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REJUVENATION OF THE PRE-CAMBRIAN NAJD FAULT SYSTEM AND ITS IMPORTANCE IN THE OIL PROVINCE OF SAUDI ARABIA.

Doğan PERİNÇEK, Salih SANER and Khattab G.Al-Hinai**

ABSTRACT.- Structural interpretation covering the Central Saudi Arabia was carried out through Landsat, Radar images, topographic maps and seismic data. Existing geology maps provide materialized evidence for this study. A strong northwest trending lineament system has been mapped in the region and is interpreted as being related to the reactivated Najd Fault System. Elongate hills, strait-going creeks, offset along valley and ridges, and pull-apart basins are evident, indicating rejuvenation of the Najd transtensional sinistral movement. Geological map shows evidence indicating a northwestward dragging on the sedimentary cover along a NW trending regional lineament in the region which extend from South Ghawar to An Nafud Basin in Saudi Arabia. Northeast trending structures in Saudi Arabia are related to the pre-Permian structuring and Oman-Masirah stress regime. The Ghawar (Saudi Arabia), Dukhan (Qatar) and other north-northwest trending anticlines were reshaped by the rejuvenated Najd stress regime. The northwest trending sinistral Najd Fault was initiated in Precambrian and was reactivated at various times, probably during Paleozoic and late Jurassic times, and continuously, though of variable intensity, from late Cretaceous to the late Tertiary time. The Carboniferous, Late Cretaceous and Tertiary events are overprinted on one another in the region. The Oman stress regime and the stress regime that is related to oblique obduction of the Masirah Ophiolite are the principal controlling event for the anticline structures in Central Arabia. Dominant structural elements of the area are N-S anticline axis that suggests approximate E-W compressional stress direction, which is consistent with Oman and reactivated Najd tectonic regimes. The effect of the Tertiary orogenic overprint of the Oman-Masirah stress regime in eastern Arabia was to favor a slight renewed movement along the old basement faults such as the Najd Trend. Reactivated Najd system, Oman principal horizontal stress regime and obduction of the Masirah Ophiolite onto the Arabian continent have produced a combined effect on the structures in Eastern Arabian Plate. The Zagros stress regime may have produced little effect in the region.

Key words: rejuvenation, Najd Fault, Saudi Arabia, Ghawar

INTRODUCTION

The tectonic elements of the Arabian Peninsula is simplified from the geologic map of the Saudi Arabia (USGS and ARAMCO, 1963). Figure 1 shows "Western Arabian/Najd Fault System" (WAFS), "Eastern Arabian/Najd Fault System" (EAFS) and the other structural elements of the region.

Structural interpretation covering the central Saudi Arabia region was carried out through Landsat images, L-band Radar imagery and topographic maps (Perinçek et al., 1998*b*). Existing geological maps provided materialized evidence for the regional study. A strong northwest trending lineament system has been mapped in the region and is interpreted as being related to the reactivated Najd Fault System (Perinçek et al., 1998 *a-b*, Husseini, 2000). This apparently extends from Qatar and south Ghawar to An-Nafud Basin and finally reaches to Palmyra Fold Belt (Figures. 1, 2 and 3). The Dead Sea Fault Zone and rejuvenation of the Najd Fault system may have produced a combined effect on the structures in the Palmyra Fold Belt causing rejuvenation along the pre-Tertiary faults (Figures 1 and 3).

* Çanakkale Onsekiz Mart Üniversitesi, Mühendislik Mimarlık Fakültesi, Çanakkale
** King Fahd University of Petroleum and Minerals, Saudi Arabia

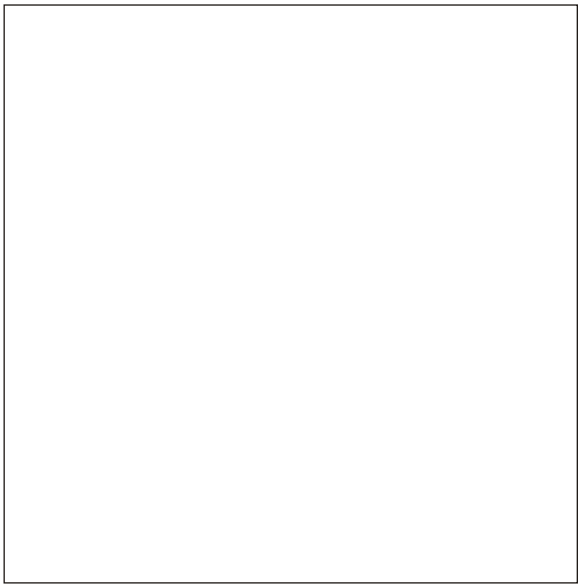

Figure 1- Tectonic elements of the Arabian Peninsula. Numbers refer to tectonic features. 1- EAFS, Eastern Arabian / Najd Fault System, 2- WAFS, Western Arabian / Najd Fault System (light gray), 3- DSF, Dead Sea Fault, 4- EAF, East Anatolian Fault, 5- Bitlis/ Zagros Suture Zone, 6- Limit of Zagros Type Folds, 7- Palmyra Fold Belt, 8- Masirah Fault.

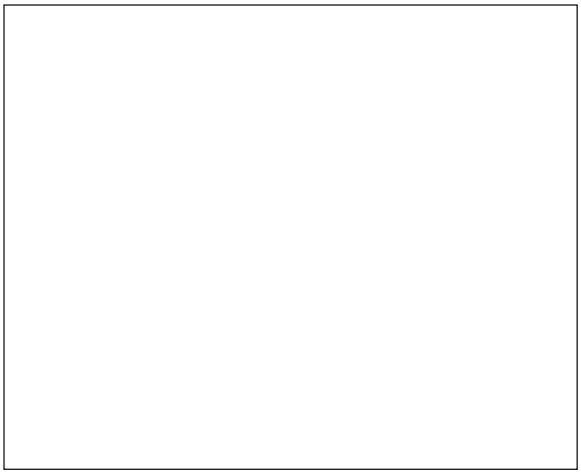

Figure 2- The petroleum fields of Saudi Arabia, Qatar and Bahrain (Husseini, 1995, 1997). Dragging on the southern end of Dukhan field, offset in the middle of Abqaiq and northern Ghawar structures are evident which probably related to rejuvenated Najd Fault zone. The lineaments picked from the topographic maps and Land Sat images in the southern end of Ghawar and Khurais structures could be related to the reactivated Najd Fault System. Tinat, Dilam, Raghib and Abu Markhah fields are aligned with same fault zone (Perinçek et al., 1998*b*, 2000*a-b*).

The Ghawar structure is bounded by normal faults, along which repeated movements have taken place, cutting all pre-Permian strata, and flexuring and fracturing the overlying units ranging from Permian to Miocene period. Four events overprinted in the Central Saudi Arabia on the Ghawar Field (Wender et al., 1998): (1) The Carboniferous Event, in which initial faulting occurred and caused extensive erosion along the crest of the Ghawar anticline. (2) Early Triassic Event (Zagros Rifting). (3) The Late Cretaceous Event, in which rejuvenation of pre-Permian age faults caused folding, fracturing, and minor faulting. This event was followed by extensive erosion and the upper portion of the Middle Cretaceous (Wasia Formation) was removed from the apex of the Ghawar structure. (4) The Miocene Event, which was the final folding event for the Ghawar, Harmaliyah and Abqaiq structures (Wender et al., 1998, Perinçek et al., 1998 *a-b*, Saner et al., 2002 and 2005).

The Ghawar oil field is 225 km long and 30 - 35 km wide, an asymmetric, NNE-SSW striking anticline in the Eastern Province of Saudi Arabia (Figure 2). The highest part of the anticline, north-south trending En Nala axis was first detected by Steineke and Kock in 1935 during surface mapping in the area (Arabian American Oil Company Staff, 1959). The En Nala and some other parallel arches are believed to be basement uplifts reactivated since the Precambrian (Ayres et al., 1982), whereas some oilfield structures are of salt doming origin (Edgell, 1991). The Ghawar area is characterized by a rougher topography when compared to the surrounding, rather smooth, flat areas. This rough geomorphology of the structure can also be noticed on the

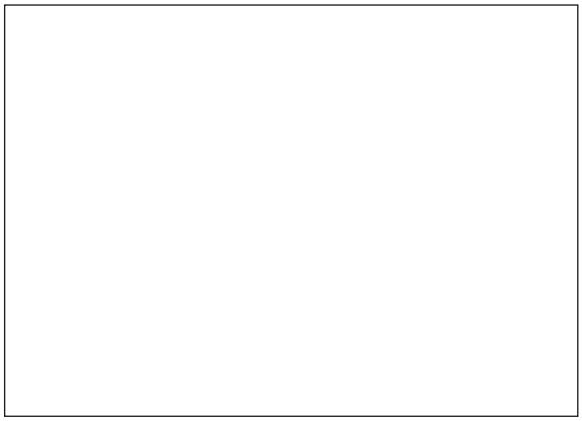

Figure 3- Reactivated Najd Fault System extends from Qatar to Damascus in Syria and to Oman in Jordan. The Dead Sea Fault Zone and rejuvenation of the Najd Fault System may have produced a combined effect on the structures in the Palmyra Fold Belt (Figure 1). Palmyra Fold Belt located near Damascus. Landsat image (Google) shows northwestern extend of the Najd Fault System (black) which represented by three fault zone (1-Al Karak-At Tubayq, 2-Sirhan-Al Jawf and 3-Khawr Umm). North-northeast trending Dead Sea Fault Zone (white) has two junction points with Najd Fault Zone near Amman and Damascus.

satellite images. A geomorphologic elevation map of the area and a subsurface structural contour map of the top Arab-D (Upper Jurassic) reservoir reveal very similar geometric shapes. A match between the directions of some topographic lineaments and projected surface traces of subsurface faults from seismic cross sections can be observed in the Ghawar area (Saner et al., 2002 and 2005). These topographic lineaments are inline with the Najd Fault System. However, at the field locations, Surface indications suggest that the structure has been active until the present day. Several investigators indicated that Ghawar structure started forming in the Jurassic and remained active during sedimentation in the Cretaceous and Tertiary periods (Arabian American Oil Company Staff, 1959, İbrahim et al., 1981). Plate movements and related tectonic stresses prevalent during Hercynian and Alpine orogenesis stages appear to be responsible for structural developments (Billo, 1983, Marzouk and El Sattar, 1995). The Ghawar anticline is a simple fold in the south, develops two crestal closures in the center, and is bifurcated in the north. Several oil fields have been identified within the Ghawar Field.

The northwest-trending sinistral Najd Fault was initiated in the Precambrian (Husseini, 2000) and was reactivated at various times in the region, probably during Paleozoic and late Jurassic times, and continuously, though of variable intensity, from late Cretaceous to the present (Halsey, 1980, Perinçek et al., 1998 *b*, 2000 *a*-*b*). A model has been proposed for the plate, stress and tectonic conditions during the Permian, which suggests interplate, non-orogenic rifting, controlled by Precambrian trends of crustal weakness (Halsey, 1980). In Late Cenozoic time, the orogenic event was severe in the Zagros but less effective in eastern Arabia, causing renewed movement along the old basement faults. Halsey (1980) also concluded that collision of the continental portions of the Arabian and Iranian plates probably began during Pliocene time and continues today, resulting in the Zagros orogeny, with the Zagros crush zone marking the suture between the two plates. Eastern Saudi Arabia and the Arabian Gulf retain their original Atlantic style margin character only slightly disturbed by Zagros deformation.

Northwest trending fault and north south trending basement structural grain are apparent all over the west-southwestern Arabian plate, from the Red Sea to the Gulf of Arabia (Figures 1 and 2). Beydoun (1991) suggested that these structures might all be related to the late Proterozoic Najd Fault System exposed in Saudi Arabia (Stoesser and Camp, 1985, Agar, 1987, Husseini, 1989).

The Carboniferous, Late Cretaceous and Tertiary (Miocene) events are overprinted on one another in the region (Halsey, 1980, Wender et

al., 1998). The E-W Oman stress regime and ESE-WNW stress regime that is related to oblique obduction of the Masirah Ophiolite (Loosveld et al., 1996) are the principal controlling events for the anticline structures in Central Arabia (Figure 4). The effect of the Tertiary orogenic overprint of the Oman-Masirah stress regime on the Arabian plate in eastern Arabia was to favor a slight renewed movement along the old basement faults such as the Najd trend (Perinçek et al., 1998 *a*-*b*). Rejuvenation of those faults caused pervasive fracturing in the brittle rocks of the sedimentary cover (Halsey, 1980).

Rejuvenation of the sinistral Najd Fault system in the Miocene caused faulting and folding in the region. The Najd and Oman principal horizontal stress regime (Figure 4) and the obduction of the Masirah Ophiolite (Loosveld et al., 1996) onto the Arabian continent have produced a combined effect on the structures in Eastern Saudi Arabian (Perinçek et al., 1998 *a*-*b*). The Zagros stress regime (Figure 4) may have produced little effect in the region (Perinçek et al., 1998 *a*-*b*).

REJUVENATION OF THE PRE-CAMBRIAN NAJD FAULT SYSTEM

Structural interpretation covering the central Saudi Arabia region was carried out through Landsat images, L-band Radar images, topographic maps and seismic data (Perinçek et al., 1998 *b*). Seismic mapping from 3D volumes provided a detailed structural map in the Ghawar Area. A strong NW trending lineament system has been mapped in the region and is interpreted as being related to the reactivated NW trending sinistral Najd Fault system (Figures 1 and 5).

Ghawar structure is recognizable from satellite images (Halbouty, 1980). This is the evidence of Late Tertiary tectonic activity deforming the young sedimentary cover. Therefore, structural traces are expected to be apparent in the surface formations of Mio-Pliocene age. Study of surface

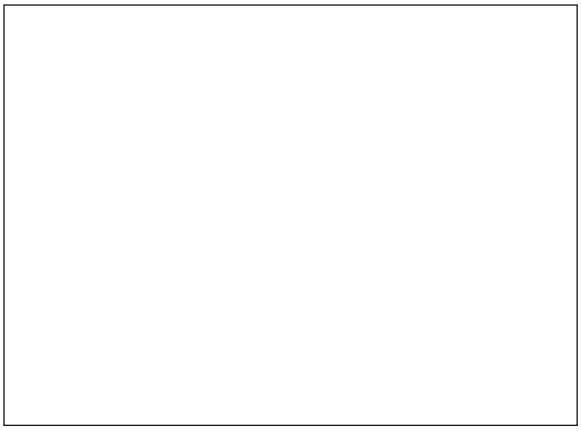

Figure 4- Stress diagram for deformation related to Najd Fault System and Oman, Zagros, Masirah stress regimes.

Figure 5- Major structural trends in Arabian Peninsula and Arabian Gulf. Dominant structural trends are N-S anticlines including Ghawar Field, NW Najd trends (WAFS), EAFS: Eastern Arabian/Najd Fault System (dotted), and WAFS: Western Arabian/Najd Fault System, NW-SE Zagros fold (gray). Limit of Zagros Type Folds (dotted). Dashed gray line shows southwestern limit of Infra-Cambrian Hormuz Salt basin. Pre-Cambrian (light gray), Cambrian - Ordovician (gray), Silurian-Devonian (dark gray), Permian (dark gray), Triassic-Jurassic (gray), Cretaceous (gray), Tertiary (gray) Tertiary-Quaternary (light gray). (After USGS and ARAMCO, 1963., Edgell, 1992., Al-Laboun, 1998, Perinçek et al., 1998*b*, 2000*a*-*b*).

structural elements provides important information for interpreting the subsurface structural model and development. The aim of the surface studies in the Ghawar area is to investigate structural features cropping out in the field, to establish a correlation between the surface and subsurface structural features of the Ghawar field (Saner et al., 2002, 2005).

The surface topography resembles the subsurface structural maps of the Ghawar field. High-resolution elevation data measured during 3-D seismic survey was used to construct a detailed topographic contour map of the area (Perinçek et al., 1998 *a-b*, Saner et al., 2002, 2005). This map and a subsurface structural contour map of the Arab-D reservoir are very similar in shape (Figure 6 in Saner et al., 2005). A comparison of the two maps provides evidence that the structure is active until the Mio-Pliocene time. Saner et al. (2005) indicated that Growth of the Ghawar structure was active in the Pleistocene and probably even in the Quaternary.

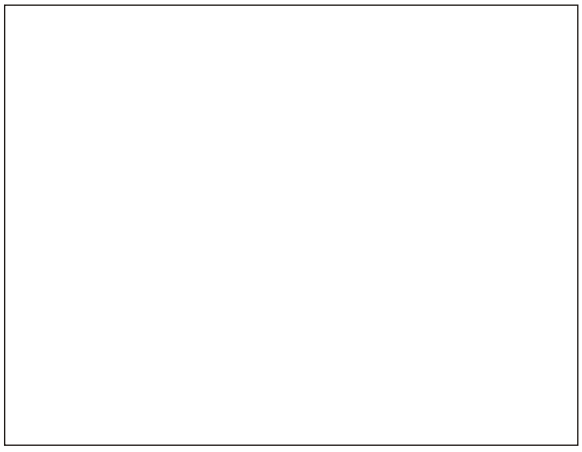

Figure 6- Elevation contours and simplified geological map of the Al Habl region-west of Ghawar area. Offset along the ridges may provide evidence for sinistral movements, on the NW trending fault system, Perinçek et al., 1998*b*, 2000*a-b*).

Interpretation of the 3D seismic data reveals that the Ghawar Structure is an anticline that consists of isolated highs. Axis of the each high is shifted towards the northwest and several of them are easily documented along the NW trending fault, suggesting sinistral movement. Sinistral event could be related to rejuvenation of the Najd Fault system. Fault rejuvenation is believed to occurred at various times in the region, in particularly during the Late Cretaceous and late Tertiary.

Dominant structural elements of the central-eastern Arabian plate are NNE-SSW Ghawar, NW Najd trends, E-W Oman stress and related N-S trend, ESE-WNW Neogene stress, which is related to oblique obduction of the Masirah Ophiolite, Zagros stress regime and related NW-SE trending structures. Most of N-S trending structures in eastern Saudi Arabia suggests approximate E-W compressional stress direction, which is consistent with Oman and reactivated Najd tectonic regimes (Figure 4).

The Oman stress regime and oblique obduction of the Masirah Ophiolite, acted during Mesozoic and Tertiary times (Loosveld et al., 1996) and they have had a major effect in the region as observed on the Harmaliyah and Abqaiq structures. On the other hand, the sinistral Najd Fault System and the related E-W stress regime, which were reactivated in Late Cretaceous, Miocene and recent times, may have produced many of the structural features (faults, folds and joints) within Ghawar Field (Perinçek et al., 1998 *a*). The reactivated Najd Fault System controlled to the thickness and distribution of the lower Aruma Formation in Late Cretaceous.

A simplified geology map shows evidence indicating a northwestward drag on the sedimentary cover along a NW trending regional lineament in the region, which extends from south Ghawar to An-Nafud Basin on the eastern portion of the Arabian plate (Figure 5). Elongate hills, straight-trending creeks, offset along valley and ridges (Figures 6, 7) and pull apart basins

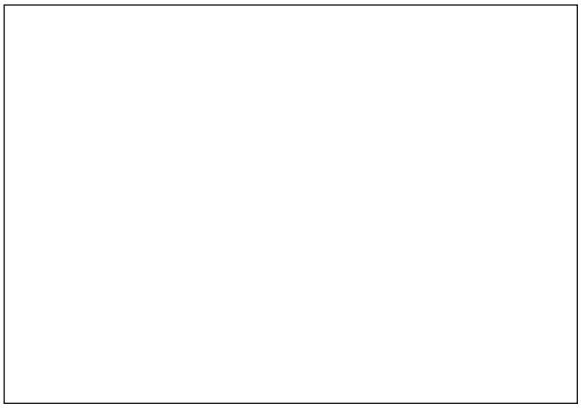

Figure 7- Al Barak - At Tubayq Fault Zone, East of Tabuk region. Straight-trending creeks, offset along valley are evident, indicating rejuvenation of the Najd Fault Zone.

(Figure 8) are evident, indicating rejuvenation of the Najd transtensional sinistral movement (Perinçek et al., 1998 *b*, 2000 *a-b*).

The Najd and Oman principal horizontal stress regime and the obduction of the Masirah Ophiolite onto the Arabian continent have produced a combined effect on the structures in Eastern Saudi Arabia (Figure 4), which have produced many of the structural features. Some of the pre-Coniacian faults were reactivated and the base Aruma unconformity was breached and refolded. The reactivated Najd Fault system created a local transtensional regime, which led the formation of normal faulting and grabens during the Cenomanian-Turonian. Sediments of the Aruma Formation (Coniacian-Maastrichtian) first filled the graben and then sealed the pre-Coniacian fault system which is evident in the northern Ghawar Field (Perinçek et al., 1998 *a*).

Figure 8- Structural elements of the An-Nafud Basin. Left bending-stepping and splay along the East Arabian Fault System probably responsible the formation of a pull-apart basin in the region. Pre-Quaternary basement (gray), Quaternary alluvium and related deposits (dotted white) and Quaternary eolian sand (white).

In conclusion, the Oman and reactivated Najd tectonic regimes caused deformation and erosion and removed the upper part of the Cretaceous (Wasia formation) from the uplifted areas, including Ghawar high. Later same tectonic events controlled the thickness and distribution of the lower Aruma formation in the Late Cretaceous. The Zagros stress regime, which acted in the NE-SW direction (Figure 4) during the early Tertiary period and continued to the present may have produced little effect in the region (Perinçek et al., 1998 *a-b*). However, the Zagros stress regime may have produced or enhanced NE-trending lineaments. Saner et al., 2005 indicated that the trend of Ghawar anticline (NNE-SSW) does not concur with the Zagros stress direction, and this complicates the interpretation of structure axis, and Zagros stress directions interrelations.

Northeast trending structures such as Abqaiq-Harmaliyah-Shaybah are related to the Oman-Masirah stress regime (figure 4). The Ghawar-Khurais-Tinat-Dilam-Dukhan (Qatar) and other north-northwest trending anticlines were reshaped by the rejuvenated Najd stress regime (Perinçek et al., 1998 *a-b*). However, Pre-Khuff basement structural grain has controlled the formation of the structures since Carboniferous (Edgell, 1992, Wender et al., 1998). Wender et al., (1998) stated that growth history of the Ghawar structure is different from the N NE trending Harmaliyah and Abqaiq structures.

Perinçek et al., 1998 *a-b*, Perinçek et al., 2000 *c*, Saner et al., 2002, 2005 and a study conducted for Saudi Aramco provides an integrated use of seismic map and surface geological information on the Ghawar Field. The Ghawar oil field is an asymmetric anticline that started forming in the Jurassic and remained active during sedimentation in the Cretaceous and Tertiary periods. Surface structural lineament interpretation and its collaboration to subsurface structural features has been investigated. Lineaments from Landsat images over the Ghawar Field reveal prominent structural trends in N55°W, N35°E and N15°W directions (Hariri et al., 1998). The lineaments picked from the high-resolution topographic map show prominent trends mainly to N35°W and secondary trends in N45°E and N85°E directions. The major NW topographic lineaments within Ghawar vicinity could be related to the reactivated sinistral Najd Fault Zone. Perinçek et al. (1998 *a*), Saner et al., (2005) used 3D seismic survey shot-point elevation data to produce high-resolution topographic map. A field study was conducted for ground truthing of lineaments picked from Landsat images and topographic maps. So far no fault planes have been observed in the field. However, surface projections of some faults, seen in seismic cross sections, match with topographic lineaments (Perinçek et al., 1998 *a-b*, figure 13 in Saner et al., 2005). Refered surface lineaments and subsurface faults represent Najd Fault System. Data for the lineaments are presented in the form of map and rose diagrams. The elevation data is an effective tool for structural interpretation of the Ghawar anticline that can be identified on topographic maps (Saner et al., 2002, 2005).

Seismic subsurface mapping indicates that the axis of the anticline of the northern Ghawar Field (Figure 2) is shifted towards the west. The west shifting is clearly documented along the NW trending fault. Dragging on the north-south trending Ghawar anticline is also evident. These observations provide evidence and suggest a sinistral movement along the northwest trending fault zone. Left lateral strike-slip event could be related to rejuvenation of the Najd Fault System (Perinçek et al., 1998 *b*, 2000 *a-b*)

Perinçek et al. (1998 *b*) conducted a study on the Ghawar Field reveals that the extensional east-west graben bounding faults are probably open, permeable and provide a conduit to fluid flow. The extensional graben system is more permeable because of their preferential susceptibility to solution widening. North-south faults could be seals and constitute barriers or restrictions to lateral flow. However, NW and NE-trending faults may be conduits or barriers (Perinçek et al., 2000 *c*). Northwest trending faults generally have strike-slip component. Local extensional regime is expected along the sinistral northwest trending fault system adjacent to the left stepping or left bending areas. The E-W trending grabens are one of the major structural features in the central Ghawar Field. It is believed that E-W grabens are parallel and N-S high angle faults are perpendicular to the major compression direction which suggests approximately E-W compressional stress direction. This compressional direction is consistent with Oman and reactivated Najd tectonic regimes (Figure 4).

CONCLUSIONS

Conclusions and interrelationship highlights of this study are as follows:

North-northeast trending structures in Saudi Arabia are related to the pre-Permian structuring and Oman-Masirah stress regime.

Dominant structural elements of the area are north-south anticline axis that suggests approximate East-West compressional stress direction. This compression direction is consistent with Oman and reactivated Najd tectonic stress regimes.

A strong northwest trending lineament system has been mapped in the region and is interpre-

ted as being related to the reactivated Najd Fault system. A simplified geology map shows evidence indicating a northwestward drag on the sedimentary cover along a NW trending regional lineament in the region. Elongate hills, straight-trending creeks, offset along valley and ridges, and pull-apart basins are evident, indicating rejuvenation of the Najd transtensional sinistral movement.

Reactivated Najd Fault system apparently extends from Qatar and south Ghawar to An-Nafud Basin and finally reaches to Palmyra Fold Belt near Damascus. The Dead Sea Fault Zone and rejuvenation of the Najd Fault System may have produced a combined effect on the structures in the Palmyra Fold Belt causing rejuvenation along the pre-Tertiary faults.

The northwest trending sinistral Najd Fault was initiated in Precambrian and was reactivated at various times in the region, in particularly during the Jurassic, late Cretaceous and late Tertiary. The sinistral Najd Fault system and the related E-W stress regime, which were reactivated continuously, though of variable intensity, may have produced many of the structural features (faults, folds and joints) in the region.

The fault rejuvenation occurred at various times in the Ghawar structure. Repeated movements have taken place, cutting all pre-Permian strata, flexuring and faulting of overlying units ranging from Permian to Tertiary age.

Reactivated Najd system, Oman principal horizontal stress regime and obduction of the Masirah Ophiolite onto the Arabian continent have produced a combined effect on the structures in Eastern Arabian Plate. The Zagros stress regime may have produced little effect in the region.

The Oman and reactivated Najd tectonic regimes, caused deformation and erosion and removed the upper part of the Cretaceous (Wasia formation) from the uplifted areas, including Ghawar high. Later same tectonic events controlled the thickness and distribution of the lower Aruma Formation in the Late Cretaceous.

The match between topographic lineaments and the trace of the fault on the surface infers that some topographic lineaments are projections of deep seated faults. NW-trending topographic lineaments are mapped as part of the Najd Fault system.

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