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WESTERN ZAGROS FOLD – THRUST BELT, PART I: THE LOW FOLDED ZONE

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ABSTRACT

The Low Folded Zone is an integral part of the Western Zagros Fold – Thrust Belt of the Iraqi territory. Field, seismic and well data have been integrated to interpret the structural styles and geometries of the folds and the associated structures and their variations across and along the zone. It is concluded that the mechanical properties of the folded sedimentary pile as well as the presence or absence of early formed structural lines of weakness have exerted first order impact on the nature of the folding and faulting processes and their subsequent evolution in this structural domain. Moreover, the classical structural – mechanical grouping of the Zagros stratigraphy in southwest Iran appears not uniform and may show significant variation in the mechanical properties. Therefore, it is found that this grouping might be partially applied in Kirkuk region of the Low Folded Zone, whereas it is totally inapplicable in Mosul region of the zone.

حزام طي وتصدع زاگروس الغربي، الجزء الأول: نطاق الطيات الواطئة

صفاء الدين فخري فؤاد

المستخلص

إن نطاق الطيات الواطئة هو جزء من حزام طي وتصدع جبال زاگروس الغربي العراقية. تم دمج المعلومات الجيولوجية الحقلية والزلزالية ومعطيات الآبار الاستكشافية لتفسير الطراز الهندسي والتركيبي للطيات والتراكيب المترافقة معها وأسباب تغيراتها بامتداد وعبر النطاق. لقد استنتجت الدراسة بان الخواص الميكانيكية للغطاء الرسوبي المطوي، إضافة إلى تواجد أو عدم تواجد خطوط ضعف تركيبية أولية قد حكمت بشكل أساسي طبيعة عملية التشويه وطريقة نشأتها وتطورها اللاحق في هذا النطاق. إضافة إلى ذلك فقد تبين أن التقسيم التركيبي – الميكانيكي التقليدي للتتابع الطبقي لزاگروس جنوب غرب إيران غير متجانس وقد يظهر تغيرات مهمة في صفاته الميكانيكية، وعليه فقد استنتج بأن هذا التقسيم العام يمكن استخدامه جزئيا في منطقة كركوك من نطاق الطيات الواطئة، ولا يمكن استخدامه كليا في منطقة الموصل من هذا النطاق.

INTRODUCTION

The Zagros Folds – Thrust Belt is the deformational product of the Cretaceous-present day convergence of the Arabian – Iranian (Eurasian) Plates. The belt extends more than 1800 Km from southern Turkey through north and east Iraq to the Strait of Hormuz southwestern Iran. It consists of a thick folded and faulted Paleozoic to Cenozoic sedimentary pile, that have accumulated on the northeastern Arabian Plate margin (Alavi, 2004; Sherkati *et al*., 2005 and Casciello *et al*., 2009).

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The Zagros Fold – Thrust Belt has been traditionally subdivided into a number of structural zones that are generally striking parallel to the plate boundary. Falcon (1969 and 1974) was the first to introduce a regional structural classification of the Zagros Orogene. He divided it into three parallel NW – SE trending structural belts. The belts, from NE to SW are; the Thrust Belt, the Imbricated Belt and the Simply Folded Belt. Since then many other structural classifications were introduced (e.g Colman-Sadd, 1978; Alavi, 1994; Berberian, 1995; Blanc *et al.*, 2003 and Homke *et al.*, 2009) by modifying more or less the original concepts of Falcon.

It is important to mention, however, that almost all of the classifications have focused on the Iranian part of the Zagros, whereas the Iraqi part have had received only a very limited attention. The Iraqi part of the Zagros mountain range, which will be termed hereinafter as the "Western Zagros" is the least studied part of the Zagros Fold – Thrust Belt. Nevertheless, it has been divided by early exploration and field geologists into several structural domains. In the present article, however, the structural classification of Fouad (2008 and 2012a) will be adopted as a base to this study. In his classification, the Western Zagros Fold – Thrust Belt has been divided into four structural domains. They are, from SW to NE; the Low Folded Zone, the High Folded Zone, the Imbricate Zone and the Suture Zone.

The main targets of the present study are multifold: (1) to define the structural geometries and styles of each zone of the belt, starting with the Low Folded Zone, (2) to show the impact of the mechanical-stratigraphy on the nature of the deformation, and (3) to discuss the tectonic and structural evolution of the belt as a whole.

GEOLOGICAL SETTING OF THE LOW FOLDED ZONE

The Iraqi part of the Zagros orogenic belt has been divided into several structural domains. Early divisions were linked more or less to oil exploration activities (Henson, 1951; Dunnington, 1958; Naqib, 1959 and Detmar, 1971). More detailed classifications were introduced later by Buday (1980); Buday and Jassim (1987) and Al-Kadhimi *et al.*, (1996). They have basically relied on the same principles by dividing the fold belt into a major roughly NW – SE trending longitudinal zones, (assigned as Foothill Zone, High Folded Zone, and the Geosynclinal Area), that have been further subdivided into a number of smaller subzones by NE – SW trending regional transverse faults. Jassim and Goff (2006) have presented another classification, which is the same as that of Buday and Jassim (1987), but with minor modification. Worth mentioning, that all these classifications, however, differ from each other by their comprehensive perspective and the structural criteria used in the classification.

Based on the structural style and intensity of deformation, stratigraphy, mechanical-stratigraphy and tectono-stratigraphy of the deformed sequences, surface physiography and morphology as well as age of deformation, Fouad (2008 and 2012a) introduced a new tectonic classification to the Iraqi territory (Fig.1). In this classification, however, the Western Zagros Fold – Thrust Belt of Iraq has been subdivided into four parallel NE – SE trending structural zones. The zones, from SW to NW, are: the Low Folded Zone, the High Folded Zone, the Imbricate Zone, and the Suture Zone, with increasing deformational intensity northeastward toward the Arabian Plate margin (Fig.2).

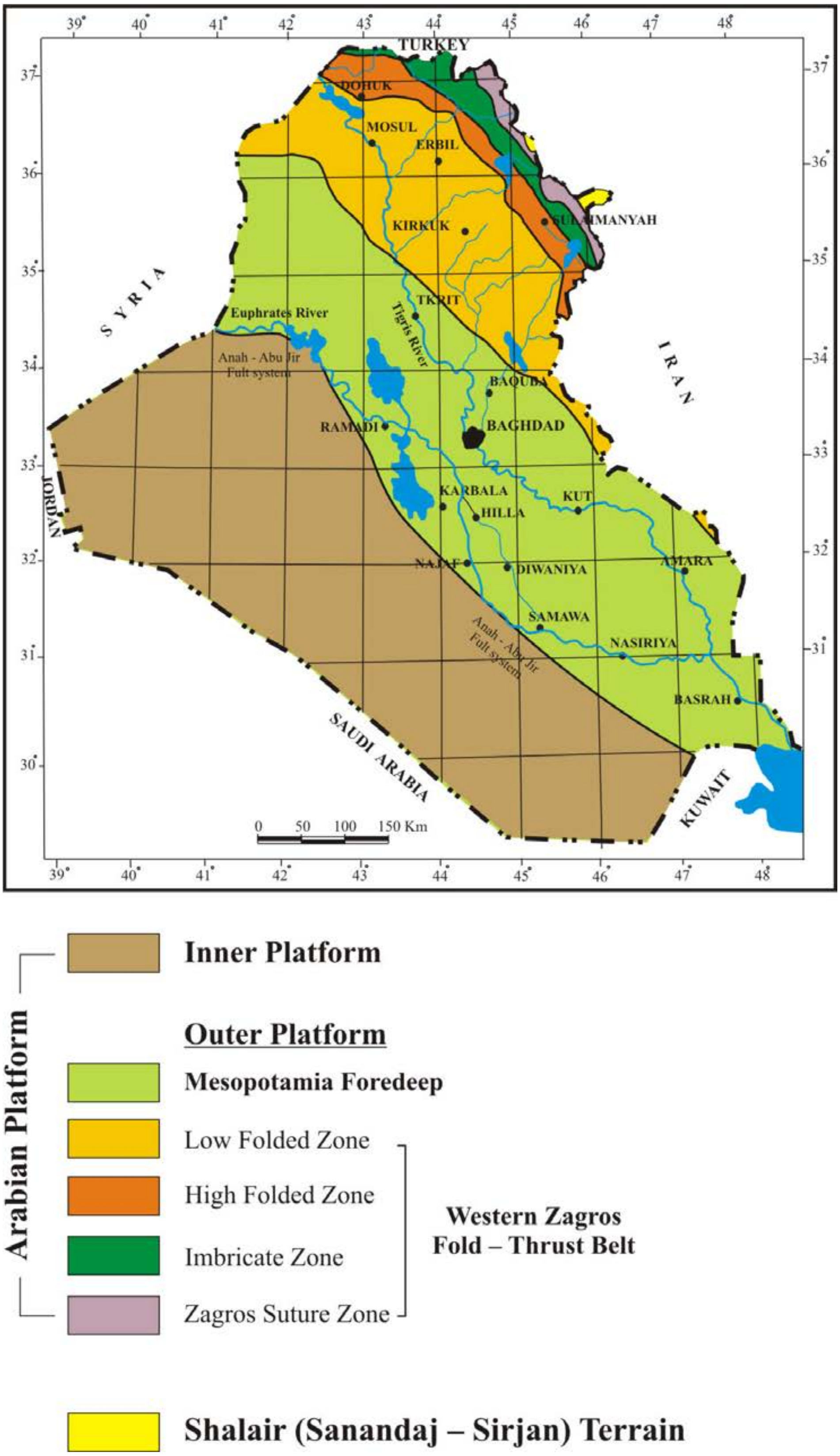


Fig.1: Tectonic divisions of Iraq (after Fouad, 2008 and 2012a)

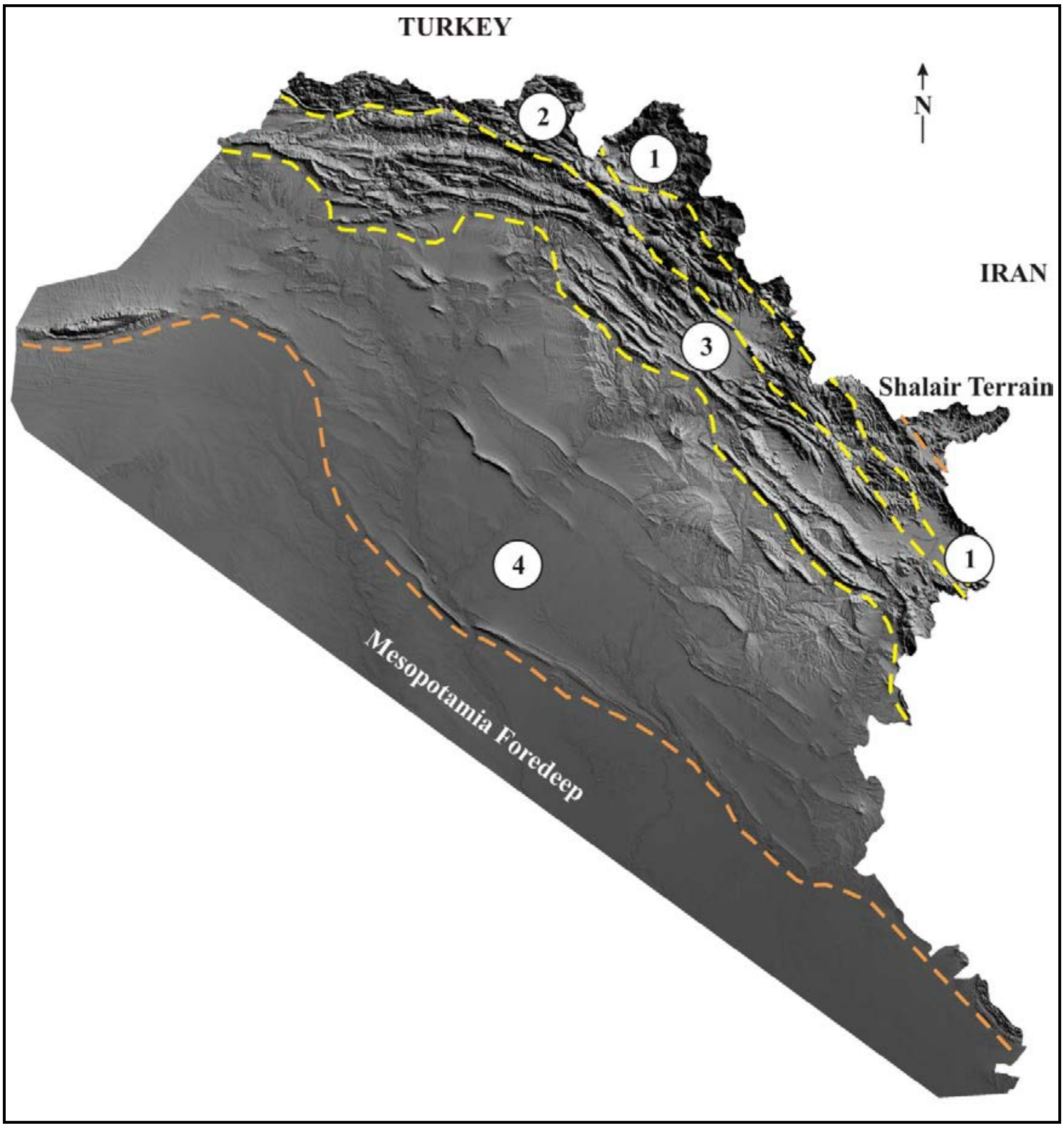


Fig.2: The tectonic subdivisions of the Western Zagros Fold – Thrust Belt
1) Zagros Suture Zone, **2)** Imbricate Zone, **3)** High Folded Zone, and **4)** Low Folded Zone
(after Fouad, 2008 and 2012a)

The Low Folded Zone (LFZ) of the Western Zagros is about 700 Km long and 100 Km wide belt, containing large number of folds of variable sizes and geometries both along and across the zone. The folds are reflected on the topography as anticlinal highs and synclinal lows expressing their young age. The folds maintain a fairly regular NW – SE trend though most of the zone, but gradually changes to E – W trend northwestward towards the Turkish territory.

The Low Folded Zone (Fig.2) is located between the Mesopotamia Foredeep from the southwest and the High Folded Zone from the northeast (Fouad, 2008; 2010 and 2012a and Fouad and Sissakian, 2011). The southern boundary of the zone with the relatively flat Mesopotamia Foredeep runs parallel to the topographic break of slope (step) made by the first front of the Zagros mountain range. The front is made by Buzurgan anticline near the Iraqi –

Iranian borders in the southeast, extending northwestward towards Badra, Zurbatiya, Hamrin South, Hamrin North anticlines, then continues northwestward across the Tigris River following Makhoul, Habbariya, Jawan, Addaya, and Sheikh Ibrahim anticlines, then swings westwards following the slopes of Sasan and Sinjar anticlines near the Iraqi – Syrian borders in the northwest (Fouad, 2008; 2012a and b and Fouad and Sissakian, 2011). On the other hand, the northeastern boundary of the zone with the High Folded Zone is taken along the slopes of the second prominent topographic and morphological step made by Bammu anticline near the Iraqi – Iranian borders in the southeast extending northwestwards following Qara Dagh, Tasloojah, Khalikan, Bana Bawi and Permam anticlines, then swing to the E – W direction following Aqra, Gully Keer, Ain Sifni, Alqosh, Dahkan, Dohuk, and Baikhair anticlines in the northwest near the Iraqi – Syrian borders.

It is noteworthy to mention that the mountain front made by the High Folded Zone is much higher both topographically and structurally than that made by the Low Folded Zone with the Mesopotamia Foredeep. The southwestern and northeastern boundaries of the Low Folded Zone, however, are well established tectonic boundaries along the entire length of the Zagros Fold – Thrust Belt from Turkey through Iraq to Iran, though are known with different names such as the Zagros deformational front (Emami *et al*., 2010 and Leturmy *et al*., 2010) and the Zagros Mountain Front (Berberian, 1995; Sepehr *et al*., 2006 and Burbrry *et al*., 2010).

The boundary between the Low Folded and the High Folded Zones along the entire length of the front is not a straight one. Indeed, it is sinuous defining a number of tectonic salients (arcs), and re-entrants (embayments). Two arcs (Fars and Lurestan) and one embayment (Dezful) are within the Iranian territory, whereas only one embayment (Kirkuk) is within the Iraqi territory. The majority of the folds of the Low Folded Zone of Iraq fall within Kirkuk Embayment.

STRATIGRAPHY

Rock units as far as Middle Miocene in age are widely exposed in the Low Folded Zone. Very limited exceptional cases do occur too, where older rock units (Early Miocene to Late Cretaceous) are exposed.

The Middle Miocene lagoonal and restricted marine Fatha Formation, which dominates the zone, consists of cyclic alternations of claystones, limestones and evaporites. The thickness of the formation, is highly variable ranging from (150 – 900) m. Worth mentioning that in the southeastern part of the zone (i.e. Kirkuk region), the evaporite of the formation consists of anhydrite, gypsum and rock salt, whereas in the northwestern part of the zone (i.e. Mosul region), the rock salt is not recorded anywhere.

The Fatha Formation is conformably overlain by the Upper Miocene Fluvio-deltaic Injana Formation, which consists of alternation of sandstones and claystones, The formation, which shows vertical and lateral lithological variation, has an average thickness of 600 m.

The Injana Formation is conformably overlain by the fluvial Upper Miocene – Pliocene Mukdadiya Formation with a gradational contact. The formation consists of coarsening upward cycles of claystones, siltstones, and pebbly sandstones. The maximum thickness of the formation is recorded in Kirkuk region (~ 2000 m) southwest of the zone, but progressively thins northwestwards, where it becomes completely absent west of Mosul region.

The Plio – Pleistocene fluvial Bai Hassan Formation conformably overlies Mukdadiya Formation with a gradational contact. The Bai Hassan Formation consists of coarsening upwards cycles of claystones, sandstones and conglomerates. The maximum thickness of the formation is around 2500 m, in the southeastern part of the zone within Kirkuk region. The formation thins northwestwards until it becomes totally absent roughly west of the Tigris River.

Information about older sedimentary units is known mainly from boreholes and geophysical data. Magnetic data indicate that the depth of the basement beneath the Low Folded Zone increases from NW to SE and estimated to be between (10 – 13) Km (CGG, 1974; Buday and Jassim, 1987 and Jassim and Goff, 2006). The basement is neither penetrated by deep boreholes, nor identified by seismic data. The Paleozoic sedimentary sequence is not penetrated by any borehole in the zone, but has been estimated indirectly to be around (4500) m (Jassim and Goff, 2006). By correlation with west and north Iraq (Hassan *et al*., 1991; Fouad 2007 and Fouad and Nasir, 2009) and Arabia (Beydoun, 1991 and Beydoun and Hughes Clark, 1992), the Paleozoic sequence is dominated by siliciclastic sediments (Alsharhan and Nairn, 1997; Brew, 2001 and Sharland *et al*., 2001).

Non of the exploration boreholes had penetrated the entire Mesozoic sequence within the Low Folded Zone, which is estimated to be around 5000 m thick. The Mesozoic sequence, which shows general thickness increase northeastwards, exhibits considerable facial changes both along and across the former depoaxis of the depositional basin. In the northwestern part of the zone, Ain Zala-29 well penetrated about 3500 m of the Mesozoic sequence assigned to Middle Triassic Geli Khana, Late Triassic Kurra Chine, Early Jurassic Butmah, Adaiyah, Mus and Alan, Middle Jurassic Sargelu, Early Cretaceous Shuaiba, Batiwah, Mauddud and Late Cretaceous Gir Bir, Mashorah and Shiranish formations.

The Cenozoic sequence exhibits strong lithological changes both along and across its former depositional basin. Moreover, it shows a rapid thickness increase northeastwards. The full thickness may reach 5000 m, but the average is between (2500 – 3000) m, except at Mosul vicinity where it is less than 1000 m. In the southeastern part of the zone, Badra 1 well penetrated ~ 3500 m of Cenozoic sediments assigned to Paleocene – Early Eocene Aliji, Middle – Late Eocene Jaddala, Oligocene Tarjel, Early Miocene Serikagni, Dhiban and Jeribe, Middle Miocene Fatha, Late Miocene Injana and Late Miocene – Paleocene Mukdadiya and Plio-Pleistocene Bai Hassan formations.

MECHANICAL STRATIGRAPHY

The regional stratigraphy of the "Zagros Mountain Belt" is best studied in southwest Iran since the mid of the last century. O'Brien (1950 and 1957), and Dunnington (1962) have divided the stratigraphic pile in southwest Iran into five structural – mechanical groups based on their relative competency and mechanical behavior (Fig.3). These groups, from bottom to top, are:

- The Basement Group: It consists of the Proterozoic stiff igneous and metamorphic rocks of the Arabian Plate basement.
- The Lower Mobile Group: It is represented by the Late Proterozoic – Early Cambrian Hormuz evaporites. It is a highly mobile group that overlies the basement with an average thickness of about 1000 m (Stocklin, 1968).
- The Competent Group: It is the thickest group in the sequence, and consists of Cambrian to Early Miocene relatively competent carbonates and sandstones with minor shales and evaporites. The thickness of the group is 6000 – 7000 m (Colman-Sadd, 1978).

- The Upper Mobile Group: It consists of the highly mobile Miocene evaporites known as Gachsaran Formation in Iran. The thickness is variable and ranges between a few hundred meters up to 2000 m (Bahroudi, 2003 and Verges *et al*., 2011).
- The Passive (or the Incompetent) Group: It consists of the Late Miocene – Quaternary clastics including sandstones, claystones and conglomerates. The thickness is highly variable due to unstable tectonic conditions during their deposition, but an average thickness between (3000 – 4000) m is more frequent.

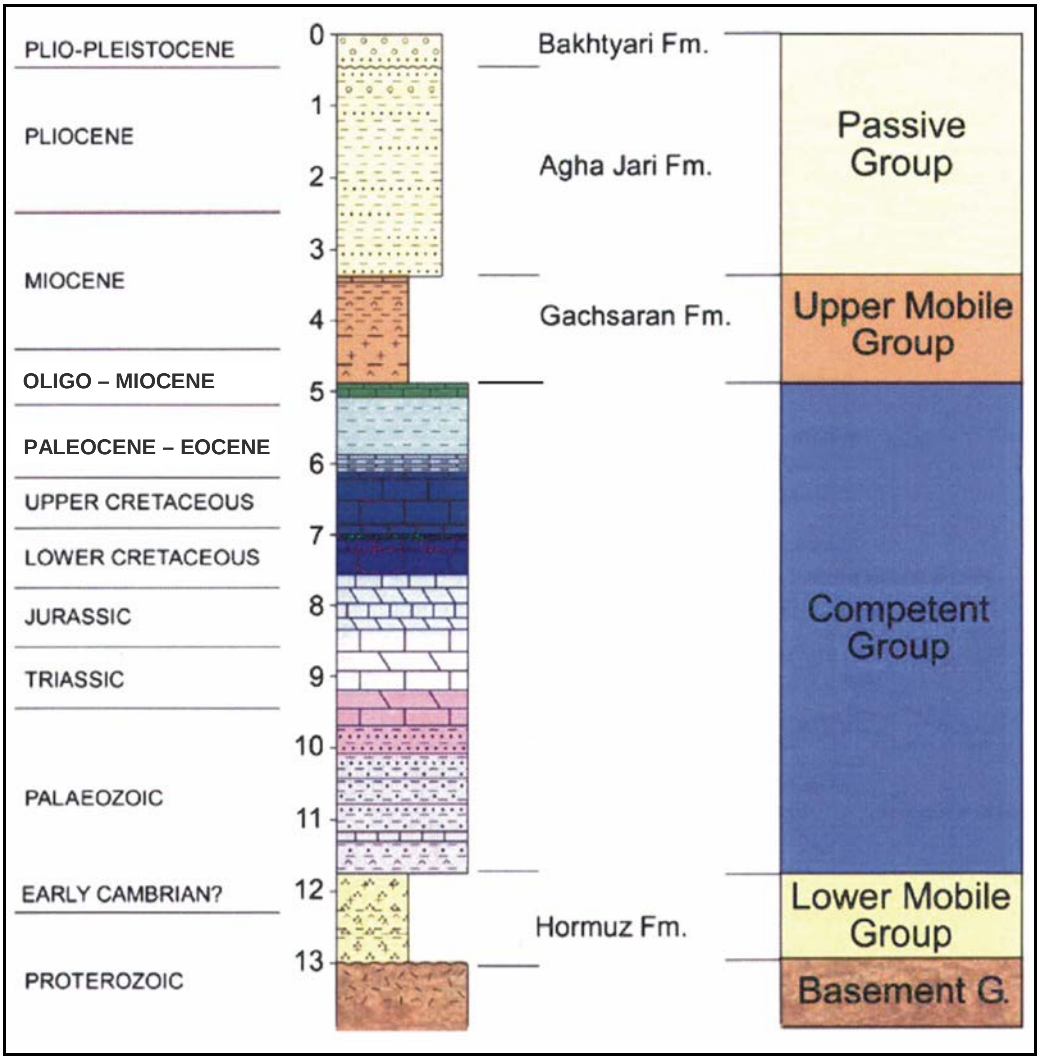


Fig.3: Simplified stratigraphic column of Southwest Iran, combined with mechanical strength based on O'Brien (1950) and Dunnington (1958) (vertical scale in Km)

It is now became well established that the five structural – mechanical groups have imposed a first order impact on the fold geometry and folding process in the region, so that the two mobile groups have had provided an efficient detachment surfaces allowing the Competent and the Passive Groups to be folded and faulted independent of each other (Colman- Sadd, 1978; Blanc *et al*., 2003; Sherkati *et al*., 2005 and 2006; Sepehr *et al*., 2006; Casciello *et al*., 2009; Farzipour *et al*., 2009; Emami *et al*., 2010 and Verges *et al*., 2011).

It is noteworthy to mention that these structural – mechanical groups are not quite uniform and may exhibit considerable lateral and vertical lithological and thickness changes both along and across the Zagros Mountain Belt (Casciello *et al*., 2009 and Verges *et al*., 2011).

In the Western Zagros of the Iraqi territory, however, these general structural – mechanical grouping of the Zagros stratigraphy of southwest Iran is not universally valid, due to a significant lithological changes within the sedimentary pile. The changes might be briefly shown as follow:

─ **The Lower Mobile Group:** The Infracambrian – Early Cambrian Hormuz salt, which form the major basal detachment between the stiff Basement Group and the overlying Competent Group in southwest Iran, has only a very limited extension. It is restricted to the extreme southern part of the Iraqi territory as inferred indirectly by a solitary salt plug (Sanam salt plug) and the dominance of the north – south trending "Arabian" structures of south Iraq and the Gulf region (Bahroudi, 2003 and Fouad, 2010). Hormuz Salt thins rapidly northwestwards and it's existence has not been confirmed in Lurstan Arc and northwards as inferred from the total absence of salt plugs and the change in the fold style (Bahroudi and Koyi, 2004; Sepehr and Cosgrove, 2004 and Emami *et al*., 2010). Moreover, it's time equivalent, which is exposed in Turkey, consists of 3000 m of fluvial-deltaic clastics (Kent, 2010). This provides another evidence for the absence of the Lower Mobile Group in the majority of Iraqi territory and eventually in the Western Zagros.

─ **The Competent Group:** The Cambrian to Early Miocene rock units that form the Competent Group are fairly similar in both regions. Nevertheless, this group may contain some local secondary detachment horizons. In the Western Zagros, however, such horizons might not have the same thickness, lithology or time equivalents of those in southwest Iran. Anyway, on the surface no such local detachments were recorded and deeper once are not reported due to the lack of deep drilling and seismic data.

─ **The Upper Mobile Group:** The Middle Miocene Fatha Formation (previously known as Lower Fars Formation) is the Western Zagros equivalent to the highly mobile Gachsaran Formation of southwest Iran. The formation, which covers many parts of the Iraqi territory including the Mesopotamia Foredeep, Low Folded Zone and parts of the High Folded Zone consists of cyclic alternation of evaporates (including gypsum, anhydrite and rock salt), carbonates and claystones. The thickness and the facies of the formation vary significantly across and along the Western Zagros; nevertheless, it forms the main cap rock of most hydrocarbon reservoirs in the Low Folded Zone (Naqib, 1959; Dunnungton, 1962; Beydoun, 1991 and Beydoun and Hughes Clark, 1992). It is important to mention that the rock salt of Fatha Formation is neither exposed nor reported anywhere in Iraq. It is only known from wells in Kirkuk region at the southeastern part of the Low Folded Zone, where it has had provided regional detachment horizon. In the major part of the Low Folded Zone, however, where the rock salt is absent, such as Mosul region (Munir and Domas, 1977; Mohi Ad-Din, 1977; Ma'ala *et al*., 1989; Fouad, 2002 and Fouad *et al*., 2004), the Fatha Formation is not capable to form a detachment, though it consists mainly of gypsum and anhydrite. Therefore, the mobility of Fatha Formation, as an Upper Mobile Group, is a function to the amount of rock salt in particular area. Moreover, the entire evaporitic facies of Fatha Formation diminishes northeast and northwards, when passing toward the High Folded Zone.

STRUCTURES OF THE LOW FOLDED ZONE

The Low Folded Zone contains a variety of surface structures including folds and faults of different types:

▪ Folds

A large number of folds are present in the zone. They exhibit variable size and geometry both along and across the zone. They maintain regular NW – SE axial trend along the zone, except in the extreme northwestern part, where it changes to E – W direction. The folds are gentle to open, Plio – Pleistocene in age, and reflected in the topography as anticlinal highs and synclinal lows. The folds are usually exposed to the stratigraphic level of the Middle Miocene Fatha Formation and less frequent to the level of the younger Neogene rock units. Exceptional cases, where older rock units are exposed exist too, but are very limited.

Two categories of the folds can be recognized from the plane view of the zone (Fig.4). The first occurs roughly to the east of the Tigris River within Kirkuk region, and the other to the west of the river within Mosul region of the zone.

─ **Folds of the East Tigris Rives (Kirkuk region):** Folds of Kirkuk region show the following structural characteristics:

- The folds are extremely long and narrow structures (Fig.4). Their axial length vary between (80 – 250) Km, and their width between (5 – 8) Km, accordingly they exhibit high aspect (length/ width) ratio and fall within the linear folds category of Jaroszewski (1984).
- The folds are NW – SE trending, asymmetrical with southwest vergence.
- They are frequently associated with thrust faults, where their back limbs have been thrusted southwestwards over their forelimbs. Most of the thrust faults are traceable on the surface for long distances (Fig.4).
- The folds cross-sections or their seismic profiles exhibit a very diagnostic structural feature; tectonic disharmony.
- The salt rich beds in the lower part of Fatha Formation have had provided an efficient detachment surfaces, and the formation acted as an active regional Upper Mobile Group, of the classical Zagros regional structural – mechanical stratigraphy.

Figure (5) is a seismic profile passing across typical structures of Kirkuk region. The profile shows three distinct structural – mechanical groups. The lower one is represented by the carbonates and sandstones of the Early Miocene and older rock units, forming a relatively thick "Competent Group". The middle is a "Mobile Group" represented by the salt rich lower part of Fatha Formation, which acted as a detachment surface, and the upper one represented by the clastics dominated sediments of upper part of Fatha, Injana, Mukdadiya and Bai Hassan formations forming a "Passive Group" over the detachment surface of the mobile group.

It is clearly seen that the structures above and below the mobile unit are decoupled and the mobile unit has acted as a basal detachment surface. The top of the Competent Group deformed as simple rounded anticlines, whereas the Passive Group deformed by folding and thrusting that is not directly linked to the structures below, and a tectonic decoupling is clearly observed (Fig.5).

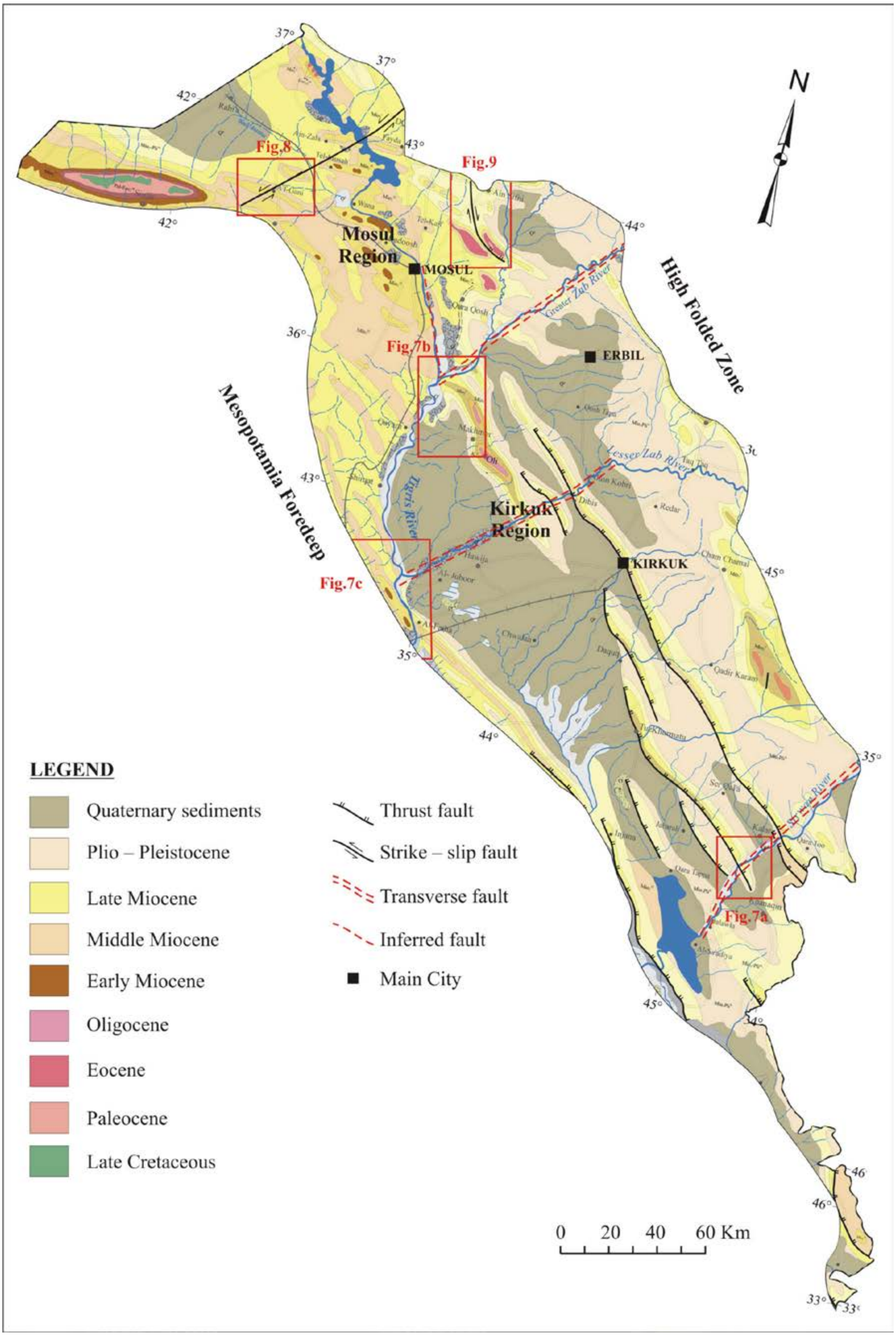


Fig.4: Geological map of the Low Folded Zone. Red rectangles show location of text figures (after Sissakian and Fouad, 2012)

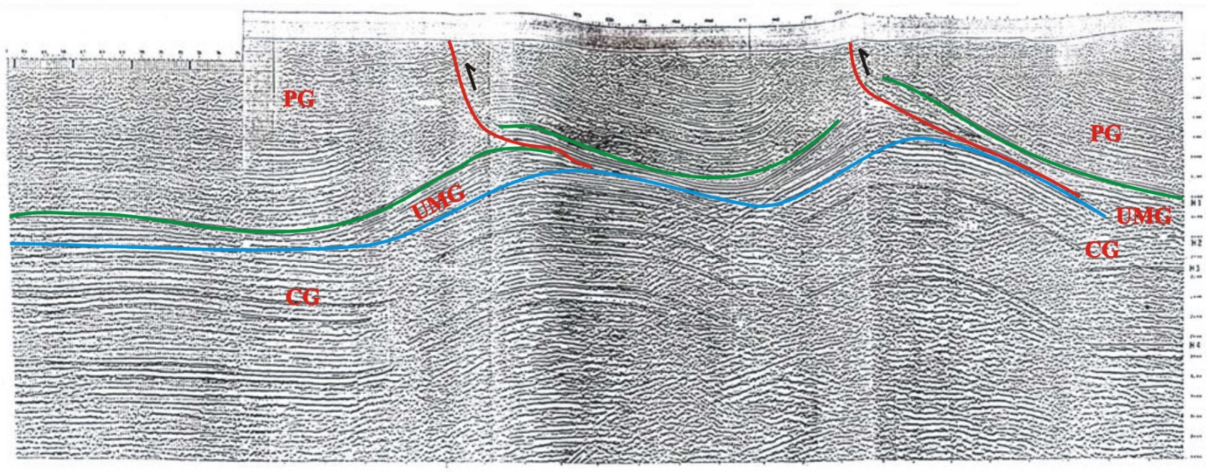


Fig.5: Seismic profile across a pair of anticlines in Kirkuk region
— Marker within Fatha Fn. — Marker denoting top of Competent Group — Thrust Fault
CG: Competent Group **UMG:** Upper Mobile Group **PG:** Passive Group

The Competent Group is not exposed within Kirkuk region except at Qara Chouq anticline, where the top of the group represented by the Late Miocene and Oligocene resistant carbonates are nicely exposed as a typical Dahilstrom's (1969) "whale back" concentric fold.

The thrust faults seem to have initiated at the back limbs of the structures within the salt horizons of the lower part of the Mobile Group, propagating almost parallel to the bedding for considerable distance, then stepping up and cutting through the Passive Group at high angle near the crests, advancing toward the forelimb then to the surface, where the faults reach their maximum dip.

Thickness variation of the Mobile Group is frequently observed across the structures of Kirkuk region. In Figure (5), lateral flow of the evaporites away from the anticlinal crest and over thickening towards the adjacent synclines is well imaged. This "against the rule" migration of the evaporites, seems quite common through the Zagros. It was first observed by O'Brien (1957) in Dezful and Dunnington (1962) in Kirkuk, then it was confirmed by many others in the recent year as a result of increasing seismic and exploration well data (Emami *et al*., 2010 and Verges *et al*., 2011).

– **Folds of the west Tigris River (Mosul region):** Folds in Mosul region exhibit the following structural characteristics:

- The folds have low length to width aspect ratio in general. The ratio rarely exceeds 5, and the folds fall within the brachy folds category of Jaroszewski (1984). Few exceptional cases do exist.
- The folds are northwest – southeast trending in the southern part of the region, but change to east – west direction in the northern part. The folds are asymmetrical to slightly asymmetrical with southwestern and south vergence. Opposed vergence exists too (e.g. Sinjar anticline).
- The folds are not associated with thrusting, and there is on thrust faults are observed at the surface.
- The evaporitic content of Fatha Formation (i.e. The Upper Mobile Group) lacks totally the salt facies.

Seismic profiles in Mosul region show that almost all folds are structural highs that have had originated above an initial structural lows (i.e. grabens, half-grabens and fault blocks). Eventually, they are considered as inversion structures (Peel and Wight, 1990; Fouad, 1997 and Fouad and Nasir, 2009).

Figure (6) shows a seismic profile across one of south Mosul region anticlines. As is the case in almost all of the structures of Mosul region, the stratigraphic sequence can be broadly subdivided into three tectono-stratigraphic groups: pre-rift, syn-rift and post-rift. The pre-rift group, which had deposited prior to any extensional movement, exhibits unchanged thickness across the initial fault bounded trough, whereas the syn-rift group displays abrupt thickness change across the trough pointing to that the deposition took place during the period of the active subsidence of the fault bounded trough (Fig.6). The post-rift group, which have deposited after the cessation of active trough subsidence displays unchanged thickness across the structure (Harding, 1985 and Cooper and Williams, 1989).

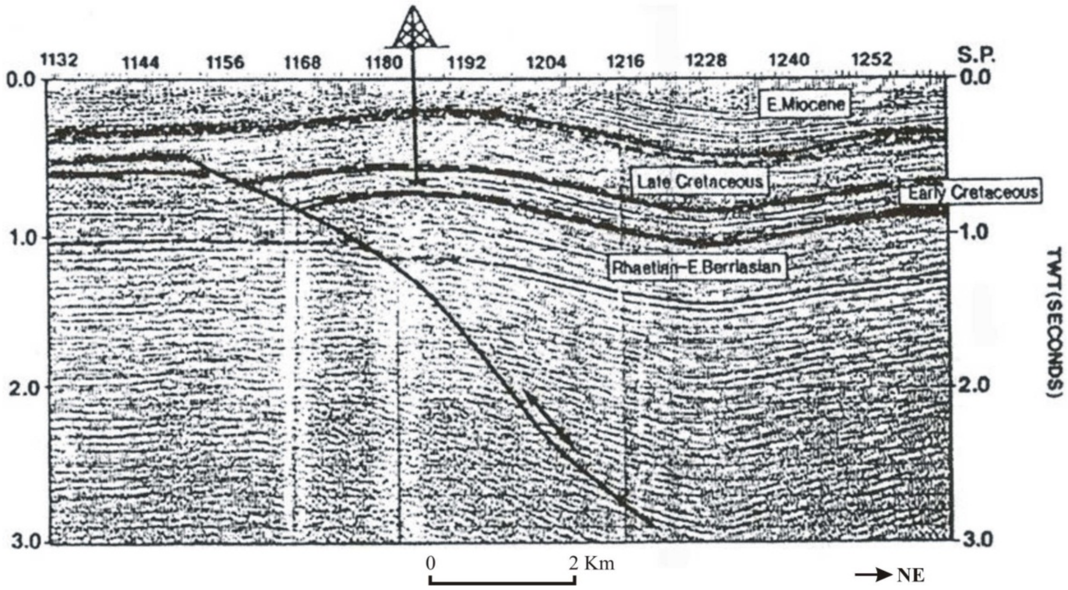


Fig.6: Seismic profile across of Mosul region inverted half-grabens, with Late Cretaceous syn-rift sedimentary sequence (after Peel and Wright, 1990)

Exploration wells and seismic data gathered from northwest Iraq and northeast Syria indicate that the pre-rift group consists of the pre-Late Cretaceous and older rock units, and the syn-rift group consists of Campanian – Maastrichtian Shiranish Formation (or equivalent rock units), whereas the post-rift group consists of the Tertiary rocks units (Lovelock, 1984; Peel and Wright, 1990; de Ruiter *et al*., 1994; Fouad, 1997; Fouad and Nasir, 2009 and Brew, 2001).

It is important to note that Upper Mobile Group in Mosul region appears no longer efficient to from an active detachment surface. Fatha Formation, which forms the Upper Mobile Group in Kirkuk behaves differently in Mosul region, where it appears to confirm exactly to the shape of underlying structures and there are no decoupling observed (i.e. structural disharmony). The absence of rock salt within the sequence of the formation is the reason to this behavior. Accordingly, the classical structural – mechanical stratigraphic classification of Zagros stratigraphy is not valid in Mosul region of the Low Folded Zone, due to the significant lithological changes of the stratigraphic sequences, which have resulted in the absence of both lower and upper mobile groups.

▪ **Faults**

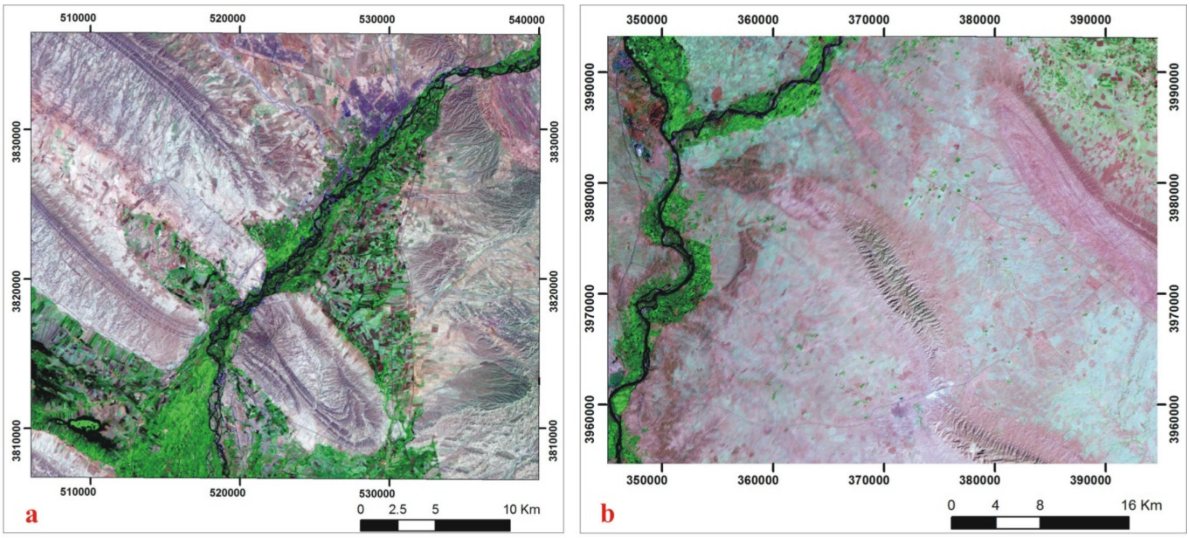
Regional faults in the Low Folded zone were classified according to their geometric relationship with respect to the trend of the mountain front of the belt into three categories; longitudinal, transverse and oblique faults.

─ **Longitudinal Faults:** Regional NW – SE trending, strike-parallel faults are usually thrust faults. They are well developed in Kirkuk region (Fig.4). The faults normally initiated as bedding thrust at the back limbs of the associated folds, within the salt beds of the Upper Mobile Group (Fatha Formation) propagating towards the crest of the structures, then steeply stepping up cutting through the Passive Group towards the surface. Thrust faults in Kirkuk region usually extend for long distances (up to 250 Km) with displacements between few hundred of meters up to more than 5 Km. It is important to mention that no regional thrust faults were recorded at the surface in Mosul region of the Low Folded Zone.

The Competent Group within Kirkuk region have had accommodated the tectonic shortening mainly by simple buckle folding, whereas the Mobile and the Passive groups responded by folding, flowage and thrusting producing decoupling and tectonic disharmony above and below the detachment surface (Fig.5). When the displacement of the thrust fault is large enough, a complete decoupling may occur, and the structures above the detachment cannot be directly linked to the structures of the Competent Group below. This complication in the geometry between surface and subsurface structures may impose additional difficulties in hydrocarbon exploration in Kirkuk region of the Low Folded Zone.

─ **Transverse Faults:** The Low Folded Zone is transected by three major transverse faults tending NE – SW perpendicular to the trend of the mountain front of belt (Fig.4). Because the fault traces running parallel to the regional slope of the belt, they have provided deep valleys and channels that have been occupied by persistent river courses. These faults are named hereafter, from north to south; Upper Zab (Greater) River Fault, Lower Zab (Lesser) River Fault and Sirwan River Fault. These faults may reflect complex history of movements and activities. Moreover, on the surface, it is hard to determine the exact displacement type(s) that took place on them due to the severe erosion that occurred on their traces. Therefore, indirect structural and morphological criteria were used to identify these faults. Among these criteria are:

- The sharp change in the style and geometry of some folds when passing across such faults. Figure (7a) clearly displays such change, where Naodoman and Pulkhana anticlines passing across Sirwan River Fault.
- The clear deflection in the trend of fold axes when crossing (e.g. Barda Sur and Chia Surkh anticlines across Sirwan River Fault), or approaching [e.g Qara Chouq North near Upper Zab River Fault, (Fig.7b)] these Faults. Fold axis deflection in line with the trend of the faults were recorded too, [e.g. Makhul anticline axis deflection in line with the trend of Lower Zab River fault, (Fig.7c)].
- Marked topographic elevation difference of the crestal line of the same fold on both sides of the fault.
- The distinguished linearity of their traces and the sharp angular (almost perpendicular) geometric relationship against the local fold structures [e.g. Lower Zab River Fault against Kirkuk, Bai Hassan, and Qara Chouq anticlines, (Fig.4)].



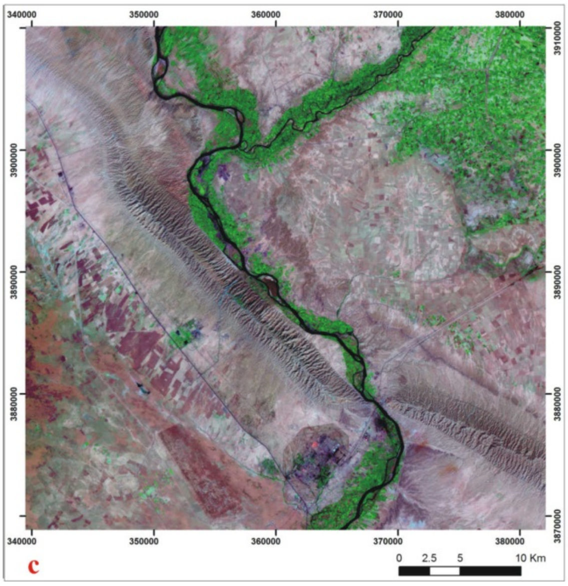


Fig.7: Satellite images showing

a: sharp change in fold geometry across Sirwan River Transverse Fault.

b: fold axis deflection close to Upper Zab River Transverse Fault.

c: fold axis deflection in line with the trend of Lower Zab River Transverse Fault.

See Fig. (4) for location

― **Oblique Faults:** This category of regional faults include those which are neither parallel nor perpendicular to the trend of the mountain front of the belt, but are oblique to it with different angles.

- Baikhair – Sasan Fault is the major oblique trending fault that cross-cut almost the entire Low Folded Zone, in Mosul region. It is a NE – SW trending, 90 Km long left-lateral strike-slip fault, extending between Baikhair anticline at the north and Sasan anticline at the south (Fig.4). The left-lateral displacement is between (200 – 300) m as measured on the displaced axis and limbs of Baikhair and Qusair anticlines (Al-Mosawi, 2002) the fault have had effected the folds of the region by different ways (Fig.8). The effects can be observed through; the actual displacement and truncation of fold axis and limbs (Baikhair and Qusair anticlines); deflection of fold axis trend (Ain Zala and Zainiyat anticlines); sudden termination of folds against the fault trace (Ravan and Butmah West anticlines) and drastic change of fold geometry across and/ or adjacent to the fault (Shkaft and Sasan anticlines).

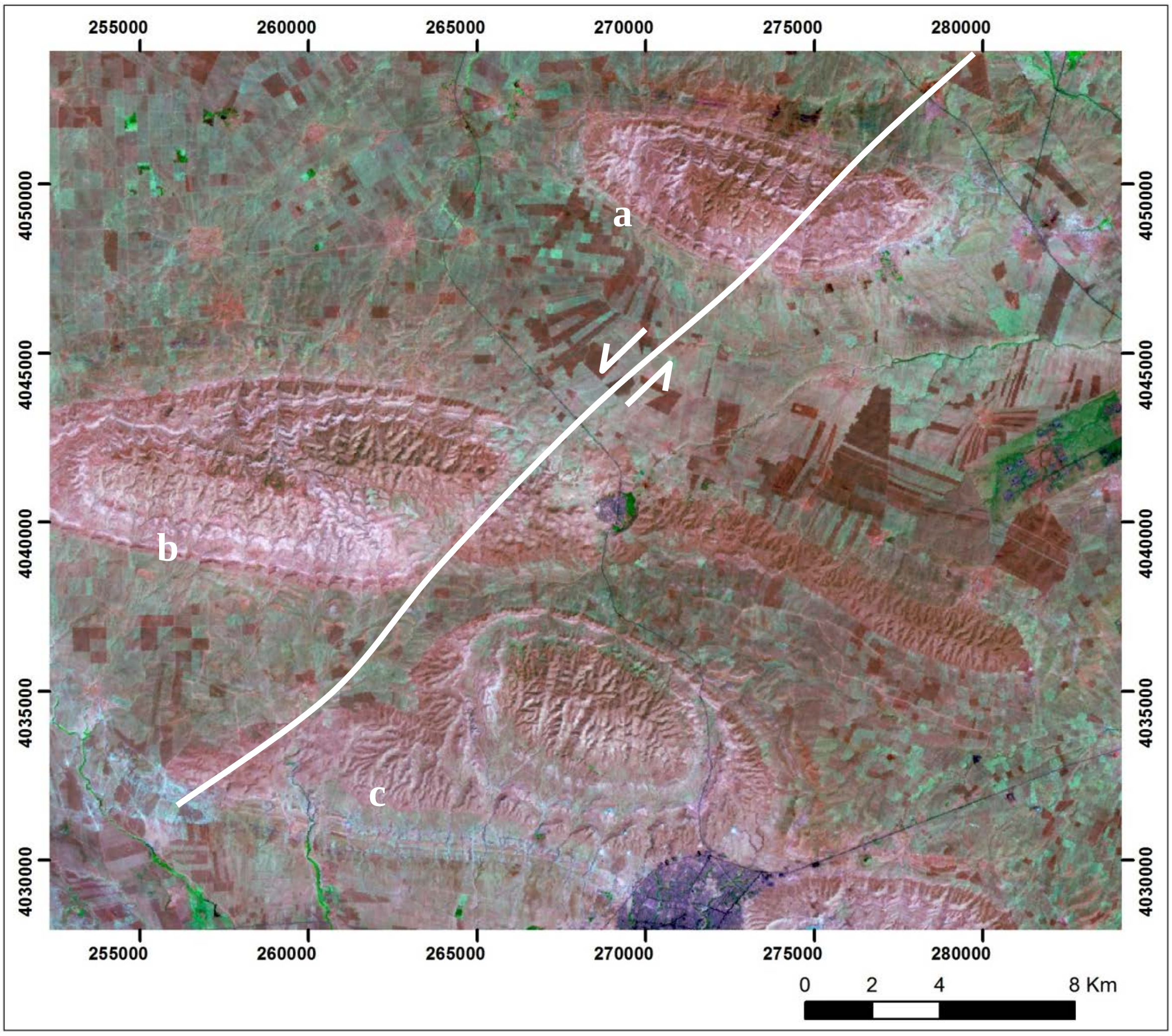


Fig.8: Satellite image showing Baikhair – Sasan left-lateral strike-slip fault. Note the displaced axes and limbs and sharp changes in fold geometry across the fault,
a) Qusair, **b)** Shkaft, and **c)** Sasan anticlines

- A right-lateral strike-slip fault might be inferred indirectly along the Tigris River course. The fault, which is trending NNW – SSE, extends 40 Km between Mosul City to the junction with the Upper Zab River (Fig.4). The presence of series of en-echelon arranged folds along the western bank of the river that terminate sharply against the river course without any structural continuity on the other bank, as well as the marked topographic elevation difference (20 – 70 m) between the two banks along the faults may support this inference.
- Another NNW – SSE trending right-lateral strike-slip fault (Ain Sifni Fault) can be traced for about 25 Km between Gully Keer anticline (within the High Folded Zone) and Maqloub anticline (Fig.9). The fault possibly forms an oblique lateral ramp connecting Shaikhan and Maqloub frontal ramps. The fault may have a restraining bend on which an abnormally N – S trending anticline has developed upon (Fig.9). Displaced limbs and axes as well as changes in fold geometry and style are common structural features that can be observed along the fault.

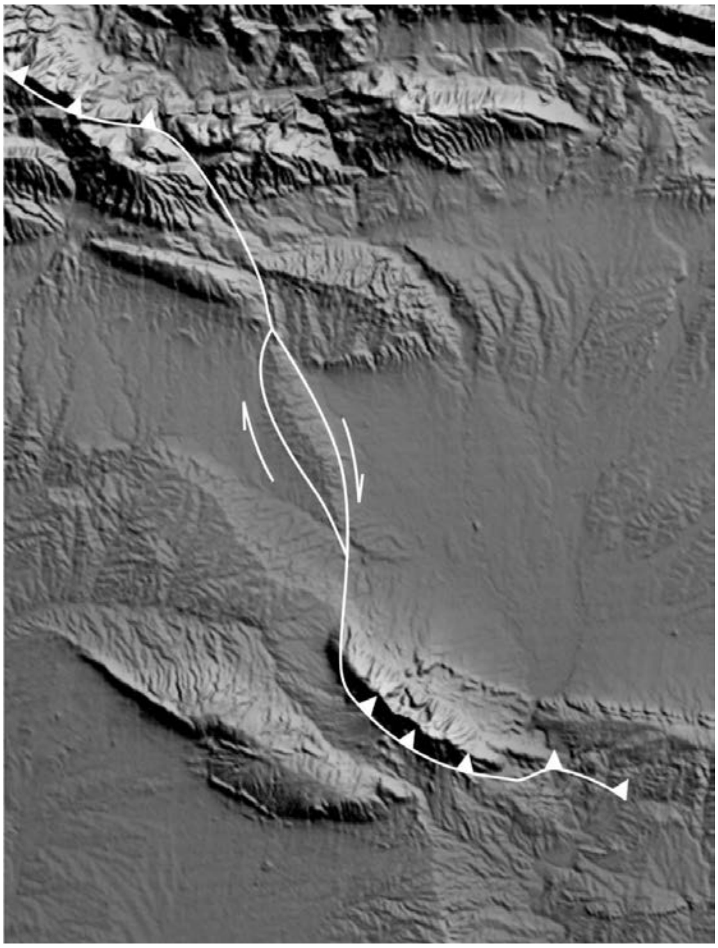


Fig.9: Ain Sifni strike-slip fault, which extends between Shaikhan and Maqloub frontal ramps. The abnormal N – S trending anticline in between, might have developed upon a restraining bend along the fault

TECTONIC AND STRUCTURAL EVOLUTION

Late Cretaceous convergence and ophiolite – radiolarite obduction on the Arabian Plate, resulted in the deformation of the northern Arabian Plate passive margin and the formation of an epicontinental foreland basin in front of the advancing napps (Kazmin *et al*., 1986; Peel and Wright, 1990; Alavi, 2004; Bahroudi and Koyi, 2004; Cascillo *et al*., 2009; Fouad, 2010 and Leturmy and Robin, 2010).

The sedimentary pile of the Western Zagros (including the Low Folded Zone) is therefore can be broadly split up into three major assemblages, when their geological setting at the time of deposition is concerned. The assemblages are: Late Proterozoic – Late Paleozoic Gondwana intraplate assemblage, Late Permian – Early Cretaceous Neo-Tethys passive margin assemblage, and Late Cretaceous – present foreland basin assemblage (Fouad, 2010).

The Late Proterozoic – Late Paleozoic assemblage is neither exposed nor reached by boreholes in the Low Folded Zone. Lick wise the rest of Arabia, however, is dominated by siliciclastics and shales that have deposited in a shallow epicontinental sea in a relatively stable conditions (Beydoun, 1991; Alsharhan and Nairn, 1997; Sharland *et al*., 2001 and Fouad, 2007 and 2009). The Late Permian – Early Cretaceous, Neo-Tethys passive margin assemblage is not exposed too, but being reached by few deep boreholes in the zone. It is dominated by carbonates with subordinate sandstones, shales and evaporites. The deposition of this assemblage took place in an abnormally wide, continually subsiding passive margin covered by shallow open sea. Finally, the Late Cretaceous – Present foreland basin assemblage had deposited over the destroyed Mesozoic Arabian Plate passive margin. The assemblage consists of marine sediments including flysch that grades up in to continental molasse.

Since the onset of the Campanian – Maastrichtian obduction and the following continent – continent collision, the deformation front has migrated from the collisional suture southwestward towards the current position of the Low Folded Zone and the Mesopotamia Foredeep. This implies that the earlier platformal and marginal as well as the foreland basin sedimentary units were progressively incorporated into the deformed belt of the Western Zagros. Accordingly, the manner in which deformation evolved is considered to be in sequence, and a forward developing series of fold initiation and growth is concluded. The progressive decrease in the magnitude of deformation from northeast to southwest towards the foredeep and the associated decrease in the relative age of folding in the same direction strongly support this inference, though exceptional cases do exist. Similar conclusions were reached in the Zagros Mountain range of southwest Iran (e.g. Berberian, 1995 and Emami *et al*., 2010). The Low Folded Zone contains a large number of folds of variable length, width and geometry reflecting that more than one causative mechanism were operative during fold evolution and growth.

Folds in Kirkuk region of the Low Folded Zone are long, narrow and disharmonic structures, and often associated with thrust faulting. When the mechanical properties of the sedimentary pile is considered, the deformed stratigraphic sequence can be subdivided into three mechanical – structural groups. The groups are: **1)** a lower "Competent Group" that have been folded as rounded, gentle to open simple compressive buckle folds; **2)** a middle salt rich "Mobile Group" that have been affected by flowage to be mobile enough to form a regional detachment surface capable to decouple the deformation in the underlying Competent Group and the overlying Passive Group; and **3)** an upper synorogenic molasse based "Passive Group" that have accommodated the shortening by folding and thrusting with little relationship to the structures below. Therefore, the classical mechanical – structural grouping of the Zagros stratigraphy of southwest Iraq could only be particularly applicable in Kirkuk region of the Low Folded Zone, though the Lower Mobile Group (Hormuz salt) is absent, or at least not confirmed to be present below the Western Zagros Fold – Thrust Belt (Fouad, 2012b). Nevertheless, the properties of these three mechanical – structural stratigraphic groups appear to have had governed the deformation style and the fold – fault evolution in Kirkuk region.

Thrust faults associated with the folds in Kirkuk region always appear to have initiated at the back limbs of the folds within the salt rich horizons of Fatha Formation as bedding thrusts. The faults usually propagate towards the crest and the forelimbs, where they stepping up sharply when cutting through the Passive Group before reaching the surface. Displacements on the thrust faults in Kirkuk region vary from few hundred of meters up to few kilometers. When the displacement of the thrust is large enough, a complete decoupling above and below the detachment surface may occur, producing a quite considerable shift between surface and subsurface structures. An example to this case occur between Pulkhana and Qumar anticlines, few kilometers to the northwest of Kifri town, where the northeastern back limb of Pulkhana anticline is thrusted over the crest and the forelimb of the anticline and stands against the northeastern limb of the adjacent Qumar anticline, hiding the in between syncline beneath it. Displacements on the thrust faults are exclusively southwestward, in the direction of the tectonic transport, toward the foreland. No back thrusting is recorded at the surface in the region, though minor pop-up structures were recorded in the Competent Group only (Kent, 2010). Thrust faults displacements, however, reach their highest magnitude in the central parts of the faults, but decrease laterally toward the tips of the faults, then replaced by folds where the faults die out, it is important to note that the mobility of Fatha Formation is directly linked to the amount of the rock salt within its strata. The higher the content, the higher the mobility, and eventually higher tectonic disharmony. Increasing thrust displacement and tectonic disharmony toward the southeastern part of Kirkuk region, is a function to the increasing content of the rock salt within the formation in that direction.

Folding and thrusting are not simultaneous processes. Thrust initiation and propagation is more likely to have occurred during the late stages of fold evolution as folds start to lock up. Continued shortening then, is most probably accommodated by thrust fault development. Folding and faulting are not coeval and that folding preceded fault development have been inferred in several places in the Zagros Mountain range (Sherkati *et al*., 2005; Burberry *et al*., 2010 and Verges *et al*., 2011).

Folds in Mosul region of the Low Folded Zone are significantly different from those in Kirkuk region. The folds in Mosul region are relatively short, broad, and not associated with thrust faulting. Lithological changes took place on Fatha Formation have resulted in total disappearance of rock salt from its sequence in Mosul region. Consequently, the formation appears not capable to form regional detachment. In other words, the "Upper Mobile Group" is no longer exists in Mosul region, and that the overlying Passive Group appears completely coupled to the structures below and no structural disharmony exists anymore. This intern implies that the classical regional mechanical – structural grouping of the Zagros stratigraphy of southwest Iran is not valid in Mosul region of the Low Folded Zone of the Western Zagros (Fouad, 2012b).

Folds in Mosul region of the Low Folded Zone are mostly structural highs above earlier structural lows, defining typical inversion structures (Fig.6). As an inversion structure, the folds must have had formed in two discrete deformational episodes, an early episode of extension and rift formation, followed by an episode of compression and fold formation (Harding, 1985 and Cooper and Williams, 1989). During extension and rift formation, the "pre-rift" sedimentary sequence in the hanging wall block are downthrown. As the sediments continue to deposit during fault movement and basin subsidence, the resulting trough is progressively filled by the "syn-rift" sequence. Post-rift sedimentary sequence usually deposited after cessation of active fault movement and trough subsidence. Tectono-stratigraphic sequences inferred from seismic and well data indicated that the extension took place during the Campanian – Maastrichtian age (Daly, 1990; Peel and Wright, 1990 and Fouad, 1997). This finding point out to the fact that during the Late Cretaceous, where the Arabian Plate margin was under compression due to the continental convergence and ophiolite obduction, the distal part of the newly formed foreland basin, including the present day Low Folded Zone and the Mesopotamia Foredeep of the northern Arabian Platform (Fouad, 1997 and Fouad and Nasir 2009) was under regional stretching. The stretching was enough to generate systems of intracontinental fault bounded rift basins in the form of grabens, half-grabens, and fault blocks troughs (Lovelock, 1984; Daly, 1990; de Ruiter *et al*., 1994; Fouad, 1997; Fouad and Nasir, 2009 and Brew, 2001). The extension, however, was much more pronounced in Mosul region than in Kirkuk region of the Low Folded Zone.

Structural inversion of the Late Cretaceous structural troughs occurred during the Plio – Pleistocene compression associated with final continental collision of Arabian and Eurasia Plates. The inversion achieved by the reverse reactivation of the trough bounding normal fault and the extrusion of basin fill, and eventually the formation of compressional fault-propagation folds above the former troughs. Therefore, the shape, size, trend, and location of the folds in Mosul region are largely controlled by the shape, size, trend and location of the initial underlying extensional structural troughs (Fouad, 1997 and Fouad and Nasir, 2009).

The trend and the geometrical relationship of the strike-slip faults in the Low Folded Zone are quite compatible with the direction of the tectonic transport direction in the zone. The direction of the tectonic transport, or in other words the direction of the maximum regional compression, can be determined using the average trend of the regional scale features including major thrust and first order fold trends (Elliott, 1976 and Woodward, *et al.*, 1989). The direction on the regional compression is NE – SW in the southern and the central parts of the Low Folded Zone, whereas, it is N – S in the western part of the zone. The trend of the strike-slip faults in the zone are usually at an acute angles to the direction of the regional compression. On the other hand, however, the trend of the transverse faults in the Low Folded Zone coincides with the direction of the tectonic transport. Accordingly, the faults were considered basically as extensional faults accommodating the belt parallel elongation produced by the belt perpendicular compression and shortening. Extensional structures perpendicular to the mountain front are well documented in many orogenic belts of the world (Park, 1988). However, minor strike and/ or oblique slips adjustment may took place on the transverse faults during the structural evolution of the zone.

As mentioned earlier, thrust faulting seems to have formed during the late stages of fold evolution in the Low Folded Zone. Nevertheless, the strike-slip and the transverse faults in the zone exhibit a relatively more complicated fold – fault age relationships. Evidences such as significant changes in the fold style across the faults, ductile bending of fold axes and limbs as well as sudden termination of fold against the fault traces may indicate that the faults (or at least part of it) have formed during the early stages of fold evolution, or even earlier. Other evidences, on the contrary, such as sharp fold axis and limbs truncation and displacement without association of any ductile deformation indicate that the faults may have formed during the late stages of fold evolution, or even latter. Such complicated fold-fault age relationship, however, could be observed even along different parts of the same fault.

The main folding episode of the Low Folded Zone occurred during the Plio – Pleistocene time as inferred from the deformed syn-tectonic molasse of Bai Hassan Formation (formerly known as Upper Bakhtiari Formation) and the associated sedimentary sequence. Nevertheless, several geological criteria indicate that the zone is neotectonically active and the deformation is still operative at the present time. Tilted and faulted Quaternary river terraces on the flank of Khanuga anticline (Fig.10) provide a striking evidence on the recent folding activity in the zone (Fouad, 2002). Other evidences, such as abandoned stream channels (wind gaps), deflected drainage systems, systematic fracturing of Holocene gypcrete and gypsious soil, were also recorded. Neotectonic activity, however, will be discussed in separate article.

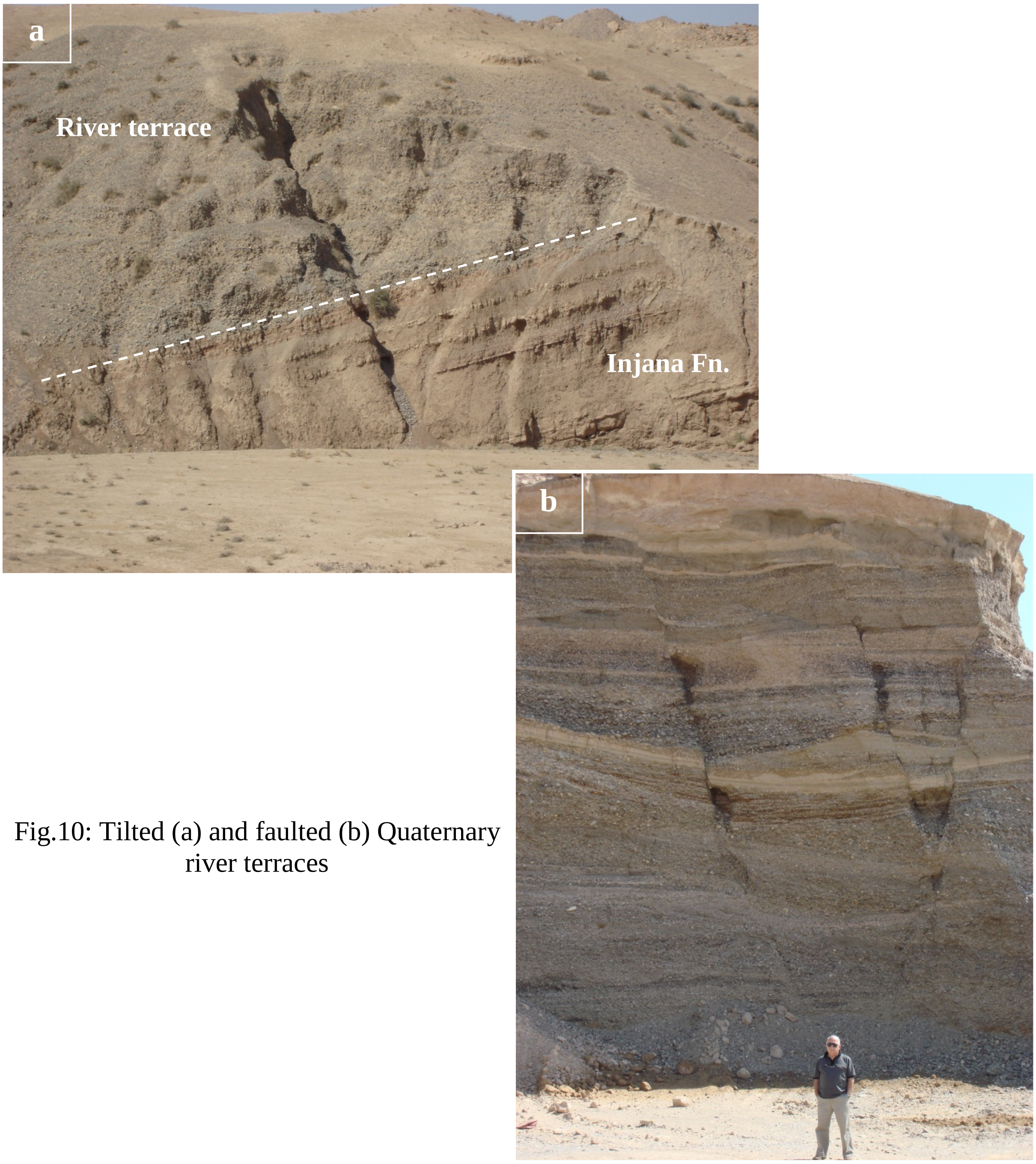


Fig.10: Tilted (a) and faulted (b) Quaternary river terraces

CONCLUSIONS

- The Low Folded Zone is an integral part of the Western Zagros Fold – Thrust Belt. It is bounded from the northeast by the prominent mountain front of the High Folded Zone, and from the southwest by the relatively flat terrains of the Mesopotamia Foredeep. These tectonic boundaries are well established along the entire length of the Zagros orogenic belt from southeast Turkey through Iraq to southwest Iran.
- The Low Folded Zone contain large number of folds with variable sizes, geometries and distribution along and across the zone. Nevertheless, the folds could be broadly categorized into two assemblages with different structural characteristics. The first occurs to the east of

the Tigris River within Kirkuk region, whereas the second to the west of river within Mosul region of the zone. The variation is directly related to two factors, the nature of mechanical properties of the folded sedimentary pile, and to the presence or absence of early formed structural lines of weakness within the body of the Arabian Platform.

- Folds in Kirkuk region are long, narrow and disharmonic structures that are often associated with thrust faults. Seismic profiles and geological cross-sections revealed that the folded sedimentary sequence exhibit three distinct structural – mechanical groups. **1)** a lower "Competent Group" built up by Early Miocene and older carbonate dominated sediments that have responded to the regional compression by buckling to form simple rounded folds; **2)** an upper "Passive Group" dominated by Middle Miocene to Pleistocene sallow marine to continental syn-tectonic clastics (molasse) that have accommodated the shortening by folding and thrusting; and **3)** a middle salt rich "Mobile Group" capable to flow and to form regional detachment, so that folding and faulting in the upper Passive Group are independent and not directly linked to those in the Competent Group, and consequently a tectonic decoupling and disharmony are observed. However, the efficiency of the detachment is proportional to the amount of the salt in the Mobile Group in particular area.
- Folds in Mosul region are relatively short and broad and not associated with thrusting. The folded sedimentary pile appears completely coupled to each other and no structural disharmony is observed. Most of the folds are structural highs above an earlier structural lows, and consequently they are considered as inversion structures. Structural analysis of tectono-stratigraphic sequences in Mosul region indicate that the folds have had formed in two distinct episodes; an early Campanian – Maastrichtian episode of extension and rift formation, followed by Plio – Pleistocene episode of compression and fold formation.
- The classical structural – mechanical grouping of the Zagros stratigraphy in southwest Iran is not universally uniform and may show considerable variations in the mechanical properties throughout the Zagros region. In the Low Folded Zone of the Western Zagros, however, this grouping can be partially applied in Kirkuk region of the zone, where the salt of Fatha Formation (Lower Fars) is mobile enough to form regional detachment able to decouple the structures above and below it producing distinctive structural disharmony. On the other hand, in Mosul region of the zone, the grouping is totally not valid due to significant lithological changes.
- The type and orientation of the regional faults in the Low Folded Zone are quite compatible with the direction of the regional compression and the direction of the tectonic transport. Thrust faults seem to have developed during the late stages of fold evolution to accommodate shortening as the folds started to tighten. The transverse faults, which are perpendicular to the mountain front are basically normal faults accommodating the belt parallel elongation. These faults, however, may have suffered multiple episodes of displacement during the structural evolution of the area. While accommodating the regional shortening, strike-slip faults produced belt parallel elongation too. Nevertheless, such faults exhibit more complicated fold-fault age relationship in the zone.
- The main deformation processes including folding and faulting in the Low Folded Zone took place during the Plio – Pleistocene. The young age of the folds is reflected in the present topography as anticlinal highs and synclinal lows. The manner in which deformation evolved, however, appears in sequence and foreland directed. Moreover, several geological criteria indicate that the Low Folded Zone is neotectonically active and the deformation is still operative at the present time.

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