ABSTRACT

Jebel Abd Al Aziz, one of the most prominent topographic features in northeastern Syria, is a large surface anticline. An integrated structural and stratigraphic study conducted by Unocal from 1988 to 1995 resulted in recognition that Jebel Abd Al Aziz originated from inversion of a pre-existing graben. Understanding the complex structural and stratigraphic history of the Jebel Abd Al Aziz is important to hydrocarbon exploration and development in the northern Arabian tectonic plate. This importance is demonstrated by the strong correlation between hydrocarbon productive areas and the areas of Plio-Pleistocene structural inversion.

Our study illustrates how the evolution of this structure is recorded in its local stratigraphy. Prior to the development of the Jebel Abd Al Aziz structure, Senonian shelf carbonates prograded southward from Turkey into the Palmyride-Sinjar Trough that extended from west central to northeastern Syria. The shelf edge of this carbonate system was south of and subparallel to the Syrian border. In the Jebel Abd Al Aziz area, fine-grained basinal mudstones were deposited on a thin, transgressive, rudistid, bioclastic unit. In Early Maastrichtian, an east-west-trending graben developed at the present site of Jebel Abd Al Aziz. Reactivated northwest- and northeast-striking faults bound structural blocks within the graben. Seismic data indicate that the edges of the rift basin were deeply eroded. Valleys, cut into the sides of the basin along the trend of the older cross-cutting regional faults, exposed Carboniferous and possibly older strata. Olistostromes formed along the basin-bounding fault scarps and small turbidite fans developed at the channel mouths. Paleocurrent direction data from the turbidite sand bodies corresponds well with the trends of the valleys mapped on seismic data.

Maastrichtian-age sediments are largely confined to the graben proper. Early Tertiary sediments filled a wider basin, but there is evidence that minor episodic inversion on some northeast and northwest trending faults occurred during the Eocene and early Miocene. The main inversion of the Jebel Abd Al Aziz structure occurred in the Late Pliocene and Pleistocene. Inversion produced a large fault-propagation fold above east-west trending faults near the northern margin of the graben. Smaller folds developed above other graben-bounding faults and the northeast- and northwest-striking faults within the graben underwent oblique slip during the deformation.

INTRODUCTION

In 1988, Unocal Corporation began an exploration program to evaluate the hydrocarbon potential of the Jebel Abd Al Aziz area (Figures 1 and 2). In 1989, Unocal signed a work commitment with the Syrian Government for the Al Hasakah Block. This work program was continued in 1992 with an agreement covering the Tel Abyad Block (Figure 2). Over the course of the two, three-year contracts, Unocal acquired 1,150 kilometers (km) of two-dimensional seismic data, reprocessed 6,657 km of existing seismic data and drilled six exploratory wells in the area surrounding Jebel Abd Al Aziz (Figure 3).

Although the main focus of the exploration program was to evaluate the economic potential of Paleozoic reservoirs in northeastern Syria, a significant benefit of the program has been the recognition that Jebel Abd Al Aziz originated by inversion of a pre-existing graben. This conclusion resulted from an
improved understanding of the local stratigraphy and structural development of Jebel Abd Al Aziz. Recognition of the complexity in the origin of the Jebel is essential to hydrocarbon exploration in the region.

The east-west trending Jebel Abd Al Aziz anticlinal structure is over 60 km long and 10 to 15 km wide. The Jebel is segmented into three parts by northeast-striking faults. In each segment the anticline resembles a fault-propagation fold, but in the different segments the geometry of the fold ranges from nearly symmetrical to strongly asymmetrical. The three parts of the structure developed contemporaneously as the result of north-south shortening of the earlier graben. Seismic data reveal both the early extensional structures and the later compressional features.

**PREVIOUS WORK**

Early geologic exploration in the area by the Iraqi Oil Company culminated with the drilling of the Toul Abba well on the Abba structure west of Jebel Abd Al Aziz in 1949 (Figure 3). A detailed 1:200,000
scale geologic map of the Al Hasakah Quadrangle that includes the Jebel was made by Soviet geologists with geological party chiefs, A.B. Galaktionov and B.Ya. Ponikarov. This mapping was done as part of the International Agreement on Economic and Technical Cooperation consummated in 1958 between the U.S.S.R. and the Syrian Republic. During the early 1970’s, Rompetrol collected seismic data in the vicinity of the Jebel and drilled several exploration wells on seismic structures along the mountain’s southern flank.
The Syrian Petroleum Company carried out extensive seismic surveys and exploration drilling on the eastern flank of the Jebel Abd Al Aziz and the western flank of Jebel Sinjar (Figure 3). Additionally, several international oil companies including Pecten, Nest, Arco, British Petroleum and others have studied the area surrounding the Jebel. However, much of the work done by the oil companies is held as proprietary information with only basic well and seismic data are publicly available. Sawaf et al. (1993) published a paper describing a north-south geotransect across the northern Arabian platform, eastern Syria. Their transect crosses the Jebel Abd Al Aziz structure and includes a brief discussion about the area’s structural development. The paper is part of a large volume of work on the structure and stratigraphy of Syria done by numerous researchers at the Syrian Petroleum Company and M. Barazangi and his colleagues and students at Cornell University.

**REGIONAL SETTING**

Syria forms part of the Arabian platform. Regional work by Unocal and others (Lovelock, 1984; Leonov et al., 1989; Best et al., 1993) illustrates that from the Devonian through the Late Jurassic (?), a northeast-trending basin developed across central Syria (Figure 4). The northwest-trending Beida Arch divides this basin into two segments, the Palmyride Trough and the Sinjar Trough. The northwestern flank of the Palmyride-Sinar basin is the Aleppo-Mardin High. Stratigraphic data indicate that the Aleppo-Mardin High has existed as a positive structural element from the late Precambrian to the Recent. The southeastern flank of the Palmyride-Sinar basin is the Rutbah High, a positive structural element that formed in the Early Devonian and that has persisted as a positive structural element for most of its history.
The Jebel Abd Al Aziz structure is a younger feature that was superimposed over the older regional tectonic features. It is on trend with, and probably of similar origin as, the Jebel Sinjar anticline (Figure 3). Extensional faulting at Jebel Abd Al Aziz also was contemporaneous with some of the extension of the Euphrates Graben to the south as indicated by thickness changes in Lower Cretaceous and Maastrichtian sediments there (Sawaf et al., 1993).

**STRUCTURAL HISTORY**

Figure 5 shows two, south to north, seismic lines across Jebel Abd Al Aziz. Both of these lines show structures indicating strong similarity to classic inversion structures (Williams et al., 1989). We have found an adaptation of this model (Figure 6) to be a useful tool for understanding the evolution of the Abd Al Aziz structure. Most notably, both Figures 5 and 6 illustrate stratigraphic dips that diverge toward the anticlinal structural crest.

In the model, stratigraphic sequences correspond to pre-rift, syn-rift, post-rift and syn-inversion sediments. Stratigraphic syn-rift and syn-inversion sequences have a genetic relationship to movements on the boundary fault. During syn-rift time, normal displacement of the boundary fault creates the accommodation space for deposition of the syn-rift sequence. During syn-inversion time, reverse movement on the same fault creates the source topography of the syn-inversion sequence. The fault at
Figure 5: Representative examples of seismic data available or acquired early in the Unocal study. General interpretations of these data show stratigraphic geometry similar to the classic inversion model. The colors of the interpreted horizons generally correspond to units defined in Figure 6. The yellow marker is near base of the syn-inversion sequence; the blue horizon is within the post-inversion sequence; the green marker is near-top syn-rift sequence; and the pink horizon is near-top pre-rift sequence.

Figure 6: Schematic diagram of the classical positive inversion structure (modified from Williams et al., 1989).
the end of the stratigraphic syn-inversion sequence has normal displacement below the dashed line or null line, and reverse displacement above this line. In three dimensions the null line expands in to a null surface.

Using this model the structural history of the Jebel Abd Al Aziz structure can be divided into pre-rift, rift, post-rift and inversion time intervals. Additionally, we subdivide the rift time interval into early extension and syn-rift episodes. The northern Arabian tectonic plate was subjected to multiple rift episodes. We have elected to use terminology that specifically emphasizes the development of the Jebel Abd Al Aziz structure. At least two rift events occurred in northeastern Syria during the Cretaceous. We refer to the Early Cretaceous deformation as early extension. The Late Cretaceous rift episode, that is directly related to the development of the Aziz Graben, we refer to as syn-rift. The two rift episodes result in structures that have cross-cutting relationships in the Jebel Abd Al Aziz area.

A characteristic stratigraphic section represents each of these structural intervals defined above. Figure 7 is a stratigraphic correlation chart that shows the relationship of these stratigraphic sequences to the tectonic events. The structural elements of one time interval were often reactivated in subsequent time intervals.

**PRE-RIFT**

Late Paleozoic and Early Mesozoic sedimentation in the Jebel Abd Al Aziz area was controlled by normal faults along the northwest flank of the Palmyrid-Sinjar Trough. Both northeast- and northwest-striking sets of faults are present. Paleozoic and Lower Mesozoic rocks thin northwestward onto Aleppo-Mardin High (Ala and Moss, 1979). Throughout most of the early history of the area, the northeast-trending faults had the most pronounced control on stratigraphic thickness. Reactivation of the Palmyrid-Sinjar basin-bounding, normal faults between the deposition of each major stratigraphic unit resulted in abrupt thickness changes at the major fault traces.

**SYN-RIFT**

**Early Extension**

The onset of the early extension event is marked by a regional unconformity at the base of the Cretaceous section. Because the Jebel Abd Al Aziz area is located on the flank of the Aleppo-Mardin High, upper Triassic, Jurassic and Lower Cretaceous stratigraphic units seen elsewhere in northeastern Syria are not present over most of the area. However, occasionally Lower Cretaceous and pre-Cretaceous units are preserved as erosional remnants in small half-grabens and grabens related to the early extension. The preserved Lower Cretaceous strata show that multiple cycles of Lower Cretaceous lowstand sandstone and highstand carbonate units were deposited across the area. These strata also suggest that the early extension was episodic. Erosion and rejuvenation of northeast- and northwest-trending faults between the depositional cycles further enhanced the effect of these faults on the preserved thickness of these sediments. However, the preserved early extension stratigraphic units, like the pre-rift stratigraphic units, do not show significant facies relationship to the structure location in which they are preserved.

Examples of the early extensional event and its related stratigraphic units are illustrated in Figure 8. Area A in Figure 8 shows where Lower Triassic dolomite is preserved below the Early Cretaceous unconformity in northwest-trending grabens. Area B in Figure 8 is an area where the Neocomian to Barremian-age Zubair sandstone is preserved in a half-graben formed against the Abba Fault. These grabens and half-grabens are parallel to the crest of the Beida Arch (Figure 4) and are contemporaneous with development of the northwest-trending Euphrates Graben System. The displacement of these faults is small, relative to the faults of the later rift episode.

Between the early extension and the syn-rift time, the Coniacian to Late Campanian was an interval of relative stability. During this time, shelf carbonates of the Massive Limestone prograded southward from the Mardin High of southern Turkey into Syria. The southernmost extent of this carbonate shelf
Figure 7: Northeast Syria, generalized stratigraphic correlation chart showing the stratigraphic units used in Unocal's study and their correlation to the interpreted tectono-stratigraphic sequences. The thickness indicated for individual units is diagrammatic.
edge was south of and subparallel to the Syrian-Turkish border. At the same time, further south in the Jebel Abd Al Aziz area, fine-grained basinal mudstones were deposited on a thin, transgressive, bioclastic unit. Figure 9 shows an example of the down-lap of the Massive Limestone on seismic line AF-14 south of the Afendi-1 well location. Figure 10 is a map that shows the location of the down-lap of the Massive Limestone in relationship to the bounding faults of the Aziz Graben. Seismic data indicate that most of the displacement on these faults occurred after the deposition of the Massive Limestone.

It has been suggested that Senonian carbonates are absent from most of northeastern Syria by erosion related to tectonic uplift of the area (Ala and Moss, 1979). While there is evidence that erosion has modified the upper contact of the Massive Limestone, seismic data suggest that Senonian shelf carbonates are absent from this area by non-deposition and that a condensed section represents the equivalent stratigraphic interval.

**Syn-Rift**

In Early Maastrichtian time, renewed extension caused a major half-graben to form along the south dipping Jafar Fault system shown in red in Figure 11. The Aziz Graben, shown in yellow in Figure 11, was internally segmented into blocks by the northwest- and northeast-striking faults. With continued extension, the north-dipping Syrom Fault, also shown in red in Figure 11, developed along the southern side of the half-graben and the basin developed a graben profile. Figure 12 is a block diagram illustrating the components of the Aziz Graben. This diagram serves as an index for the following discussion on the features of the Aziz Graben.
Figure 9: Seismic line AF-14/AF14N through the Afendi-1 well showing the Massive Limestone down-lap (see Figure 10 for location.) The Massive Limestone is composed of at least two progradational cycles A and B as illustrated by the section in the Afendi-1 well. These units thin by depositional down-lap north of the Jafar Fault. The surface of the progradational down-lap was modified by erosion prior to the deposition of the Maastrichtian Shiranish Formation.

Figure 10: Map of the Massive Limestone down-lap. The blue band indicates the extent that the Massive Limestone sediment wedge was mapped during this study.
Development of the Aziz Graben resulted in substantial changes in depositional patterns. Highstand carbonate deposition was replaced by erosion along the northern margin of the graben and deep-water clastic deposition within the graben. Faulting produced substantial relief at the graben edges. Valleys, localized by the older cross-cutting regional faults, were cut into the northern margin of the basin.

The end of seismic line SY-34 north of the Jebel Abd Al Aziz is shown in Figure 13 (see Figures 12 and 13 for location). This seismic line illustrates the syn-rift unconformity. The unconformity, shown by the red marker, cuts from the top of the Massive Limestone on the right-hand, northern, side of the

Figure 11: Fault index map. Faults indicated in red originated during the development of the Aziz Graben (shown in yellow). Faults indicated in blue existed prior to the development of the Aziz Graben, but many of these faults were reactivated during the Aziz rifting. Sense of slip is not indicated for the faults because the magnitude and sense of displacement for most faults vary with location and time.

Figure 12: Block diagram of the Aziz Graben during Maastrichtian time. This figure illustrates the spatial relationship of Figures 13, 14, 16 and 17 to the Aziz Graben.
Figure 13: North end of seismic line SY-34 (see Figures 3, 11, 12 and 15 for location). The syn-rift unconformity, indicated by the red line on the section, passes from the top of the Massive Limestone at the right end of the section to the top of the Carboniferous at the Jafar Fault (J-1). The seismic line is fortuitously located such that it intersects one of the valleys cut into the north side of Aziz Graben. The data shown in this figure are shown reversed from that of Figure 5.

Figure 14: Segment of seismic line SY-48N (see Figures 3, 11, 12 and 15 for location). Seismic line SY-48N shows one of the valleys cut into the Carboniferous at the north side of Aziz Graben. The valleys are located on trend with the pre-existing northeast and northwest fault systems.

Figure 13 through the Lower Cretaceous and Triassic and into the Carboniferous section at J-1 splay of the Jafar Fault on the left-hand, southern, side of the figure. Above this unconformity, the Shiranish Formation thins northward across the toe of the Massive Limestone down-lap. The seismic section shows that the main part of the later inversion of the Jafar fault system took place along a fault splay south of the graben boundary fault.

Seismic line SY-34 ties seismic line SY-48N north of the graben-bounding splay of the Jafar Fault (see Figure 12 for location). At this intersection seismic line SY-48N crosses one example of the valleys cut
into the side of the graben (Figure 14). This and other valleys were eroded deeply enough to expose Carboniferous or older (?) strata as demonstrated by data on the north end of seismic line SY-34 (Figure 13).

Sediment eroded from the syn-rift unconformity surface was transported into the graben. The presence of clasts from these formations within the Late Cretaceous graben-fill helps to confirm this interpretation.

Slump blocks in outcrops along the north face of the Jebel Abd Al Aziz were described by Fairbridge and Badoux (1960). This communication initiated a discussion whether the slump blocks were of structural or of stratigraphic origin. Data from stratigraphic sections measured by Unocal and others (Leonov et al., 1986), indicate that the slump blocks are part of a debris flow-turbidite fan complex that developed along the basin-bounding Jafar Fault scarp.

Figure 15 is a map of the subcrop below the syn-rift unconformity. This unconformity eroded into the Lower Cretaceous sediments along the Jafar Fault where it bounds the Aziz Graben. The Lower Cretaceous subcrop is shown in orange on the map. The syn-rift unconformity cuts into the Carboniferous and older strata at the locations of northwest-striking faults that offset the Jafar Fault. The Carboniferous and older subcrop is shown in purple on the map.

Figure 16 is a photograph of a submarine channel system exposed along the northern margin of the Jebel Abd Al Aziz. The map location of this outcrop is shown in Figure 15 and the depositional location within the graben is shown on the block diagram, Figure 12. The outset circle in figure 15 shows the paleocurrent data measured at this outcrop. Paleocurrent directions, determined from the sand bodies,
are similar to the trends of the valleys mapped from seismic data. Measured stratigraphic sections indicate that the Shiranish Formation grades vertically from the fan-complex lithology into fine-grained marls of Maastrichtian age (Figure 17).

Lower Maastrichtian sediments are largely confined to the graben proper. As shown on seismic line SY-34 (Figure 13), the depositional basin of the Shiranish Formation extended a short distance north of the Jafar Fault. However, south of the graben on the up-thrown side of the Syrom Fault, Upper Maastrichtian sediments extend outside of the graben to the limit of our data. Isopach mapping of the Shiranish Formation indicates that the northwest- and northeast-trending fault systems were reactivated with normal displacement during the Maastrichtian. The Lower Tertiary sediments filled a broader depositional basin than the graben. The upward fining of the Shiranish, the depositional area of the upper Shiranish and the depositional area of the Lower Tertiary units indicates a continued decrease in influence on sedimentation by the Aziz Graben bounding faults.

Unlike pre-rift units, syn-rift stratigraphic units have depositional facies that are clearly related to the structures active during their deposition. Identification of the related structure implies the existence of these facies, and vice versa.

**Post-Rift**

Determination of the timing of the onset of rifting is relatively straightforward. However, documenting the timing of inversion is less precise because there appear to have been several periods of relatively minor, local inversion prior to the major inversion that created the present-day Jebel Abd Al Aziz.
Stratigraphic units of this post-rift, pre-main inversion interval have wide facies tracts and structural influence on the facies in these units is subtle and difficult to distinguish from other causes. However, stratigraphic relationships that suggest several periods of local inversion can be seen both in outcrop and on seismic sections.

Figure 18 is a cross-section between Unocal’s Kharbaka-1 well on the Jebel Abd Al Aziz structure and Hamadani-1 well on the Abba structure (see Figure 3 for location). This cross-section demonstrates that the Abba Fault which separates the two wells had normal displacement, down to the west, prior to the pre-rift unconformity in the Early Cretaceous. The Upper Triassic units were eroded from the upthrown side of the fault by the pre-rift unconformity. After the syn-rift unconformity in Maastrichtian, however, the Abba Fault has displacement down to the east. Down to the east displacement occurred in at least two episodes. The first is shown by the thickness changes in the Shiranish Formation and the second by the thickness changes in the Chilou and Euphrates formations. Seismic data confirm this interpretation.

Figure 17: Stratigraphic measured section at the north side of Jebel Abd Al Aziz. The interval labeled Lower Cretaceous Undifferentiated includes the Barremian-Valanginian age Zubair Sandstone, the Aptian age ‘marker limestone’ (Ghouna Limestone equivalent?), and an undated dolomite (Judea Dolomite?). The Massive Limestone equivalent is a carbonate unit consisting of coarse skeletal packstone and grainstone at the base grading to calcareous clay shale at the top. The skeletal material includes transported rudists. The Shiranish Formation grades from interbedded conglomerate, calcareous sandstone, siltstone and calcareous claystone at the base to clayey limestone and calcareous claystone at the top. The conglomerate and sandstone units tend to be localized in channels. Exotic blocks of various age and composition are common throughout the lower part of the unit. The blocks include Ordovician (?) quartzite, Carboniferous fossiliferous limestone, Triassic (?) crystalline dolomites and Cretaceous (?) sandstone. The Jaddala Formation is massively bedded lime grainstone composed of organic debris, including large foraminifera, and algal, shell, and coral fragments.
Figure 18: Cross-section A-A' between the Hamadani-1 well on the Abba Structure and the Kharbaka-1 well on the Jebel Abd Al Aziz structure. See Figure 3 for location. The cross-section shows that the Abba Fault that separates the two wells had normal displacement to the west prior to the pre-rift unconformity and normal displacement to the east after the pre-rift unconformity.
The Jafar Fault and the E-2 Fault (Figure 11) also show evidence of early inversion. Mapping of the Jaddala Formation over the central culmination of the Jebel Abd Al Aziz reveals an area where the formation is thin or absent (Figure 19). In outcrops on Jebel Abd Al Aziz, there is a pronounced local angular unconformity between the upper part of the Shiranish Formation, of Maastrichtian age, and the overlying Jaddala Formation which includes strata of Middle and Late Eocene age. This unconformity indicates Early Tertiary deformation. The Jaddala Formation in this area also thins from more than 100 meters to zero near the crest of the Jebel Abd Al Aziz anticline (Figure 20). The

Figure 19: Geologic map showing thinning of the Jaddala limestone over the crest of the Jebel Abd Al Aziz anticline near the village of El Garra. See Figure 3 for location. The Cretaceous outcrop, shown in green on this map, is the area that occurs as a white area on the north side of Jebel Abd Al Aziz in the upper center of Figure 1.

Figure 20: Photograph and line drawing of the Jaddala Formation where the unit thins depositionally and is absent. View is to the west 1.7 miles west of El Garra (see Figure 19 for location).
upper part of the Jaddala Formation consists of a thick limestone bed containing abundant large forams, pelecypods, sponges, algae, echinoderms and small corals. This bed probably formed as a carbonate bank deposit. Immediately overlying the thick limestone bed is a zone a few centimeters thick consisting of black shale or calcareous marls with phosphate pellets. This zone is of latest Eocene age based on nannofossil data.

These lithologies and ages suggest development of the carbonate bank deposits, followed by a rapid sea level rise in the latest Eocene that flooded the bank and resulted in a period of slow deposition marked by the phosphate pellets. This implies that the areas of thin or no Jaddala Formation were areas of non-deposition rather than places where the unit was removed by erosion. These areas were subtle highs during the later Eocene. The exposed area of thin Jaddala Formation coincides with the present-day structural high suggesting a tectonic origin for the Late Eocene stratigraphic changes.

The areal distribution and facies of the Dibbane Formation, of Early Miocene age, also suggest that parts of the present structurally high area were also elevated during the early Miocene. The unit is absent from the central culmination of the Jebel Abd Al Aziz anticline, while on the east and west culmination of the anticline the unit consists of interbedded limestone and anhydrite. Over a few kilometers to the northeast, the unit grades northeast from nearly solid limestone to mostly anhydrite in exposures at the Maghloja-1 well site (see Figure 3 for location). In the Sheikh Suleiman-1 well, located about 20 km east-northeast of the eastern anticlinal culmination, the unit consists mostly of a thick sequence of bedded salt overlain by a thin sequence of interbedded anhydrite and salt.

Lateral facies changes from salt to anhydrite to limestone could reflect the effects of a varying sea level on a gently sloping basin margin. During lowstands, salt was deposited in low parts of the basin with restricted circulation; during intermediate sea level conditions, anhydrite was precipitated over a larger area; and during highest water levels, carbonate deposition took place on topographically still higher areas. This suggests that during the Early Miocene, the Jebel Abd Al Aziz anticline also was a low relief topographic high.

West of Tell Tayyan (Figure 3), the Geologic Map of Syria (Sheet J 37 V, XI, V; Ponikarov, 1963) shows an abrupt thinning of the Lower Fars Formation by erosion of the upper member of the unit near the E-2 Fault. An unconformity correlative in age to this unit can be mapped on satellite images from the west edge of this map sheet to the Balikh River (Figure 3). This pattern suggests that much of the overall Jebel area was a subtle high during the Middle Miocene.

The stratigraphic relationships described above suggest that periods of minor inversion occurred during the Late Eocene, Early Miocene, and Middle Miocene. However, the amount of differential uplift at these times was small relative to the main inversion. Also the areal extent of the Eocene inversion appears to have been restricted (Figure 19).

INVERSION

Onset of the major inversion that resulted in the Jebel Abd Al Aziz anticline began in the Late Pliocene and continued into Early Pleistocene. A result of this inversion was the onset of coarse clastic sedimentation of the Plio-Pleistocene Bakhtiari Formation (Figure 7). The recent capture of Wadi El Hemar’s headwater by the Khabour River north of the Jebel suggests that the uplift may still be occurring today (Figure 3).

As a result of the inversion, a large fault-propagation fold developed above the east-west-trending Jafar Fault System. Along the north side of Jebel Abd Al Aziz, displacement has occurred on two faults, J-1 and J-2 (Figure 11). Normal displacement occurred along the J-1 Fault System while reverse movement occurred on the J-2 Fault System. The J-2 Fault System lies up to a kilometer south of the main graben-bounding normal fault, J-1. East of the town of Hasakah, the reverse displacement has occurred along the more northerly J-1 Fault. In this area, the reverse displacement took place on the same fault as the initial normal movement. The sense and magnitude of displacement on these faults
changes with depth where both senses of movement occur along the same surface. An idealized cross-section, Figure 21, illustrates the fault displacement is the result of extension and compression. Although this model is useful for describing key components of the structure’s history, a three-dimensional model aids in visualizing spatial relationships of these elements.

With the change from extension to compression, the older systems of northeast- and northwest-trending faults were again reactivated, this time with strike-slip component of displacement that is in the opposite direction to the earlier strike-slip movement on these faults. The E-2 and E-5 faults are examples where earlier faults were reactivated with strike-slip displacement with opposite sense (Figure 11). Segments of this type of fault also have displacement that changes along their length in both magnitude and direction (Figure 22).

Some northeast- and northwest-trending faults, such as E-0 and E-1, have oblique-slip (Figure 23). Fault propagation folds are developed along parts of the northeast- and northwest-trending faults. Displacement at the north side of the Jebel along these faults illustrates strike-slip displacement in the hanging wall of these faults. The complexity documented on these smaller faults is an indication that the larger Jafar and Syrom Faults may have a small component of strike-slip displacement. Complex displacement on the major faults is likely, given the improbability that all of the multiple episodes of extension and compression occurred in exactly opposite directions.

Figure 23 and Figure 24 demonstrate the benefit of integrating surface geology with the seismic data to simplify interpretation. On the seismic data the J-2 and E-1 faults form an apparent graben. Figure 23 shows that the two faults intersect at approximately 90 degrees. Reverse displacement of the north face of the Jebel along the Jafar Fault system is segmented by the E-1 Fault with the east side of the E-1 Fault displaced farther north.
Figure 22: Simplified block diagram of the Jebel Abd Al Aziz inversion structure. Arrows indicate displacement. A two-dimensional model of an inversion structure focuses on displacement in the vertical plane and null points and null lines in the horizontal plane. The three-dimensional model emphasizes that inversion occurs as a result of horizontal displacement and that there are corresponding null points and null lines in vertical planes. Null surfaces are useful in visualizing changes in fluid migration pathways.

Figure 24 is a composite of seismic lines 89UN-310 and SY-09S-75 (see Figure 3 for location). The two lines provide a seismic profile across the width of the Jebel Abd Al Aziz inversion structure. This profile shows the features of a classic inversion structure and the effects of the reactivated older structures that are oblique to the main structure.

Structures, that are oblique to the main graben trend, further complicate the interpretation of Jebel Abd Al Aziz's structural history. This is due to both the increased geological complexity and the location of the seismic lines with respect to the oblique structures. The seismic lines were located at points of easy access across the topographic relief of the Jebel. These access points are commonly in modern valleys associated with the northeast- or northwest-trending faults (Figure 23). The result is that the E-1 and J-2 faults appear to form a graben on seismic line 89UN-310, whereas they actually intersect at close to a 90 degree angle one kilometer east of the seismic line.

Seismic line SY-09S-75 extends south from the end of seismic line 89UN-310 across the southern edge of the inverted structure. The intersection of the northeast-trending Maghlouja Horst and the east-
west-trending Syrom Fault (Figure 11) at the south side of the inverted graben is recorded on the north end of seismic line SY-09S-75 (Figure 24). The intersection of these oblique structural elements also creates complexity not seen in the ideal models.

However, the seismic line and the cross-section made from it (Figure 25a) illustrate several key points of the inversion. The dip of the pre-rift unconformity and thickening of the Maastrichtian sediments, into the graben are illustrated by both the seismic and well data. Both strands of the Jafar Fault are shown. J-1 is the normal fault at the north side of the graben, while J-2 is the reactivated normal fault along which reverse motion occurred. The deepest part of the graben was adjacent to these fault traces, as documented by the Shiranish Formation depocenter.

At the center of the inversion structure, the cross-section is partly diagrammatic due to the poor quality of the seismic data obtained from the pre-Shiranish section. However, evidence for multiple episodes of displacement for these oblique faults is seen at the location where the seismic line crosses the E-4 Fault. Here the identity of the stratigraphic units is confirmed by the Syrom-2 well. Below the pre-Cretaceous unconformity, the Triassic units thicken into the half-graben formed by the E-4 Fault at the western side of the Maghlouja Horst. On the southern part of the Maghlouja Horst, the Upper Triassic units are absent where they have been removed by pre-Cretaceous erosion. The E-4 Fault was subsequently inverted such that now the Triassic age isopach thick is on the upthrown side of the fault. Salt dissolution is present in the Lower Miocene stratigraphic interval along a fault antithetic to the E-4 Fault.

Figure 25b is a restored cross-section illustrating the Aziz Graben geometry at the end of the Cretaceous. Folding and reverse-slip reactivation of faults during inversion produced less than 1% shortening over the entire length of the cross-section. This is a minimum value because it ignores minor strike-slip displacement on the northeast-striking, E-1, E-2 and E-4 faults and deformation on structures beyond seismic resolution. The relatively small amount of shortening during inversion resulted in more than 500 m of vertical relief along the Jafar Fault System. Creation of this vertical relief was marked by the deposition of Upper Pliocene conglomeratic units around the uplift. The conglomerates are composed of clasts eroded from the uplift. Again, these units, like the graben fill, have facies which clearly indicate a relationship between active structures and sediment deposition.
Figure 25: Structural restoration of the structural cross-section along composite seismic line 89UN-310 and SY-9S-75. The section was constructed by a flexural slip restoration of the fault blocks. This algorithm maintains cross-sectional areas and the length of beds that are horizontal in the deformed-state section. The stratigraphic section is not decompacted.
Figure 24: Composite Seismic Line 89UN-310 and SY09S-75 and north-south structural cross-section constructed along the same profile. Both illustrations show similarities to the classic inversion model, but structural elements oblique to the profile create additional complexity. This figure in conjunction with Figure 23 emphasizes the need for a three-dimensional approach to interpreting the structure of Jebel Abd Al Aziz.
CONCLUSIONS

In the most limited context, the Jebel Abd Al Aziz is the result of Plio-Pleistocene structural inversion of an extensional graben that developed during the Early Maastrichtian. However, our data indicate that the development of the Jebel was strongly influenced by pre-existing structural elements. Although the extensional faults related to the development of the Euphrates Graben have the greatest influence on the development of the Jebel, structural elements of pre-Cretaceous age also have influenced its growth. The integration of both structural and stratigraphic, geological and geophysical data were necessary to develop this interpretation.

In a larger context, understanding the development of the Jebel Abd Al Aziz structure takes on greater significance when it is placed in regional perspective. Figure 26 is a map showing areal distribution of the Plio-Pleistocene inversion as determined from the Lower Fars outcrop pattern. It illustrates that the Jebel Abd Al Aziz inversion is one element in an inversion terrain. Additionally, the figure shows that most of the known oil reserves of the northern Arabian plate are within the area of the Plio-Pleistocene structural inversion. In many cases, Cretaceous rifting influenced the depositional distribution of source and reservoir rocks, but the combination of both rifting and later inversion affected maturation, migration and trapping of hydrocarbons.

The combined geometry of the rift basin and its subsequent inversion, control the distribution of mature hydrocarbon source rock. Structural inversion destroys early hydrocarbon traps, remobilize hydrocarbons, modifies, or sometimes substantially alters, fluid migration pathways and creates new hydrocarbon traps.

Figure 26: Map showing the partial extent of the Plio-Pleistocene inversion. This map was constructed by mapping the outcrop of the Miocene age Lower Fars Formation in Syria on Landsat images. The orange striped area on the map indicates where subsurface data were used in construction of the map. The map was extended into Turkey and Iraq based on published geologic maps (Baysal, 1989; Jassim et al., 1986). The map shows that most of the known oil and gas accumulations of the northern Arabian tectonic plate are associated with the Plio-Pleistocene inversion.
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