

TECTONIC AND STRUCTURAL EVOLUTION

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ABSTRACT

The available geological information including stratigraphic sequence, unconformities pattern, drill-hole data, seismic and structural elements have been integrated to infer the tectonic and the structural evolution of the Iraqi Western Desert.

The Western Desert is a part of the northern Arabian Platform, where relatively thin Phanerozoic sediments cover the Precambrian N – S and NW – SE fractured continental basement complex. The platform itself is divided into two parts, a stable one to the west (within which the Western Desert is located) and an unstable one to north and east. The boundary between the two parts of the platform is taken along Anah – Abu Jir Fault Zones.

The Paleozoic sequence is dominated by silici-clastic sediments deposited in a shallow epicontinental sea in a relatively stable conditions, whereas the Mesozoic sequence show a major change in the depositional system from a primary silici-clastic Paleozoic regime to a major carbonate deposition with interspersed clastic episodes. However, the Cenozoic sequence displays gradual retreat of the sea and final transition to the continental conditions.

Structurally, the two major Paleozoic orogenic movements (Caledonian and Hercynian) were identified by their effects on sea level changes rather than their orogenic deformation. On the other hand, however, the sedimentation pattern through most of the Mesozoic era was a reflection to a fluctuating sea level and periodical movements of Hail – Rutbah Arch. Nevertheless, by the late Tertiary a significant tectonic activity took place along the boundary of the stable/ unstable parts of the platform, causing the structural inversion of Anah Graben, and a limited right lateral strike-slip movement on Abu Jir Fault Zone.

Finally, conclusive evidences on the nature of Hauran Fault System as well as the recent activity along Anah – Abu Jir Fault Systems are introduced.

النشأة التكتونية والتركيبية

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المستخلص

تم استخدام المعطيات الجيولوجية المتوفرة بما فيها التتابعات الطبقيّة وأسطح عدم التوافق وتوزيعها ومعلومات الآبار والمعلومات الزلزالية والعناصر التركيبية لاستنتاج النشأة التركيبية والتطور التركيبى لمنطقة الصحراء الغربية العراقية. إن الصحراء الغربية جزء من شمال المسطبة العربية، حيث تغطي رسوبيات نحيفة نسبياً من الحقبة الفانيروزوية صخور القاعدة القارية المتصدعة باتجاهات شمال – جنوب و شمال غرب – جنوب شرق. إن المسطبة العربية في العراق مقسمة الى جزئين، جزء مستقر الى الغرب (حيث تتواجد الصحراء الغربية) وآخر غير مستقر الى الشمال والشرق. إن الحد الفاصل بين هذين الجزئين قد اعتبر بامتداد انطقة تصدع عنه – أبو جير. إن تتابعات الدهر القديم (الباليوزوي) الصخرية تتسببها رواسب فتاتيه سليكية تراكمت في بيئة بحرية قارية ضحلة مستقرة نسبياً في حين إن تتابعات الدهر الوسيط (الميوزوي) الصخرية تظهر تغير كبير في نظام الترسيب من رسوبيات فتاتيه سليكية الى رسوبيات تسودها الصخور السليكية مع رسوبيات فتاتيه بينية. أما تتابعات الدهر الحديث (السينوزوي) الصخرية فإنها تعكس تراجع تدريجي للبحر ثم التحول الى البيئة القارية.

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من الناحية التركيبية أمكن الاستدلال على الحركتين الأرضيتين الرئيسيتين للدهر القديم (الكاليدونية الهرسينية) عن طريق تأثيرهما على مستوى سطح البحر حيث إنهما لم تخلفا آثار تشويهية. من الناحية الأخرى يعكس نظام الترسيب لمعظم فترة الدهر الوسيط (الميسوزوي) تأثيره بالتغيرات اليوستاتية لمستوى سطح البحر إضافة إلى الحركات المتكررة لقوس حائل - رطبة. وفي نهاية العصر الثلاثي حدثت فعالية تكتونية مهمة بامتداد الحد الفاصل بين جزئي المسطبة المستقر وغير المستقر أدت إلى حدوث انقلاب تركيبي لمنخسف عنه وحركة مضربيه يمينية محدودة على نطاق تصدع أبو جبر. أخيراً تم تبيان شواهد حاسمة عن طبيعة نظام تصدع حوران إضافة إلى الحركات الحديثة بامتداد أنطقه تصدع عنه - أبو جبر.

INTRODUCTION

It has long been known that the region lie to the west of the Euphrates River within the Iraqi territory is referred to as the Western and the Southern Deserts. There are no structural or physiographic boundaries between the two deserts, and the distinction is strictly geographic. The present work however, focuses on the Western Desert only (Fig.1).

Structurally, the present Arabian Plate is broadly divided, from southwest to northeast, into the exposed Arabian Shield, the sediment-covered platform with its stable and unstable parts and the Zagros Thrust Belt.

The Iraqi Western Desert lies on the stable part of the Arabian platform where Mesozoic and Cenozoic rock units are exposed and slopping gently north and east towards the unstable part of the platform, except at its western part, where a westerly dipping strata are present.

The present work deals with the tectonic and structural evolution of the Western Desert as a part of the Arabian Platform as inferred from the available information including the stratigraphic sequence, the pattern of the unconformities, well information, seismic sections and the structural elements of the area. Moreover, the boundary between the stable and the unstable parts of the platform will be one of the main objectives of the work.

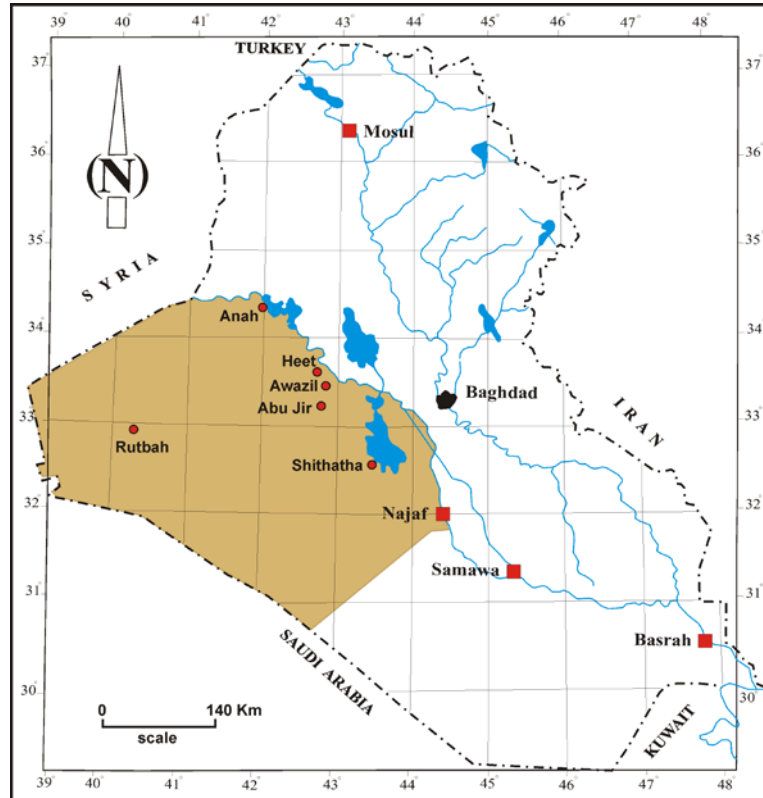


Fig.1: Location map showing the Iraqi Western Desert

STRATIGRAPHY OF THE IRAQI WESTERN DESERT

The exposed sedimentary sequence in the Western Desert ranges from the Permocarboniferous to Pleistocene in age with several regional and local unconformities punctuating the column. The sequence provides significant tectonic and the structural information as it record (more or less) the activities that were operative at the time of the deposition. The following is a brief review to the stratigraphic column of the area including the basement.

▪ The Basement

Basement outcrops are completely absent in Iraq. Moreover, no well penetrated to the basement; therefore basement characteristics and depth are estimated indirectly. It is well accepted that the Arabian Shield formed as a result of a Proterozoic amalgamation of island arcs and micro plates against northeast Africa as part of the Pan African orogenic system most probably occurred between ~ 950 Ma and 640 Ma (Stoesser and Camp, 1985; Beydoun, 1991 and Alsharhan and Nairn, 1997). The convergence of these fragments occurred in a general East – West direction and eventually left a North – South trending substantial lines of weakness. By the end of the cratonization of Arabia ~ 620 Ma to 550 Ma, strike-slip movement on NW – SE trending faults took place on what is known as "Najd Fault System".

Similar to the N – S trending "Hijaz" lines, Najd Fault System imposed significant NW – SE trending lines of weakness. However, these inherited lines of weakness played an important role in the style and location of the later formed structures and sedimentation patterns.

The estimated depth of the basement within the Western Desert, based on the CGG (1974) aeromagnetic interpretation, ranges between (10 – 7) Km with a general north, northeast and east slopes. The shallowest depth of the basement roughly aligned in a N – S to NNE – SSE direction, extending from Saudi Arabia through west Iraq. It is worth mentioning that the basement almost every where in the Western Desert cannot be identified through the available reflection seismic data due to the bad quality of the profiles.

▪ The Paleozoic (570 – 245) Ma

The full Paleozoic section is neither exposed nor penetrated by any borehole in the Iraqi Western Desert. Only limited Permocarboniferous rock units are exposed in Ga`ara region of the Western Desert (Fig.2).

Akkas1 well, which is located at the northern part of the Western Desert, is the only well that penetrated part of the Paleozoic sequence, revealing 3133m of a predominantly silici-clastics assigned to the Ordovician Khabour, Silurian (?) Akkas, Late Devonian to Early Carboniferous Kaista and Ora formations. The sequence is overlain by 148 m, thick Red Beds of undeterminable age, which in turn overlain by the Maastrichtian Tayarat Formation (Al-Habba *et al.*, 1994; Al-Siddiki *et al.*, 1994 and Aqrawi, 1998).

Akkas1 well didn't penetrate the entire thickness of the Ordovician Khabour Formation. By correlation however, with deep wells in Syria, Jordan and Saudi Arabia, Cambrian and Early Ordovician sequences in Western Iraq are expected (Al-Habba *et al.*, 1994) and most probably consisted of silici-clastics similar to its equivalents in the rest of Arabia.

At Ga`ara Depression in the central sector of the Western Desert, the Permocarboniferous Ga`ara Formation is exposed representing the uppermost part of the Paleozoic sequence. The exposed 100 m. Of the formation consists of alternating clastic cycles of sandstones, siltstones and claystones. Ga`ara Formation is completely missing in Akkas1 well. The Paleozoic contact with the younger sequences is exposed only at Ga`ara Depression in a

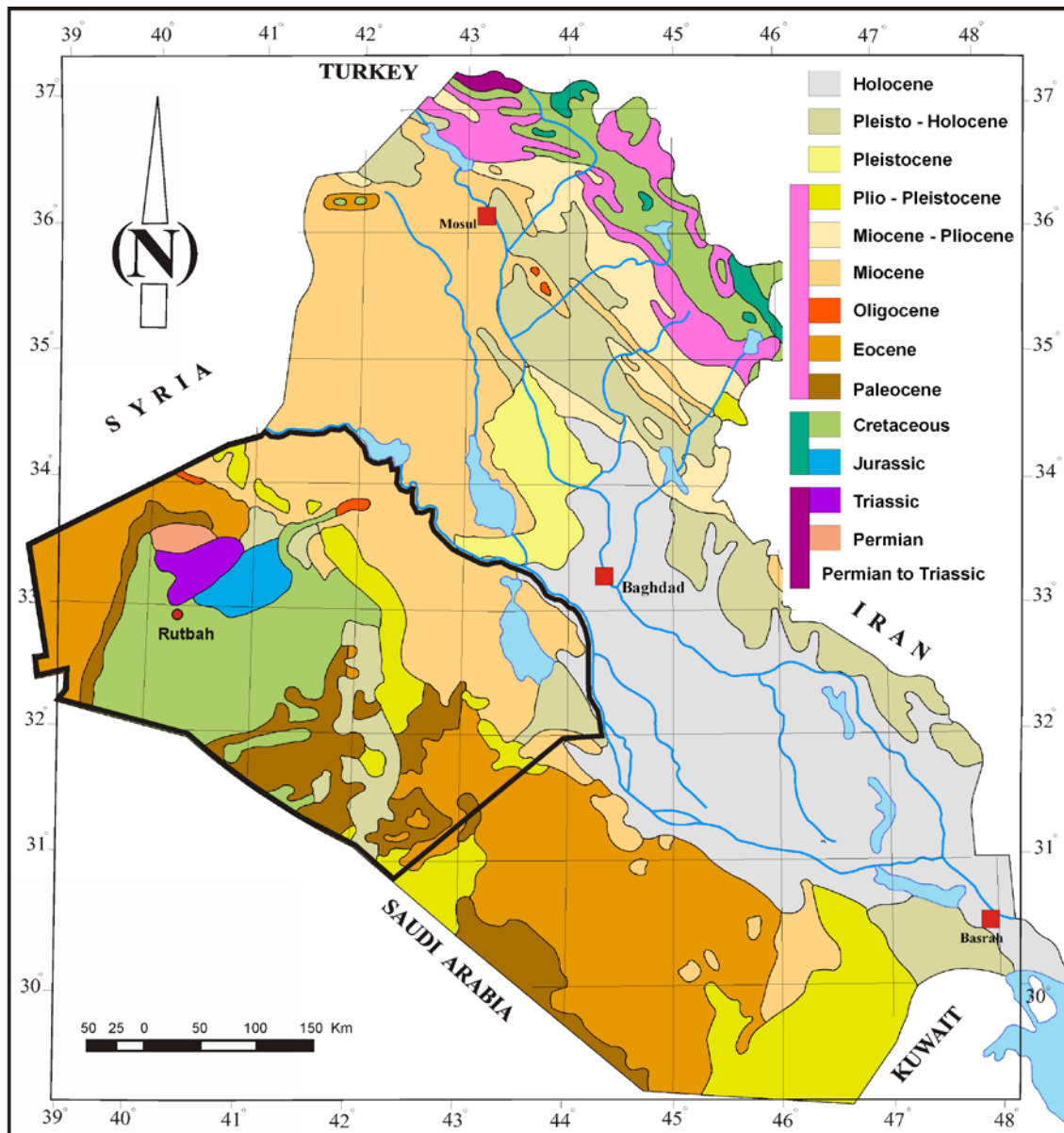


Fig.2: Crono-Geological map of the Western Desert

rather complex pattern. The Permocarboniferous Ga'ara Formation is unconformably overlain by the Late Triassic Carbonate at the southern rim of Ga'ara Depression, whereas at the northern and western rims it is unconformably overlain by Late Cretaceous sequence, and by Early Eocene carbonates at the eastern rim (Al-Mubarak and Amin 1983; Al-Mubarak 1996 and Tamar-Agha *et al.*, 1997). It is interesting to note that all these drastic variations occur within the Ga'ara Depression which is only 70 Km long and 30 Km wide. However, the Paleozoic era ended by a major erosional phase of a wide areal extension.

▪ The Mesozoic (245 – 65) Ma

The Mesozoic sequence is bounded by two major unconformities. At the southern rim of Ga'ara Depression where the best exposures are found, the Mesozoic sequence starts with about 150 m of Late Triassic (Carnian – Rhaetian) very shallow carbonate facies denoting a first marine transgression in the area after an extensive erosional period. Followed

unconformably by the Jurassic sequence, which is represented by five formations with a maximum thickness of about 450 m. Each formation has an unconformable lower and upper boundary and consists of lower clastic and upper carbonate rock units.

The formations are assigned to the Early Jurassic Ubaid and Hussainiyat formations, Middle Jurassic Amij Formation, Middle to Late Jurassic Muhaiwir Formation and Late Jurassic Najmah Formation. The Cretaceous sequence which is lying unconformably over the older rock units is represented in the Western Desert by seven formations. The formations are; the Albion – Cenomanian Nahr Umr and Maaddud, the Cenomanian (?) – Turonian Rutbah and Ms`ad, the Late Campanian – Early Maastrichtian Hartha, the Maastrichtian Tayarat and Digma formations. All of these formations consist of lower clastic and upper carbonate rock units, except Hartha, Tayarat and Digma formations, which consist solely of about (190 – 210) m thick open marine carbonates. The Mesozoic sequence is terminated by a regional unconformity that extends almost along the entire Arabian platform.

▪ The Cenozoic (65 Ma – Present)

The Cenozoic sequence overlies unconformably the Mesozoic rock units. The break is of regional nature extending to vast areas of the Arabian platform. The sequence is represented by the Paleocene Umm Er Radhuma and Akashat, Eocene Ratga and Jaddala, the Oligocene Group, Early Miocene Ghar and Euphrates, Middle Miocene, Fat`ha and Nfayil, Late Miocene Injana and the Pliocene – Pleistocene Zahra and Dibdibba formations. The formations are conformably overlying each other except the Oligocene Group which is bounded by upper and lower erosional surfaces.

It is important to note that the mentioned successions represent the general stratigraphic column in the Western Desert. Eventually, it doesn't mean that it is present everywhere in the region. As already mentioned, there are many unconformities punctuate the column and according one or two or several formations might be missing from place to another depending on its position and the magnitude of the erosional and/ or the non – depositional period. As an example to this, the Cretaceous rock units in the Western Desert lie unconformably on the Jurassic, Triassic and Paleozoic rock units with a break ranging from 30 to 200 Ma (Al- Bassam *et al.*, 2004).

STRUCTURAL GEOLOGY OF THE WESTERN DESERT

The Western Desert is a part of the Arabian platform where a relatively thin Phanerozoic sequence covers the Precambrian basement complex. The area lacks expressive Alpine related compressional structures in general. The exposed Mesozoic and Cenozoic rock units show a general N, NE and E regional dip except the extreme western part of the region where the strata exhibit westward regional dip.

However, in the first part of this section the regional tectonic boundaries of the platform and eventually, the boundaries of the Western Desert will be high-lighted, and then followed by the main structural elements.

▪ The Boundaries

The Arabian Platform within the Iraqi territory has long been divided into two main structural domains, the Stable Shelf to the west and the Unstable Shelf to the east. The eastern boundary of the Western and the Southern Deserts coincide within the boundary between the stable and the unstable parts of the platform.

Several workers tried to delineate this boundary by considering different geological aspects. Eventually, the results were different somehow. However, Buday and Jassim (1987) were the last to propose the boundary. Based on earlier work of Buday (1973), they

subdivided the Stable Shelf into two parts, the western Rutbah – Jezira and the eastern Salman Zones (Fig.3). They placed the boundary between the stable/ unstable parts of the shelf along the eastern rim of the Salman Zone. This implies that the Euphrates and Abu Jir Fault Zones delineate the boundary from southern Iraq northward to the vicinity of Heet city, in the west. Then they extended the boundary across the Euphrates river valley, following Al-Tharthar valley northward to meet the Low Folded Zone (Hamrin – Makhul Subzone), where it dies out just south of Sinjar area (Fig.3). This boundary, particularly its northern part, contradicts with that proposed by Henson (1951), Dunnington (1958), Ditmar *et al.* (1971 and 1972) and even with the earlier work of Buday (1973) on which they based upon. However, there are few objections on the boundary in the southern part to Heet, but there are many doubts on its northern extension. The main objection to this division is that it relies on physiographic and gravity data and disregarded the proper structural and seismic data as well as the main tectonic framework of the Middle East and stratigraphic sequence.

It is important to mention that the seismic data do not show such faulting along Al-Tharthar valley and on the contrary, Fouad (1997 and 2000) using reflection seismic data showed that Abu Jir Fault Zone terminates against Anah Graben and it never continues northwards. Therefore, it is proposed that the boundary between the stable and the unstable parts of the platform is to be along Abu Jir – Anah Fault Zones (Fig.4). Anah Fault Zone (or commonly Anah Graben) extends more than 100 Km in an East – West direction from Al-Qaim city, in the Iraqi – Syrian borders to the east of Anah city, then meet Abu Jir Fault Zone, where the zone changes direction to southeast extending for about 600 Km across the Iraqi territory towards Al-Batin lineament, northwest Kuwait. This proposed boundary represents the first basement involved fault zone that extends (partly) to the surface separating the stable (to the west) and the unstable (to the east) parts of the platform. The zone had significant influence on the thickness and the distribution of the sediments across it. Moreover, it inhibited the effect of the far field stress associated with the major collisioned phase of the Alpine Orogeny to propagate further southwest by acting as a mobile zone as will be shown later. This boundary, which is running parallel to the Zagros – Taurus Fold and Thrust Belt (i.e. the Arabian Plate margin) is more consistent with the regional tectonic framework of the northern part of the Arabian Plate. This is the main concept that let the author to propose that the boundary between the stable and the unstable parts of the platform to be placed along Anah – Abu Jir Fault Zone.

Detailed structural description to parts of the boundary fault zones are mentioned hereinafter:

– The Northern Boundary; Anah Graben

Anah Graben is an East – West trending 250 Km long subsurface graben that is directly overlain by a similarly trending 90 Km long expressive monocline, exposing rock units as far as Middle Oligocene. The fault bounded trough display different geometries along its strike including symmetric and half graben styles, as well as inverted and non – inverted styles. The trough contains about 2000 m thick Campanian – Maastrichtian syn-rift sequence, followed by a relatively thin uniform Tertiary post-rift sequence.

The active graben subsidence was terminated by the end of the Cretaceous as indicated by the absence of faulting and the uniform thickness of the post-rift Tertiary sequence in passing across the graben. However, during the Late Alpine compression the graben boundary normal faults were reactivated as reverse faults leading to a partial inversion of the basin and the formation of a monoclinical structure above the former basin (Fouad, 1997). The magnitude of the reverse movement on the boundary faults was relatively small and insufficient to cancel

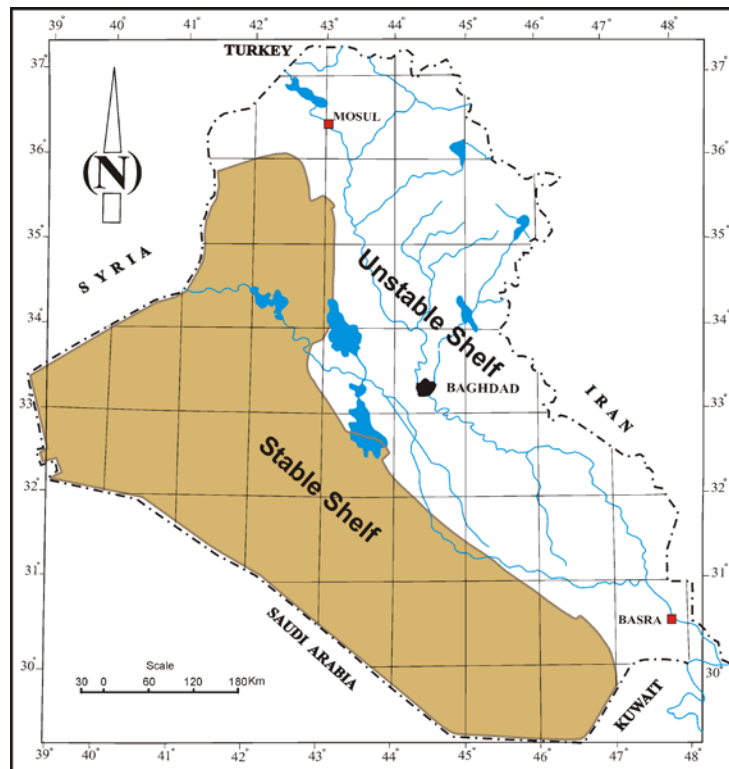


Fig.3: The boundary between the Stable and the Unstable Shelves of the Arabian Platform in the Iraqi territory based on Buday and Jassim's tectonic division of Iraq (1987)

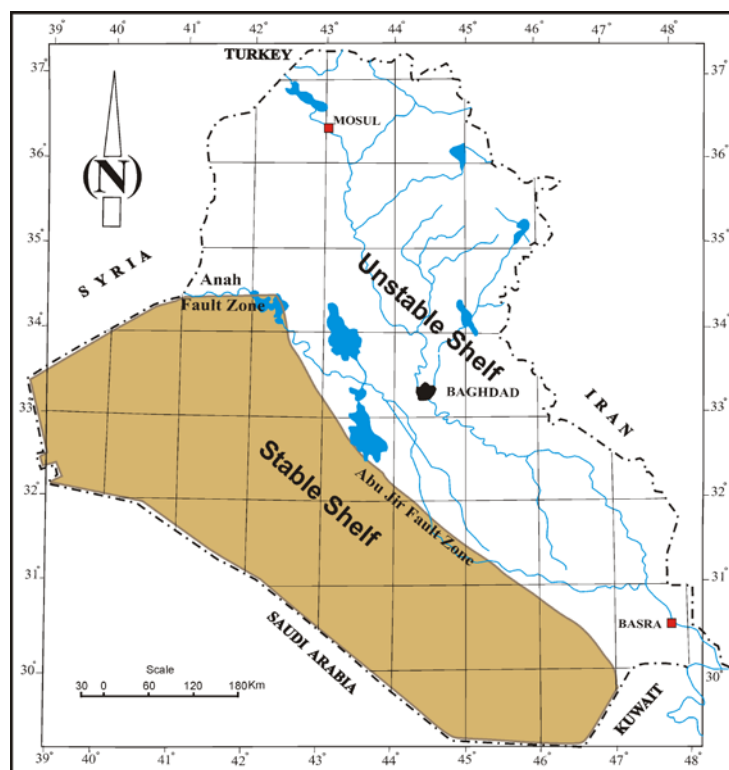


Fig.4: The proposed boundary between the Stable and the Unstable Shelves of the platform (the present study)

the initial normal throw (Fig.5). Therefore, the earlier style of faulting is preserved at depth and the reverse reactivation is discernible only near the surface. Consequently, Anah Graben display two distinct geometrical relationships; the complex variation in stratigraphic separation along the bounding faults and the superposition of a shallow anticlinal forced fold (Anah Monocline) directly above a thick sequence of sediment in an initially structured low. These relationships are diagnostic to the positively inverted structures (Harding, 1985; Lowell, 1985; Cooper and Williams, 1989 and Mitra, 1993).

– The Eastern Boundary; Abu Jir Fault Zone

The eastern boundary of the Western Desert and eventually the boundary of the stable part of the platform is considered to be along Abu Jir Fault Zone. The zone consists of several NW – SE trending faults that extend from Anah Graben, across the Euphrates River valley to Heet, Awasil, Abu Jir, Shithatha (Fig.1), along the western side of the Euphrates river through Kerbala, Najaf and Samawa to meet Hafr Al-Batin lineament west Basrah and northwest Kuwait. It forms an expressive linear feature across the Iraqi territory for about 600 Km that is clearly visible from satellite images.

Fouad (2002 and 2004) using reflection seismic sections covering the northern part of the zone, showed that the cross-sectional shape of the fault zone, which often resembles the longitudinal view of a cone, is not uniform with an abrupt variation in appearance and style along the zone. The zone consists of several steeply dipping normal faults that converge downwards. It is generally wider at higher levels than lower ones (Fig.6). Some horizons were draped over the tip of the faults to define antiforms and/ or synforms with axes parallel to the zone. He concluded that these antiforms and synforms represent positive and negative flower structures and that the presence of such structures provides conclusive evidence to the occurrence of strike-slip movement along the fault zone imposed on the earlier normal one. The movement is thought to be right-lateral. Furthermore, Abu Jir Fault Zone exhibits some geomorphological features that are directly related to the lateral movement of the zone. The most expressive is Heet pressure ridge and the associated compressive mesoscopic structures, as well as Awasil, Al-Jabha, Al-Mudowar and Abu Jir Depressions or sag ponds. Such features are distinctive to strike-slip faults, and their formation depends on the bending geometry of the fault surface relative to its slip vector and the magnitude of the movement (Harding 1985; Park, 1988 and Woodcock and Schubert, 1994).

– The Intra-Stable Platform Fault Systems

Anah – Abu Jir Fault Zones are considered as the external fault systems that bound the Stable Platform. However, several fault systems were identified within the stable part of the platform. The faults were inferred by various methods including field observation (Al-Mubarak and Amin 1983; Qassir *et al.*, 1993; Al-Azzawi *et al.*, 1996 and Al-Bassam *et al.*, 2004), landsat images (Al-Ameri, 1978) geophysical (gravity) method (Al-Kadhimi, 1997) and by regional compilation (Buday and Jassim, 1987 and Al-Kadhimi *et al.*, 1996). Many of these faults are speculative and subject to debate. In this study, however, the author will focus on the geologically proven faults only. However, there are two main fault systems in the Western Desert, the NW – SE and N – S trending fault systems.

– The NW – SE Trending Faults; Hauran Strike – Slip Fault System

Several NW – SE trending faults are well developed in the central part of the Western Desert. Al-Mubarak and Amin (1983) also Al-Bassam *et al.* (2004) described these faults as a vertical horst and graben forming normal faults that are partly associated with horizontal displacement. In the present study the author present the name "**Hauran Fault System**" as a formal name denoting these faults (Fig.2). The faults of the system are very expressive on the surface and in landsat images (Fig.7). They have extremely straight traces extending between



Fig.5: Seismic section across Anah Graben. The section showing the partial inversion of the graben and the development of Anah Monocline directly above the thickened Late Cretaceous syn-rift sequence. The position of well is shown too, (after Fouad, 1997). H1, H2 are seismic markers denoting tops of Oligocene and Late Cretaceous syn-rift sequence, H3 top pre-rift sequence and H4 and H5 within pre-rift sequence

few to 120 Km, with some sharp linear escarpments. Moreover, many valley courses and drainage channels show sharp and straight offsets along these fault traces. However, careful observations point that Hauran Fault System, is strike-slip faults. The lateral movements are quite clear as the faults displace the successive lithological contacts (Fig.7). The displacement, which is of left-lateral nature, vary considerably along the faults ranging from few meters to 6 Km. Minor component of vertical displacement on some of these faults is also evident.

Field mapping previously had revealed the presence of small anticlines and synclines trending almost parallel to the fault traces. Also, Al-Mubarak, (1996) pointed to the development of a series of small and large playas along some of the fault traces. Such surface structures are considered as additional evidence to the recognition of strike-slip faulting (Harding, 1985; Sylvester, 1988; Pluijm and Marshak, 1997 and McClay and Bonora, 2001). Further evidence is provided by the present study by the identification of a series of fault bounded silvers along some principal fault traces (Fig.8). These elongated doubly tapered silvers which are known as "horses or shear lenses", (Park, 1988 and Woodcock and Schubert, 1994) are pieces from one side of the main fault that had been sliced off and transferred along the fault zone as the displacement continue. Obviously the presence of such conclusive structures leaves no doubt about the nature of these faults. Finally, Hauran Strike-Slip Fault System displace Mesozoic and older rock units only (Fig.2), accordingly it is concluded that the fault system formed or at least reactivated during the Late Cretaceous.

– The N – S trending faults; Nukhaib Fault System

The N – S trending faults are restricted to the southern part of the Western Desert. Al-Mubarak and Amin (1983) described them as a set of normal faults with long traces (80 – 150) Km and clear vertical displacement. The fault system form a north – south trending, 160 Km long and (70 – 80) Km wide graben known as "Nukhaib Graben". Al-Bassam *et al.* (1997) presented an extended discussion concerning the geology and origin of Nukhaib Graben, using different geological, geophysical, geochemical and hydrogeological data. They pointed out that the graben formed above basement high (granitic intrusion and salt dome), and that the graben bounding faults displace the Mesozoic and Cenozoic stratigraphic sequences. However, there is no enough data available to the author while conducting the study to add further information on this fault system.

Other faults such as the NE – SW and E – W trending were also recorded by many workers (e.g. Al-Ameri, 1978; Al-Mubarak and Amin 1983 and Al-Bassam *et al.*, 2004). With limited data available, however, many of these faults can not be verified or discussed in detail.

▪ Arches

Several major arches dominated the structural pattern of Arabia and the Middle East. Among them is Hail arch, the longest one in the Middle East that extends from Arabia to northern Iraq. This structural element was described and referred to (or at least part of it) with different names by many workers including Hail Arch, Hail – Rutbah Arch, Hail – Rutbah – Ga`ara Arch, Rutbah Uplift, Hauran High, Rutbah – Khleissia High ...etc.

However, there is so much confusion and debate about Hail – Rutbah Arch within the Iraqi territory. Its nature, position and periodic activity largely remain unknown because of the lack of deep wells and seismic data. Nevertheless, the available data point out that Hail Arch is a broad up-warped that extends from the northern margin of the Arabian Shield northward to northwest Iraq affecting large parts of western Iraq, northeastern Jordan and southeastern Syria. The arch itself has a series of highs such as Rutbah, Ga`ara and Khleissia separated by several lows.

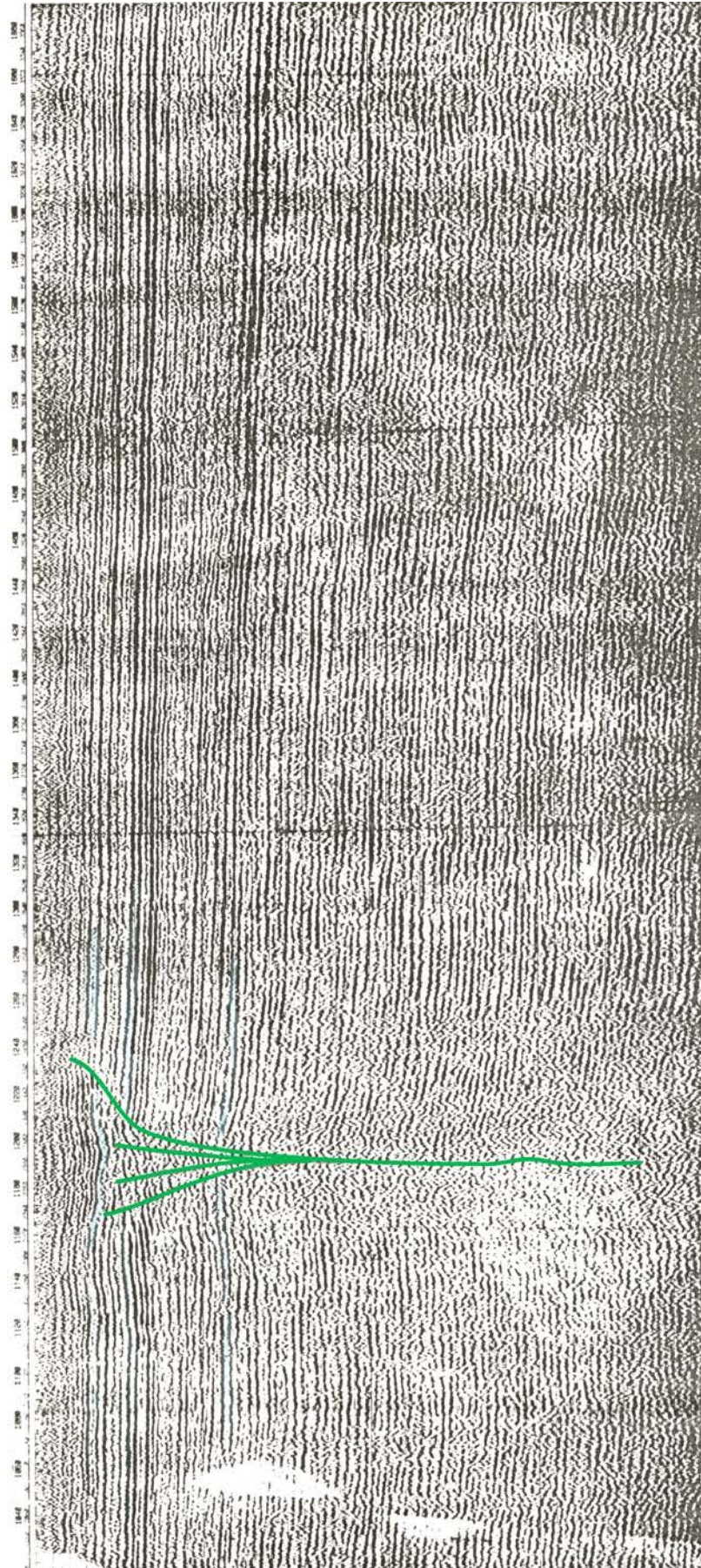


Fig.6: Seismic section across Abu-Jir Fault Zone between Heet and Shithatha. The zone consists of several steeply dipping faults that converge downwards, (after Fouad, 2002 and 2004)



Fig.7: Hauran Strike-Slip Fault System

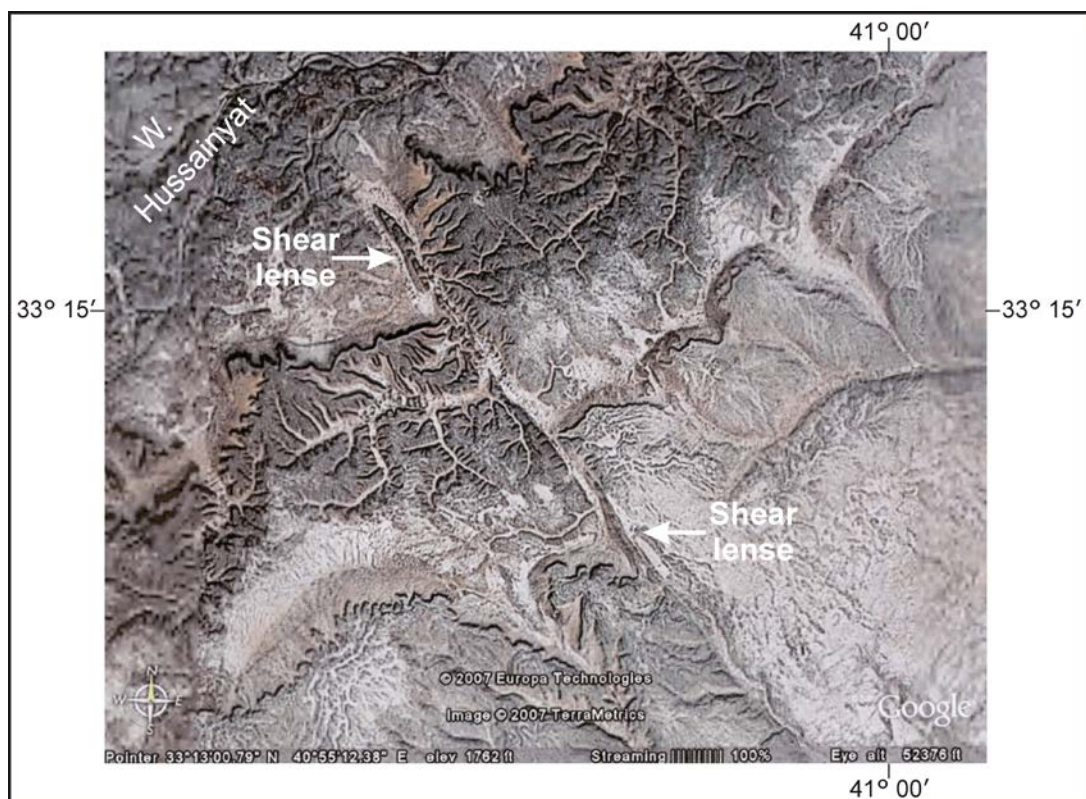


Fig.8: Elongated doubly tapered shear lenses (horses) along the fault trace of Hauran Strike-Slip Fault System

Hail – Rutbah Arch is marked by a prominent positive gravity anomaly indicating the presence of basement at a relatively shallow depth. The shallowest locality being at Ga`ara Depression. The (4 – 6) Km thick Paleozoic sequence that deposited across the axis of the arch display no thickness or facial changes, whereas the Mesozoic sequence show the least complete section above the arch (Lovelock, 1984 and Alsharhan and Nairn, 1997). Moreover, it is quite clear that the arch acted as a prominent divide separating different basins and sediments distribution on its eastern and western flanks during the Cenozoic era (Al-Bassam *et al.*, 2004).

It is important to mention that at the time of the Hail – Rutbah Arch activity either by up warping or subsidence, it is not necessary that the entire arch display the same magnitude of activity, instead in many occasions the available data point out that some parts of the arch may remain inactive or at least show lesser activity than the others. This is clearly reflected by the non-uniform spatial distribution of the unconformities or the erosional surfaces and their time span along and at the vicinity of the arch in the Western Desert. Ga`ara Depression is an example to this where the Paleozoic Ga`ara Formation is overlain by Late Triassic carbonates with a break of about 30 Ma at the southern rim of the depression, whereas the same formation at the eastern rim of the depression is overlain by Eocene carbonate with about 200 Ma break (Al-Bassam *et al.*, 2004). All this drastic variation occur within the 70 Km length of the depression. The differently oriented initial depositional dip of the exposed rock units around Ga`ara Depression support this conclusion too.

TECTONIC EVOLUTION

By integrating the data already displayed, the tectonic and structural evolution of the Western Desert as a part of the Stable Platform of the Arabian Plate can be broadly outlined.

Arabia as well as several continental microplates including Turkey, Central Iran, Afgan, India and other smaller fragments collectively formed part of long wide northern passive margin of the Gondwana super continent bordering the southern shore of the Paleo-Tethys ocean. These microplates remained together until the Latest Paleozoic when Gondwana start to break up.

The accretion and cratonization of Arabia though out the Proterozoic (950 – 640) Ma and the following Latest Proterozoic – Earliest Paleozoic (620 – 550) Ma intercontinental failure and strike-slip faulting of Najd printed two main trends of weakness within the body of the continental basement of Arabia. These north – south and northwest – southeast trending lines of weakness grossly controlled the location and the style of some of the later Phanerozoic deformation.

▪ The Paleozoic Evolution (570 – 245) Ma

The Cambrian (570 – 510) Ma is dominated by the deposition of widely spread sheets of silici-clastic sediments deposited in a shallow epicontinental sea in a relatively stable condition. Exceptional event occurred through the Middle Cambrian (~ 525 Ma) when global sea level rise caused the deposition of an extensive carbonate horizons (Burj Limestone) of a wide regional extent. Due to the high impedance contrast with the surrounding clastic rocks, this horizon forms a prominent reflection event, which is correlatable across much of northern Arabia (Best *et al.*, 1993).

Evidence for major Paleozoic tectonic movement is spare or absent. Nonetheless, many unconformities punctuate the Paleozoic section. The unconformities are related to minor epeirogenic adjustments and eustatic sea level fluctuation. Because much of Arabia was covered by shallow water at that time, such events might easily cause emergence and erosion.

The regional unconformities in northern Arabia are the Late Ordovician – Early Silurian that is related to the Arabian glaciation and the related sea level fall (Beydoun, 1991 and Brew, 2001). The unconformity is clear in Akkas1 well between Khabour and Akkas formations. However, deglaciation in Early Silurian caused regional sea level rising. The second regional unconformity took place through the Late Silurian in response to regional uplifting of the Caledonian movement. The Late Devonian – Early Carboniferous unconformity is related to the second Paleozoic orogeny "the Hercynian movement". It is important to mention that in Arabia, the two major Paleozoic orogenic movements are identified by their effects on sea level changes, rather than by their orogenic deformation.

The Middle – Late Carboniferous to Early Permian unconformity was the result of the second glaciation of the southern part of Arabia, which caused sea level drop and exposure of considerable parts of Arabia (Husseini, 1992).

▪ **Late Paleozoic – Early Mesozoic Evolution**

At the Late Permian the area underwent broad uplift and was again exposed and eroded as a consequence of uplifting of the shoulders of the newly forming rifts that dominated the northern margin of Gondwana. This was the beginning of the Neo-Tethys ocean formation.

The Cimmerian microcontinents broke away from Gondwana towards the northeast through oceanic accretion. The opening of the Neo-Tethys continues as the Cimmerian microplates proceeded to drift northeastward causing the shrinkage of the Paleo-Tethys as its oceanic crust subducted beneath Leaurasia. Opening of the Neo-Tethys Ocean in the Permo – Triassic brought drastic changes in the regional tectonic and sedimentation pattern of the entire Arabian plate that lasted until the final closure of the Neo-Tethys in the Late Cenozoic.

▪ **The Mesozoic Evolution (245 – 65) Ma**

The Mesozoic witnessed the birth and development of the Atlantic-type Arabian passive margin that bordered the western shore of the Neo-Tethys Ocean. An extraordinarily wide, shallow marine epeiric shelf developed on this ENE-dipping platform (Beydon, 1991). The first order impact of the Mesozoic era is reflected by a major change in sedimentation from a primarily silici-clastic Paleozoic regime to a major carbonate with interspersed clastic episodes. In the Western Desert region, however, this is reflected by the deposition of the Late Triassic carbonates over the eroded Permian clastics. The predominance of carbonate during most of the Mesozoic reflects the Paleo-latitudinal position of Arabia within tropical to equatorial climatic belt (Beydoun, 1991; Brew, 2001 and Ziegler, 2001).

Sea floor spreading continues through the Triassic leading to a progressive expansion of the Neo-Tethys Ocean. In the mean time the passive margin went through steady subsidence due to the influence of the accumulated sediments.

The first tectonic event of the Jurassic was the closure of the Paleo-Tethys Ocean by the collision of central Iran with the mass of Laurasia. At that time the Neo-Tethys reached its maximum width which was (2000 – 4000) Km (Dercourt *et al.*, 1986). This event was too far to be felt on the platform. Nevertheless, on the Western Desert region of the stable platform it was also evident that upwarping along Hail – Rutbah Arch became clearly effective.

The western part of the Western Desert was exposed, forming a source area for the clastics throughout the entire Jurassic (Al-Bassam *et al.*, 2004). However, the Late Jurassic (also Early Cretaceous) was the time of a significant regional unconformity throughout the northern Arabian platform associated with a globally low sea level. Thus the sedimentary pattern on the platform including the Western Desert during the Jurassic (208– 145) Ma is a reflection of a fluctuating sea level and minor epeirogenic movements along Hail – Rutbah Arch.

The Cretaceous period (145 – 60) Ma display three distinct phases of evolution. The first phase persisted throughout the Early Cretaceous to Turonian/ Coniacian, where the oceanic part of the Arabian Plate was continuously consumed by subduction beneath Iranian plate. The subduction had very weak effect on the Arabian platform. Accordingly during that period of time, the depositional environment conditions of a shallow carbonate shelf with clastic influxes persisted over the region, following the pattern established during the Jurassic. Therefore, sedimentations pattern and facies variations reflect global sea level fluctuation and minor upwarping along Hail – Rutbah Arch which left the western part of the Western Desert as an exposed area.

The second phase of the Cretaceous evolution was remarkable and sharp. During the Campanian – Maastrichtian, the Arabian Plate underwent regional stretching. The stretching was enough to generate systems of intracontinental elongated rift basins in the northern Arabian platform (Lovelock, 1984; Daly, 1990; Peel and Wright, 1990, Ruiter *et al.*, 1994; Fouad, 1997 and Brew, 2001).

The extensional phase produced numerous E – W and NW – SE trending fault bounded troughs as grabens and half-grabens that dominated the northern Arabian platform including north and eastern Syria and north western Iraq (Fig.9). Most of these rifts developed along pre-existing lines of weakness that were related to the Neo-Tethys rifting and development.

Anah and Abu Jir Fault Zones, which formed during this extensional period of time, started receiving significant Campanian – Maastrichtian syn-rift sedimentary infill. The syn-rift sequence, which is represented by the Shiranish Formation display a huge thickness increase in passing from the shoulders towards the center of the basin particularly in Anah Graben. Simultaneous sedimentation and basin subsidence conditions continued between (20 – 15) Ma. This time span was associated with a major global sea level rise. The marine transgression was extensive, covering almost the entire Western Desert including Hail – Rutbah Arch except the Ga`ara region which was the highest part of the arch at that time. Al-Bassam *et al.* (2004) pointed out that though mostly submerged, Hail – Rutbah Arch acted as basin divide at that time separating different marine facies on its flanks. Owing to its orientation with respect to the N – S stretching, the NW – SE trending Abu Jir Fault Zone underwent a transtensional movement rather than pure extensional movement (Fig.9), and that may explain the reduced thickness of the associated syn-rift sequence in comparison with that of Anah Graben.

The third and the final phase of the Cretaceous evolution occurred in the Latest Maastrichtian when the Arabian passive margin was under compression for the first time as a consequence of the first phase of the Alpine Orogeny. The compressive phase is related to the ophiolites obduction and emplacement along the Arabian Plate margin (Dercourt *et al.* 1986; Kazmin *et al.* 1986; Daly, 1990; Ruiter *et al.* 1994; Fouad, 1997 and Brew, 2001). Away from the compressed and destroyed margin, however, within the interior of the Arabian Plate body, the compression caused the cessation and termination of the active Late Cretaceous grabens subsidence followed by a regional emergence of the entire stable part of the platform. The Cretaceous period therefore, is terminated by an extensive region wide unconformity.

It is noteworthy to mention that, though the left lateral displacement on Hauran Fault System is a Late Cretaceous event, earlier history of fault formation might be expected since there are signs of multiple deformations on the faults. However, further scrutiny is needed to reveal more details on this fault system.

▪ The Cenozoic Evolution (65 Ma – present)

After a relatively short but extensive break, the Cenozoic era started with a large scale transgression, covering the entire platform. The Paleocene – Eocene (65 – 35) Ma was largely

a time of quiescence in the northern Arabian platform and deposition of significant open marine sediments. Hail – Rutbah Arch though mostly submerged except its highest part around Ga`ara region, remained active in separating local basins east and west of the arch (Al-Bassam *et al.* 2000). The Eocene sea was the last to cover almost all of the Western Desert. After the Eocene period of time, the western part of the Western Desert including Hail – Rutbah Arch, remained as positive land all the way through. Later marine transgression covered only limited portions of the eastern part of the Western Desert. Middle Eocene was the time for early collision of the Arabian Plate with Bitlis fragments of the Turkish Plate (Hempton, 1985; Yalmaz, 1993). This event was too remote to leave any effect on the interior of the Arabian plate.

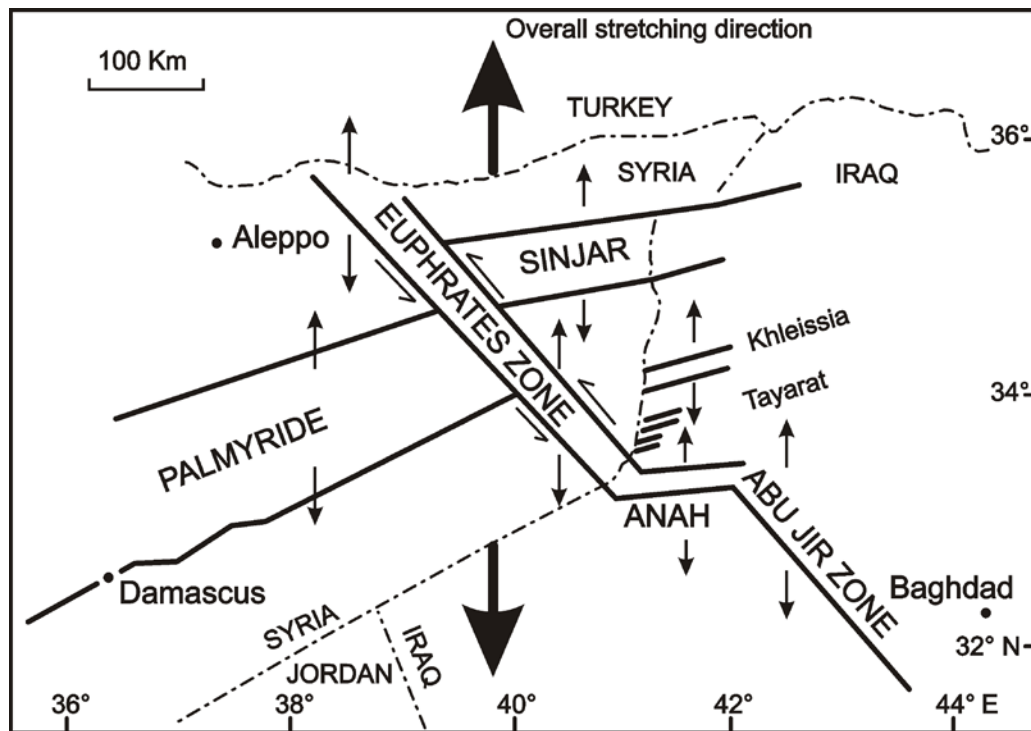


Fig.9: Simplified sketch map illustrating the Late Cretaceous extension and the formation of the intracontinental rift basins in the Northern Arabian Platform (modified after Lovelock, 1984; Peel Wright, 1990, Ruiter *et al.*, 1994 and Fouad, 1997 and 2004)

The Oligocene (35 – 25) Ma started with sharp global sea level fall exposing large areas of the Western Desert to erosion. The sea, later on returned back to the eastern part of the Western Desert only. The Oligocene ended by another wide areal exposure. It is not clear if this exposure was related to the regional upwarping associated with the early initiation of the Red Sea rift.

The Early Miocene (25 – 17) Ma witnessed the final marine transgression on the eastern and northern parts of the Western Desert. Different Middle Miocene sedimentary facies were deposited on both sides of Anah – Abu Jir Fault Zone. The sediments contain extensive syn-depositional (soft-sediments) deformational features along most of the zone, indicating the seismic activity of Anah – Abu Jir Fault System at that time (Fouad, 1997 and 2000 and Fouad *et al.* 1986).

The Late Miocene (~11 Ma) was the time of the final transition to continental condition. Late Miocene onwards is marked as a time of increasing compression as collision along the

northern and eastern boundaries of the Arabian Plate with Iran/ Anatolia portions of Eurasia proceeded, then culminated through the Pliocene (5.3 Ma). The compression produced regional folding and thrusting of the north Arabian Plate margin. In the interior of the plate body, however the far field compression caused structural inversion of the Late Cretaceous rift basins, not only to the proximal basins such as Abdel Aziz and Sinjar, but also to the distal ones such as the Palmyra and Anah (Fig.10).

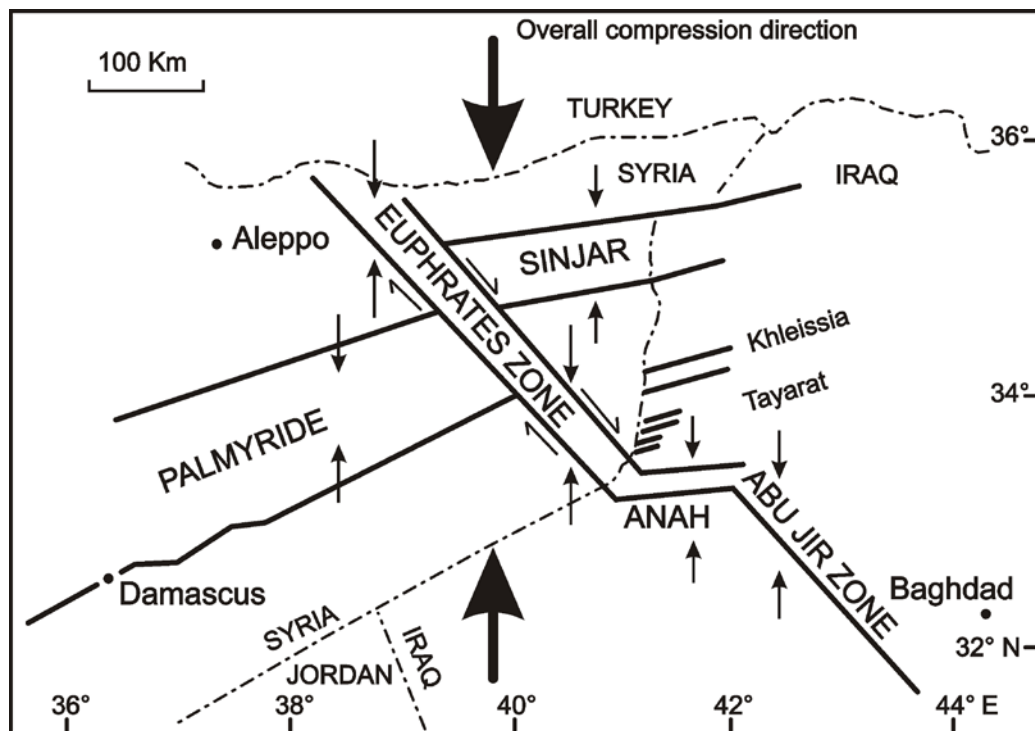


Fig.10: Simplified sketch map illustrating the Late Tertiary compression, which produced structural basin inversion and transpressive movements on some of the North Arabian rift basins, (modified after the same authors in Fig.9)

The inversion of Anah Graben as the northern boundary of the stable platform and the Western Desert occurred by the compressional reverse reactivation of the pre-existing basin boundary normal faults. The partial extrusion of the Campanian – Maastrichtian syn-rift fill as a result of the basin inversion forced the upper most part of the syn-rift and the entire post-rift units to drape over the tip of the boundary faults generating pronounced fold known in the region as Anah Monocline (Fig.5).

Late Tertiary collision exerted compressive stresses perpendicular to the E – W trending troughs of the northern Arabian platform such as the Palmyra, Sinjar and Anah, but imposed transpressive movement along the NW – SE trending fault zones such as the Euphrates of eastern Syria and Abu Jir (Fig.10).

The associated flower structures, pressure ridges pull-apart and sag ponds provide additional evidences to the occurrence of right lateral movement on these fault zones (Ruiter *et al.* 1994; Fouad, 1997 and 2000 and Brew, 2001). Moreover, because of their orientation with respect to the regional N – S compression, the NW – SE trending fault zones escaped significant structural inversion.

It is very important to note that Anah – Abu Jir Fault Zones acted as a mobile zone by accommodating the Late Cretaceous extension by subsidence and the Late Tertiary

compression either by lateral movement or structural inversion. This behavior hindered the far field stresses to propagate further within the stable part of the platform.

Recent activity is evident along Anah – Abu Jir Fault Zone. The continuous subsidence of Al-Jabha sag pond within Abu Jir Fault Zone is an example to the current activity of the zone. The successive terraces like lithified bitumen flows around the periphery of the depression pointing out to the continues widening and deepening of the depression (Fig.11). Each active period of extension was accompanied with eruption of bitumen flow and formation of a new step like terrace. At least five stages of bitumen terraces are preserved around the depression. These terraces, which are younging upwards, are separated from each other by a horizons of aeolian sand mixed with reworked bituminous materials pointing to the quite periods between the successive eruptions.

The sudden gas explosion at the remote village of Abu Jir in the Western Desert in 1982 provides another interesting example. The gas seeped out through newly formed cracks in the ground and went into flame as witnessed by the local villagers (Fig.12). However, this event remained unknown to the geologist and other specialists until recorded for the first time by the author and his colleagues in (1999). This fire is called "Sea`aria" by the local villagers which mean "Little Hell", but the author give it the name "Abu Jir Eternal Fire" in tribute to the famous "Kirkuk Eternal Fire".

Other geomorphological evidences were recorded by Brew (2001) and Sissakian (in press) along the Euphrates and Anah. However, this evidences collectively indicating the active nature of the Euphrates – Anah – Abu Jir mega lineament of the northern Arabian Plate. The continuous changing in trends of valleys and accumulation of terraces around them is another evidence for the activity of the Abu Jir Fault Zone (Sissakian and Ibrahim, 2006).



Fig.11: Successive terraces of bitumen flows around the periphery of Al-Jabha Depression. Each active period of extension was accompanied with eruption of bitumen frow and formation of a new terrace



Fig.12: "Little Hell" or Sea`aria as called by the local villagers. A burning gas leakage, called here the Abu Jir Eternal Fire

CONCLUSIONS

- The Iraqi Western Desert is a part of the northern Arabian platform where relatively thin Phanerozoic sediments cover the Precambrian continental basement complex. The area lacks expressive Alpine related compressional structures.
- The basement itself contains two printed trends of an inherited lines of weakness related to its Proterozoic – Earliest Phanerozoic (950 – 550) Ma accretion and cratonization. These N – S and NW – SE trending lines of weakness grossly controlled the location and styles of some later Phanerozoic deformation.
- The northern Arabian platform within the Iraqi territory has long been divided into two parts, a stable one to the west (within which the Western Desert is located) and an unstable one to the north and east. The present study, based on more reliable geological criteria, introduce a new modified boundary between the two parts of the platform. The proposed boundary is to be along Anah – Abu Jir Fault Zone. The fault zone, which runs parallel to the Arabian Plate boundary, forms a mega lineament more than 700 Km across the Iraqi territory. However, the proposed boundary is more compatible with the tectonic framework of the northern Arabian Plate and the adjacent Middle East structures.
- The Paleozoic (570 – 245) Ma sequence is dominated by silici-clastic sediments deposited in a shallow epicontinental sea in a relatively stable conditions. Exceptional event occurred through the Middle Cambrian ~ 525 Ma when a uniform carbonate horizon (Burj Limestone) of a wide extension deposited due to a global sea level rise.
- Several unconformities punctuated the Paleozoic sequence. They are related to sea level fluctuations including glaciation and deglaciation. In Arabia however, the two major Paleozoic orogenic movements (the Caledonian and Hercynian) are identified by their effects on sea level changes rather than by their orogenic effects.

- Late Paleozoic – Early Mesozoic was time of the Cimmerian plates separation from Gondwana and the opening of the Neo-Tethys Ocean. This event produced a significant region wide unconformity throughout the northern Arabian platform.
- The Mesozoic witnessed the birth and development of the Arabian Plate passive margin which bordered the western shore of the Neo-Tethys Ocean. The Mesozoic exhibit a major change in sedimentation from a primary silici-clastic Paleozoic regime to a major carbonate deposition with interspersed clastic episodes. This intern reflects the tropical to equatorial Paleolatitudinal position of Arabian throughout that time span.
- The sedimentation pattern of the stable platform and eventually, the Western Desert, through the Triassic and Jurassic (245 – 145) Ma era was a reflection to a fluctuating sea level and a periodic movements of Hail – Rutbah Arch.
- The Cretaceous period (145 – 65) Ma exhibit three distinct evolutionary episodes. The first one which persisted through the Early Cretaceous to Turonian/ Coniacian (145 – 84) Ma, was the continuation to the sedimentation pattern established during the Jurassic. The second was associated with a regional stretching and formation of intracontinental rift basins in the northern Arabian platform including Anah – Abu Jir Fault Zone, which form the eastern boundary of the stable platform. The extension prevailed throughout the Campanian – Maastrichtian as recorded by the associated syn-rift sequence. The Campanian – Maastrichtian was a time of a significant global sea level rise. The third evolutionary episode established during the Latest Maastrichtian, when the active intracontinental basin subsidence terminated, followed by a regional emergence of the entire stable platform and development of an extensive region wide unconformity. The event was the consequence of the early phase of the Alpine Orogeny in which ophiolites obducted and emplaced along the Arabian Plate margin.
- The Cenozoic era started with an extensive sea transgression that covered the entire platform. The Paleocene – Eocene (65 – 35) Ma was a time of quiescence and deposition of significant open marine carbonate and phosphorites. In the meantime, though mostly submerged, Hail – Rutbah Arch remained active in separately local basins east and west of it. Gradual retreat of the sea took place by the end of the Eocene and the western and central portions of the Western Desert including Hail – Rutbah Arch became positive land all the way through. The regression continued throughout the Oligocene to Miocene with some limited transgressions until the final transition to continental condition by the Late Miocene (~11 Ma).
- The compressional conditions prevailed by the Late Miocene due to the collision of Arabia with Iran and Anatolia. The compression culminated through the Pliocene (5.3 Ma), producing Zagros Fold and Thrust Belt on their plate boundaries. However, within the interior of the Arabian platform, the far field stress exerted compression on the northern boundary of the stable platform resulting in the structural basin inversion of Anah Graben and the formation of Anah Monocline, whereas exerted transpression on the eastern boundary resulting in a right-lateral movement on Abu Jir Fault Zone. Therefore, by accommodating the Late Cretaceous extension and Late Tertiary compression, Anah – Abu Jir Fault Zones acted as a mobile zone hindered the Alpine far field stress to propagate further through the stable platform.
- Conclusive evidences on the left-lateral movement on the "Hauran Strike-Slip Fault System" were identified and presented here for the first time. Of these evidences are the positive flower structures, negative flower structures, offsets in valley courses and shear lenses.
- Several recent activities are evident along Anah – Abu Jir Fault Zone. They are collectively pointing to the current active nature of Anah – Abu Jir mega lineament.

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