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Structural Elements of Onshore Kuwait

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ABSTRACT

Five structural trends are recognized in Kuwait: (1) Three sub-parallel anticlinal trends (005°-015°) occur on the west flank of the Kuwait Arch and trap oil in Lower Cretaceous and Jurassic strata. (2) North-south trending structures, including the Kuwait Arch, are probably founded on basement horsts. These were reactivated from Late Jurassic to post-Turonian time and contain the largest oil pools in Kuwait (e.g. Greater Burgan) in Middle Cretaceous, Lower Cretaceous and Upper Jurassic strata. (3) A northwest trend (320°-340°) in north and west Kuwait reflects the structural grain of the underlying Arabian Shelf and while generally dry in Middle Cretaceous strata has proven oil in Lower Cretaceous and Jurassic strata. (4) East-northeast (030°-050°) anticlines are present mid-flank the Kuwait Arch to the west and north. They contain oil in Jurassic and Lower Cretaceous strata, and Middle Cretaceous strata where north-south trends are overprinted. They may be related to northeast trending shear zones. (5) The Ahmadi Ridge is a rare north-northwest contraction trend probably related to the Zagros orogeny and traps oil where it overprints the Kuwait Arch trend.

The apparently simple anticlinal oil field structures are cut by normal faults, which are mapped as radial, with throws up to 50 meters but averaging 15 meters. Structural compartmentalization of reservoirs has not been conclusively identified. The faults are near-vertical and often occur in swarms; the majority deform strata below the Mishrif Unconformity while rare faults reach the surface. Reverse throws are evident on seismic and in one well. Dextral offsets along northwest and northeast trending fault and lineaments indicate strike-slip. Wellbore breakouts, processed borehole imagery data and outcrop joint data define a principal maximum stress field orientation of 040°-050° consistent with regional trends.

INTRODUCTION

Kuwait is located on the Arabian Plate between the Precambrian Arabian Shield to the west and the Zagros Foldbelt to the east. Compared to these neighboring structural terranes relatively simple structural elements may be expected. However, many publications describe an unexpected complexity, particularly relating to surface geology (Cox, 1932; Milton, 1965; Al-Sarawi, 1980, 1982); gravity structure (Bou-Rabee 1986, 1996; Warsi, 1990) and oil field structures (Henson, 1951; Fox, 1956, 1959, 1961; Adasani, 1965, 1967, 1985; Milton and Davies, 1965; Nelson, 1968; Al-Rawi, 1981; Brennan, 1990a, b; Al-Anzi, 1995).

This paper describes the major structural elements identified onshore Kuwait and illustrates and discusses the specific characteristics of selected structural elements using gravity, seismic and well data. The location and names the structures commonly used by petroleum geologists and hydro-geologists in Kuwait and some important observations concerning distinctive suites of structural trends are presented and related to the regional structure.

STRUCTURAL ELEMENTS OF KUWAIT

The structural elements of Kuwait (Figure 1) are seen on seismic lines, seismic structure maps, in oil field wells (stratigraphic data and logs), remote sensing/imaging data (including gravity, Landsat and borehole imagery) and in rocks (cores and outcrops). These elements range from structural arches, regional highs and lows, to megascale (anticlines and synclines, troughs, regional gradients), mesoscale (e.g. faults) and microscale structures (sedimentary structures, fractures and stylolites). The following discussion presents some examples of structural elements to demonstrate the variety present in Kuwait with an emphasis on megascale to mesoscale features (Figure 1).

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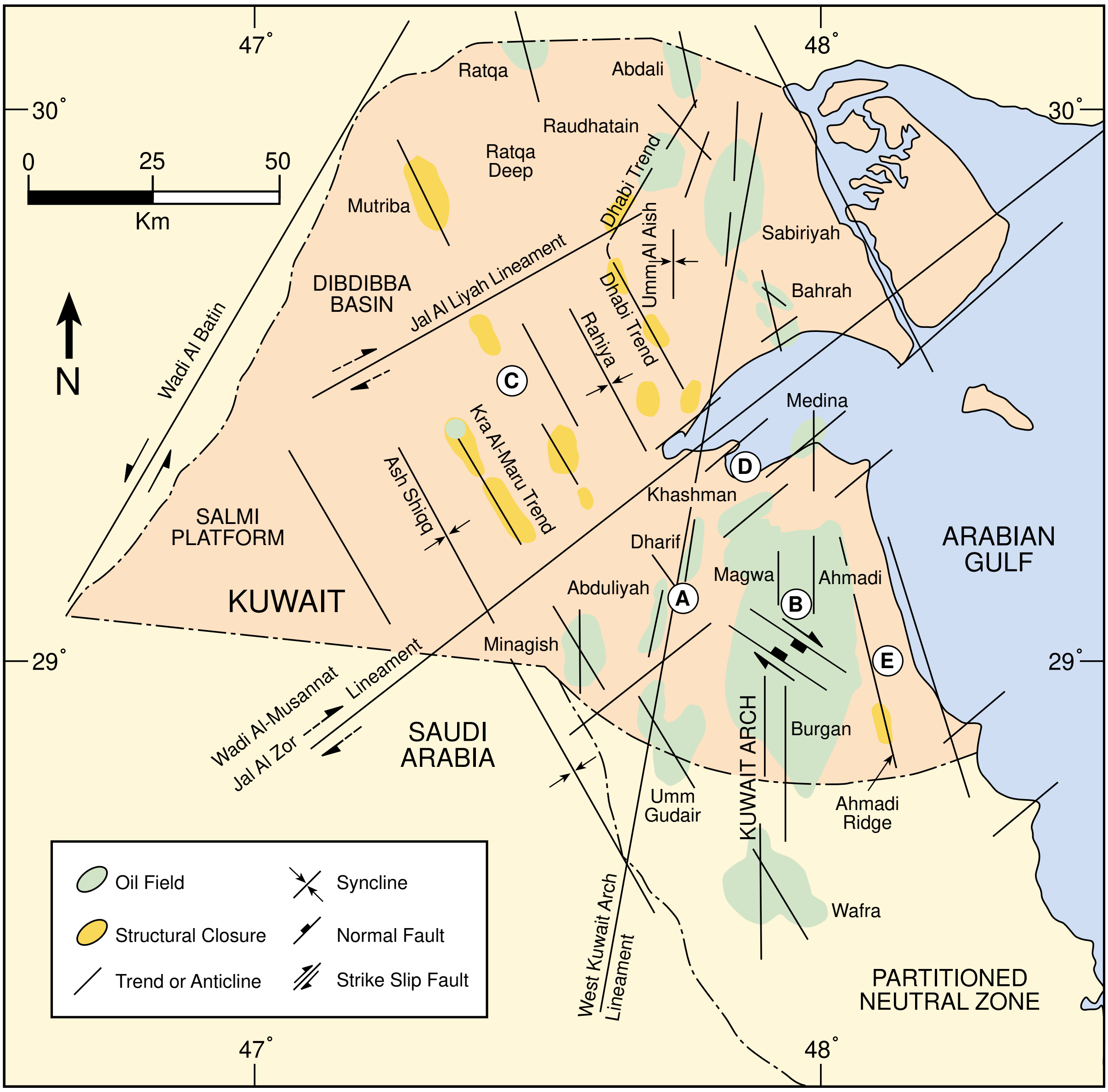

Figure 1: Structural Elements of Onshore Kuwait based on subsurface structure (see figures 3 and 4). A to E are structural families of trends and interpretative northeasterly trending lineaments at Al-Liyah, Al-Zor and West Kuwait Arch are discussed in the structural synthesis.

A suite of four maps present the regional structural form of the surface topographic (unconformity) land surface (Figure 2); the depth-structure, based on well and seismic data, at the top of the Albian/Cenomanian Ahmadi Formation (Figure 3); depth structure at the base of the Upper Jurassic Gotnia salt sequence (Figure 4) and the regional Bouguer Anomaly Map (Figure 5). Figure 6 illustrates the Kuwait stratigraphy and the relation of the mapped surfaces to regional unconformities and tectonic events.

MEGASCALE ELEMENTS

Salmi Platform

The Salmi Platform is located in southwest Kuwait (Figure 1) and has gentle 0.5°-1° regional dip towards the northeast characteristic of the Arabian Homocline. This structure is expressed by the present day topography of Kuwait (Figure 2) and mapping of geophysical data (Figures 3, 4 and 5). The Salmi Platform is characterized by minor irregularities, embayments, structural re-entrants and small closures/rollovers (approx. 10 square kilometers). Oil exploration wells were drilled on some of these closures in the 1960s and one at Rugei recovered a small quantity of oil by reverse circulation but no commercial

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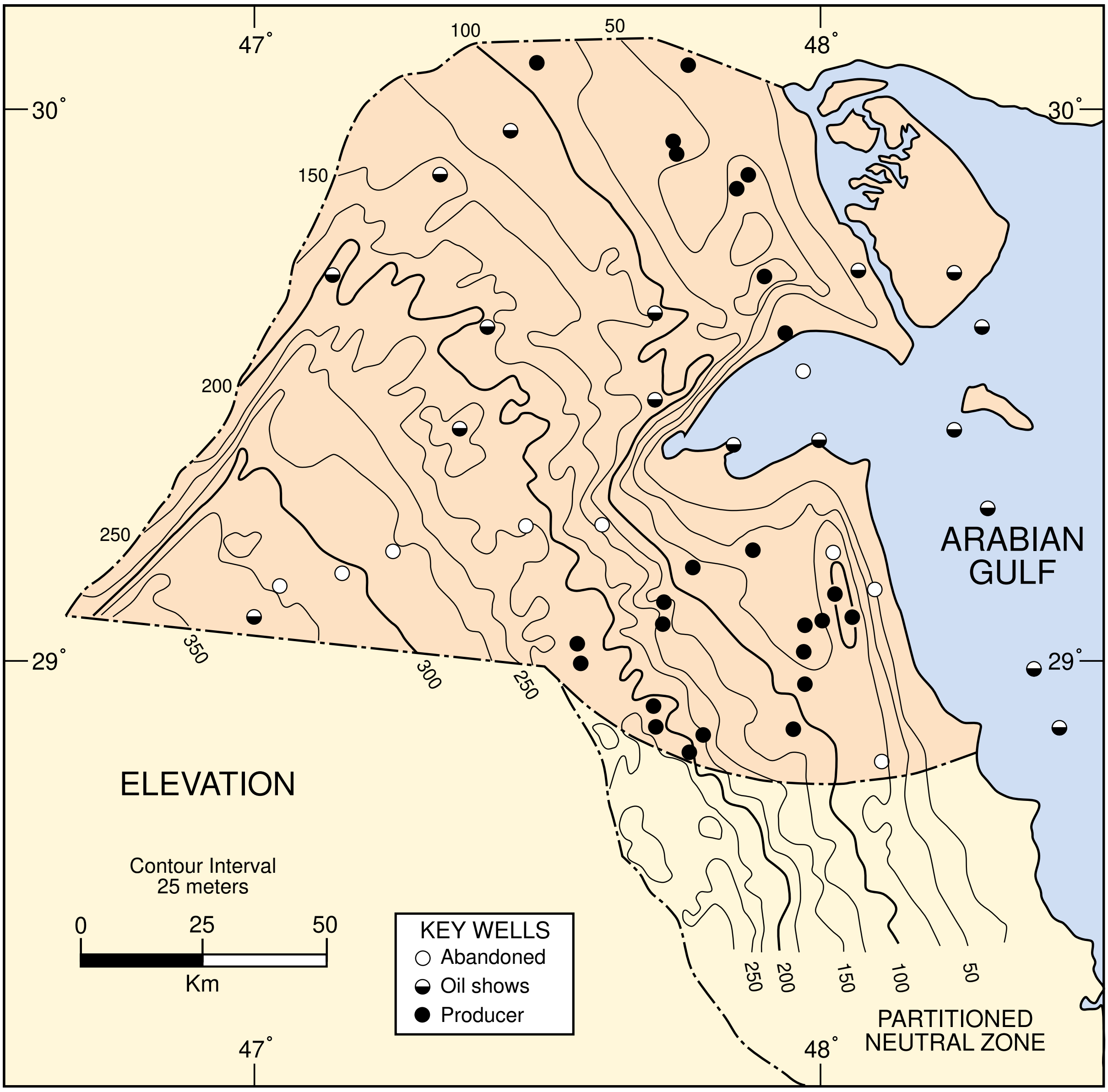

Figure 2: Topography and location of key wells, Onshore Kuwait.

production has been established. Al-Laboun (1987) illustrates the Summan Platform as a structural element of the Arabian Homocline close to southwest Kuwait. It is a probable continuation of the Salmi Platform possibly separated only by the northeast trending Wadi Al-Musannat feature (Figure 1).

Kuwait Arch

The Kuwait Arch is a prominent north-south trend with a topographic expression of approx. 100 meters (m). In the subsurface the arch has a vertical closure of 380 m at the Ahmadi and 600 m at the Gotnia/Najmah levels (Figures 3 and 4). The Bouguer anomaly map of Kuwait (Figure 5; Warsi, 1990) illustrates the arch centered about Kuwait Bay with a 15 mgal amplitude. However, well and seismic data indicate that the structural crest is located farther south in the Kuwait-Saudi Partioned Neutral Zone (PNZ). Three separate depth-structural closures occur on the Kuwait Arch and these correspond to Burgan, Ahmadi and Magwa fields, usually referred to collectively as the Greater Burgan field. Greater Burgan is over 750 square kilometers in area with an aspect ratio/ellipticity of 0.5 and has been classified the largest clastic oil field in the world (Carmalt and St. John, 1986).

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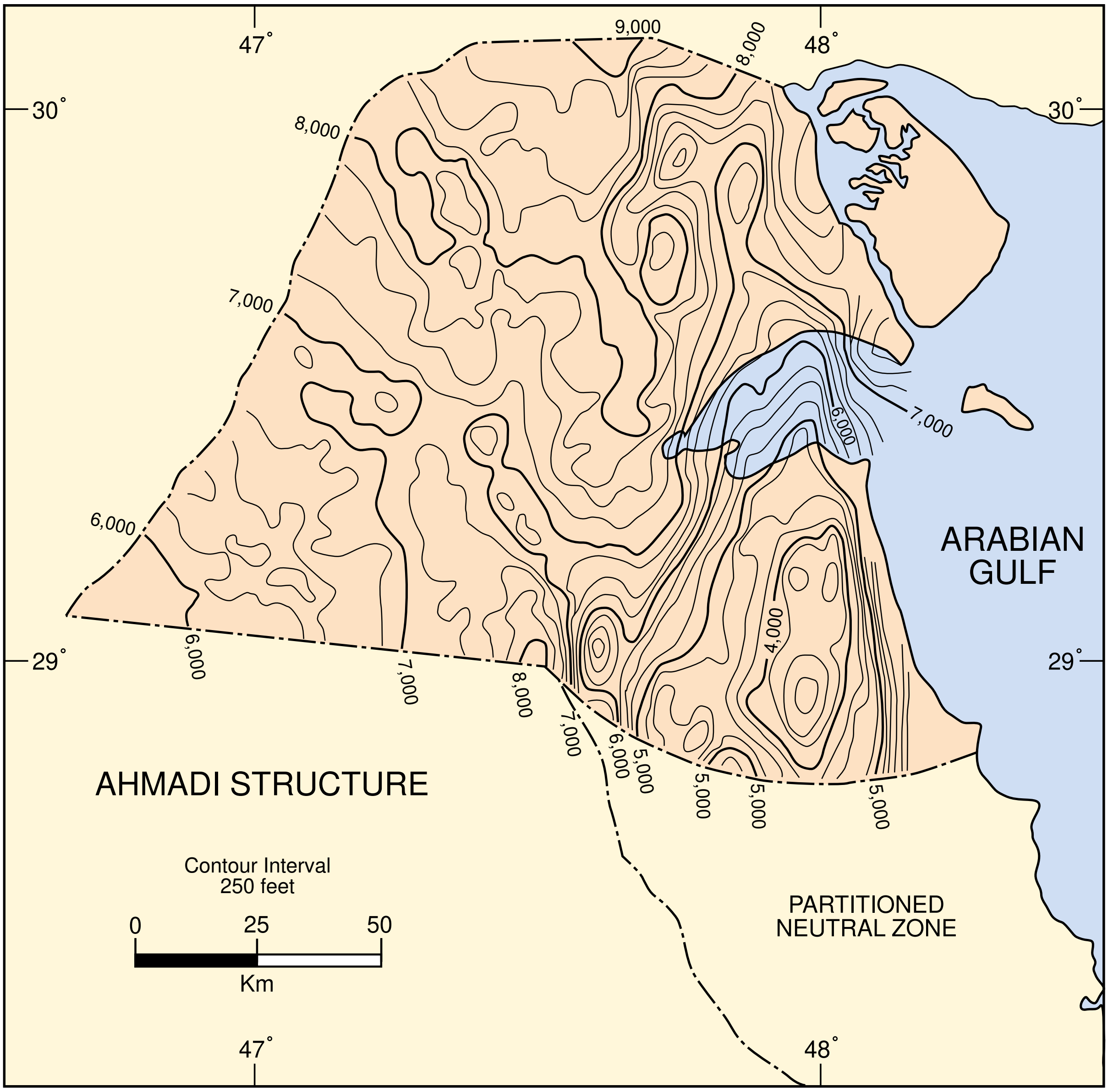

Figure 3: Top Ahmadi (Albian/Cenomanian) depth structure map.

The domal closures of the Kuwait Arch are separated by northwest trending graben faults across which dextral lateral displacement occurs (see below). The Kuwait Arch is asymmetric in profile; its west flank dips about 2°-3° west-northwest and the eastern flank has a steeper dip of about 10°. It plunges some 1,500 m north within Kuwait (approx. 2°). Absence of seismic data along the coastal zone does not permit any interpretation of the structural relationship of the eastern flank of the arch with the western margin of the offshore North Arabian Gulf Basin. It is likely to be simple homoclinal easterly dip as was modeled by Bou-Rabee (1986).

Separate structural closures on the northern plunge and flank areas of the Kuwait Arch contain the Sabiriyah, Bahrah and Medina fields in north Kuwait; the Khashman, Dharif and Abduliyah oil fields to the west and the Umm Gudair field to the southwest. The Raudhatain field to the northwest and Minagish field to the west are further downflank and are considered to be off the main Kuwait Arch structure; all are described in some detail below.

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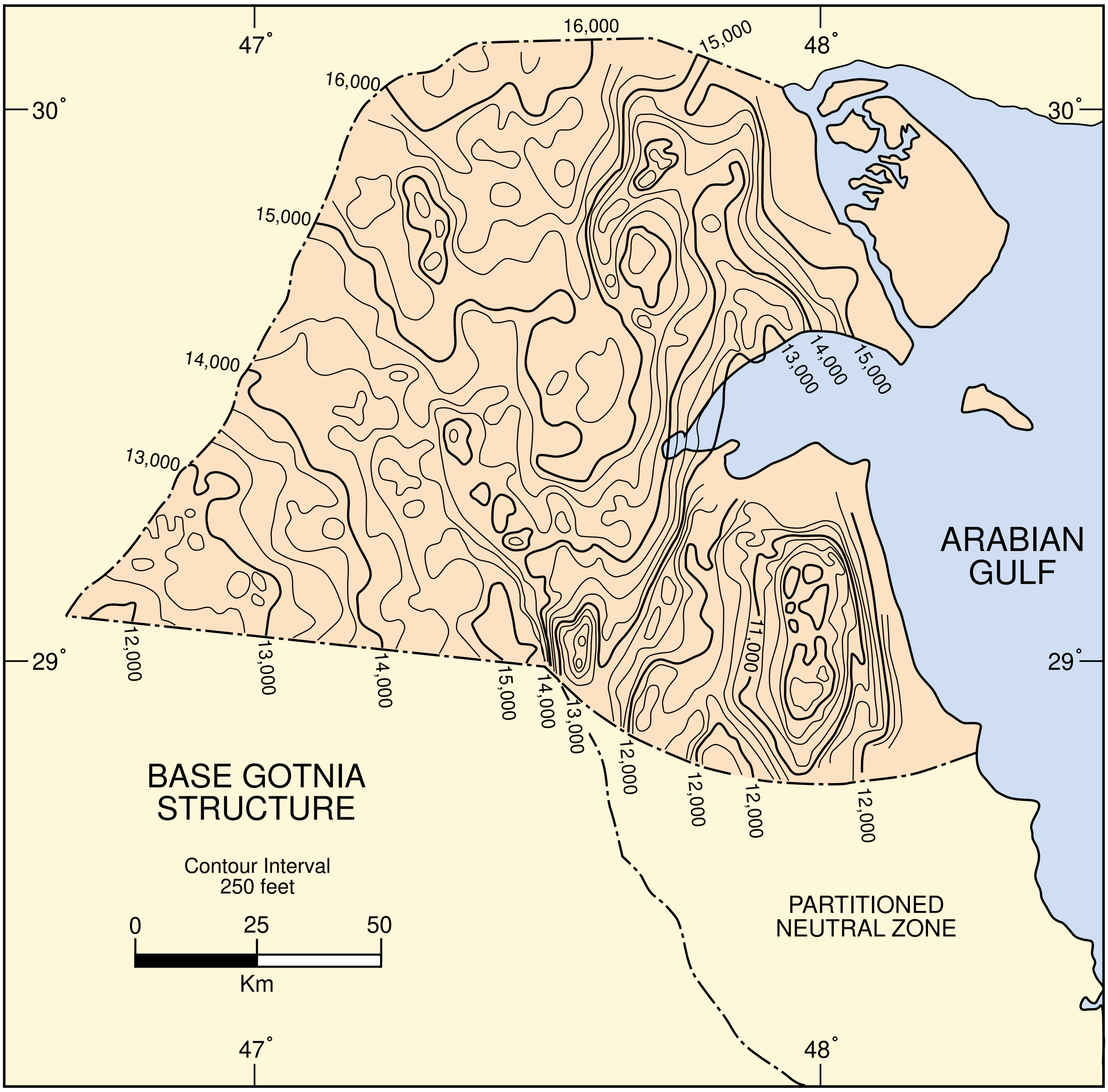

Figure 4: Near Base Gotnia (Kimmeridgian) depth structure map.

Dibdibba Basin

The Dibdibba Basin as referred to here contains Mesozoic and Palaeogene sedimentary accumulations west of the Kuwait Arch and east of the Arabian Interior Homocline as generally described by Al-Naqib (1967), Ibrahim (1979), Adasani (1985) and Bou-Rabee (1986). It is comprised of a thick sequence of coarse clastic sediments deposited during the Early and Middle Cretaceous with significant sedimentary volumes being in the Zubair and Burgan formations amounting to some 12.5 and 21 km^3, respectively. The Dibdibba Basin has been referred to as the Zubair Basin by some geologists (Ibrahim, 1979; Bou-Rabee, 1986); this term is not commonly used in Kuwait.

The Dibdibba Basin has a dominant north trend controlled by the Kuwait Arch, and in Kuwait reaches its maximum thickness of >8,500 m in the north where it is the likely source (kitchen area) for some oil accumulations west of the Kuwait Arch.

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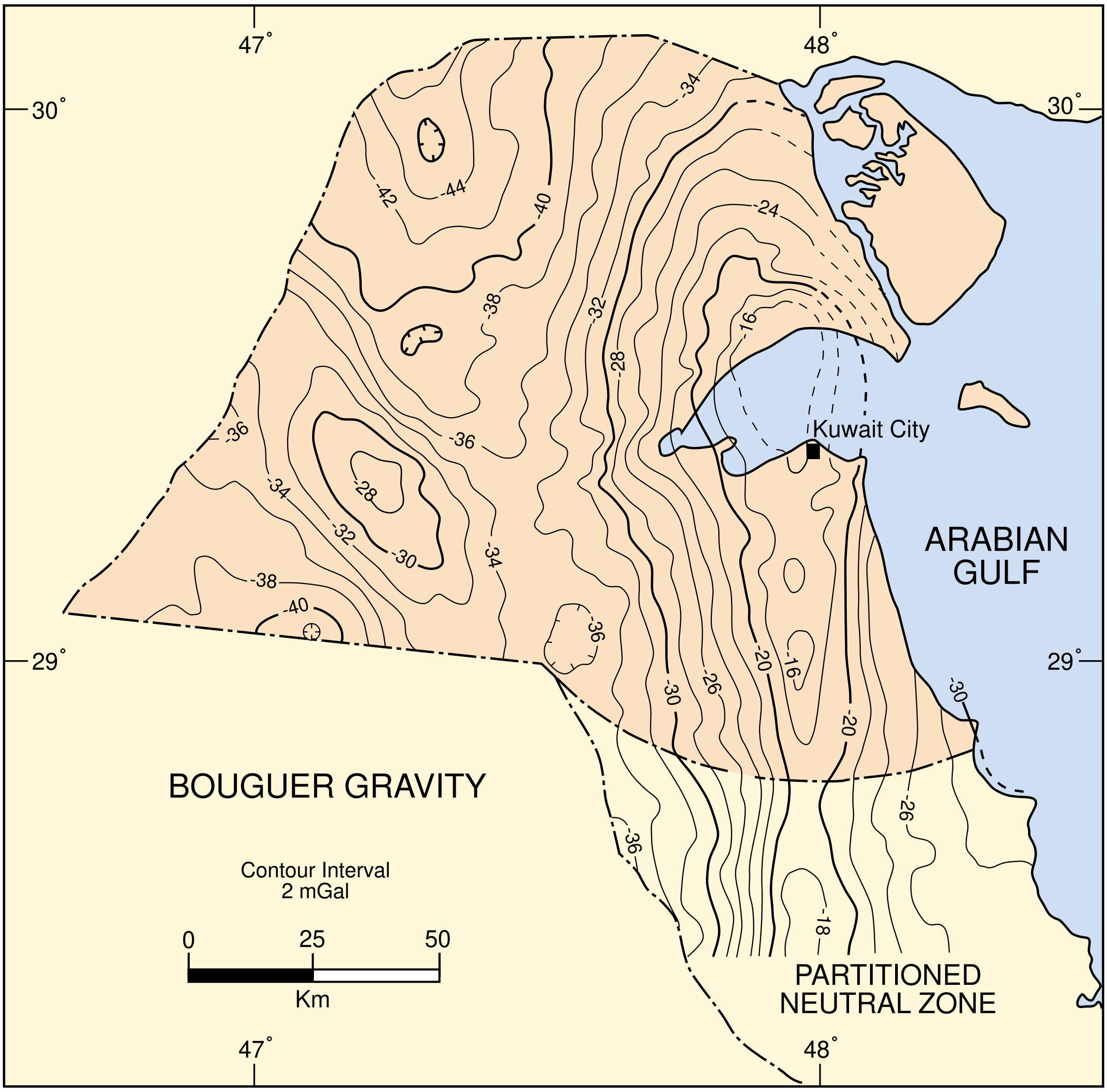

Figure 5: Bouguer Anomalies, Onshore Kuwait (after Warsi, 1990).

Figure 6: Stratigraphic column, onshore Kuwait and tectonostratigraphy (after Owen and Nasr, 1958; Harris et al., 1984; Bou-Rabee, 1986; Grabowski et al., 1995; Hooper et al., 1995). The deepest well in Kuwait has penetrated steeply dipping beds of indeterminate age below the Khuff Formation (Khan, 1989).

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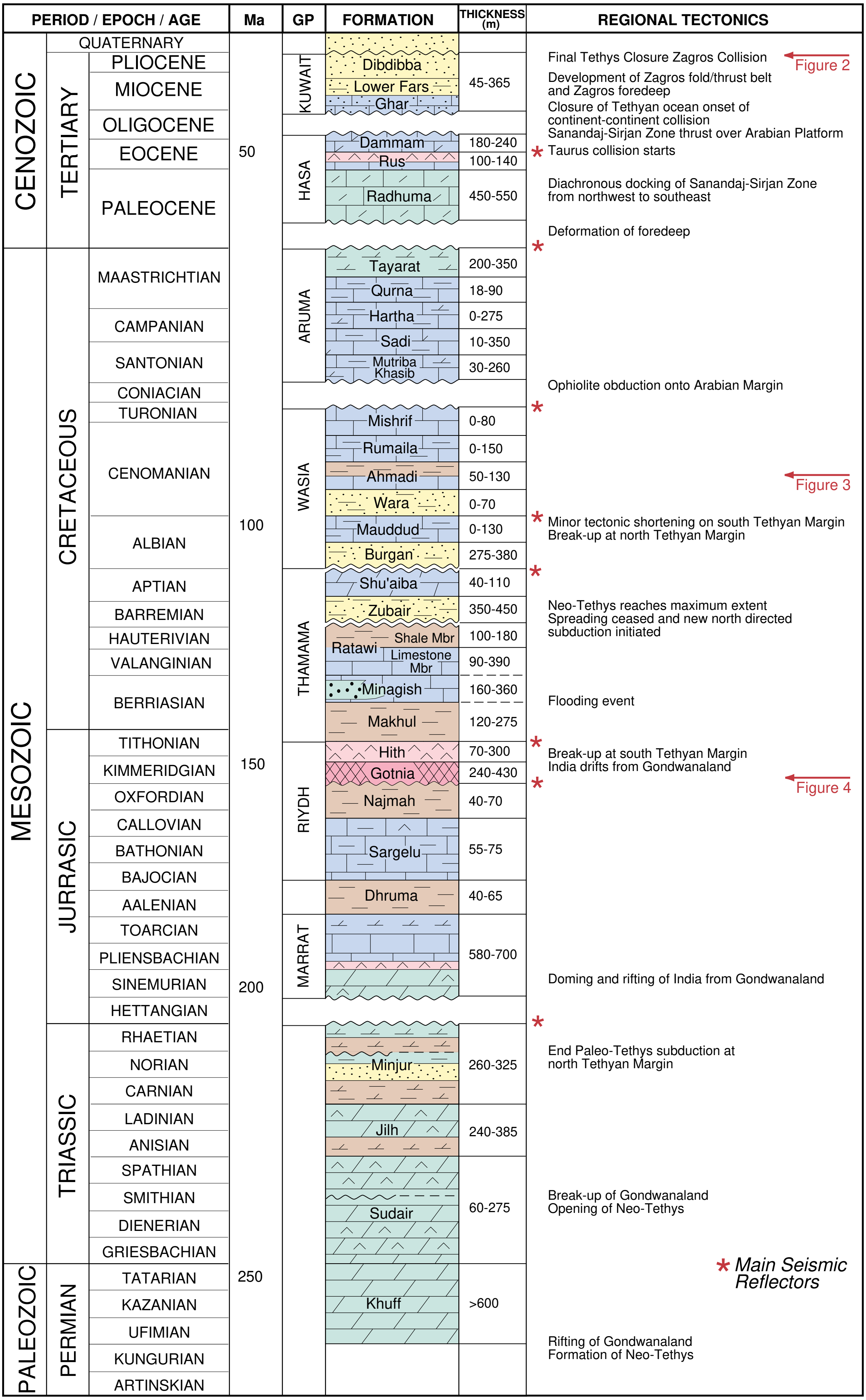

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KUWAIT OIL FIELDS

The megascale structures in Kuwait which contain commercial accumulations of oil are better understood than smaller and possibly more complicated mesoscale structural elements. Selected oil fields and smaller structural elements are summarized geographically from northeast to southwest in the following sections.

Raudhatain Field

The Raudhatain field, discovered in 1955, is a faulted anticlinal dome (Figure 7) which has produced from reservoirs in the Ratawi, Zubair, Burgan and Mauddud formations and has been described by Milton and Davies (1965), Adasani (1967), Al-Rawi (1981) and Brennan (1990a). Its structure is expressed

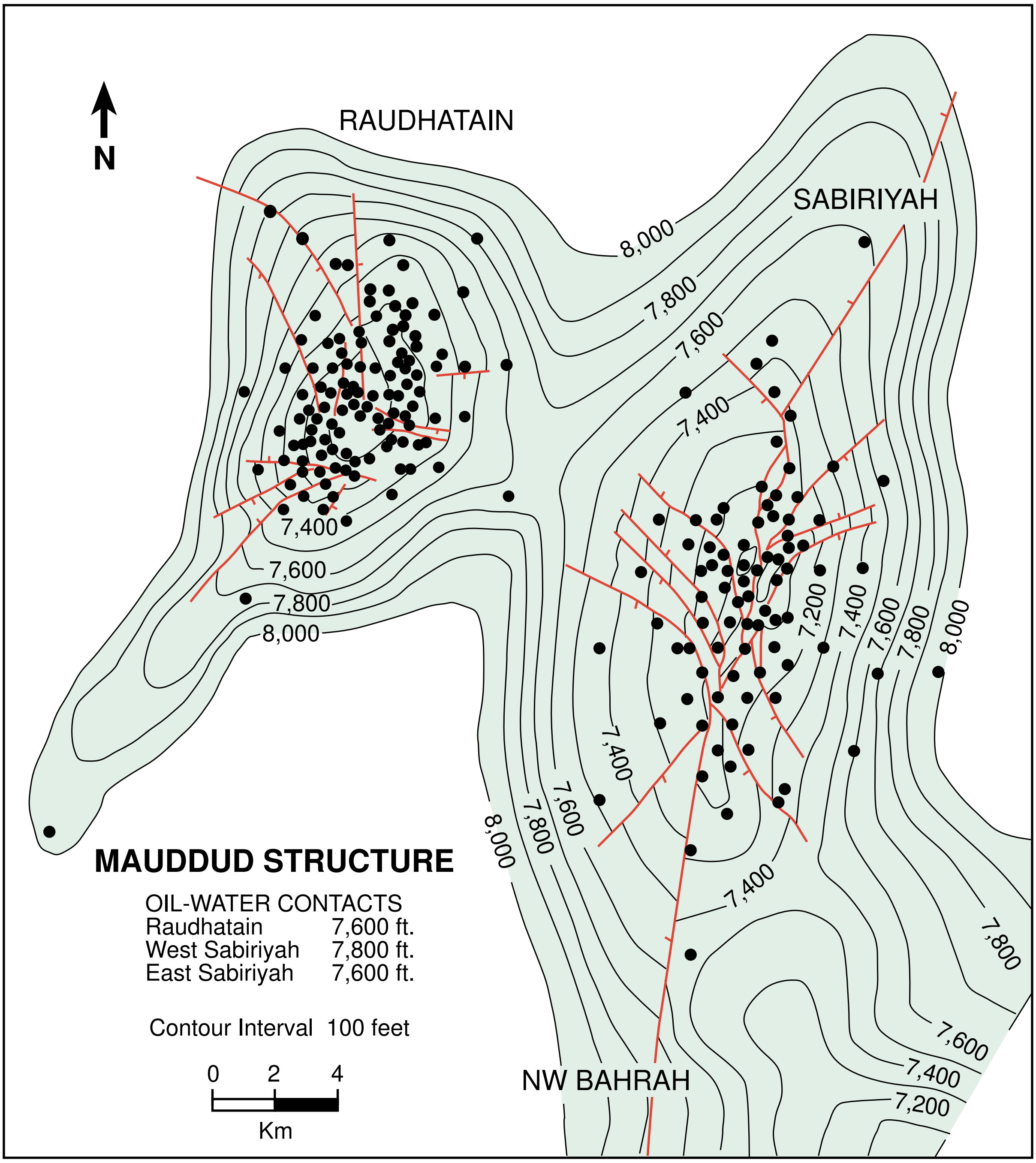

Figure 7: Raudhatain and Sabiriyah fields structure at top Mauddud Formation based on wells and seismic.

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at the surface by 20-28 m of topographic relief (Figure 2) with a superimposed subtle semi-radial drainage pattern on the northeast flank. Subsurface structure is defined by approx. 50 line kilometers of seismic and 117 wells. The Zubair reservoir structure is a gentle dome, slightly elongated northeast-southwest, trending 025° with over 100 m vertical closure (Al-Rawi, 1981). The Ahmadi structural contours (Figure 3) have a larger vertical closure of 138 m with a contrasting trend of 036°. The northwest flank of the Raudhatain structure broadens to define a north-northwest trending lobe (Figure 7) that coincides with a small closure of the 50 m topographic contour in a region where the overall topography slopes gently northeast (Figure 2).

Steep, near-vertical faults are identified in several Raudhatain wells but the seismic data are too sparse for reliable fault correlation. Eleven faults are mapped with a quasi-radial fault pattern. Brennan (1990a) suggested a primary origin by uplift or piercement and Bou-Rabee (1986) considered them to be deep, diapir-related faults although deep seismic data are of poor quality and do not aid interpretation. In Kuwait, normal faults are often interpreted from isopach anomalies and stratigraphic correlation between development wells with little or no azimuthal control. The largest fault interpreted at Raudhatain has a throw of 45 m intersected in a well in the Mutriba Formation above the Mishrif Formation; the average fault throw is 15 m.

Isopach data are interpreted to indicate structural growth in areas of thinner sedimentation (Milton and Davies, 1965; Al-Rawi, 1981; Yousef and Nouman, 1995). At Raudhatain both Late Jurassic and Cretaceous strata thin onto the structure. Without detailed facies mapping this observation is inconclusive but structural developments since the Late Jurassic provide one explanation.

The Raudhatain field produces 28°-40°API oil from Cretaceous reservoirs with multiple oil-water contacts (Figure 7). An ill-defined closure suggests hydraulic communication (possibly continuously through oil in some reservoirs) with the Sabiriyah field to the east (Adasani, 1965; Al-Rawi, 1981; Brennan, 1990a).

Sabiriyah Field

The Sabiriyah field is an elongate, faulted anticline bearing 012°-018° (Figure 7) which trends distinctly more northerly (by about 18°) than the neighboring Raudhatain structure. The field was discovered in 1956 using seismic and is now defined by approx. 100 line kilometers of seismic and 98 wells. Flank dips range from 8° to the east to approx. 4° to the west indicating a marked asymmetry. Structural plunge is about 2°-3.5° to the north and south. The structure at the Mauddud level is more than twice as long as it is wide (ellipticity is 0.42). Mapped vertical closure (about 150 m) is greater than at the Raudhatain field and only subtle saddles separates the Sabriyah Mauddud structure from the Bahrah structure to the south and the Raudhatain field to the west (Al-Rawi, 1981); the deeper oil-water contact in the Mauddud at Raudhatain (Adasani, 1967; Brennan, 1990a) is perhaps restricted by an impermeable zone.

Eleven faults are mapped on the Sabiriyah field; one with approx. 38 m throw is correlated through nine wells and is mapped over 20 km parallel and close to the structural axial trace. Only three faults have throws exceeding 20 m and the average fault throw, interpreted from 35 well-isopach-anomalies, is 18 m. The faults as mapped occur in three orientations; the majority are northwest-southeast whilst others are northeast-southwest and north northeast-south southwest (parallel to the fold axis). Other fault trends may become evident with denser seismic data coverage.

The Sabiriyah reservoirs produce 28°-32° API oils from Burgan and Mauddud reservoirs and thin oil sands in the Ratawi Formation are possibly stratigraphically trapped.

Bahrah Field

The north-northwest plunging antiform at Bahrah was the first Kuwait structure to be surveyed and drilled. It was described (Cox, 1932; Cox and Rhoades, 1935) and re-described by Salman (1979) and Al-Sarawi (1982). The Bahrah oil pools are in Cretaceous Burgan and Mauddud formations and commonly occur in association with faulted structures (Al-Anzi, 1995). Individual pools are <5 km^2 in size (Figure 8) and their vertical and areal closures are ill defined.

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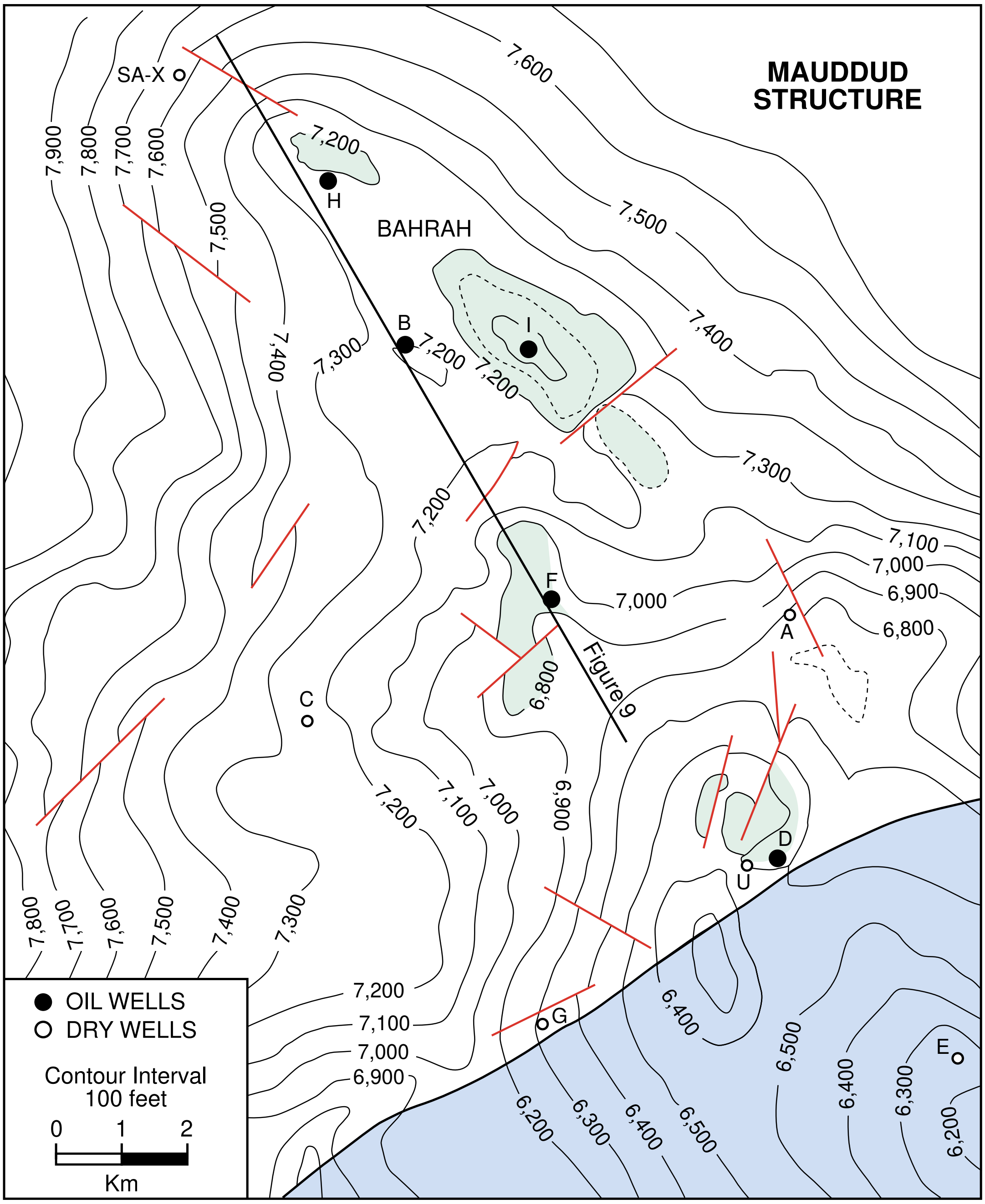

Figure 8: Bahrah field Top Mauddud structure map (after Al Anzi, 1995).

Regional Bouguer anomaly maps (Warsi, 1990; Figure 5) show the Bahrah structure is part of the Kuwait Arch. Seismic data define the Bahrah structures as gentle low-relief, fault related structural culminations (Figure 8). At the top Mauddud level the arch has a northwest plunging nose approx. 10 km wide with a saddle separating the Bahrah area from the Sabiriyah oil field to the north.

The Bahrah structure is also well demonstrated by surface topography (Figure 2) and outcrop of Lower Fars sediments along the 80 m south facing Jal Al Zor escarpment. Salman (1979) and Al-Sarawi (1982) suggested Neogene retreat of the escarpment from a fault(s) located offshore in Kuwait Bay. Onshore seismic data (Figure 9) illustrate near-vertical, branching fault systems with no major throws suggesting such faulting may be strike-slip.

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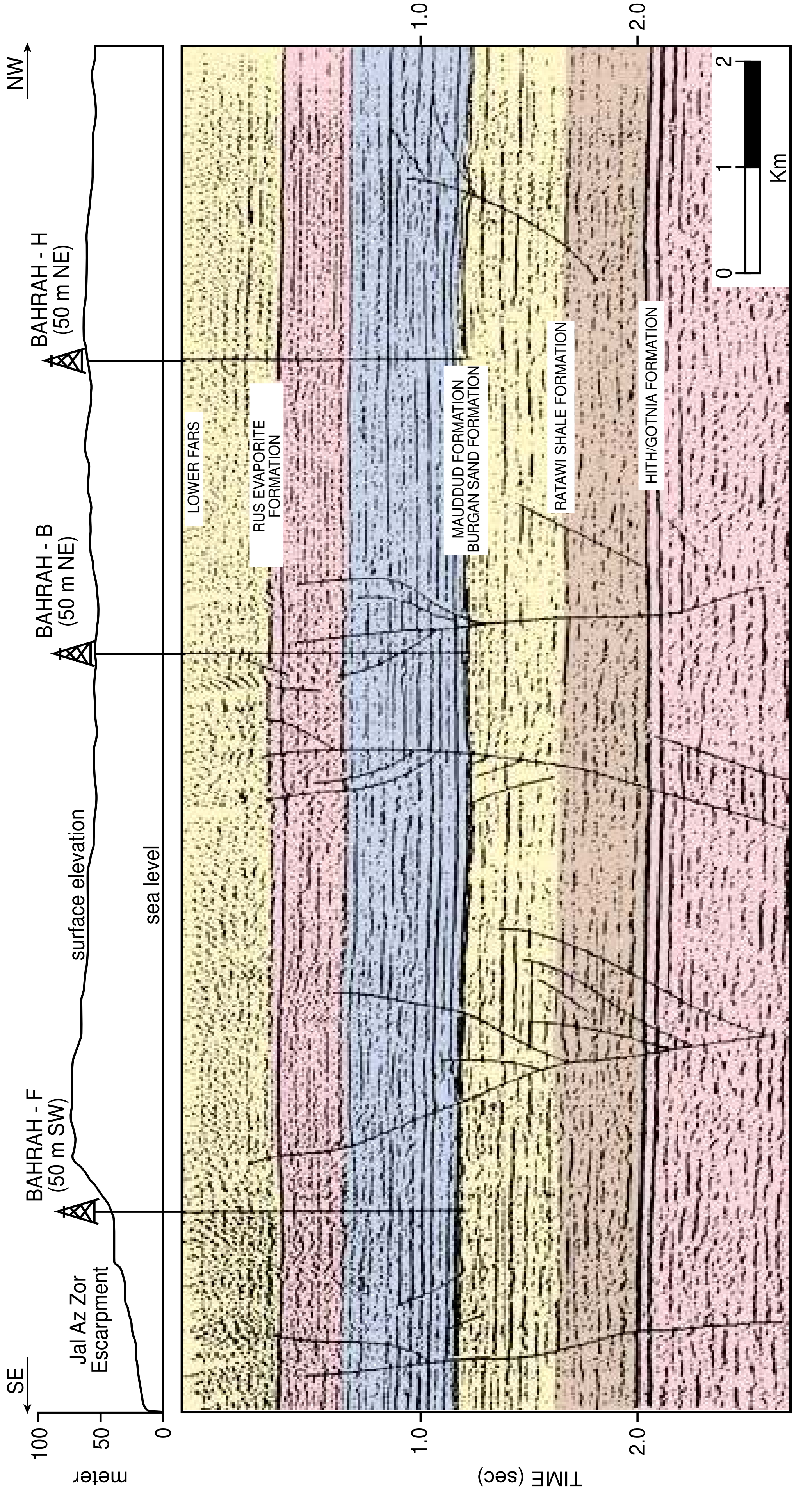

Figure 9: Seismic section along the Bahrah field area (after Al Anzi, 1995). See Figure 8 for location.

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Medina Field

The Medina structure is a dip closure, possibly fault-bounded to the south, located beneath Kuwait City, on the north plunging nose of the Kuwait Arch. It was appraised with offshore seismic and three wells in 1966 which discovered oil in Cretaceous reservoirs. The accumulation has not been placed on production and there is inadequate seismic data onshore to accurately delineate the structure. Figure 10 shows an interpretation of the structural form suggesting the closure has a northeast trend similar to the Khashman structure (see below). This trend is parallel to many promontories along the eastern Kuwait seaboard and is considered to be of structural significance.

Khashman Field

This field, discovered in 1963, is defined by 8 wells and approx. 50 line kilometers of seismic over an area of 25 km^2. The top Mauddud structure is mapped as three northeast trending (050°) faulted anticlines each about 2 km in width, 6-10 km long and with vertical closures of 30-35 m. They are located on the northwest flank of the Kuwait Arch, 15 km northwest of, and some 300-400 m structurally deeper (at the Mauddud and Marrat levels) than the Magwa Dome. Interpretation of seismic data suggests the anticlinal folds are bound by northeast trending faults and are cross-cut by steep, near-vertical faults of 1-3 km length with throws up to 40 milliseconds (msec). More generally the fault throws are less than 20 msec. A topographic high on the Kuwait City Sixth Ring Road (near the intersection with the Seventh Ring) is possibly related to subsurface faulting and structure. The northeasterly Khashman and Medina anticlinal axes and faults (Figure 10) contrast markedly to the northwest trending faults on the Magwa Dome suggesting a significant structural element separates the two. The Khashman field produces 30°-31° API oil from Wara, Mauddud and Burgan reservoirs and oil is proven in Jurassic reservoirs.

Greater Burgan Field

The Greater Burgan field consists of three giant fields (Burgan, Magwa and Ahmadi, Figure 11) located near the crest of the Kuwait Arch (Fox, 1961; Adasani, 1965; Brennan, 1990b). The first wells on these fields were drilled in 1938, 1951 and 1952 respectively.

Burgan Field

The Burgan field is an ovate dome of some 500 km^2 with a high ellipticity of 0.7 and a slight elongation striking north. Figure 11 illustrates the structural map derived from seismic and 460 wells. Mapped structural closure at the Mauddud level is approx. 380 m. The Mauddud oil-water contact has not been penetrated but is considered to be at 4,466 ft subsea (Brennan, 1990b). The structure is cut by nearly 30 faults mapped as straight, part radial and commonly 3-4 km in length. Throws are generally less than 15 m, which is sufficient to complicate horizontal development drilling in the 6-8 m thick Mauddud reservoir, but they have not yet been proven to form effective compartments within the Burgan reservoirs. The largest fault identified has a 73 meter throw. The structural dips are uniformly about 1° in all directions.

Burgan Graben

The Burgan Graben, separating the Burgan Dome from the Magwa Dome, has two pronounced northwest-southeast (333°) trending bounding faults of 30-150 m throw at the Mauddud level and approx. 20 km length. The graben is 1 to 1.5 km wide and is defined by seismic and field development wells between the faults. The axial trace at the Mauddud level is dextrally displaced about 4 km to the southeast on the north side of the graben indicating some strike-slip movement. Five kilometers to the northeast of the Burgan Graben and adjacent to the Ahmadi field, six wells define a shorter (10 km) graben of similar width and throw (Figure 11).

Magwa Field

The Magwa field is 186 km^2 in area with an ellipticity of 0.75 defining a slight northerly trend mapped from 178 wells and seismic. The Mauddud structure at Magwa is some 150 m deeper than at the Burgan Dome crest and structural dips are about 1 degree or less. The structure is transected by over 20 faults of 3-6 km in length with a northwest-southeast trend. The north flank of the Magwa dome is cut by a northwest trending pair of faults defining a small graben about 10 km long and causing a net 15 m upthrow to the north again with dextral offset (Figure 11).

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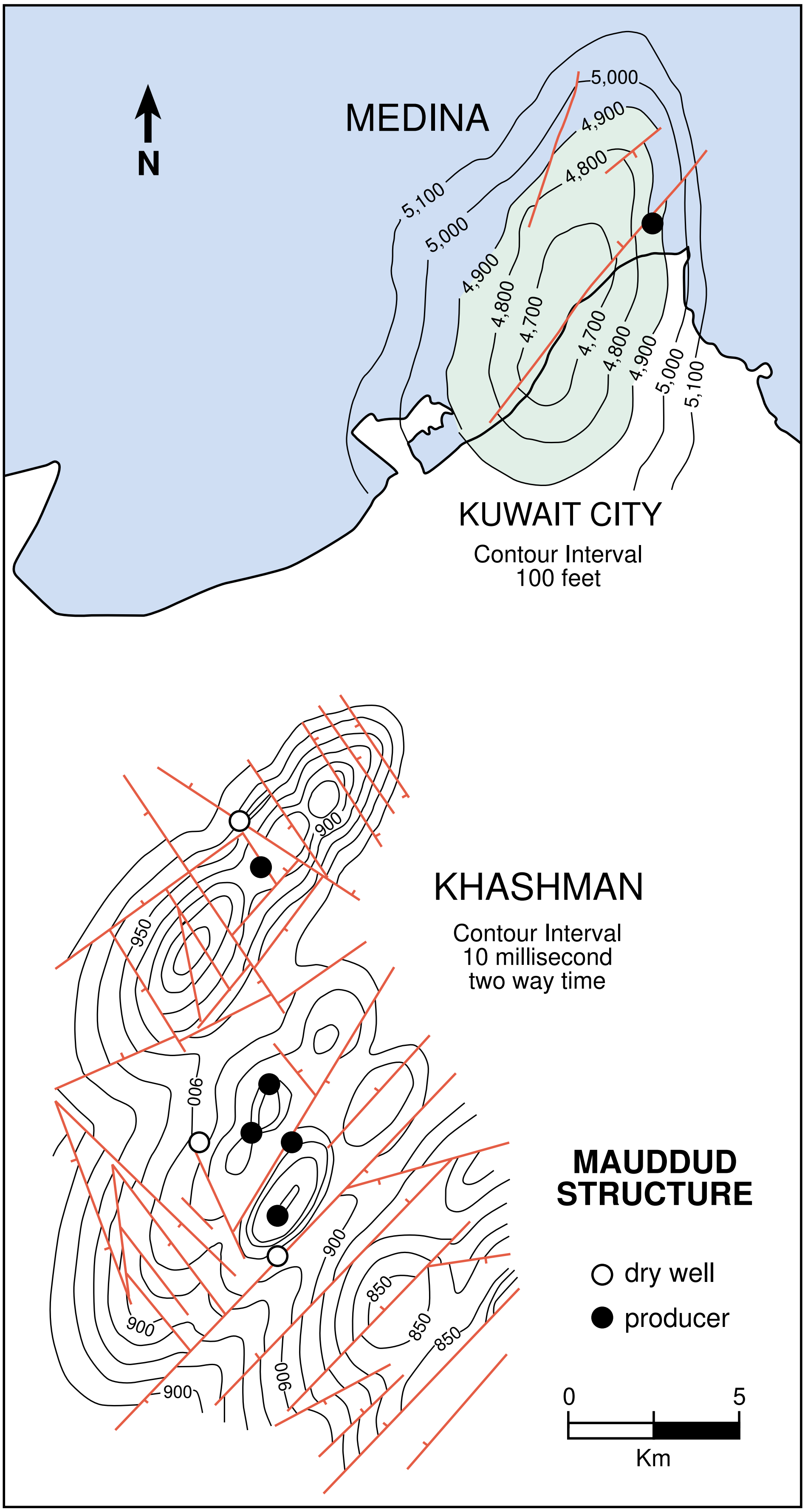

Figure 10: Mauddud structural form of the Medina (feet subsea) and Khashman (msec TWT) areas.

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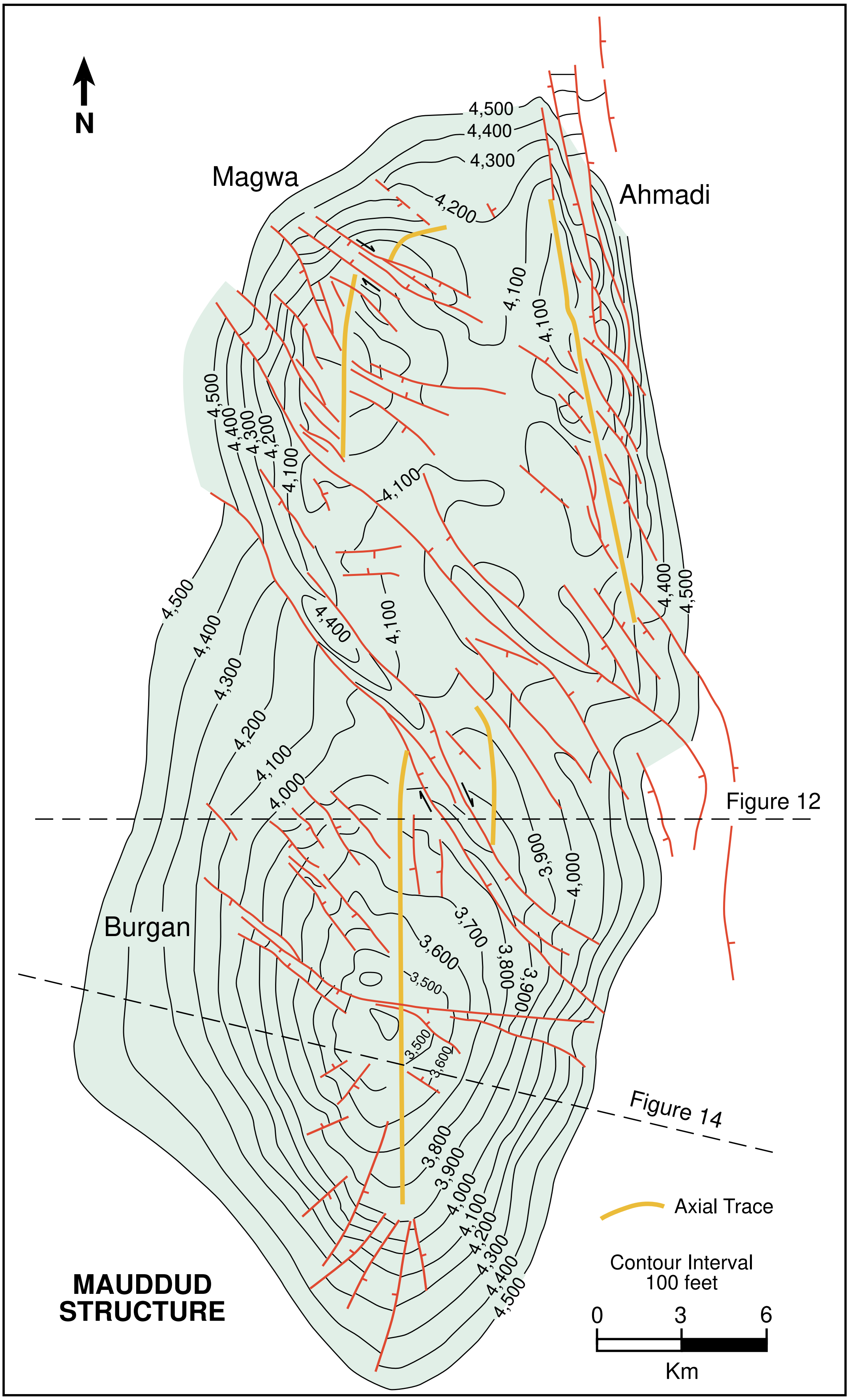

Figure 11: Greater Burgan Top Mauddud Structure map (contour interval 100 feet/30.4 m).

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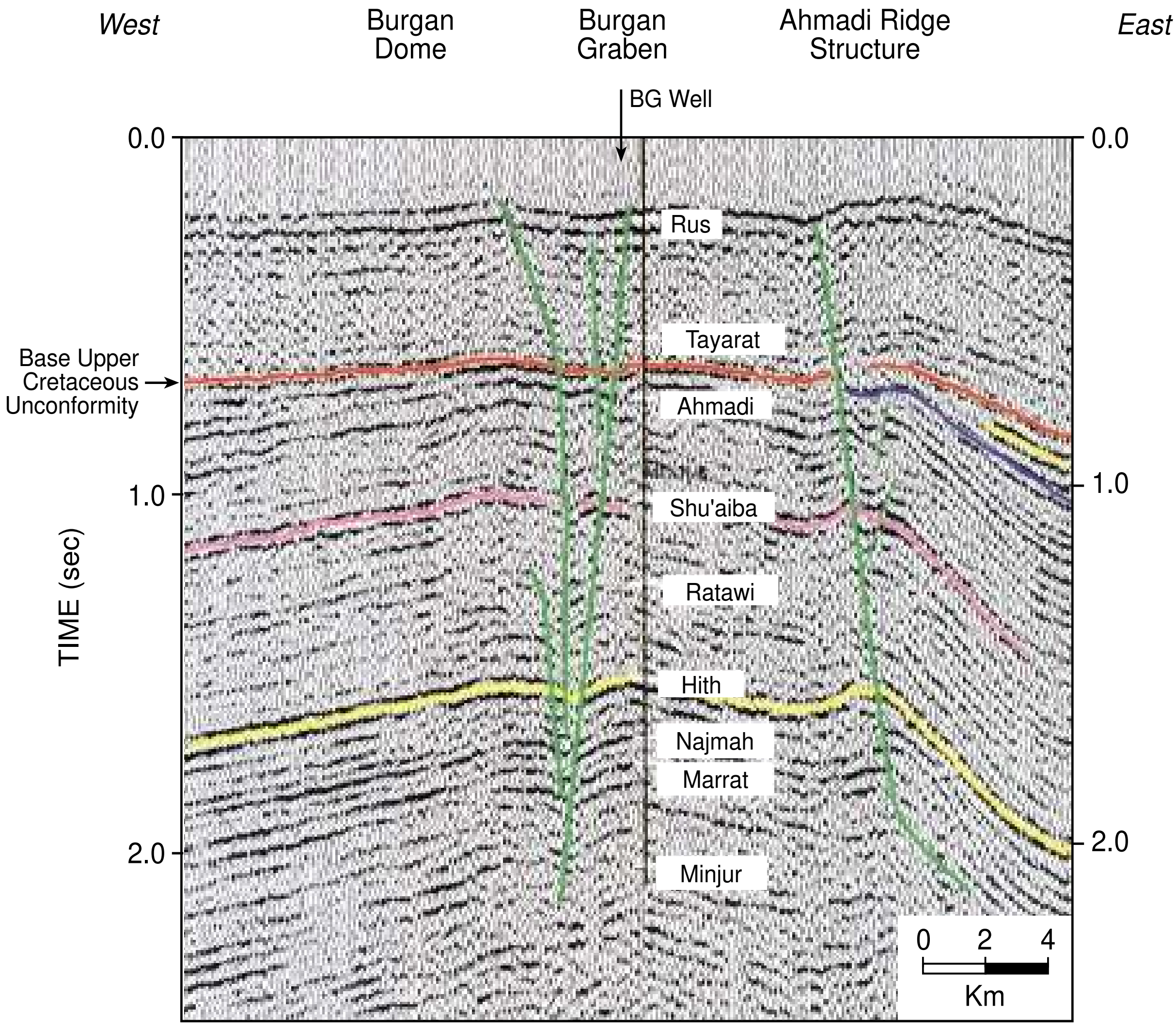

Figure 12: Seismic section E-82-5 (unmigrated) showing Kuwait Arch asymmetry, Burgan Dome, Burgan Graben faults cutting to near surface and Ahmadi Ridge structure with shallow reverse fault interpretation and subcrop of reflectors to the Base Cretaceous Unconformity. Line location shown in Figure 11.

Ahmadi Field

The Ahmadi field, with an area of some 144 km^2, consists of a north-northwest trending antiform (345°) segmented by four en-echelon faults, striking some 20-25 km with a 500 m spacing and several, short north-northwest trending faults. The fault throws are generally less than 15 m with the largest throw being 106 m on the northern plunge of the structure. The depth of the Ahmadi crest at the Mauddud level is at 3,900 ft subsea - similar to the Magwa crest. The high ellipticity of 0.27 demonstrates the exceptionally pronounced trend of the Ahmadi structure. The structure is distinctly asymmetric with easterly vergence at the Mauddud level (7° dips to the east and very gentle to flat dips west) and is considered to be a Zagros overprint on the Kuwait Arch (see later).

The structure of the Greater Burgan field which is mapped from wells and seismic (Figures 3, 4, 11, 12 and 14a,b) is asymmetric with west flank dips of <2° and east flank dips locally as high as 10°. The crest of the Burgan Dome Cretaceous structure is offset about 2 km to the east of the Jurassic crest illustrating vertical disharmony. Structural asymmetry is also demonstrated by the structure of the Eocene Dammam Formation which has a near-surface culmination (at <10 m depth) in the Ahmadi quarry some 10 km east of the Cretaceous structural axis (Fuchs, et al., 1968). On Figure 2, the 75 m and 100 m topographic contours reflect the location and elongate nature of the Ahmadi structure previously observed by Fox (1956), Adasani (1965) and Brenann (1990b). A large re-entrant of the 75 m contour in the central Burgan area accurately reflects the subsurface location of the Burgan Graben.

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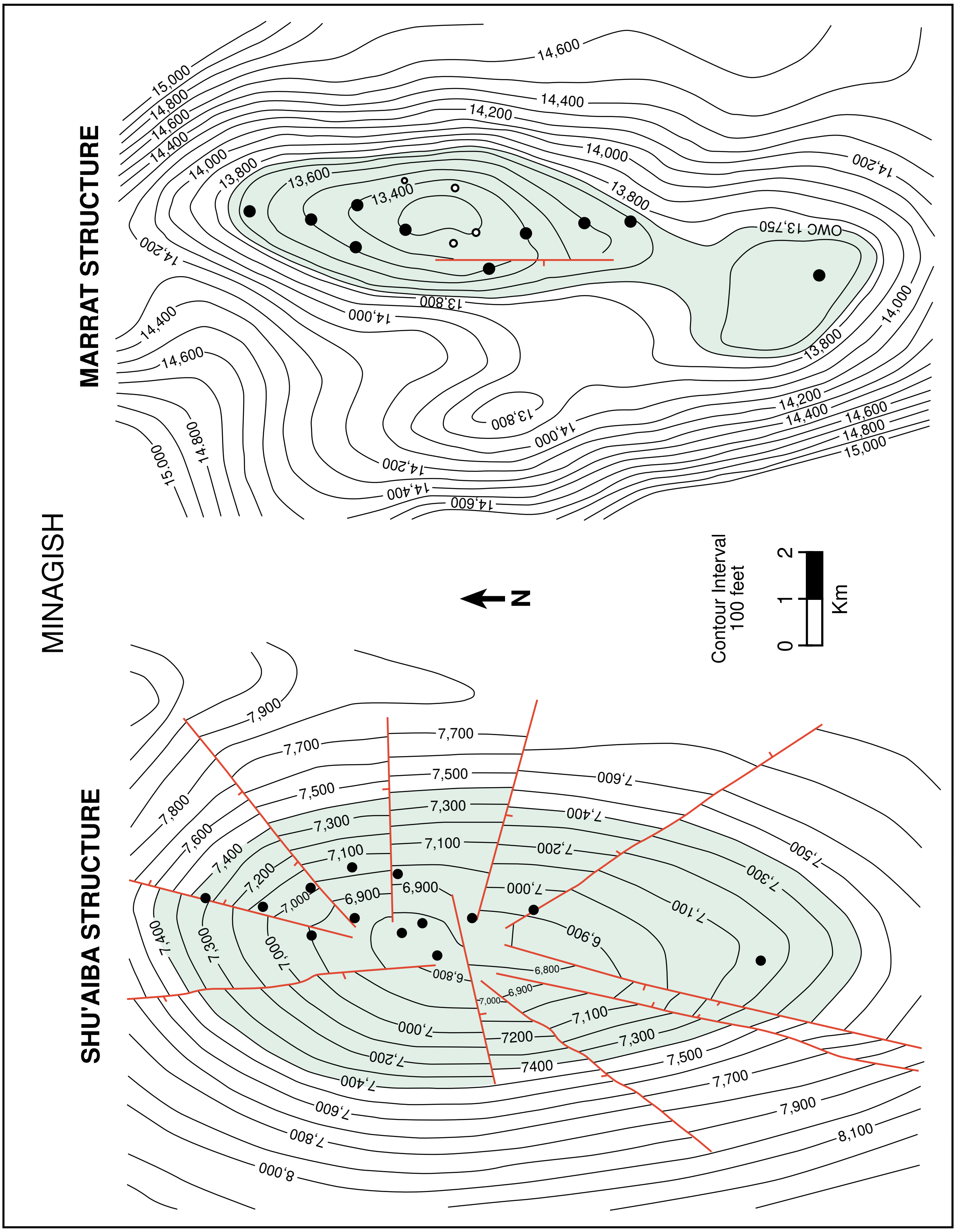

Figure 13: Structure contours on Cretaceous Shu'aiba and Jurassic Marrat formations, Minagish field.

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Minagish Field

Oil was discovered in Cretaceous Minagish Oolite in 1959; in Cretaceous Burgan, Wara and Mishrif formations in 1963/64 and in Jurassic rocks in 1983 (Marrat) and 1985 (Sargelu/Najmah). Seismic and appraisal drilling were the basis for field delineation (El-Aouar and Rasool, 1970; Adasani, 1985; Youash and Mukhopadhyay, 1982). There are no obvious geomorphic anomalies related to the Minagish

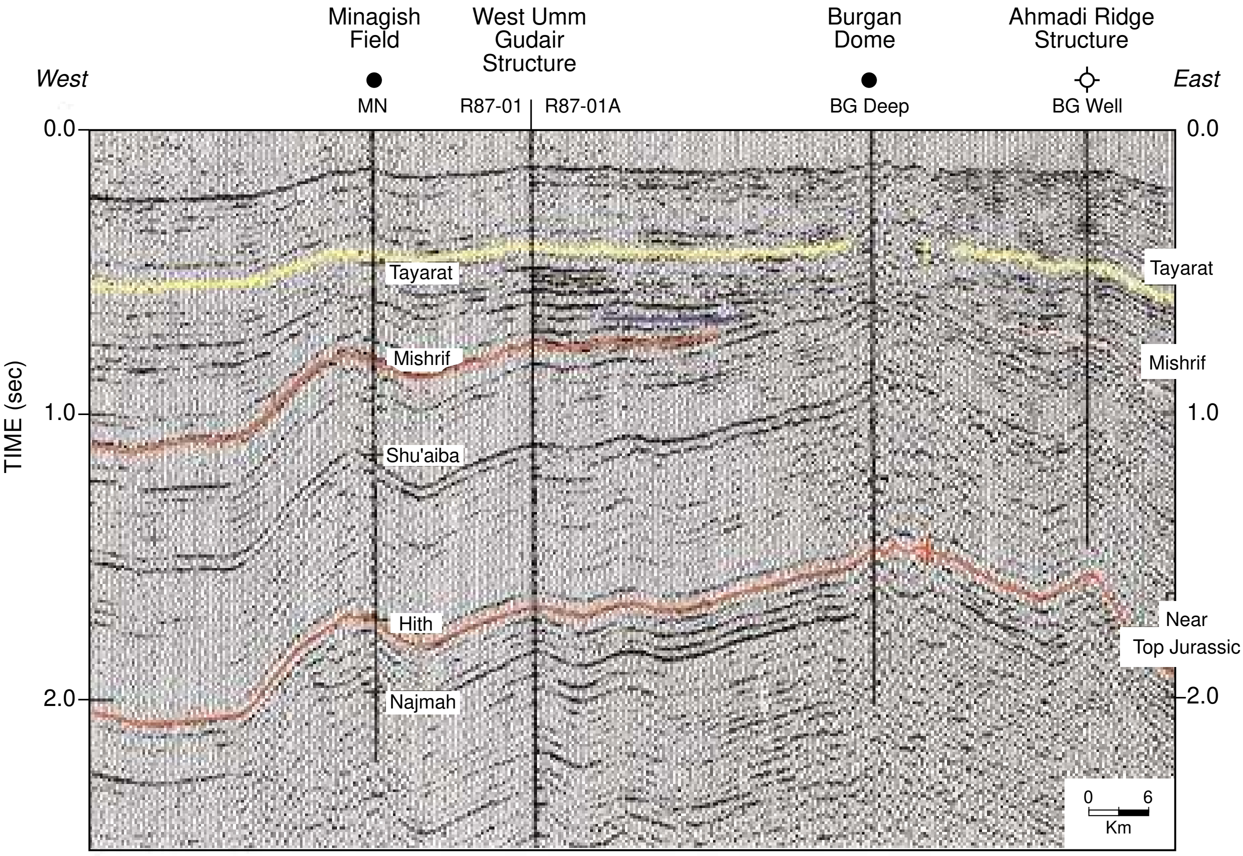

Figure 14a: Seismic sections R87-01/01A (unmigrated) showing asymmetry of the Kuwait Arch, structural form of the Minagish, West Umm Gudair, Burgan Dome and Ahmadi Ridge structures and onlap above the Mishrif (base Upper Cretaceous) Unconformity. Location shown in Figures 11 and 15.

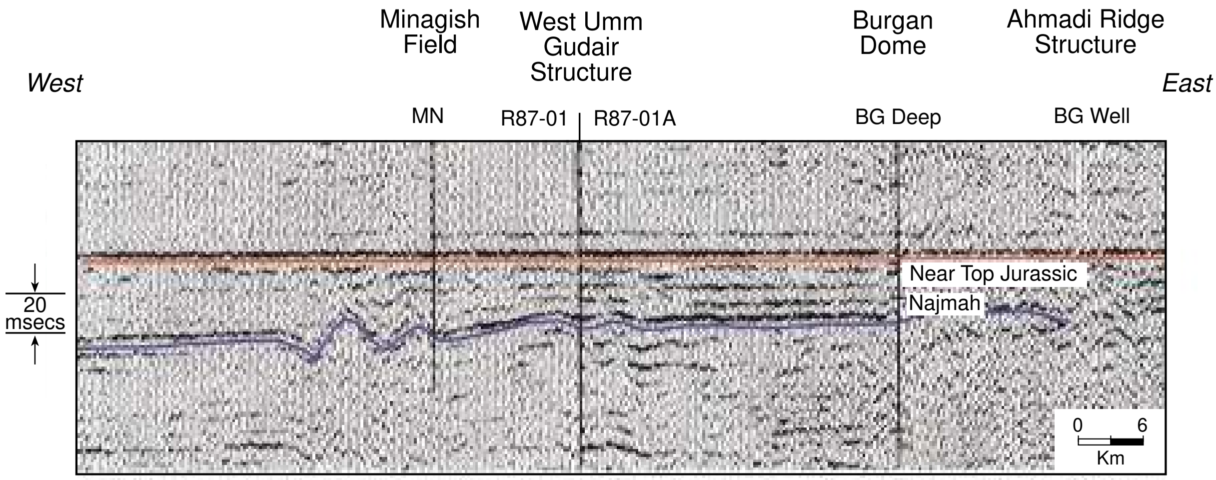

Figure 14b: Seismic section flattened on the near top Jurassic marker suggesting earlier structural development in the west at Minagish, and less structure development at the Burgan Dome area at Late Jurassic time.

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structure. The structure is defined by an irregular 2 by 1 km grid (60 line kilometers) and 56 wells. It is a relatively simple, elongated, symmetrical anticline with moderately uniform 5°-7° dipping flanks. Its structural axis trends north-northeast (008˚) and ten faults radiating from the crestal area (Figure 13) are mapped as affecting the structure from the Khasib level down to the bottom of the Lower Cretaceous (Adasani, 1985). The faults have steep hades and normal displacements are generally less than 20m. The Cretaceous structure is productive from the Minagish, Burgan and Wara formations.

Fourteen wells have been drilled to Jurassic Marrat reservoirs and together with seismic define a steeper, more complex, and slightly narrower structure than at the Cretaceous level; separate closed areas occur on the southern and western flanks (Figure 13). Seismic resolution and well density are at present not sufficient to define fault trends in the Jurassic strata. Faults and fractures are thought important controls on production from both Marrat and Najmah/Sargelu formations. Seismic data across Minagish (and West Umm Gudair), flattened at the Late Jurassic Hith level, suggests the western structures developed earlier than the eastern (Figure 14b).

Abduliyah and Dharif Fields

Oil bearing reservoirs in the Marrat Formation were discovered in the Abduliyah and Dharif structures, on the west flank of the Kuwait Arch, in 1984 and 1988 respectively. Seismic and eight wells define the structures as north-northeast elongate antiforms (Figure 15) with asymmetric profiles (Yousef and Nouman, 1995) which are approx. 900 m structurally lower than the Burgan and Magwa Domes. Both Abduliyah and Dharif have an ellipticity of 0.2 and occur respectively west and east of a seismically-defined, fault, probably with some 225 m of reverse (west verging) movement at Dharif and 60 m of normal easterly downthrow at Abduliyah. The Abduliyah hangingwall closure has a steeper west flank whilst the Dharif hangingwall closure has an asymmetric steeper (regional) east flank. The north-northeast structural trend of both structures is 015° which is similar to the West Umm Gudair trends (see below).

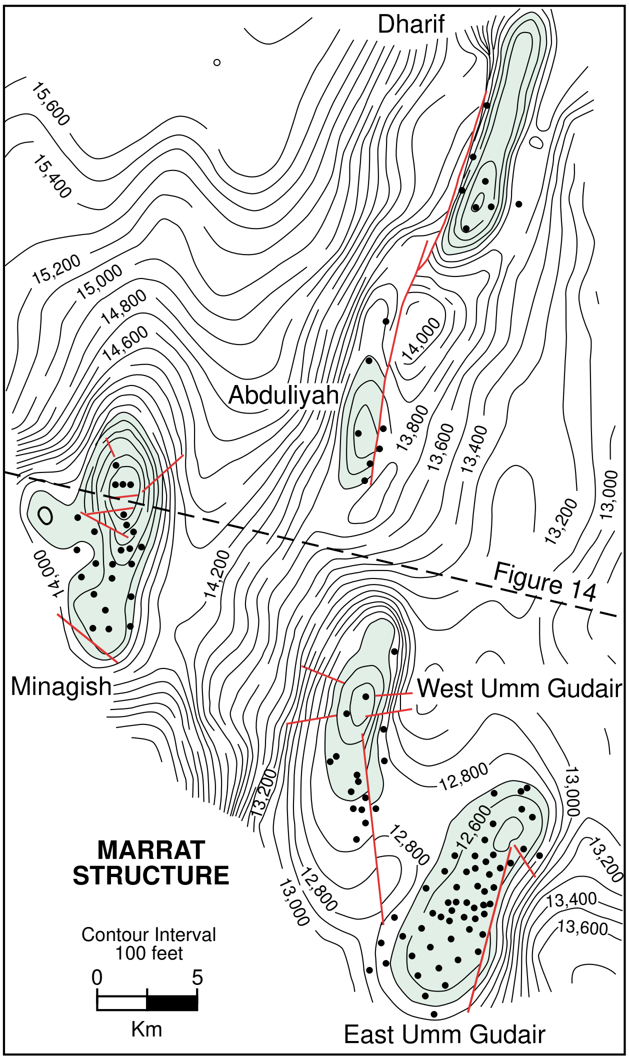

Figure 15: Abduliyah, Dharif and Umm Gudair fields structure at intra-Jurassic Marrat level (after Adasani, 1965; Yousef and Nouman, 1995).

Umm Gudair Field

The Umm Gudair field is located on the southwest flank of the Kuwait Arch, 30 km from the Burgan field. Oil was discovered in Cretaceous Minagish reservoirs in 1962, and Jurassic reservoirs in 1984 (Sargelu) and 1989 (Marrat). The structure is defined by 100 line kilometers of seismic and 71 wells. The overall domal structure is comprised of two elongate anticlinal structures (Figure 15) called West and East Umm Gudair (Adasani, 1985).

The West Umm Gudair structure trends north-northeast (005°-015°) and occurs along trend of the Abduliyah - Dharif structures. The East Umm Gudair structure trends northeast (030°-040°) and is separated from the West by a shallow (approx. 30 m) saddle. The East Umm Gudair structure extends southward into the Kuwait/ Saudi Arabia PNZ and is occasionally referred to as the South Umm Gudair field.

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The overall Umm Gudair dome is symmetric but the subdivision into two crestal antiforms imparts an element of asymmetry (Figure 15). Seismic data flattened on top of the Hith Formation illustrates that the West Umm Gudair Structure had commenced structural growth during the Late Jurassic whereas the East Umm Gudair structural developments were later.

Yousef and Nouman (1995) illustrated a structural section through Minagish-Umm Gudair-Burgan suggesting the Minagish and Umm Gudair structures are Jurassic, fault-bound horsts with >150 m elevation. Bou-Rabee (1986) analyzed a gravity profile across Umm Gudair (her section A-A') and concluded that a down-to-the-west fault with about 400 m throw and a west dipping upper/lower crustal boundary satisfactorily modeled the observed gravity data without inferring horsts. Seismic data shows the structure is relatively simple with only a few minor faults at the Jurassic level.

MESOSCALE STRUCTURAL LINEAMENTS

The regional structure maps (Figures 3, 4 and 5) demonstrate ten additional structures, of which two are synclinal commercial water resources and the others are drilled antiforms but not yet proven as commercial hydrocarbon traps.

Kra Al Maru Trend

The Kra Al Maru Structural Trend (Figure 1) is a prominent northwest (327°) trending subsurface ridge (Figures 3 and 4) some 40 km long by 8 km wide with a subsurface structural amplitude/closure of 150 m (at Mid-Cretaceous level) defined by seismic and two wells near its axis. The location of the Kra Al Maru trend is also indicated by a saddle expressed on the Bouguer Anomaly map for Kuwait (Warsi, 1990) and has subtle surface expression as topographic rises such as Kra Al Maru (25 m elevation). Other rises occur along the trend at Umm Rijim, Khashm Al Afri, Khaluhah, As Saddah and Al Minagish and may be indicative of Recent structural development. On subsurface structure maps (Figures 3 and 4) the Kra Al Maru trend terminates abruptly to the northwest suggesting some fault control. The discovery of 30° oil in Ratawi and 48° oil in Najmah/Sargelu reservoirs at Kra Al Maru was announced in October 1995.

Dhabi Trend

The Dhabi Trend (Figure 1) is a curvi-linear, antiformal high on subsurface structure maps which trends 12 km southwest from the Raudhatain structure, swings southerly for 10 km and southeast for a further 12 km where it rejoins the main Kuwait Arch. The Dhabi Trend is defined by regional seismic data and three wells located near the axial trace. It is named after the Dhabi-1 well which drilled through the Gotnia salt in 1985 with no shows recorded. The structure is approx. 8 km wide at the Late Jurassic level and has over 150 m relief above the Umm Al Aish Depression to the east and the Rahiyah Syncline to the west (see below). The Dhabi-1 well penetrated thinned sections of Najmah, Sargelu and Dhruma formations suggesting Late Jurassic growth. The structure does not appear to have any surface topographic expression or obvious feature on the Bouguer Anomaly map. Seismically-defined faults in the Dhabi-Bahrah area are essentially vertical and occur in small branching swarms that mostly terminate in intra-Jurassic, Lower Cretaceous and Middle Cretaceous strata; some breach the Mishrif-Tayarat interval.

Mutriba High

The Mutriba High (Figure 1) is a seismically-defined subsurface structure with no clear surface topographic or positive gravity expression. Three wells on the structure, one reaching the Najmah Formation, had oil shows in Cretaceous strata. Together with nearby exploratory wells, they confirm a high above the regional structure. The Mutriba High is an elongate, ovate, northwest trending anticline with about 150 m vertical closure and three separate Cretaceous culminations within a larger 60 km^2 area. The southern closure is offset 3 km from the northern two closures and trends more northerly suggesting dextral shear (Figures 3 and 4). The Mutriba structure plunges to the northwest into the Ratqa Deep and is separated from the Salmi Platform by the Al-Liyah Trend to the southeast (see below).

The Mutriba Structure is characterized by a Bouguer gravity low (Figure 5; Warsi 1990) which Bou-Rabee (1986) modeled by invoking a deep, lenticular, pre-Khuff salt body 1.5 km thick below the Mutriba area.

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Umm Al Aish Depression

The Umm Al Aish Depression (Figure 1) is a seismically-defined, structural low occurring between the Sabiriyah and Raudhatain structures and the Dhabi Trend mapped at Jurassic and Cretaceous levels; it is about 300 m deep at the Mauddud level. The structure is also demonstrated by shallow structure determined from commercial wells producing potable water from the Dammam and Lower Fars formations.

Ash Shiqq Depression

The Ash Shiqq Depression (Figure 1), located southwest of the Kra Al Maru trend and east/northeast of the Salmi Platform, is defined by shallow water wells and seismic maps for the Cretaceous and Jurassic strata (Figures 3 and 4). The depression trends northwest-southeast and is some 150-300 m deep compared with its flanks. It plunges southeast towards a narrow trough in northern Saudi Arabia within which the top Jurassic is >3 km deep (Cole et al., 1994). The depression is named after a wadi and a Kuwaiti local district name southwest of Minagish. Cox and Rhoades (1935) referred to the feature as Shaqq Depression.

The Ash Shiqq Depression is coincident with location of a positive gravity feature (Figure 5). Bou-Rabee (1986) modeled this as a shallow syncline overlying a horst with 1,600 m elevation at the pre-Khuff level to account for the observed gravity (the 'Minagish High' in her model B-B' version 2). Unfortunately the available seismic does not adequately define structure at Khuff depths. Warsi (1990), who referred to the same feature as the Dibdibba Arch, supported this model and concluded that both gravity and magnetic characteristics could be caused by a basement suture below west Kuwait. The superimposition of the (Mesozoic) Ash Shiqq Depression over the interpreted deeper basement high may be an example of structural inversion in Kuwait.

Ratqa Deep

The Ratqa Deep (Figure 1) is defined by both regional seismic and regional well control and extends over an area >2,000 km^2. It is the main depocentre of the Dibdibba Basin within Kuwait where over 4,750 m of post-Jurassic strata have accumulated, and is broadly coincident with the onshore depocentre of the Late Jurassic Gotnia Basin. The Ratqa Deep has probably been a structural low since Oxfordian times and probably contains important organic rich petroleum source rocks. The shallower Dibdibba Basin contains important aquifers providing hydrodynamic support for neighboring oil fields and a water resource for domestic and industrial use. The Lower Fars sediments contain extensive deposits of heavy (10^o-12^o API) oil in over 110 wells in this area; no commercial production has yet been established.

Rahiyah Syncline

The Rahiyah Syncline (Figure 1) is a southern extension of the Ratqa Deep separating the Kra-Al Maru/ Salmi Platform elements from the north plunging Kuwait Arch and the Dhabi trend. The Rahiyah well (drilled in 1989) provides good stratigraphic control in this broad, 30 by 60 km symmetric structure striking north-northwest.

Ahmadi Ridge

The Ahmadi Ridge (Figure 1) is a surface topographic feature locally reaching 100 m elevation above sea level in an elliptical area trending 350^o (Figure 2). The 75 m contour parallels the coastline inland some 8-10 km defining a feature about 40 km long and 5-10 km wide. The northern end is coincident with the eastern fault segments of the Ahmadi field and is offset 1.5 km east of the axial trace of the subsurface Ahmadi/Mauddud culmination. The southern extremity of the ellipsoid defined by the 75 m contour passes through BG-274 some 10-15 km east of the crest of the Burgan Dome. Interpretation of seismic data suggests the subsurface Ahmadi Ridge structure is a thrusted, west-verging, asymmetric anticline (Figure 12).

Comparison of isopachs suggests the Ahmadi (Ridge) Structure formed later than the neighboring Magwa Dome (Fox, 1956; Brennan, 1990b) with thinning in post-Mishrif formations suggesting it is related to Zagros deformation (Fox, 1956; Milton, 1965; Warsi, 1990).

Al-Liyah Ridge

The Al-Liyah Ridge (Figure 1) is a geomorphic feature in west central Kuwait trending east-northeast. Salman (1979) described the Jal Al Liyah as merging with the Jal Az Zor escarpment at Al Aujah via a

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gravel-topped ridge, evident on geomorphic maps and Landsat imagery. Jal Al Liyah is about 1 km wide on the Kuwait-Basra road but farther west it widens to form a large low plateau. The maximum elevation is about 138 m above sea level in the west and 70 m in the east but in general only forms a 12 m topographic rise above the adjacent ground level. The Ahmadi structure map (Figure 3) shows the west end of the Jal Al Liyah Ridge is expressed by a northeast trending break on the Salmi Platform and the southern end of the Mutriba Structure. A north-northeast nose is also apparent on the Jurassic structure map (Figure 4) but there is no evidence for the lineament extending across the Rahiyah Syncline. The correlation of the Jal Al Liyah and Al-Zor ridges at the surface is possibly induced by mega-foresets in the Lower Fars sediments and it appears more likely that the Jal Al Liyah lineament is a major, strike-slip lineament that is possibly responsible for the separation of the Raudhatain and Sabiriyah Anticlines.

Wadi Al Batin

Wadi Al Batin (Figure 1) is a remarkably linear, steep sided valley which is 2 to 10 km wide trending 040˚ and traceable for a distance of over 300 km from the Mesopotamian Plains into Saudi Arabia. It dissects a low plateau of near horizontal Neogene sediments and Palaeogene strata. The Wadi Al Batin feature is spectacularly illustrated on Landsat images. Al-Sarawi (1980) described three en-echelon northeast trending faults identified on seismic supported by water well drawdown data on the southeast side of Al Batin and suggested they throw 25 m down to the southeast. Hancock et al. (1981) describe a 20 km sinistral offset across Al Batin near latitude 28^{o}. A major northwest-southeast lineament seen on satellite imagery, approximating closely to the interpreted boundary between the Arabian Interior Homocline and Platform within southern Iraq appears to terminate, or is possibly sinistrally offset, at the Al Batin lineament.

FAULTS

Regional faults have not been mapped in Kuwait (hence no faults are shown on Figures 3 and 4). Important fault-related observations reported in this paper are the steep dips and small throws; graben on the Kuwait Arch; the north trending axial fault at Sabiriyah; the sensitivity of oil-trapping mechanisms to faults cutting Cretaceous (at Bahrah) and Jurassic strata (at Abduliyah field); and interpreted transverse faults zones. Reverse displacements interpreted on seismic at Dharif, Bahrah and the Ahmadi Ridge structures are quite likely to be related to steep dipping strike-slip faults.

Faults interpreted in Kuwaiti wells are characterized by steep dips and small normal throws, commonly less than 15 m, and should map as straight line segments of less than 1 km length. The radial patterns mapped in some areas infers a primary origin by vertical uplift or overprinting of several stress fields. Fox (1959) and Murris (1980) considered the Burgan and Magwa culminations on the Kuwait Arch were uplifts caused by deep halokinetic mobilization of the 'Infra-Cambrian' Hormuz Salt Series. Regional evidence suggests Hormuz salt basins developed along the eastern margin of the Arabian Plate including a North Gulf Salt Basin (Alsharhan and Kendall, 1986, their Figure 3). There is compelling, but not definitive, evidence of salt piercement at the present day land surface at Jabal Sanam very close to the Kuwait border in southern Iraq (Masin et al., 1965; Al-Naqib, 1970). However the deep wells in Kuwait (e.g. BG-399A down to 22,200 ft, Khan, 1989) and northeastern Saudi Arabia (at Safinayah) suggest the Hormuz salt is not present over the crests of the regional arches. Variable palaeo-stress fields related to the history of rotation and translation of the Arabian Plate may better explain the high diversity of fault trends, mapped as radial on Kuwait fields.

Faults have not yet been demonstrated to affect reservoir drainage in most of Kuwait's thicker reservoirs. Important conclusions are:

(1) it appears that extensive faults with large throws are rare in Kuwait which is probably a function of its location on the stable Arabian Shelf;
(2) some faults identified on seismic affecting the Jurassic strata appear to not affect the Cretaceous;
(3) steep, near vertical, faults in the Cretaceous commonly have throws less than 15 m and are more common below the Mishrif Unconformity;
(4) faults in the Late Cretaceous Aruma Group (above the Mishrif Unconformity) and rare faults reaching the surface are observed; and
(5) steep branching faults seen on seismic in local areas suggest important horizontal movements.

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STRESS FIELD INDICATORS

At present the coverage and quality of seismic data onshore Kuwait does not allow a thorough analysis of fault orientations (and density) and deformation ellipsoids. However well borehole breakouts (ellipticity) and fracture trends (measured from borehole imaging tools) provide some evidence for the Principal Horizontal Stress. Preliminary manual analysis of 4-arm caliper data indicating borehole breakout for six wells on the Minagish field demonstrate a strong preference for northwesterly oriented borehole breakouts. Four wells on the Umm Gudair field (Figure 16) show some preference for the same northwest breakouts but the dominant direction is north-northeast.

In Kuwait, borehole imaging tools have been successfully used to measure near-vertical, frequently open, fractures in horizontal holes mostly in the Mauddud Formation. Two Burgan, two Magwa, one Sabiriyah and one Raudhatain well all indicate a strong open fracture trend to the northeast (040° -050°) which together with the Minagish breakout trends suggest a Principal Horizontal Stress oriented northeast (Figure 16). Open joints in the outcrops along the Jal Al Zor Ridge trend northeasterly and closed joints trend northwesterly (Salman, 1979).

The present-day northeasterly trend for the Principal Horizontal Stress field is consistent with other trends on the Arabian Plate (Akbar and Sapru, 1994) reported as the Zagros Stress field in the Oman and Abu Dhabi region (Marzouk and El-Sattar, 1995). The northerly breakouts at Umm Gudair and a northerly fracture set at Magwa-173 (Figure 16) are indicative of an east-west Maximum Horizontal Stress field which is probably related to an older tectonic event, possibly the Oman Event (Jørgensen et al., 1995). Further work is required to examine local variations in the stress field, especially in close proximity to overprinted trends, near faults and around fault tip lines.

STRUCTURAL SYNTHESIS

Figure 1 summarizes the major oil field, outcrop and geomorphic trends onshore Kuwait. Twenty-five structural elements and selected fault patterns define five families of structure (A to E in Figure 1).

A north-northeastern trend (005°-015°; A in Figure 1) of sub-parallel anticlines mapped at the Jurassic level occur through the Dharif, Abduliyah and West Umm Gudair area and are associated with a seismic-defined reverse fault at Dharif. They occur along trend of branching faults seen on seismic, and a swing in the trend of the Kuwait Arch, in the Bahrah area suggesting regional strike-slip movements. These north-northeast structures are interpreted to be related to a regional West Kuwait Arch Lineament (Figure 1). These structures are best expressed at intra-Jurassic levels, have much less structure at Cretaceous and shallower levels (i.e. are disharmonic) and are amongst the oldest structures recognized onshore Kuwait. They contain some of Kuwait's smaller oil fields in Early Cretaceous and Jurassic strata and the available evidence suggest they are highly dependent on faulting. The Sabiriyah structure appears to have both north-northeast and north-south fold trends and may be related to the West Kuwait Arch Lineament. Alternatively the Dhabi Trend with possible late Jurassic movements may be a better relation.

North-south Trend (B in Figure 1): The Kuwait Arch, the Minagish Anticline, the Rahiyah Syncline (in part) and probably the Raudhatain and Sabiriyah structures have a north-south trend that cuts and dominates over all other trends. The inferred principal maximum horizontal stress is east-west. Isopach and seismic data indicates structural movements on these trends probably occurred intermittently from Late Jurassic to Turonian time. These large regional anticlines may be founded on basement horsts formed initially during Early Devonian continental margin rifting. The largest hydrocarbon accumulations in Kuwait are found in these structures in Middle Cretaceous, Lower Cretaceous, Upper Jurassic and (to a lesser extent) Lower Jurassic strata.

Both structure and subcrop patterns of the Wara, Ahmadi and Mishrif formations below the Turonian Mishrif Unconformity demonstrate that discrete areas of uplift and erosion occurred at the Burgan and Magwa domes (Figure 17). The Greater Burgan structure is cut by northwest trending graben and related splay faults between these domes which are interpreted to post-date the main uplift. However seismic data show some faults also cut up to the Rus Formation (Figure 12) inferring some repeated (or possibly continuous) growth through to the Eocene and probably more recent time.

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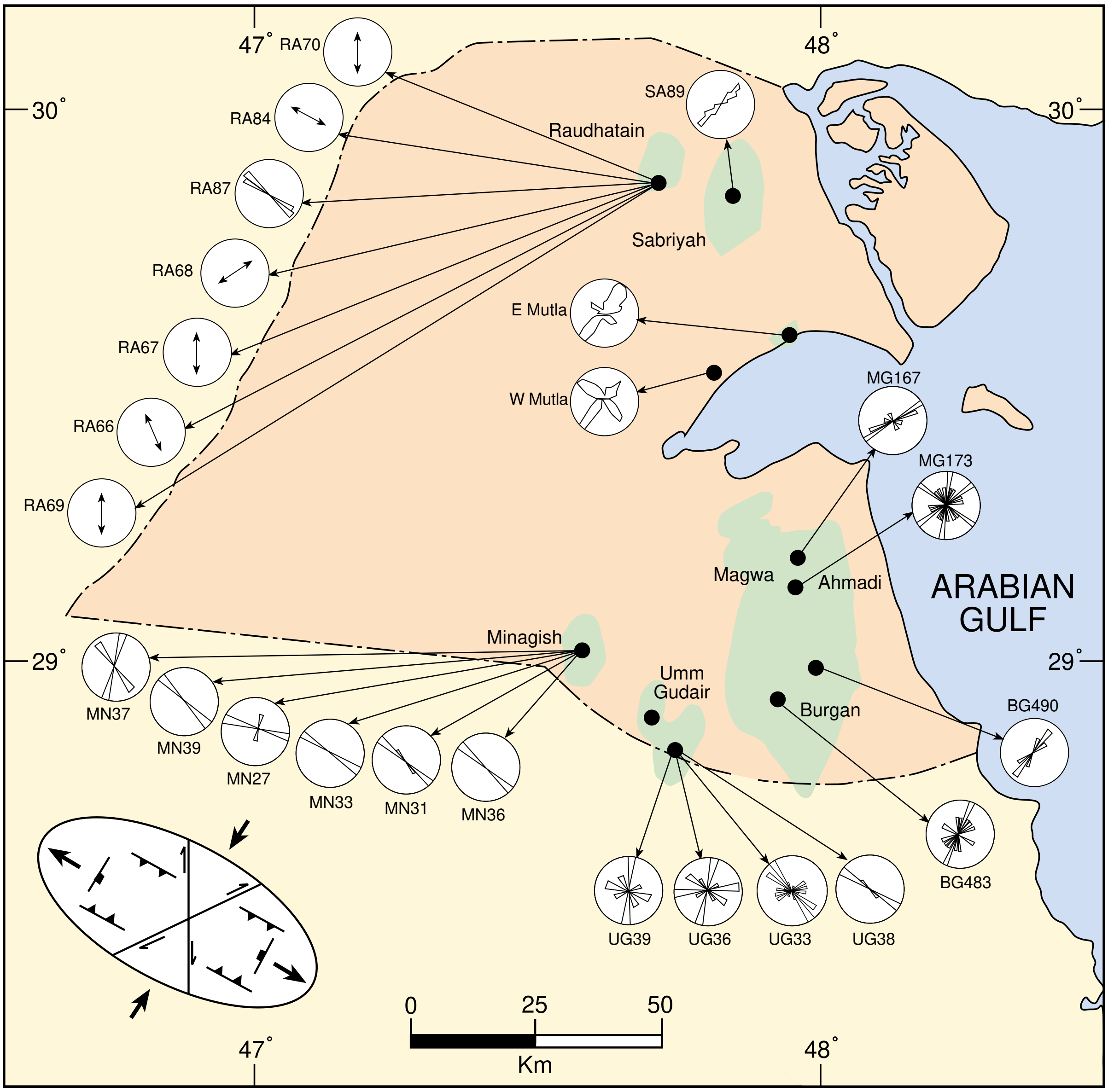

Figure 16: Regional stress field indicators from Cretaceous oil fields and Tertiary outcrops. For Burgan, Raudhatain, Umm Gudair and Minagish fields the indicators are borehole breakout data from calliper logs. Sabiriyah-89, Raudhatain-87 and Magwa-167, 173 are open fracture trends from imagery logs and open joint trends from the Mutla (Jal Al Zor) Ridge Tertiary outcrops are shown after Salman (1979).

Northwest trends (320°-340°; C in Figure 1) are exhibited by a suite of structures including the Mutriba, Kra Al Maru, Ratqa-Rumaila, Abdali-Zubair Anticlines, the southern part of the Dhabi trend, the nose of the Kuwait Arch in the Bahrah area, the Ash Shiqq Syncline, the Burgan Graben and similar graben faults separating the Magwa and Ahmadi structures. The structure is evident at the Jurassic, Cretaceous and to a lesser extent the Palaeogene levels and possibly reflects a structural grain inherited from the underlying Arabian Shelf basement. Recent reactivation and/or drape of cover sediments over these lineaments producing gentle warps in the Mesozoic cover, is consistent with an inferred principal maximum horizontal stress oriented northeast-southwest. These structures are generally dry in the Middle Cretaceous strata (possibly because of a lack of seal) but have proven oil in Lower Cretaceous and, in one instance, Late Jurassic strata.

East-northeasterly trends (030° -050°; D in Figure 1) are exhibited in subsurface folds at Medina, Khashman and (partly) East Umm Gudair at Jurassic to Rus levels and also by coastline morphology. These anticlines contain oil in Jurassic and Early Cretaceous strata and, where north-south trends are overprinted, oil is also trapped in Middle Cretaceous rocks. They are interpreted to be folds associated with northeast trending shear zones referred to here as the Al-Liyah, Al-Musannat-Jal Al Zor and the Khashman Lineaments (Figure 1).

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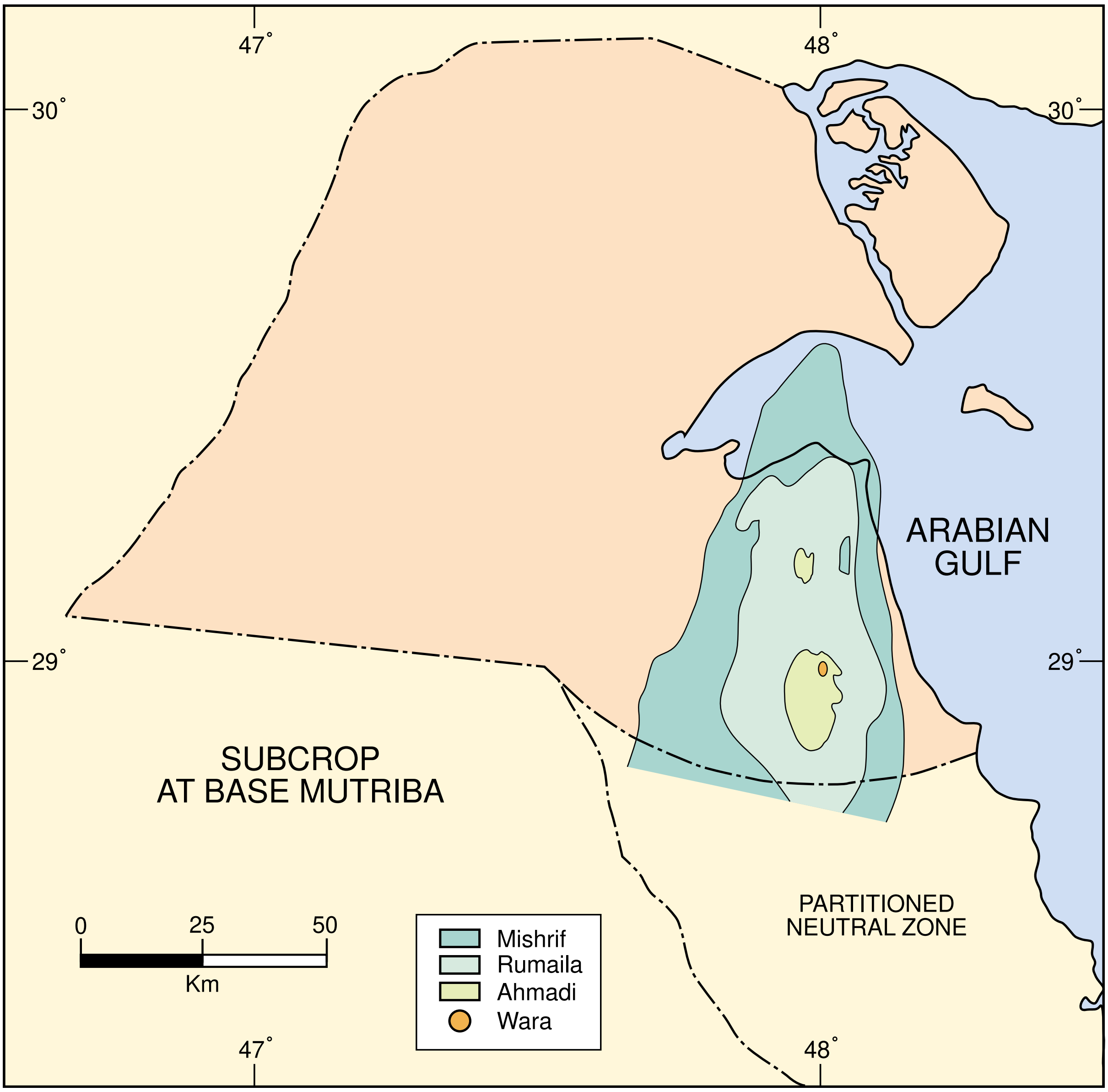

Figure 17: Subcrop of the Mishrif Unconformity. The Wara subcrop is controlled by one well penetration.

A north-northwesterly trend (350°; E in Figure 1) is recognized only at the Ahmadi Ridge which deforms the eastern flank of the Kuwait Arch trend notably at the Ahmadi field. The inferred principal maximum horizontal stress is northeast-southwest which is interpreted to be a Zagros-related deformation of an older Ahmadi dome (possibly Magwa dome twin). The Ahmadi Ridge structure may be one of the most recently formed structures recognized in Kuwait. To date oil accumulations have only been proven in Cretaceous strata where the structure overprints older north-south oil-bearing structures; other trap possibilities may be expected at the intersection with the Burgan Graben faults.

The onshore structural elements of Kuwait demonstrate significant variation in trend. The variation represents the interaction of a principal horizontal stress which has ranged through a northeasterly arc (north-northwest to east) from Early Cretaceous to recent times, and a structural grain inherited from the basement. The present day maximum horizontal stress field is northeast-southwest. The varied structural trends and the inferred variation in stress field may explain the high diversity of fault trends, mapped as radial, on Kuwaiti fields.

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While it is not yet possible to accurately determine the chronology of these events some broad conclusions are possible:

(1) The northeasterly trending structures at Abduliyah and Dharif (A in Figure 1) are some of the oldest structures and appear to have decelerated growth after the Cretaceous. They are interpreted to have formed by local shear.
(2) The north-south trending suite of structures (B in Figure 1) probably have the oldest origins based on ?Devonian horsts which were subsequently re-activated during the Late Jurassic-Early Cretaceous. Structural growth accelerated during Turonian time as reflected by the Mishrif Unconformity (Figure 17) but was thereafter slowly continuous, perhaps intermittently, through to quite recent time. These structures infer an east-west vector for compression.
(3) A suite of northwesterly trending structures (C in Figure 1) are mapped west of the Kuwait Arch and infer a northeasterly maximum horizontal stress field. These structures are expressed at Jurassic to Palaeogene levels and, whilst they have an older inherited northwest grain, they are interpreted to have been reactivated during post Rus (post Miocene) time.
(4) The northeast-southwest axial trend of the Khashman-Medina antiforms and associated normal faults (D in Figure 1) are possibly anomalous affects produced by the sparse data and require better definition. These structures are expressed by the structure of the Rus Formation and are therefore post Eocene in age.
(5) The Ahmadi Ridge (E in Figure 1) is considered possibly the youngest fold structure in Kuwait and has high structural amplitude at the Rus Formation. It has a unique trend in Kuwait with the inferred maximum horizontal stress direction (i.e. the direction of shortening) aligned 80^{o} east of north. The Ahmadi Ridge structural stress field may have generated northeasterly dextral strike-slip similar in direction to the observed Al Liyah and Al Zor Lineaments.

The above discussion suggests that a possible relation exists between the stratigraphic level of the hydrocarbon trap and its structural evolution. However variations in reservoir quality and seal capacity, as well as the maturation of source rock requires an integrated basin study to understand the distribution of Kuwait's oil. Some structural trends may have had a long intermittent history of influencing sedimentation patterns. This is suggested by broad east-west Jurassic facies belts and isopach trends (Langdon and Malecek, 1987; Koepnick et al., 1995; Yousef and Nouman, 1995), the Gotnia Basin, the structural separation of the Tuwaiq and Najmah source rocks (Koepnick et al., 1995; Ali, 1995) and the localized distribution of some Cretaceous oolitic reservoirs. These facies belts, in turn, could have affected the distribution of hydrocarbons.

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