



Abstract

Despite the surface geology of Kuwait appears to be scarce and most of the country is covered with Quaternary deposits except for a few outcrops of Oligo-Miocene to Pleistocene age, the subsurface geology of Kuwait is quite unique and astonishing. The discovery of hydrocarbon in Kuwait at the beginning of the last century helped geologists to better understand the structural geology of Kuwait especially by utilizing geophysical methods such as potential field methods (e.g., gravity and magnetic) and seismic reflection. Being part of the Arabian Peninsula, the structural geology of Kuwait shares many of the Arabian Peninsula structural trends. The dominant N-S trending structures of the Arabian Plate are manifested in the Kuwait Arch which is one of the major structures of the country where many of the oil and gas oil fields are associated with. Other dominant structural trends of the Arabian Plate such as NE-SW and NW-SE are resembled in Kuwait as Jal Az-Zor and Dibdibah Trough, respectively. Paleo- and in-situ stress analysis is an important subject for oil and gas exploration, and many studies have been commissioned to better understand them in most of the Kuwaiti fields. The present-day in-situ stress in Kuwait is oriented NE-SW resembling the current tectonic setting of the region due to the collision of the Arabian Plate with the Eurasia Plate since the Oligocene. This chapter will present a thorough review of the previous studies discussing the surface and subsurface structural geology of Kuwait.

M. Naqi (✉)
Department of Earth and Environmental Sciences, Kuwait
University, P.O. Box 5969 13060 Safat, Kuwait
e-mail: m.naqi@ku.edu.kw

A. Amer
Schlumberger, East Ahmadi, Block No. 6 - Building 193, 194,
P.O. Box 9056 61001 Ahmadi, Kuwait

5.1 Introduction

Kuwait is located in the north-eastern region of the Arabian Peninsula (Fig. 5.1).

Geologically, Kuwait is suited as part of the Arabian Plate which was part of the Proterozoic Gondwana Supercontinent through most of the Phanerozoic. Therefore, it shares the geological history and the tectono-stratigraphy of the Arabian Peninsula.

Even though the surface geology of Kuwait looks scarce and most of the country is covered by Quaternary deposits except for a few outcrops of the Oligo-Miocene to Pleistocene age, the subsurface geology of Kuwait is quite unique and astonishing. Interests of the geology of Kuwait started in the early 20th century (around 1914) during the exploration of oil in the region and after the discovery of oil in Iran in 1908 (Milton, 1967). Few geological reconnaissances have been prepared to understand the geology in Kuwait by the British and Americans. In 1914 S. L. James, who held a British Admiralty commission, recommended shallow wells to be drilled based on oil seepage (Milton, 1967). Oil seepages were described in two locations near Bahrah—north of Kuwait Bay—and Burgan area—south of Kuwait. Further investigations of Kuwait were made in 1917 by S. L. James and G. W. Halse; in 1926, by B. K. N. Wyllie and A. G. H. Mayhew; in 1931, by T. Dewhurst; and in 1931–32, by P. T. Cox (Milton, 1967). Also, based on the surface geological survey, a gentle anticline in the Miocene Formations at the Bahrah area was identified (Fox, 1956). This preliminary surface geology survey provided limited surface evidence of structures; thus, it was decided to drill a test hole in the Bahrah area, north of Kuwait Bay in 1936 along with the geophysical survey. The geophysical survey included gravity, magnetic and seismic surveys (Boots & McKee, 1946).

After the successful discovery of commercial oil in 1936, more geological studies were a must to improve the understanding of the subsurface geology of Kuwait especially by



Fig. 5.1 Digital Elevation map of the Arabian Plate with the main plate boundaries. The Arabian Plate is bounded from the northeast by collision margin of Zagros Fold and Thrust Belt. Rift margin to the west

and southwest, Red Sea and Gulf of Aden, respectively. Strike-slip margin of the Dead Sea to the northwest (Modified after Sharland et al., 2001)

utilizing more sophisticated geophysical methods such as gravity, magnetic and reflection seismology. This has revealed the complicated geological history of Kuwait and resulted in major oil and gas discoveries over the past several decades which made Kuwait one of the major oil exporters in the world.

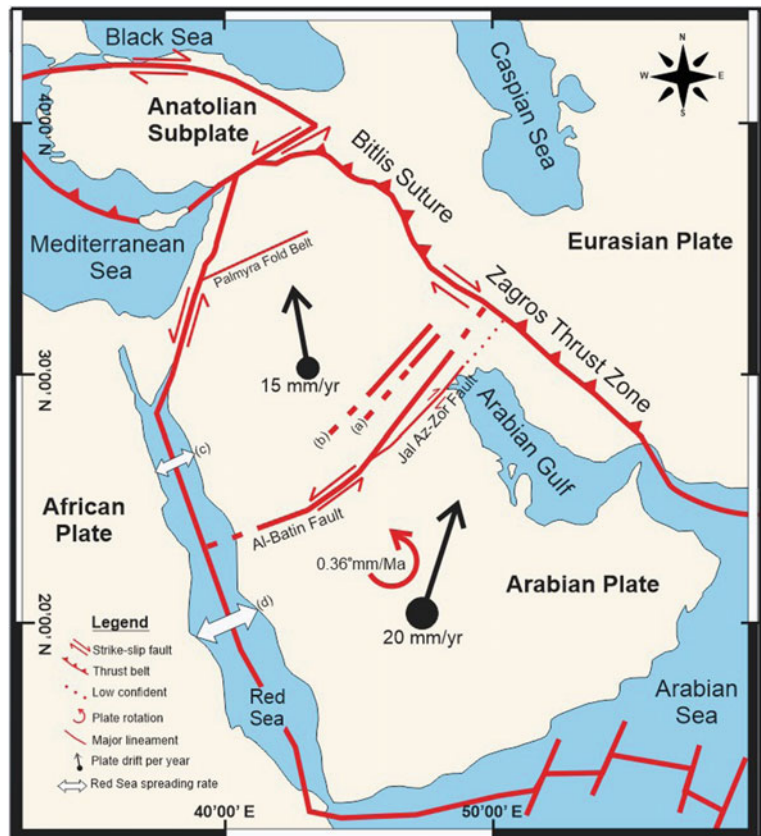
This chapter will review and summarize the regional tectonics settings of the Arabian Plate and the structural elements of the State of Kuwait. Discussing the development and evolution of the major surface and subsurface structural elements of the country through the geological history. Geological evidence reveals that the structural geology of Kuwait and the major structural trends were shaped since the Precambrian and many of the subsequent structural pulses reactivated those structures. Concluding with shedding the light on some geomechanical aspects; present-day in-situ stress and paleostress. These studies have grown in the past

decade and shown their significance in order to improve oil recovery and to minimize risks related to Hydrocarbon exploration and production.

5.2 Geological Settings

The Arabian plate is bounded by different structural regimes (Figs. 5.1 and 5.2); from the north and northeast margins by a compressional tectonic setting forming the Bitlis Suture and eastward by the Zagros Fold and Thrust Belt and to the east with the Makran subduction zone, where the subduction occurs in the Gulf of Oman; the Owen Fracture Zone and Gulf of Aden rifting to the south and southwest, and to the west the Red Sea rift system and the Gulf of Aqaba and the Dead Sea transform fault to the northwest. The Arabian Plate has been a coherent and potentially stable block since the

Fig. 5.2 Arabian Plate tectonic boundaries and kinematics (after Amer & Al-Hajeri, 2020)



end of the Precambrian. The entire Middle East region was an integral part of the African Plate throughout most of the Phanerozoic. The separation of the Arabian Plate from the African Plate took place by the rise of the Afar Region triple junction in the Cenozoic (25–30 Ma ago). Since that time, the plate has rotated anticlockwise and drifted north, currently at a rate of 2–3 cm/year (Fig. 5.2) (Bird, 2002).

As part of the Arabian Plate during most of the Phanerozoic time, Kuwait's structures and tectonics capture the complex geological history of the region. The manifestation of the geological record, in both surface and subsurface, represents several long-term periods of tectonic deformation intermitted with periods of relative quiescence.

The Arabian Plate formed during the late Precambrian by suturing of several basic volcanic and plutonic terranes (Haq & Al-Qahtani, 2005; Stern & Johnson, 2010). The main structural elements were formed during the formation of the Arabian Shield trending northeast and north-northwest basement sutures (Al-Husseini, 2000; Ziegler, 2001).

The Najd strike-slip system took place during the late Precambrian time, which is observed from Egypt to Oman, and might have a continuation into the Indian Plate (Al-Husseini, 1988, 2000). The Najd strike-slip system deformation was accompanied by the evolution of rift basins where the Hormuz and Ara salt were deposited. The deposition of thick Precambrian Hormuz salt might play a role in

the architecture of some of the oil field structures in Kuwait (Fox, 1956; Murriss, 1980; Singh, 2012).

Another significant structural pulses that widely influenced the Arabian Plate and resembled the structural geology of Kuwait was the so-called Hercynian Orogeny, which took place during the Late Devonian to Permian in North America and Europe. However, the timing of this Orogeny in the Arabian Plate is more restricted to Late Devonian through Late Carboniferous forming multiple episodes of compression and faulting (Haq & Al-Qahtani, 2005; Stern & Johnson, 2010). This deformation pulse formed a major unconformity in the subsurface of the Arabian Plate (Haq & Al-Qahtani, 2005) and reactivated many of the north-south trending structures that were initially formed during the Precambrian assembly of the Arabian Plate. In Burgan and Umm Gudair area, in Kuwait, the Permian Khuff Formation unconformably overlies altered basic igneous rocks and older clastic of presumably of Proterozoic age, while in the north of Kuwait Arch Khuff overlies Permo-Carboniferous Unayzah Formation (Tanoli et al., 2015). This observation along with regional analogues and Gravity-Magnetic data can be interpreted that the proto-Burgan structure was reactivated during the Hercynian Orogeny (Tanoli et al., 2015).

From the thickness variation of the Triassic Sudair and Lower Jilh Formations, where both formations are thinner over the Kuwait Arch and thicker on both sides, Dibdibba

Trough to the west and eastward in the offshore trough. This variation indicates that the Kuwait arch remained relatively higher during that time. However, during Late Triassic to Late Jurassic, little tectonic activity took place on the Arabian plate during this time and the Kuwait Arch was mainly inactive during this period (Tanoli et al., 2015).

A compressive regime was developed in the Arabian plate during the Late Cretaceous because of the convergence between the Asian and Arabian Plates which resulted in the obduction of the Ophiolite sequence of the Neo-Tethyan oceanic crust in the northeastern margin of the Arabian Plate (Haq & Al-Qahtani, 2005; Sharland et al., 2001). This compressive regime is called Alpine-1 Orogeny. Uplift and erosion took place over many of the reactivated structural highs due to the compressive stress and were recorded as Pre-Aruma Unconformity. This Unconformity is well demonstrated at the Burgan and Magwa structures where onlaps are clearly observed, on seismic data, on the eastern and western sides of the structures. The Alpine-1 structural event is captured in Kuwait by the accentuation of earlier structures in a more NW-SE trend. Many of the older structural highs such as Burgan, Minagish, Umm Gudair, Raudhatain and Sabriyah were strongly reactivated (Tanoli et al., 2015). The majority of these faults ceased at the Late Cretaceous Tayarat Formation.

The Alpine-2 Orogeny took place in Late Eocene to the present day. The Arabian Plate began to collide with Asia and the closure of the Neo-Tethyan Ocean was complete by the Late Oligocene. The development of the Zagros Fold and Thrust Belt is directly associated with this Orogeny (Richard et al., 2014) and caused uplift and erosion in Kuwait developing into the top Dammam Unconformity. Most of the major structures, in Kuwait, show truncation and gentle arching over them. This compressive tectonic event led to the inversion of many normal faults and amplified anticlines at the Jurassic section and the development of long wave anticline in the shallower successions (Tanoli et al., 2015).

5.3 Basement Structural Configuration and Trends

The Arabian Plate is divided into the Arabian Shield to the west and the Arabian Platform to the east (Fig. 5.3). Basement structural trends vary across the Arabian Peninsula. In the west where the Arabian shield is present, basement structures such as folds, faults, shear zones and dykes can be well identified, and their orientation can be easily determined by direct observation. However, to the east and north of the Arabian shield, where Kuwait is located, the basement is covered, and structural trends can only be inferred from geophysical methods e.g., magnetic, gravity, and seismic data, and as a result, are less well known.

The Arabian Plate is characterized based on basement structural trends into three main basement structural domains (Stern & Johnson, 2010) (Fig. 5.3). Stern and Johnson (2010) divided the domains as follows: (1) The Arabian Shield and the south-central part of the Arabian platform which is characterized by northerly and northwesterly structural trends; (2) a north-central domain marked by northerly structural trends and a broad northeasterly trend; and (3) northeasterly dominated structural trends in the eastern domain. Based on this classification, Kuwait is located in the north-central domain where the basement structures are dominated by northerly and northeasterly trends such as Ahmadi ridge, Kuwait Arch (Khurais-Burgan anticline) and Al-Batin Arch.

The Arabian Plate crustal thickness varies. The thickest part is under the Arabian Platform and thins toward the west near the Red Sea. Several studies have been conducted to measure the crustal thickness of the Arabian Plate (Stern & Johnson, 2010), finding that the Arabian Plate crustal thickness reaches about 22 km near the Red Sea and 53 km in the eastern part of the Arabian Plate. Pasyanos et al. (2007) measured the crustal thickness beneath Kuwait by using surface waves and receiver-function data and concluded that 8 km sediments overlaying 37 km thick crust. On the other hand, Midzi (2005) utilized receiver function techniques to teleseismic arrivals at six seismic stations and found out the crust was about 42.6 ± 1.8 km thick beneath Kuwait. Sediment thickness in Kuwait is between 7 and 8 km based on seismic methods (Pasyanos et al., 2007, Laske & Masters, 1997).

5.4 Structural Architecture and Elements of Kuwait

5.4.1 Kuwait Arch

One of the major structural expressions manifested in Kuwait is the N-S trending Kuwait Arch (Fig. 5.4) representing the northern end of the giant Khurais-Burgan Anticline, a structure that is underlain by faulted Precambrian basement blocks. The Khurais-Burgan structure is about 500 km long, and tens of kilometers wide (Al-Husseini, 2004). This structure along with the other N-S trending structures (e.g., Summan Platform, Hawtah and En Nala Ghwar structures) is bounded by an ancestral fracture system of N-S trending faults that formed in the late-Proterozoic Amar Collision between about 640 and 620 Ma (Al-Husseini, 2000) and most likely rejuvenated during the mid-Carboniferous compressional structural pulse (Al-Husseini, 2004).

Kuwait Arch has a relief of about 100 meters (m) south of Kuwait. This structural high was first captured by Warsi (1990) via gravity survey. His Bouguer anomaly map

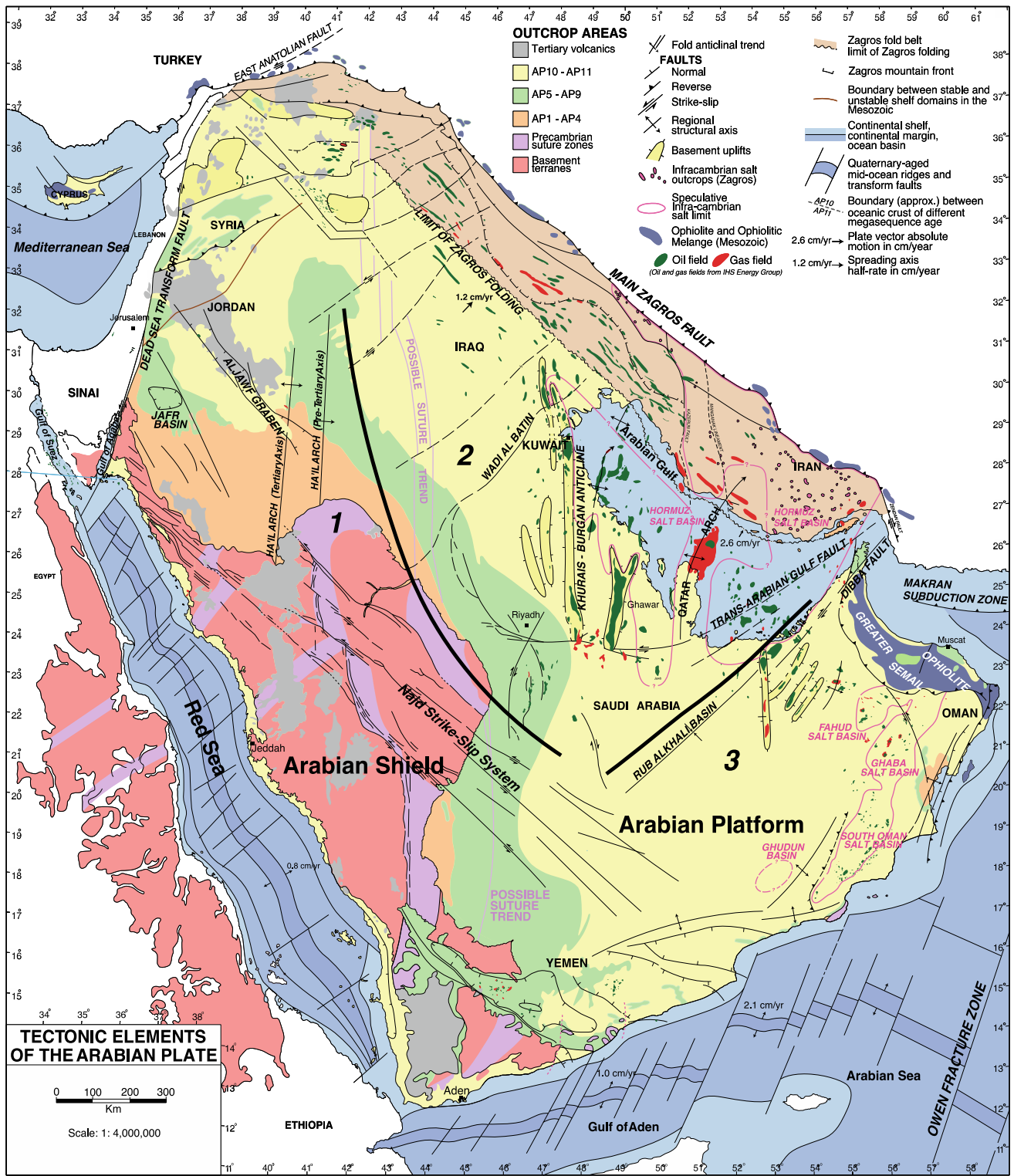


Fig. 5.3 Tectonic elements of the Arabian plates showing the main structural trends. Also, showing three structural domains (after Stern & Johnson, 2010)

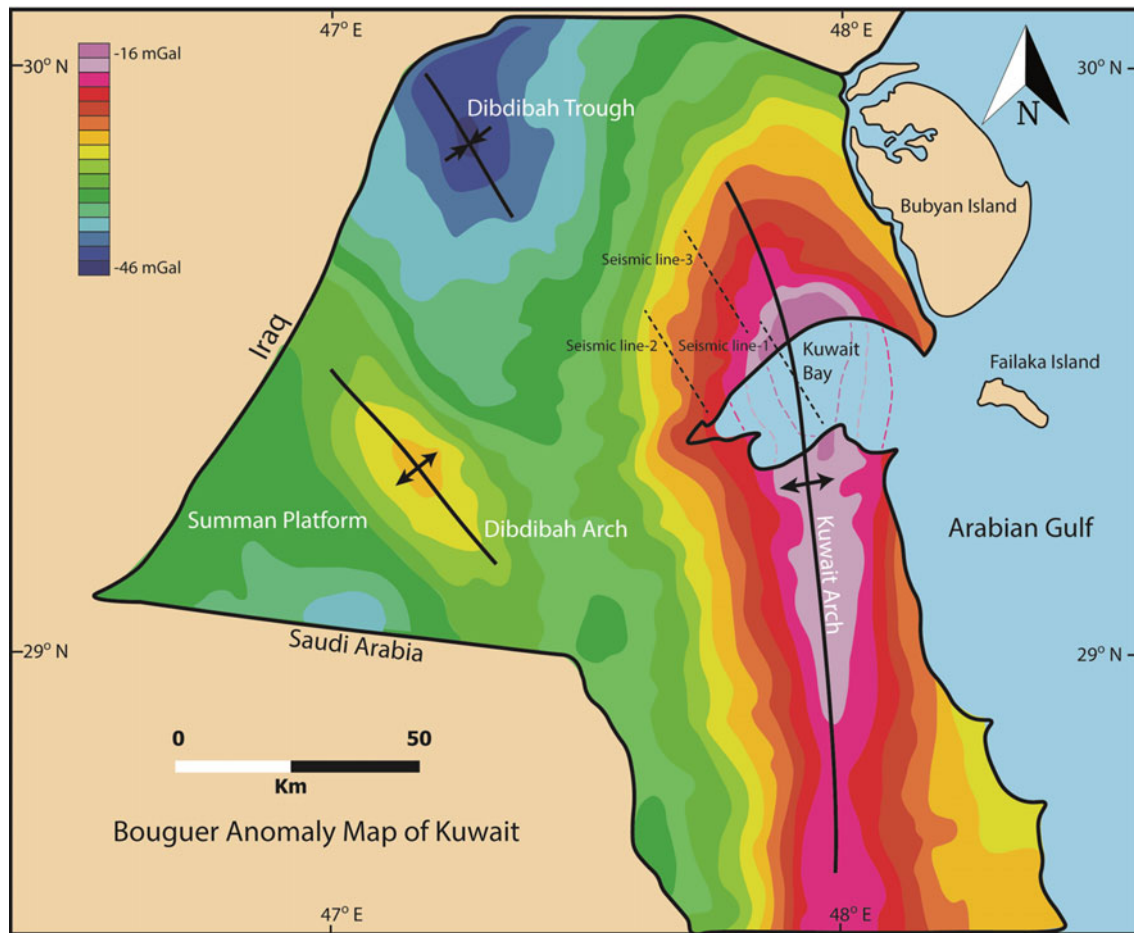


Fig. 5.4 Bouguer map of Kuwait showing the major structural elements of the State of Kuwait trending N-S and NNW-SSE (after Warsi, 1990). Dashed lines are location of seismic lines in Fig. 5.7

(Fig. 5.4) shows that the crestal area of the arch is located within Kuwait Bay. While subsurface seismic and well data indicate that the center of the Arch is located to the south in the Kuwait-Saudi Partitioned Neutral Zone (PNZ) (Carmen, 1996). The geometric configuration of Kuwait Arch resembles asymmetric where its western flank dips about 2° – 3° and the eastern flank shows a steeper dip of about 10° . Many of Kuwait oil fields are associated with Kuwait Arch e.g., Burgan, Magwa, Ahmadi, Bahrah Sabriyah, Raudhatain, and Wafra oil fields (Fig. 5.5).

Amer and Alhajeri's (2020) study shows that the thickness of the middle Eocene Damman Formation is relatively constant suggesting the structural quiescence of Kuwait Arch during its deposition. However, the drastic decrease in thickness of the overlain Kuwait Formation indicates the reactivation of the Kuwait Arch during Late Eocene to

Pliocene. This structural reactivation could be associated with the Alpine-2 structural pulse in the Arabian Peninsula region (Richard et al., 2014).

5.4.2 Dibdibba Trough

Dibdibba Trough is a major structural element in the state of Kuwait (Fig. 5.4). It is located to the west of Kuwait Arch and east and northeast of Summan Platform and it might be related to the Najd fault system. It is trending NNW-SSE. It is estimated that the maximum sedimentary thickness reaches up to 28,000 feet in the central part of Dibdibba Trough (Singh et al., 2011). Along the center of the Trough, West Kuwait High is located. This High comprises of Minagish, Kra Al-Marzu and Khabrat Ali structural highs that



Fig. 5.5 Major and minor oil fields of the State of Kuwait

trending NNW. These structures were likely formed and modified by reactivation of basement faults and by the halokinesis of the Infracambrian Hormuz salt during major tectonic episodes (Tanoli et al., 2015).

5.4.3 Summan Platform

This structure located west of Kuwait Arch (Fig. 5.4) and extends to the south into the northeastern part of Saudi Arabia where the Summan Platform is bounded by N-S trending faults following the Late Proterozoic structural grain. These faults were reactivated during the mid-Carboniferous tectonic pulse (Al-Husseini, 2004). It is located on the western side of Kuwait and is characterized by a gradual rising basement to the west.

5.4.4 Wadi Al Batin

Wadi Al Batin is located west of Kuwait forming a natural boundary between the State of Kuwait and Iraq (Fig. 5.6). The wadi exhibits a linear, steep-sided valley about 5–10 km wide and trends N35 °E with a relief of about 60 m. It can be traceable for 700 km on satellite imagery from Saudi Arabia and extends to the south of Iraq (Al-Sarawi, 1980). It might represent the northern continuation of Wadi Ar-Rimah in Saudi Arabia. Parts of the Wadi are covered by Quaternary and Tertiary gravels of igneous and metamorphic rock that have been transported by large streams from the Saudi Arabian and Syrian deserts during Pleistocene pluvial episodes (Holm, 1960). From Seismic and water well draw-down data Al-Sarawi (1980) identified three en-echelon faults trending northeast with a throw of about 25 m to the

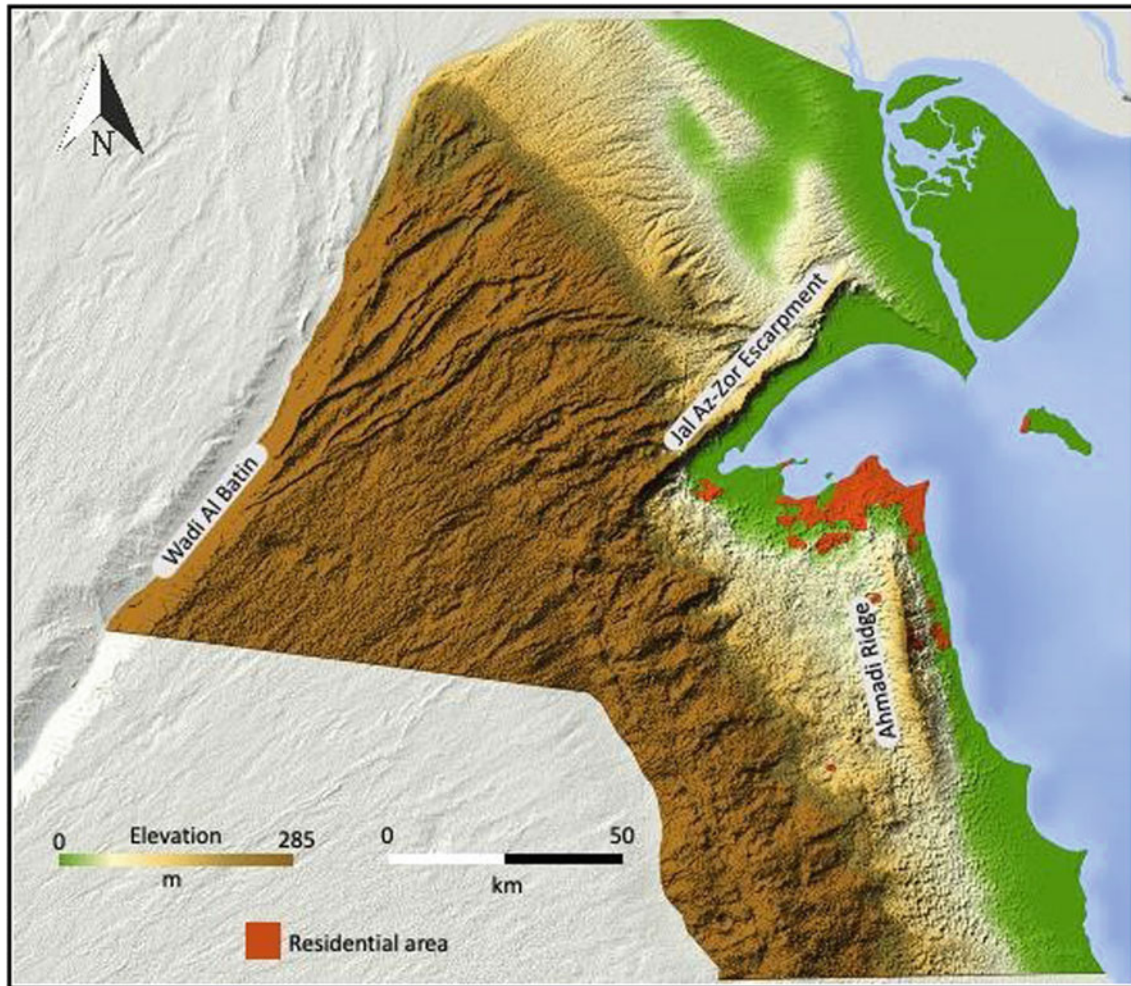


Fig. 5.6 Topographic map of the State of Kuwait showing the main geomorphological features; Wadi Al Batin, Ahmadi Ridge and Jal Az-Zor escarpment

southwest. He assigned the age of the faults to be Late Eocene to Miocene, although minor movement may have continued during Pliocene. The trend of these faults is similar to the major basement faults system in Saudi Arabia (e.g., Wadi Ar-Rimah). Hancock et al. (1981) proposed a 20 km of sinistral offset along a strike-slip fault, positioned along the continuation of Wadi Al Batin in Saudi Arabia, based on outcrop contacts of Cretaceous and Paleogene and Paleogene and Neogene strata. In addition, a few small faults cutting the Neogene rocks of the wadi was identified from the high pass, filter band 7, Landsat image 179 (path)/40 (row) from the Saudi Arabia mosaic (Hancock et al., 1981).

5.4.5 Jal Az Zor

The Jal Az-Zor escarpment (Fig. 5.6) represents the most prominent surface rock exposure in Kuwait. It extends for about 60 km from the north of Al-Jahra to the Al-Sabiyah

area, trending NE-SE parallel to the northern shore of Kuwait Bay, forming a cliff that reaches about 36m high (Amer & Al-Hajeri, 2020). Several studies investigated the origin of the Jal Az-Zor escarpment (Salman, 1979, Al-Sarawi, 1982; Carmen, 1996; Amer & Al-Hajeri, 2020) proposing a range of scenarios. Al-Sarawi (1982) proposed based on the lithostratigraphic correlation between several wells drilled around the escarpment, suggesting that origin of the Jal Az-Zor escarpment to be the retreat of a major fault lineament located offshore in the center of Kuwait Bay during the Neogene through erosion to its current position. Bou-Rabee and Kleinkopf (1994) based on free air and Bouguer gravity anomaly proposed that the Jal Az-Zor escarpment is a surface expression of a basement strike-slip fault with minor displacement. Based on NW-SE 2D seismic section acquired in 1960s, Al-Anzi (1995) proposed the occurrence of a series of wrench faults with no major throw close the Jal Az-Zor escarpment without surface expression. However, this interpretation was based on notably poor-quality seismic data

(Amer & Al-Hajeri, 2020). Carman (1996) also placed the Jal Az-Zor fault in the center of Kuwait Bay.

Amer and Al-Hajeri (2020) from reprocessed seismic data were able to clearly identify faults and their associated structures beneath the Jan Az-Zor escarpment. From 3 seismic lines across the escarpment (Fig. 5.7), they interpreted the existence of detachment folds, recumbent folds, thrust faults, and fault propagation folds, forming a complex duplex system within the upper Dammam Formation below Jal Az-Zor (Fig. 5.8). They suggested that the present-day relief of Jal Az-Zor is a manifestation of fault kinematics along with complex folding as a result of increased basal friction towards the south. They also indicated based on 2D structural restoration and balancing along with GPS velocities and vectors for the Arabian Plate that the layers under Jal Az-Zor escarpment accommodated about 6.25 km of shortening that occurred within the last 1 Ma.

5.5 Kuwait Tectonic Stresses

Having discussed the various structural elements over Kuwait, in this section in-situ stress will be discussed and its relation to Kuwait's surface and subsurface geology. The following section will be divided into two parts, the first will discuss the present day in-situ stress that effect Kuwait today. The second part will discuss the paleostresses or historic stresses that resulted in the formation of the fold and fault systems in the past but still observed today.

5.5.1 Present day In-Situ Stress

For decades in-situ stress measurements have been collected over the different hydrocarbon fields in Kuwait, using different techniques such as borehole images, caliper logs, and sonic logs. The borehole image logs are arguably the most effective measurement that can provide details on the stress direction by recognizing drilling induced features. Over electrical borehole image logs these features can range between borehole breakouts and drilling induced fractures (Amer & Alexander, 2005; Cesaro et al., 2000). Over vertical wells the borehole breakouts would indicate the minimum horizontal stress direction (S_{Hmin}), whereas the drilling induced fractures will indicate the maximum horizontal stress direction (S_{Hmax}) (von Winterfeld et al., 2005). Caliper and sonic logs, on the other hand, can only detect one of the in-situ horizontal stresses. Caliper logs for instance can only detect borehole breakouts, reflecting the minimum horizontal stresses (Plumb & Hickman, 1985), and sonic logs through dipole-shear anisotropy processing can detect the fast shear direction indicating the maximum

horizontal stress direction (Esmersoy et al., 1994, 1995). The overburden stresses or vertical stresses (S_v) is the last component of the 3 main principal stresses, and it generally determines the stress regime (Fig. 5.9). In Kuwait this stress exhibits a vertical direction and is calculated by the integration of the rock densities with depth, hence it increases as we go deeper into the earth's crust. The horizontal stresses magnitudes, on the other hand, are calculated using the poroelastic equation:

$$S_{Hmin} = \frac{\nu}{1-\nu}(S_v - aP_p) + \frac{1-2\nu}{1-\nu}aP_p + \nu E_{ps}e_{Hmax} + E_{ps}e_{Hmin}$$

$$S_{Hmax} = \frac{\nu}{1-\nu}(S_v - aP_p) + \frac{1-2\nu}{1-\nu}aP_p + E_{ps}e_{Hmax} + \nu E_{ps}e_{Hmin}$$

where plane-strain Young's modulus (E_{ps}); Poisson's ratio (ν); vertical stresses (S_v); Biot's coefficient (a); considering tectonic strains (e_{Hmax} and e_{Hmin}); pore pressure (P_p).

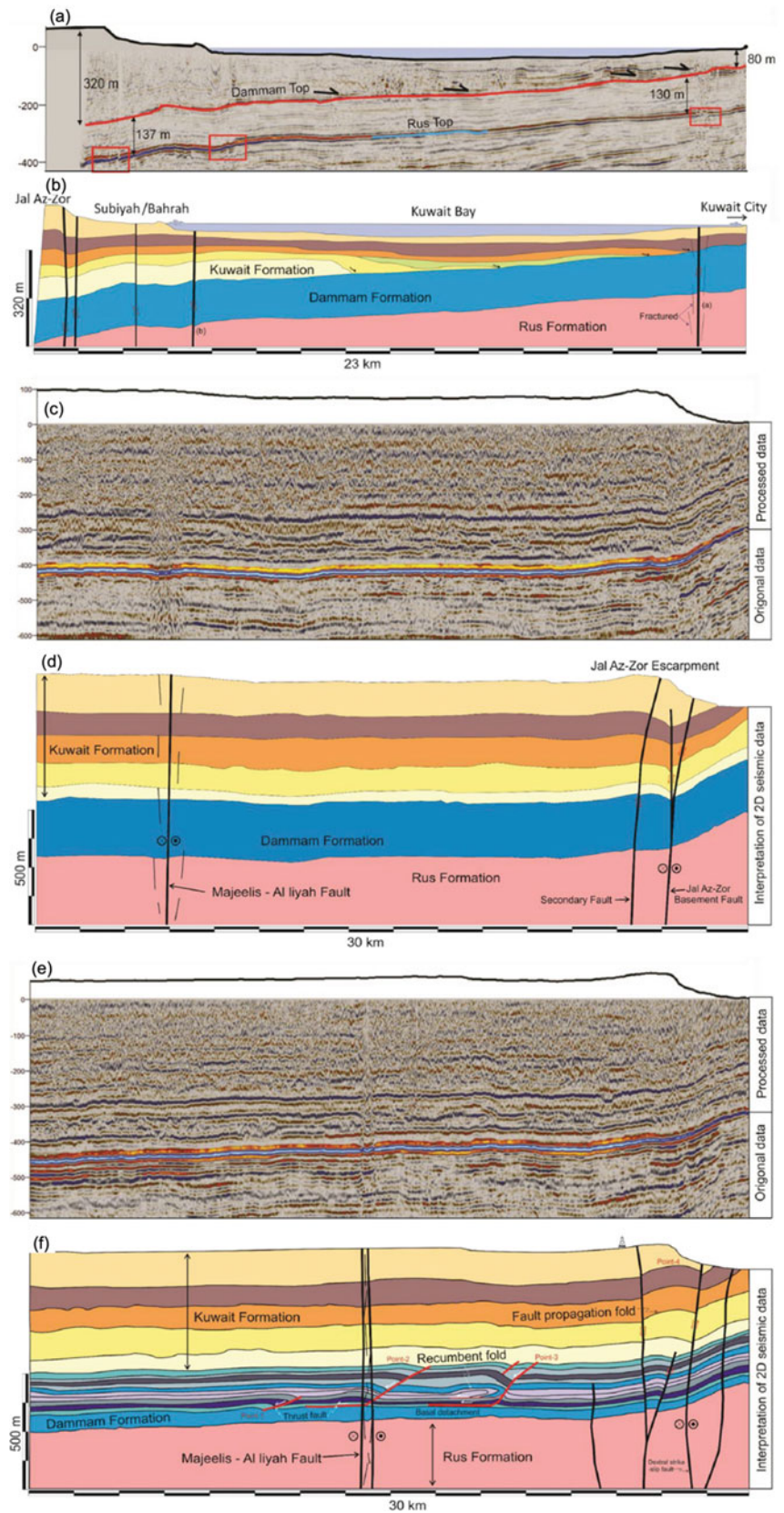
Young's modulus and Poisson's ratio can be either measured in the lab or calculated from openhole logs. The Biot's coefficient is best measured in the lab, but in most cases, it is equal to 1. The pore pressure is best measured using downhole pressure measuring tools or estimated using Eaton's method. Using these techniques, the stress magnitudes have been calculated over Kuwait and it shows a general strike-slip stress regime (Al-Kandary et al., 2012; Perumalla et al., 2014). However over specific zones along the stratigraphy of Kuwait this stress regime can change to normal or reverse depending on the proximity to the major fault plane and mechanical layering that can alter the stress regime and direction (Amer et al., 2013) (Fig. 5.10).

Several geomechanical studies have been commissioned by Kuwait Oil Company (KOC) to study the in-situ horizontal stresses over Kuwait (Al-Kandary et al., 2012; Amer et al., 2013; Carman, 1996; Dey et al., 2009; Perumalla et al., 2014; Richard et al., 2014).

Carman (1996) studied the structural elements of onshore Kuwait and identified the in-situ stress over the Cretaceous successes. Though he identified the stress over Minagish, Umm Gudair, Burgan, Magwa, Sabriyah, and Raudhatain fields (Fig. 5.5), due to its complexity and notable variation it was suggested that more work is required to explain the local variations (Fig. 5.11).

Al-Kandary et al., (2012) focused on the northern region of Kuwait and covered Abdali, Bahrah, Dhabi, Mutriba, Raudhatain, Ratqa, Sabriyah, and Umm Niqa fields. By focusing on the Jurassic and Cretaceous sections, the authors were able to identify discrepancies between the two sections. This was found to be a result of the stress decoupling as a

Fig. 5.7 Interpreted seismic sections across Jal Az-Zor escarpment showing the different structure in the subsurface (after Amer & Al-Hajeri, 2020). Location of the seismic lines are shown in Fig. 5.4



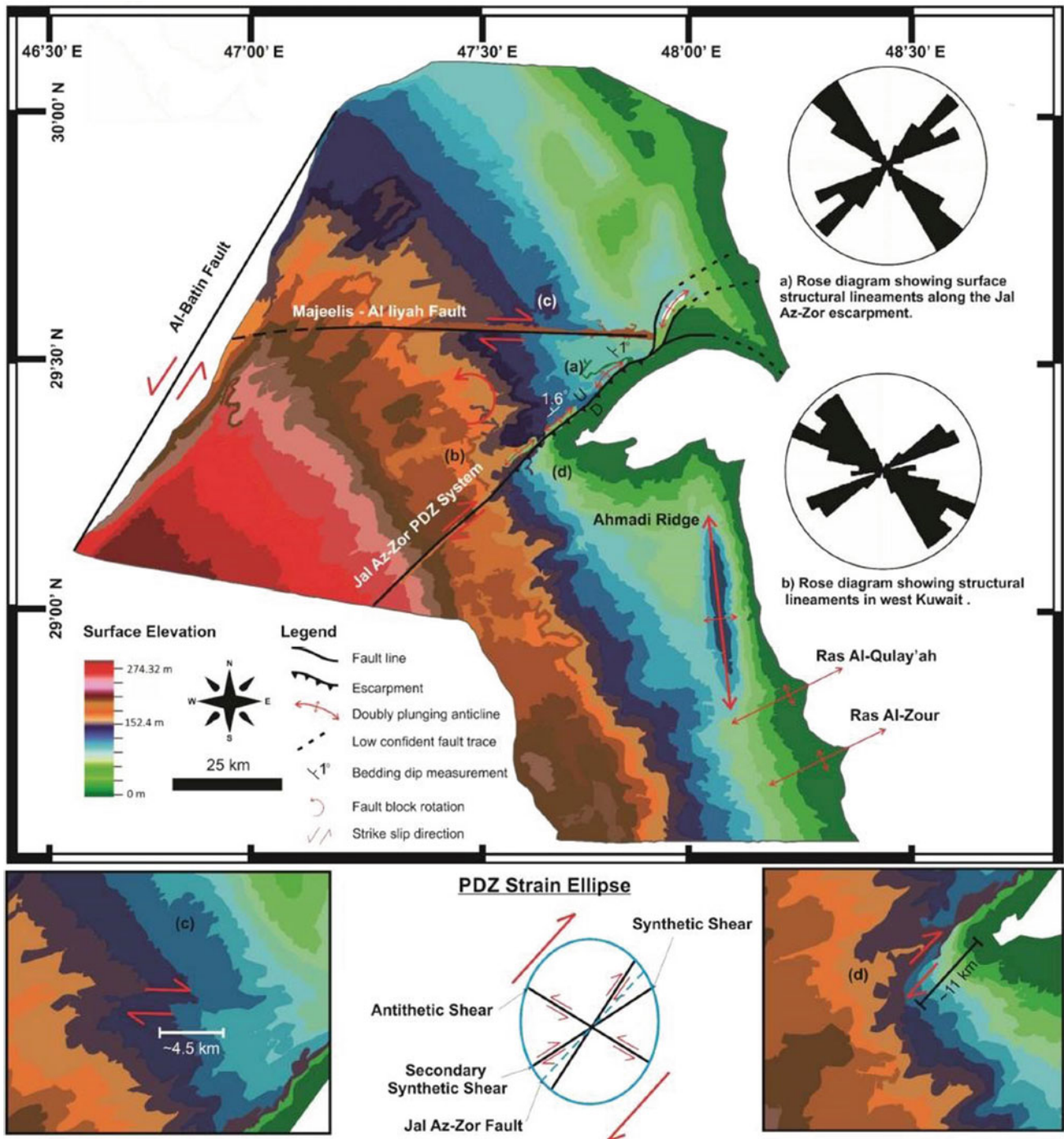


Fig. 5.8 Surface topographic contour map of Kuwait showing the interpreted structures from surface expressions (after Amer & Al-Hajeri, 2020)

result of the Gotnia Formation salt. Amer et al., (2013, 2014) confirmed this observation and documented a total of 1.8 km offset between the structural crests observed at the Jurassic Najmah Formation and the Gotnia Formation tops in the SW direction suggesting detachment at the base of Gotnia Formation associated with thrust faults (Fig. 5.12). Amer et al (2013) for the first time indicated the reserves stress regime

component that is intermittently observed especially over the Jurassic section, helping in forming a better understanding of Kuwait’s stress regime.

Perumalla et al. (2014) followed up on the work performed by Al-Kandary et al. (2012) and extended their quest to understand the stress regime for both Jurassic and Cretaceous sections for all Kuwait using a wider range of stress

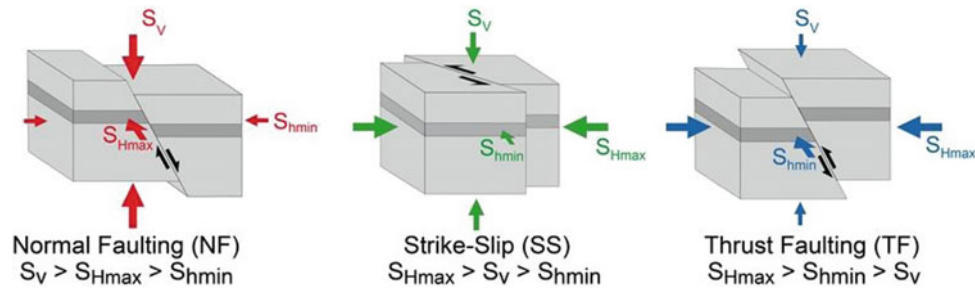


Fig. 5.9 The main principal stress regimes

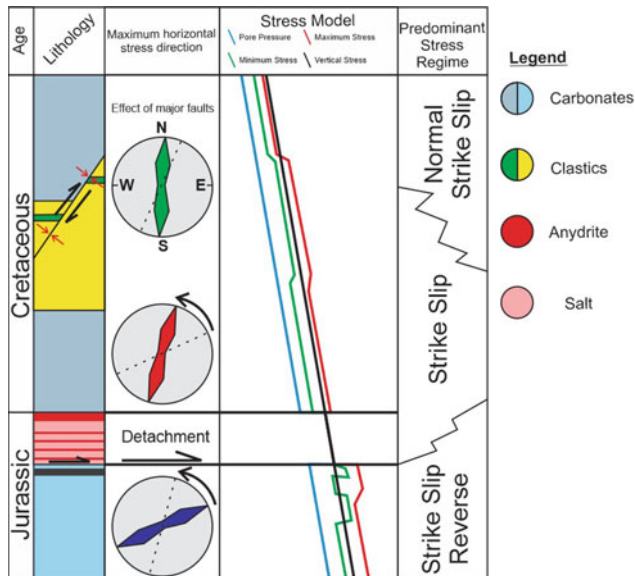


Fig. 5.10 Schematic representation of the Jurassic and Cretaceous section of Kuwait and the different maximum in-situ stress general change in direction in areas with significant detachment along Gotnia Formation (dominantly composed of salt). The illustration also shows the potential of stress rotation around major faults. The stress model shows the evolution of stress with depth and the predominant stress regime over each interval

measurements such as caliper logs and borehole images (Fig. 5.11). In general, they found that the vertical stresses (S_v) for the Cretaceous section is on average 19.5 ppg and for the Jurassic section it is 21 ppg. Such increase in the vertical stresses is expected as depth increase. The minimum horizontal stress (S_{hmin}) magnitude on average for the Cretaceous section is 16 ppg and for the Jurassic is 18 ppg. The increase can be attributed to the increasing pore pressure gradient with depth. And finally, the maximum horizontal stress (S_{Hmax}) magnitude for the Cretaceous is on average 20.5 ppg and for the Jurassic 24.3 ppg. Such increase is generally a result of the continues NE drift of the Arabian Plate towards the Eurasia plate combined with rotation (Amer & Al-Hajeri, 2020) (Fig. 5.2).

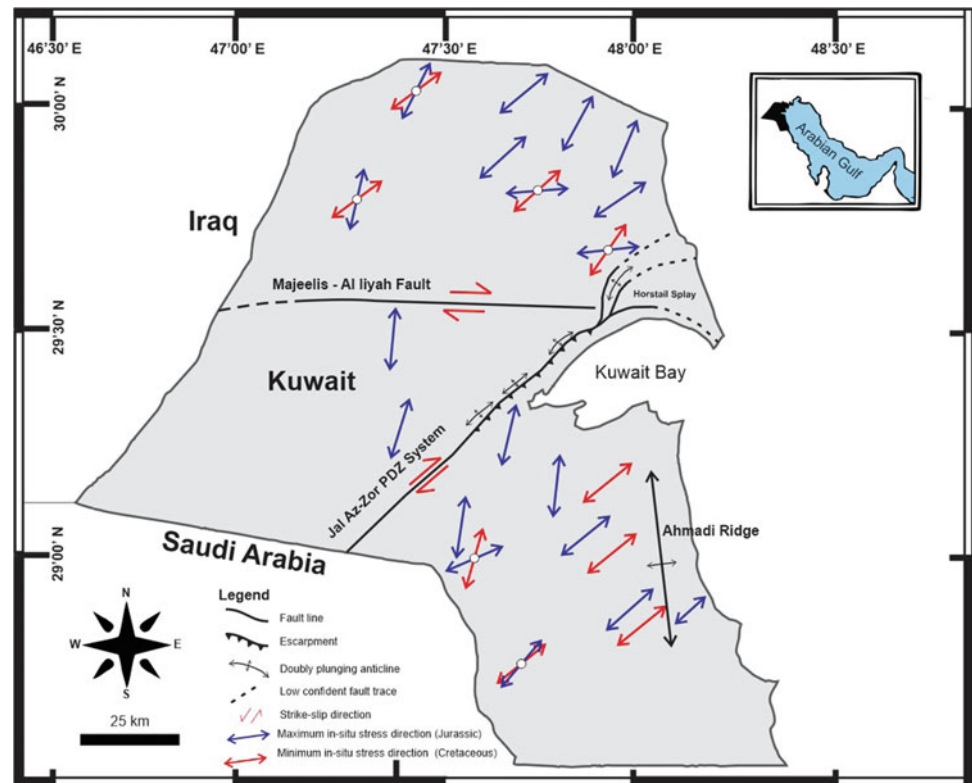
5.5.2 Kuwait Paleostresses

The paleostresses that effected the region of Kuwait during the Jurassic and Cretaceous are governed by transtensional tectonics (Alpine-1), whereas the mid-to-late Tertiary Kuwait is dominated with transpression (Alpine-2) (Amer & Al-Hajeri, 2020; Filbrandt et al., 2006; Richard et al., 2014; Sharland et al., 2001; Ziegler, 2001).

Based on the work of Richard et al. (2014) over Bahrah, Dhahi, Raudhatain, Sabriyah, and Umm Niqqa fields during the Jurassic the overall stress regime was characterized by an extensional stress regime setting associated with a N-S maximum horizontal stress direction (Fig. 5.13). This evolved to a transtensional stress regime during the Cretaceous that was associated with a NW-SE maximum horizontal stress direction (Al-Kandary et al., 2012; Perumalla et al., 2014; Richard et al., 2014; Verma et al., 2007). The final stress rotation event in Kuwait occurred during the Tertiary. These times were associated with a transpressional stress regime associated with the Oligo-Miocene Zagros Orogeny and exhibits a NE-SW maximum stress direction, which is consistent with the present day in-situ stress (Richard et al., 2014).

Abu-Hebail et al. (2018) attempted to model the paleotectonic stress history of the fault systems over Kra Al-Marū and Rikṣah structures, west Kuwait. This system area is characterized by a principal displacement zone that exhibits a NE-SW direction (Amer et al., 2013, 2014). The technique is based on a new generation paleostress inversion geotechnical based method (Maerten, 2010). The paleotectonic stress history inversion simulated over 1000 possible scenarios and resulted in a stress inversion plot that showed the structures analyzed where formed under a NE-SW stress orientation. The stress regime is characterized by normal and strike slip tectonics (transpressional stress regime). By combining the understanding of the geological stress history and paleotectonic stress history the timing of faulting or fracturing can be better assisted, which in this case is during the Tertiary (Fig. 5.14).

Fig. 5.11 Kuwait map showing major surface structural elements along with the Jurassic and Cretaceous present day horizontal in-situ stresses



5.6 Conclusions

Geologically, Kuwait is suited as part of the Arabian Plate which was part of the Proterozoic Gondwana Supercontinent through most of the Phanerozoic. Therefore, it shares the geological history and the tectono-stratigraphy of the Arabian Peninsula. The surface geology of Kuwait looks scarce and most of the country is covered by Quaternary deposits except for few outcrops of Oligo-Miocene to Pleistocene age however, the subsurface geology of Kuwait is quite unique and astonishing. Kuwait went through multiple structural episodes.

The oldest recorded structural pulse was during the formation of the Arabian Plate in the Precambrian. This pulse generated NE and N-NW trending structures (Najd Fault System). Another important structural pulse is the so-called Hercynian Orogeny, which took place during the Late Devonian to Late Carboniferous. This compressional event has reactivated many of the older structures that trend N-S. During the Jurassic and Late Cretaceous a transtensional tectonics event took place (Alpine-1), whereas the mid-to-late Tertiary Kuwait is dominated with transpression (Alpine-2).

One of the major structural expressions manifested in Kuwait is the N-S trending Kuwait Arch, representing the northern end of the giant Khurais-Burgan Anticline, a structure that is underlain by faulted Precambrian basement blocks. Many of Kuwait oil fields are associated with Kuwait Arch e.g., Burgan, Magwa, Ahmadi, Bahrah Sabriyah, Raudhatain, and Wafra oil fields.

Dibdibba Trough is a major structural element in the state of Kuwait, trending NNW-SSE. It is located to the west of Kuwait Arch and east and northeast of Summan Platform and it might be related to the Najd fault system.

The Summan Platform structure located west of Kuwait Arch and extends to the south into the northeastern part of Saudi Arabia where is the Summan Platform is bounded by N-S trending faults following the Late Proterozoic structural grain.

Another major structural element in Kuwait is Wadi Al Batin which is located west of Kuwait forming a natural boundary between the State of Kuwait and Iraq trending N35°E. From Seismic and water well drawdown data Al-Sarawi (1980) identified three en-echelon faults trending northeast with a throw of about 25 m to the southwest.

The Jal Az-Zor escarpment represents the most prominent surface rock exposure in Kuwait. Based on a recent study by Amer and Al-Hajeri (2020), they were able to clearly

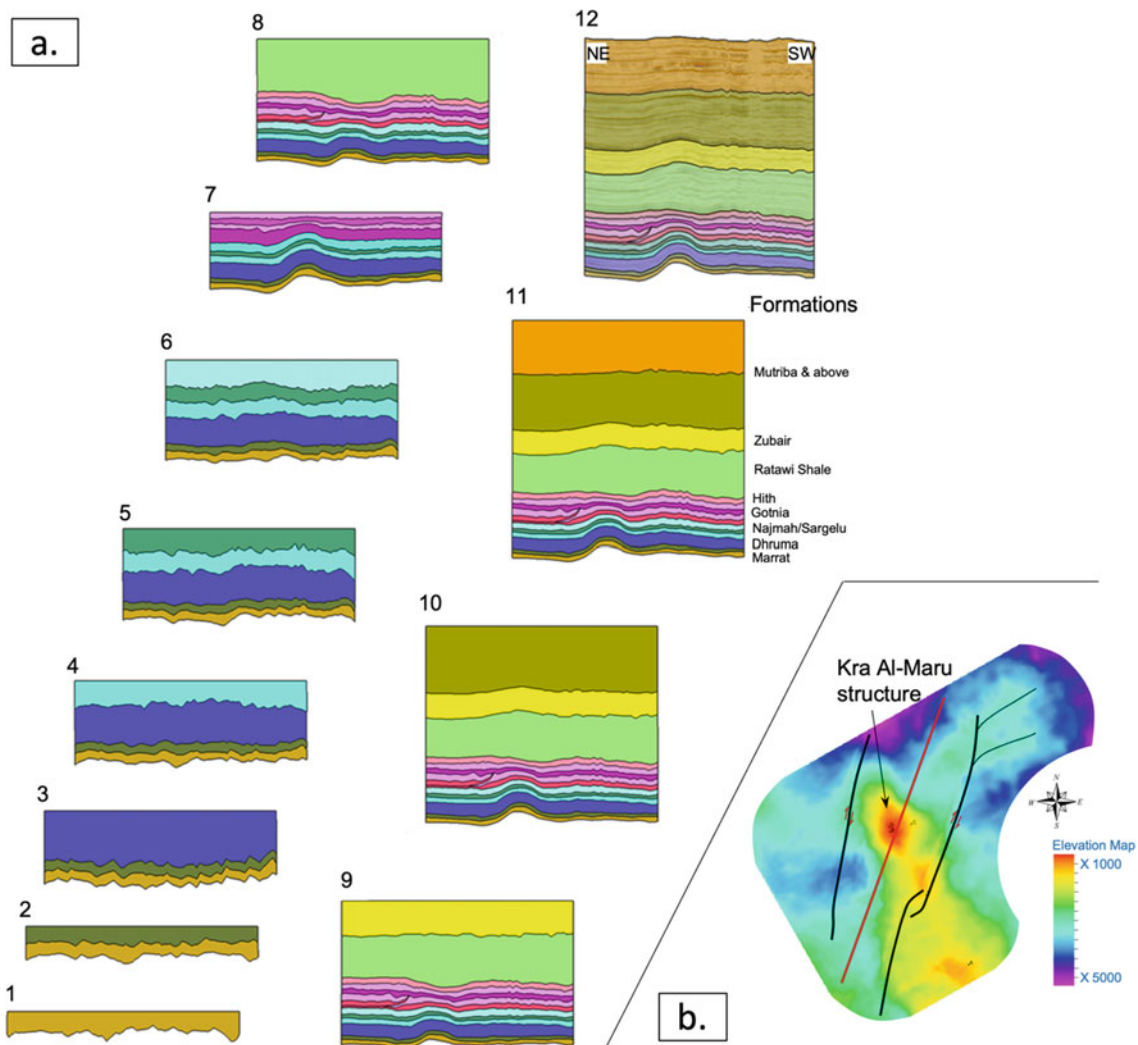


Fig. 5.12 a Structural restoration of Kra Al-Marzu field showing shift in the structural crest between Najmah and Gotnia formations, along with the thrust faulting at the base of Gotnia salts. b Elevation map

showing the location of the section in red crossing Kra Al-Marzu structure (see Fig. 5.5 for the location of the Kra Al-Marzu structure), (Amer et al., 2014)

identify faults and their associated structures beneath Jan Az-Zor escarpment. They interpreted the existence of detachment folds, recumbent folds, thrust faults, and fault propagation folds, forming a complex duplex system within the upper Dammam Formation below Jal Az-Zor.

For decades in-situ stress measurements have been collected over the different hydrocarbon fields in Kuwait, using different techniques such as borehole images, caliper logs, and sonic logs. The present day in-situ stress in Kuwait is

oriented NE-SW resembling the current tectonic setting of the region due to the collision of the Arabian Plate with the Eurasia Plate since the Oligocene. The stress magnitudes have been calculated over Kuwait and it shows a general strike-slip stress regime. However over specific zones along the stratigraphy of Kuwait this stress regime can change to normal or reverse depending on the proximity to the major fault plane and mechanical layering that can alter the stress regime and direction (Amer et al., 2013).

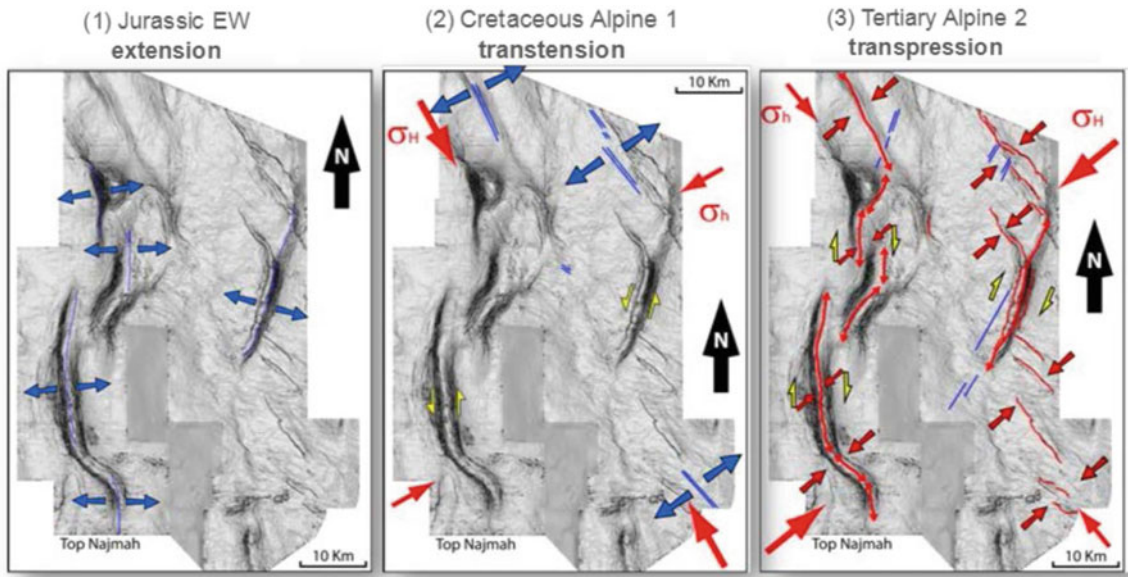
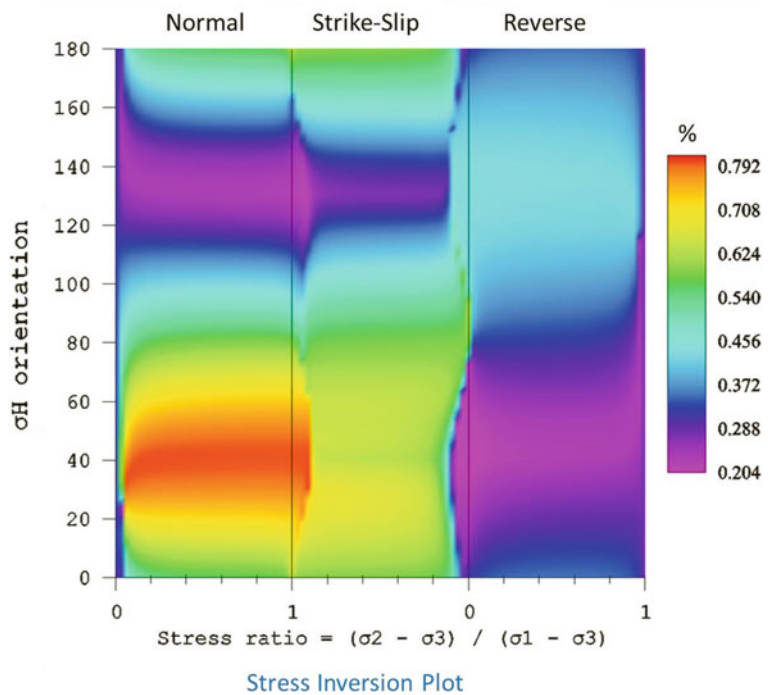
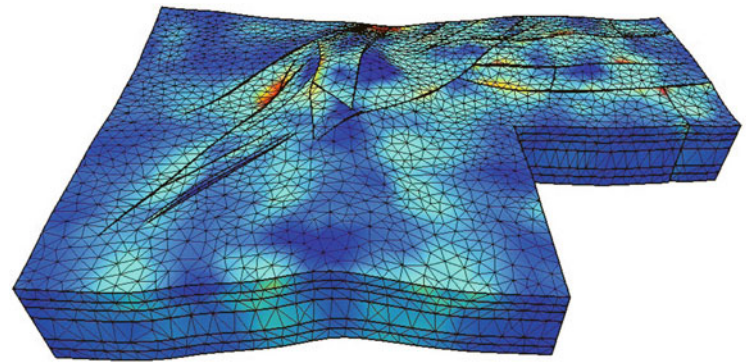


Fig. 5.13 Variation of the paleostress of Kuwait through time. (1) Extensional phase of deformation during the Jurassic with N-S maximum horizontal stress. (2) Transtensional phase of deformation during Cretaceous with NW–SE maximum horizontal stress. (3) Transpressional phase of deformation during the Tertiary with NE–SW maximum horizontal stress (after Richard et al., 2014)

Fig. 5.14 3D model for Kra Al-Marū and Rikṣah structures showing the major faults and stress inversion plot for the area. Note the red area represents the stress direction and regime, where a normal and strike-slip components is represented



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