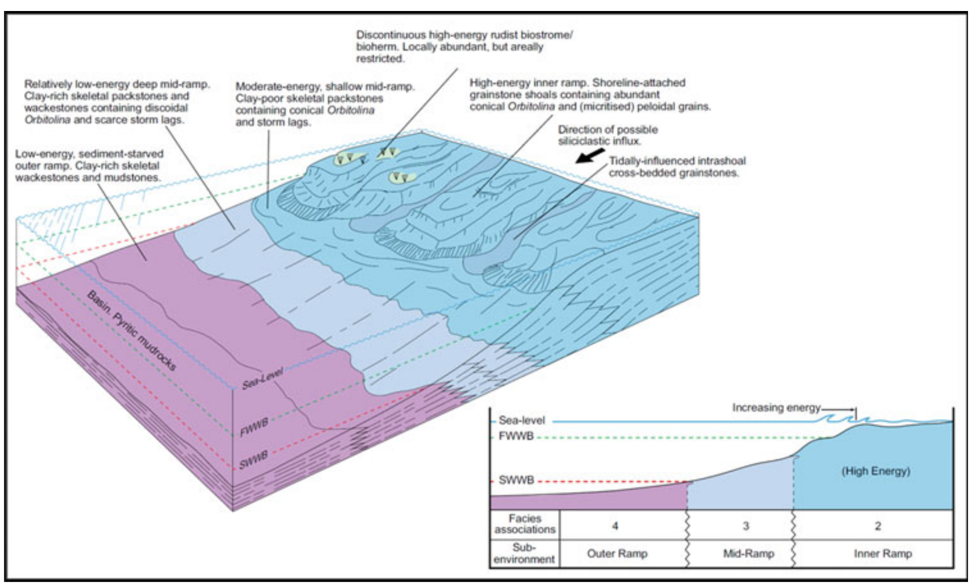


Fig. 2.6 Hypothetical carbonate ramp depositional model of Muaddud Formation in Raudhatain and Sabiriyah Fields (modified after Cross et al., 2010)

sandstones of the underlying Upper Burgan Formation that interpreted to indicate a substantial decrease in the supply of siliciclastic sediment from the Arabian Shield following the regional flooding event.

Mauddud Formation is highly affected by carbonate diagenesis, which enhances the hydrocarbon reservoir properties, especially on Kuwait's northern side. These include interparticle porosities created by allochems dissolution and fracturing (Cross et al., 2010).

The Mauddud carbonate reservoir is considered one of the primary oil producers in the domal structures of Raudhatain and Sabiriyah Fields, located in northern Kuwait (Cross et al., 2010).

2.3.2.7 Wara Formation

The Wara Formation consists of sandstone and interbedded shale. Carbonates are developed in the upper part of the formation in the north and northeast, whereas shale is dominant in the south and southwest of Kuwait (Al-Sharhan & Nairn, 2003).

The formation is a shallow marine clastic deposited in the progradation deltaic system of the offshore environment. The average thickness of Wara Formation from south to north is 151 ft (46 m)–299ft (91 m), respectively, and in the Greater Burgan Field, it ranges in thickness from 140–180ft (40–50 m) of which up to 60% of the total thickness comprises reservoir sand (Al-Sharhan & Nairn, 2003).

Palynological data helped Al-Enezi et al. (2011) reconstruct the relative sea level for the Burgan, Mauddod, and Wara Formations in the Greater Burgan field. They demonstrate that Burgan Formation was deposited during most of the Albian, whereas Mauddud is of the Late Albian age. Wara shales are early Cenomanian, while Wara sand and basal Ahmadi are of the Cenomanian age.

The Wara Formation is conformably overlain by the Ahmadi Formation, while it lies with slight disconformity on the Mauddud reservoir, forming a suitable hydrocarbon sealing rock (mudstone) (Bellen et al., 1959).

2.3.2.8 Ahmadi Formation

The transgressive Ahmadi Formation was deposited during the Early Cretaceous, Early Cenomanian age (Sharland et al., 2001). The sedimentary facies of the Ahmadi Formation were divided into discrete members, the upper and the lower. The upper member comprises clastic shale, while the lower member comprises wackestone and packstone carbonate rocks. The Lower Ahmadi carbonate is interbedded between Ahmadi shale at the top and Wara shale below (Zaidi et al., 2009). Ahmadi Formation is deposited in the middle ramp to the offshore environment. The thickness ranges from 203 ft (62 m) to 266 ft (81 m) (Al-Sharhan & Nairn, 2003).

A precise sequence boundary was identified between the non-calcareous lagoonal shale of the upper Ahmadi Formation and the highly fossiliferous, calcareous marine shale at the base of the Rumaila Formation (Youssef et al., 2014).

2.3.2.9 Rumaila Formation

Rumaila Formation is the second member of the Wasia Group deposited earlier than the Mishrif Formation. It was deposited in the Early Cenomanian age (Early Late Cretaceous). The Rumaila comprises mudstone, partially dolomitized bioclastic wackestone, calcareous shale, and marl with abundant microfossils and nanofossils (foraminifera and ostracods) (Youssef et al., 2014). The Rumaila Shale is described by Jaber (1972) as representing "the time of maximum Cenomanian transgression".

The proposed depositional environment ranges between the middle and the outer ramp with occasional inner ramp facies (Yossef et al., 2014). Correlation of the formation between the wells indicates that the thickness of Rumaila varies from 140 ft (43 m) in southeastern Kuwait to about 450 ft (137 m) in northern Kuwait (Al-Sharhan & Nairn, 2003).

The Rumaila Formation lies above Ahmadi Formation, with clear contact from non-calcareous lagoonal shale to highly fossiliferous, calcareous marine shale at the bottom of the Rumaila formation. The upper contact with Mishrif Formation was identified by the lithofacies' variation representing the difference in the deposition environments. The deeper facies of the Rumaila were marked by a much richer planktonic mudstone/wackestone. On the Other hand, the shallower facies of the overlying Mishrif Formation were observed by the recrystallization of the dominant packstone and occasional grainstone mainly enriched by praealveolinids, algal debree, permocalculus, with shell fragments, gastropods, and bivalves enriched upward with rudistid and coralline components (Youssef et al., 2014).

The Rumaila is meant to be a vital hydrocarbon seal rock in Kuwait, while the Mishrif is considered a satisfactory reservoir towards the south (Youssef et al., 2014).

2.3.2.10 Mishrif Formation

Mishrif is the youngest formation in the Wasia Group, spanning from the latest Aptian, Albian, and Cenomanian to the earliest Turonian ages of the Middle Cretaceous period (Youssef et al., 2014). The Wasia Group in Kuwait is constructed of six members arranging from the oldest to the youngest: Burgan, Mauddud, Wara, Ahmadi, Rumaila, and Mishrif. Mishrif was deposited during the Late Cretaceous, late Cenomanian, to possibly the early Turonian age (Al-Fares et al., 1998).

The Mishrif Formation is comprising mainly of bioclastic wacke/mudstone and contains various fossils, planktonic and benthonic foraminifera, ostracods, miliolids, and rudist bioherms with a chalky limestone fabric (Youssef et al., 2014; Ziegler, 2001). There is an unambiguous fossil changing upward of the Mishrif Formation. The lower Mishrif has abundant planktonic and benthonic foraminifera, while the upper part comprises many rudists and shell fragments (Yossef et al., 2014; Ziegler, 2001). This change is caused mainly by the middle ramp's regression to the inner ramp depositional environment (back reef, lagoon, and shoal) (Youssef et al., 2014).

The thickness of Mishrif is about 249 ft (76 m), and it was entirely eroded over the Burgan and Khafji–Nowruz Arches due to the pre-Aruma regional erosional surface (Al-Sharhan & Nairn, 2003; Ziegler, 2001).

The contact between the Mishrif Formation with the underlying Rumaila Formation is sharp and clear, showing regression from the deeper water facies of Rumaila to the shallower water facies of Mishrif (Yossef et al., 2014). The upper boundary marked hiatus followed marine deposits of the Mishrif Formation developed unconformity (Sharland et al., 2001). It is a tectonostratigraphic megasequence boundary (represents upper AP8) formed during Middle Turonian, causing variously erosive unconformity between the base of the Mutriba Formation and the top of Mishrif Formation Fig. (1) (Sharland et al., 2001; Ziegler, 2001; Youssef et al., 2014).

The diagenesis in Mishrif Formation has enhanced the hydrocarbon reservoir properties with vuggy porosity and fractures (Sharland et al., 2001; Youssef et al., 2014).

2.3.2.11 Mutriba

The Mutriba Formation is the oldest member of the Aruma Group in Kuwait. This group is constructed from four formations ranging from oldest to youngest as Mutriba, Sadi, Hartha, and Tayarat (Al-Sharhan & Nairn, 2003).

Mutriba consists of white to gray, dense detrital limestone, interbedded with shale horizons near its base. Lateral/geographic and vertical/stratigraphic wells correlations indicate that the formation is thinnest to the south, with thickness ranges from 928 ft (283 m) on the northern side of Kuwait to 79ft (24 m) on the southern side (Al-Sharhan & Nairn, 2003; Sharland et al., 2001).

Mutriba Formation lying above the Middle Turonian unconformity developed between the Aruma (above) and Wasia (below) lithostratigraphic groups resulting from the start of ophiolite obduction along the eastern margin of the Arabian Plate (Ziegler, 2001). This formation was deposited in the Early Cretaceous during the Santonian age. The upper Boundary with the Sadi formation is conformable.

2.3.2.12 Sadi Formation

The Sadi Formation is the second oldest Member of the Aruma Group, overlying the Mutriba Formation. Sadi Formation was deposited during the Late Cretaceous Period from the Early Santonian to Campanian age, and it lies conformably above Mutriba and unconformably overlain by Hartha Formation. The formation the thickest towards the north, from 39 ft (12 m) in the south to around 997 ft (304 m) in the north. The lithology consists mainly of fossiliferous lime mudstone interbedded with shale and dolomite (Al-Sharhan & Nairn, 2003; Han et al., 2015).

The hypothetical depositional environment of the Sadi Formation in Kuwait is correlated with that of southeast Iraq. Han et al. (2015) analyzed the characteristics and the genesis of the carbonate Sadi Formation reservoir in southeast Iraq. They found that Sadi Formation represents a third-order depositional cycle consisting of limestones and marlstones containing planktonic foraminifera and bioclastic debris as well as significantly bioturbated argillaceous rocks, believed to be deposited on a carbonate ramp setting.

Sadi and the overlying Hartha Formations are relatively shallow reservoirs that occur at depths ranging from 3500 ft (1067 m) to 4000ft (1219 m) in the southern part of the Burgan Field (Singavarapu et al., 2015).

2.3.2.13 Hartha Formation

The Hartha Formation is the third Member of the Aruma Group, on top of the Sadi Formation. There is no apparent contact between Sadi and Hartha, except that Hartha is composed of organic-rich limestone.

Hartha was deposited in the Late Cretaceous (Late Campanian to Early Maastrichtian) (Al-Sharhan & Nairn, 2003). Singavarapu et al. (2015) stated that the lithology of the Hartha Formation is limestone interbedded with shale. The thickness ranges from zero thickness over the crestal part of the great Burgan anticline to about 200ft (61 m), with a distribution that closely follows the structural trend. Singavarapu et al. (2015) assumed the depositional environment for the Hartha Formation as observed from the Minagish Field's cores to be distal inner to the middle ramp.

The formation is subdivided into three depositional units: upper, middle, and lower. The upper unit is typically composed of shaly limestone, and the middle unit is mostly wackestone to packstone in other areas. The lower unit is primarily wackestone grading upward into packstone (Singavarapu et al., 2015).

2.3.2.14 Tayarat Formation

Tayarat Formation represents the upper Cretaceous succession in Kuwait's stratigraphic column (Fig. 2.1) (Al-Sharhan & Nairn, 2003). The formations dips towards north and northeast cause variation in thickness from north to south of Kuwait, where it is around 656ft (200 m) in the south and about 1148 ft (350 m) in the north (Al-Sharhan & Nairn, 2003; Hayat et al., 2018). The Tayarat Formation in the Burgan field is roughly 800 ft (about 244 m) thick (Al-Hajeri & Bowden, 2018).

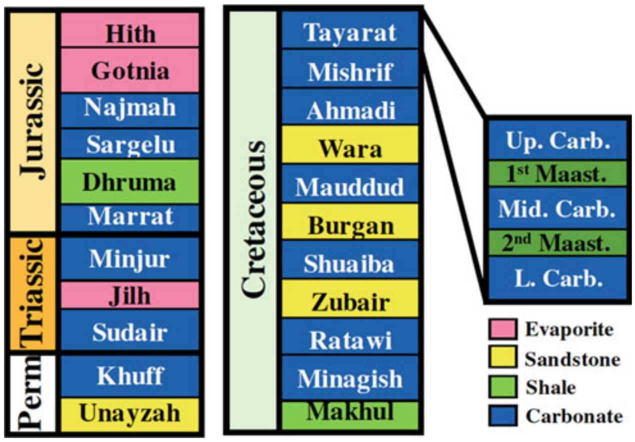


Fig. 2.7 Simplified stratigraphic column of Kuwait showing the five geological units of Tayarat Formation (After Al-Hajeri and Bowden, 2018)

Tayarat Formation is estimated to be a part of a shallow-water carbonate platform complex deposited across the Arabian Shield's interior during the late Maastrichtian stage of the Late Cretaceous (Al-Sharhan & Nairn, 2003; Dunnington, 1958; Owen & Nasr, 1958).

The Tayarat Formation comprises five geological units, three carbonate units interbedded with two thin carbonaceous shale zones, classified from top to bottom as follows: (1) the upper carbonate unit composed mainly of wackestone; (2) first Maastrichtian carbonaceous shale; (3) middle carbonate unit comprises of mudstone intercalated with wackestone; (4) second Maastrichtian carbonaceous shale; and (5) lower carbonate unit composed of packstone (reservoir pay zone), floatstones, and argillaceous floatstones intercalated with mudstones and shales (Fig. 2.7) (Al-Hajeri & Bowden, 2018).

The upper boundary of the Tayarat Formation represents the top of the tectonostratigraphic megasequence (AP9) that corresponds to the unconformity between the Mesozoic and Cenozoic. In Arabian Peninsula, this Pre-Cenozoic unconformity marks the end of the last phase of major Cretaceous ophiolite obduction along the northern plate margin and results in widespread regression (Fig. 2.1; Beydoun, 1991; Shalrland et al., 2001). Mud-logging data detected a thin shale separating the Tayarat Formation from the overlying Radhuma Formation (Taqi et al., 2018).

Tayarat and Radhuma Formations are shallow carbonate reservoirs in Kuwait (Al-Hajeri and Bowden, 2018). The Tayarat Formation truncated in the Burgan Field is highly dolomitized because of its complex depositional history and subsequent diagenetic processes (Buza, 2007).

2.4 Cenozoic

The Cenozoic Era is divided into Tertiary and Quaternary Periods; the Tertiary is classified into Paleogene and Neogene. The Paleogene is represented by Paleocene, Eocene, and Oligocene Epochs and consists of Radhuma, Rus, and Dammam Formations of the Hasa Group. The Neogene Period is designated by Miocene and Pliocene Epochs and consists of Ghar, Lower Fars, and Dibdibba Formations of the Kuwait Group.

Tertiary sediments are the primary source of usable groundwater in Kuwait. The Tertiary sedimentation began with a marine transgression in the Paleocene. Shallow marine to sabkha conditions prevailed in the area until the end of the Eocene; during this period, a carbonate-evaporite sequence (Radhuma, Rus, and Dammam Formations) was deposited (Mukhopadhyay et al., 1996).

The sea regressed at the end of Eocene, and a widespread unconformity, causing the loss of Oligocene deposits over most of the area. During this period, the karstification of the Dammam Limestone Formation produced localized accessible pathways for groundwater (Mukhopadhyay et al., 1996).

In the early Miocene, the deposition of the Kuwait Group's clastic sediments and its equivalents on the stable shelf started under mostly continental conditions. Occasional rainstorms recharge the Tertiary aquifers in Kuwait from the outcrops in Saudi Arabia and Iraq (Mukhopadhyay et al., 1996).

2.4.1 Paleogene

2.4.1.1 Paleocene

Radhuma

Radhuma Formation or Um Er Radhuma Formation (Radhuma is the commonly used name in Kuwait), named after the Umm Er-Radhuma water well in Saudi Arabia (Power et al., 1966).

Rudhuma Formation is the oldest known formation in the Hasa group. It comprises three carbonate-evaporite sequences: Radhuma, Rus, and Dammam Formations (AL-Sharhan & Nairn, 2003).

Based on carbon isotope dating, Youssef (2016) estimated that the formation is Paleocene–Eocene in age, which is confirmed by Dirks et al. (2018) and Mukhopadhyay et al. (1996). Radhuma formation is bounded by Rus Formation at the top, and it rests at erosional unconformity surface developed at the top of the Tayarat Formation. It is composed mainly of carbonate rocks, fine to coarse-grained dominant dolostone, and limestone with minor anhydrite streaks interbedded with dolostone. Shale is present at the top of the formation. In addition, lenses of lignitic, gypsiferous dolomite, and silicified anhydrite (Dirks et al., 2018; Mukhopadhyay et al., 1996; Youssef, 2016).

The formation is well developed and correlated all over Kuwait. Its thickness varies from 426 to 610 m in the North of Kuwait and shoreline areas (Mukhopadhyay et al., 1996).

Radhuma Formation was deposited in major transgression covering the Arabian Peninsula (Dirks et al., 2018). The predicted depositional environment of the Radhuma Formation is a shallow environment within an inner and middle ramp. It ranges from intertidal to supratidal and lagoon environments. There is shoals' development in some areas (Dirks et al., 2018; Mukhopadhyay et al., 1996). The fossil contents in the formation are mainly shallow-water fossils composed of mainly planktonic foraminifers, echinoderms, and Mollusca. In Sabriyah Field, some gastropods were present (Youssef, 2016).

From field observation and data collected while drilling (i.e., cutting samples or core data) in Kuwait oil fields, the contact between the Rus and the Radhuma Formations was recognized as sharp because Rus is mainly anhydrite while Radhuma is dolomite dominated. The contact between Radhuma and the underlying Tayarat Formation is sharp due to the thin shale layer present at the top of the Tayarat formation (Taqi et al., 2018).

The Radhuma Formation is considered as one of the major and significant aquafers in Oman (Mukhopadhyay, 1995) and Saudi Arabia (Dirks et al., 2018), while in Kuwait, it is not exploited (Mukhopadhyay et al., 1996). The water produced from the formation is used for agricultural and industrial use with partial domestic use but not for drinking as the salinity is high (UN-ESCWA and BGR, 2013).

2.4.1.2 Eocene

Rus Formation

Saudi ARAMCO geologist Bramkamp named Rus Formation after Um Er Rus. It is a small hill located on the southeastern flank of the Dammam dome in east Saudi Arabia (Power et al., 1966). Rus Formation was deposited during the Early Eocene, and it is dominantly evaporitic. The dominant rock type is white anhydrite and nonfossiliferous limestone with minor marls and shale. The formation thickness ranges from 450 ft (150 m) in the Northern area to 650 ft (200 m) in the offshore and southern regions (Al-Sharhan & Nairn, 2003).

The Rus Formation consists of two shallowing upward successions, each expected to represent a peritidal environment, i.e., starting with subtidal followed by intertidal and ultimately ending with supratidal setting (Tamar-Agha & Saleh, 2016).

The sharp contact between Rus and the above Dammam formation shows apparent changes from limestone to anhydrite, and this is also true for the contact between Rus and Radhuma as the lithology changes sharply from anhydrite to dolomite (Tanoli & Al-Bloushi, 2017).

Dammam Formation

Dammam Formation is the youngest carbonate unit developed in Kuwait, and it was named after the Dammam dome based in the Dammam Peninsula on the eastern side of the Kingdom of Saudi Arabia (Al-Sharhan & Nairn, 2003). In Kuwait, the upper Dammam Formation is exposed to the surface due to industrial activities in a quarry at the Al-Ahmadi area located in southeast Kuwait on the Al-Ahmadi ridge that extends parallel to the east coast of Kuwait and encounters within the Greater Burgan oil field (Fig. 2.8). On the other hand, the aquifer is exploited in the country's central and southern parts (Mukhopadhyay, 1995).

Several authors investigated the Dammam Formation in Kuwait, and they interpreted the geology, petrography, diageneses, lithostratigraphy, biofacies, geochemistry, hydrology, and the depositional history of the Dammam Formation (e.g., Burdon & Al-Sharhan, 1968; Mukhopadhyay, 1995; Al-Awadi et al., 1997, 1998a, 1998b; Mukhopadhyay & Al-Otaibi, 2002; Khalaf & Abdullah, 2015; Khalaf et al., 2018; Tanoli & Al-Bloushi, 2017).

The Dammam Formation represents the upper half of the sequence stratigraphic Palaeocene–Eocene megasequence AP10 of Sharland et al. (2001). The lower half of this megasequence includes the Rus and the Radhuma formations. Owen and Naser (1958) estimated that the Dammam Formation was deposited during the Middle Eocene Epoch. Ziegler (2001) also documented that the Dammam Formation contains nummulites and dated from its foraminiferal content as upper Ypresian to Priabonian (Middle Eocene Epoch).

The Dammam Limestone is found at depths ranging from the surface et al.-Ahmadi quarry to about 1,200 ft (366 m) in northeastern Kuwait. It dips at about 9 ft (2.7 m) per mile from southwest to northeast unless interrupted by post-Eocene structures (Milton, 1967).

The thickness of the Dammam Formation in Kuwait varies from about 492ft (150 m) in the southeast to about

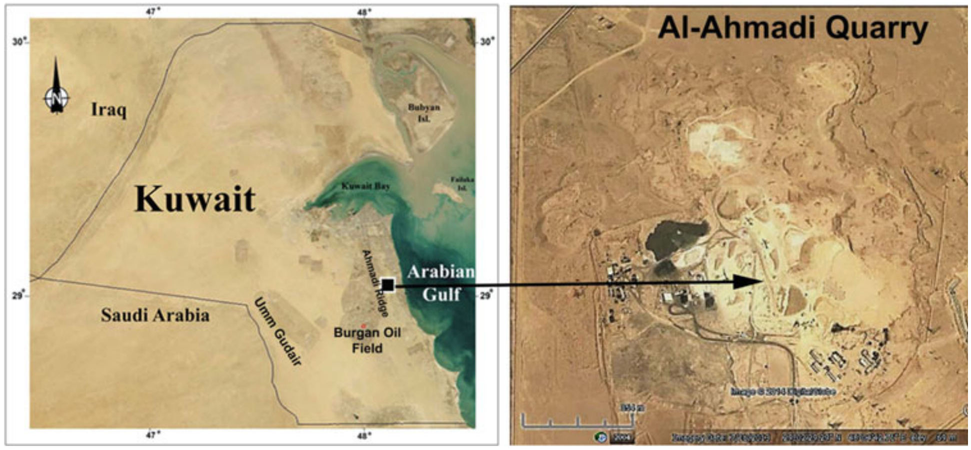


Fig. 2.8 Location map of the Al-Ahamdi Quarry (black circle) (after Khalaf et al., 2018)

902 ft (275 m) in the northeast (Khalaf et al., 2018), and it consists mainly of dolomitized limestone chalky fossiliferous limestone and shale. It is represented by cycles of limestone and dolostone. Dammam Formation was subdivided into three members based on lithology and biofacies (Burdon & Al-Sharhan, 1968; Khalaf et al., 1989; Al-Awadi et al., 1997, 1998a, b).

The upper member range in thickness between 60 and 90 m (Al-Awadi et al., 1998a, b) and consists of white, very friable, porous dolomite with thin chert lenses and nodules. This unit's top is distinct by a karstified and cherty zone below the disconformity (Khalaf, 2011). Khalaf et al. (1989) further subdivided this unit into four lithotypes, from top to bottom are (a) vuggy chertified dolomicrite, (b) dense chalky dolomicrite, (c) massive earthly dolomicrite, and (d) vuggy dolomite. Al-Awadi et al., (1998a, b) identified an abundant number of molds and casts of bivalves and gastropods, tests of foraminifera, echinoid spheres, and ostracods in this friable chalky dolomite.

The middle member ranges in thickness from 30 to 40 m and is essentially composed of laminated biomicrite, dolomicrite, and lignitic seams and lenses (Al-Awadi et al., 1998b). Khalaf (2011) subdivided this unit into six sub-members, named as follows: (1) algal limestone, (2) fossiliferous limestone, (3) dolomite, (4) dolomitic limestone, (5) lignite, and (6) dolomitized limestone. This unit is rich in elongated or round yellow crystals of phosphates (Al-Awadi et al., 1998b).

The thickness of the lower Dammam Formation ranges from 50 to 70 m, and it is mainly composed of nummulitic limestone with phosphate-rich layers of dolomite (Al-Awadi et al., 1998a, b). It was also documented by Khalaf (2011) that it consists of shale interlayers at the base and grading into fossiliferous limestone at the top. Table 2.2 in Al-Awadi et al., (1998a, b) described in detail the different biofacies that characterized the three major lithostratigraphic units of the Dammam Formation in the Umm Guadair area, located in southwest Kuwait as identified by Khalaf et al. (1989).

The Dammam sediments were assumed to have been deposited in a shallow marine inner shelf environment that has gradually become shallower with time. Regional regression and surface exposure to weathering and erosion during the Late Eocene Epoch marked the sedimentation's end (Al-Sharhan & Nairn, 2003; Al-Awadi et al., 1997, 1998 a,b; Mukhopadhyay, 1995; Khalaf et al., 2018; Tanoli & Al-Bloushi, 2017).

The dolomitic Dammam Formation is laying conformably on the anhydritic Rus Formation (Fig. 2.9), and it is capped by a paleokarstic zone delineating the regional disconformity with the overlying Ghar Formation, the oldest formation of the Neogene clastic deposits in Kuwait (Al-Awadi et al., 1998a, 1998b; Khalaf, 2011). Burdon and Al-Sharhan (1968) were the first to recognize this zone in the Al-Ahmadi quarry.

The pre-Neogene unconformity developed on the top of the dolomitic Dammam Formation was interpreted as a result of the tectonic uplift associated with the compression occurring on the northeast margin of the Arabian Plate (Goff et al., 1995). The top of the formation has pronounced karstification associated with this unconformity. The depositional history of the Dammam Formation in Kuwait is well discussed by Al-Awadi et al., (1998a, 1998b) and Tanoli and Al-Bloushi (2017).

Data yield from drilled core and cutting in Kuwait oil fields helped to specify the sharp contact between the dolomitized limestone of Dammam Formation (base of AP11) and the overlying sandstone with minor shale characterizing the Ghar formation. It is also true for the underlying Rus formation characterized by anhydrite with minor dolomite, limestone, and shale.

The Dammam limestone Formation is one of the principal aquifers of the Arabian Gulf region. In Kuwait, it is

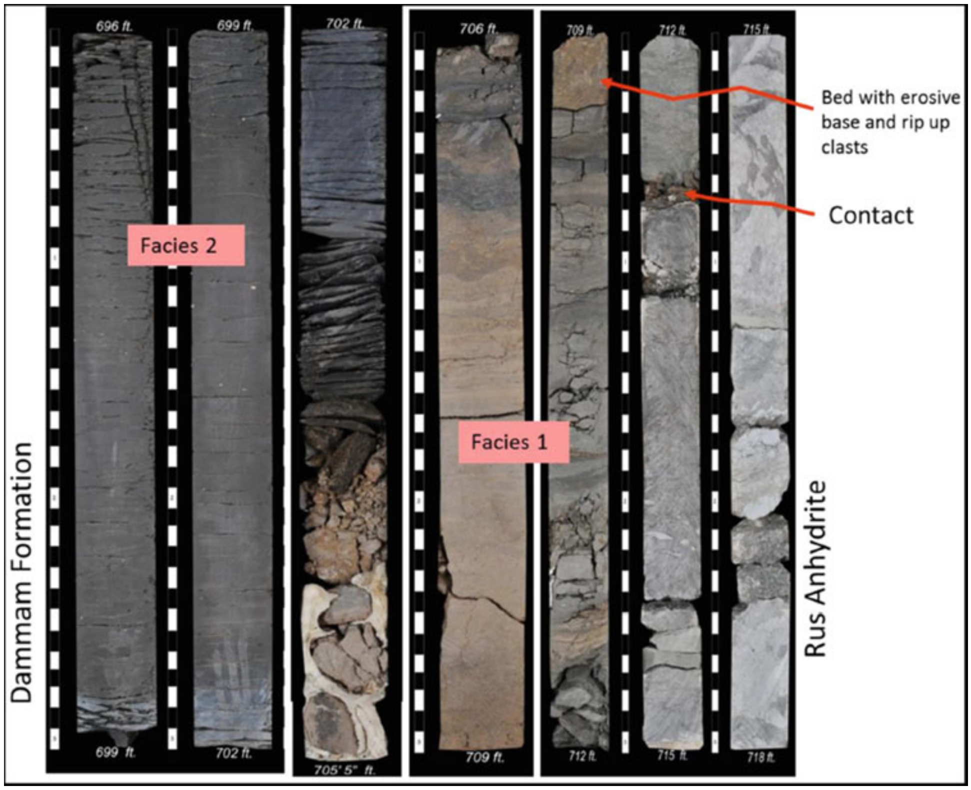


Fig. 2.9 Core Photographs under white light illustrating the sharp contact between the Dammam Formation and the underlying Rus Formation. The contact between the two formations is the red arrow at around 713 ft. From 696 ft. to 707 ft. is the Dammam gray to lack mudstone Facies 2. After that, it converts to Facies 1, which is Dammam brown limestone. Rus Anhydrite starts from 713 ft. (After Tanoli & Al-Bloushi, 2017)

considered one of the significant brackish water aquifers (Al-Awadi et al., 1998a, 1998b). This formation and the overlying the Mio-Pleistocene clastic deposits form the important aquifer system containing compatible quality of the brackish water (Khalaf, 2011).

2.4.1.3 Oligocene

The opening of the Red Sea and the Gulf of Aden in the west of the Arabian plate and the closure of the Neo-Tethys in the east of the Arabian plate begins at the late Eocene and passing through Oligocene to the present time, causes pronounced fall in the sea level to expose almost the entire Arabian Plate. A significant unconformity and sedimentary hiatus mark the boundary between megasequences AP10 and AP11 (Fig. 2.1) (Ellis et al., 1996; Sharland et al., 2001; Ziegler, 2001; Albaroot et al., 2016).

2.4.2 Neogene

2.4.2.1 Miocene

Ghar formation

Ghar formation was named after a locality in the Al-Basra area of Iraq. It constitutes the basal part of the Kuwait Group siliciclastic sequence that unconformably overly the Eocene Dammam Formation in southern Iraq and Kuwait (Owen and Naser, 1958). Power et al. (1966) correlate Ghar Formation with that of the Hadrukh Formation (Early Miocene) in Saudi Arabia, where its base also rests unconformably upon Eocene Dammam limestone. Owen and Naser (1958) accredit the Ghar Formation of Oligocene to Early Miocene in age as they only assigned its deposition time concerning stratigraphic considerations.

The Kuwait Group was subdivided into three formations in northern Kuwait, from bottom to top: Ghar, Lower Far, and Dibdibba Formations. This stratigraphic subdivision is based on the presence of the fossiliferous clay bed that correlated with the Lower Fars Formation in Iran. These beds were deposited during the Early to Middle Miocene and separated the overlying Dibdibba Formation from the underlying Ghar Formation; both comprise essentially marginal to nonmarine coarse clastics that lack age-diagnostic fossils (Owen & Naser, 1958; Milton, 1967; Picha & Saleh, 1977). In southern Kuwait, however, no such subdivision is possible, as the fossiliferous Lower Fars Formation is absent, and the Kuwait Group is defined by an undifferentiated sequence of clastic deposits (Mukhopadhyay et al., 1996).

In Bahra1 Well (Northeast Kuwait), the thickness of the Ghar Formation is 800ft (244 m) (Milton, 1967), and it is around 984 ft (300 m) in Um-Gudair (Southwest Kuwait) (Al-Rawdan et al., 1998). Al-Awadi et al. (1997) and Al-Rawdan et al. (1998) studied and identified the subsurface stratigraphy of the Kuwait Group of Miocene to Pleistocene age in different locations and linked it with the surface exposure in JalAz-zor escarpment (Northeast Kuwait). Formation boundaries were debatable because their studies lack field and fossils indicators. Milton (1967) was the first to link the lithology of an 800 ft (244 m) section characterized by subsurface Ghar formation encountered in Kuwait Oil Company Bahra 1 well with a 100 ft (30.5 m) thick sequence surface exposure in Jal Az-Zor escarpment in the Bahrah area. As discussed in the previous chapter, Khalaf et al. (2019) studied the occurrence and genesis of the exposed Oligo-Miocene Ghar Formation in Northern Kuwait.

The main composition of the Ghar Formation is clastic sequences comprising of non-fossiliferous cross-bedded, coarse-grained to pebbly sandstone intercalated with few green mud beds. These are interbedded with sandy limestone (calcareous sandstone), gypsum laminae, and minor shale (Al-Rawdan et al., 1998; Milton, 1967).

Ghar Formation was deposited in a fluvial environment characterized by cross-bedded fining-upward cycles of clastic sediments of alluvial fan and shallow marine deposition (Aqrawi et al., 2010). In the lower part, where shale is present, the proposed environment is a restricted low-energy environment (lagoonal) (Al-Rawdan et al., 1998).

The lower contact of the Ghar Formation with the Dammam Formation is unconformable, and the contact between Ghar and the overlying Lower Fars Formation is transitional and distinguished by sediment color and the presence of fossils (Owen and Naser, 1958; Al-Sharhan & Nairn, 2003).

Lower Fars

Owen and Naser (1958) referred to the Lower Fars Formation nomenclature defined from exposures in the Fars Province, southwest Iran. The formation was considered deposited during the Early to Middle Miocene age (Owen and Naser, 1958). Its age is amended in the light of more reliable biostratigraphic data from late Serravalian (12 Ma) to late Langhian (15.5 Ma) (Burdoun and Al-Sharhan, 1968; Sharland et al., 2004).

Lower Fars Formation ranges in thickness from 200ft (61 m) in the west of Kuwait to more than 600 ft (183 m) in the eastern offshore area (Al-Sharhan & Nairn, 2003). Between the depth of 345ft (105 m) to 704 ft (215 m) in the Raudhatain well No. 1 (Kuwait Oil Company), the Lower Fars Formation of 359 ft (109 m) thick was clearly identifiable. It mainly consists of anhydrites, gypsum, clays, marls, and shallow-water limestones. Remains of Ostrea latimarginata, Clausinella, and Quinquiloculina sp. were identified (Owen and Naser, 1958). Milton, 1967 and Amer et al., 2019; described facies architecture of the Lower Fars Formation exposed at the Jal Az Zor escarpment mentioned in the previous chapter.

Ferdous et al. (2013) demonstrate that Lower Fars Formation truncated at a shallow depth of less than 800 ft (244m) and extended laterally to cover a vast area in northern Kuwait. It consists of two unconsolidated sandstone units separated by a middle shale unit. Intervening siltstone and shale units commonly divide the two sandstone units into four stratified reservoir units of Upper A and B and Lower A and B zones. Each zone varies in thickness from about 10–30 ft (3–9 m).

The depositional environment is predicted based on the vertical and lateral distribution of approximately 15 different Lithofacies types. This suggests a fluvio-deltaic complex with fluvial channels delivering fresh water and sediments from the south and west to the river's mouth in the north, where they fed and formed a series of delta lobes. The northern part of this fluvio-deltaic complex has been flooded and transgressed by shallow-marine deposits on an episodic basis. These transgressive events, which were relatively short-lived, transformed the delta complex's distal parts into estuarine to shoreface depositional environments (Ferdous et al., 2013).

The contact between the Lower Fars Formation and the overlying Dibdibba delineated by 20-30 ft (6–9 m) thick shale unit, sealing the unconsolidated sandstone reservoir system of the Lower Fars. The contact with the underlying Ghar Formation is gradational (Ferdous et al., 2013).

The Lower Fars Formation is a shallow-depth, multi-stacked sandstone oil reservoir covering a vast area in northern Kuwait (Ferdous et al., 2013). It is one of the essential oil-bearing formations in Ratqa, Raudhatain, Sabriyah, Bahrah, and Mutriba oil fields (Abdul Razak et al., 2018).

2.4.2.2 Pliocene

Dibdibba Formation

Dibdibba Formation is the youngest formation of the Kuwait Group. The name of Dibdibba was first used by Macfadyen (1938) to describe superficial gravel beds deposited in southern Iraq. According to Milton (1967), the Dibdibba Formation in Kuwait comprises all beds above the fossiliferous horizon of the Lower Fars Formation, except for the Recent sediments. The exposed Dibdibba Formation in Kuwait is discussed in the earlier chapter.

The formation is of Miocene to Pliocene in age (Milton, 1967; Mukhopadhyay et al., 1996). Dibdibba Formation is underlain by Lower Fars Formation and overlain by the surface sediments in some areas where it is not exposed to the surface.

Dibdibba Formation deposition took place in an alluvial fan setting (AlShuaibi & Khalaf, 2011; Milton, 1967). The subsurface Dibdibba Formation in Kuwait can be divided into two members; the lower member is of Mio-Pliocene age and consists of coarse-grained, poorly sorted gritty, and pebbly sandstone lithified by chalk and carbonate cement. The upper member is of the Plio-Pleistocene age and composed of gravelly sand and sandy gravel. Gypsiferous is a common cement, while calcareous cement is limited (Owen & Naser, 1958; Mukhopadhyay et al., 1996). The gravels deposited in sheets and trains originated from igneous and metamorphic rocks derived from Najed, Al-Hijaz, the Syrian Desert, and Northern Arabia. There are no index fossils documented in Dibdibba Formation (Owen & Naser, 1958; Milton, 1967 and reference therein; Picha & Saleh, 1977).

The contact with the underlying Lower Fars formation is gradational. The sand and gravel beds of the Dibdibba Formation are capped by coarse pebbles of rounded igneous, metamorphic, or sedimentary dreikanter (three-edged) shaped deposited on a typical desert floor (Owen & Naser, 1958). As mentioned earlier, in southern Kuwait, the fossiliferous Lower Fars Formation is absent, and the Kuwait Group is defined by an undifferentiated sequence of clastic deposits (Mukhopadhyay et al., 1996).

In northern Kuwait, the contact between Dibdibba and Lower Fars is sharp due to the presence of a 20–30 ft (6–9 m) thick shale at the base of the Dibdibba Formation, forming a regional barrier and a sealing unit for the shallow Lower Fars reservoir system (Ferdous et al., 2013).

A well drilled to approximately 100 ft (30.5 m) in northern Kuwait during 1960 and found an accumulation of potable water in the Dibdibba Formation. This well was drilled in a topographical low west of the Raudhatain oil field where the Raudhatain anticline has changed the regional dip (Milton, 1967).

2.4.3 Quaternary

2.4.3.1 Recent Sediments (Surface)

The Quaternary deposits in Kuwait are discussed in the previous chapter as part of the surface sediments of Kuwait, it characterized by an abundance of gravel. Dibdibba is the most extensive occurrence of these Quaternary gravels. The Dibdibba Formation covers most of the northern area of Kuwait (Al-Sulaimi et al., 1997). The exposed sediments in the surface of Kuwait are dated from the Early Miocene to recent (Milton, 1967). These surface deposits have two major environments: desert-related depositions and costal related depositions (Al-Hurban, 2016).

2.5 Summary and Conclusions

This chapter presents informative information in a simple geological expression to entice geoscience educators to develop their knowledge in understanding subsurface geology and paleoenvironments that once dominated Kuwait's geologic past.

The subsurface stratigraphy of Kuwait introduced in this chapter, adopted published reports, conference proceeding articles, and research papers associated with the geological descriptions of the Phanerozoic succession of Kuwait and neighboring countries (Saudi Arabia, Iran, and Iraq). Those publications are based on oil industry activities, groundwater aquifer research, and linking surface exposure outcrops of some stratigraphic Formations to subsurface analog.

Most lithostratigraphic Formations in Kuwait consisted of carbonate rocks deposited in a shallow water environments through the Phanerozoic succession. Exception goes to Lower Cretaceous, where the deltaic system dominated the area and deposited clastic sediments. One of the significant challenges in this chapter is the lack of publication for non-hydrocarbon, non-aquifer, and deeper Formations.

Understanding all possible integrated geologic characterization and features enabled many researchers to interpret Kuwait's surface and subsurface lithological strata and understand past geologic events, such as sea-level fluctuation, climate changes, and tectonic events. Accordingly, paleoenvironments and depositional history were reconstructed, and a successful Kuwait stratigraphic column was established.

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