1 Surface Geology of Kuwait

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Abstract

This chapter represents a comprehensive review of Kuwait's surface geology and stratigraphy from previous works accomplished by numerous geoscience researchers in the past decades. The surface of Kuwait is characterized by nearly flat topography, featureless to gently undulating, apart from a few tens of meters of escarpments in the north and south, and flat low to moderately elevated hills and ridges. It predominantly consists of siliciclastic sediments and sedimentary rock units ranging in age from Middle Eocene to Holocene. The main stratigraphic exposed successions are located in Jal Az-Zor escarpment, Al-Subyiah (Bahrah) area, Ahmadi Quarry, the Khiran Ridges, and the Enjefa Beach. The oldest exposed rock units are represented by the Middle Eocene Dammam Formation, which is exposed at the Ahmadi Quarry, whereas the youngest recent deposits cover most of Kuwait's surficial area and lie on top of the Kuwait Group's deposits. This chapter will illustrate the geology and stratigraphy of Kuwait's surface sediments and sedimentary rock strata. Recommendations and future insights were also documented as part of the way forward to improve the presently available work for the surface geology of Kuwait.

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1.1 Introduction

The surface geology of Kuwait is dominated by the presence of flat to near-flat, featureless to gently undulating, sands and gravels covered deserts with few low to moderately elevated hills and ridges (Al-Awadi et al., 1997; Khalaf et al., 1984). These elevated hills and ridges are in both northern (e.g., Jal Az-Zor Escarpment and Al-Subyiah Ridges) and southern (e.g., the Ahmadi Quarry and the Khiran Ridges) parts of Kuwait (Al-Awadi et al., 1997; Khalaf et al., 1984). Kuwait's surface and near-surface deposits are dominated by siliciclastic sediments and sedimentary rock units, with some carbonate deposits in the southern regions. The age of these deposits ranges from Middle Paleogene (Middle Eocene) to Quaternary (recent/Holocene) (Milton, 1967). The oldest exposed rock units are represented by the Middle Eocene Dammam Formation, which is exposed at the Ahmadi Quarry, whereas the youngest recent deposits cover most of Kuwait's surficial area and lie on top of the Kuwait Group's deposits (Milton, 1967).

This chapter will illustrate the geology and stratigraphy of Kuwait's surface sediments and sedimentary rock strata. The description of the sedimentary rock units within outcrops of Jal Az-Zor escarpment, Al-Subyiah (Bahrah) area, Ahmadi Quarry, the Khiran Ridges, the Enjefa Beach, along with the surface sediment cover of Kuwait will be demonstrated in the subsequent sections (Fig. 1.1).

1.1.1 Regional Geological Setting and Surface Stratigraphy of Kuwait

Kuwait is located in the northeastern part of the Arabian Plate, particularly on the eastern flank of the Arabian Platform. The platform consists of a thick sequence of siliciclastic and carbonate sedimentary rock strata deposited on top of the Arabian Shield basement rocks. These rock units within the platform are gently dipping 1–2 degrees toward

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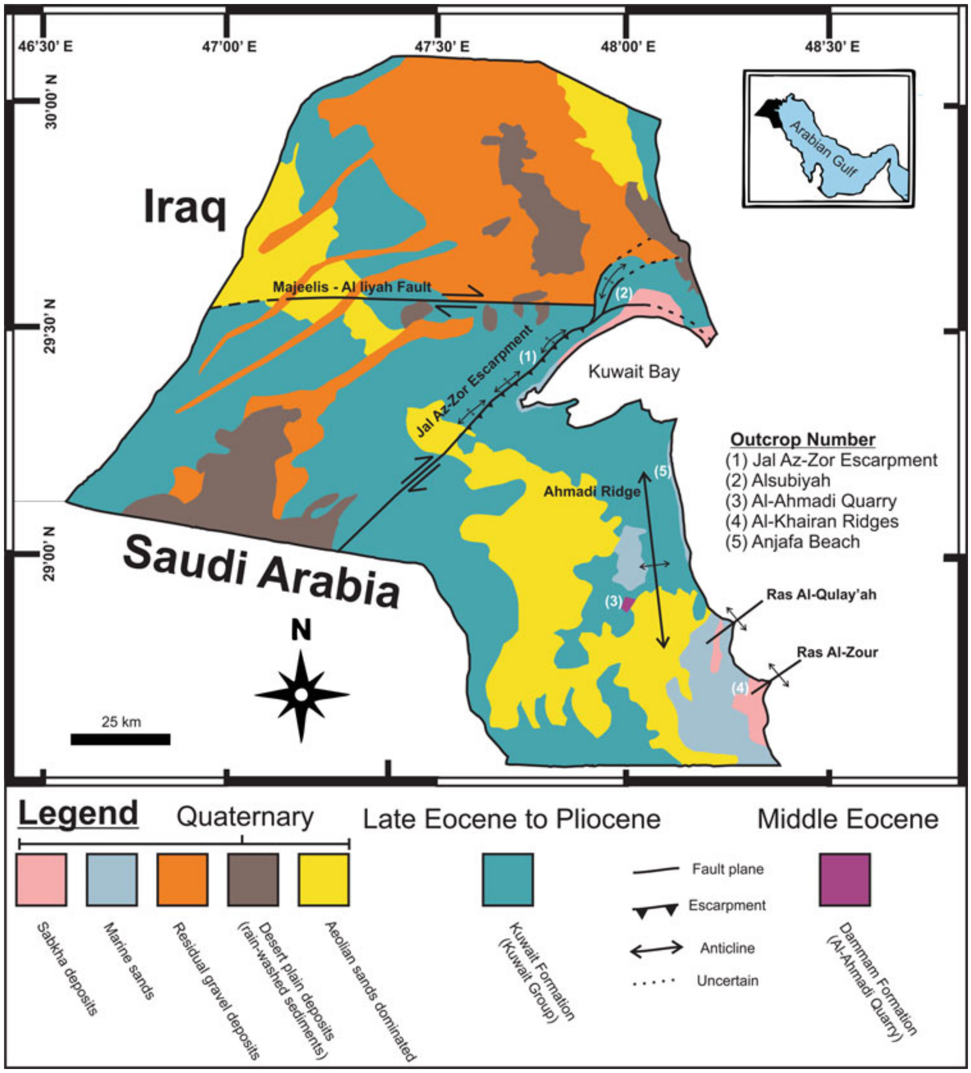

Fig. 1.1 Surface geologic map of Kuwait showing the age and location of outcrops and sediment cover (Modified after Khalaf et al., 1984 and Amer & Al-Hajeri, 2020)

the northeast and thicken further away from the Arabian Shield towards the Zagros Mountains to the East (Owen & Nasr, 1958). The exposed units of this sequence in Kuwait are represented by the carbonate Middle Eocene Dammam Formation and the clastic Oligo-Pleistocene to the recent Kuwait Group (Owen & Nasr, 1958; Amer & Al-Hajeri, 2019). The Dammam Formation is mainly composed of carbonates with evaporites, shale deposits, and minor chert (Al-Awadi et al., 1997). The uppermost portion of the formation is exposed at the Ahmadi Quarry. The Kuwait Group overlies the Dammam Formation unconformably. This Group is dominated by clastic deposits that range in age from the Early Oligocene to Pleistocene (Amer & Al-Hajeri, 2019). The Kuwait Group is divided into three major formations—from oldest to youngest—the Ghar Formation, the Lower Fars Formation, and the Dibdibba Formation (Owen & Nasr, 1958). The Ghar Formation is believed to be exposed et al.-Subyiah (Bahrah) area, whereas the Lower Fars and Dibdibba Formations are exposed at Jal Az-Zor and as surface sediment cover.

One of the earliest geological reports about Kuwait was by Gregory (1929), where he briefly discussed the Fars Group and the Euphrates limestone in neighboring Iraq. At this time, as the Arabian Gulf and the Persian region became an active area for oil exploration, several attempts by surface geologists were increasingly reported to be the first to discover oil in the area. Following Gregory, several research and studies were conducted by Cox and Rhodes (1935), Own and Nasr (1958), Milton (1967), Fuchs et al. (1968), and Salman (1979). Another phase of research and studies was started in the 1980s by Al-Sarawi (1982) and Khalaf et al. (1984). From the 1980s, we can notice a gap in the research related to Jal Az-Zor in particular, while regional studies emerged such as Ziegler (2001) and Sharland et al. (2004) for the whole Arabian Gulf regional geology. These studies were important in the context of understanding the tectonostratigraphic evolution. During the last 5 years, several attempts by geologists from oil companies to study the escarpment resulted in a few important publications such as Tanoli et al. (2015), Amer et al. (2017, 2019a), Benham et al. (2018), Amer and Al-Hajeri (2019), and Tanoli et al. (2019).

Gregory (1929) mentioned that within Kuwait, the presence of horizontal beds that have been described as the Kuwait series with little to be known about the age of such beds. It was concluded that nothing was known about the age of these rock units. The first stratigraphic work conducted over the area was by Owen and Nasr (1958). In this work, the authors introduced for the first time the term "Kuwait Group," and they divided the group into Ghar, Lower Fars, and Dibdibba formations. Owen and Nasr (1958) described the Ghar Formation as sands associated with subordinate gravels and occasional clays. The Lower Fars Formation was described as an evaporitic sequence characterized by anhydrite, gypsum, marls, and shallow-water limestones. The Dibdibba Formation represents the third Kuwait Group unit, and it is composed of sands, gravels, and subordinate marls. The age range given to the Kuwait Group by these authors was Miocene to Pleistocene (Owen & Nasr, 1958). The name "Dibdibba beds" was first used by Macfadyen (1938) in Iraq. The terms of Kuwait Group and it is subunits are informally used by Kuwait Oil Company in the subsurface. Tanoli et al. (2015) described the Ghar and Lower Fars formations of the Kuwait Group to have identical lithologies.

The Kuwait Group formations of Ghar, Lower Fars, and Dibdibba, as later adopted by Bergstrom and Aten (1965), focused mainly on groundwater, but no attempt to date the formations were made. Khalaf and El-Sayed (1989) studied the western part of the Jal Az-Zor escarpment with two cores from boreholes drilled, one at the top and the other at its foot focused on the calcrete development and types within the Dibdibba units. Salman (1979), in his Kuwait University Master thesis, suggested significant changes to the Kuwait Group nomenclature: it was the first time the Oligocene was introduced to Kuwait, where Ghar Formation was deposited. The Lower Fars Formation was divided into Mutla and Jal Az-Zor, extending from the Miocene to Pliocene. The Dibdibba Formation was of Pleistocene in age. This nomenclature was not popular, except for the partial utilization by Al-Awadi et al. (1997).

Fuchs et al. (1968) identified the boundary between Lower Fars and Dibdibba formations based on heavy minerals content and a lithostratigraphic correlation between the Lower Fars Formation in Kuwait with the Fars Group in Iran. Fuchs et al. (1968) described a 1–2 m thick fossiliferous layer at the base of Jal Az-Zor escarpment that contains *Ostrea Lamimaginula* and *Clausinella*. They suggested that this unit belongs to the Late Miocene based on this biostratigraphic contents.

A radiometric isotope age dating work carried out by Amer and Al-Hajeri (2019) of oyster shells from the same bed indicated that they are Burdigalian in age (Early Miocene). Moreover, recent research by Amer et al. (2019a) found that the heavy minerals in this unit are not sufficient to differentiate between Lower Fars and Dibdibba formations. The chemostratigraphic sedimentary provenance study work done by Amer et al. (2017) compared sediments of Jal Az-Zor to the Arabian Shield in Saudi Arabia and concluded that the source of sediments was identified to come from the ophiolite basaltic and andesitic outcrops along an area known as Darb Zubaydah in the Arabian Shield.

In 1996, a newly adopted stratigraphic chart was published by Mukhopadhyay et al. (1996), suggesting an overall Miocene to Pleistocene age for the Kuwait Group. However, the Lower Fars Formation was restricted to the Middle Miocene, and the Dibdibba Formation was extended Late Miocene. The area's stratigraphy was yet again on an appointment to change with the work of Al-Ameri et al. (2011), Duane et al. (2015). following the work of (Sharland et al., 2004). These two authors suggested no erosion at the top and base of the Lower Fars Formation, and they presented a stratigraphic scenario similar to Mukhopadhyay et al. (1996). The only difference was slight variations in age suggested for Dibdibba Formation with no apparent justification.

Prior to this time, all attempts have been primarily based on lithostratigraphic correlation to neighboring Saudi Arabia, Iraq, and Iran. Tanoli et al. (2019) attempted to refine the age and nomenclature of the Lower Fars Formation based on subsurface core analyses. They suggested replacing this formation name with Jal Az-Zor Formation, and based on biostratigraphic taxonomic groups, the age was determined to be late Burdigalian–early Langhian (Early to Middle Miocene). However, though the Lower Fars Formation naming has been suggested to change to Jal Az-Zor Formation, neither correlation nor analysis was performed on the Jal Az-Zor exposure, and all the analysis was mainly focused on five wells drilled in the subsurface north Kuwait. Furthermore, some of the fauna presented had a long taxon ranging, making the ages define uncertain, and the upper and lower boundaries of the proposed Jal Az-Zor Formation were left undefined, adding additional perplexity to an already equivocal nomenclature.

Amer and Al-Hajeri (2019) proposed utilizing numerical radiometric dating of strontium isotope ratio ($^{87}Sr/^{86}Sr$) over subsurface and surface exposures of Kuwait. The researchers collected samples along the Jal Az-Zor escarpment near Mutla and Sabriyah roadcut, and from the subsurface, by sampling core data from a well drilled in north Kuwait. They used the global strontium isotope seawater curve of Veizer et al. (1999) to determine the exact age of the Kuwait Group. They found that the age ranged from Priabonian to Burdigalian (Late Eocene to Early Miocene). These workers did not exclude the middle and late Miocene from the Kuwait Group, as the upper section of the drilled well was not possible to core, and the upper section of the Jal Az-Zor escarpment was not fully covered in their novel study. This work suggests that the Oligocene in Kuwait is not eroded or non-deposited as previously thought (Mukhopadhyay et al., 1996; Sharland et al., 2001, 2004; Ziegler, 2001; Al-Ameri et al., 2011; Duane et al., 2015; Tanoli et al., 2019). Consequently, the tectonostratigraphic evolution of the area will need to be reassessed to accommodate such findings (Fig. 1.2).

Furthermore, Amer and Al-Hajeri (2019) presented a 2D seismic section acquired along the drilled well and the Jal Az-Zor escarpment that was interpreted after a well-to-seismic tie. This work included the incorporation of the outcrop exposed rocks at the Jal Az-Zor, and the analysis showed a unique perspective on the relationship between surface and the subsurface age equivalent units (Fig. 1.3). Based on this work, Amer and Al-Hajeri (2019) suggested renaming the undifferentiated Kuwait Group of Owen and Nasr (1958) to the Kuwait Formation, eliminating the equivocal tripartite subdivision believed to be inadequate to Kuwait.

1.2 Surface Recent (Holocene) Sediment Cover of Kuwait

These surficial deposits of Kuwait have two major depositional environment settings: desert-related depositions or coast-related depositions (Khalaf et al., 1984). Khalaf et al. (1984) have divided Kuwait's deserts into four physiographic regions: Al-Dibdibba gravel (Northern Kuwait), the sand flat area (Sothern Kuwait), the coastal flat (southern Kuwait), and the coastal hills at Jal Az-Zor at North and the Ahmadi Ridge in the South of Kuwait.

In the North of Kuwait, the surface sediments are mainly siliciclastics that vary in size from gravel size to very coarse to pebbly sand size (Khalaf et al., 1984). These sediments are derived and transported from the Hejaz mountains in the western parts to the eastern parts of the Arabian Plate by flooding events at Wadi Al-Batin (Khalaf et al., 1982). In the South of Kuwait, sediments are mainly sand to mud-sized and rich in carbonate deposits. The finer sizes in the southern

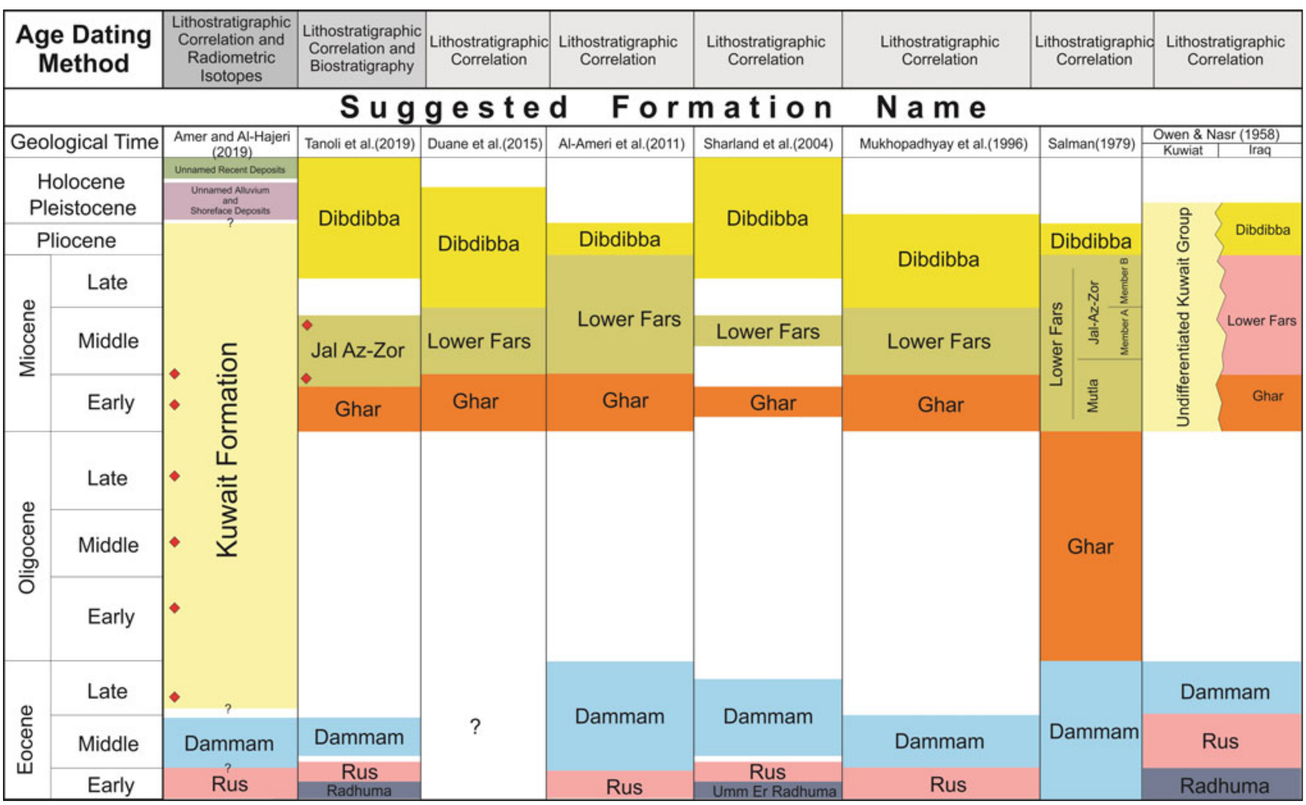

Fig. 1.2 Stratigraphic chart compilation over Paleogene-Neogene section in Kuwait. The color scheme is as follows; (light, dark yellow, orange, light gold) clastic dominated; (purple) evaporites; (light and dark blue) carbonate. Red diamond symbols indicate zones of age control by the respective authors

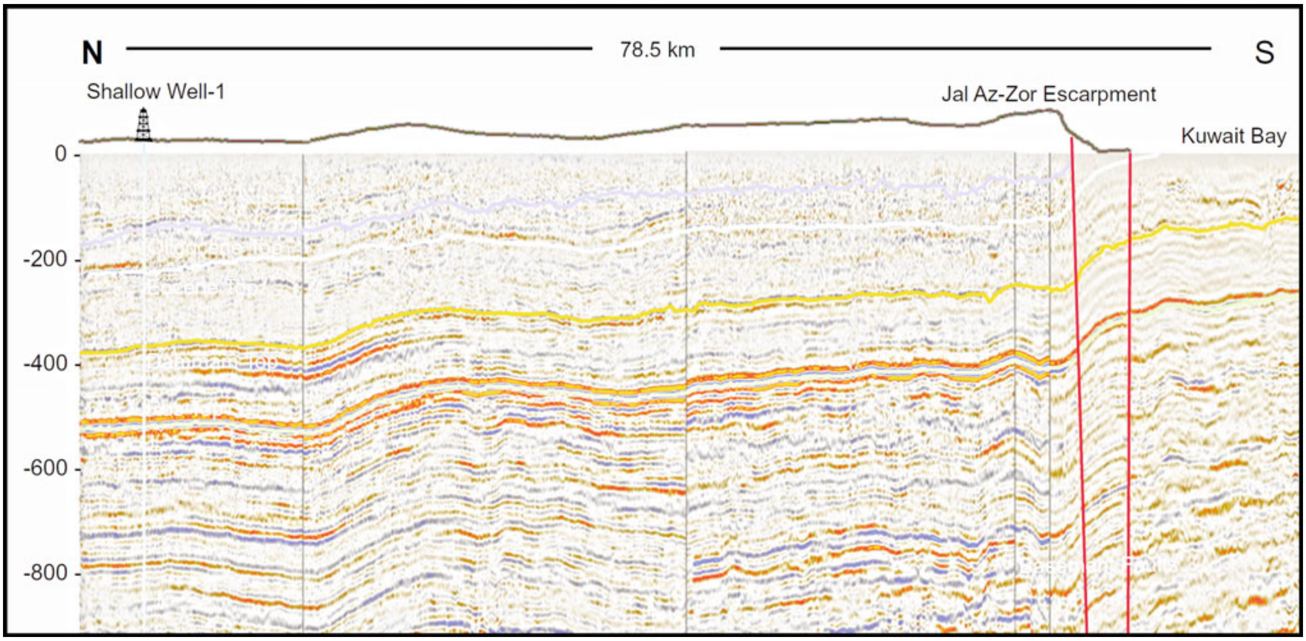

Fig. 1.3 Arbitrary 2D seismic line crossing a radiometrically sampled well in north Kuwait and the dated section of the Jal Az-Zor escarpment. The interpretation shows that the Oligocene is outcropping at the foot of the escarpment. Displayed scale in (ms). (After Amer & Al-Hajeri, 2019)

parts of Kuwait are believed to result from the flood's energy decreasing southward (AlShuaibi & Khalaf, 2011). The sediments at the southern coasts of Kuwait are also characterized by modern carbonate deposits of oolite, dolomite, and microbial mats (e.g., Al-Khiran and Azzor areas) (Gischler & Lomando, 2005). Khalaf et al. (1984) subdivided these surface deposits into six classes based on their characteristics and mode of occurrence, which are aeolian and sand deposits, desert plain deposits, residual gravel deposits, playa deposits, coastal deposits, and slope and alluvial fan deposits. The aeolian and sand deposits are sand sheets, sand dunes and drifts, and wadi fill. They cover more than 50% of Kuwait's surficial area (Al-Sulaimi & Mukhopadhyay, 2000; Khalaf et al., 1984). The desert plain deposits are Holocene aged of various grain sizes laid down in shallow and broad depressions by running rainwater. They can be found in scattered fields in the northern and western areas of Kuwait. The residual gravel deposits consist of various grain sizes, from gravel to clay. They were formed due to wind deflation of the Dibdibba deposits where fine-grained sediments were removed, leaving behind the larger and heavier grains as a desert pavement layer. These deposits are mainly found in the northern areas of Kuwait.

The playa deposits are mainly associated with drainage systems in the northwestern deserts of Kuwait (Al-Sulaimi & Mukhopadhyay, 2000). They can be found in low areas and depressions seasonally filled with rainwater forming ephemeral lakes. Sediments that fill those playas are believed to be transported and deposited by running water from the drainage systems within the area. The coastal deposits are found along Kuwait's shoreline, and they are represented by the coastal dunes, coastal plains, beaches, tidal flats, and sabkha deposits. They mainly consist of siliciclastics, carbonates, and evaporitic deposits. The slope and alluvial fan deposits can be found at the foothill of the relatively steep slope hills and escarpments of Jal Az-Zor, Al-Subyiah, Al-Ahmadi Ridge, and Wadi Al-Batin (Khalaf et al., 1984). They consist of a mixture of coarse- and fine-grained sediments with an abundance of calcareous boulder-sized blocks that fell down-cliff due to gravitational force.

1.3 Jal Az-Zor Escarpments

The Jal Az-Zor escarpment represents the most pronounced and studied exposure over the surface geology of Kuwait (Fig. 1.4). The stratigraphic successions of the Jal Az-Zor escarpment are predominantly comprised of siliciclastic deposits. It extends for almost 60 km with a cliff-like face of about 36 m from the escarpment base (Amer et al., 2019a) and reaches up to 135 m from the mean sea level (Al-Sarawi, 1982). It exhibits a predominant NE-SW trend as a result of deep-seated basement faults (Own & Naser, 1958, Fuchs et al., 1968; Bou-Rabee & Kleinkopf, 1994; Al-Anzi, 1995; Singh et al., 2011; Amer et al., 2017; Amer & Al-Hajeri, 2020). The importance of this fault is discussed in the structural geology chapter.

Fig. 1.4 A section of the Jal Az-Zor Escarpment showing a few exposed lithofacies

1.3.1 Stratigraphic Successions of Jal Az-Zor Escarpment

The stratigraphic successions of Jal Az-Zor escarpment were recently studied intensively by researchers in the last five years, from sedimentology to stratigraphy up to conceptual depositional models. Amer et al. (2019a) introduced a detailed sedimentological description, analysis, facies, facies association, and conceptual depositional setting of the Jal Az-Zor stratigraphic successions. The study used a descriptive approach to the main units, both laterally and vertically, as several traverses were conducted in different locations. Though, the limitation of the exposed rock as well as the accessibility led to combining the stratigraphic successions in one composite stratigraphic column of the area. The study was described and interpreted at the main location (764,249.00 m E, 3,260,452.00 m N) and concluded the facies into 16 genetically related facies and six facies associations (Table 1.1). The six facies associations are an estuarine complex, tidal channel complex, shoreface complex, terrestrial facies, barrier island complex, and back-barrier complex.

The paleocurrent analysis of these genetic-related facies and facies associations measured by Amer et al. (2019a) indicates that the axis of the estuary, tidal, and fluvial channel systems is towards the NE direction suggesting an NW–SW paleoshoreline at the time of deposition. The produced facies model demonstrates a complex architecture that can be expressed in the lateral and vertical facies changes (Fig. 1.8).

The main facies, facies association, and depositional setting of the stratigraphic units described at the Jal Az-Zor escarpment presented herein are adopted after Amer et al. (2019a). The briefed description of these facies recognized are:

1. *Bioturbated cross-bedded facies*:

It is observed as the basal unit of most sequences over the Jal Az-Zor escarpment. It occurs in 1–3 m thick units characterized by large-scale low-angle cross-bedding, poorly sorted calcareous sands with the presence of granules and pebble grain sizes. It contains a high level of bioturbation, which is considered the main characteristic of this unit, dominated by Thalassinoides, Skolithos, Ophiomorpha, and less common Gyrolithes. XRD analysis of samples taken from these units suggests that the rocks are composed of 46% quartz, 20% illite, 27% muscovite, and 7% calcite.

2. *Cross-bedded conglomeratic facies*:

These facies form large concave lenses, trough cross-bedding, with the absence of bioturbation activity; those are generally sandwiched between the highly bioturbated cross-bedded facies. The presence of these facies is very localized within the studied area. It is characterized by an erosional base with a relatively flat top.

3. *Red claystone facies*:

Bedded, reddish-to-pinkish color with absence of bioturbation. The thickness of this unit can reach a maximum of 1.5 m, and dramatic vertical and lateral changes in facies do occur. In some locations, they tend to change into yellowish-green claystone facies. Tracing these facies over a short distance reveals that it changes laterally over a short distance. The XRD analysis resulted in quartz that reaches 48%, followed by muscovite representing 28.5%, illite 23%, and calcite 0.5%.

Table 1.1 Facies, facies associations, and proposed depositional setting observed in the Jal Az-Zor escarpments (Amer et al., 2019a)

Facies association	No	Facies	Abbreviation	Depositional environment
FA-1 Estuarine complex	1	Bioturbated cross-bedded facies	(F1)	Estuarine central bay (channel bar)
	2	Cross-bedded conglomeratic facies	(F2)	Estuarine channel fill
	3	Red claystone facies	(F3a)	Distal Estuarine intertidal flat
	4	Reddish-green claystone facies	(F3b)	Proximal Estuarine intertidal flat
	5	Calcareous sandstone facies	(F4)	Estuary mouth bar (shoreface/inlet shoal)
FA-2 Tidal channel complex	6	Cross-bedded sandstone facies	(F5a)	Tidal channel fill
	7	Lateral accretion red sandstone facies	(F5b)	Tidal channel point bar
	8	Bedded red muddy sandstone facies	(F5c)	Tidal channel overbank
FA-3 Shoreface complex	9	Fine-grained bedded sandstone facies	(F6b)	Foreshore
	10	Microbialites facies	(F6c)	Intertidal to supratidal
FA-4 Terrestrial facies	11	Yellowish-green siltstone facies	(F8)	Fluvial overbank
	12	Trough cross-bedded sandstone facies	(F7)	Fluvial channel fill
FA-5 Barrier island complex	13	Coarsening-upward calcareous sandstone	(F9)	Barrier island
	14	Fossiliferous sandstone facies	(F6a)	Fossiliferous shoal
	15	Microbialites facies	(F6c)	Intertidal to supratidal
FA-6 Back-barrier complex	16	Unconsolidated silty-sand facies	(F6d)	Backshore/berm
	17	Calcareous sandstone lenses	(F10)	Shoal inlet
	18	Yellowish-green siltstone facies	(F8)	Back-barrier lagoon
	19	Microbialites facies	(F6c)	Intertidal to supratidal

4. *Reddish-green claystone facies*:

These facies are characterized by the yellowish-green color of clay grain size sediments with the likelihood of silts towards the top. The thickness of this unit can reach 1.5 m. They are laterally changing into the Red claystone facies. Water escape structures were observed towards the top of the section. It has an erosional surface at the top where Ophiomorpha is observed to burrow from the overlaying Calcareous sandstone facies. The XRD analysis of one sample taken shows that these facies exhibit a similar mineralogical composition to red claystone facies with the addition of nimite that belongs to the chlorite group and represents 25%.

5. *Calcareous sandstone facies*:

These facies are the major occurrence and distinctive in the exposed successions; hence, it is the cliff-forming units in the Jal Az-Zor area. It is characterized by an amalgamated blocky pattern of poorly sorted calcareous sandstones to gravelly sandstones. It is associated with faint cross-bedding, scouring bases, and channeling features. It has various thicknesses across the escarpment with an average of 4 m. Grain size is dominated by medium-grained sands that vary from fine to very coarse, and in some cases, granules form thick layers. Reworked lithoclasts and bioclasts are abundant towards the base; those degrade and fade upwards. Faint Bioturbation is presently represented by Skolithos burrows towards the base and midsection, whereas Ophiomorpha is common towards the top. The XRD analysis of seven samples revealed an average of 38% calcite, 37% quartz, 20% muscovite, and 5% illite. It is believed that most of the calcite is related to the cement between the quartz grains, which might be the reason for extreme hardness.

6. *Cross-bedded sandstone facies*:

These facies are intermittently present over the Jal Az-Zor escarpment, mainly in the lower and middle sections of the escarpment successions. They are characterized by the fine-to-medium gain size of red and yellow sandstones representing bundles, trough, and planner cross-stratified, poorly to loosely cement sands. The thickness of these units is averaging tens of centimeters with an average of 70 cm. Bioturbation is dominated by Skolithos and Thalassinoides with the highest concentration towards the base of the facies. Uncommon fossil fragments such as echinoderms can be observed.

7. *Lateral accretion red sandstone facies*:

These facies are located at the lowermost part of the studied location of the Jal Az-Zor escarpment. It is characterized by large-scale inclined clinoformal-like beds, and in some cases, sigmoidal bedding is observed of fine-to-coarse red and yellowish sandstone. The thickness is averaging 2 m in general. The bioturbation is dominated by Skolithos, which is more intense towards the base. The lower contact is erosional and is marked by lag deposits.

8. *Bedded red muddy sandstone facies*:

These facies are thin units that occurred with the lateral accretion of red sandstone facies at the top and are considered the top cover for these facies. It is characterized by bedded red-to-yellow fine-grained sandstones, with occasional thin yellowish-green claystone beds lacking bioturbation. The thickness of these units is considered in tens of centimeters.

9. *Fine-grained bedded sandstone facies*:

These facies are composed of fine- to medium-grained calcareous sandstone. It generally exhibits a coarsening-upward succession, red-stained laminated sands, and in some localities, it laterally transitions to trough cross-bedded sandstone facies. The thickness of these facies ranges from 1 to 2 m.

10. *Microbialites facies*:

These facies are characterized by white grayish colored, carbonate-dominated sediments with a common mixture of sand, silt, and green muds. The main characteristic of this unit is that commonly found at the top of the sequences overlaying several facies such as calcareous sandstone facies, fine-grained-bedded sandstone facies, and coarsening-upward calcareous sandstone facies. It has been suggested that diagenesis may have played a role in partially altering the surface exposures of these biogenic layers forming a caliche (calcrete) crust in some localities (Khalaf & El-Sayed, 1989). The upper part of the facies is characterized by clotted and small domal structures. The XRD analysis results are 71.4% of calcite, 28.6% of quartz, and a high amount of phosphorus contents. The thickness of this unit varies between 5 and 50 cm.

11. *Trough cross-bedded sandstone facies*:

These facies are comprised of light brown-colored sandstones that vary from fine to very coarse grain sizes. It is thin in thickness, with a maximum measured thickness of 1 m, with a small scale trough cross-bedding with the absence of bioturbation. It is observed mainly at the upper part of the Jal Az-Zor escarpment. The base is marked by lag deposits, while the upper contact is marked by soft-sediment deformation and water escape structures in places.

12. *Yellowish-green siltstone facies*:

These facies are mainly comprised of loose cemented yellowish-green-colored sandy siltstone. It ranges in thickness between a few centimeters to 30 cm with a localized extend. Overall, they are underlain by the calcareous sandstone facies or microbialites facies and overlain by the bioturbated cross-bedded facies. The unit is overall massive with no visible internal structures. The XRD analysis of these facies shows 47% quartz, 28% muscovite, and 25% nimite. The latter is responsible for the yellowish-green color facies and infers a terrestrial origin of such deposits.

13. *Coarsening-upward calcareous sandstone facies*:

These facies are characterized by white-colored, fine- to medium-grained sandstones with poorly sorted grains at the top of calcareous sandstone lithology. Towards to top, granules, pebble-sized-grained, and reworked lithoclasts are observed. The base of this unit is generally covered, and the maximum measured thickness is around 1.5 m. These lithofacies are only found towards the foot of the Jal Az-Zor escarpment and are generally capped by calcrete-like units of microbialites facies and occasionally fine-grained bedded. sandstone facies. The XRD analysis shows the content of 61% quartz, 35% calcite, and 4% illite.

14. *Fossiliferous sandstone facies*:

These facies are only observed in one unit in the area towards the foot of the Jal Az-Zor escarpment. They are dominated by fossiliferous calcareous sandstones with abundant gastropods, bivalves, and occasional oyster shells. The thickness of these facies is around 0.2–1 m, and it fits the description of the fossiliferous sandstone bed described by Fuchs et al. (1968). The XRD analysis shows 52% quartz, 44% calcite, and 5% illite.

15. *Unconsolidated silty-sand facies*:

These facies are represented by structureless, loosely cemented, unconsolidated, gray-to-white silt and sands with white calcrete lithoclasts. The sands are fine- to very fine-grained, and faint red silty laminae and mud can be observed. These facies have a thickness that varies from 2 to 4 m observed in the middle of the escarpment succession.

16. *Calcareous sandstone lenses*:

These facies are characterized by lenses of white calcareous sandstones that exhibit an erosional base and flat upper boundaries. The lower part of the lens is dominated by calcite, and towards to top, it transitions into microbialites facies. Lithoclasts of microbialites facies are commonly found in these facies. Internal grading is evident with inclined beds that exhibit an NW dip direction and exhibit possible lateral accretion surface. These lenses have a limited lateral extent and can only be found at some localities. The thickness of this unit can reach 1.5 m, and it can be partially associated with yellowish-green siltstones of F8a facies (Figs. 1.5, 1.6, 1.7 and 1.8).

1.4 Al-Subiyah Area

The outcrops of the Al-Subiyah area are located at the North and northwestern coastal plain of Kuwait Bay, trending northeast to southwest and covering an approximate area of 95 square kilometers (Fig. 1.1). This area is also known as Bahrah as the Bahrah oil field is the biggest part of the area. These outcrops are bounded by Jal Az-Zor escarpments from the North and the northwest and by Kuwait Bay's northern coast from the South and the southeast. Outcrops at the Al-Subiyah area are characterized by relatively low relief, flat-top, terrace-like, elongated, and scattered hills geomorphologically formed by aeolian, fluvial, and sea-level fluctuation erosional processes (Dalongeville & Sanlaville, 1987; Al-Asfour, 1982). These outcrops are surrounded by coastal sabkha and tidal flat environments in recent times and are covered with aeolian sand dunes and sand sheets. Beds within these hills are generally dipping 2–5 degrees towards the northeast (Khalaf et al., 2019; Al-Hajeri et al., 2020). These outcrops consist mainly of siliciclastic rock units deposited in terrestrial to shallow marine environments during the Oligo-Miocene times. They are believed to be the uppermost part of the Oligocene–Lower Miocene Ghar Formation based on the surface and subsurface correlation of the Ghar Formation in southern Iraq (Al-Juboury et al., 2010; Khalaf et al., 2019). Milton (1967) was the first to describe these outcrops as calcareous cross-bedded sandstone interbedded with green-colored claystone and tied them to the deposits above the Dammam Formation unconformity in a subsurface drilled well within the same area (Khalaf et al., 2019). The stratigraphy of the Ghar Formation and the Kuwait Group were illustrated in previous sections. It is assumed from the stratigraphic superposition. aspect that the stratigraphic units of the Al-Subiyah area are the basal units of Jal Az-Zor successions.

1.4.1 Al-Subiyah (Bahrah) Outcrop Stratigraphy and Lithofacies

Khalaf et al. (2019) conducted a sedimentological and petrographical study on several Ghar Formation outcrops at the Bahrah area. They stated that these outcrops are dominated by calcareous clastic lithofacies and subdivide these rock units into four major lithofacies:

1. *The Fawn Sandstone Facies*:

This lithofacies is the most dominant within Bahrah Area. Khalaf et al. (2019) further subdivided these lithofacies into three subfacies which are:

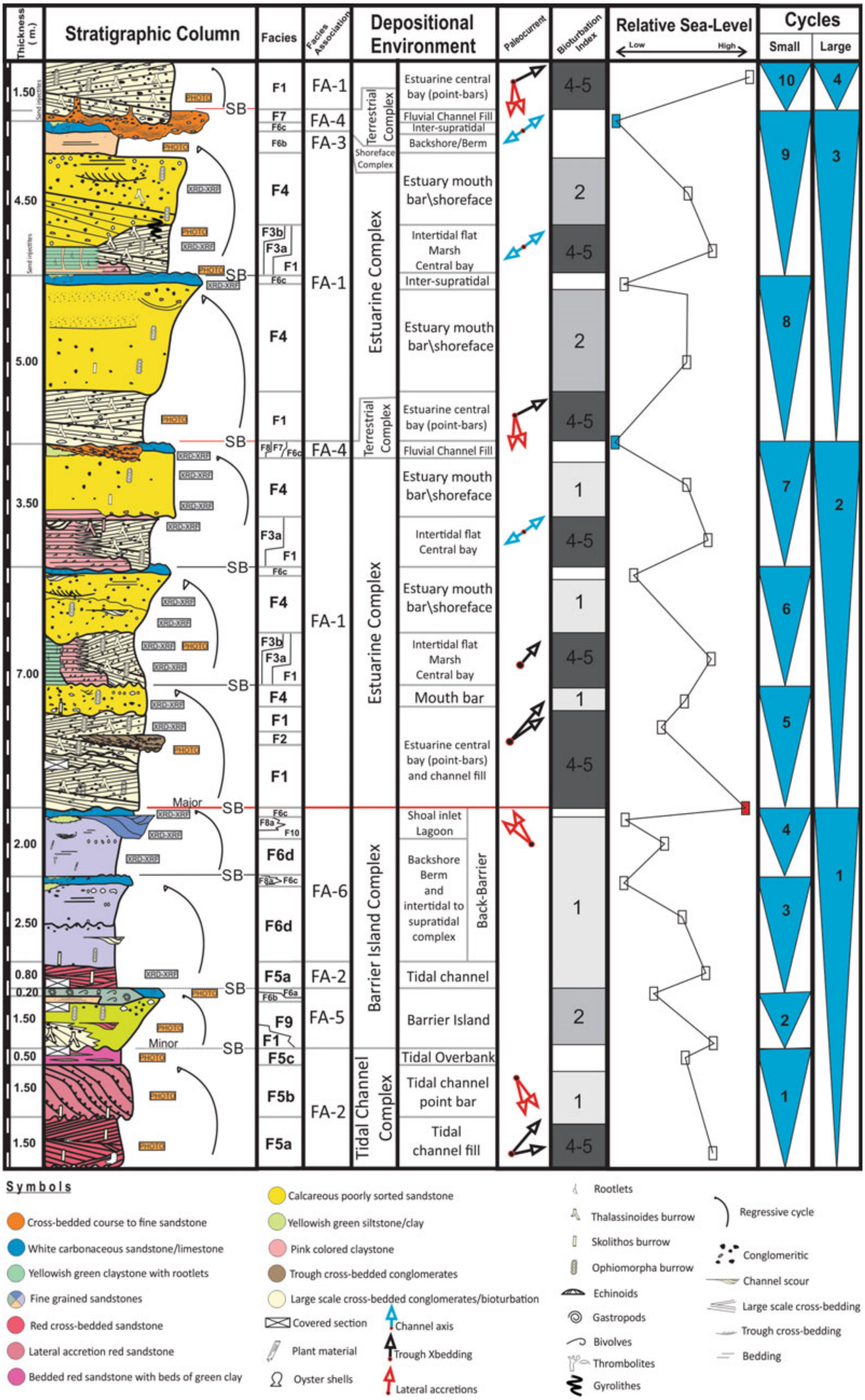

Fig. 1.5 A representative stratigraphic sequence of Jal Az-Zor Escarpment (after Amer et al., 2019a)

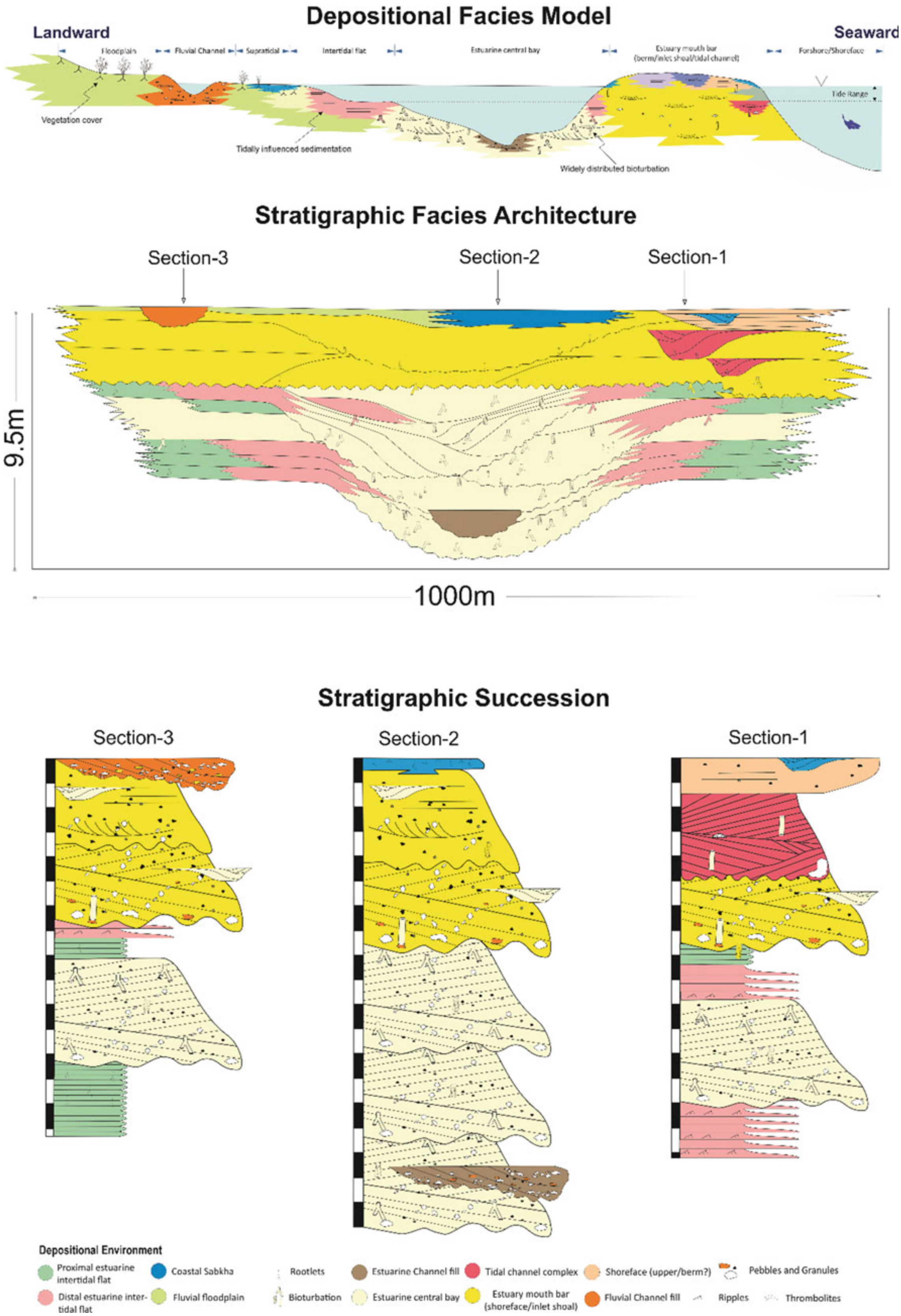

Fig. 1.6 Depositional model and facies architecture of the Jal Az-Zor escarpment (after Amer et al., 2019a)

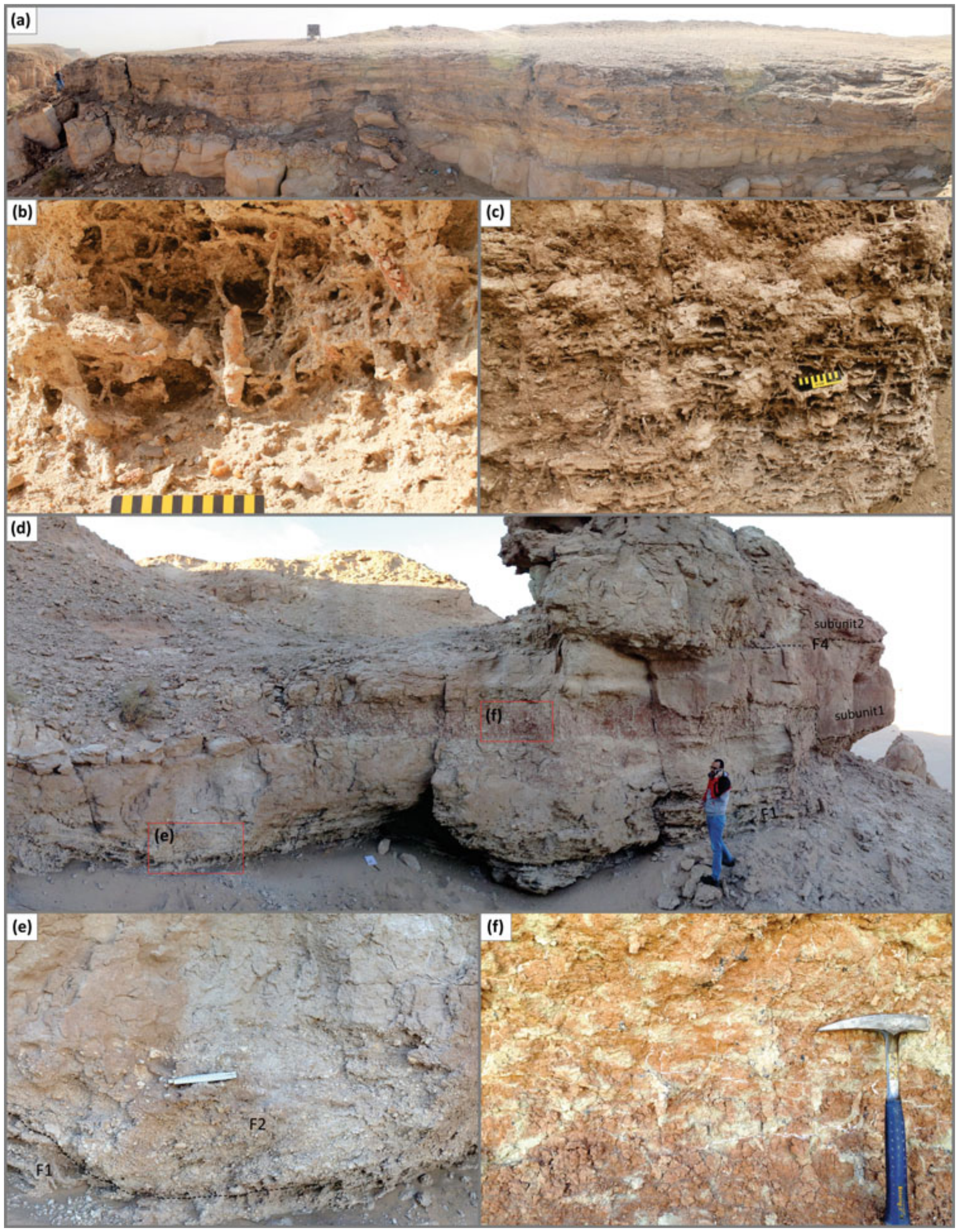

Fig. 1.7 Examples of the facies described at Jal Az-Zor Escarpment (after Amer et al., 2019a)

a. The Cross-Bedded Sandstone Subfacies: these subfacies are most dominant within the area. It is composed of buff to reddish colored, medium-grained, hard, clean, cross-bedded, well cemented by calcite, sandstone containing some re-worked fossils (gastropods and bivalves), and borrows (Al-Hajeri et al., 2020).
b. The Planar Thin-Bedded Subfacies: These subfacies consist of red-colored, hard, clean, planar bedded, rippled, arenite cemented with calcite that interbedded with the cross-bedded sandstone and the palustrine dolomicrite lithofacies.
c. The Massive Bioturbated Sandstone Subfacies: This unit consists of extensively bioturbated sandstone with large-sized borrows. It usually overlies the palustrine sandy dolomicrite lithofacies.

2. *The Palestine Sandy Dolomicrite Lithofacies*:

This lithofacies is the second most dominant in the Al-Subiyah area. It is usually interbedded with the fawn thin-bedded and cross-bedded sandstone lithofacies. It occurs as discontinuous lenses of whitish marly sediments

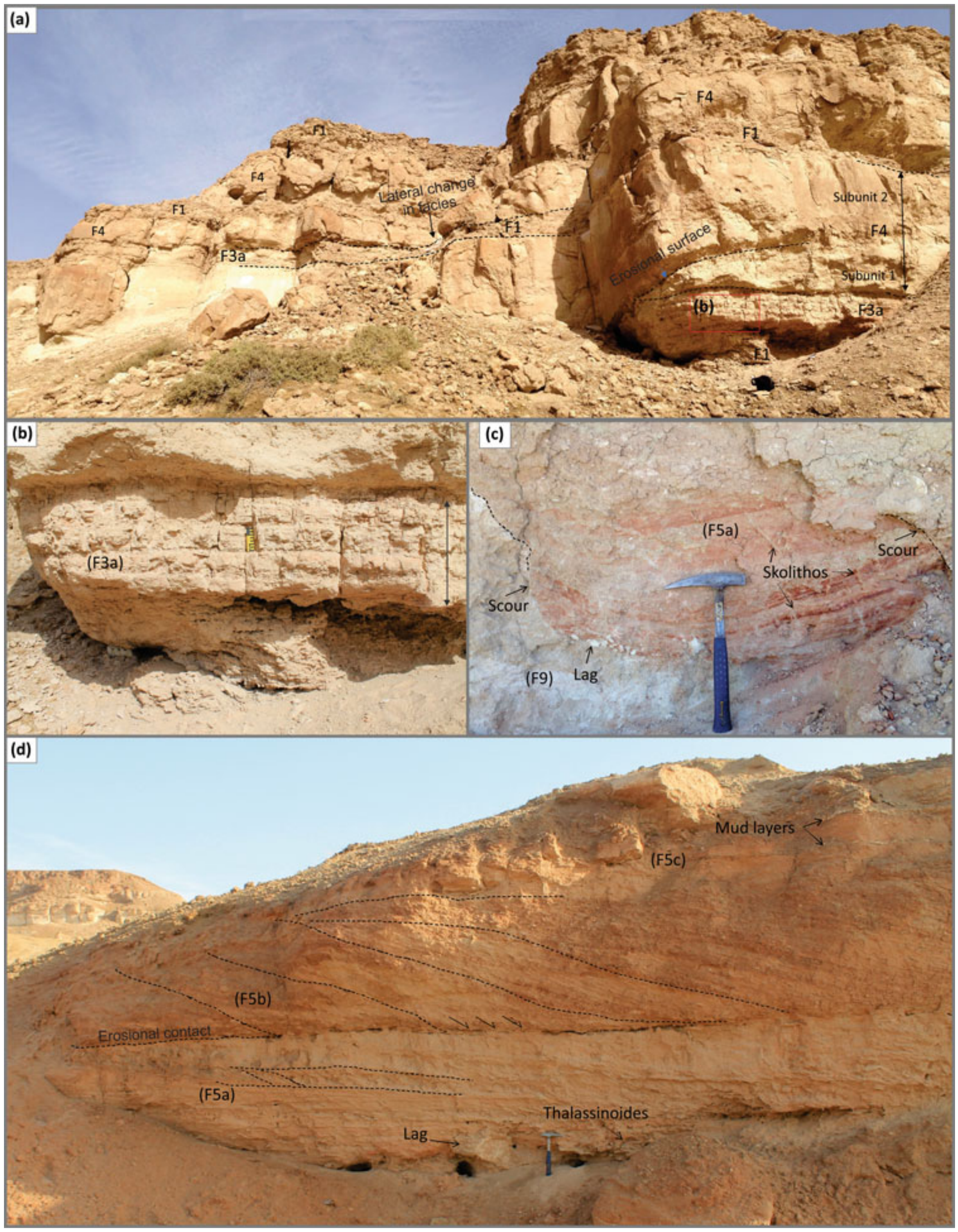

Fig. 1.8 Examples of the facies described at Jal Az-Zor escarpment (after Amer et al., 2019a)

that are generally heavily bioturbated. This lithofacies is characterized by various sizes of cracks and exhibits large karstic hollows.

3. *The Mudstone Lithofacies*:

This lithofacies consists of grayish to reddish colored, thinly laminated to flaky mudstone enclosing thin bands and lenses of hard sandy mud. These lithofacies can be found mainly in the middle section of the Ghar Formation.

4. *The Carbonate Lithofacies*:

This lithofacies is limited in occurrence, and it is represented with coquina, quartzitic limestone, oolitic limestone, and dolostone. The coquina quartzitic limestone is found at the top of the Ghar Formation and superimposed by the Lower Fars clastic deposits. This lithofacies comprises of white-colored, chalky, and very porous limestone, commonly with herring-bone trough cross-bedding. The oolitic limestone and dolostone are generally found as discrete thin beds within the middle and the lower section of the sequence (Fig. 1.9).

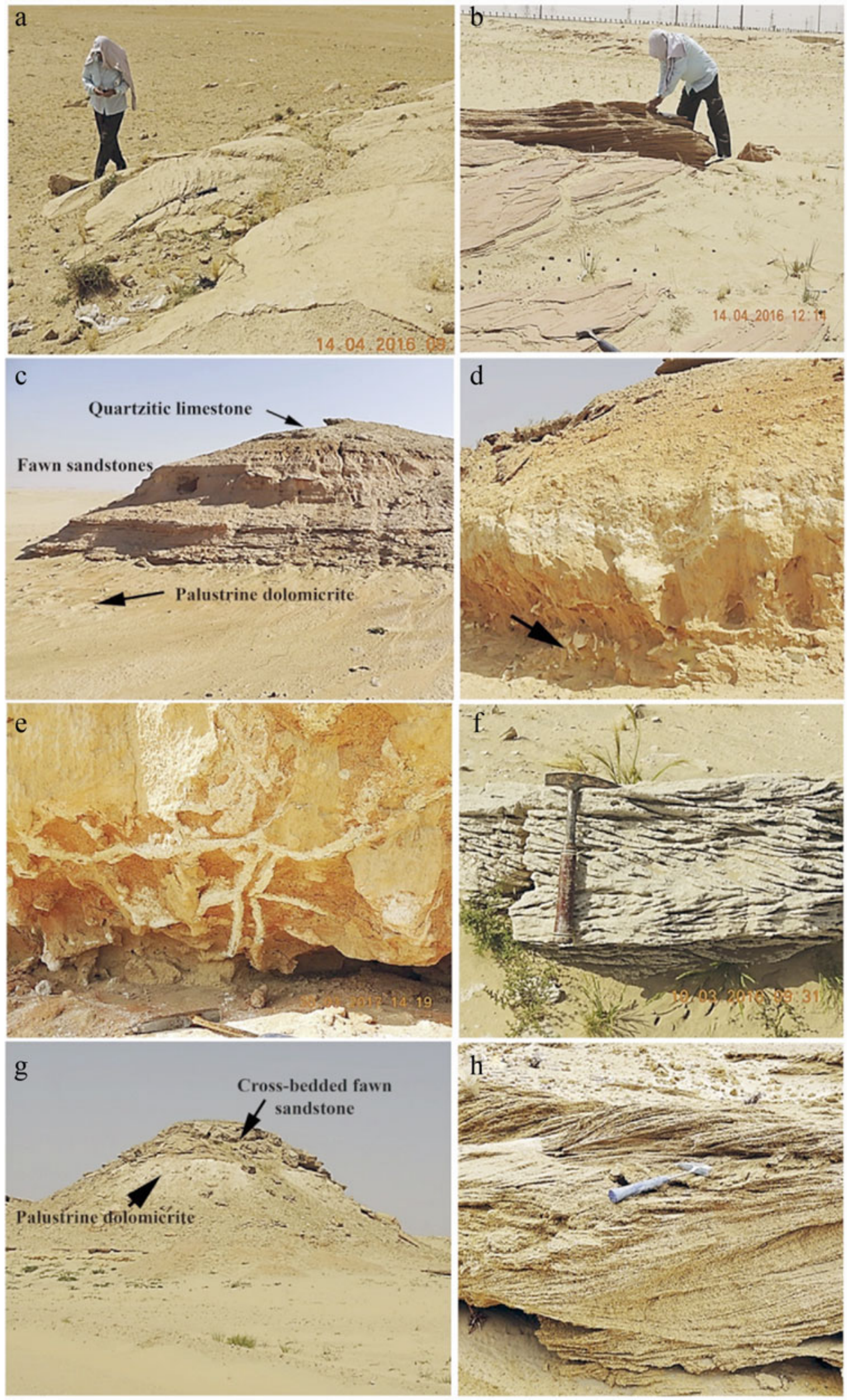

Fig. 1.9 Examples of the facies described et al.-Subyiah area (After Khalaf et al., 2019)

1.4.2 The Clastic Intrusion Zones at Al-Subyiah (Bahrah) Area

Clastic intrusions are distinctive tabular sedimentary structures highly associated with soft-sediment deformation of unconsolidated sediments (Jolly & Lonergan, 2002). Clastic intrusions are represented by many terminologies in literature such as sand volcanoes, sand blows, sand dykes, sand pipes, injectites, mud volcanoes, etc. They vary in length and diameter between a few centimeters to around several meters (Jolly & Lonergan, 2002). They can be found in various depositional settings in both shallow and deep depositional environments (e.g., shallow marine, glacial, lacustrine, fluvial, tidal flat, and deep marine environments) (Jolly & Lonergan, 2002; Duane et al., 2015; Al-Hajeri et al., 2020). They are often formed within tectonically active areas with high sedimentation rates; however, they can also be formed from near-surface sources within low tectonic activity regions (Jolly & Lonergan, 2002; Al-Hajeri et al., 2020).

Numerous sand intrusions can be found in northern Kuwait Bay et al.-Subyiah (Bahrah) area. They can be found within the basal portion of the Ghar Formation within the cross-bedded sandstone unit (more frequent in the fawn sandstone lithofacies) covering the coastal plain of the Bahrah area (Duane et al., 2015; Al-Hajeri et al., 2020). Duane et al. (2015) documented such clastic intrusions with various shapes and diameters within three zones in Bahrah coastal/tidal flat area. They identified these intrusions as mud volcanoes and seismites that were ejected from the feeder system (possibly Dammam Aquifer) due to seismicactivities within the area and filled with mud and brecciated sandstone clasts along with dolomite, calcite, and partial marine bivalves. Duane et al. (2015) suggested that these mud volcanoes formed due to seismic induced liquefaction processes within the area (Fig. 1.10).

Recently, Al-Hajeri et al. (2020) thoroughly studied the clastic intrusions within the Bahrah area. They analyzed these intrusions quantitatively and qualitatively and proposed a conceptual model for the formation mechanism of these sand intrusions, calling them sand injectites. Al-Hajeri et al. (2020) identified two types of sand injectites with diverse forms and patterns in two different locations within the Bahrah area: the sand injection pipes and the polygonal to semi-circular sinuous sand injectites (Table 1.2). The sand injection pipes are associated with the cross-bedded sandstone lithofacies (the fawn sandstone lithofacies) within Al-Subyiah Ridges. They are characterized by their cylindrical shape and well calcite-cemented outer boundary. They ranged in color from red to yellow with very fine to coarse sand grain size. Around 200 pipes were identified with an average of 5-m height within the area and with diameters ranging from a few centimeters to meters. The larger intrusions have a relative trend of northeast–southwest and northwest–southeast. The polygonal to semi-circular sinuous sand injectites are found within a separate reddish to brownish lithified terrane within Bahrah tidal flat/Sabkha area. Features within this area vary in size, shape, patterns, relief, and distribution. They can be divided into three groups: 1. Breccia-filled, 2. Yellow sand-filled, and 3. suture line.

Al-Hajeri et al. (2020) proposed a non-tectonic-related conceptual model for the formation of these sand intrusions, which is called: “the near-surface complex focused fluid injection conceptual model.” This model suggests that the sediments and the injected fluids are both from the same source. A near-surface geobody that is dominated by loose, very porous, and unconsolidated sand is formed due to the deposition of the paleoshoreline. Water is trapped within this geobody due to its high porosity. This process increases the pore pressure within these near-surface geobodies. Biological activities—mainly bacterial activities—within the near-surface hydrocarbon reservoir facilitate further pressure build-up. Then loose unconsolidated sediments within the geobody are injected due to the fluids’ overpressure forming sand injectites in more lithified sandstone host rock.

1.5 The Ahmadi Quarry

The Ahmadi Quarry is located in the southeastern part of Kuwait near the Ahmadi City (29°02′23.2‶N, 48°04′36.0"E) (Fig. 1.1). Structurally, it is located on the eastern edge of the Ahmadi Structural Ridge. The quarry is administrated by the National Industries Company and covers approximately 10 square kilometers. The Ahmadi Ridge is an asymmetrical north–northwest-trending anticline structure with an approximate topographic height of 100 m (Carman, 1996) (Fig. 1.1).

In Kuwait’s subsurface, the Dammam Formation and the Kuwait Group are primary aquifers covering useable brackish water in Kuwait. The Dammam Formation is a limestone–dolomite sequence of Middle Eocene age with approximately 600–700 feet thickness (183–213 m) (Bergstrom & Aten, 1965; Burdon & Al-Sharhan, 1968). These deposits were precipitated in shallow marine/marginal environments forming an extensive carbonate platform that extends over the Arabian Plate’s eastern regions during the Eocene. The thickness of the Dammam deposits slightly increases towards the East (Schlumberger, 1972; Lababidi & Hamdan, 1985). The Dammam Formation is unconformably overlain by Kuwait Group, represented by Ghar, and underlain by Rus Formation. A karstification zone was

Table 1.2 Types of sand injectites with various forms and patterns at the Al-Subyiah (Bahrah) area described by Al-Hajeri et al. (2020).

Pipe type	Description	Map view photo
Circular with annular rings	Geometry:isolated circular to semi-circular standalone vertical to sub-vertical pipe forming a cylindrical geometry Size:from few centimeters to decimeter in diameter Grain size:pipe fill is fine to medium and the host rock is medium to coarse sand. The fill material is well cemented with $CaC0_3$ Rings:decrease in frequency inward and their range in thickness in few millimeters	
Hollow circular pipe	Geometry:isolated circular to semi-circular standalone vertical to sub-vertical pipe forming a cylindrical geometry Size: from few centimeters to few decimeters in diameter were recorded in the field Grain size: pipe fill is loose fine to medium sand (verv easy to remove with hand) and the host rock is medium to coarse sand. The boundary is very well cemented with $CaC0_3$	
Pipes associated with cemented veins	Geometry: isolated circular to semi-circular standalone and others are cross cuttin g two or more pipes with vertical to sub-vertical pipe forming a cylindrical geometry Size: from few centimeters to decimeter in diameter Grain size: pipe fill is fine to medium and the host rock is medium to coarse sand. The fill material (if present) is well cemented with $CaC0_3$ Rings: some of them are with ring and their frequency decrease inward and their range in thickness in few millimeters Veins: most of the veins stop along the boundary of the pipe and rarely cross-cut the pipe structure. Most of the veins are linear and few are circular to sub-circular. The veins are composed of fine sand cemented with $CaC0_3$ making them very resistive to erosion	
Hypotrochoid pipe	Geometry: circular to sub-circular, single or group of pipes in the middle surrounded with a group of distinct arcs and circles of cemented veins Size: decimeter up to few meters in diameter Grain size:pipe fill is fine to medium and the host rock is medium to coarse sand. The fill material (if present) is well cemented with $CaC0_3$ Veins: their geometry form arcs that cross-cut each other and most of the veins stop along the boundary of the pipe. The veins are composed of fine sand cemented with CaC03 making them very resistive to erosion. Some of them show striation marks on them indicating vertical movement along them	

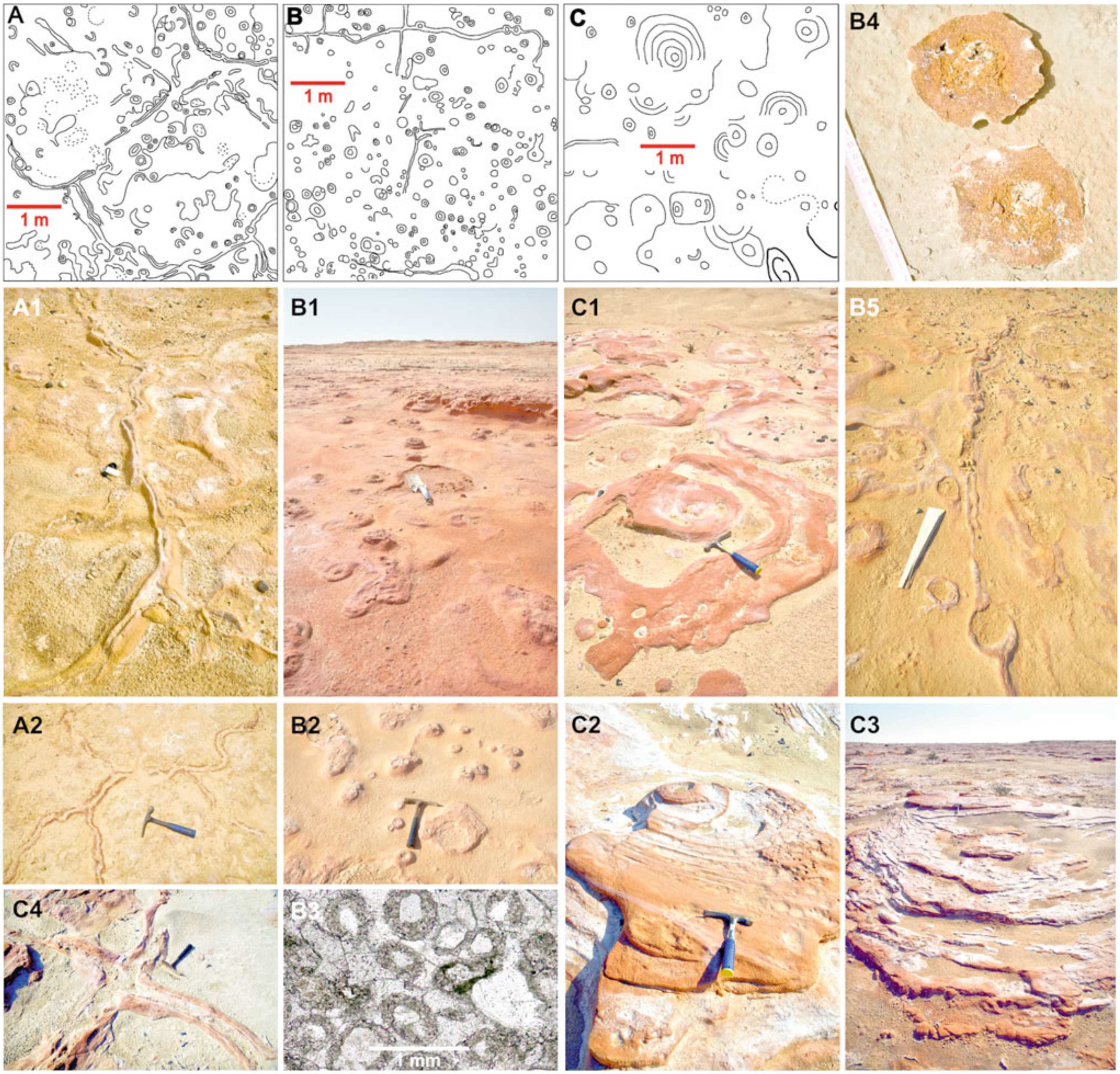

Fig. 1.10 Various types and shapes of mud volcanoes (sand intrusions) et al.-Subyiah (Bahrah) area (After Duane et al., 2015)

identified within the topmost part of the Dammam Formation that marks a major disconformity between the Dammam Formation and the overlying Mio-Pleistocene Kuwait Group clastic deposits (Owen & Nasr, 1958; Milton, 1967; Burdon & Al-Sharhan, 1968; Khalaf et al., 1989; Khalaf & Abdullah, 2014). The Ahmadi Quarry has nearly 10–25 m exposure of the topmost part of the Dammam Formation and the lower part of the Kuwait Group clastic deposits (Al-Awadi et al., 1997) (Fig. 1.11).

Fig. 1.11 A section of the Ahmadi Quarry showing the uppermost part of the Dammam Formation and the lowermost of the Kuwait Group

1.5.1 Stratigraphy and Lithofacies of The Dammam Formation and Kuwait Group deposits at The Ahmadi Quarry Outcrop

The Ahmadi Quarry outcrops consist of two major units: the carbonate-dominated uppermost part of the Dammam Formation and the clastic-dominated Kuwait Group. These units were studied by Al-Awadi et al. (1997), Khalaf and Abdullah (2013), Khalaf and Abdullah (2014), and recently by Khalaf et al. (2017). These studies mainly focused on the Dammam Formation lithofacies, whereas the Kuwait Group deposits at the quarry gain less attention and their lithofacies are not well identified. The lithofacies of Ahmadi Quarry can be summarized from oldest to youngest as follows (Al-Awadi et al., 1997; Khalaf et al., 2017) (Fig. 1.12):

1.5.1.1 The Dammam Formation

1. Chalky dolostone Unit: This unit is composed of white, porous, thick, friable, and granular chalky dolostone with thin chert bands and lenses (Al-Awadi et al., 1997; Khalaf et al., 2017). This unit is around 10 m thick in the Ahmadi Quarry (Al-Awadi et al., 1997; Khalaf et al., 2017). The chert bands are thin and discontinue, with sharp straight tops and irregular bottoms that formed along the bedding planes. These chert bands vary in thickness through this unit from a few centimeters to up to 50 cm (Khalaf et al., 2017). Chert was observed as lens-shaped within this unit. The upper contact of the chalky dolostone unit is gradational. There are a few fossil-rich zones within this unit in the Ahmadi Quarry. Fossils found in the Ahmadi Quarry include shell fragments of Gastropods and Pelecypods (Al-Awadi et al., 1997).
2. Karstic Dolostone Unit: This unit was first identified by Burdon and Al-Sharhan (1968) at the Ahmadi Quarry. It overlies the chalky dolostone unit and underlies the karst carapace unit. Both upper and lower contacts of this unit are gradational. The unit is composed of hard, karstic-rich dolostone with chert bands and lenses (Khalaf & Abdullah, 2014; Khalaf et al., 2017). This unit is approximately around 9 m thick in the northern parts of the quarry, whereas it thins out to less than 1 m and completely eroded towards the southern parts of the quarry (Khalaf et al., 2017).
3. Karst carapace Unit: This unit overlies the karstic dolostone unit with gradual contact. The upper contact of the unit is unconformable with the Kuwait Group deposits. This unit consists of white to yellowish-orange color, hard, dense calcitized, and silcretized dolocretic duricrust with pseudobreccia filling the cracks of the dolostone (Khalaf, 2011; Khalaf & Abdullah, 2014; Khalaf et al., 2017). The karst carapace unit has a thickness of around 3 m in the northern parts of the quarry and thins out towards the south (Fig. 1.13).

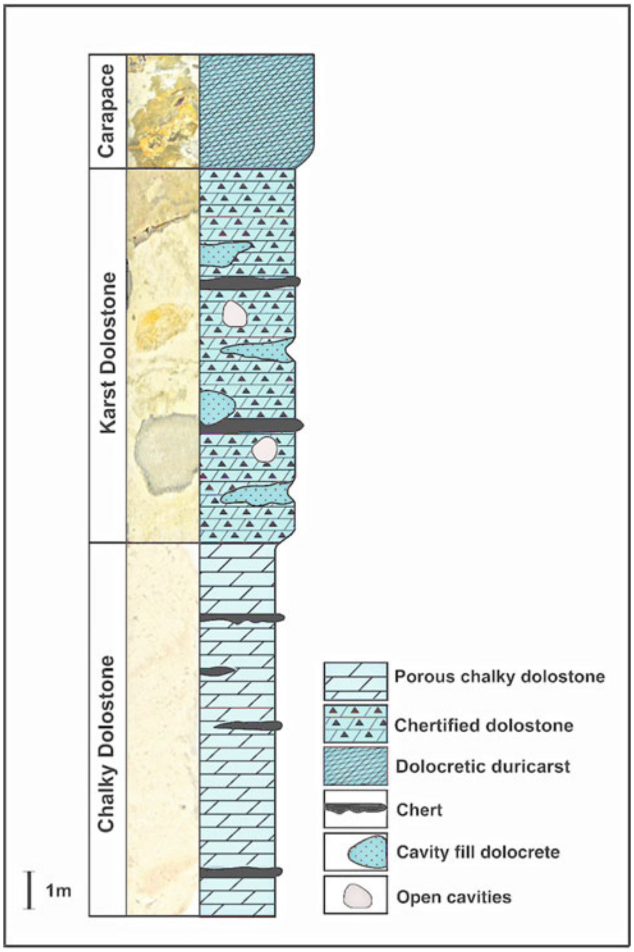

Fig. 1.12 A simplified lithostratigraphy of the Dammam Formation, the Ahmadi Quarry (after Khalaf et al., 2017)

Diagenesis and Diagenetic Stages of the Dammam Formation:

All the Dammam Formation units were subjected to various stages of diagenesis. These units were initially deposited as calcareous wackestone and mudstone within tidal flat and backshore lagoons settings and then later were altered completely to dolostone through dolomitization diagenetic processes (Khalaf et al., 2017). However, the sedimentary textures and structures of the original rock type were retained, allowing the identification of their facies and their depositional environment (Al-Awadi et al., 1997; Khalaf et al., 2017). Other forms of diagenesis within the formation include chertification, silcretization, dissolution, compaction, fracturing and karstification, stage cavity fill dolocretes, and karst carapace (Khalaf, 2011; Khalaf & Abdullah, 2014; Khalaf et al., 2017).

1.5.1.2 Kuwait Group Deposits

The Kuwait Group stratigraphy and lithofacies were discussed in previous sections. In the Ahmadi Quarry, only a few meters of the lower portion of the Kuwait Group (i.e., Ghar Formation) is exposed, whereas the topmost portion of the group is completely eroded. A karstification zone in the top part of the Dammam Formation marks the lower boundary of the Mio-Pleistocene Kuwait Group clastic deposits with a major erosional surface (disconformity) (Khalaf & Abdullah, 2014). A half-meter calcareous zone is about a meter above this unconformity (Al-Awadi et al., 1997). The Ghar Formation, which is exposed at the Ahmadi Quarry, consists of loose red to white–yellow sands without any conspicuous layering and cementation (Al-Awadi et al., 1997).

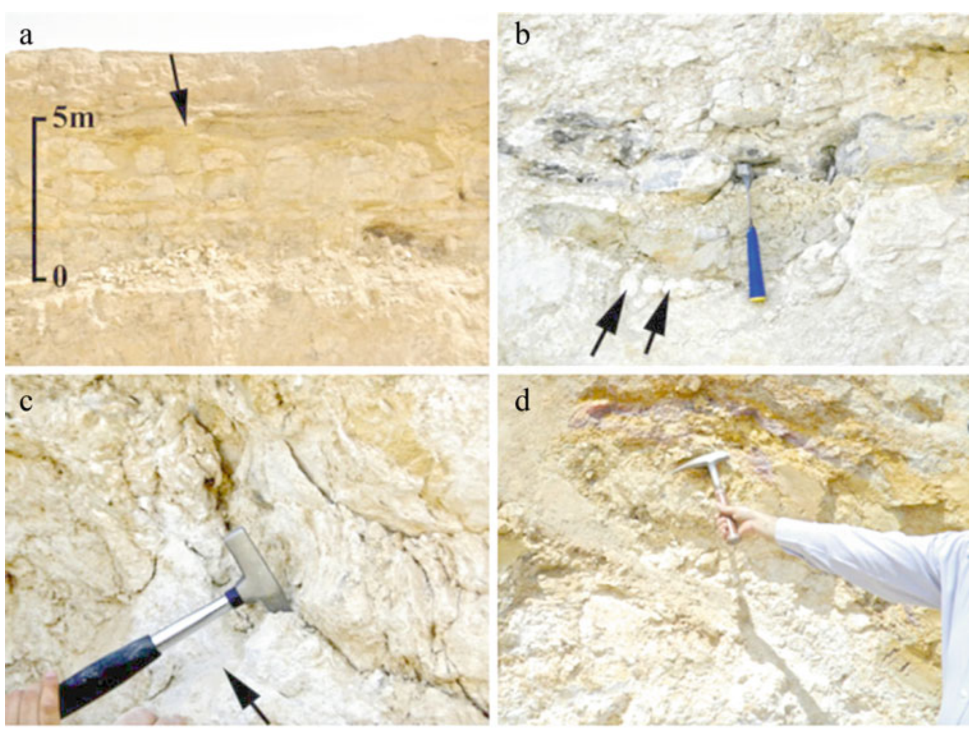

Fig. 1.13 Lithofacies examples and Paleokarstic surfaces in the Dammam Formation, the Ahmadi Quarry (After Khalaf et al., 2017)

1.6 The Khiran Ridges

The Khiran Ridges are located in the southern part of Kuwait et al.-Khairan coastal area (Fig. 1.1). They are a series of lithified parallel coastal ridges trending North–Northwest to South–Southeast parallel to the Arabian Gulf Coast. These ridges vary in height and length, ranging from 5 to 15 m high and 450 to 4000 m in length, covering an area of around 100 square meters (Picha & Saleh, 1977; Picha, 1978; Al-Hurban & Al-Sulaimi, 2009). These ridges were studied by several researchers (e.g., Saleh, 1975; Picha & Saleh, 1977; Picha, 1978; Al-Sarawi et al., 1993; Al-Hurban & Al-Sulaimi, 2009). The age of these ridges is not precisely defined and varies from Pleistocene to Holocene. The formation of these ridges was linked to the Quaternary eustatic sea-level fluctuation during different phases of sea level that occurred due to the glacial and interglacial episodes (Saleh, 1975; Al-Sarawi et al., 1993). The older ridges are located further inland, whereas the younger ridges are closer to the present-day shoreline (Picha & Saleh, 1977; Picha, 1978). The older sediments at the base of the Khiran Ridges are believed to be of fluvial terrestrial origin, which were eroded and transported from the source lands west of the Arabian Plate during the Pleistocene Epoch (Al-Sarawi et al., 1993). However, the younger sediments at the top of these ridges are mainly Holocene in age (Picha & Saleh, 1977; Picha, 1978). Gunatilaka (1986) estimated that the formation of the Khiran Ridges is from 8,450 to 7,650 ± 70 (yBP) to 2,190 ± 70 yBP, whereas Al-Sarawi et al. (1993) believed that these ridges formed in the past 8,000 years during the Holocene eustatic sea-level fluctuations (Fig. 1.14).

1.6.1 Stratigraphy and Lithofacies of The Khiran Ridges and Outcrops

The Khiran Ridges and outcrops are mainly composed of siliciclastic deposits deposited in shallow marine barriers, ancient and recent beaches, and coastal dunes environments (Picha, 1978; Al-Hurban & Al-Sulaimi, 2009). Their lithology varies from oolitic marine sandstone to calcareous coastal aeolian sandstone (Picha, 1978; Al-Hurban & Al-Sulaimi, 2009). Picha and Saleh (1977) and Picha (1978) identified and described five lithostratigraphic complexes within the Khiran Ridges based on aerial photographs as follows:

(1) The Oolitic-Quartzose Sandstone Complex: This complex is considered the oldest and further inland. Its age is estimated to be the Late Pleistocene. This complex is exposed along a coastal cliff and can also be found in the subsurface by drilling at the base of the oolitic ridge complex. Most of the oolitic-quartzose sandstones lie below the present sealevel and are saturated with saline groundwater. This complex represents transgressive marine facies that are composed of coarse, slightly cemented, cross-bedded sandstone with well-rounded quartz grains, skeletal fragments, and oolites. The base of this complex shows a herringbone-type of cross-stratification with broken shell fragments that indicate a more tidal-influenced depositional setting. The uppermost part of this complex is marked by a 50 cm thick fossiliferous zone abundant with skeletal debris that mainly consists of gastropod shells. The

Fig. 1.14 Panoramic view of one of Al-Khiran Ridges, South of Kuwait

bedding of the upper part of this bridge complex is laminar and dipping towards the shoreline (i.e., East). Saleh (1975) described traces of root structure (e.g., rhizocretion) at the top of the southern complexes, which indicates a more coastal aeolian depositional setting.

(2) The Quartz-Oolitic Sandstone Complex: This complex is also estimated to be a late Pleistocene in age. It is located farthermost inland with a height of 15 m. This complex consists of several sets of cross-bedded marine and aeolian sandstones.

(3) The Older Oolitic Limestone Complex: This Pleistocene-aged complex is composed of cross-stratified aeolian-formed parallel ridges. They are 4–10 m high. They are composed almost entirely of chalky white ooids with only a small admixture of skeletal fragments, pellets, and quartz grains that are subaerially cemented by granular sparry calcite. The oolites lost their original luster due to partial dissolution and recrystallization of the cortex under atmospheric conditions. The nuclei of oolites are mostly quartz grains and structureless carbonate pellets, less frequently skeletal fragments, feldspars, and other detrital minerals.

(4) The Younger Oolitic Limestone Complex: This complex is Pleistocene in age. It forms ridges along the present coastline. These ridges are 2–8 m in height. They can be easily distinguished from the older oolitic ridges by their creamy-colored and highly lustrous hard surface of oolites that are little affected by subaerial processes. They are almost entirely aragonitic and display a very low degree of lithification.

(5) The Holocene oolitic Sediments: Represent the recent (Holocene) unconsolidated sediments on beaches, tidal flats, khors, and coastal dunes.

Al-Hurban and Al-Sulaimi (2009) revisited the Khiran Ridge complexes and furtherly studied their morphological and lithological characteristics. They described and identified two different settings of parallel ridges within the Khiran area, which are:

(1) **The Oolitic Limestone Composition Sets:** Two outcrops of the oolitic limestone outcrops were identified by Al-Hurban and Al-Sulaimi (2009) within the Khiran area: the creamy-colored outcrops and the chalky-white colored outcrops. These color differentiation are referred to as the differences in the lithification and diagenetic processes. These ridges range between 2 and 8 m high, 100 and 4000 m long, and around 100 and 300 m wide (Picha, 1978; Al-Hurban & Al-Sulaimi, 2009). These ridges are characterized by a thin fossil-rich unit (bivalves and gastropods) at the base of the section indicating a marine depositional setting. Aeolian cross-bedding can be found within some of these ridges indicating the South to North flow direction. Fluvial influence is also noted at the base of these ridges, where well-rounded gravel-size oolitic clasts can be found. Rock units within the creamy ridge are composed of low cemented and very well sorted to well-sorted oolites. The nuclei of these ooids are mainly carbonate grains. The chalky-white colored ridge is composed primarily of larger-sized concentric oolites with carbonates, quartz, less common shell fragments, feldspar, amphibolite, and other detrital nuclei. These nuclei are relatively larger than the ones at the creamy-colored ridge. It is believed that the greater size of ooids is linked to the secondary oolitization process during the Holocene.

(2) **The Sandstone-Composition Sets:**
The sandstone-rich ridge sets at the Khiran area are approximately 19–20 m high, 100–200 m wide, and 2.5–3 km long. They are steeper on the western side and obliquely oriented to the present-day shoreline. They consist of thick, fine-sized cross-bedded sandstone deposited in terrestrial to marginal-transitional marine depositional settings followed by laminated to graded bedded sandstone with 10–30 cm fossiliferous zone at the top. The upper portion of the sandstone ridge comprises medium-sized, planar-cross bedded, calcareous sandstone with ooid grains. The amount of ooid grains diminishes very rapidly towards the top of the unit.

1.7 The Enjefa Beach Outcrop

The Enjefa Beach represents a modest exposure located along the coastline of the greater Kuwait City district of Salwa and extends for approximately 900 m in length (Fig. 1.1). The composite height of the exposed stratigraphic sequence has a total thickness of 3 m (Amer et al., 2018). The age of the exposed lithofacies was largely assumed to be Quaternary in age (Khalaf, 1988). A detailed radiometric dating study was not done until Tanoli (2015) performed ^{14}C radiocarbon dating on two shell fragments extracted from the upper portion of the exposed units. The radiometric age of these two samples revealed late Holocene (2260 ± 30 and 3160 ± 30 years BP). Though Tanoli et al. (2012) and Tanoli (2015) attempted to study the sedimentary structures and lithofacies overview of the exposed unit, it was not until Amer et al. (2018) studied the detailed facies architecture and tectonostratigraphic significance of this exposure and how it documented the final stages of Kuwait's uplift and emergence. Amer et al. (2018) suggested that the Ahmadi Ridge has played a significant role in shaping the depositional patterns of the lateral accretion facies of the tidal channel facies association. This work was followed by a detailed 3D geological model reconstruction for outcrop by Amer et al. (2019b) for educational purposes. The following section will briefly discuss the consist of facies associations, tectonostratigraphic significance, and 3D geological model of the Enjefa Beach outcrop.

1.7.1 Facies and Facies Associations of Enjefa Beach Outcrop

The Enjefa Beach exposure is composed of marginal marine deposits that consist of two genetically related facies associations. These are shoreface facies association and tidal channel facies association (Amer et al., 2018) (Fig. 1.1).

1. Shoreface facies association:

Based on the work performed by Amer et al., (2018, 2019b), the shoreface facies association can be divided into three genetically depositional facies. These are middle shoreface, upper shoreface, and foreshore facies.

The middle shoreface facies have been characterized by a thin bed of 30 cm at the base of the sequence (low tide waterline), fine-grained sands, trough cross-bedded, and extensive bioturbation (Thalassinoides). The upper shoreface facies are relatively thin ($\sim$50 cm), fine-to-coarse grain size sands that are characterized by large-scale trough cross-bedding (trough width $\geq$ 2.5 m), and ophiomorpha burrows. Amer et al. (2018) indicated that the paleocurrent direction of these facies is predominantly to the NW. The third facies over this facies association is the foreshore facies that rarely exceed 20 cm in thickness. These facies are represented by planar-laminated fine to medium grain-sized sands and gently dip towards the present-day shoreline. In places, these facies can be represented by bioclastic facies (Fig. 1.15).

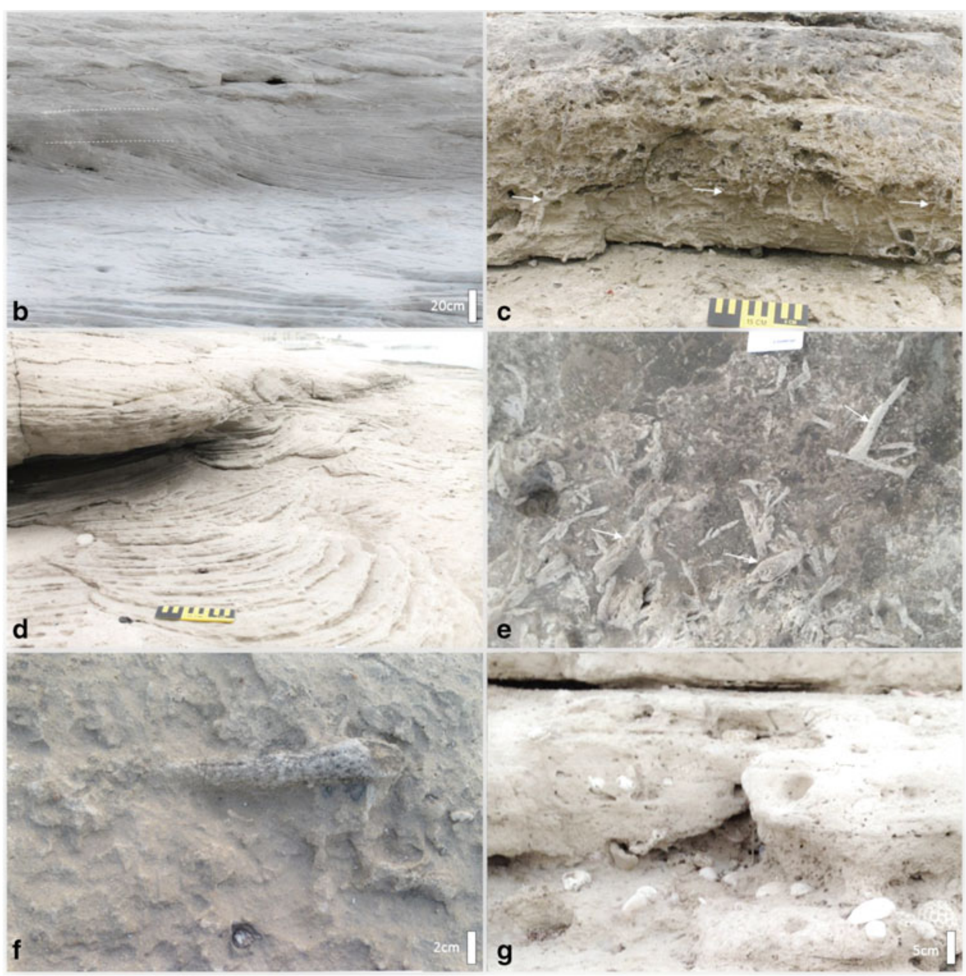

Fig. 1.15 Outcrop photographs of the Enjefa Beach outcrop show; **b** foreshore facies that are bounded by erosional surfaces; **c** middle shoreface highly bioturbated interval; **d** upper shoreface large-scale trough cross-bedding top view; **e** top view of middle shoreface horizontal Thalassinoides burrows; **f** upper shoreface Ophiomorpha burrowing) Tidal channel-fill/abandonment facies with lag deposits (Modified after Amer et al., 2018)

2. Tidal facies association:

The tidal channel facies association is dominated by lateral accretion facies, trough cross-bedded channel facies, and channel fill/abandonment facies. The lateral accretion surfaces are characterized by inclined bedding surfaces that record the point bar's migration associated with ophiomorpha burrows. The paleocurrent measurements performed by Amer et al. (2018) indicate a unidirectional NNW migration path. Amer et al. (2018) suggested that the Ahmadi Ridge has played a significant role in shaping the depositional patterns of the lateral accretion facies of the tidal channel facies association. The unimodal paleocurrent direction of the lateral accretion surfaces shows a predominant NNW direction. It was observed that this direction is parallel to the Late Holocene and the present-day shoreline, and no southern trend is found. In a normal point bar system, and because of the migration nature within a meandering tidal channel system, it would be expected to have multiple lateral accretion directions. However, over the Enjefa Beach outcrop, only a unidirectional paleocurrent is observed. The second facies is represented by cross-bedded channel facies. These facies are composed of fine-to-coarse, relatively small-scale trough cross-bedding (trough width ±0.5 m) and a bimodal paleocurrent direction to the WNW and WSW.

The third and last facies are Channel fill/abandonment facies. These facies are represented by fine-to-medium-grained sands, abundant fossil fragments such as gastropods, bivalves, and coral fragments (Fig. 1.16).

1.7.2 Enjefa Beach Outcrop 3D Geological Model

In general, modeling can be classified into two techniques: analogue and numerical modeling (Nieuwland, 2003). Over the Enjefa Beach outcrop, the analogues approach was used. Though using this method can raise questions on continuity and scale (McClay, 1990; Brun et al., 1994), the Enjefa Beach 3D geological model can be used to better understand the sedimentary processes and for educational purposes.

The Enjefa 3D static model developed by Amer et al. (2019b) was based on the geostatistical modeling approach introduced by Amer (2017) (Fig. 1.17). The model developed expressed the present-day digital elevation as the top boundary of the model and the lowest point of the section as the base. Three measured sections were used as input to the model and used to distribute the shoreface and tidal channel facies associations. The unique aspect of this model is that it captures the lateral accretion migration towards the NNW direction, supporting the understanding of sedimentary

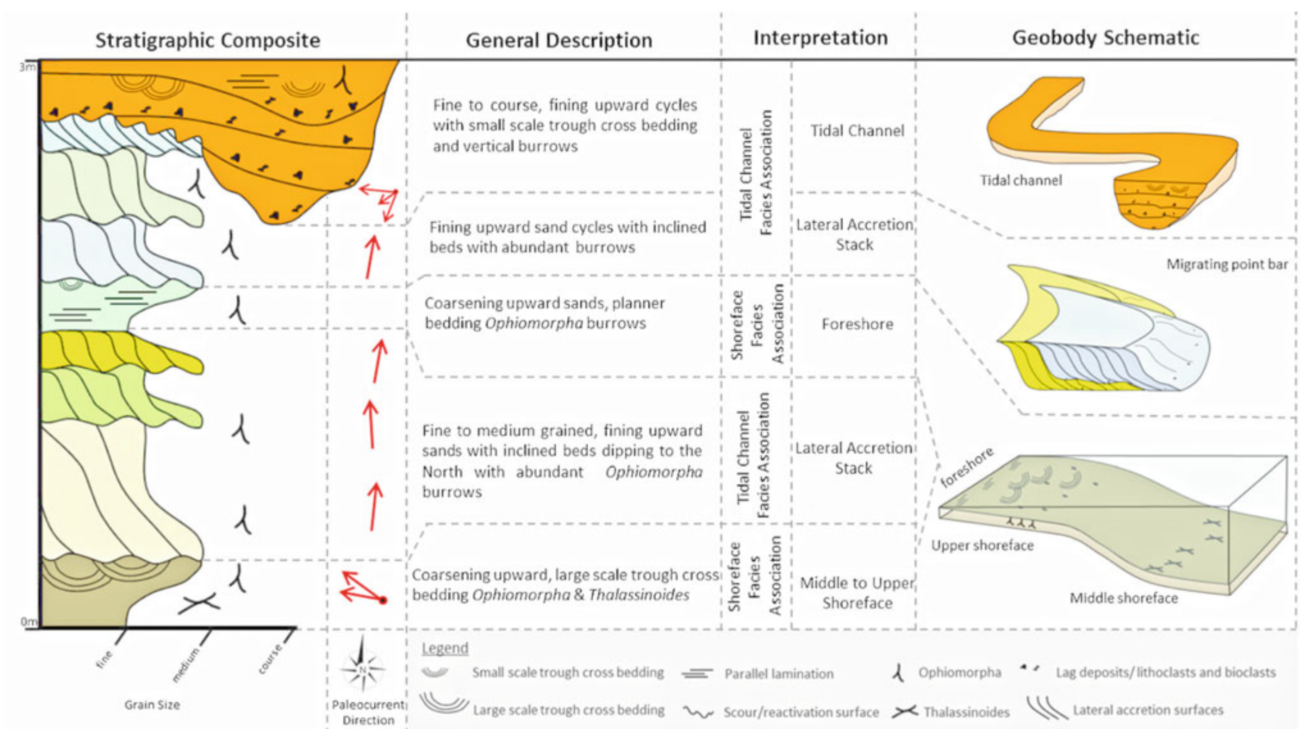

Fig. 1.16 Stratigraphic composite plot of the Enjefa outcrop illustrating the various associated geobodies responsible for the facies accumulation. (After Amer et al., 2018)

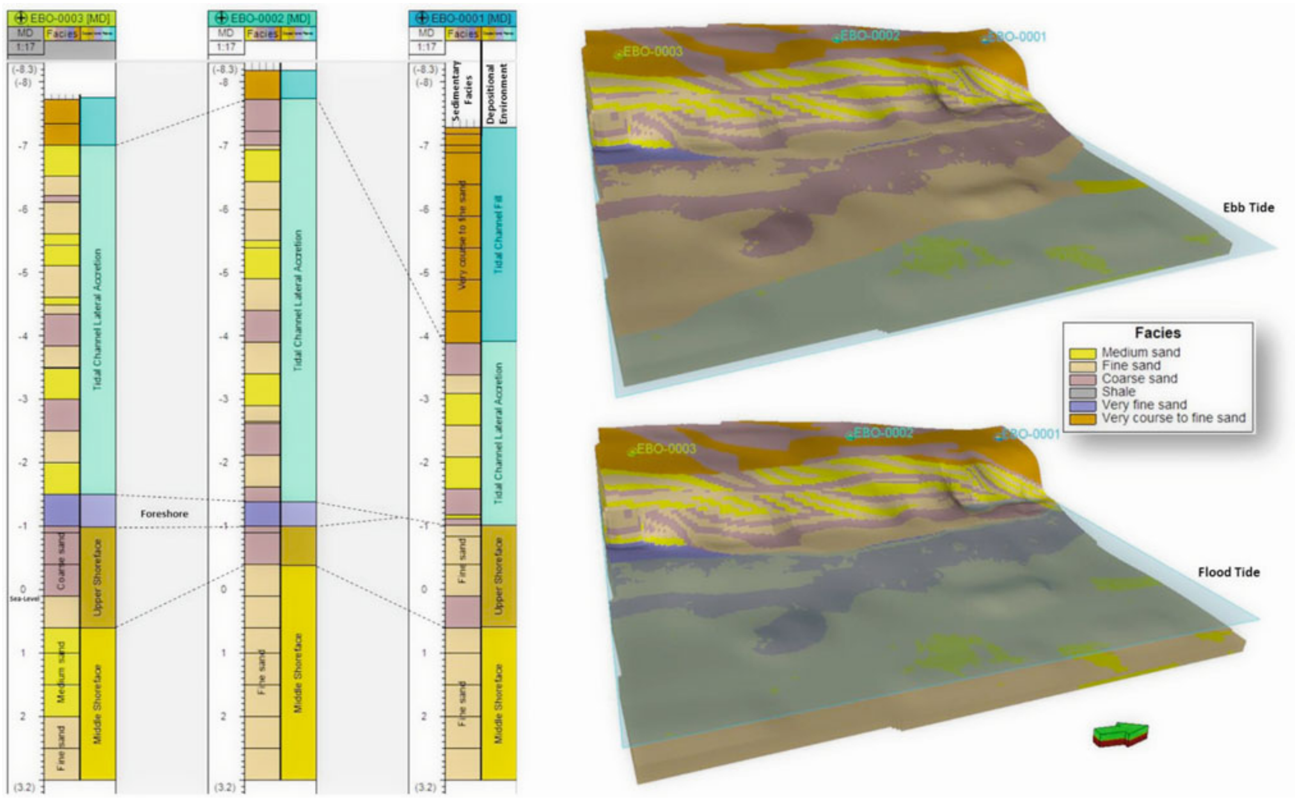

Fig. 1.17 Three measured sections along with the Enjefa Beach outcrop model. Note the inclined lateral accretion surfaces, the erosional nature of the capping tidal channel facies, and the present-day tidal range. After Amer et al. (2019b)

accretion and accommodation space. The model is capped by the tidal channel facies that express an erosional base nature, especially towards the northern end of the model. The authors also developed a synthetic seismic 3D model for the Enjefa Beach outcrop and used it for the base to understand similar sedimentary processes in the subsurface, making the Enjefa Beach a good analogue for subsurface shoreface and tidal facies.

1.8 Conclusion

Despite the numerous previous geological works and research conducted throughout the past decades, Kuwait's surface geology and stratigraphy are still poorly illustrated. Further modern and sophisticated studies are needed to enhance these domains. Several of the cited research in this chapter that demonstrates the fundamentals of the surface geology of Kuwait in various locations are relatively outdated. These researches were conducted during the past few decades of the past century (60s, 70s, 80s, and 90s). Therefore, it is essential to revisit and refine these previous studies using modern methods and technologies unavailable in the past. Despite the few recent attempts that were made to overcome this matter (e.g., Khalaf et al., 2017, 2019; Amer et al., 2019b; Al-Hajeri et al., 2020), many early discussed areas are still in great need of further advanced and thorough studies covering all aspects of Kuwait's surface geology. Furthermore, the surface stratigraphic nomenclature of Kuwait rock units is another aspect that requires refining and re-establishing. The stratigraphic nomenclature of surface rock units of Kuwait—as discussed earlier—was established based on lithostratigraphic correlation to neighboring Saudi Arabia, Iraq, and Iran. This correlation must reassess, and more accurate modern methods must be applied to establish a better well-defined correlation and nomenclature. The contacts between the Kuwait Group's formations are also not well assigned and require more reevaluations. The naming of these formations (e.g., Ghar, Lower Fars, and Dibdibba) is also uncertain as the definitions of these formations' contacts are unclear and not well assigned. Several authors used different names for the same formations and different ages as well. Additionally, the age dating of most of Kuwait's surface rock units lack accurate estimation. Very few recent attempts were made to age date some of these formations to constrain a better understanding of Kuwait's surface and near-surface geology and stratigraphy (e.g., Amer et al., 2017, 2019b; Amer & Al-Hajeri 2019; Tanoli et al., 2019); however, many of the previously discussed outcrops are not yet accurately age dated in Kuwait.

Furthermore, the linkage between the exposed rock units and their presumed subsurface equivalent units is still not well established and requires further studies.

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