WESTERN ZAGROS FOLD – THRUST BELT, PART II: THE HIGH FOLDED ZONE

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ABSTRACT

The High Folded Zone is an integral part of the Western Zagros Fold – Thrust Belt of Iraq. It is characterized by the presence of a huge number of NW – SE and E – W trending, high amplitude, short wavelength southwest and south vergent folds. The landforms in the zone are highly structural and reflected on the topography as high rugged anticlinal mountains separated by deep narrow synclinal valleys.

The Folds display wide range of geometries and sizes, reflecting that more than one folding mechanism is possibly responsible for their initiation and development. Judging by their style and geometry, simple buckle folds, generated by flexural-slip and neutral-surface folding mechanisms, as well as fault-propagation folds appear to dominate fold types in the zone.

Significant topographic and structural relief is clearly observed across the boundary between the High Folded and Low Folded zones of the belt. This structural uplift is attributed to the involvement of the basement by thrust faulting beneath the sedimentary cover, and the deformation is considered to be a "thick skin" type in the zone.

حزام طي وتصدع زاگروس الغربي، الجزء الثاني: نطاق الطيات العالية

صفاء الدين فخري فؤاد

المستخلص

يعتبر نطاق الطيات العالية جزء من حزام طي وتصدع جبال زاگروس الغربية العراقية. يتميز النطاق باحتوائه على عدد كبير من طيات ذات سعة عالية وطول موجي قصير غير متناظر ومتكئة الى الجنوب والجنوب الغربي. وتتجه محاورها باتجاه الجنوب الشرقي – الشمال الغربي وتتحول تدريجيا الى اتجاه شرق – غرب في الجزء الشمالي من النطاق. الأشكال الأرضية ضمن النطاق ذات طبيعة تركيبية بشكل كبير وقد انعكست على طوبوغرافية السطح كجبال وعرة تشكلها الطيات المحدبة تفصل ما بينها وديان ضيقة وعميقة تشكلها الطيات المقعرة.

تبدي الطيات مدى واسعا من الأحجام والخواص الهندسية وهذا يعكس احتمالية وجود أكثر من ميكانيكية طي واحدة مسؤولة عن نشوئها وتطورها. واعتمادا على الطراز والخواص الهندسية يبدو أن الطيات الناتجة عن الطي الانضغاطي المنجز عن طريق ميكانيكيتي الانزلاق الانثنائي والسطح المتعادل إضافة الى تلك الناتجة عن تقدم الصدوع هي أكثر أنواع الطيات انتشارا في النطاق.

هناك فرق ارتفاع طوبوغرافي وتركيبي كبير يمكن ملاحظته على طرفي الخط الفاصل بين نطاقي الطيات العالية والواطئة. هذا الارتفاع قد اعزي الى شمول صخور القاعدة بالتشويه والتصدع العكسي تحت الغطاء الرسوبي.

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INTRODUCTION

The Western Zagros Fold – Thrust Belt (WZFTB) of the Iraqi territory is an integral part of the Zagros Orogenic system that extends more than 1800 Km from the Bitlis suture zone of south Turkey in the northwest to the boundary with the Makran accretionary wedge of southwest Iran in the southeast. The belt, which represents the deformed northeastern margin of the Arabian plate, is the result of the Arabian – Iranian (Eurasian) plates collision. The WZFTB has been subdivided into four subparallel zones with different structural characteristics (Fouad, 2008 and 2012a, b and c). The zones, from southwest to northeast are the Low Folded Zone, the High Folded Zone, the Imbricate Zone, and the Suture Zone (Fig.1). As mentioned in part I (Fouad, 2012), part II of the study is concerned with the structural characteristics of the High Folded Zone only.

The High Folded Zone is about 400 Km long and (25 – 50) Km wide belt (Fig.1), containing a number of topographically high anticlines of different shapes and sizes trending NW – SE in the eastern part of the zone, and E – W in the northern part.

GEOLOGICAL SETTING

The High Folded Zone is limited to the north and northeast by the Imbricate Zone and to the south and southeast by the Low Folded Zone (Fig.2). The zone extends from the Iraqi – Iranian borders where the folds are tending NW – SE, but gradually changes to E – W as the folds continue northwards towards the Iraqi – Turkish borders. The Zone contains a number of high amplitude, short wavelength anticlines with different dimensions. The folds are generally close to tight, asymmetrical with southwest and south vergence. Folds with vertical and overturned limbs are common in the zone too. Local thrust faults are found associated with the steep southeastern and southern limbs of some anticlines whereas regional surface faulting are absent in the zone. The landforms in the zone are largely structural, so that the erosion resistant Cetaceous rock units dominate the topography forming high rugged anticlinal mountains separated by deep and narrow synclinal valleys.

The boundary between the Low Folded Zone and the High Folded Zone is delineated along the western limb of Sharwaldar anticline along the Iraqi – Iranian borders, extending north towards Bammo anticline where it sharply changes to northwest direction following the southwestern limbs of Qara Dagh, Khalikan, Bana Bawi, Permam anticlines, then swings westerly following the southern limbs of Peris, Aqra, Gally Keer, Alqosh, Dohuk and Bai Khair anticlines (Fig.2).

It is important to mention that the boundary form a prominent regional physiographic – morphological step across which a strong topographic and structural relief change occurs, where low topography occurs to the southwest and high topography to the northeast (Fig.2). This regional front, which coincides with the exposures of the resistant carbonates of the Pila Spi Formation, is well persistent along the entire length of the Zagros range from Iraq to Iran and thought to have been formed above a major basement blind thrust fault (Berberian, 1995). The front is not straight, when viewed from above, and shows some irregularities defining tectonic salients (arcs) and re-enterants (embayments). Two arcs and one embayment occur in Iran, and one embayment (Kirkuk Embayment) occur within the Iraqi territory. Along the Zagros mountain range, however, this front is known by many workers by different names such as, Zagros Mountains Front (Berberian, 1995), Zagros Frontal Fault (Burberry *et al*., 2010), and Mountain Front Flexure (Emami *et al*., 2010, and Verges *et al*., 2011). The boundary with Imbricate Zone (Fig.2), on the other hand, is less clear in the eastern part and thought to pass through Sirwan gorge extending northwest towards Azmur anticline then swings more to the north towards Qalat Diza, Sanga Sar towns, extending northwest following Zozik, Bradost anticlines, towards the Shamdainan River then to the vicinity of Sanina village then swings westerly towards the Greater Zab and Khabour rivers, and continues westwards following the southern limb of the giant Ora anticline towards the Iraqi – Turkish borders. The boundary is delineated along the appearance of the first thrust fault of the regional imbricate thrust fan system in the area.

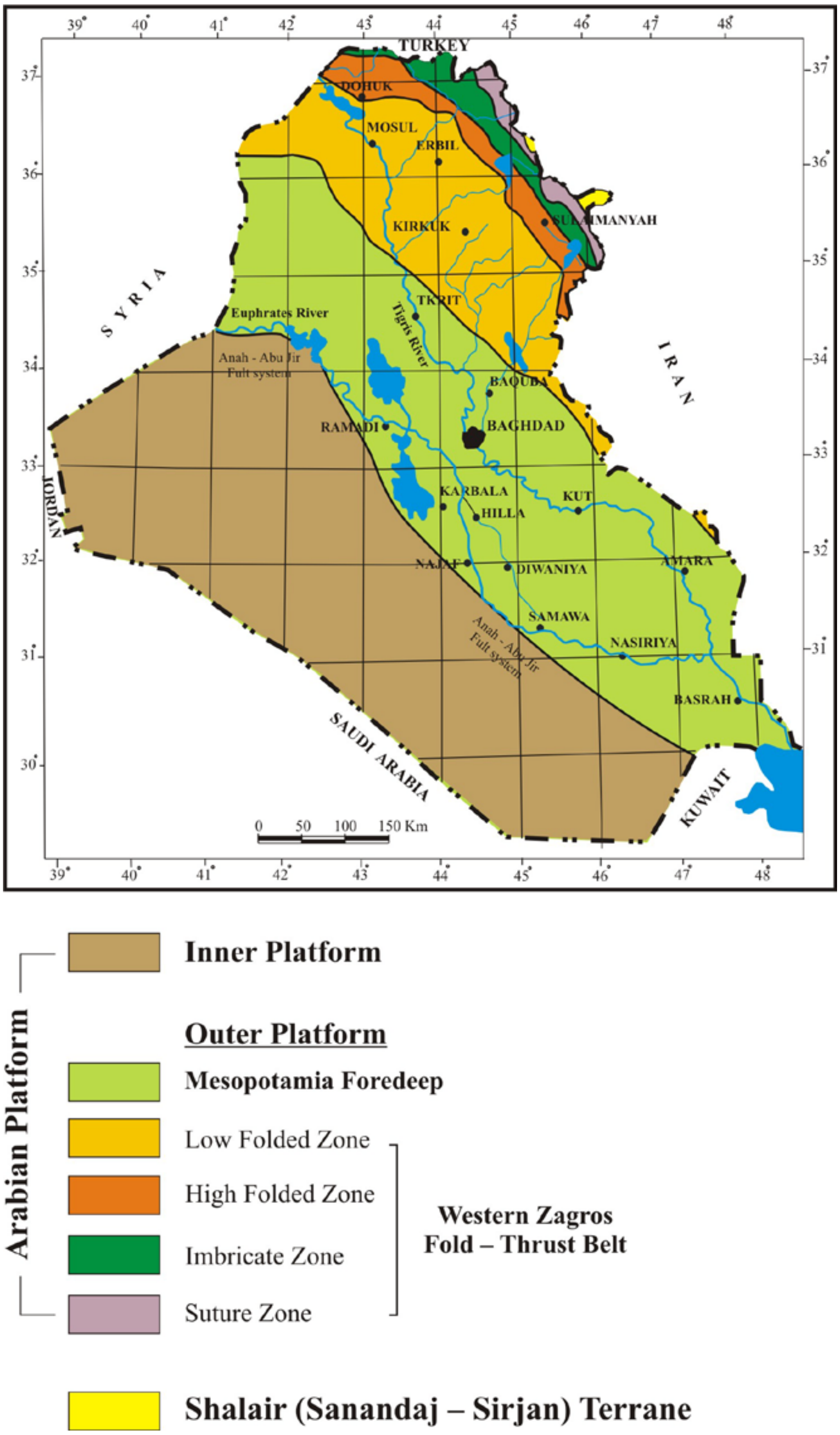


Fig.1: Tectonic divisions of Iraq (after Fouad, 2008 and 2012a)

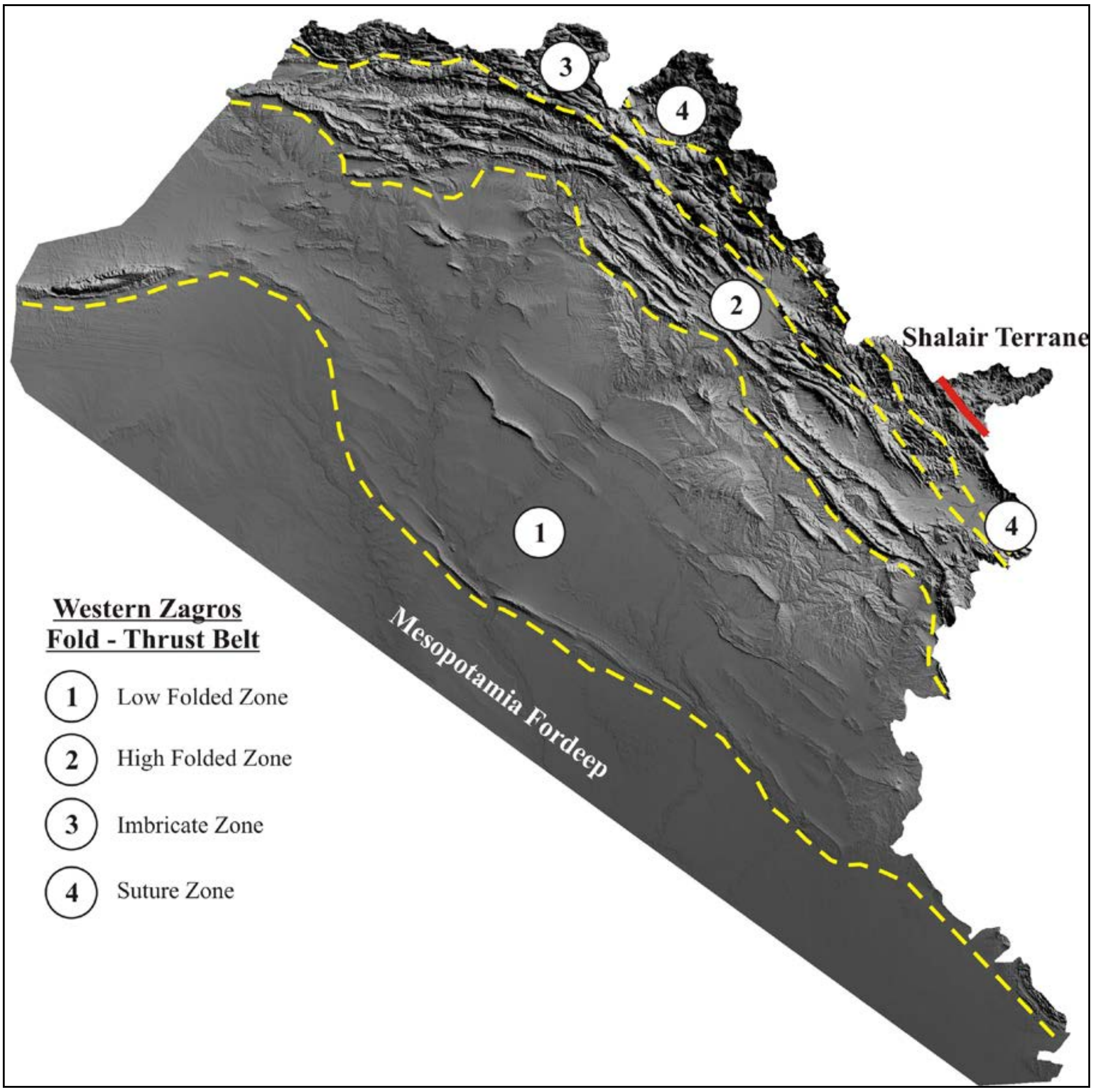


Fig.2: The tectonic subdivisions of the Western Zagros Fold – Thrust Belt
1) Low Folded Zone, **2)** High Folded Zone, **3)** Imbricate Zone, and **4)** Suture Zone
(after Fouad, 2008 and 2012a)

STRATIGRAPHY

The basement is neither exposed nor penetrated by any borehole in the High Folded Zone. The average depth of the basement has been estimated by Jassim and Goff (2006) to be (~ 8) Km. This implies that the basement is shallower in the High Folded Zone as compared to its depth in the Low Folded Zone.

Paleozoic and Early Mesozoic rock units are not exposed in the zone. Data from exploration wells deep enough to reach these rock units is not available too. The Paleozoic sequence, however is estimated to be ~ 4500 m thick (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; Beydoun and Huges Clark, 1992; Alsharhan and Nairn, 1997; Brew, 2001; Sharland *et al*., 2001, and Alavi, 2004), the Paleozoic sequence is dominated by siliciclastic sediments deposited in a relatively stable shallow marine conditions.

The Mesozoic is (3000 – 6000) m thick sequence of carbonates, marls and subordinate clastics. Cretaceous and Jurassic rock units are widely exposed, whereas only the uppermost part of the Triassic rocks units (Baluti formation) is exposed in a very limited parts of the zone. The Jurassic sequence is represented by 300 m thick carbonates of the Liassic Sarki Formation, 180 m of bituminous carbonates of the Late Liassic Sehkaniyan Formation, 120 m of thinly bedded carbonates of the Bathonian Sargelu Formation, 14 m of black laminated carbonates and shale of the Oxfordian – Kimmeridgian Naokelekan Formation, 17 m of laminated and stramotolitic carbonates and chert of the Kimmeridgian Early Tithonian Barsarin Formation, and (200 – 120) m of thinly bedded ammonite rich carbonates and shales of Late Tithonian – Berriasian Chia Gara Formation.

The Cretaceous rock unit is (2000 – 5000) m thick sequence of mainly carbonates, marls and subordinate clastics, assigned to the Valanganian – Hauterivian Garagu, Valanganian – Turonian Balambo, Hauterivian – Barremian Sarmord, Aptian – Early Cenomanian Qamchuqa, Toronian – Early Campanian Kometan, Late Campanian – Late Maastrichtian Aqra – Bekhma, Late Campanian – Late Maastrichtian Shiranish, Late Campanian – Late Maastrichtian Tanjero formations.

The Cenozoic rock units are about (1000 – 3250) m sequence of clastics and subordinate carbonates. The sequence can be divided into two groups; Paleocene – Late Eocene, and Miocene – Pleistocene groups. Paleocene – Late Eocene group is widely exposed in the zone, and consists of clastics and subordinate carbonates. The group, which is 500 – 2250 m thick is assigned to the Paleocene – Early Eocene clastics of Kolosh Formation, Late Paleocene – Early Eocene carbonates of Sinjar Khurmala Formation, Early – Middle Eocene clastics of Gercus Formation, and Middle – Late Eocene carbonates of Pila Spi Formation. Thin (5 – 10) m layers of possibly Oligocene – Early Miocene age were reported too in some scattered localities.

The second group is the Miocene – Pleistocene group, which is (500 – 1200) m sequence dominated by clastics and vary rare carbonates. Rock units of this group are basically exposed along the south and southwestern slopes of the regional topographic step which marks the boundary between the Low Folded Zone and the High Folded Zone and almost absent within the High Folded Zone except in Duhok – Zakho region in the western part of the zone. The sequence, however, is assigned to the Middle Miocene Fatha, Late Miocene Injana, late Miocene – Pliocene Mukdadiya and Pliocene – Pleistocene Bai Hassan formations.

▪ Structure of the High Folded Zone

The High Folded Zone contains a large number of folds with different shapes and sizes, but with higher amplitudes and shorted wavelengths when compared to those of the Low Folded Zone (Fig.2). The folds profile shape ranges from open, close, tight to overturned. The folds generally trend NW – SE in the eastern and the central parts of the zone, but gradually changes to E – W direction as they extend northwestwards towards the Turkish borders. The folds have southwest and south vergence in general and reflected on the surface as high anticlinal mountains separated by deep and narrow synclinal valleys. The anticlines are mostly exposed to the level of the erosion-resistant Cretaceous carbonate rock units that form the carapace of most anticlines.

Early studies on Zagros Mountains Range, which took place in Iran, led to the consideration that the stratigraphic column characteristics had controlled the folding in the belt. The stratigraphic column has been divided into five structural-mechanical groups with different properties (O'Brien, 1950 and 1957, and Dunnington, 1962). The groups, from bottom to top, are; Precambrian Basement Group, Late Infracambrian – Early Cambrian Lower Mobile Group (Hormuz evaporites), Paleozoic – Early Miocene Competent Group, Miocene Upper Mobile Group (Fars Group), and Late Miocene – Pleistocene Passive Group. This grouping was therefore, considered to govern the folding process in the Zagros, so that the two mobile groups have provided an efficient regional detachment surfaces allowing the competent and passive groups to fold independent of each other, while the Basement Group remains largely undeformed. In other words, the detachment folding was considered as the main folding mechanism in the Zagros region.

Since the midle of the last century, however, the Zagros region became the primary oil exploration target due to the discovery of a huge number of large oil and gas fields. Therefore, it became extremely important for the exploration strategies to gain more and more information about the nature of the folds and their behavior at depth since they form the main oil and gas traps of the region. Accordingly a huge field, well and seismic information has been continually added and new interpretations and perspectives were introduced.

It is now become clearly evident that more than one folding mechanism is responsible for fold initiation and growth in the ZFTB, and that each mechanism is reflected more or less on the geometry, size and distribution of the folds in the belt. The competition between factors controlling fold-fault initiation and growth including nature of instabilities, structural-mechanical properties of the sedimentary column, thickness of the folded multilayer, and the strain rate determine which fold style will develop. Thus, a broad spectrum of fold types may occur in the same belt. In recent years, however, several fold styles were recognized within the ZFTB. Among the commonest are detachment folds, simple buckle folds, fault-bend folds, fault – propagation folds, forced folds and inversion folds (Colamn-Sadd, 1978; Blanc *et al*., 2003; Sherkati *et al*., 2005; Sepehr *et al*., 2006; Casciello *et al*., 2009; Burberry *et al*., 2010; Emami *et al*., 2010; Leturmy *et al*., 2010, and Fouad, 2012a, b and c).

The folds in the High Folded Zone of the Western Zagros exhibit a wide range of geometry and dimensions, implying that several folding mechanisms might be responsible for their generation and development. The lack of detailed field measurements and observation, well information and seismic data, however, make the accurate identification of fold style, their behavior at depth and their generating mechanism to be rather a difficult task.

In the following discussion, however, the author will try to highlight fold styles and the candidate folding mechanism(s) for fold initiation and growth in the High Fold Zone of the Western Zagros.

─ **Detachment Folding:** This type is one of the oldest folding styles that have been identified and adopted in southwest Iran (Fig.3), (O'Brien, 1950, 1957, and Falcon, 1969). The presence of an efficient regional detachment surface provided by the ~ 1000 m thick salt of Hormuz Formation allowed the Competent Group to shorten independently of the underlying stiff Basement Group, which considered to remain essentially undeformed. Meanwhile the presence of the second mobile group of Fars evaporates above the Competent Group allowed the overlying Passive Group to fold and fault with little relation to the underlying Competent Group, and tectonic decoupling is evident. Recent studies have shown that Hormuz Salt thins rapidly and display strong lateral lithological variation as it extends northwestwards from Fars region of southwest Iran (Bahroudi and Koyi, 2004; Sepehr and Cosgrove, 2004, and Emami *et al*., 2010), so that its existence is not confirmed within the Western Zagros (Blanc *et al*., 2003, Kent, 2010, and Fouad 2012b and c). In other words, no regional lower detachment is expected beneath the High Folded Zone. Moreover, the evaporites of Fatha Formation which acted as the upper detachment surface in Kirkuk region of the Low Folded Zone of the Western Zagros is totally absent in the zone (Fouad, 2012a, b and c). Consequently, regional detachment folding model is not expected or at least not favorable to be the dominant folding mechanism in the High Folded Zone. Lithologies suitable to form some local or intermediate detachment(s) are present within the stratigraphic column of the High Folded Zone, such as the Jurassic and Early Cretaceous shales. Nevertheless, such lithological rock units do not appear efficient enough to form considerable intermediate detachment surfaces. This fact can be clearly observed when such rock units are exposed in some deeply eroded or incised folds.

– **Buckle Folding:** Buckle folds occur when the layered rock mass is subjected to shortening oriented parallel to the original layering (Ramsey, 1967; Hobbs *et al*., 1976; Spencer, 1977; Suppe 1985; Bogillo-Ares *et al*., 2000, and Groshong, 2006). The Layering has an important mechanical importance in buckle folds, and the orthogonal thickness of the folded layer is maintained unchanged. Buckling produce what is geometrically known as parallel or concentric folds (Ramsey and Huber, 1987, and van der Pluijm and Marshak, 1997).

Simple buckle folding can be achieved by two mechanisms, flexural-slip and neutral-surface folding mechanisms (Fig.3). Flexural-slip folds are folds that form in association with slip between the folded layers (Fig.3). The slip, which is generally perpendicular to the fold axis, is zero at the hinge and maximum at the fold inflection point (Tanner, 1989).

In natural-surface folding, the rock layer folded as if it is stretched (extended) at the outer arc and shortened (compressed) at the inner arc (Fig.3) This implies that, at time of active fold development, there must be a surface in the fold where there is no strain separating the extended outer arcs from the compressed inner arcs. This surface gives the mechanism its name, neutral-surface folding. In such folds the strain is maximum at the fold hinge and decreases away from it.

Both flexural-slip and neutral-surface folding mechanisms produce parallel (concentric) folds. Therefore, parallel folds are diagnostic features of buckling, but not diagnostic for the mechanism by which they are formed; only strain patterns do.

In the High Folded Zone, however, many folds exhibit concentrically folded layered rock units that show no thickness change across the fold. Moreover, such layers contain several minor structures reflecting the occurrence of layer-parallel shearing, whereas their bedding surfaces display numerous slickenside striations oriented towards the fold hinges (Fig.4). Among many, Permam and Alqosh are good examples of such folds, and consequently can be regarded as simple flexural-slip buckle folds.

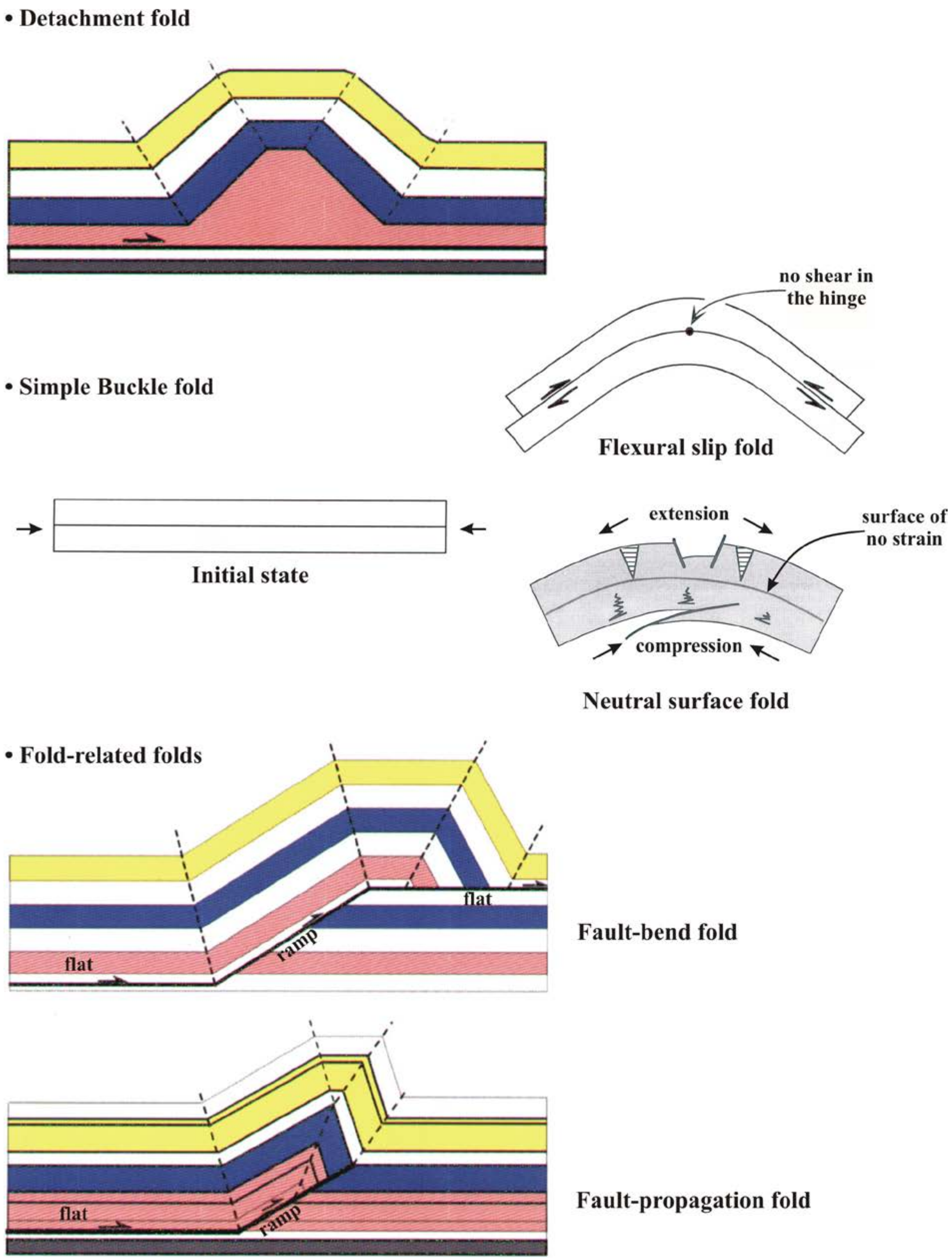


Fig.3: Different fold types recorded in Zagros Fold – Thrust Belt

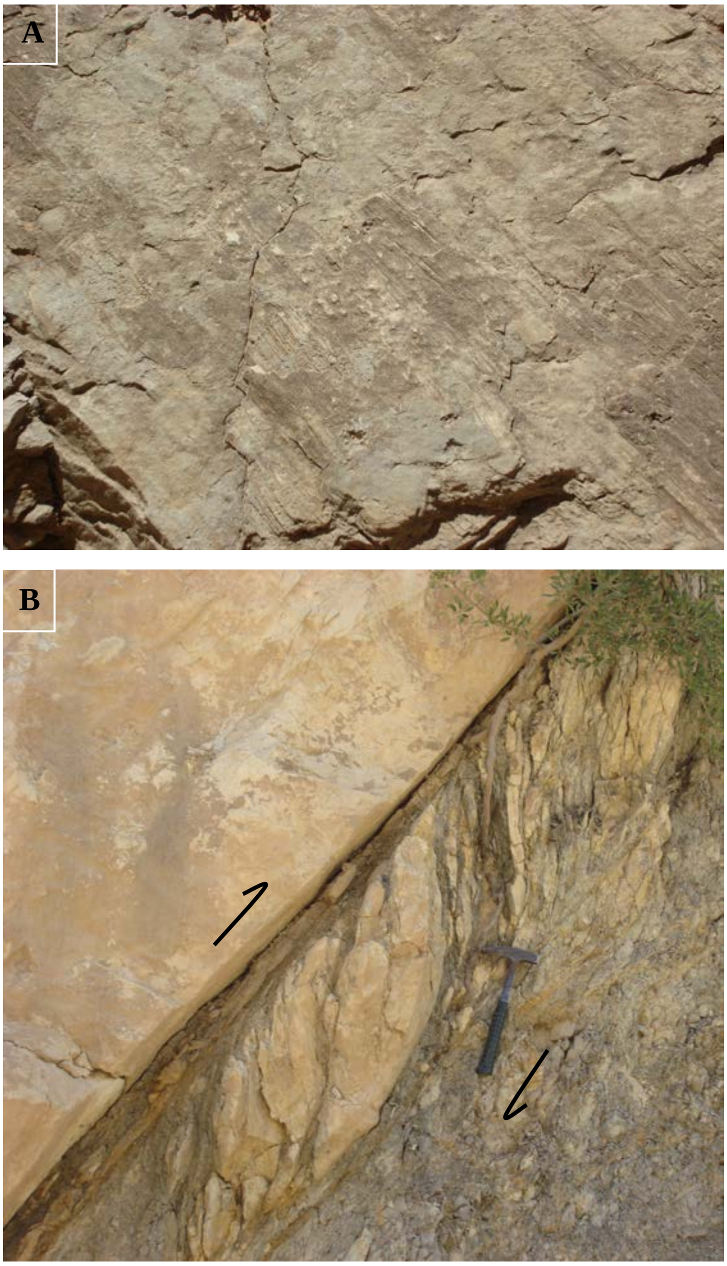
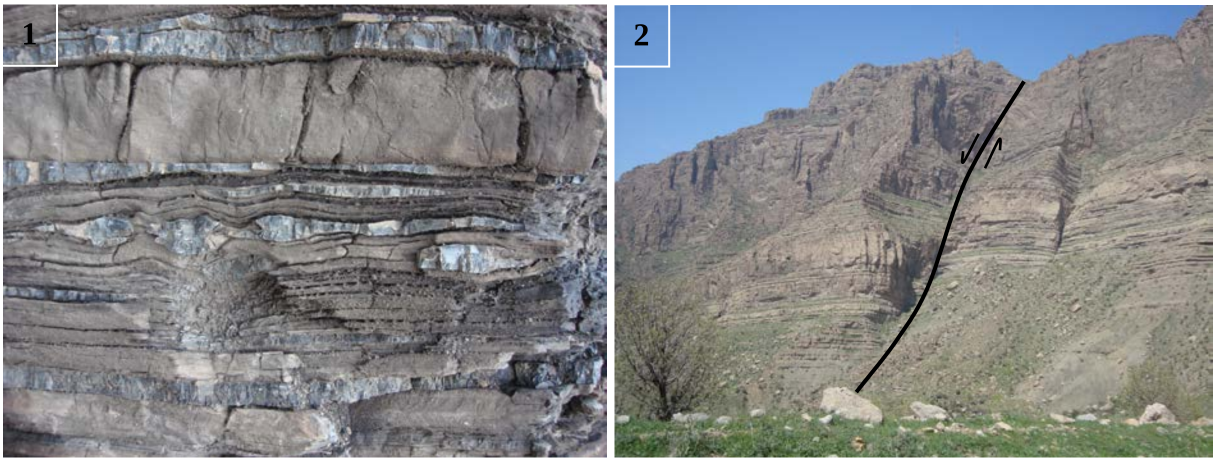


Fig.4: Features associated with flexural-slip folding
A) Slickenside striation on bedding surface, **B)** Sheared incompetent layer enclosed between competent layers due to layer-parallel shear toward the high of the fold

Meanwhile, many other folds exhibit evidence to the occurrence of extension (stretching) and compression (shortening) at their outer and inner arcs respectively (Fig.5). Consequently, such folds are considered as neutral-surface buckle folds. Among many Pera Magroon and Sordash anticlines are good examples of such folds. Note that many folds in the zone reflect indications that the position of the neutral-surface is not fixed and had migrated towards the fold inner arcs as the folds continue to grow (Fig.6). Such cases were recorded too in experiments and at different orogenic belts (Ramsey and Huber, 1987; van der Pluijm and Marshak, 1997; Hayes and Hank, 2008 and Deng *et al*., 2013).



A: 1) bondins structures, **2)** extensional normal fault

B: 1) tightly deformed minor folds, **2)** chevron fold with stylolitic hinge zone, and **3)** duplexing and reveres faulting

Fig.5: Features associated with (**A**) extended outer arcs, and (**B**) contracted inner arcs, of neutral-surface folds

Fig.6: Reverse and normal faults affecting the same layered sequence in Pera Magroon anticline, indicating the possible migration of the neutral-surface towards the fold inner arcs as the fold grow

It is very important to mention that folds in nature are rarely found as pure flexural-slip or pure neutral-surface buckle folds. In fact, such is the case in the High Folded Zone, the majority of buckle folds were achieved by a combination of the two folding mechanisms.

─ Fault Related Folding: In fold – thrust belts, many folds are generated as a direct result of fault movement beneath them. Such "fault controlled" folds are commonly referred to as fault related folds (McClay, 1992, and Deng *et al*., 2013).

Movement on thrust faults however, can produce two basic types of fault related folds; fault-bend folds and fault propagation folds (Fig.3).

▪ **Fault-bend Folds**

Regional thrust faults often show non-planer fault surface, and commonly form staircase-like geometry as the fault cuts upsection through stratigraphy (Dahlstrom, 1969). Flats and ramps (Fig.3) mark this geometry. Flats are the horizontal parts of the fault surface, and usually develop in the incompetent and weak layers. Ramps, on the contrary, are the steep parts of the fault surface, and commonly develop when the thrust fault cuts competent and stiff rock types. When the hanging wall starts to move up, its shape must be adjusted to conform to the shape of the underlying fault surface and consequently undergo folding (Fig.3). Such folds induced by movement on bends (changes in dip) on the fault surface are known as fault-bend folds, (Suppe, 1983; Jamison 1987; Ramsey and Huber, 1987, and Rowland *et al*., 2007). In its simplest form, fault-bend fold occurs when a thrust fault steps up from a structurally lower flat (lower detachment) to a higher flat (upper detachment). Therefore, it forms only in the hanging wall, while the footwall remains undeformed.

In the High Folded Zone in general, and in deeply incised anticlines in particular, no flats or detachment surfaces were identified. If we assume that the lower flats (or the lower detachment surface) are too deep to be exposed, this will not hold true for the upper flats. Moreover, as a result of style of formation and evolution, fault-bend folds can be identified from their characteristic kink geometry and broad hinge zones (Fig.3). Besides, they are usually associated with undeformed footwall block under and away from the handing wall block (Rowland *et al*., 2007, and Burberry *et al*., 2010). Field observation as well as map and satellite images rarely indicate the presence of such structural geometries associated with the folds of the zone. Therefore, in accordance with these evidences, the occurrence of fault-bend folds appears unlikely in the zone.

- **Fault-propagation Folds**

Fault-propagation fold (Fig.3) occurs when a propagating thrust fault loses slip and terminate upsection by transferring its shortening to a fold developing at it's tip (Suppe, 1985; Jamison, 1987, and Mitra, 1990). The lower tip of the fault commonly links with a floor thrust (or detachment surface). Fault-propagation folds are strongly asymmetrical with short steep forelimb and long gentle back limb. Vertical and overturned forelimbs are common feature of these folds. As a fault related folds, there are several important geometrical relationships between the exposed part of the fold and the associated thrust fault that can be used to infer the subsurface geometry of the structure, especially in the absence of other information.

In the High Folded Zone, however, folds are often asymmetrical in the direction of the foreland (i.e. SW). Many of the folds exhibit short very steep to overturned forelimbs and long gentle back limbs, connected by a relatively narrow and angular hinge zone. Moreover, in some deeply eroded fold cores, thrust faults can be distinguished and traced upsection to the point where they die out and replaced by folds in front of their upper tips (Fig.7). These characteristics are important clues to be added in favour of fault-propagation folding, and consequently fault-propagation folds are regarded as one of the common fold types in the High Folded Zone.

─ **Other Types of Folds:** Folds other than those discussed earlier might be expected in the zone too, but to a lesser extent. The lack of well information, seismic data and enough field observations make the identification of such folds extremely difficult if not impossible. Among these types, folds generated by positive structural inversion might be a possible option. The occurrence of rapid facial variation of some lithologies and the drastic thickness changes of others as well as the presence of some exposed growth strata (Fig.8) might support this option.

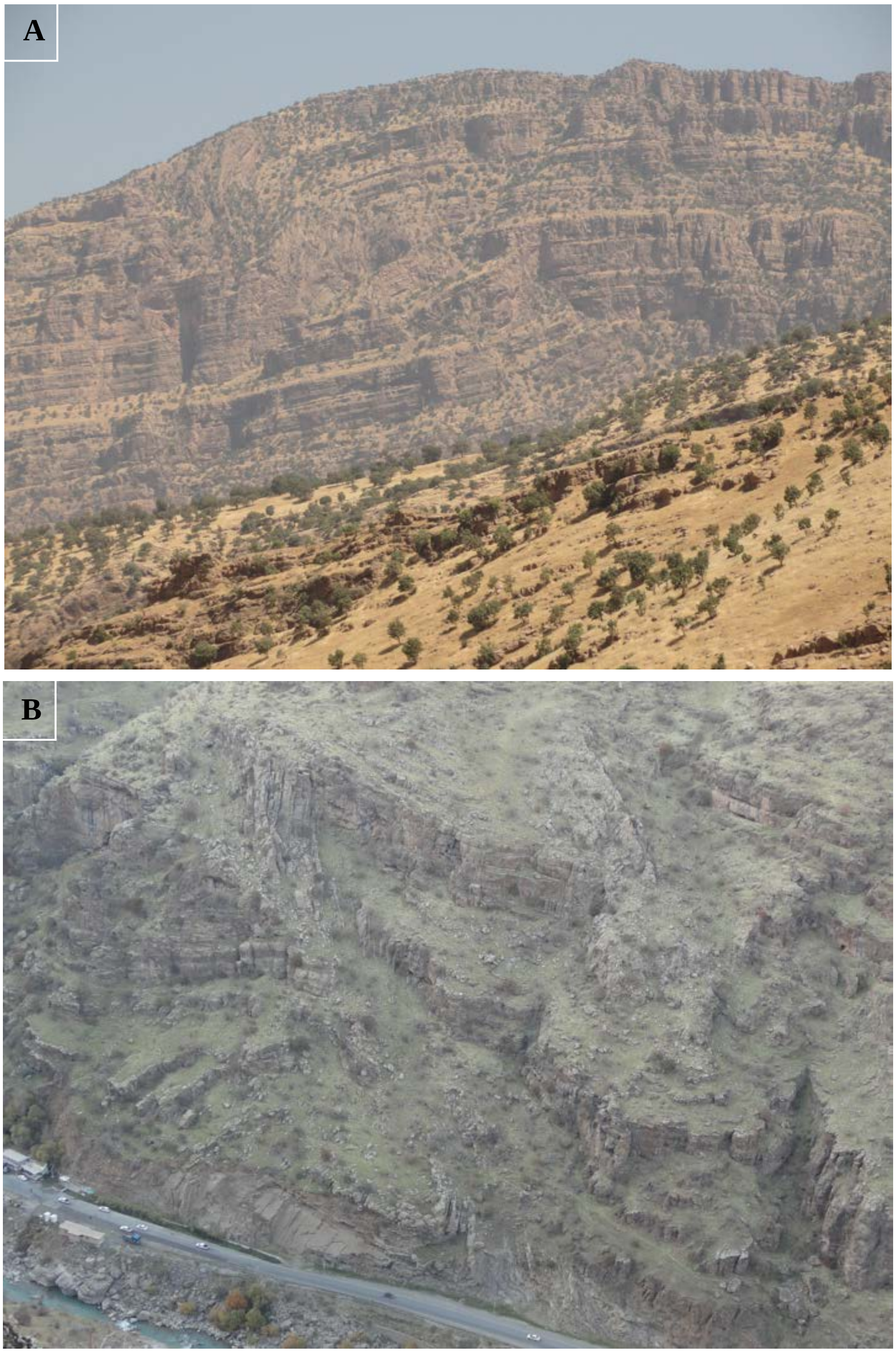


Fig.7: Fault-propagation folds

A) Thrust fault terminate upsection replacing its displacement by folding in front of the fault tip. **B)** Thrust fault exposed at the core of a fault-propagation fold.

Fig.8: Growth strata in Cretaceous carbonates, Peris anticline. Note the rapid change in thickness and dip of strata between the upper and the lower beds

TECTONIC AND STRUCTURAL EVOLUTION

After the accretion and cratonization of Arabia throughout the Proterozoic, Arabia and several other continental micro plates including Turkey, central Iran, Afghanistan, India and other smaller fragments collectively have formed part of the Paleozoic long wide northern margin of Gondwana supercontinent which bordered the southern shore of the Paleo-Tethys ocean.

This period of time was dominated by the deposition of a relatively uniform siliciclastic sediments which deposited in a shallow epicontinental sea. Therefore the Paleozoic sediments were considered to represent a sedimentary group that was deposited in an intercontinental setting in a relatively stable conditions (Beydoun, 1991; Brew, 2001; Alavi, 2004, and Fouad 2007 and 2012c).

By the end of the Paleozoic (Late Permian) and the beginning of the Mesozoic (Early Triassic), rifting dominated the northern margin of Gondwana. The Cimmerian microcontinents started to break away from Gondwana and drifted northeastwards through oceanic accreation and the formation of the Neo-Tethys Ocean. The Neo-Tethys continued to expand on the expense of the Paleo-Tethys shrinkage as its oceanic crust continued to subduct beneath Leaurasia. The Mesozoic had witnessed the birth and the development of the Atlantic-type Arabian passive margin that bordered the western shore of the Neo-Tethys Ocean. This new depositional setting had persisted through most of the Mesozoic. The passive margin was a site for huge sediment accumulation under continual subsidence. The final closure the Paleo-Tethys took place in the Jurassic when central Iran collided with the mass of Leaurasia. At that time the Neo-Tethys reached its maximum width (Aubouin *et al*., 1986). The collision was followed at the Early Cretaceous by the subduction of oceanic floor of the Neo-Tethys beneath the Eurasia (Iranian) plate. Both events (collision and subduction) were too remote to cast significant effect on the Arabian plate passive margin. Continental coverage between Arabia and Eurasia and the shrinkage of the Neo-Tethys continued until the Late Cretaceous, when the oceanic crust of the Neo-Tethys was obducted over the Arabian plate passive margin as ophiolite-radiolarite thrust sheets. The obduction resulted in the destruction of the passive margin and the formation of a new epicontinental depositional basin ahead of the thrusted ophiolite sheets (Kazmin *et al*., 1978; Peel and Wight, 1990). This Late Cretaceous basin is known as Zagros foreland basin (Kazmin *et al*., 1978; Alavi, 2004; Bahroudi and Koyi, 2004; Fouad, 2010 and Leturmy and Robin, 2010). Foreland basins formed primarily as a result of the down flexing of the continental lithosphere in response to the excess load imposed by the adjacent active nappes and the developing fold-thrust belt (Dickinson, 1974; Allen and Allen, 1990; Macqeen and Lechie, 1992; Decells and Giles; 1996; Chahil, 2006, and Egan and William, 2006). As it is the case in all foreland basins, Zagos foreland basin was asymmetrical with deep proximal part adjacent to the mountain front and a gentler craton-wards shallow part. During the Campanian – Maastrichtian period of time when the oceanic fragments (and the associated radiolarites) were rising above the Arabian continental margin, their load forced the margin to subside, and a relative deep marine conditions prevailed on the proximal part of the foreland. This early stage can be pointed by the deposition of the relatively deep marine marls and marly limestones of Shiranish Formation. The overthrust sheets continue to move up and a significant topographic reliefs have formed above the sea level by the Maastrichtian. The erosion of the resulting topographic high (ophiolite-radiolarite sheets) provided large volumes of clastic detritus deposited in the foredeep. These deposited detritus which is known as "flysch deposits", mark the first influx of clastics that denote a reversed in the sedimentary transport direction from the customary southwest (Nubia – Arabian craton) to the northeast direction (i.e. the newly evolving orogenic belt). Accordingly, Tanjero Formation is considered as the "first" flysch deposits that mark the early stage of the Western Zagros foreland basin evolution.

The Late Cretaceous foreland basin which started with the deposition of Campanian – Maastrichtian Shiranish and Tanjero flysch went through several depositional episodes but eventually became shaded by terrestrial coarse clastic sediments known as molasses (Bai Hasan Formation) during the Plio-Pliestocene. During that time span the thrust sheets and the deformational front continued to migrate towards the south and southwest forcing the foreland basin to move ahead, further and further onto the Arabian (foreland) plate. Therefore, foreland basin strata and pre-foreland basin platformal and marginal strata and structures were continually modified, as they progressively incorporated into the deformed belt of the WZFTB.

The evolution of deformation processes in the High Folded Zone appear to be in sequence, and a forward-developing series of fold and fault initiation and growth is concluded. The progressive decrease in the percentage of shortening, and the general drop in structural and topographic relief towards the south and southeastern margin of the belt as well as the associated younging in the relative age of folding in the same direction, strongly support this conclusion. This rule is not universally valid and some exceptional cases do exist.

Folds in the High Folded Zone exhibit several geometries and dimensions reflecting that more than one folding mechanism were operative during fold initiation and growth. Nevertheless, simple buckling through flexural-slip and neutral-surface folding mechanisms as well as fault-propagation folding appear the dominant folding mechanisms in the belt, while other mechanisms are less favorable. No regional surface faulting is recorded in the High Folded Zone. Minor thrust faults, however, are found associated with the forelimbs of some anticlines (Harier anticline for example). Such thrust faults appear to have been formed as a consequence of fold tightening and fold lock up to accommodate increasing shortening during the final stages of fold growth.

The boundary between the Low Folded Zone and the High Folded Zone always form a prominent step (or front) of considerable topographic and structural relief. This front persists along the entire length of the Western Zagros fold-thrust belt of Iraq and continues southeastwards along the entire Zagros range to the strait of Hormuz, southwest Iran. This step is considered to be underlain by a segmented basement involving master blind thrust fault that cast an important structural and topographic characteristic in Iran and Iraq, (Berberian, 1995; Blanc *et al*., 2003; Leturmy *et al*., 2010; Emami *et al*., 2010, and Sherkati *et al*., 2006). This fault controls also the morphotectonic character of the cover succession so that low topography occurs to the south and southwest (i.e. Kirkuk Embayment) and high topography to the north and northwest of it.

The amount of structural relief (or uplift) in the High Folded Zone, can be quantified or measured by using the simple rules of cross-section balancing technique. The variation in the elevation of a line connecting certain marker horizon(s) at the hinges of the synclines across this Low Folded/ High Folded zones boundary fault will give near approximation to such structural relief. This procedure depends on the fact that marker horizon has had the same initial regional level before the deformation (Woodward *et al*., 1989 and Emami *et al*., 2010). Variations in the structural relief between (~ 1000 – 2500) m can be observed on such marker(s) between the two zones in different sectors. Shortening across the Zagros was calculated by using several balanced cross-sections and estimated to be between (6 – 20) %, (Blanc *et al*., 2003; McQuarrie, 2004; Sherkati *et al*., 2005; Carruba *et al*., 2007; Sepeher, *et al*., 2006, and Verges *et al*., 2011). Such low values of tectonic shortening cannot be held responsible for producing the observed structural uplift, particularly in the absence of considerably thick and efficient mobile horizons. Therefore, the additional elevation should be the result of basement involvement by thrusting. Present seismicity as recorded in Iran supports this conclusion so that the shortening in the Zagros basement occurs by thrust faulting beneath the sedimentary cover (Jackson, 1980; Berberian, 1995; Berberian and King, 1981; Talebinn and Jackson, 2004, and Hatzfeld *et al*., 2010).

CONCLUSIONS

- The High Folded Zone is an integral part of the Western Zagros Fold-Thrust Belt of Iraq. It consists of several high amplitude and short wavelength folds of different shapes and sizes with south – southwest vergence.
- The landforms are highly structural and reflected in the morphology as topographically high anticlinal mountains separated by deep and narrow synclinal valleys.
- The boundary between the Low Folded Zone and the High Folded Zone always forms a prominent front of considerable topographic and structural relief, and thought to be underlain by a master, basement involved, blind thrust.
- Mesozoic and Cenozoic sediments are widely exposed in the zone. The Phanerozoic stratigraphic column, however, can broadly be considered as consisting of three major tectonostratigraphic groups; Cambrian-Early Permian Gondwana intraplate group dominated by siliciclastic deposits; Late Permian-Cretaceous Neo-Tethys passive margin group dominated by carbonate; and Late Cretaceous-Present foreland group consists of deep marine and flysch deposits that grades upwards in to continental molasse deposits.
- Folds of the zone exhibit a wide range of geometries and sizes, indicating that more than one folding mechanism was responsible for their generation and development. Judging by

their style, geometrical characteristics, and the nature of the associated mesoscopic structures, simple buckle folds generated by flexural-slip and neutral-surface mechanisms as well as fault-propagation folds appear the dominant fold types in the zone.

- The progressive decrease in the intensity of deformation and amount of shortening from north and northeast towards south and southwest part of the zone, as well as the relative younging of folds in the same direction point to the forward-developing serial nature of fold evolution in the High Folded Zone.
- The remarkable difference in the topographic and structured uplift between the High Folded Zone and the Low Folded Zone indicate that the deformation in the High Folded Zone is thick skin and the basement is shortened by thrust faulting. The low values of shortening and the absence of thick mobile detachment, as well as the nature of the present seismic activity in the zone support this conclusion.

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