INVERSION AND FOLDING OF THE SOUTHERN UN-ELEVATED FOLDED BELT IN NORTH IRAQ

*Nahidh Z. Marouf and **Manal Sh. A. Al-Kubaisi

*Consultant Geologist, Al-Zab Geological Consultant Bureau
**Department of Geology, College of Science, University of Baghdad

ABSTRACT

The southern parts of the un-elevated (Foothills zone) folded belt in Iraq includes the area of Kirkuk and Diyala governorates. It is part of the Zagros fold thrust belt and it is characterized by presence of long relatively narrow northwest trending anticlines separated by broad flat bottom synclines. The northeastern flanks of all the exposed anticlines suffered from thrusting parallel to their axial trends. The surface thrusts always initiate within the salt bearing horizons of the Lower – Middle Miocene mobile sequence and migrate up stratigraphy to the post-Middle Miocene upper competent sequence. The pre-Miocene lower competent sequence is always affected by at least two high angles major up thrusts dipping toward each others, and trending parallel to the axial trend of the major anticlines.

Geometrical analyses based on surface and subsurface (seismic and drill holes) data elucidate the following. The major anticlines are fault propagation folds formed in response to the thrust movements on the major up thrusts. Thickness variations of the Maestrichtian strata across the major up thrusts postulates that these up thrusts were actually normal faults forming grabens and half grabens during the Maestrichtian age. Reactivation of the extension movements on these grabens during the lower and the middle Miocene ages resulted in the restricted deposition of the lower and the middle Miocene rock salt facies of both Dhiban and Fatha Formations. Compressive stress field acting during and after the Pliocene resulted in inversion of movements of the former normal faults and converts them into up thrusts and also resulted into formation of the major and the minor structures of the studied area. The onlapping of Maqdadiah – Bai Hassan sequences over the top of Injanah Formation postulates that the contraction and the elevation of the major anticlines were started at the onset of the Pliocene. This contraction phase was coaxial with the former extension phases, and both were oriented in NE – SW direction.

The major structures were formed by a combination of neutral surface flexure slip and flow, and body translation mechanisms. The flexure slip and flow of the rocks of the mobile sequence resulted into formation of several types of duplexes and triangle zones. The lower Miocene reservoir rocks are intensively influenced by these duplexes and triangle zones especially at the down flanks of the major anticlines and beneath the surface synclines. This criterion has a special importance in the oil industry.
INTRODUCTION

The Zagros thrust fold belt extends from south west Iran to north east and north Iraq to north Syria and south east Turkey. It is trending in North West direction in south west Iran and north east Iraq and in East West direction in north Iraq, north Syria and south east Turkey. Longitudinally, the Zagros thrust fold belt is subdivided into north eastern inner thrust belt and south western outer simply folded belt (Rigo de Righi et al., 1964; Elhan, 1967; Stocklen, 1968; Falcon, 1979).

In the thrust belt, Mesozoic eugeosyncline sequences thrust on each others and on the miogeosynclinal sequences of the simply folded belt (Rigo de Righi et al., 1964; Elhan, 1967; Stocklen, 1968; Falcon, 1974; Bolton, 1958; Stocklen, 1974; Marouf, 1999). Thrusting frequently takes place at relatively low angles and the movements on the hanging walls are always directed toward the south west which reflects a south west ward directed tectonic transport (Marouf, 1999). In contrast, Phanerozoic miogeosynclinal sequences are folded and thrust in the simply folded belt. The intensity of the deformation also decreases in south west direction, which assures the south west
directed tectonic transport (Rigo de Righi et al., 1964; Stocklen, 1968; Stocklen, 1974; Marouf, 1999).

Longitudinally, the Zagros simply folded belt is subdivided into elevated and un-elevated folded belts (Marouf, 1999). The elevated folded belt is characterized by the elevation of the rock units above their stratigraphic positions at the syncline troughs. In contrast the rock units are kept at their stratigraphic positions in the syncline troughs of the un-elevated folded belt. The elevated folded belt generally corresponds to the high folded and imbricate zones of (Bolton, 1958), whereas the un-elevated folded belt is corresponding to the foothills zone of (Bolton, 1958).

The terminology of Bolton is descriptive and based on the old description of the mountain front (the first exposure of the main limestone of the BP, 1965). In contrast the differentiation between the elevated and the un-elevated folded belt is sharp and has a structure applications, because the elevation of the synclinal troughs could not occur unless these troughs and consequently the whole belt is underlain by a subsurface thrust fan or duplexes (Marouf, 1999).

In this work we well concentrate the lights on the southern part of the un-elevated folded belt in Kirkuk and Diyala area. The concentration of our work on this area is based on the following:

1. The area is characterized by very good to excellent exposures of the anticline features.
2. The area was subjected to several seismic surveys which allow us to study the variations in the structural picture of the anticlines and the synclines with depth. Most of the previous structural work was restricted to the surface anticlines (Ameen, 1979; Al-Ubaidi, 1980; Al-Naib, 1982; Marouf, 1983; Fouad, 1983 and others). In all of these studies the variations in the subsurface structural pictures of the studied anticlines were interpretive and ambiguous and based on several assumptions. By correlation with the seismic picture, most of the assumptions of the previous studies were not accurate and consequently their interpretations of the subsurface structures were also not accurate. As we will show later, neither the drape bend folding model of (Ameen, 1979) nor the detachment buckle folding model of the others is comparable with the present seismic picture.
3. The folded sequence in this area, is widely various from mechanical point of view. These mechanical variations insert a wide range of responses to the applied stress fields and resulted in a wide range of macroscopic and mesoscopic structural features.
4. The studied area is characterized by huge amounts of explored and unexplored hydrocarbon prospects. All of these hydrocarbon reservoirs are controlled by the subsurface structures. Consequently the better structure interpretations are very important and have industrial applications. These industrial applications will be shown at the end of this work.

**GEOLOGIC SETTING**

The un-elevated folded belt in north Iraq consists of many long relatively narrow anticlines separated by broad synclines. With few exceptions, in all of the anticlines, Neogene rock units are exposed on the surface, whereas the synclines are mostly filled with recent sediments (Fig.1). Although some of the major anticlines consist of a single
dome, most of the others are composed of several major and minor domes. The hinge lines of the adjacent domes and the adjacent major anticlines frequently bypass each others forming left or right stepping arrangements (Fig.1). The arrangement of the hinge lines of the adjacent domes of a single major anticline is frequently un-usual. In some cases the hinges of two adjacent completely in line domes bypass each others, and in other cases the hinge lines of two partly or completely out of line adjacent domes connect with each others inducing a sharp swing in the hinge line of the major anticlines (ex: Hemrin south) (Fig.2).

Kirkuk – Diyala area is also characterizing by major thrusting. The north eastern flanks of the major anticlines thrust toward the southwest (Fig.1). The thrust displacement is variable along the strike and the direction of dip. In some cases, the maximum thrust displacement exceeds 3 Km and brings the north eastern flanks of the surface anticlines over the adjacent synclines (ex: Chia Surkh and Kor Mor structures) or on the south western flanks of them (Kirkuk and Al-Mansuriah structures). In most of the other cases the maximum thrust displacement is about 2 Km and it brings the north eastern flanks of the surface anticlines over their hinge zones (Kirkuk, Jambur, Pulknana, Qumar and Hemrin south). In few cases the maximum thrust displacement is less than 1 Km and it results in thrusting of the north eastern flanks over themselves. Along the individual surface anticlines, the thrust displacements decrease from their maximum values at the anticlines culminations to nil toward the anticlines plunges. The individual thrust sheet is either consisting of individual thrust or several thrust slices, occasionally separated by tear faults.

Along the direction dip, frequently each thrust sheet consists of few secondary thrusts. Subsurface data show that the oldest rock unit influenced by this thrusting process is the rock salt bearing units of the middle Miocene Fatha formation and the lower Miocene Dhiban Fn.
Fig. 2: Hinge lines of the major anticline of the studied area
Notice: the un-named hinge lines belongs to subsurface anticlines
formed beneath the surface synclines

SOURCE OF SUBSURFACE DATA

Hundreds of 2D seismic lines were shot along and across Kirkuk – Diyala area during the seventies and the eighties of the last century. All of these lines were 4 to 5 seconds time range with 12 to 24 folds coverage. Most of these lines were reprocessed during the nineties using the Land Mark station. The quality of these lines ranges between fair to very good quality. The studied area is also penetrated by more than 600 wells. Most of these wells are Tertiary wells and they are concentrated in Kirkuk area. The rest of the wells are Tertiary wells and they are concentrated in Kirkuk area. The rest of the wells are Cretaceous wells and few are Jurassic wells. By correlation between drilling and seismic data, five seismic horizons were recognized (Fig.3) these are:

1. Horizon H1 coincides with top of the middle Miocene Fatha Formation which is slightly above the top of the mobile sequence.
2. Horizon H2 coincides with the bottom of the mobile sequence. In Kirkuk area it coincides with the top of the Oligocene group. Southward in Jambur area, it coincides with top of the lower Miocene Jeribe Formation. In the rest of the studied area, horizon H2 coincides with the top of the lower Miocene Euphrates formation.
3. Horizon H3 represents the top of the upper Cretaceous rift sequence and it coincides with the top of the Shiranish Formation.
4. Horizon H4 is located within the pre upper Cretaceous rift sequence and it coincides either with the top of the Albian in the northern parts or with the top of the Tourorian in the southern parts of the area.
5. Horizon H5 is an upper Jurassic reflector.

The upper three horizons are very good quality seismic reflectors and persist along and across the whole of the studied area. Horizon H4 is very well recognized in the synclines and on the flanks of the major anticlines and it appears in fair to good quality in the cores of the major anticlines. In contrast horizon H5 appears in good quality only in the synclines and the flanks of the major anticlines and it is hardly recognized in the cores of the anticlines. Multiples of H1-H2 intervals occasionally disturbed the seismic picture of H4 and H5, but these multiples are easily recognizable.
The subsurface data are fair enough to us to study the structural picture of the studied area down to at least 4 Km below the ground surface.

TECTONOSTRATIGRAPHY

Careful study of figure (3) elucidates that the folded sequence is subdivided into lower competent and upper competent sequences separated by a mobile sequence. The upper and lower competent sequences maintain their pre-folding thicknesses, whereas the mobile sequence suffers from intensive thickness variations resulted from deformational processes associated with folding.

In Kirkuk area, the mobile sequence is restricted to the salt bearing horizons of the middle Miocene Fatha Formation (Fig.4). But southward in Diyala area, the mobile sequence also includes the salt bearing horizons of the lower Miocene Dhiban Formation. The competent carbonate units of the lower part of Fatha Formation, Jeribe Formation and the upper part of Dhiban formation sandwiched between these two salt bearing horizons, control the geometry of the internal structures developed within the mobile sequence (Fig.4). From seismic point of view, the mobile sequence is restricted to the middle part of the seismic interval sandwiched between H1 and H2 horizons.

In Kirkuk area, the axial zones of the synclines are completely free from the salt bearing rocks. No indication of any deformational flowage of material exists. In addition to this phenomenon the sequence equivalent to the mobile sequence of the anticlines is too thin. In other words, the presence the mobile sequence is restricted to the anticlines of Kirkuk area whereas it persists along and across all Diyala area. The thickness of the mobile sequence is variable. In Kirkuk area, it varies between zeros in the down flanks up to 250m in the anticline crests, whereas in Diyala area, the thickness of the mobile sequence ranges between zeros in the median parts of the northeastern flanks up to 400 m in the anticline crests (Fig.2). In the syncline axial zones of Diyala area the thicknesses of the mobile sequence also ranges between zeros to 200 meters.

The upper and lower competent sequences are formed of the post middle Miocene and pre Miocene rocks respectively. The upper competent sequence is translated laterally above the mobile sequence and always affected by the thrusting that influencing the underlying mobile sequence. The bed rocks of the upper competent sequence maintain their original thicknesses (Fig.3). The thickness of the upper competent sequence ranges from 900 m in Kirkuk area to 2000 in Diyala area.

The lower competent sequence consists of three subsequences. The middle subsequence is the upper Cretaceous (Maestrichtian) syn-rift subsequence, the upper subsequence is the Paleogene post rift subsequence and the lower subsequence is the pre-Maestrichtian pre-rift subsequence. The Maestrichtian Shiranish syn-rift subsequence always exhibits abrupt syn-depositional thickness variations across the structure bounding faults (up thrusts) (Fig.3). These thickness variations range between zeros and 1500m, and there is not any indication of thickness variations related to the folding process. The pre-rift and the post-rift subsequences also maintain their pre-folding thicknesses and they are characterized by their uniform thickness. The thickness of the lower competent sequence is possibly more than 10 Km. The lower competent sequence always affected by weak to moderate folding (dip 40) and displacement on the pre-existing faults.
Fig. 3: Definition of the structural elements and the geometrical relationships of the anticlinal cross section
### Kirkuk Area

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<th>Formation</th>
<th>Member</th>
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<th>Tectono-stratigraphy</th>
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### Diyala Area

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Fig. 4: Definition of the mobile sequence in Kirkuk and Diyala regions
Rock flowage and thrusting within the mobile sequence postulate that this sequence was deformed by a combination of flexural flow, flexural slip and translation mechanisms. Accordingly the mobile sequence could be regarded as a single major mechanical plate consists of several smaller sub plates. In contrast, the upper competent sequence is deformed mainly by neutral surface folding and body translation over the upper thrust, and it consequently considered as a single mechanical plate. On the other hand the lower competent unit is also considered as a single mechanical bed deformed by body translation and folded by a combination of neutral surface and flexural slip mechanisms and possibly block movement and rotation along the pre exerting faults.

In the synclines of Kirkuk area, and wherever the mobile sequence is absent (as in north and northwest Iraq), the whole sedimentary sequence form a single competent mechanical plate deformed mainly by body translation. This mechanism is indicated by the complete absence of any internal flow folding or faulting and the maintenance of the pre-folding thickness.

In contrast, in the synclines of Diyala area the upper and lower competent sequences are very well recognized and deformed by body translations over the upper and lower detachments respectively, whereas the mobile sequence is deformed by a combination of flexural flow and flexure slip mechanisms.

CROSS SECTIONAL GEOMETRY OF THE MAJOR ANTICLINE

It was previously explained that each tectonostratigraphic unit is characterized by distinctive structural relations that aid the recognition of each major tectonostratigraphic unit. On this we will describe the geometrical relations appear in each tectonostratigraphic unit.

- Structures of the lower competent sequence
  The major anticlines are always bounded by at least two high angles up thrusts. These up thrusts are trending in northwest direction parallel to the anticline hinge lines. The up thrusts are always dipping toward each others (Fig.3). The southwestern up thrusts dip toward the north east and break through the south western flanks of the major anticlines. The sense of movement of the hanging walls of these up thrusts is parallel to the general direction of the contraction tectonic transport and accordingly we will call them synthetic up thrusts. In opposite, the northeastern up thrusts dip toward the southwest and displace the north eastern flanks of the major anticlines. The sense of movement of the hanging walls of these faults is in opposite direction to the contraction tectonic transport and accordingly we will call them the antithetic up thrusts. Occasionally, there are two synthetic up thrusts and one or two antithetic up thrust. The inner synthetic up thrust occasionally breaks through the anticline hinge zone. On the other hand, in few cases the inner antithetic fault is up thrust and the other (more toward the adjacent syncline) antithetic fault is still normal fault.

  The up thrusts always break through the whole lower competent sequence and frequently die within the mobile sequence. In some cases, the synthetic up thrusts break also through the whole mobile sequence and die either within the upper competent sequence or at the ground surface. Less frequently the antithetic up thrust also breaks through the mobile sequence. Abrupt thickness variations in the Maestrichtian Shrianish Formation always took place across these structures bounding up thrusts. The area
bounded by the structure bounding up thrusts always contains thicker Shiranish than the regions outside them. The thickness variations are less than 100 meters in Kirkuk area, whereas it is up to 1000 meters in Diyala area. This phenomenon postulates the following:
1. The up thrusts were originally normal (gravity) faults inherited from the Maestrichtian extension phase.
2. The sense of movement on those normal faults was inverted during the contraction phase and the faults inverted to up thrusts. Similar types of faults were described by many workers (Harding, 1985; Cooper & Williams, 1989; Mitra, 1993; Buchanam & Buchanan, 1995), and called them positively inverted faults and the process is called structural inversion.

Thrust displacement on the pre-Tertiary sequence varies between zeros up to 700 m, and decreases within the post-Tertiary sequence and dies fast within the mobile sequence, and in rare cases it dies within the upper competent sequence (Figs.3 and 5). The fast upwards (up stratigraphy) dying of the displacements on the major up thrusts usually take place by bifurcations of the up thrust into several smaller thrusts called the up thrust fan (Fig.3). Each up thrust fan consists of several secondary up thrusts and each of these secondary up thrusts initiates from the major up thrust surface and migrates as a foot wall or hanging wall shortcut and dies within the mobile sequence (Fig.3). The dip of each individual secondary up thrust frequently decreases upward, and the dips of the secondary up thrusts forming the up thrust fan usually decrease towards the adjacent syncline (Figs.3 and 5). The secondary thrusts forming the antithetic up thrust fan break through approximately constant Minimum thicknesses of the syn-rift subsequence (Figs.3 and 5). In opposite, the secondary thrusts of the synthetic up thrust fan break through a wedge of the syn-rift subsequence. The thicknesses of these wedges are always decreasing toward the adjacent syncline (Figs.3 and 5). These phenomena suggest that the secondary thrusts of the antithetic up thrust fan were formed as foot wall short cuts, whereas the secondary thrusts of the synthetic up thrust fan were either formed as foot wall short cuts or as hanging wall short cuts. The kinetic evolution of the antithetic and the synthetic up thrust fans will be discussed later. The strata of the whole lower competent sequence inside the up thrust flower and outside it on the northeastern flanks of the major structures are always folded. In opposite the strata of the syn-rift and the pre-rift subsequences maintain their pre-folding dips outside the up thrust flower on the southwestern flanks of the major structures, whereas the strata of the post-rift subsequence are also folded at these locations (Figs.3 and 5).

**STRUCTURES OF THE MOBILE SEQUENCES**

The internal structures of the mobile sequence can be subdivided into two major categories.

The hinge zone lenses and the down flank lenses and triangles. Both of them result from the interaction of the up thrusting with the incompetent response of the mobile sequence to the applied tangential stresses. In the following we will describe the details of each of them.
Fig. 5: Structure cross section across Himrin south. Notice the following:

1. The antithetic up thrust, thickening takes place across fault no. 1, faults 2 – 5 breaks through constant thickness of shiranish, according they are footwall shortsuts.
2. The synthetic up thrust break through the maximum thickness of shiranish, thickening takes place across fault no. 1 according faults no. 2, 3 and 4 are hanging wall shortsuts.
3. The distribution of the synthetic and the antithetic up thrusts and up thrust fans suggest a clockwise rotation of the up thrust block during the inversion.
4. The limited extend of the upper bedding thrusts in the down flank direction.
5. The on lapping on the top of Injanah.
1. The hinge zone lenses

The hinge zone lens is the body of the mobile sequence extending on the hinge zone of the major anticline. Each hinge zone lens is bounded from the top by the synthetic and the antithetic upper thrusts and from the bottom by the top of the lower competent sequence which is partly a decollement surface. From the north eastern side the upper and the lower boundaries converge approximately at the median point of the north eastern flank, whereas these boundaries usually approach to each others, but do not converge at the south western side of each hinge zone lens (Figs.3 and 5).

The hinge zone lenses are either slim or thick, when they are slim, the associated down flank lenses and triangles are also slim and the opposite is always correct. Generally, the hinge zone lenses and the down flank lenses and triangles are both slim in Kirkuk area and thick in Diyala. This phenomenon is in reality inherited from the original thickness distribution of the mobile sequence.

The internal structure of each hinge zone lens consists of a series of Individual bedding thrusts. Each of these bedding thrusts coincides with a salt horizon. The slip on the hanging walls of these bedding thrusts is always directed toward the hinge of the major anticline (Fig.6). The movements on these bedding thrusts result in body translation of the competent carbonate beds and flow of the low shear resistance rock salts toward the hinge area. With progressive deformation the rock salts gradually depleted from the sides of each lens and crumbled at the hinge area. Usually complete depletion of the rock salt materials takes place on the north eastern side of each lens whereas partial depletion occurs on the south western side of the hinge zone lenses. This apparent differential depletion is possibly partly resulted from the original thickness distribution of the mobile sequence. Seismic sections across relatively slightly deformed structures shows an increase in the thicknesses of the individual beds of the mobile sequence and in the numbers of these beds toward the southwest flanks of the major anticlines. Usually the thickest mobile sequence is located directly above the synthetic major up thrust. This differential depletion of the rock salt produce the disharmony between the upper and the lower boundaries of each hinge zone lens. The Complete depletion of the rock salts results in stacking of the bedding thrusts over each others on the north eastern sides of each hinge lens and the deformation proceeds by flexural slip mechanism on these parts. The complete depletion of the rock salts from the north eastern sides of each hinge zone lens also results in the approximate convergence of the lower and the upper boundaries of each hinge zone lens (Fig.6).

The flowage of rock salts in front of each advancing bedding thrust results in rock salt crumbling in the hinge ward direction. When the crumbled rock salts reach a considerable volume sticking in the direction of movement of each bedding thrust takes place enforcing these thrusts to migrate up stratigraphy. These up stratigraphy migrating thrust ramps usually converge with the stratigraphically higher bedding thrust. With progressive deformation many duplexes form in the hinge wards direction from each side of the lens. The oppositely directed duplexes imbricate over each others at the hinge zone producing an inter-fingering duplex system at the hinge maximum. This duplexing and the formation of the inter-fingering of the opposite duplexes produce the relative thickening of the hinge maximum of the hinge zone lenses (Fig.6).
It is clear from the above described geometrical relationships that the deformation proceeds at the early stages by a flexural flow mechanism. But wherever the rock salts were depleted, the deformation proceeds by flexural slip mechanism.

On the north eastern sides of the hinge zone lenses where the rock salts are completely depleted, duplexing within the competent horizons is occasionally observed. In these duplexes the dips of the individual ramps are gentler toward the north eastern edge of each lens. This criterion suggests that these duplexes were formed in back ward direction possibly during the very late stages of progressive deformation. Figure (6) illustrates the development of a hinge zone lens and the variations in the internal geometry of it during the progressive deformation.

Most of the studied structures in the whole area are asymmetrical on the top of the mobile sequence and the stratigraphic horizons above it, and they are approximately symmetrical at the bottom of the mobile sequence and the horizons below it. This variation in the symmetry produces the disharmony and the shift in the hinge surface of the major structures across the mobile sequence.

On the top of the mobile sequence the north eastern flanks of the major structures are longer and have gentler dips than the south western flanks. We believe that this phenomenon is attributed to the excess amount of slip and flow that took place on the north eastern flanks than the south western flanks. In other words, most of the horizontal shortening was consumed by slip and flow of rock material with little amount of rotation of the northeastern flanks. On the other hand and because of its lesser amount of slip and flow of rock materials, more rotation took place on the south western flanks to accommodate the total horizontal shortening.

Occasionally the inner synthetic up thrusts break through the whole hinge zone lenses (Fig.6) and more rarely the inner antithetic up thrust break through the side of the hinge zone lenses and produce bending in the upper competent sequence and the synthetic upper thrust. During progressive deformation a new ramp usually developed from the surface of the upper synthetic thrust at the site of bending (Fig.5). These late stage deformations usually result in modification of the general shape of the hinge zone lenses.

The displacement of the mobile sequence by the up thrusts also results in displacement of the upper bedding thrusts producing highly dipping ramps (Fig.6). Occasionally mesoscopic folding within the upper competent sequence developed on the hanging wall sides of these highly dipping ramps (Fig.6). These folds are detachment folds detached in back ward direction on the synthetic upper bedding thrust also on the top of the upper most salt horizon of the mobile sequence. These detachment folds developed in response to the very late stages of horizontal shortening mostly because of buttresses effect of the foot wall side of highly dipping ramp in the direction of movement on the synthetic upper thrusts. It is important to notice that these detachment folds are different than the previously described fault propagation folds developed in front of the advancing synthetic upper bedding thrust.
Fig. 6: Stages of structural evolution of the hinge zone lenses and their relation to the downflank structures and structures of the upper competent sequence.
2. The down flanks lenses and Triangles

The down flanks lenses and triangles are bodies of the mobile sequence developed down the median parts of each flank (Figs. 7 and 8), these bodies are always bounded from the top and bottom by the upper and the lower boundaries of the mobile sequence respectively, and these boundaries are both decollement surfaces (Figs. 7 and 8). The lower boundary of the mobile sequence is usually displaced by the structure bounding up thrusts. This displacement is either preceded by considerable rotation of the lower boundary of the mobile sequence or by relatively small rotation. Consequently the considerable rotation consumes most of the horizontal shortening and the displacement on the up thrust is the minimum and the developed structures are the down flank lenses (Fig. 7). In opposite when the displacement of the lower boundary of the mobile sequence is preceded by relatively little rotation, most of the shortening is consumed by relatively large displacement on the major up thrust and down flank triangles were developed (Fig. 8). The down flank triangles are restricted to the north eastern flanks of the major structures and never found on the south western flanks whereas down flank lenses are developed on both flanks. The absence of the down flank triangles from the south western flanks of the major structures is attributed to the general asymmetry of the major structure and the possible presence of the originally thicker mobile sequence on the south eastern sides of the mother garbens. In the following we will discuss the internal geometry of the down flank lenses and triangles.

2a. The down flank lenses

The down flank lenses developed between the median part of the anticline limb and the medians part of the adjacent synclinal limb. At these parts, the lenses have their minimum thicknesses. The maximum thicknesses of the down flank lenses always observed at the inflection point at the tip of the major up thrust (Fig. 7). In some relatively complex cases, more than one down flank lens developed on the north eastern flanks of the major structures, each lens develops above a major antithetic up thrust (Fig. 3).

Figure (7) illustrates the internal geometry of a down flank lens. Rock materials squeezed from the median parts of the neighbor anticline and syncline flanks toward the inflection point. The squeeze of materials takes place by bedding thrusting and flowage. With progressive deformation the bedding thrusting developed into duplexes. The duplexes of the opposite sides inter-finger at the inflection point and result in the deformational thickening of the mobile sequence in this area. The internal geometry and the deformational thickening are magnified at the inflection area by the thrusting associated with up thrust fan (Fig. 7). Occasionally during the late stages of deformation, the well developed down flank lenses are completely displaced by the synthetic major up thrust. The major up thrust breaks through the upper competent sequence also, and high angle ramp is developed. Detachment folding on the up thrown side of this ramp is also frequently developed (Fig. 6).

2b. The down flank triangles

In their early stages of formation, these down flanks triangles form as a lenses, and soon after the breaking of the lower boundaries of them by the antithetic major up thrusts, the deformation within the up thrown side of the former lens diminish and all the shortening is consumed by the down thrown side of the major up thrust (Fig. 8).
relicts of the former lens is always preserved on the up thrown side of the major up thrust (Fig.8).

Basing on the internal deformation of the down flank triangles, the rock materials within these triangles are either deformed by detachment folding or fault bend folding (Fig.8).

Fig.7: The internal geometry of the down flank lenses
2b1. Fault bend folding triangles

In these structures, the major up thrust breaks through the mobile sequence at a relatively moderate angle, a wide up thrust fan is associated with it. The dip of each individual short cut up thrust decrease upward and the dips of faults forming the up thrust fan decrease toward the adjacent syncline. The shortening on these up thrust fan result in development of fault bend folds and duplexes directed toward the adjacent synclines (Fig.8a).

2b2. Detachment folding triangles

When the major up thrust break through the mobile sequence at a relatively high angle, it is usually a unique fault and the associated up thrust fan is either too slim or absent. In this case, the rock materials of the mobile sequence crumbled on the down
thrown side and detachment folding developed within it. In this case, the lower boundary of the mobile sequence act as decollement surface to the newly developed detachment folds. The intensity of the detachment folding decrease away from the major up thrust (Fig.8b). The mechanism and the kinetic of the development of these detachment folds are similar to those of the previously described detachment folds that developed against the ramps of the synthetic up thrusts. The differences are:

1. The detachment folds of the down flank triangles developed within the mobile sequence whereas the previously described ones developed within the upper competent sequence.
2. The detachment folds of the down flank triangles developed on the down thrown side of the major antithetic up thrust, whereas the previously described detachment folds developed on the up thrown sides of the major synthetic up thrusts.

The important geometrical and kinetic difference between the down flank triangles (Fig.8) and their counterpart of the down flank lenses (Fig.7) is that the direction of shortening and duplexing and consequently the sense of movement on the lower boundary of the mobile sequence is in opposite between the down flank lenses and the down flank triangles.

CROSS SECTIONAL GEOMETRY OF THE PLUNGES OF THE MAJOR ANTIKLINES

Mitra, 1990 stated that along the axial trends of the folds, the intensity of the deformation decreases toward the plunges of the folds, consequently the geometrical features of these plunges resembles the geometrical features of the early stages of the development of the folds. Accordingly, the geometrical analysis of the plunges of any fold gives a great support to our understanding of the kinetic evolution of the major folds.

Figure (9) is cross section (based on seismic data) near the plunge of one of major anticlines in Diyala area. The following structure features are observed:

1. The upper competent sequence is folded maintaining its depositional thickness. The upper synthetic and antithetic bedding thrusts are in very early stages of their development and in some places, they are not initiated yet. The strata of Muqdadiah – Bai Hassan Formations are conformable with the underlying strata of injanah formation.
2. Rock flowage and thickness variations takes place within the mobile sequence, and the internal deformational features initiated starting from the lower most salt horizon of the mobile sequence. The flowage of the rock materials started from the median part of the northeastern flank and it is directed toward the anticline hinge and the southwestern flank. The down flank lenses and triangles also started to develop.
3. The antithetic up thrust breaks through the bottom of the mobile sequence whereas the synthetic up thrust is still not. The up thrust fan are either slightly developed or do not develop yet. The post rift subsequence is folded inside and out side the up thrust fault flower. The syn- and pre- rift subsequences are rotated and folded within the up thrust flower and out side it on the north eastern side, whereas they maintain their original dips on the southwestern side.

The strata of the whole lower competent sequence maintain their depositional thicknesses.
4. The disharmonic folding across the mobile sequence is also begun to develop across the mobile sequence.

Fig.9: Structural cross sections across the plunge of Qumar anticline (based on seismic data). Section (a) at the plunge of the structure, and section (b) is slightly far from the plunge

CROSS SECTIONAL GEOMETRY OF THE MAJOR SYNCLINES

The synclines are very simple, broad, flat bottom synclines in the northern half of the studied area. The lower middle Miocene sequence is completely free from rock salts, as there isn't any internal deformation took place within it. Accordingly, the deposition of the lower – middle Miocene rock salts seems to be restricted to depressions formed above the pre-existing upper Cretaceous grabens and half grabens. But it is not clear whether those pre-existing normal faults were directly controlled the deposition of the lower middle Miocene rock salt facies or not? Any how in the northern parts of the studied area and due to the complete absence of the lower – middle Miocene rock salts and consequently the absence of the mobile sequence, the whole sedimentary sequence act as a single mechanical plate in the major synclines.

In Diyala area, the structural situation of the major synclines is different. On the ground surface, the major synclines are very simple depressions filled with recent sediments. And at the level of the upper competent sequence, the major synclines are also simple broad flat bottom or very gently folded synclines (Fig.10). But beneath the upper competent sequence, the mobile sequence is existing and suffered from rock salt flowage and thrusting of the relatively competent strata under the influence of the tangential stresses (Fig.10). On the other hand, the lower competent sequence beneath the surface synclines is usually affected by several positively inverted faults and fault flowers (Fig.10).
In the western parts of Diyala area, the per-Tertiary sequence enclosed between the inverted faults and fault flowers suffered from rigid block relation whereas the Tertiary sequence is folded in front of the advancing inverted faults (Fig.10 case A). The mobile sequence directly above these positively inverted fault flowers flows and thrusts from the local anticline hinge toward the adjacent local synclines. These opposite directions of flowage of rock materials are reflected by opposite directions of thrusting and duplexing within the mobile sequence (Fig.10 case A). In these cases the upper boundary of the mobile sequence act as a passive roof thrust. Occasionally, very gentle anticline developed within the upper competent sequence above the previously described positively inverted fault flower. The previously described disharmonic folding of the major anticlines is frequently absent in those relatively small anticlines. We believe that the harmonic against disharmonic folding across the mobile sequence is inherited from the relatively uniform against non uniform depositional thickness distribution of the mobile sequence respectively.

![Fig.10: The geometry of two different types of synclines; synclines with passive Roof Thrust (case A); and synclines with active Roof Thrust (case B). Cross sections based on seismic data](image)

Eastward in Diyala area, the structural situation of the major synclines is slightly different (Fig.10 case B). Thrusting and duplexing within the mobile sequence is frequently directed toward the west, and huge amounts of rock materials of the mobile sequence flow southwest ward toward the north eastern flank of the adjacent major anticline (Fig.10 case B). The local anticline features developed within the lower competent sequence do not migrate upward toward the upper competent sequence (Fig.10 case B). In contrast, the progressive deformation results in complete depletion of the mobile sequence above the crests of the inverted flowers and occasionally the upper decollement surface partly scratches these crests, In this case, the upper decollement (thrust surface) locally cuts down stratigraphy in the direction of its
movement. This phenomenon is resulted from the simultaneous movements on the upper decollement surface and the up thrusts that forming the inverted flower. Similar cases were described by Vann et al. (1986); Gillcrist et al. (1987) and Coward et al. (1991).

**COMPRESSIVE FAULT BLOCKS OF EAST DIYALA AREA**

East ward, in the area of Chia Surkh, Shakal, Qasar Shereen and Jera Pika, the structural relations are more complex. Figure (11) is a cross section through Chia Surkh structure. This figure is similar to the previously described cross sections in all of their geometrical criteria except one thing. The reflectors of the lower competent sequence (horizons H2 to H4) are actually do not fold, they are rotated on the hanging walls of the major up thrusts and maintain their original dips on the foot walls of those up thrusts. This phenomenon postulates that the original normal faults were actually broke through the lower boundary of the mobile sequence and consequently directly control the depositional thickness of it. On the other hand, horizon H1 is folded above the major synthetic up thrust suggesting that the original normal fault was dying within the mobile sequence.

The very important conclusion of this phenomenon is that the lower-middle Miocene age was influenced by an extensional phase of deformation centred in east Diyala area, and the influence of that phase was extending westward to west Diyala area and northward to Kirkuk area. The extent of the mobile sequence southward in Iran also postulates that the influence of the lower-middle Miocene extensional phase was much larger than the studied area, and possibly it was affecting the whole Zagros un-elevated fold belt in Iran.

![Fig.11: Example of development of compressive fault blocks](image)

Notice that only horizon H1 is folded whereas horizons H2 → H4 are only rotated.

UCS: upper competent sequence; MS: mobile sequence; LCS: lower competent sequence. Cross section based on seismic data
DISCUSSION

In the structural studies, it is meaningless to describe the geometrical relationships only unless it leads to better understanding of the dynamics, kinetics, and the mechanism of the deformation. Geometrical analysis also aims to clarify the structural history of the studied regions. In the following we will try to clarify the above mentioned issues.

1. Dynamics of folding

The positively inverted structures are either developed as a drape folds resulted from vertical forces (Friedan et al., 1976) (Fig.12) or as a forced folds resulted from horizontal tangential stresses (Mitra, 1993; Stearns, 1978; Lowell, 1985) (Fig.12). The drape folding characterize by inverse direction of flexural slip (the strata slip from the crest of the anticline toward the trough of the adjacent syncline) and extensive normal faulting along the crests and the gentle limb of the monocline (anticline). Both of these features are completely absent in the studied area. In contrast the development of the extensive upper bedding thrusts is a striking evidence of the presence of true tangential stresses (Boyer and Elliot, 1982; Mitra, 1986) and this is the first conclusion. But the influence of the tangential stresses could be restricted to the upper competent sequence. This influence of the tangential stresses is possible only if the mobile sequence is persisting across the adjacent synclines and the upper competent sequence could slip over it. In such a case the folding and the shortening will be restricted to the mobile and the upper competent sequences (Fig.13). But the mobile sequence is completely absent in the synclines of Kirkuk area and consequently it is not possible to assume that the surface thrusting in Hemrin north results from the transfer of the shortening from Jamber and Pulkhana. On the other hand the lower competent sequence is always deformed and in the same direction of reasoning, the folding inside and outside the major fault flowers supports the influence of the tangential stresses across the whole sequence. Accordingly it is un-reasonable to assume that the influence of the effective tangential stresses is restricted to the upper competent and the mobile sequences. The second conclusion is that the tangential stresses influenced the whole deformed sequence.

But, (Al-kubaisi, 2003, in Press) showed that the inversion of movement on such a pre-existing high angle faults (like the proposed pre-existing graben’s and half graben’s forming normal faults) under tangential stresses is impossible unless these high angle faults are related to deep subsurface detachments or at least, suffer from considerable reduction in their dip angles downward (Fig.14). The folding of the lower competent sequence on the north eastern sides of the up thrust flower is a very good indication of the possible listric shape of the synthetic up thrust and consequently the lower detachment is most probably present and it is gently dipping toward to northeast (Fig.14). In opposite the maintenance of pre-deformational dips of the lower competent sequence on the south western side of the major up thrust flower postulates that the antithetic up thrusts are not related to any lower detachment and they are most probably die at the synthetic up thrust (Figs.3 and 5). Mitra, (1993) described similar case and showed that the inversion of movement on the antithetic up thrust takes place as those antithetic faults pass through the bend of the listric fault (Figs.3 and 5). Marouf, (1999) used this criterion and deduced that the lower detachment is possibly located at the brittle-ductile crust interface at about 20 Km depth from the ground surface. Accordingly and from dynamic point of view, the folding of the studied area was
resulted from tangential stresses acting on the whole upper crust including the sedimentary sequence, and the inversion took place on a northeast dipping listric pre-existing faults.

The important question is whether this tangential compressive stress field is coaxial with the ancient extensional field or not? (Fig.15). (Coward et al., 1991; Coward, 1996) showed that in case of non coaxial inversion, wrench faulting at relatively low angles to the axial trends of the major folds usually developed. In Kirkuk – Diyala area such a wrench faulting is completely absent. Accordingly we believe that both the ancient extensional and the later tangential compressive fields were coaxial and oriented in NE – SW direction, and this is the last conclusion related to the dynamics of inversion and folding. It is important to point that (Al- Kubaisi, 2003 in press) also showed that the Tigris fault system in Al-Mosul area is a major wrench fault oriented at relatively low angle to the axial trends of the major folds in that area. In Al-Mousal area the change in the general trend of the Zagros simply folded belt from the NE direction to E – W trend takes place. It seems that the inversion process is non-coaxial with the ancient extension in Al- Mousal area.

2. Kinematics of folding

Figure (16) elucidates the stages of the kinematics evolution of the major structures of the studied area, which is based on the previous descriptions of figures (3, 5 – 11).

During the early stages of the contraction, the whole sequence was translated south west ward on the lower detachment. This translations results in an inversion of displacement on the pre existing normal faults, a thrust displacement started to develop along both the synthetic and the antithetic up thrusts (Figs.9 and 16). As the rock sequence pass through the bend of the pre-existing listric fault, the strata on the hanging wall bend (rotated) parallel to the bend of the listric fault and thrust displacement gradually developed on the antithetic up thrusts (Figs.9 and 16). The structures bounding up thrusts migrate up stratigraphy and a major fault propagation fold begin to develop within the Tertiary sequence (Figs.9 and 16). As the innermost antithetic fault pass through the bend of the synthetic up thrust, a space problem developed within the pre-Tertiary strata. This space problem resulted in folding of the pre-Tertiary sequence bounded by the synthetic and the innermost antithetic up thrusts (Figs.9 and 16). It also results in development of thrust displacement on the antithetic fault.

With new increments of progressive contraction, the synthetic and the antithetic up thrust migrated up stratigraphy and break through the lower boundary of the mobile sequence. It is possible that the antithetic up thrust suffer from counter clockwise rotation and broke through the mobile sequence before the synthetic up thrust (Figs.9 and 16). Once the antithetic up thrust displaces the lower parts of the mobile sequence, the low shear resistance rock materials of this part flows from the median zone of the northeastern flank, toward the hinge zone and the southwestern flank, and down the northeastern flank of the major anticline (Fig.16). At the onset of the flowage of the materials of the mobile sequence, the disharmony of the major fold across the mobile sequence began to develop.

Another small increment in contraction resulted in an increase in the amplitude of the major anticline, reduction in the half wave length of it, an increase in the thrust displacement on both of the up thrusts, more squeeze of material from the northeastern
flank toward the hinge zone and the southwestern flank and down the northeastern flank itself and consequently magnification of the disharmonic folding (Fig.16).

This contraction increment is actually resulted from the passing of new strata and bending of them from the nearby northeastern syncline above the bend in the lower detachment.

At this stage the up thrown side act as a buttresses against the movement of the mobile sequence on the north eastern flank, and the down flank lenses or triangles began to develop (Figs.3, 9 and 16).

At the middle stages of the contraction deformation, either the synthetic up thrust breaks through the lower part of the mobile sequence or the flowage and slipping of the competent horizons reach the upper most horizons of the mobile sequence above the antithetic up thrust.

If the former process took place, the southwestern side of the hinge zone lens and the down southwestern flank lens develop within the mobile sequence.

If the latter process occurred, the upper bedding thrust develops at the north eastern flank (Figs.3, 9 and 16).

![Drape folding model](image1)

**Fig.12:** Drape folding model (modified after Friedmann *et al.*, 1976) against forced folding model modified after Stearns (1978)

![Hypothetical case](image2)

**Fig.13:** Hypothetical case of shortening transfer above the upper decollement surface. Notice the deformation of the upper competent sequence (UCS) and the mobile sequence (MS) and the absence of any deformation within the lower competent sequence (LCS)
Fig. 14: Explain the need of shallowing of the lip of the pre-existing fault to be inverted. If the $\Theta > 60^\circ$, the inversion of movement on the fault will follow the friction envelope (a), and it is impossible to move. If $\Theta < 60^\circ$, the inversion will follow the friction envelope b and c and inversion is possible-notice that during the inversion $\Theta_1$ increase due to the fault rotation and subsequently the movement on the inverted fault will cease soon, or transfer to the foot wall shortcut [modified from Al-Kubaisi (2003)].
Fig.15: Coaxial against non Coaxial inversion, notice the relation between the fold axis and the ancient grabens and the development of the wrench faults
With progressive contraction, more antithetic faults pass through the bend of the lower detachment and up thrust displacement developed on them. Consequently more than one down northeastern flank lens or triangle developed. In details, the structurally highest antithetic up thrust pass over a sector of the synthetic up thrust with an increasing upward dip angle (Fig.17). This process results in a clock wise rotation of the whole block bounded by the major up thrusts a round a horizontal axis trending parallel to the axial trend of the major structure. But due to the space problem, this body rotation is impossible. Consequently the movement on the major antithetic up thrust is ceased and the displacement is transferred to a newly formed antithetic foot wall short cut (Fig.17). With progressive deformation, several antithetic foot wall short cuts are formed and the displacements are progressively transferred to the structurally lowest short cut (Fig.16). With respect to the former graben, these foot wall short cuts will break through the foot wall side of the former graben, and consequently they will cut the thinnest, and the relatively constant thickness parts of the syn-rift subsequence. In response to the same rotational movement, either the newly formed sectors of the major synthetic up thrust will get a progressively higher dip angles upward or the displacement transfers to a newly formed higher angle hanging wall short cut (Figs.16 and 17). Actually both of these features were observed in the studied major anticlines. In conclusion the block bounded by the major up thrusts will climb upward along the synthetic up thrust and displaced northeast ward along the relatively moderately dipping antithetic up thrust fan. This rotational movement continues till the antithetic up thrust pass over the whole curved sector of the synthetic up thrust and climb up on a sector of it with a relatively constant dip (Fig.17). At this stage the displacement on the antithetic up thrust fan will cease, and the whole block bounded by the major up thrusts will only climb up the synthetic major up thrust. This interpretation clarifies why the antithetic major up thrusts are very rarely breaking through the mobile sequence, and why the synthetic up thrusts are occasionally displacing the mobile and even the upper competent sequences.

At the same time the flowage of the incompetent rocks and the slip of competent horizons could reach the upper most horizons of the mobile sequence on the south western flank of the major anticline and the upper antithetic bedding thrust started to develop as a passive roof thrust. During this stage or the previous stage of contraction, the synthetic upper bedding thrust break through the upper competent sequence (Figs.3 and 16) and small fault propagation folds developed within this sequence in front of the advancing synthetic upper thrust.

In the late stages of the deformation, the displacement on both synthetic up thrusts and upper bedding thrusts increase. Occasionally the synthetic up thrust breaks through the upper competent system displacing the upper bedding thrust (Figs.5 and 16). In this case the foot wall side of the synthetic up thrust act as buttresses in front of the advancing hanging wall of the synthetic upper thrust and a detachment fold is developed within the upper competent sequence against the foot wall of the synthetic up thrust (Figs.5, 6 and 16). More rarely the up thrusting block of the antithetic up thrust produce a bend in the synthetic upper bedding thrust which develops later into a new thrust ramp (Fig.5).
Fig. 16: Kinetic evolution of the anticlines
UCS: upper competent sequence, MS: mobile sequence, LCS: lower competent sequence. The direction of block rotation see the text for the details.

Fig. 17: Clarifies the counter clockwise rotation of the antithetic fault (AF) as it is pass through the bend in the synthetic fault (SF). The figure also illustrates the formation of the antithetic shortcuts (ASC) and the synthetic shortcuts (SSC), and the folding of strata inside the inverted block and on the north eastern side of it.
With progressive deformation, the anti-gravity movements on the major synthetic up thrust becomes progressively hard and impossible and consequently the displacement transfers to the previously abandoned synthetic foot wall short cuts (Figs.16 and 17).

If the mobile sequence is continuous in the southwest ward direction, the next increments of the contraction results in migration of the foot wall up thrust fan of the synthetic up thrust through the mobile sequence toward the adjacent syncline which is the case in Diyala area (Figs.10 case B and 11). If the mobile sequence is not continuous in the south west ward direction, the major anticlines attend higher relieves due to the continuous contraction displacement on the lower detachments which is the case in Kirkuk area and at the southwestern edges of the whole simply folded belt (Fig.10 case A).

The build up of relatively high structural relief, the sticking of movement in front of the synthetic up thrust fan and the increasing difficulty of anti-gravity movement of the whole major structure along the synthetic up thrusts, result in an accumulation of more tangential stresses at the bend of the lower detachment. Once the accumulated shear stresses at that bend exceeds the shear resistance of the rocks, the whole system transfer southwest ward on the newly formed or the pre existing lower detachment. During this body transfer of the whole rock sequence on the lower detachment, inversion of the movement on any pre-existing normal fault could happen and the whole or parts of the previously described processes could be repeated. The amount of inversion and the intensity of the contraction associated with that inversion depend on the value of the shear resistance of the rock system and the amount of shear stresses accumulated at the branch line of this newly incorporated fault. If that shear resistance is low enough no inversion on the pre existing normal fault could happen. Slightly higher shear resistance could result in small inversion and folding. In these cases, the shortening of the pre-mobile sequence is either completely consumed by the flow of the mobile sequence (Fig.10 case B) or major part of it is consumed by the mobile sequence (Fig.10 case A). In both cases, the slipping (body translation) of the upper competent sequence over the mobile sequence (upper decollement surface) is needed to accommodate the shortening of the whole sequence.

East ward in Diyala area, it seems that, the pre existing normal faults were originally cutting the mobile sequence and have relatively shallower dips and consequently the later inversion of movement was easier. In this area most of the shortening was consumed by the thrust displacements on these inherited faults and by the flowage of the mobile sequence. The associated fault propagation folding is minimum and restricted to the upper competent sequence and the whole deformed system forms as a compressive fault block (Fig.11).

The above described kinematics of deformation is reasonable and well accepted for us to interpret the geometry of the major structures of the whole studied area, except the problem of the presence of the major syncline between Jambur, Pulkhana, and Hemrin North anticlines. It is still un-reasonable to believe that such a very wide (70 Km), thick (15 Km) completely un-deformed sequence forming this major syncline was translated southwestward above a lower detachment with no sign of any internal deformation. Similar problem also exists in northwestward direction in the continuation of the un-elevated folded zone in Erbil and Mosul area. The relatively low deformation
(shortening about 1%) (Marouf, 1999), in comparison with wide extent of the whole un-
elevated folded belt (width 100 to 150 Km) is one of the problems of the kinetic
 evolution of the Zagros folded belt. Similar very wide un-deformed synclines were also
described from the Zagros un-elevated folded belt in Iran (Faacklen, 1968; BP, 1956;
Collman, 1978). Davis et al. (1983) assumed that the shortening transfer could occur in
this manner in case of detachment on a very low shear resistance rocks, and they
suggested that the Zagros folded belt in Iran is detached over the Hormis Salt.
Unfortunately, first: there is not any indication that the Hormis Salt is continuous in
Iraq, and second: our geometrical analysis postulated that the lower detachment surface
is most probably located at the brittle-ductile crust interface not at the sedimentary-
basement interface as the stratigraphic location of the Hormis Salt. It is also un-
reasonable to assume that the brittle-ductile crust interface is a very low shear resistance
zone.

Marouf (1999) suggested that the horizontal shortening could result from some in
place tectonic process and do not need to be transferred for a relatively long distances.
He assumed that such an in place shortening could result from in place or restricted
subduction of the continental lithosphere. The evidence on such a process came from
the Cretaceous elevated folded belt. This belt was folded and elevated at the onset of
Tertiary, even before the continent-continent collision between the Arabian and the
Iranian plates that took place at the end of the lower Miocene. Accordingly the
tangential stress field and the resulted horizontal shortening that produce the Cretaceous
elevated folded belt should be resulted by a process other than the continental collision.
Recent works (Mac Niocaill and Ryan, 1999; Miller, 2001) showed that continental
subduction could occur in response to an eclogitization process of the lower part of the
continental lithosphere and this process is always preceded by considerable subsidence.
Both of the early Tertiary and the post Miocene contraction phases that developed the
elevated and the un-elevated folded belts in Iraq were preceded by considerable
subidence in the sedimentary basin during the upper Cretaceous and the Miocene-
Pliocene respectively. We believe that the continental subduction is an acceptable
solution to the problem of the horizontal shortening transfer and consequently the
kinetics and the dynamics of the inversion and folding of the Zagros fold belt in Iraq, at
least for the time being. But it is also very important to remember that the Arabian –
Iranian continental collision magnified the deformation of the previously existing
Cretaceous elevated folded belt, and possibly aids the deformation of the un-elevated
folded belt.

3. Mechanisms of folding

The detection of the mechanisms of folding and the history of the local variations in
the effective stress fields is usually based on the analysis of the microstructures. For
example the slickenside striations on the bedding planes are the direct evidence of the
flexural slip mechanism of folding and the distribution of the extensional features
(veins, fissures, mesoscopic normal faults and extensional shear joints) versus the
compressive features (stylolites, mesoscopic thrust, compressive shear joints and
congruent and incongruent mesoscopic folds) is the direct evidence of the neutral
surface folding (Donath and Parker, 1964).
At the very early stages of the deformation, the whole sequence act as a single mechanical plate deformed by body translation on the lower detachment and by neutral surface mechanism in the anticlines. But once the flowage of material within the mobile sequence is started, the whole sequence is separated into three mechanical plates, the upper and lower competent sequence (plates) and the mobile sequence. For a while the upper and lower mechanical plates continued to deform by the neutral surface mechanism. This behavior is indicated by the extensive extensional features at the outer arcs of these plates and the contraction features at the inner arcs of them. The extensional features are veins, fissures joints and extensional conjugate shear fractures and fault. All of these features are perpendicular or at a high angle to bedding. These features are widely extended in the upper Miocene and Pliocene strata of the upper competent sequence and the Paleogene and occasionally the upper Cretaceous strata of the lower competent sequence. On the other hand extensive macroscopic thrust faulting and contraction conjugate shear failure was encountered in the middle Miocene Fatha Formation and intensive vertical stylolites were also reported from the core samples of the middle – lower Cretaceous and Jurassic strata.

The mobile sequence acts also as a single mechanical plate deformed mainly by flowage of material. But the direction of flow of material is different from the usual direction of the flexural flow described by Donath and Parker (1964). In the usual flexural flow, the rock material flow from the inflection zones toward the hinge zones, and this type of flow aid in maintenance of fold shape with depth (Donath & Parker, 1964; Ramsay, 1974). In our case and at the early stages of deformation, the rock material flowed from the median parts of the north eastern flanks toward the hinge zones and the south western flanks and toward the inflection zones of the north eastern flanks. We believe that this unusual type of asymmetrical flow resulted in the previously described disharmonic folding. On the other hand this disharmonic folding is different than the usual disharmonic folding formed at the inner arcs of the detachment folds mainly due to the space problem (Mitra and Namson, 1989).

With progressive deformation and the development of the synthetic upper bedding thrust, the body translation mechanism dominates the deformation of the upper competent sequence (plate). In the lower competent sequence (plate), the space problem and the rotation of the major up thrust toward higher angles is solved by body translation on the up thrust and progressive folding of the sequence bounded by these up thrusts mainly by flexural slip mechanism. At this stage the synthetic up thrust break through the mobile sequence and the direction of flow of material is change. At this stage the rock materials flow from the median parts of both the north eastern and the south western flank toward the hinge zone and the inflection zones of both flanks. This relatively symmetrical flowage of material is still different than the usual flexural flow, but it results in the elimination of the further progressive evolution of the disharmonic folding.

At the very late stages of folding and when the synthetic up thrust breaks through the upper competent sequence, most of the shortening is consumed by body translation on the synthetic up thrust and to a lesser extended by body translation on the synthetic upper bedding thrust.
RECONSTRUCTION OF THE STRUCTURAL HISTORY

The major structural events are commonly reflected by thickness variations within the sedimentary sequences deposited during these events. The local against regional influences of these structural events is also reflected by direct or indirect thickness variations within the sedimentary sequences. In our studied case there were three sedimentary sequences suffered from pronounced thickness variations. These are the Maestrichtian Shiranish Formation, the lower middle Miocene Mobile sequence and the Pliocene Bai Hassan Maqdadiah sequence. The rest of the Cretaceous and Tertiary sequences maintain their relatively constant thickness along most parts of the studied area. Accordingly during most of the Cretaceous and Tertiary ages, the studied area suffered from relatively calm tectonic activities that restricted to regional subsidence and intervening regional uplifts. The regional subsidence phases were reflected by the deposition of the various sedimentary sequences and the regional uplifts developed the regional unconformities within the sedimentary sequences.

At the onset of the Maestrichtian age, intensive normal faulting within the pre-Maestrichtian sequence was developed and continued during the Maestrichtian inserting a direct control on the deposition of the Shiranish Formation. Asymmetrical grabens and half grabens were developed within which thicker Shiranish was deposited. It is not clear whether these normal faults are related to a lower detachment (listric type) or not (planner domino type), But the south west ward polarity of most of these grabens and half grabens is possibly (?) attributed to an underlying deeply buried north east dipping lower detachment. This extensional phase was not restricted to the studied area, but it dominated the deformation along the north eastern margin of the whole Arabian plate (Dewey, 1973). The abrupt changes in the thickness of the Shiranish Formation across these faults postulate that these normal faults were extending within the Shiranish sequence. It is a true rift phase, and it is very intensive in Diyala area than it is in Kirkuk and the rest of the un-elevated folded zone of the Zagros in north Iraq.

As it was previously described, the deposition of the lower middle Miocene rock salts and its associated facies is restricted to the present anticlines at least in Krikuk area. In other word, the deposition of the lower – middle Miocene rock salt facies is restricted to depressions developed above the pre-existing Maestrichtian grabens and half grabens. It is very hard to reconstruct the depositional thickness of this sequence because of the flowage of it during later contraction phase. But the restriction of the deposition of these facies to the above described depression postulate at least a phase of differential subsidence that took place during the lower – middle Miocene age. The question is whether the pre-existing Maestrichtian normal faults were migrated up stratigraphy (extended) to the lower parts of the mobile sequence during the lower – middle Miocene age or not? In other words is the lower – middle Miocene phase of deformation was just a differential subsidence phase or it was a true rift phase?

Mitra, 1990, 1993 and Suppe and Medwedeff (Suppe and Medwedeff, 1990) stated that in fault propagation folding, the strata are folded in front of the advancing fault until it breaks through them, and once the fault breaks through any folded layer, no further folding takes place and the later shortening is consumed by the transilation of strata on the fault surface. Reconsidering our figures (3, 5 and 9), it is clear that the pre-Tertiary strata maintain their pre-folding dips on the foot wall side of the synthetic up thrust and the Tertiary strata are folded and the angle of dip of these strata increases up
stratigraphy. Accordingly, the folding of the Tertiary strata took place in response to the advancing of the synthetic up thrust through them during the later contraction and the conservation of the pre-Tertiary strata to their per-contraction dips is attributed to the Maestrichtian breaking of these faults through the pre-Tertiary sequence. But reconsidering figure (11) the lower boundary of the mobile sequence and the pre-Miocene strata are not folded on the down thrown sides of the major synthetic up thrusts, and kept in their pre-deformational dips. This phenomenon suggests that the lower boundary of the mobile sequence and the pre-Tertiary strata were originally displaced by the pre-existing normal faults.

Basing on this line of reasoning, we believe that the pre-existing Cretaceous normal faults migrated up stratigraphy during the lower–middle Miocene age and inserted a direct control on the deposition of the mobile sequence in east Diyala area. Accordingly the lower–middle Miocene deformational phase was a true relatively restricted rift phase, and the influence of it migrated west and northward to the rest of the studied area as a differential subsidence phase associated with differential sagging. It is important to point that this extensional deformational phase was not only restricted in space, but it was also restricted in time. In details, the relatively competent Jeribe and the Transition beds of Fatha Formation that sandwiched between the rock salt facies of the lower–middle Miocene strata are extending on the whole area with relatively constant thicknesses. Accordingly the suggested lower-middle Miocene extensional phase is restricted to two relatively short time intervals corresponding to the times of the deposition of the rock salt facies of lower Miocene Dhiban and the middle Miocene Fatha Formations.

Near the plunges of the major anticlines and across the adjacent synclines of the studied area, the deposition of the Pliocene Muqdadiah Bai-Hassan sequence is conformable with the deposition of the underlying upper Miocene Injanah sequence (Fig.9). But closer to the crests of the major anticlines, the Pliocene sequence on lapping on the top of the upper Miocene sequence, especially on the south western flanks of the major anticlines (Figs.3 and 5). This phenomenon postulates that the contraction phase and its associated folding and thrusting started at the onset of the Pliocene and at the present locations of the crests of the major anticlines. At this time, the deposition of the Pliocene sequence was continuous along most of the studied area and truncated across the present location of the crests of the major anticlines. With time progress, the major anticlines grew and extended laterally along their axial trends, and consequently the truncation of the Pliocene sequence migrated and magnified in space and time. What is interesting in this situation is that during the activities of the contraction tangential regional stresses and their associated folding, the whole area was subsiding allowing the deposition of up to 1500 m of Bai Hassan Maqdadiah sequence. This subsidence is directly adjacent to the front of the elevated folded zone of the Zagros simply folded belt and we believe that it is resulted from the excess loading on the crust inserted by the elevated folded zone, in other words, during the Pliocene two major forces were influencing the studied area at the same time. These are the vertical isostatic force act in downward and the tangential contraction force.
CONCLUSIONS

Many conclusions were raised by this study, these are:

1. All the major and the minor structures of the studied area are either fault propagation folds or compressive fault blocks resulted from tangential contraction that resulted in a positive inversion of the pre-existing grabens and half grabens.

2. The inversion process started at the onset of the Pliocene and continued through the later time. Bai-Hassan and Moqdadiah Formations are syncontractional sequence. The contraction was coaxial with the former extensions and the geometry of the former grabens and half grabens inserted a direct control on the three dimensional geometry of the developed folds and compressive fault blocks.

3. Two periods of extension are recognized. The oldest one took place during the Maestrichtian and controlled the depositional configuration of the Shiranish sequence. This period was intensive extensional period and extends along the whole of the un-elevated folded zone in north Iraq, and possibly to its continuation in Iran, Syria and Turkey. The second extensional period took place during the lower – middle Miocene. In details, this period consists of two secondary periods, the oldest one took place during the lower Miocene and controlled the depositional configuration of the Dhiban Formation, and the second period occurred during the middle Miocene and controlled the deposition of the salt bearing strata of Fatha Formation. This extensional phase was centred in east Diyala area and its influence extended west ward and north ward to Kirkuk area. Both, the Maestrichtian and the lower – middle Miocene extensional phases were coaxial with each other's (Fig.18).

4. The geometry of the inverted structures and their internal geometrical relations are controlled by the interactions of the applied stress field, the geometry of the pre-existing structures, the sedimentary basin configuration and the distribution of incompetent against the competent lithologies. These interactions are as follows:
   a. The un-usual axial relationships between the major structures are directly controlled by the three dimensional configuration of the former grabens and half grabens.
   b. The disharmony of the major anticlines across the mobile sequence is inherited from the original configuration of the mobile sequence and magnified and modified by the flow of the incompetent rocks of the mobile sequence.
   c. The minor variations in the kinematics evolution of the major structures and the consequence local variations in the applied stresses results in variation in the internal structures of both the mobile and the upper competent sequences.
   d. The presence or absence of the mobile sequence is directly control the thrusting of the upper competent sequence above the mobile sequence. In Al-Mosul area (northwest Iraq), the mobile sequence is absent and consequently such a thrusting did not occur.
   e. In Diyala area where the mobile sequence is continuous along and across the whole area, the development of the upper bedding thrust as a passive roof thrust or as an active roof thrust in the synclines separating the major structures is directly depending on the intensity of the deformation and consequently the magnitudes of the applied tangential stresses.
Fig. 18: Structural history of deformation in Kirkuk, west Diyala and east Diyala
See the text for the details. E = H1; B = H2; A = H4; B - E = L.
Miocene Dibban Fn.; C - D = L. Miocene Fatha Fn.

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